



Propagating photoinduced strain waves drive ultrafast insulator-to-metal transition in a Mott material

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¹ International Research Lab Japan-France "IRL DYNACOM" (2022-2026)

Let's start with a collective experience



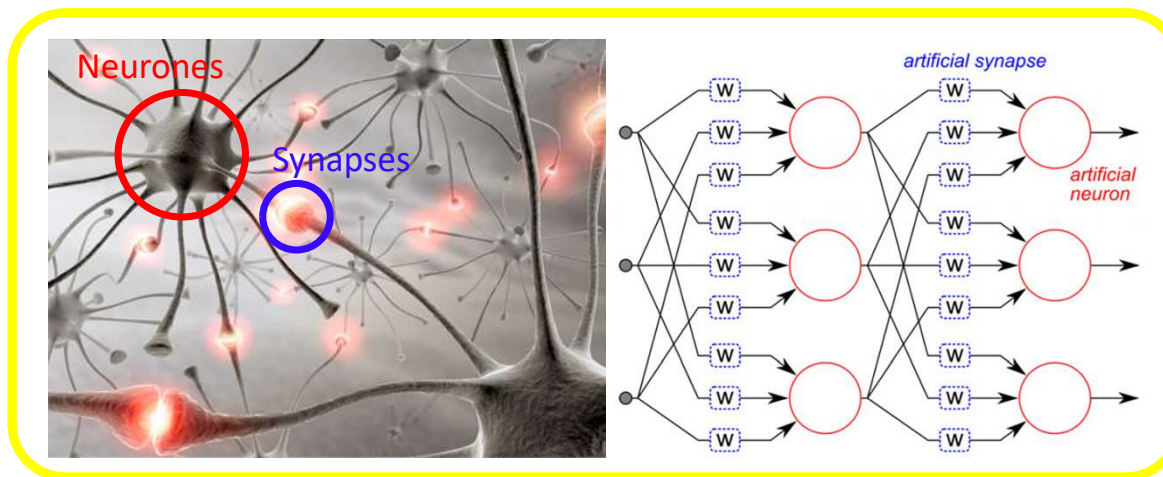
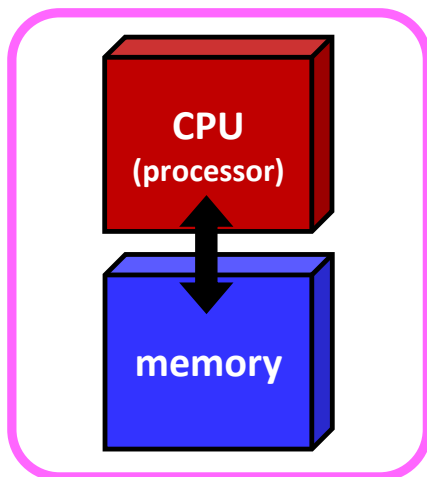
40 000 W



3 W

Information & Communication Technologies = 5-10 % of worldwide electricity consumption, strongly increasing

General context

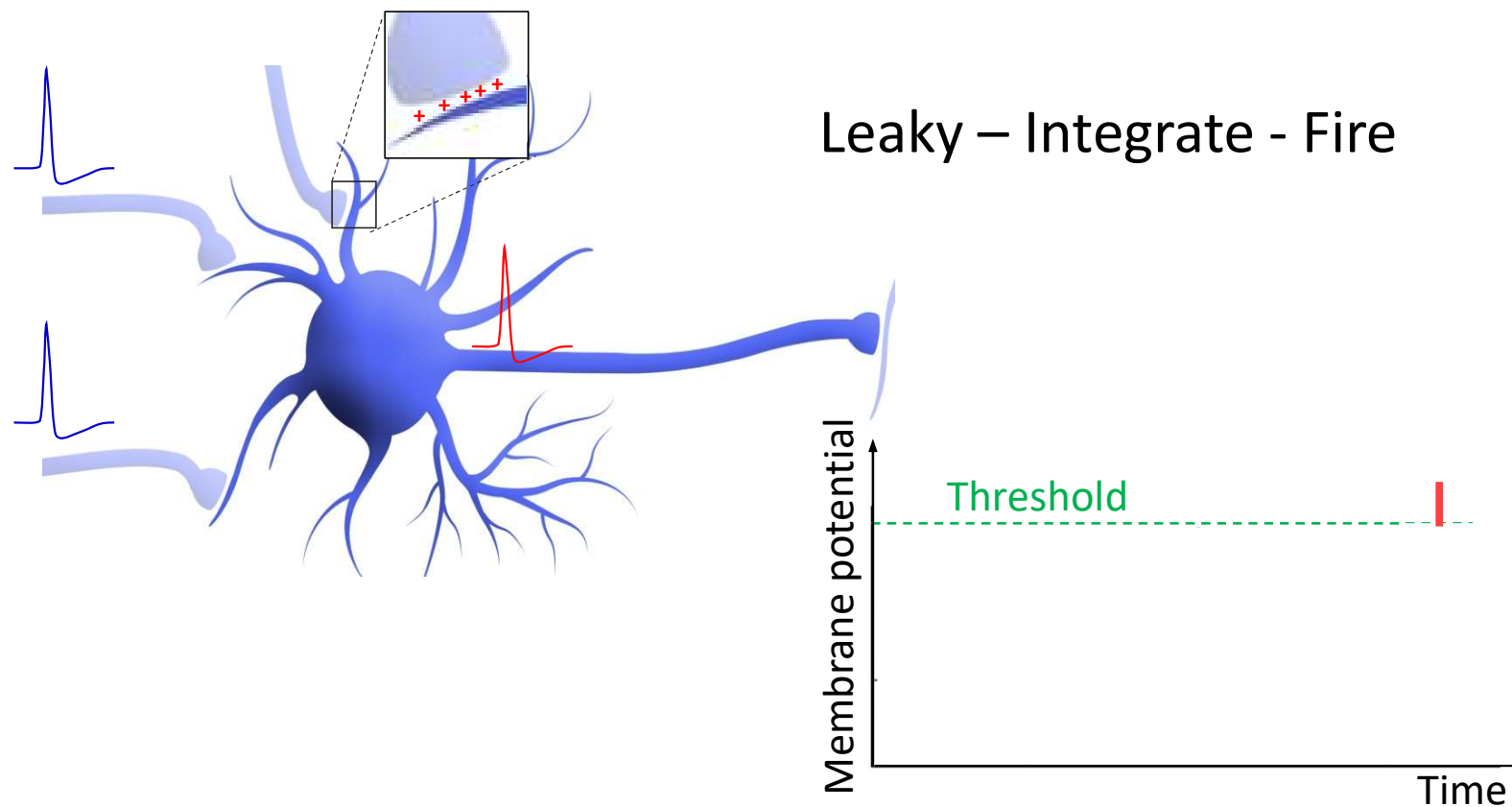


Towards energy-efficient artificial intelligence (AI) ?

General context

Optimal pathway : **Hardware Neural Network**

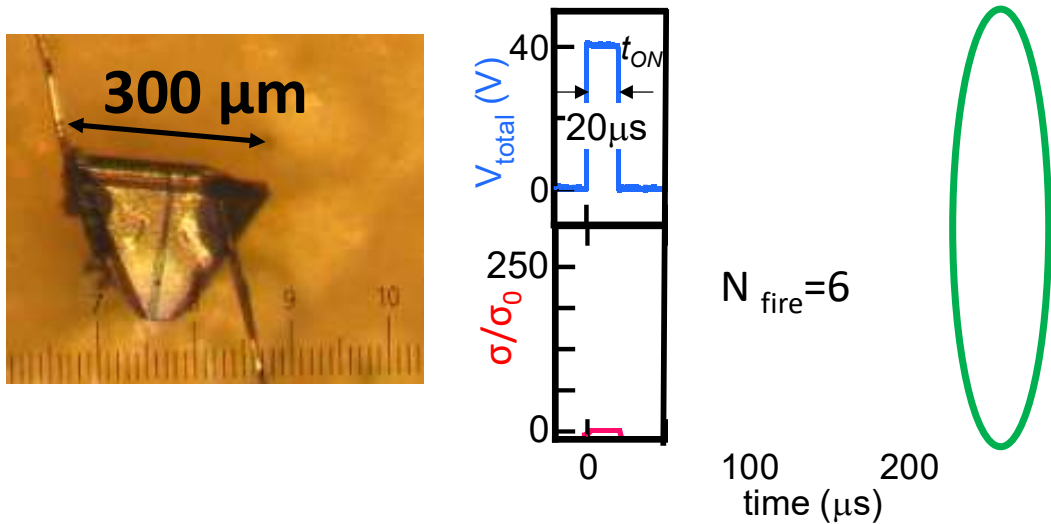
Challenge: implementing the artificial neuron behaving the same as the biological one !!



Artificial intelligence based on Mottronics ?

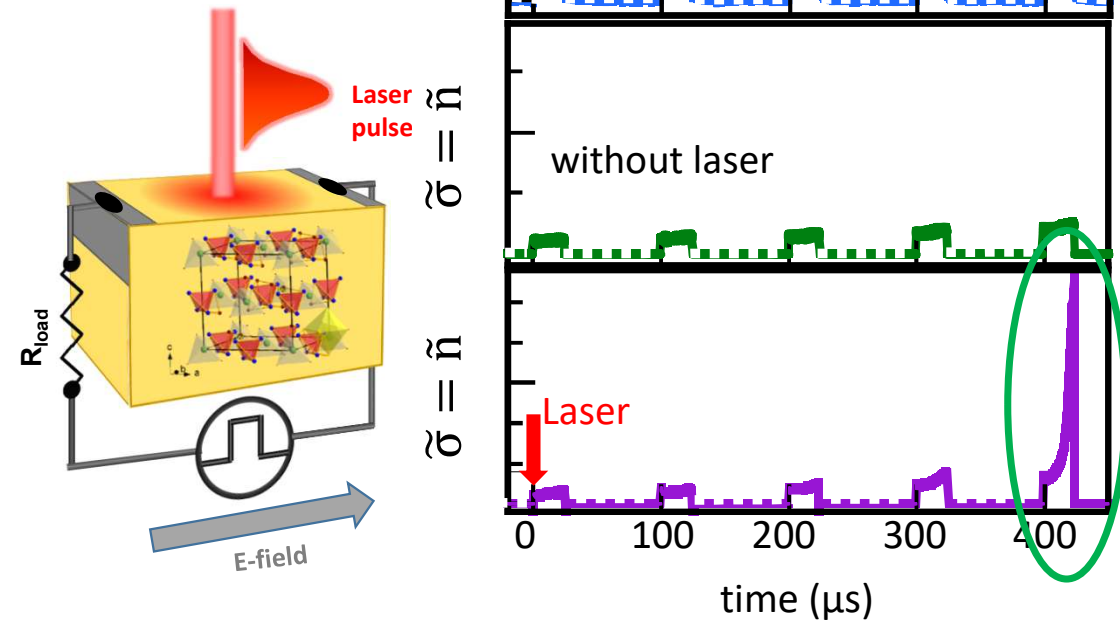
Optimal pathway : Hardware Neural Network

Mott insulators under Electric pulses



P. Stolar *et al.*, Adv. Funct. Mater. **27**, 1604740 (2017)

**Mott insulator to metal transition
→ artificial neurons !**



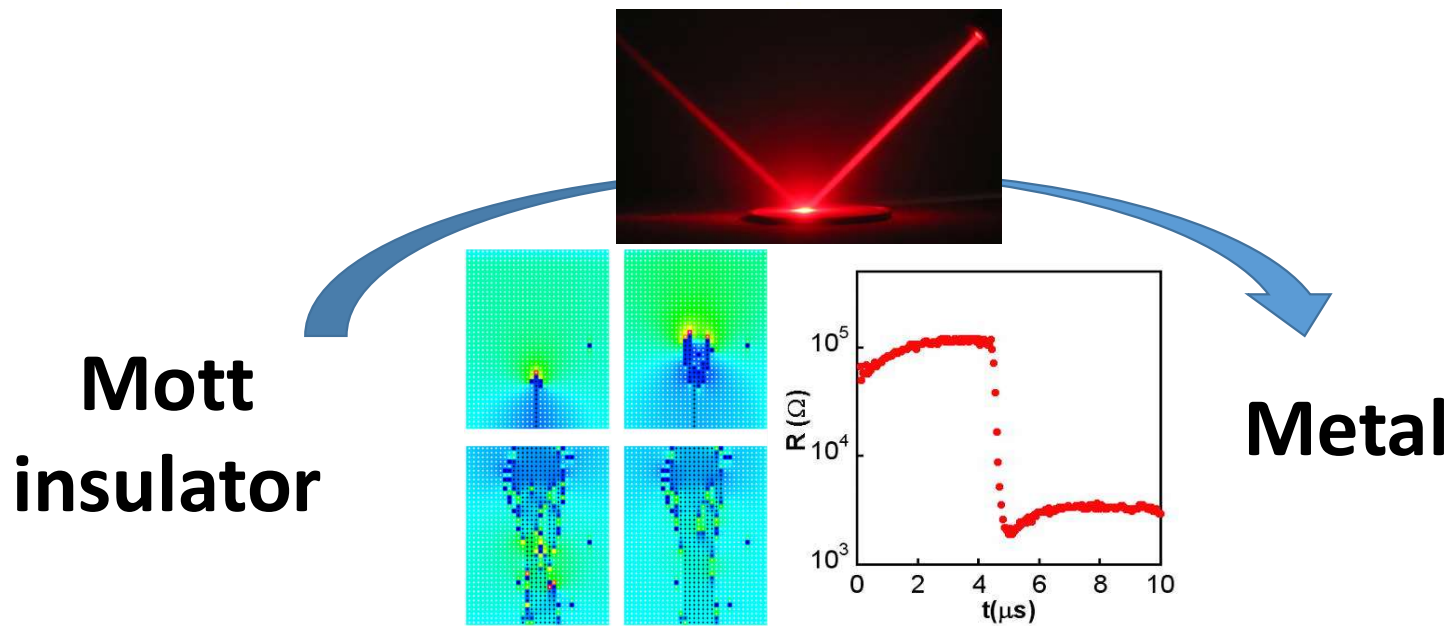
D. Babich *et al.*, PR Appl. **17**, 014040 (2022)

**Proof of principle of electro-optic Mott
neuron**

Before application, back to basics !

Basic questions: ultimate operating speed (= shortest switching time) of Mott devices ?

Answer: replace the slow (ns- μ s) **electric pulse** stimulus...
by ultrafast (fs) **light pulse** \rightarrow photoinduce Mott insulator to metal transition



*France-Japan International
Research Lab (IRL) "Dynamical
Control of Materials" (2022-26)*

<https://tokyo.office.cnrs.fr/cooperation-japan/dynacom/>

Objectives of the presentation

Driving mechanism at play in Photoinduced Phase Transition (PIPT) in quantum materials ?

Physical mechanisms governing the ultimate speed / time scale of a PIPT ?

Is a photoinduced electronic phase transition (here an insulator-to-metal transition) necessarily ultrafast ?

Distinct behaviors of symmetry-breaking and isosymmetric order parameters in PIPT's ?

Context

Propagating photoinduced strain waves drive ultrafast insulator-to-metal transition in a Mott material

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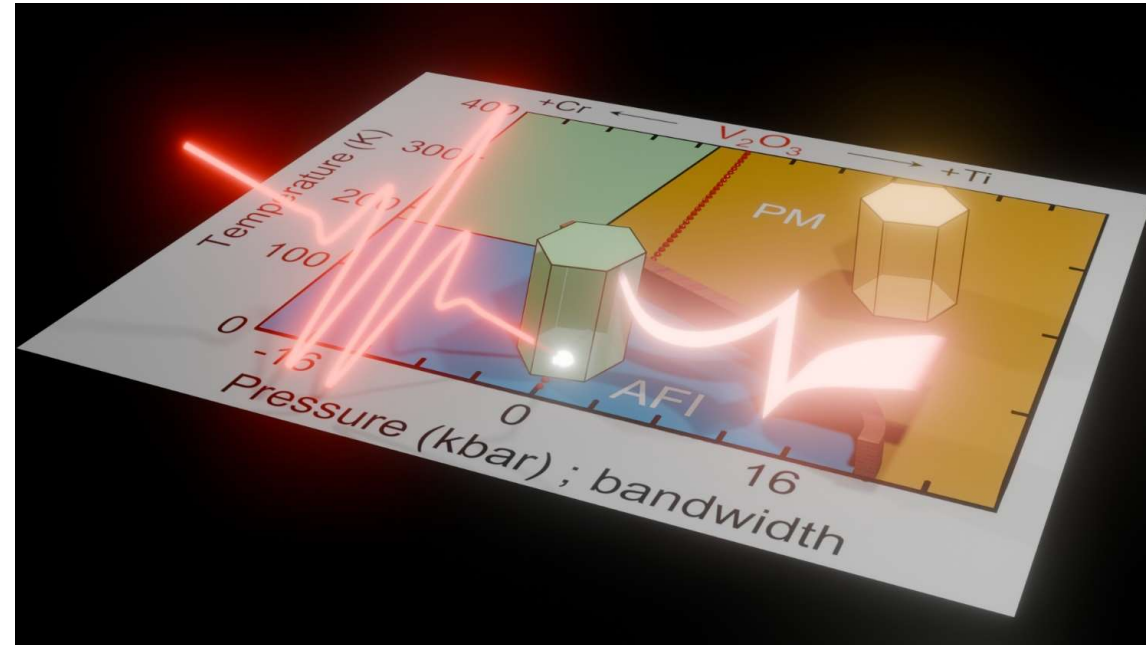
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⁹ CNRS, Univ Rennes, DYNACOM (Dynamical Control of Materials Laboratory) - IRL2015, The University of Tokyo, 7-3-1 Hongo, Tokyo 113-0033, Japan



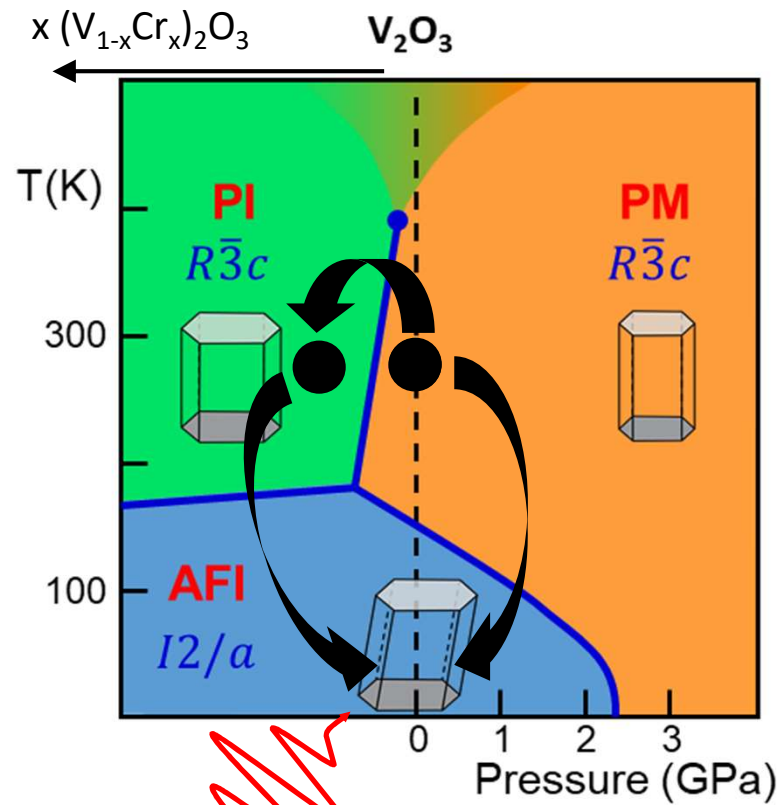
Just accepted (August 2024) in *nature physics*



A canonical quantum material: the Mott system V_2O_3

PM \rightarrow PI transition at equilibrium

PI \rightarrow AFI transition at equilibrium



PM \rightarrow AFI

electronic

lattice

Metal – Mott
Insulator Transition

Volume change
($\sim +1.5\%$)

isosymmetric

Magnetic
ordering

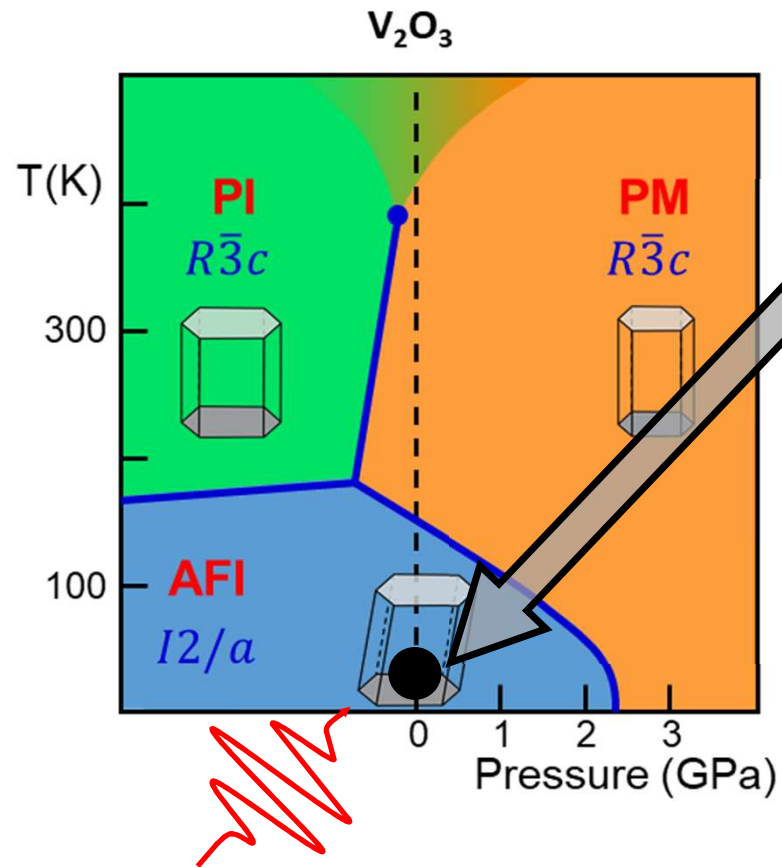
Symmetry lowering
(ferroelastic transition)

*Symmetry
- breaking*

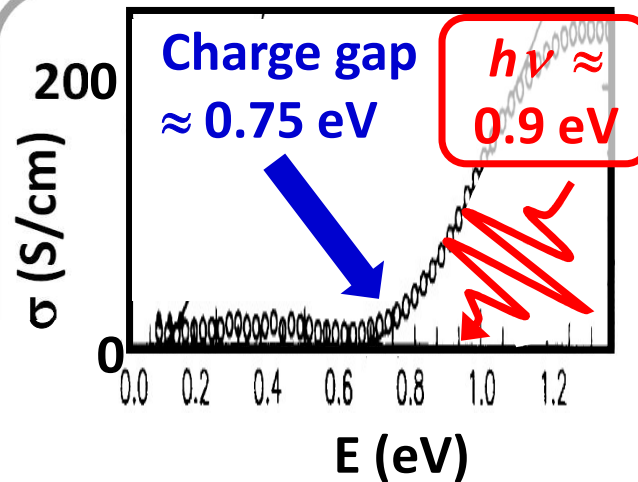
What happens if we photoexcite the AFI phase with ultrashort (< 100 fs) light pulse ?

Tuning experimental conditions minimizing thermal effect

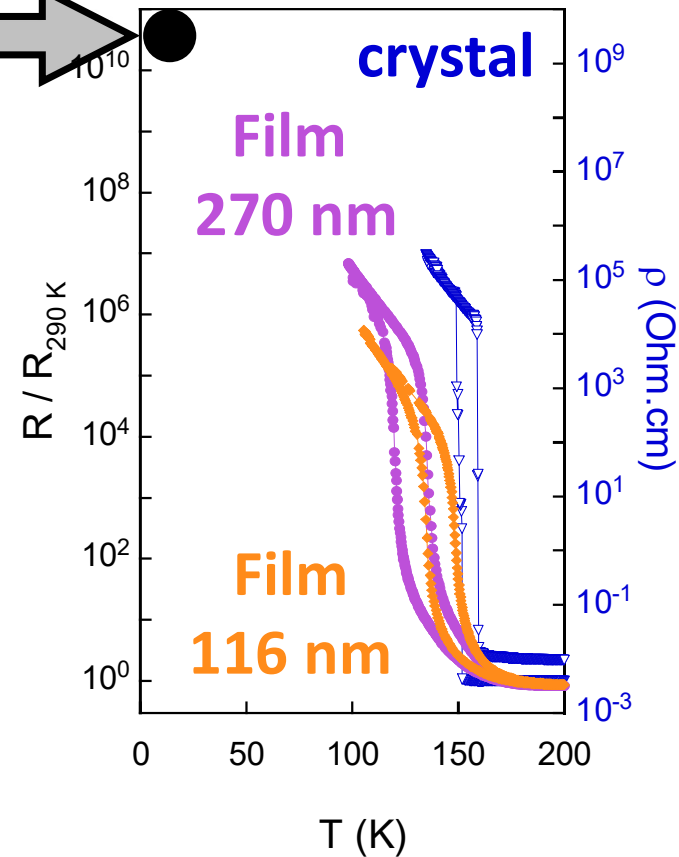
This study:



$T = 10-20$ K
 $\ll T_c \approx 130-160$ K



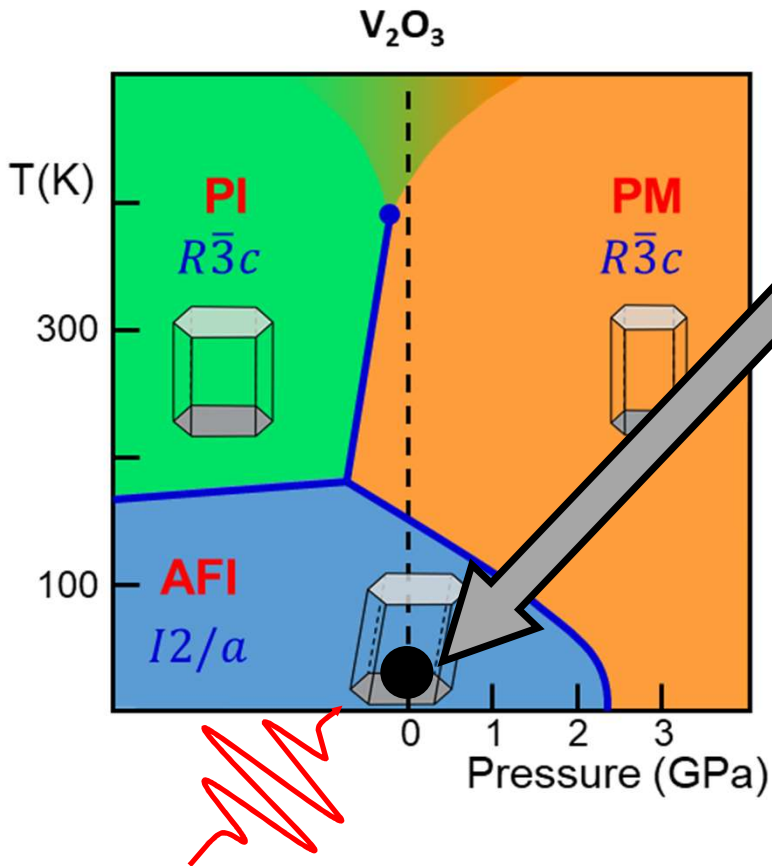
Adapted from Thomas *et al.*,
PRL **73**, 1529 (1994)



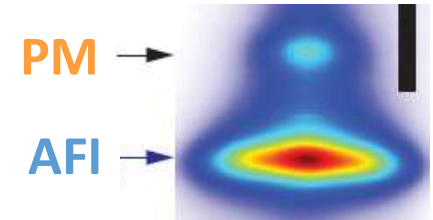
Tuning experimental conditions minimizing thermal effect

This study:

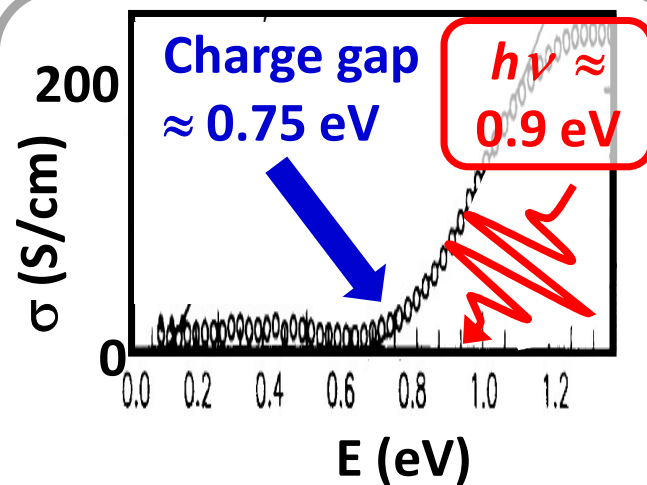
Litterature



$T = 10-20 \text{ K}$
 $\ll T_c \approx 130-160 \text{ K}$



$T = 157 \text{ K}$
 → coexistence AFI- PM

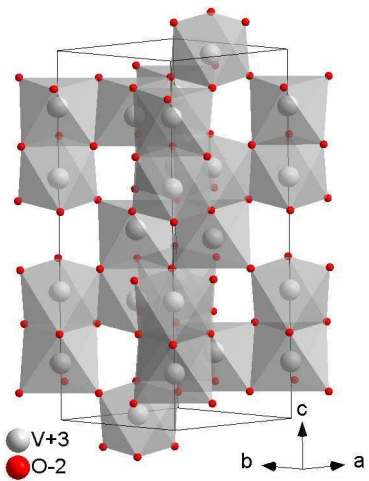


Adapted from Thomas *et al.*,
 PRL **73**, 1529 (1994)

$h\nu \approx 1.55 \text{ eV}$

A. Singer *et al.*,
 PRL **120**,
 207601 (2018)

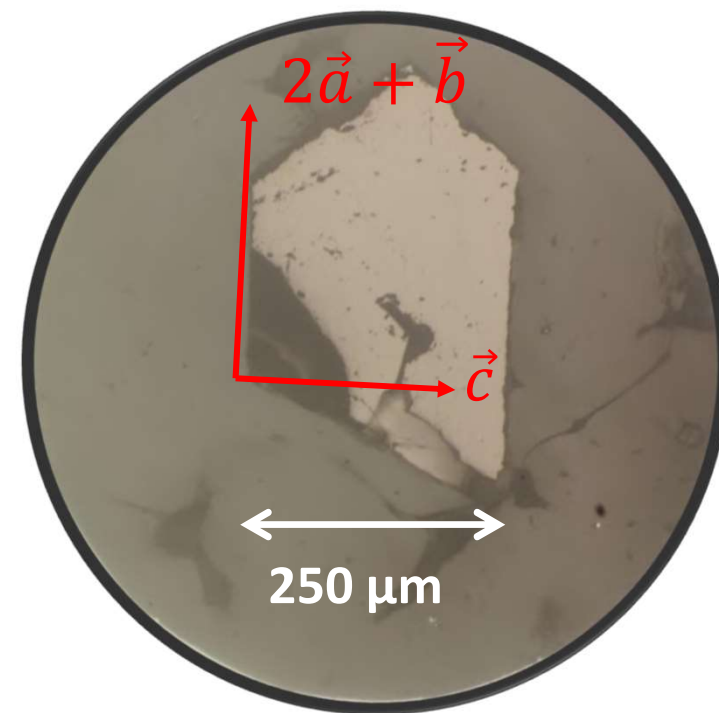
Study on two different morphologies: granular films and single crystals



V_2O_3 granular films



Oriented V_2O_3 single crystals

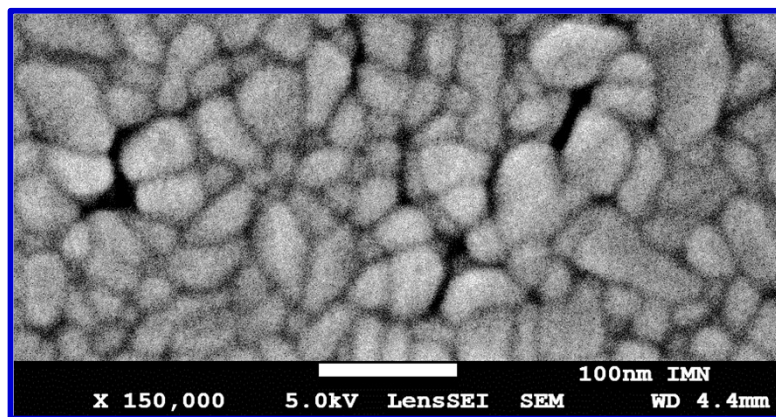


Thickness:

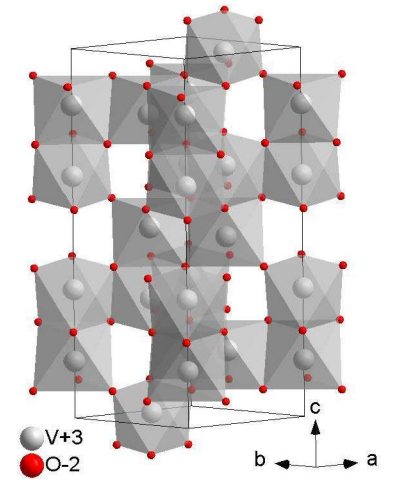
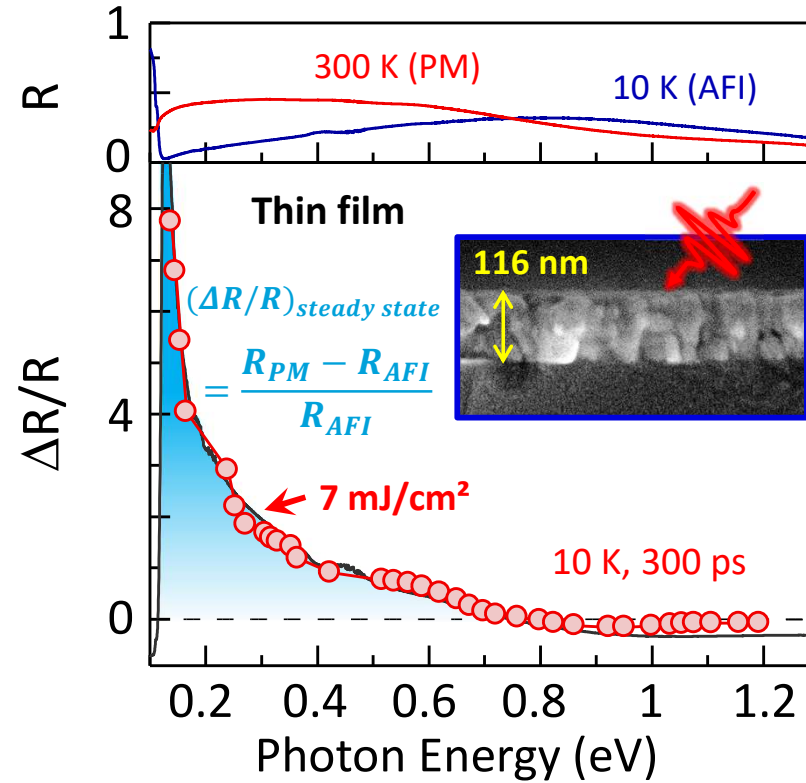
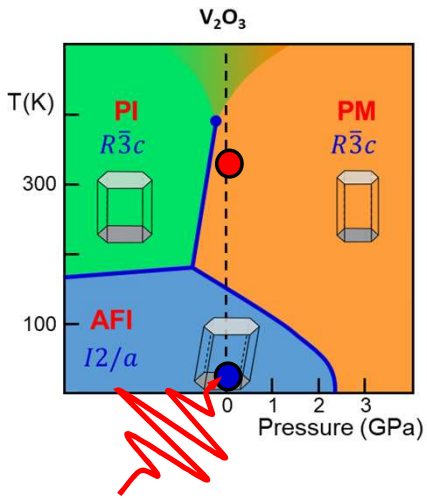
100 to 300 nm

Size ferroelastic domains (AFI):

20-25 nm



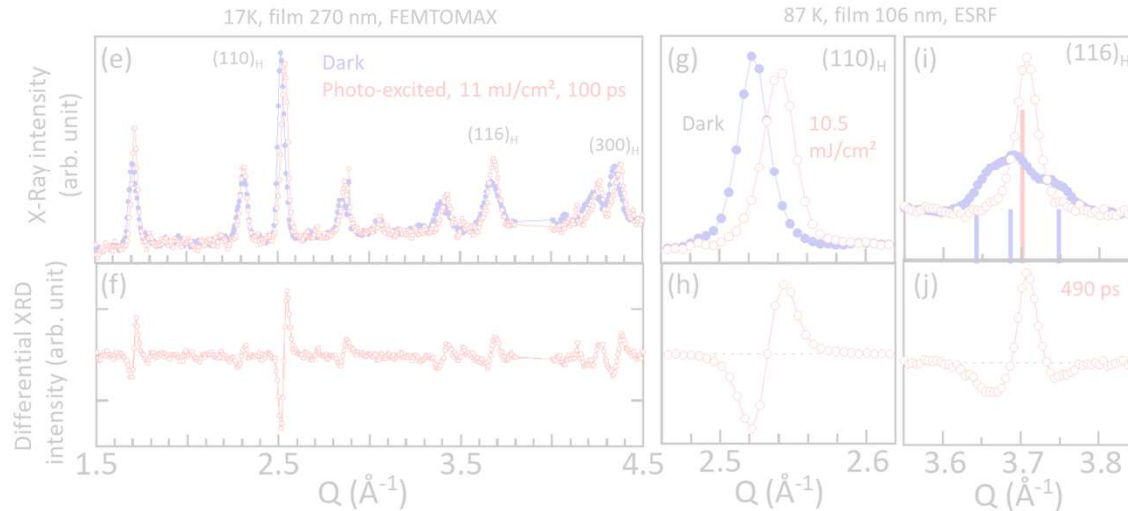
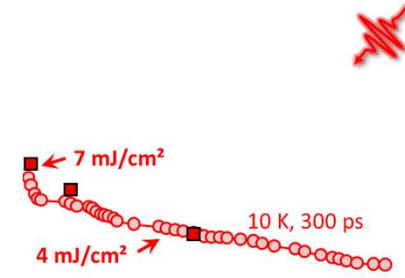
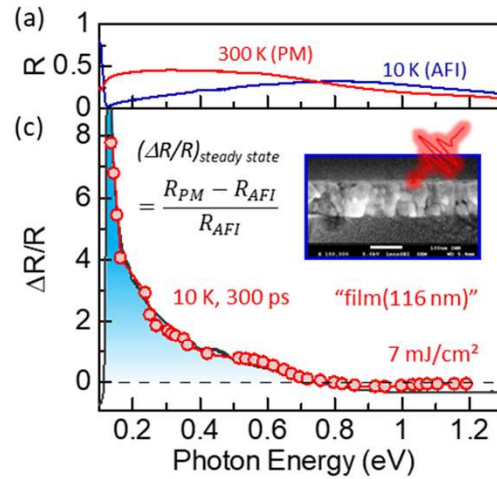
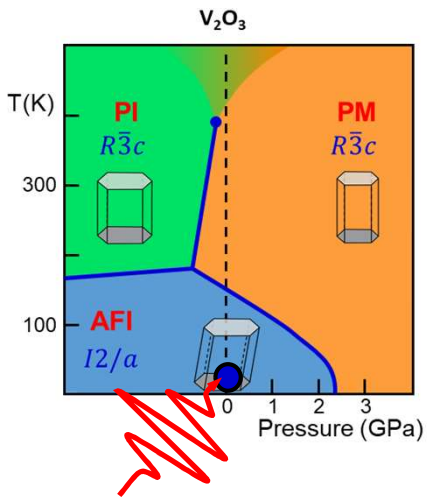
Time-resolved optical reflectivity and X-Ray diffraction studies



$7 \text{ mJ/cm}^2 \rightarrow 4 \text{ photons}$
for 100 vanadium

Full photoinduced Insulator to metal transition in thin film...

Time-resolved optical reflectivity and X-Ray diffraction studies



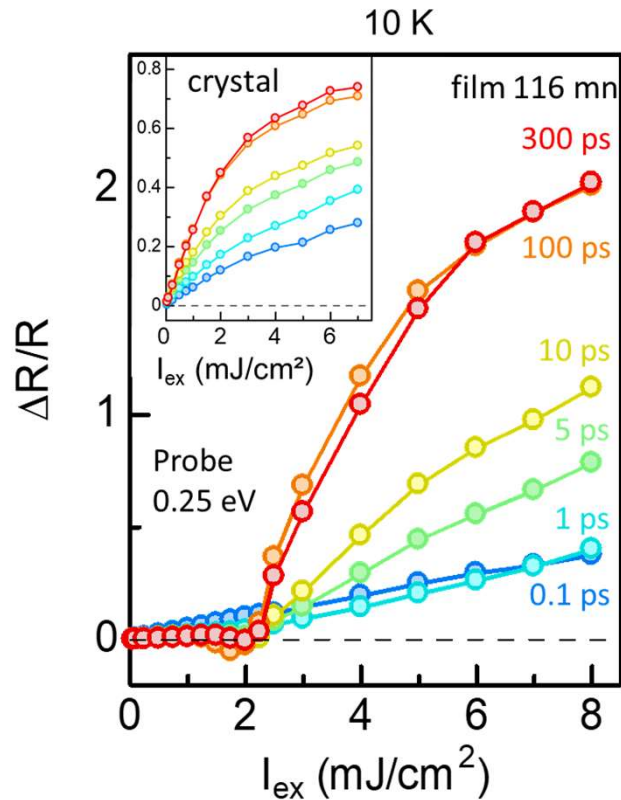
tr-XRD, granular films:
structural transition
→ PM-like phase
(symmetry change & volume drop $\approx -1.5\%$)

Full photoinduced AFI-to-M phase transition in thin film...

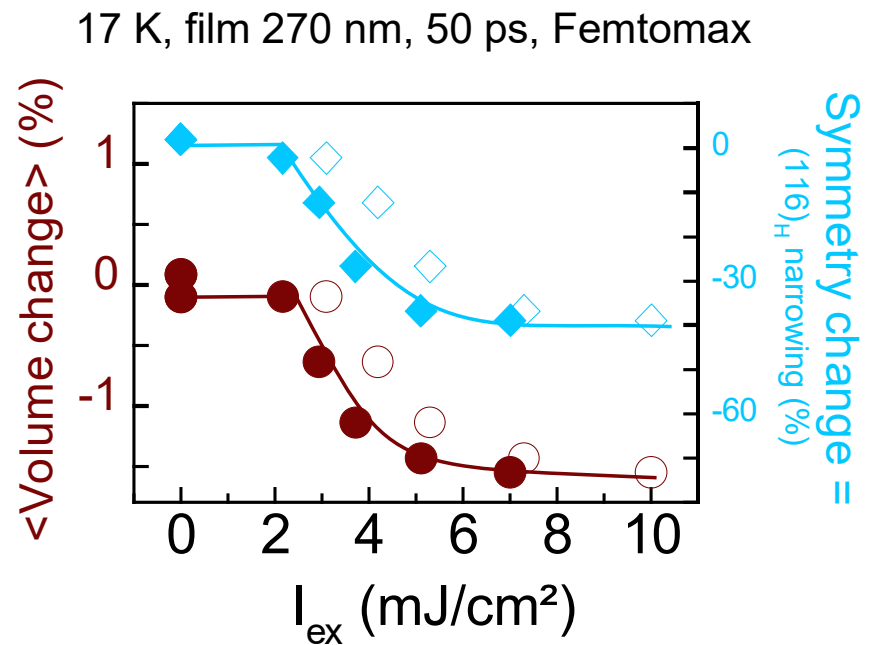
but only partial in single crystal

Ultrafast photoexcitation of V_2O_3 : effect of laser fluence

Electronic change



Structural change

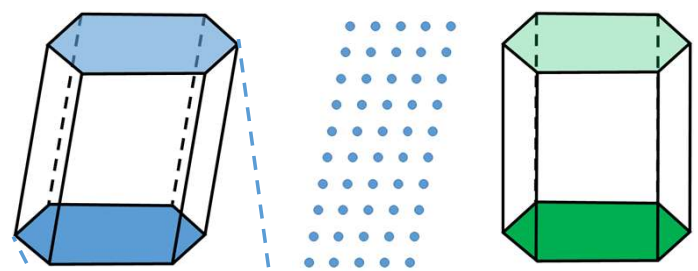
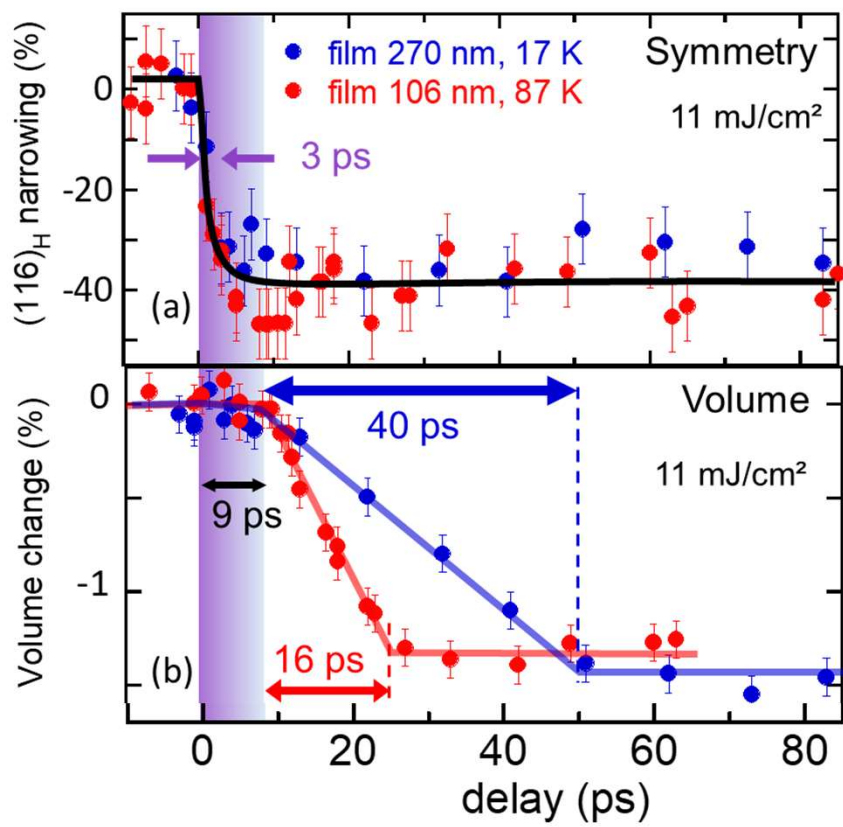


Threshold fluence $I_{threshold}$ \rightarrow launching of a cooperative effect

Above $I_{threshold}$: new metallic, high symmetry, low volume phase

PIPT in V_2O_3 AFI: distinct time scales for symmetry and <volume> changes

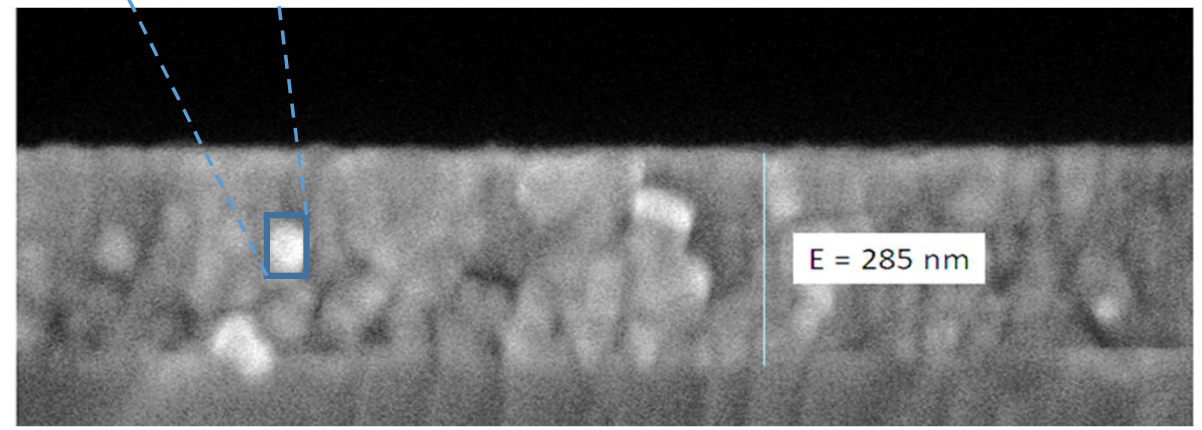
Time-resolved structural changes



Typical timescale

$$t = \frac{d}{2 \cdot v_{acoustic}^{transverse}} = \frac{20 \text{ nm}}{2.4 \text{ nm.ps}^{-1}} \approx 2.5 \text{ ps}$$

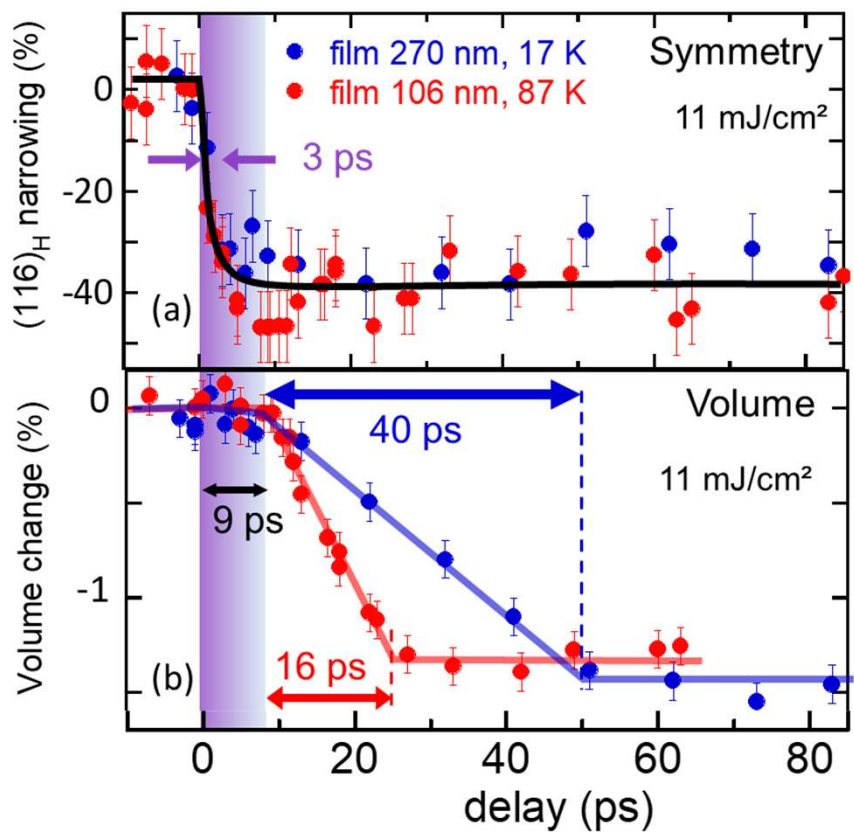
Monoclinic to hexagonal transition: driven by shear strainwave within the ferroelastic domains



Full decoupling in time between fast symmetry change (< 3 ps) and slower volume change

PIPT in V_2O_3 AFI: distinct time scales for symmetry and <volume> changes

Time-resolved structural changes

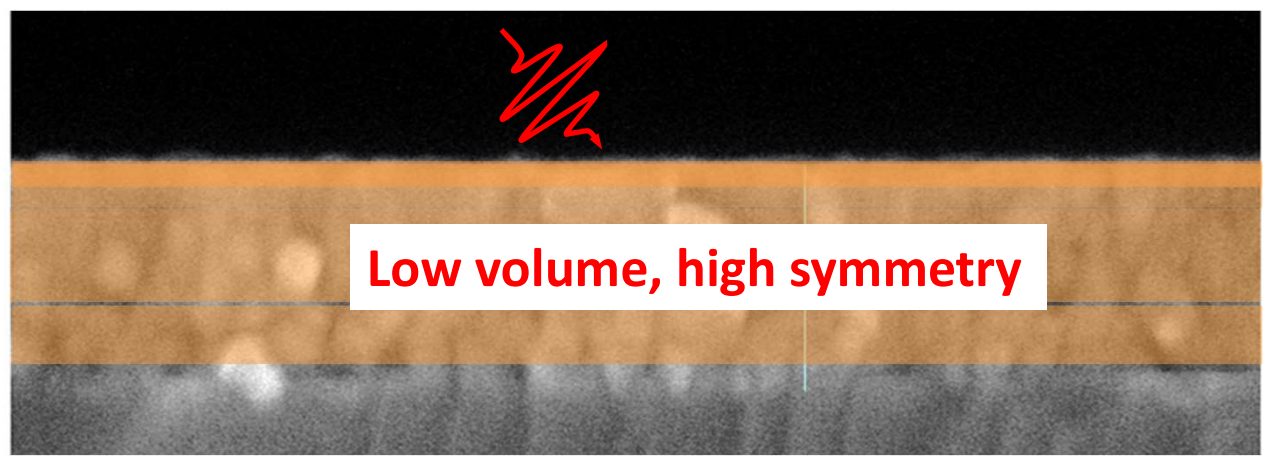


Volume change:

Film 270 nm: $t = 40 \text{ ps} \rightarrow v = \frac{270 \text{ nm}}{40 \text{ ps}} = 6.7 \text{ km. s}^{-1}$

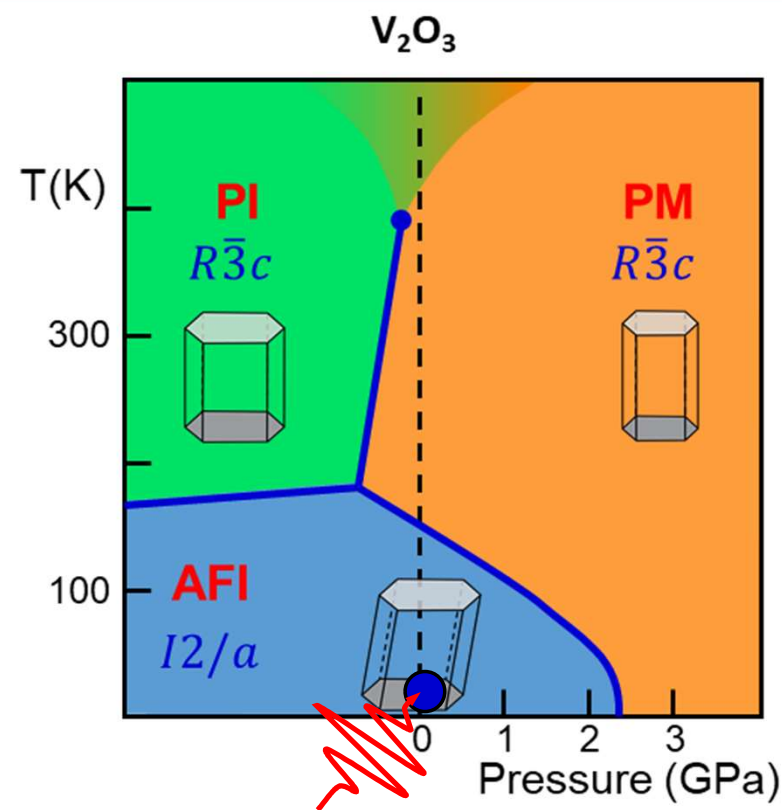
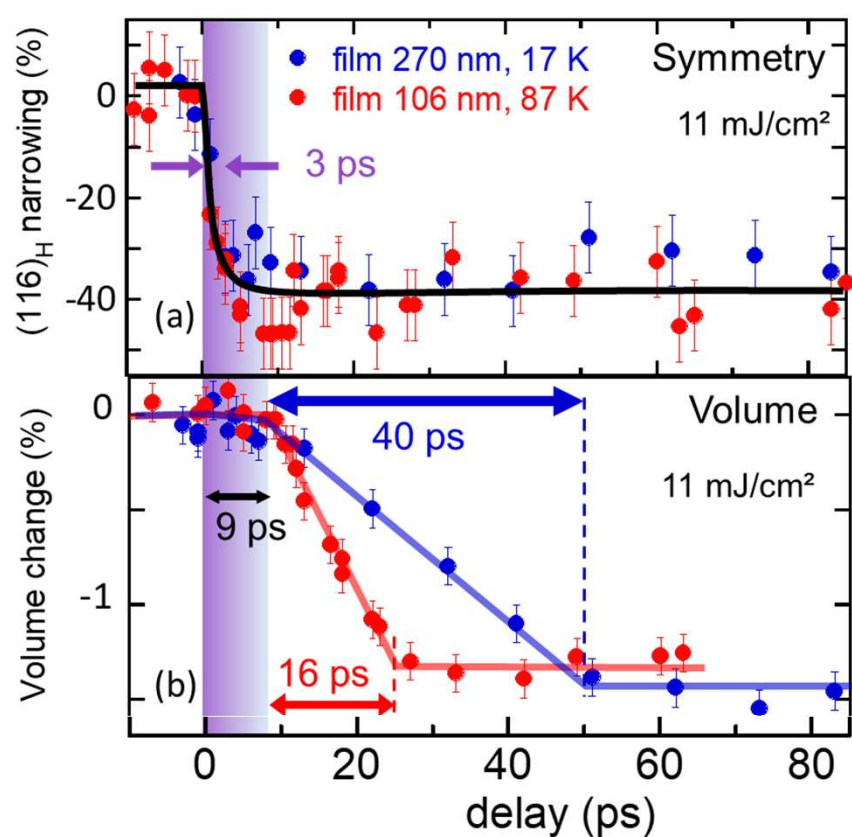
Film 106 nm: $t = 16 \text{ ps} \rightarrow v = \frac{106 \text{ nm}}{16 \text{ ps}} = 6.6 \text{ km. s}^{-1}$

→ speed of sound in V_2O_3 !



Compressive strain wave is the mechanism driving the isosymmetric volume change

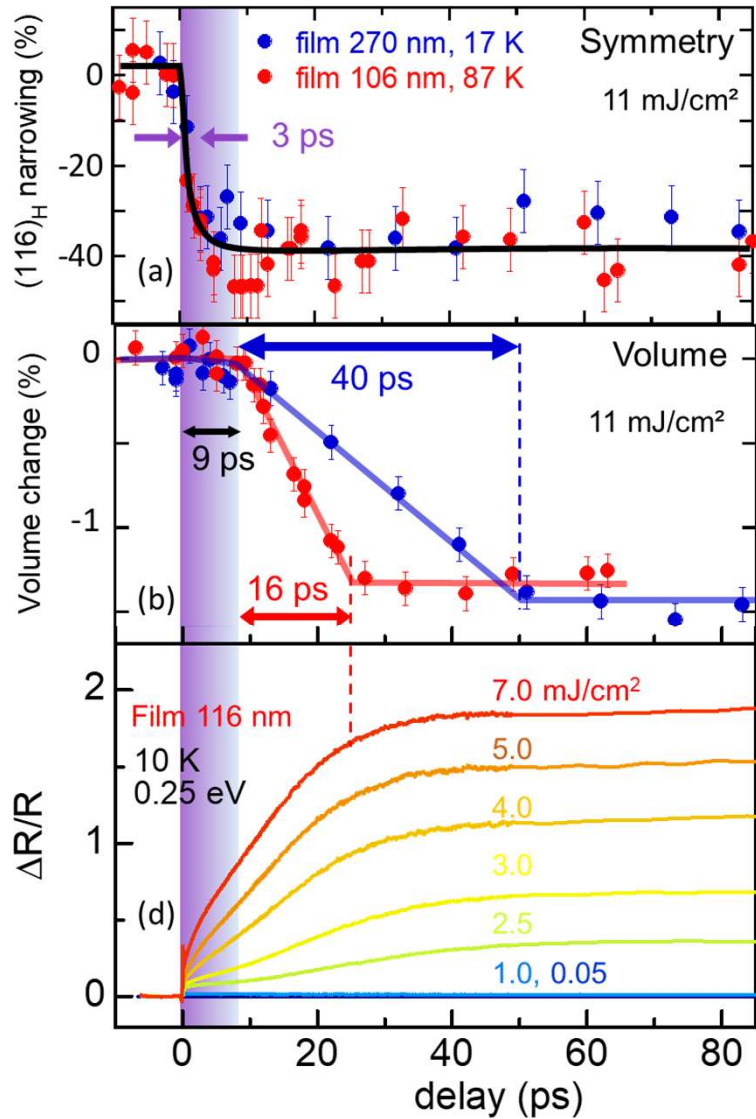
PIPT in V_2O_3 AFI: distinct time scales for symmetry and <volume> changes



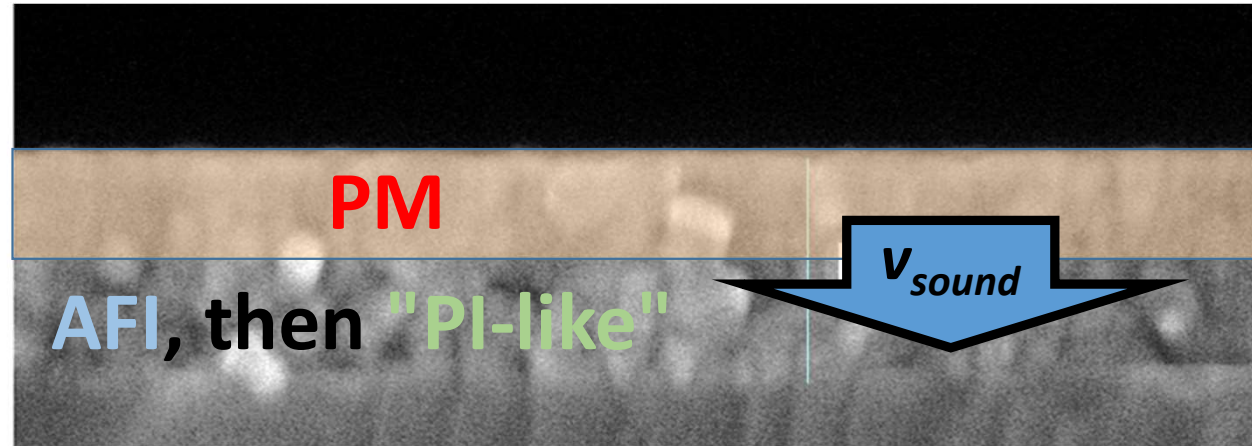
Puzzling "incubation time" of 9 ps for the onset of the compressive strain wave

➔ Transient « PI-like » phase (high symmetry, high volume) between 3 and 9 ps, non-thermally accessible

PIPT in V_2O_3 AFI: comparing the electronic and structural dynamics



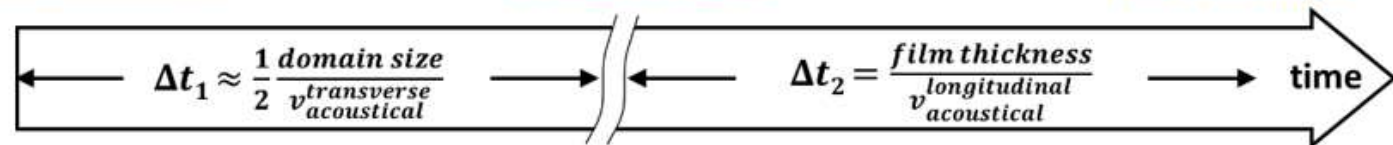
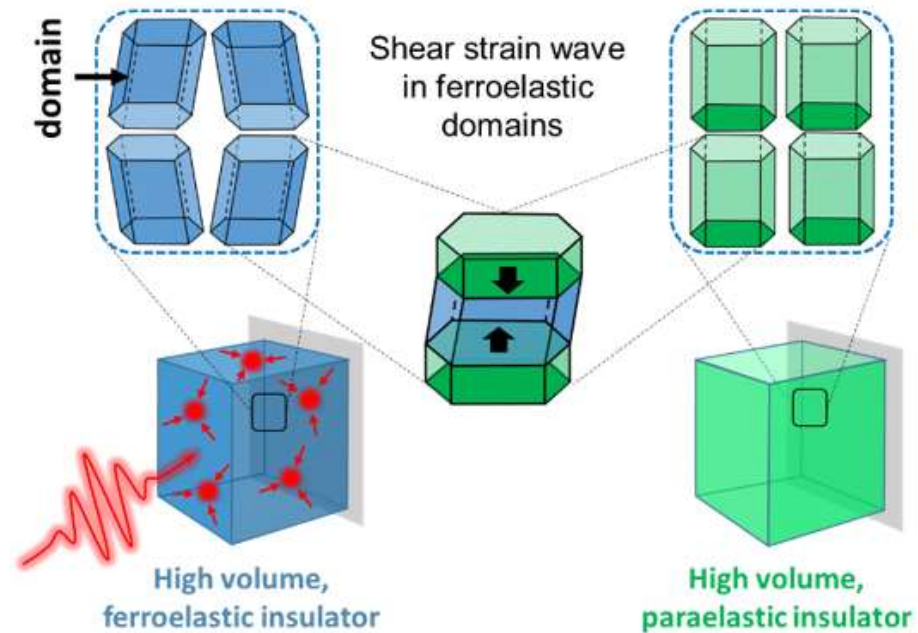
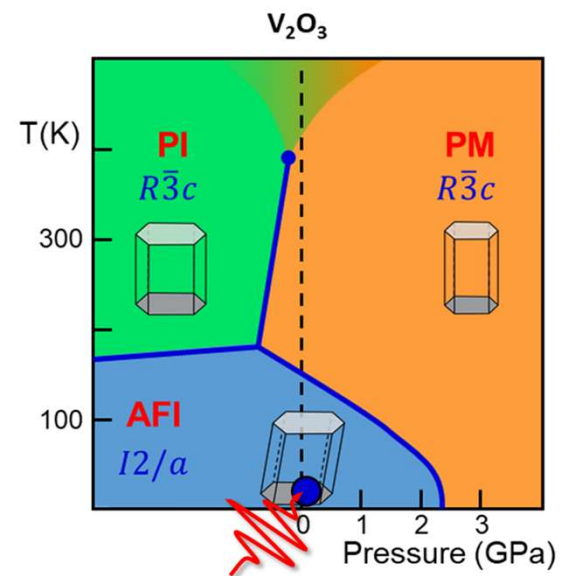
structural
electronic



Dynamics of the electronic insulator-to-metal transition = dynamics of volume compression

→ Metallic state can't be induced as long as the volume has not compressed !

PIPT in V_2O_3 AFI: the global view



PIPT in V_2O_3 AFI: conclusion

Driving mechanism at play in PIPT's in quantum materials ?

→ Strain waves, for the structural part

Physical mechanisms governing the ultimate speed of a PIPT ?

→ Acoustical speed (transverse for symmetry breaking, longitudinal for isosymmetric volume change)

Is a photoinduced insulator-to-metal transition (IMT) necessarily ultrafast ?

→ No, dynamics of IMT can be limited by the speed of sound

Distinct behaviors of symmetry-breaking and isosymmetric order parameters in PIPT's ?

→ Yes, fully different dynamics because strain waves operate on different spatial scales (domains / full sample thickness)

Surprising role of morphology: complete photoinduced transition in films with grain free to deform in all direction vs. clamped transition in single crystal !