

# LCLS, Quantum Materials, And International Context



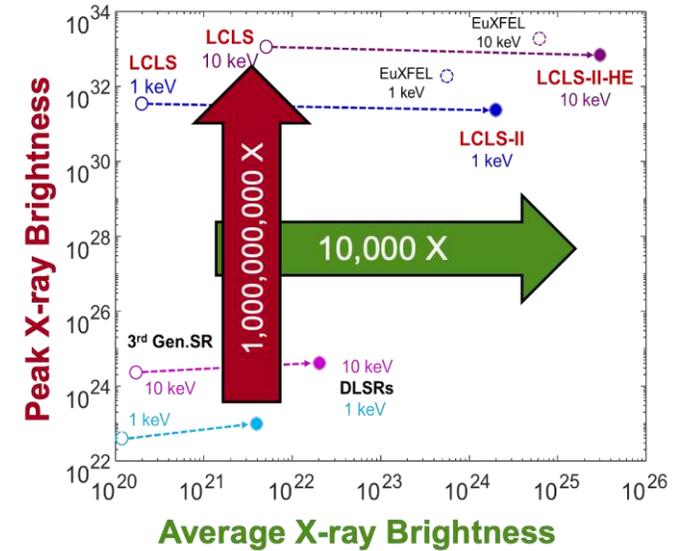
Mengning (Meng) Liang, LCLS, SLAC National Laboratory

*AFOSR + NSF Scientific Opportunities with Compact, High Intensity Accelerators*

*Feb 24-26, 2026*

# LCLS (Linac Coherent Light Source) - 2009

Coherent, Angstrom wavelength X-rays,  
delivered on femtosecond timescales –  
allowing complex dynamics to be tracked in  
heterogeneous, transient systems



# LCLS instruments

## 8 X-ray instruments

- 2 soft x-ray hutches
- 1 Tender X-ray (2keV-7keV)
- 5 hard X-ray

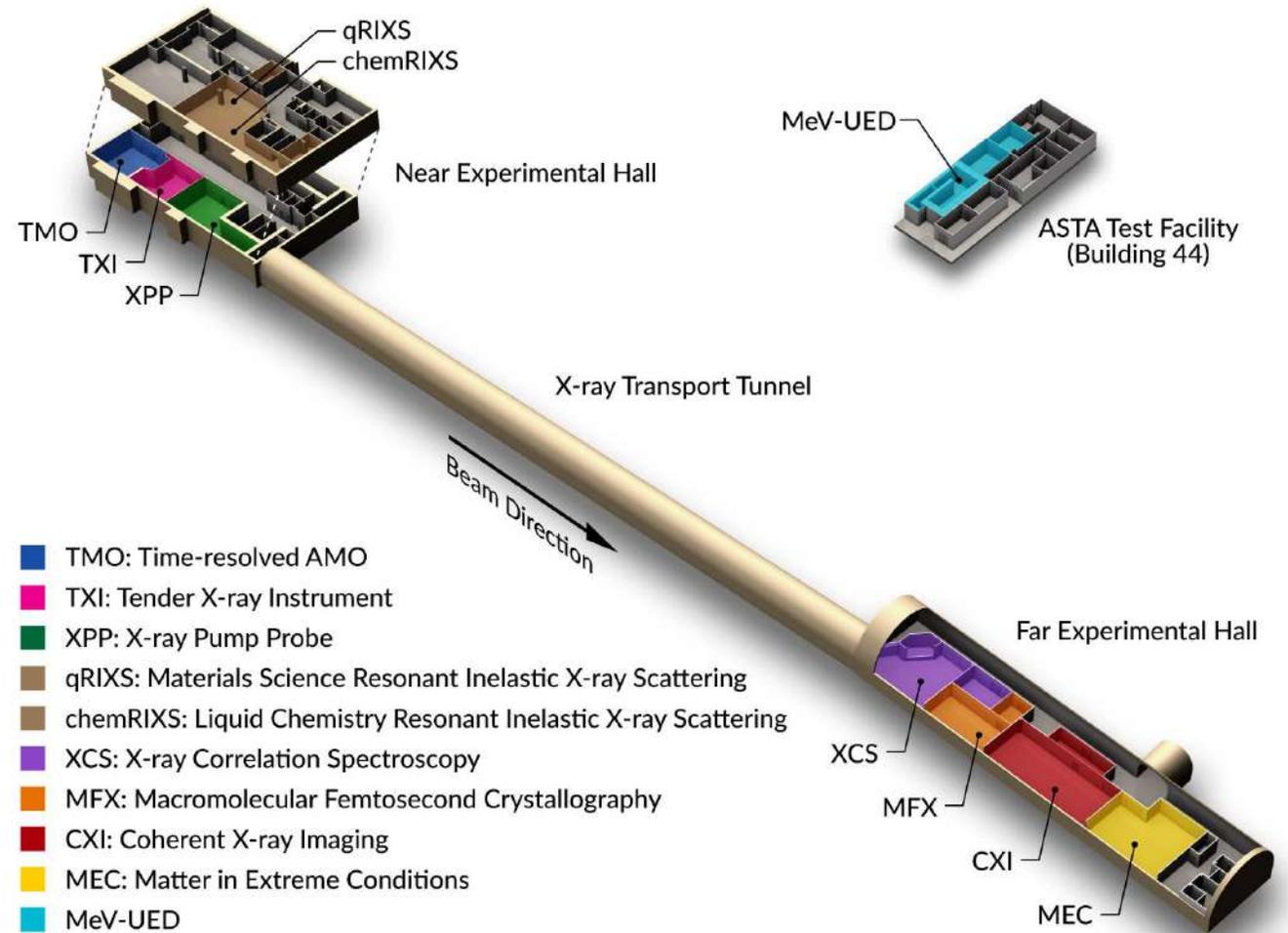
## 1 ultrafast electron source

### Materials Science instruments

qRIXS – Materials Science RIXS

XPP – X-ray Pump Probe

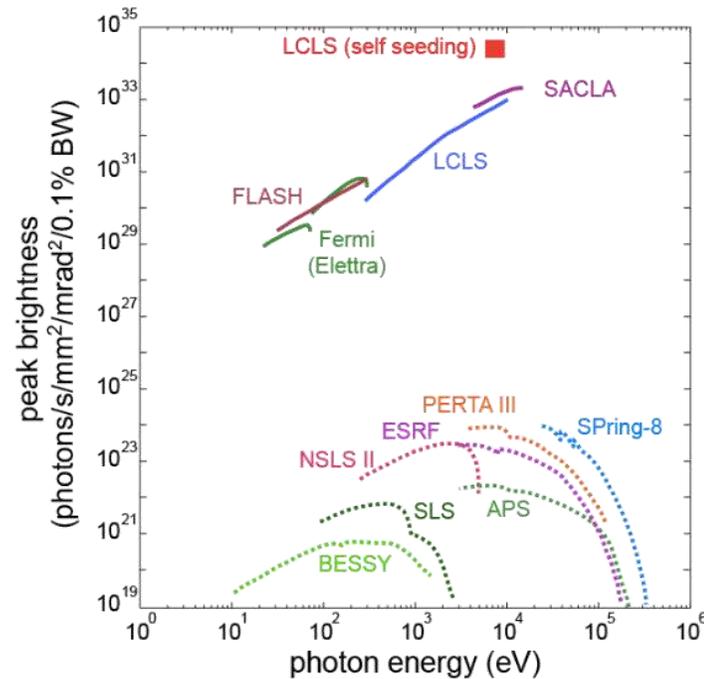
XCS – X-ray Correlation Spectroscopy



# When to use an FEL?

## High Peak Brightness

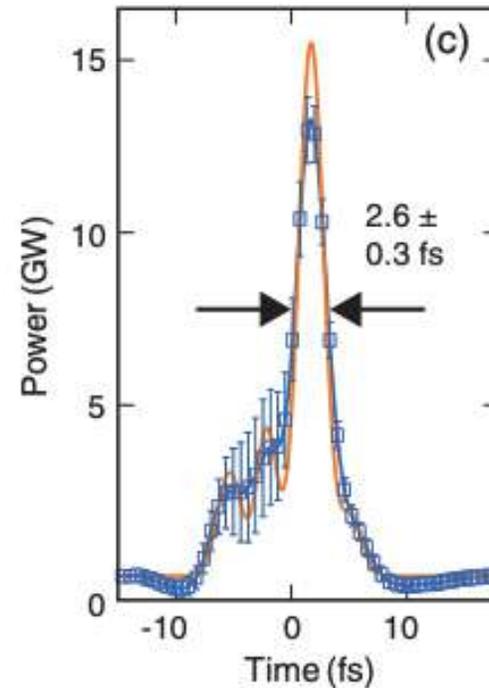
- Radiation sensitive samples
  - Diffract and Destroy
- Non-linear phenomena



Nature Photonics **6**, 693 – 698 (2012)

## Short Pulses

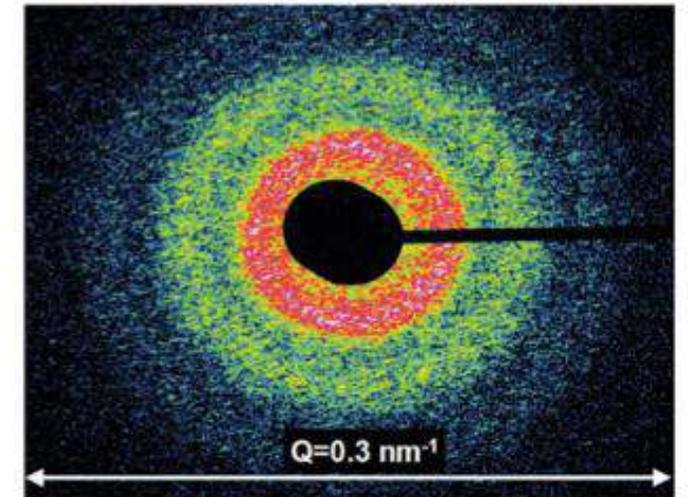
- Time-resolved dynamics
  - Fs to ns dynamics
- typical pulse is 30fs



Rev. Mod. Phys. **88**, 015007 (2016)

## Coherence

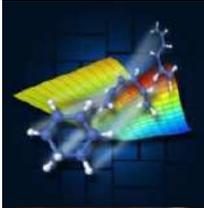
- Fully coherent laser source
- Coherent techniques (XPCS, CDI)



PRL **108**, 024801 (2012)  
Rev. Sci. Instrum. **87**, 103701 (2016)

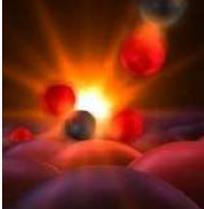
# LCLS Science

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## **Chemical dynamics:**

Charge transfer, reaction dynamics & pathways, design principles for control of molecular photocatalysts



## **Catalysis:**

Homogeneous and heterogeneous catalysis with chemical specificity, atomic resolution, *operando*



## **Matter under extreme conditions:**

High energy density, warm and hot dense matter, extreme environments, inertial fusion



## **Quantum Materials:**

Emergent phenomena, collective excitations, materials control – coherent light/matter interaction

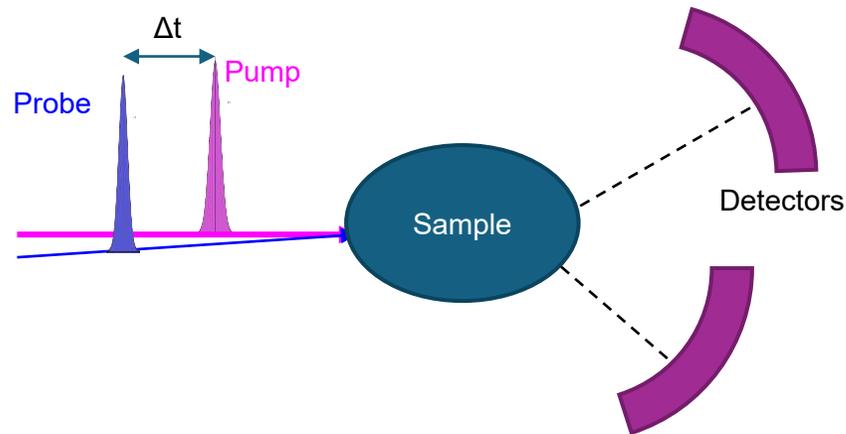


## **Biology in action:**

Bio-molecules & molecular machines – linking structural dynamics with function *in physiological conditions*

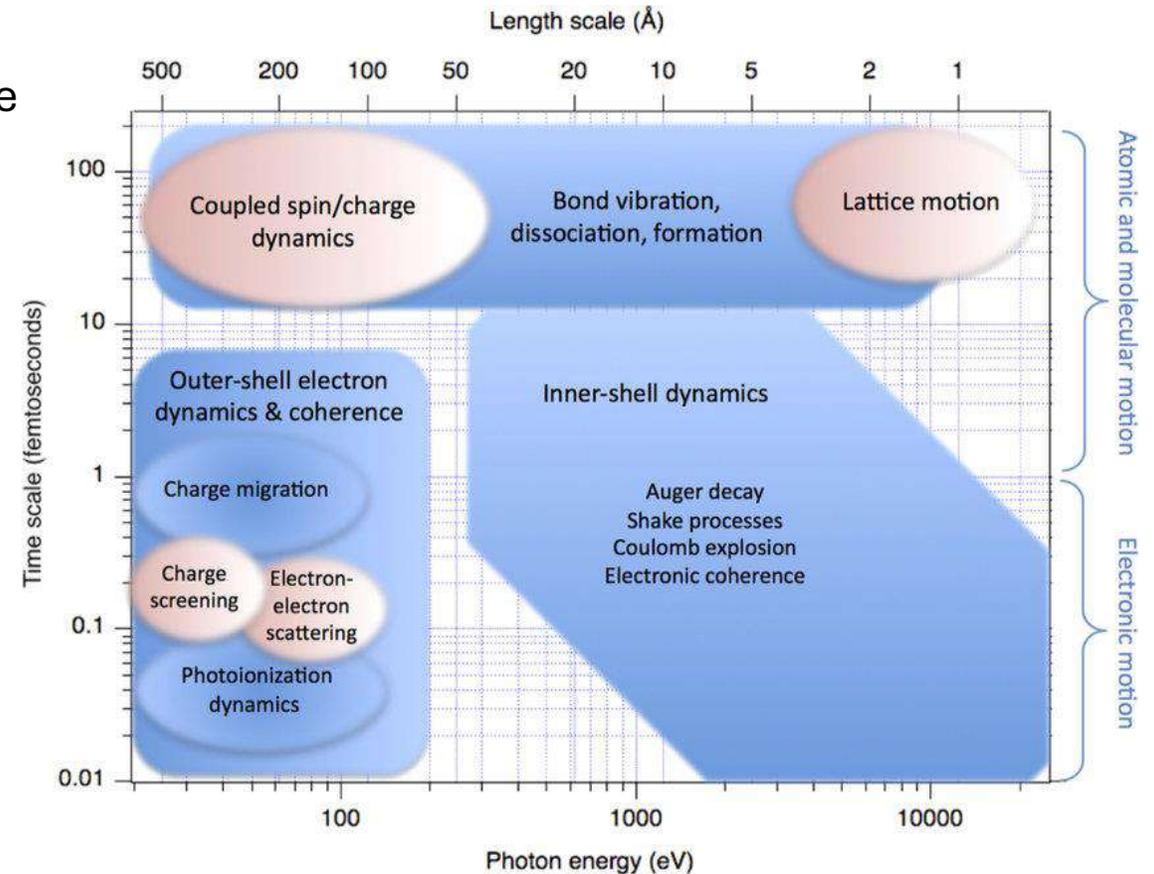
# Pump Probe

- Majority of LCLS experiments are laser pump – x-ray probe
- Timescales for which FELs are very suited fs-ns



**Pump-Probe : evolution of relative signal with X-ray probe at different time delays  $\Delta t$  after excitation (probe)**

Lasers provide a precise  $t_0$

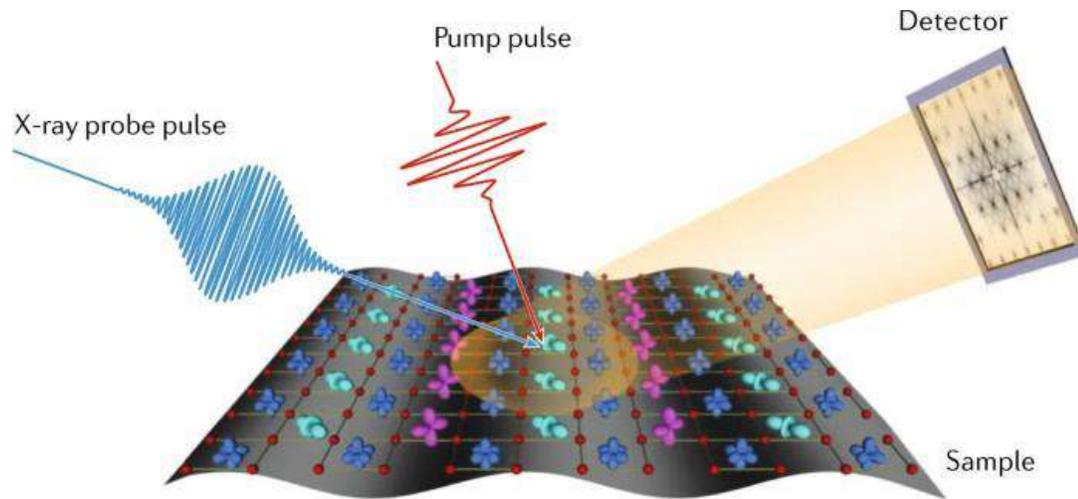


Young, Linda, et al. "Roadmap of ultrafast x-ray atomic and molecular physics." *Journal of Physics B: Atomic, Molecular and Optical Physics* 51.3 (2018): 032003.

Different processes can be excited by different laser wavelengths – UV (bond dissociation), visible (biological processes), IR (heating), THz (lattice motion), etc

# How to study QM at FELs

- Time resolved Diffraction and Scattering



Buzzi, M., Först, M., Mankowsky, R. *et al.* *Nat Rev Mater* **3**, 299–311 (2018).

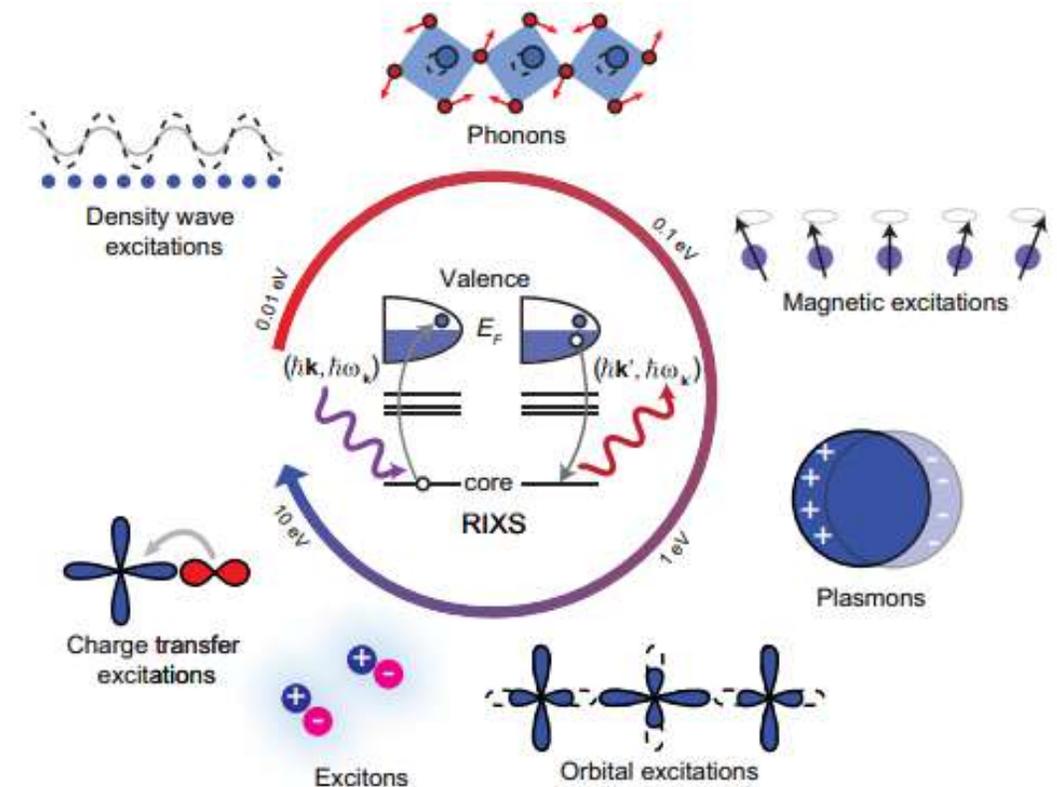
Diffraction and Scattering to study structural changes

- Superstructure
- Charge order
- Magnetic order
- Orbital peak

- Resonant Inelastic X-ray Scattering (RIXS)

Knowledge gaps:

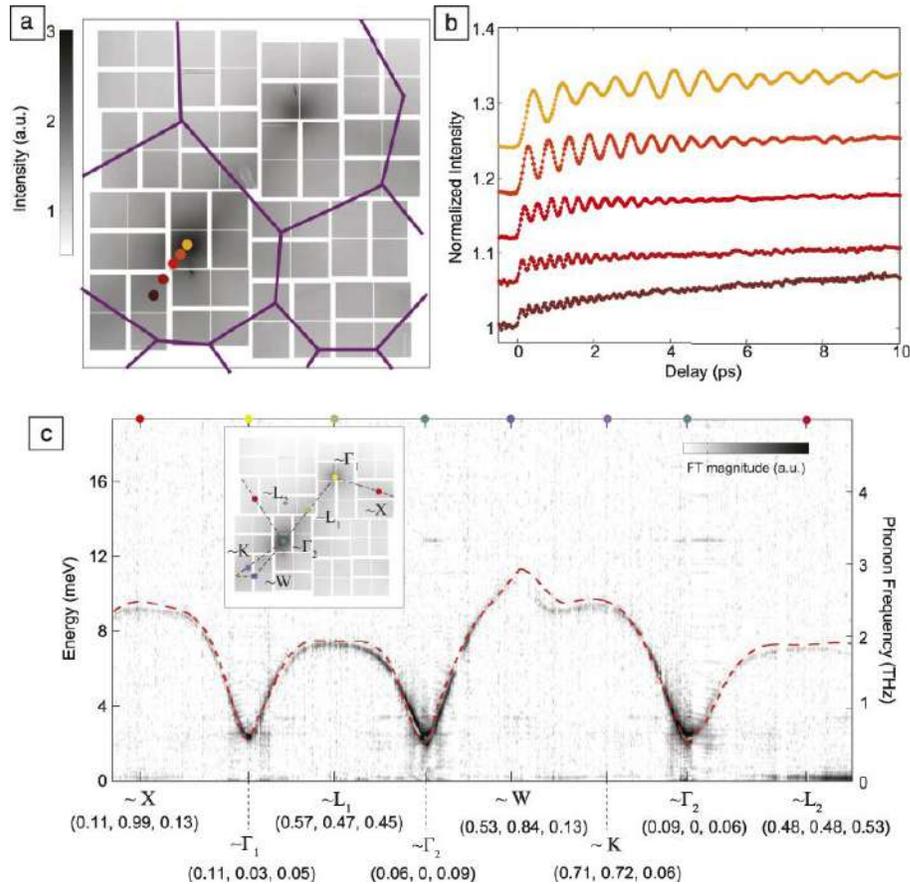
- Full dispersion for 3D materials
- Complete RIXS maps at wide range of T, doping, etc.



M. Mitrano, *et al.*, *PRX* **14**, 040501

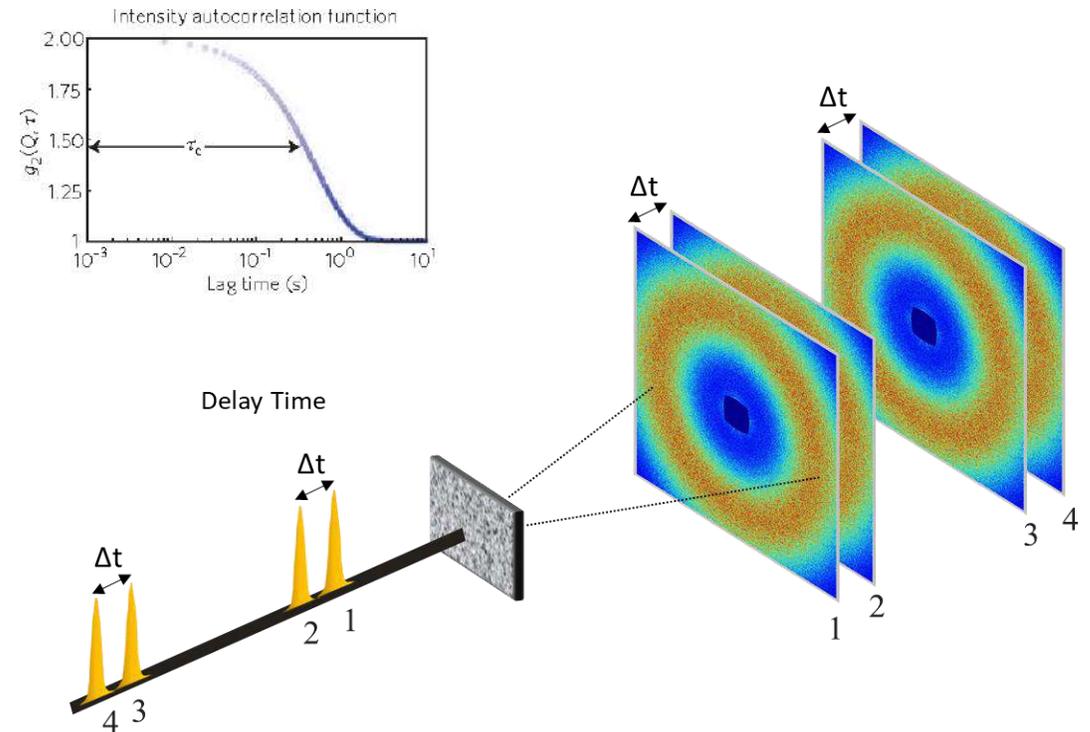
# How to study QM at FELs

- Fourier Transform Inelastic X-ray Scattering



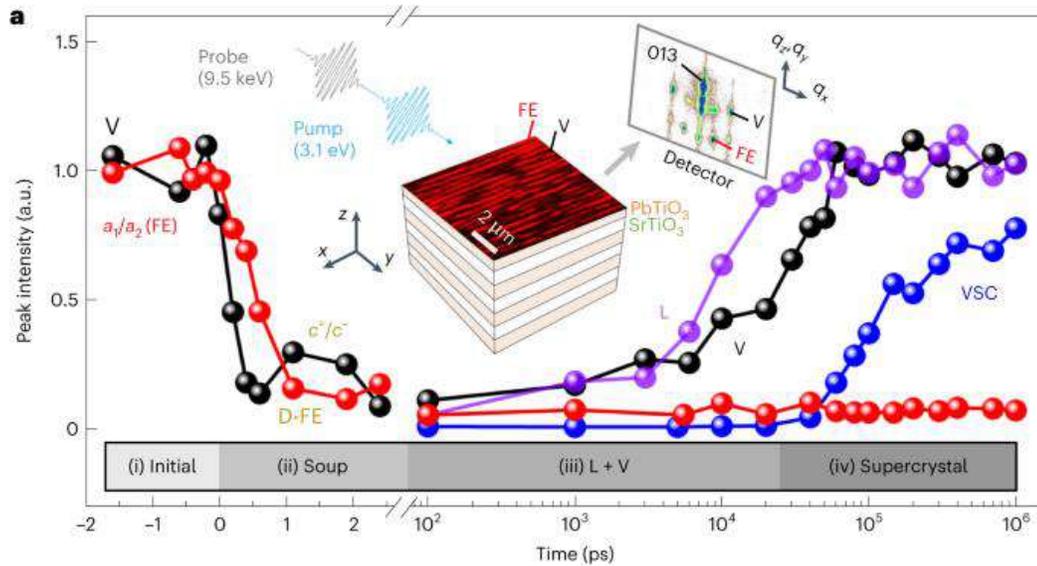
Diffuse scattering to map out the phonon dispersion

- X-ray Photon Correlation Spectroscopy

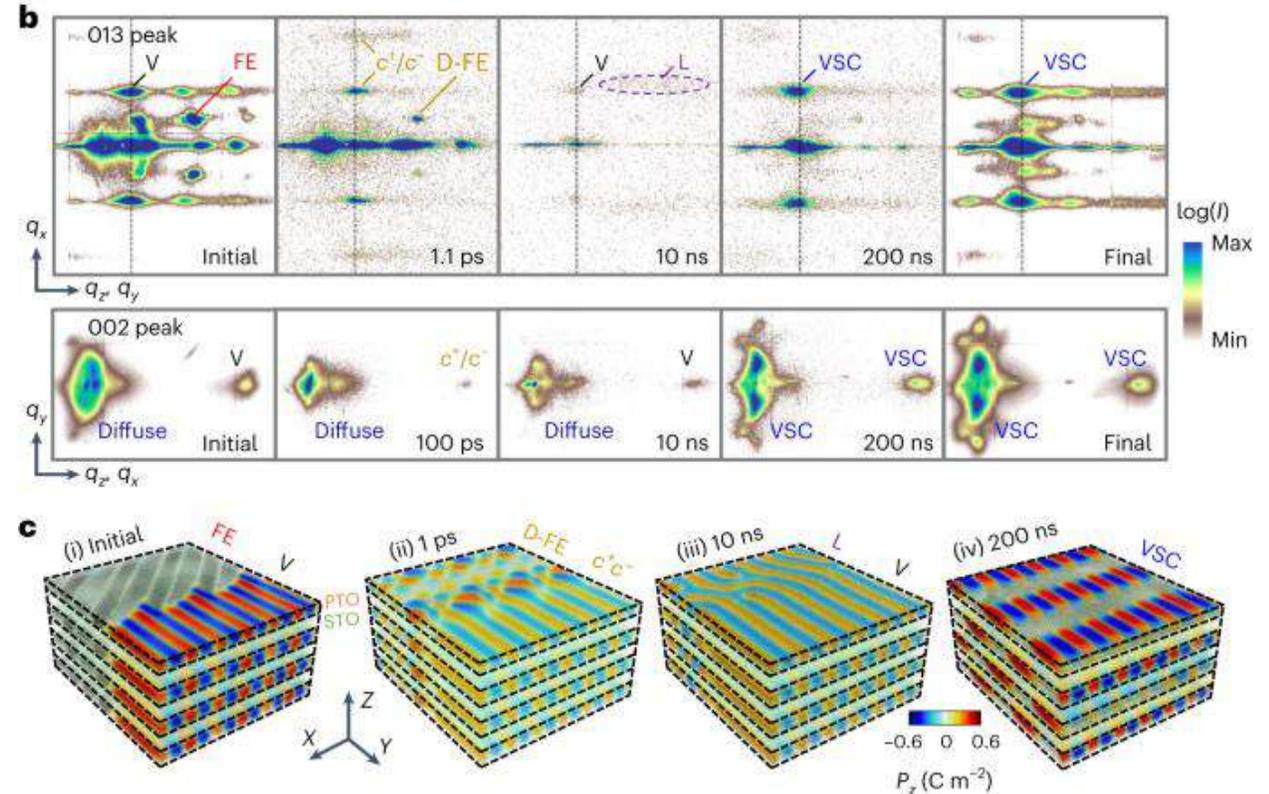


- Fluctuations, dynamics and heterogeneity at multiple time and length scales

# Polar Supertextures



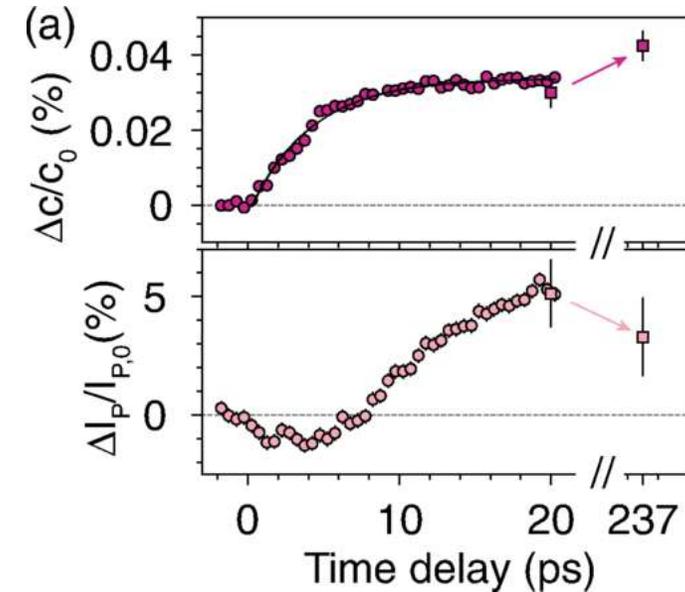
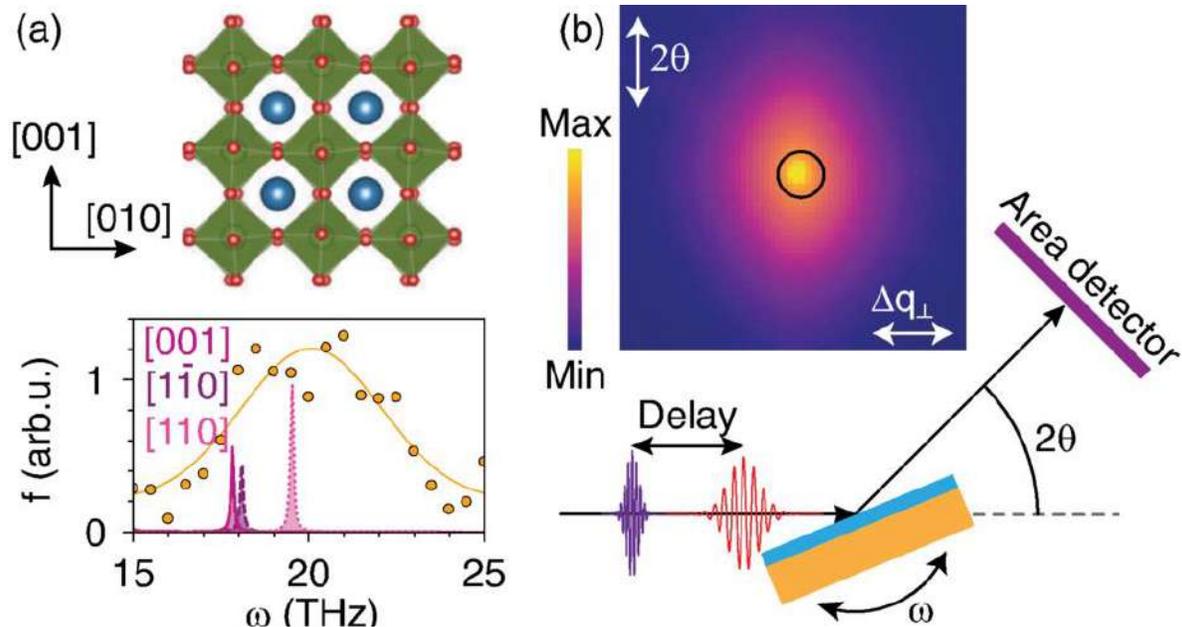
Pump-probe X-ray scattering to look at the time evolution of a (SrTiO<sub>3</sub>)<sub>16</sub>/(PbTiO<sub>3</sub>)<sub>16</sub> superlattice



- Collapse of FE and V orders at the ~1ps timescale
- 0-2ps – heterogeneous mixture of polar phase disorders
- Nanoseconds - Labyrinthine fluctuations and recovery of V phase
- >20ns VSC phase nucleates and grows

- V – polar vortex
- FE – ferroelectric
- D-FE – disordered nanoregions
- L – labyrinthine fluctuations
- VSC – Vortex supercrystal

# Picosecond Expansion in LaAlO<sub>3</sub>

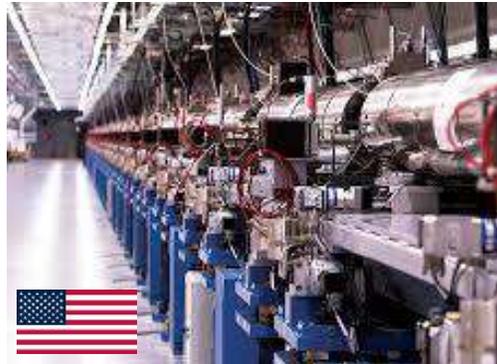


- THz pump to drive IR active phonon
- Time-resolved X-ray diffraction of the (008) Bragg peak as a probe of lattice dynamics
- Observe a lattice expansion in the direction of the film normal
- Observe a decrease in the diffuse scattering – indicating light induced ordering of the crystal planes
- Indicates a metastable ordering (few ps) due to coherent excitation of the lattice

# X-ray Free Electron Lasers Worldwide



FLASH – 2005  
XUV



LCLS - 2009



Fermi – 2010  
XUV



SACLA - 2011



PAL - 2016



SwissFEL - 2017



DCLS – 2016  
VUV

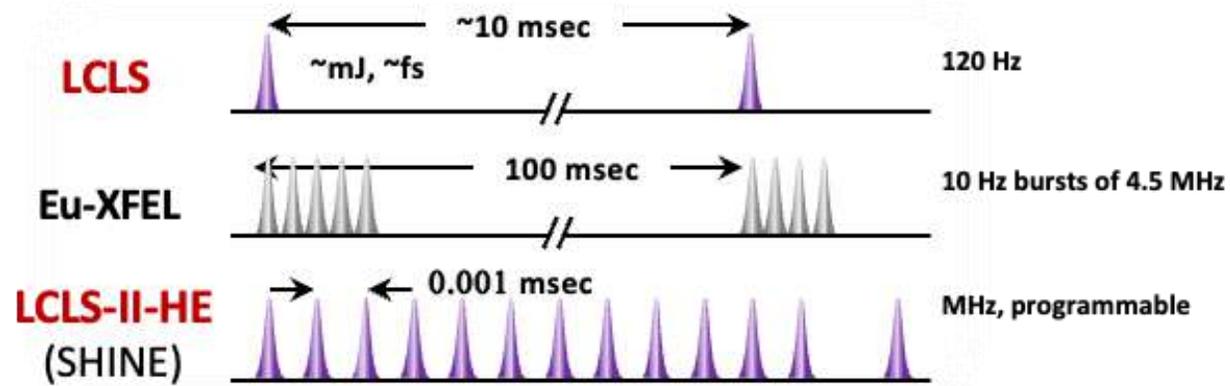


SXFEL – 2023 (users)

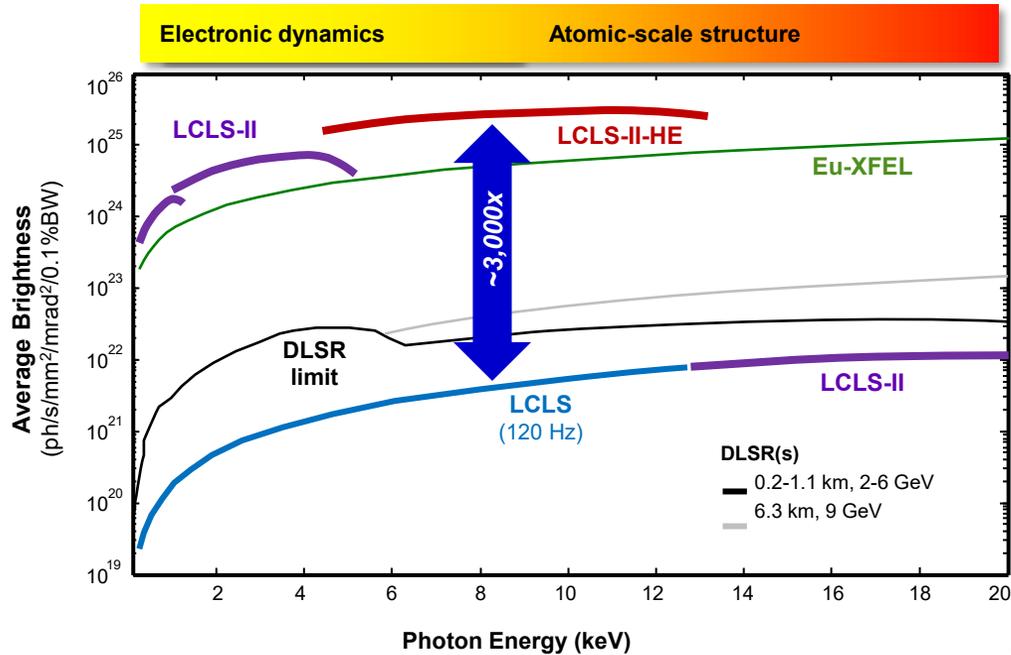
# MegaHertz FELs – Superconducting technology



European XFEL - 2017



# LCLS Upgrade (LCLS-II, LCLS-II-HE)

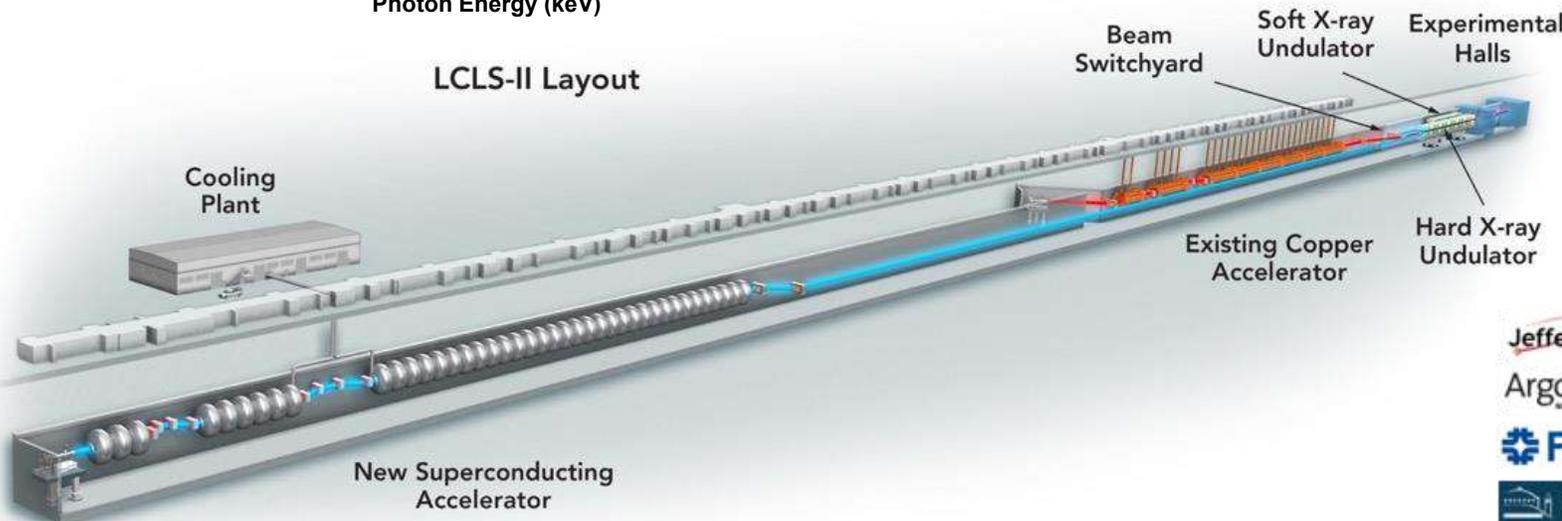


## LCLS-II-HE provides:

- 3,000-fold increase in average spectral brightness
- Full coherence (probing at the FT limit)
- 8000-fold increase in hard X-ray repetition rate
- Programmable time structure to match the system

- 23 additional cryomodules (4 GeV to 8 GeV)
- Optimize cryogenic distribution and X-ray undulators
- High power X-ray beamlines
- First instrument

LCLS-II Layout



## Full facility buildout requires:

- upgrade of 3(4) new high power X-ray instruments
- Low emittance injector to get to high photon and pulse energies



# Upcoming FELs

- Many FELs are planning upgrades, no major accelerator upgrades planned for current sources

Superconducting FELs under construction and planned:



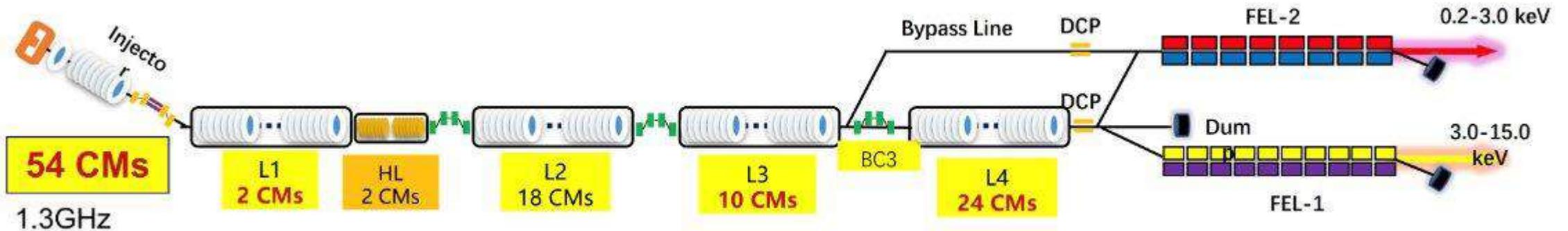
SHINE - 2027



S<sup>3</sup>FEL - 2030

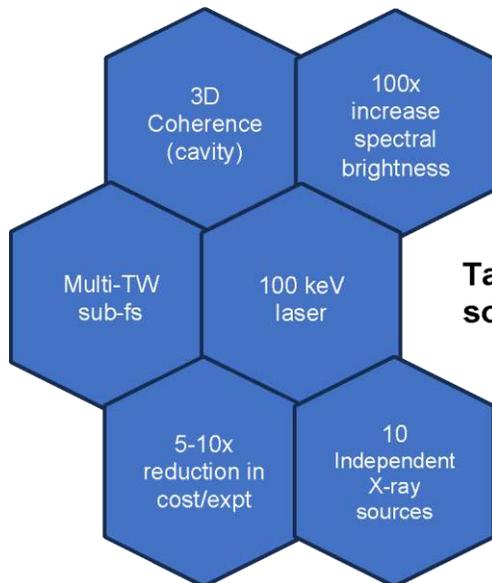


DALS (initial R&D)



1. 3CMs/month, towards SXU lasing September 2026.
2. HXR lasing same time frame as LCLS-II HE if all goes well.

# LCLS-X

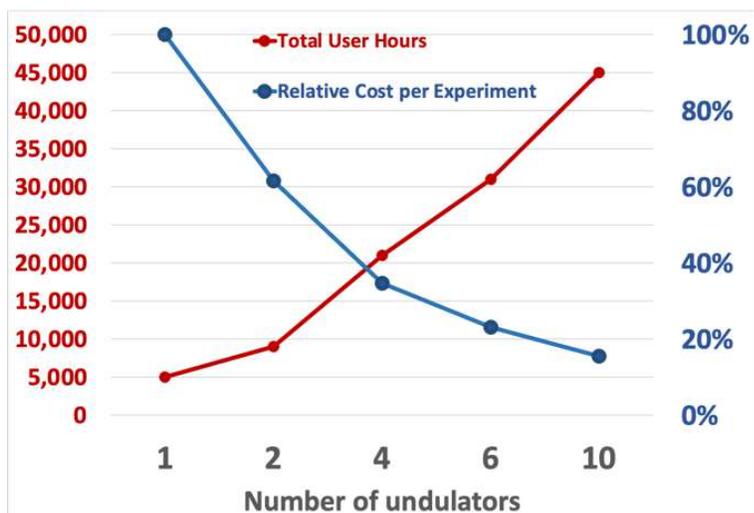
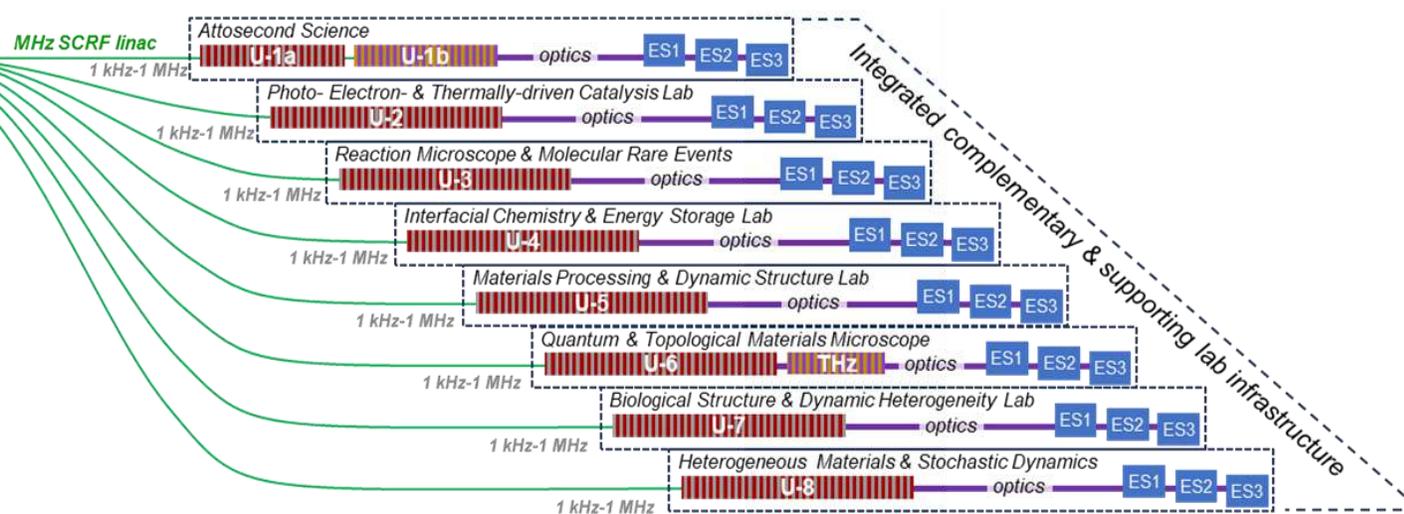


Leaps in capability

Tailored sources

Operational efficiency

## Dedicated "X-ray observatories"



## UK-FEL

