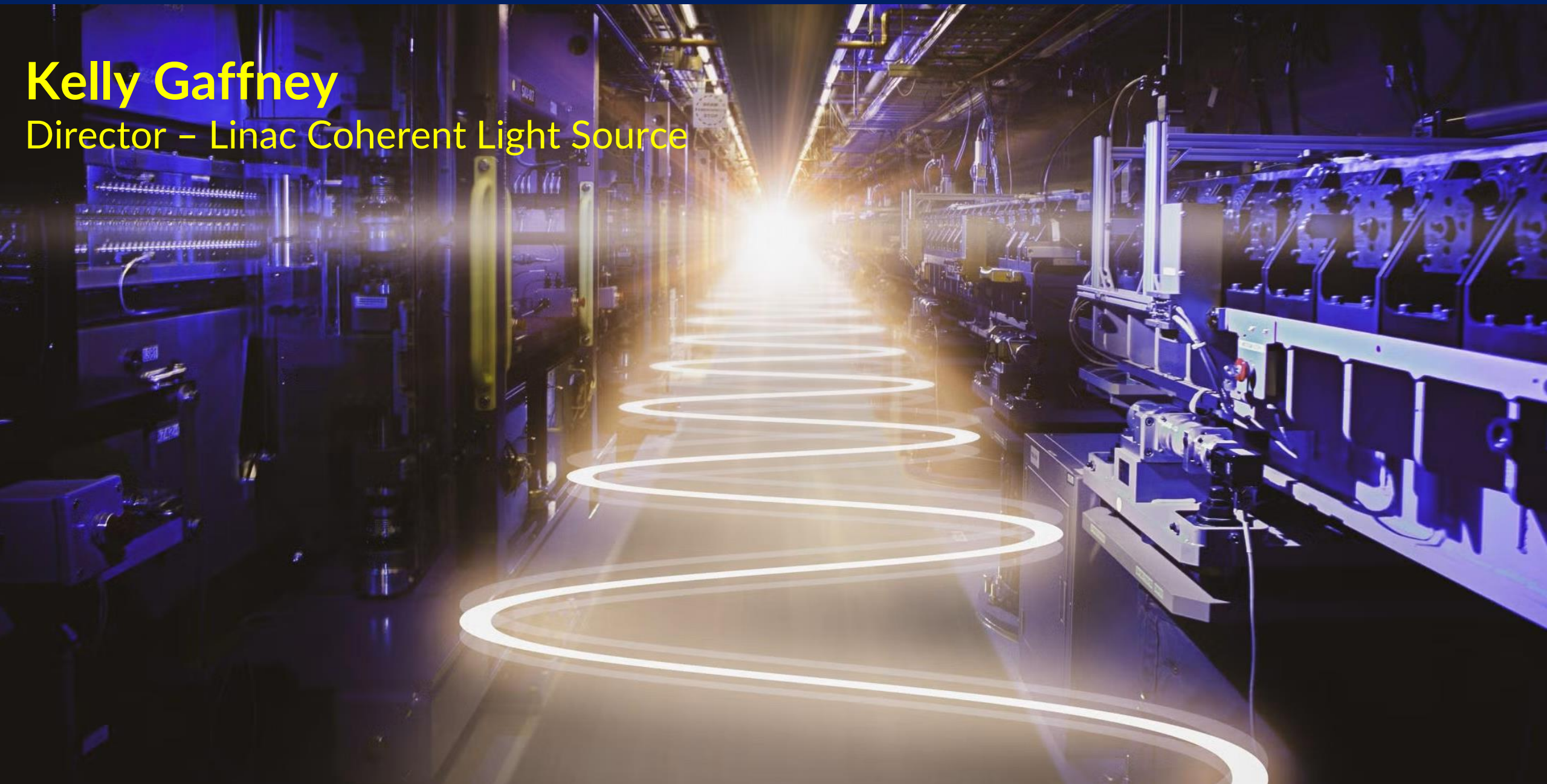
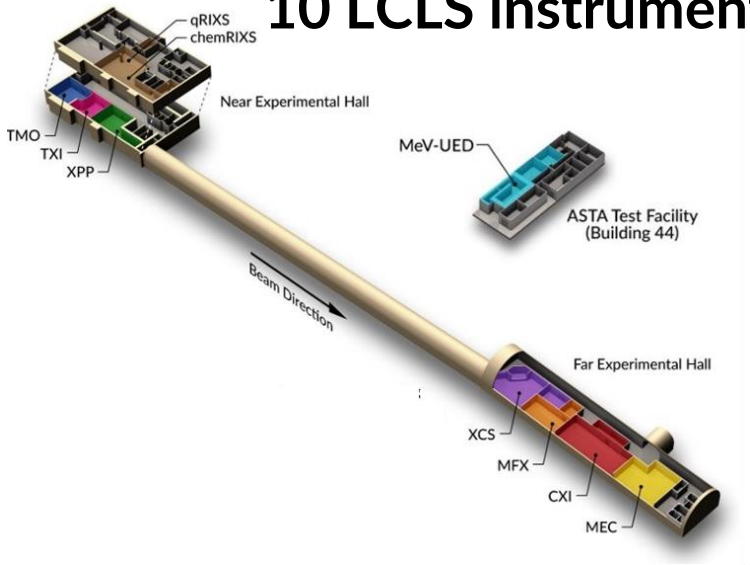
Building a better X-ray Laser for Operando Science

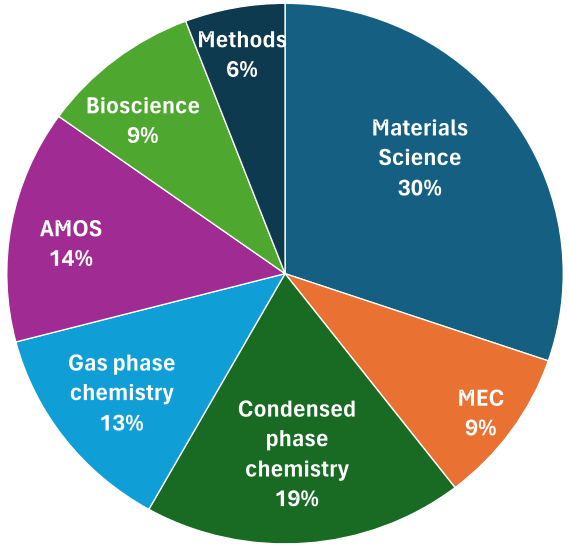


Kelly Gaffney
Director – Linac Coherent Light Source

LCLS – a facility in transition

10 LCLS instruments





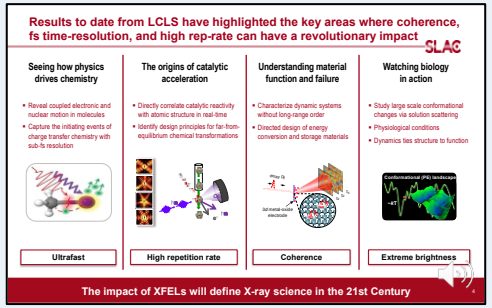
Second generation X-ray laser science builds on a strong research foundation

- **~500 users a year pushing the frontiers of X-ray laser science**

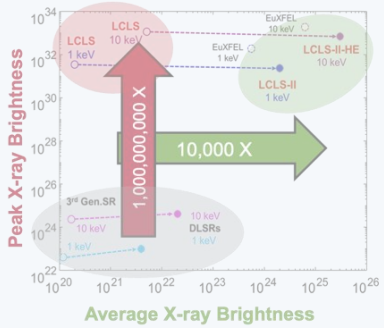
Major transition to high repetition rate X-ray laser science enabled by $2B investment in superconducting accelerator (LCLS-II & LCLS-II HE)

Research strategy focuses on four essential elements

1. Establish science mission with decadal-scale ambition

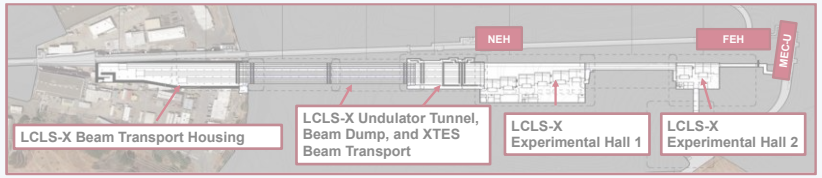


2. Driving leaps in source and facility performance (for LCLS-II, HE)



3. Foster a vibrant, integrated research ecosystem

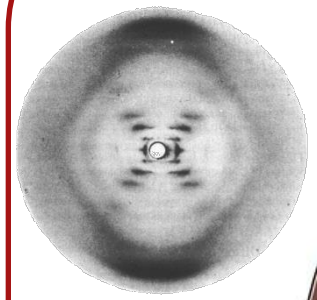
4. Make multiplexed LCLS essential platform BES mission (LCLS-X)

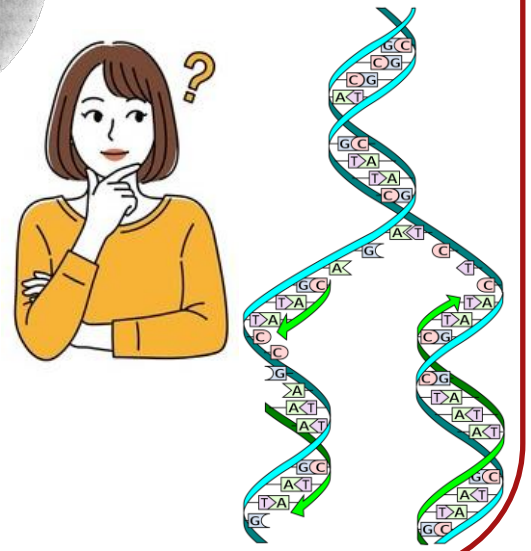


These elements will maintain LCLS as a preeminent engine for discovery and enable increased impact on use-inspired research

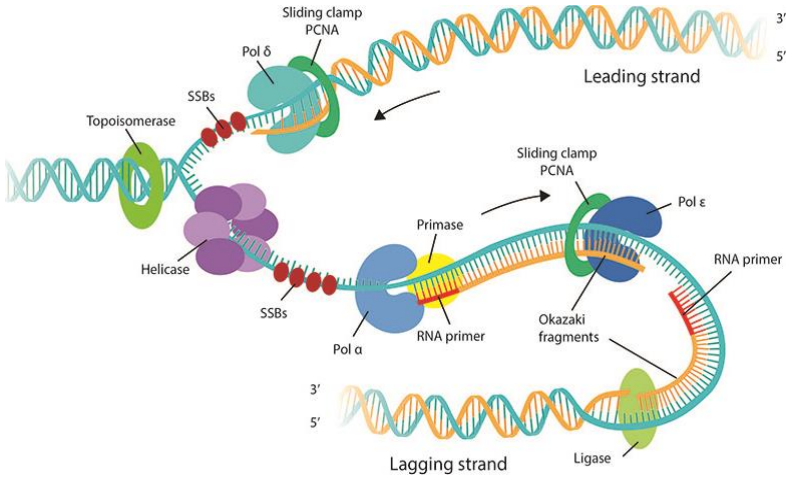
1. Science mission:
Reimagining structure-function relationship for 21st Century

Conception



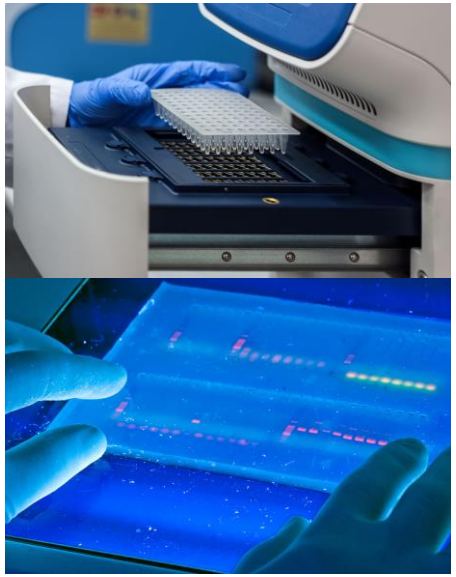


Mechanism



DNA replication: Coordinated action of numerous biomolecules

Technology



DNA replication technology essential to all DNA testing

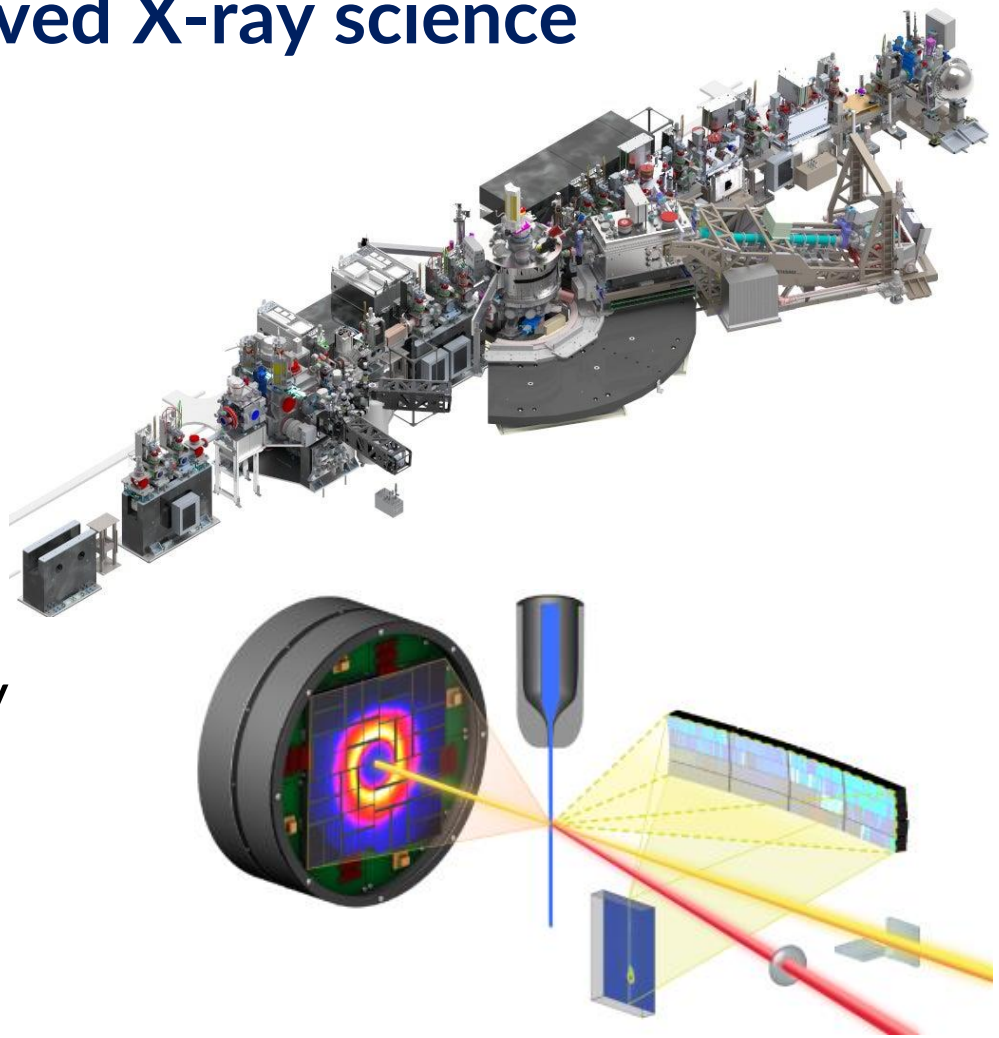
- **Accelerate discovery of design principles derived from mechanistic understanding**
- **Facilitate development of new technology**

1. Science mission:
Advancing priority research directions at LCLS

LCLS will accelerate the discovery of design principles through state-of-the-art operando and time-resolved X-ray science

The unprecedented coherent flux and spectral brightness will enable:

- Application of ultrafast X-ray science to a broad array of research challenges
- Operando coherent diffractive imaging
- Operando inelastic X-ray scattering & spectroscopy

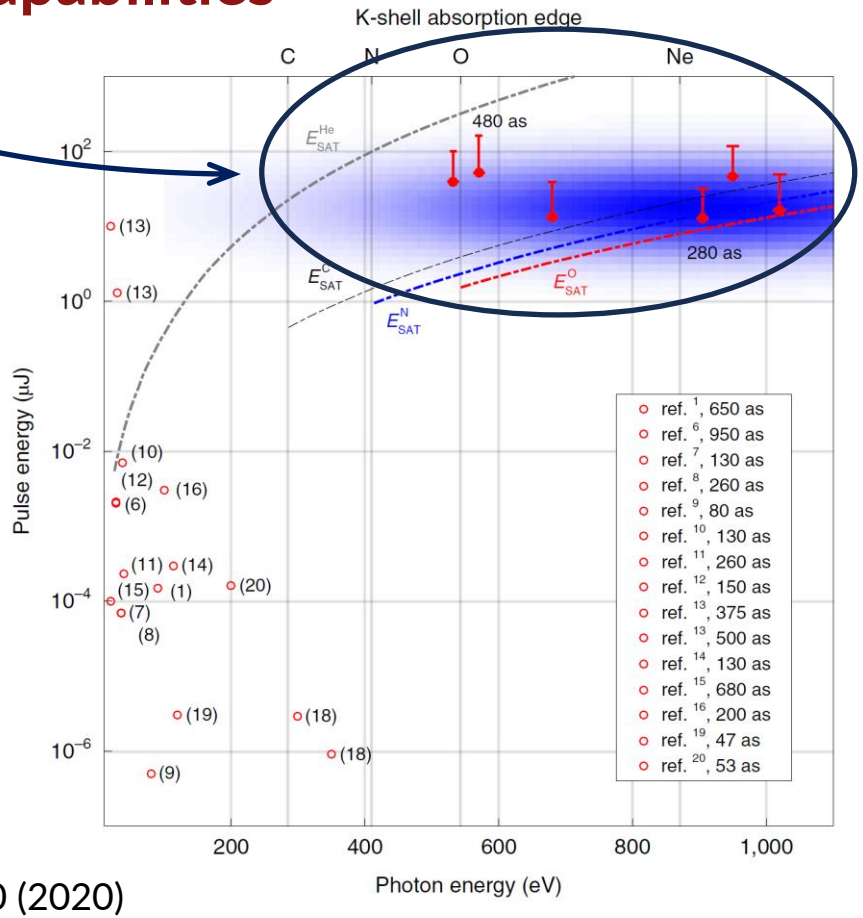


3. Fostering an integrated research ecosystem:
Pursuing new approaches to multi-disciplinary research teams

LCLS led, community driven attosecond science campaign

Cryan Marinelli

XFELs enable unique capabilities



Duris, *et al. Nature Photonics* **14**, 30 (2020)

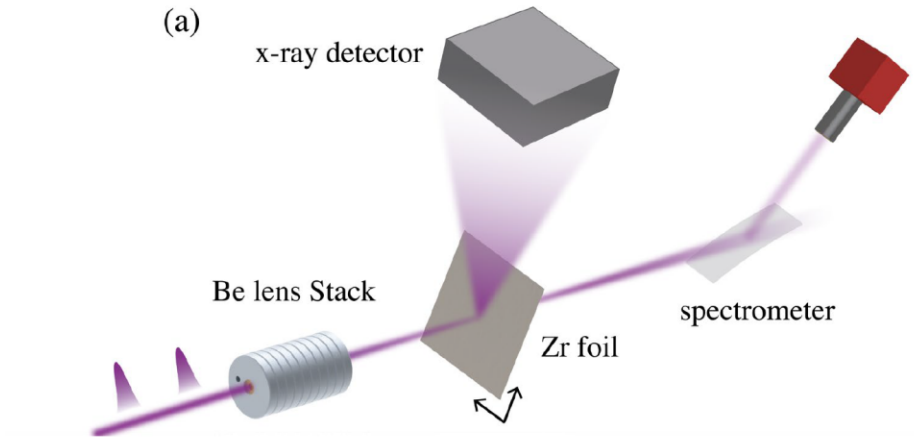
Attosecond campaign

- World leading capabilities create compelling research opportunities
- Internationally recognized staff
- Engaging thought leaders in the field

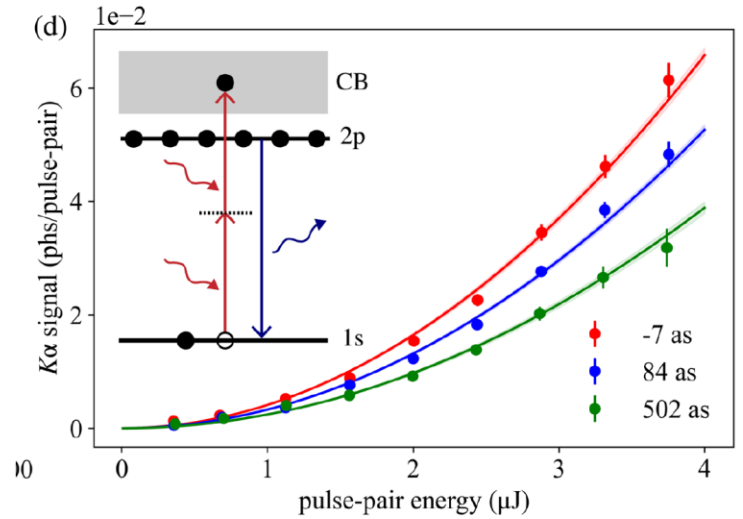
Driving community coordination to accelerate scientific impact

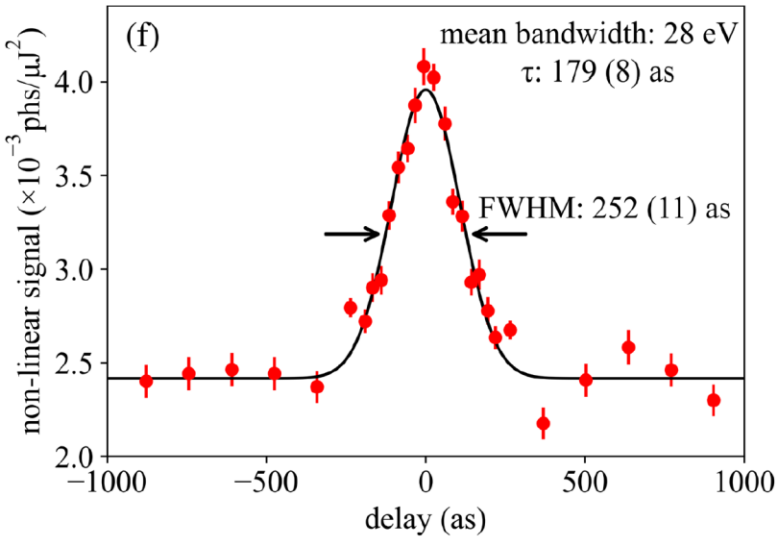
3. Fostering an integrated research ecosystem:
Extending attosecond metrology to hard X-ray regime

Fluorescence detected two-photon absorption



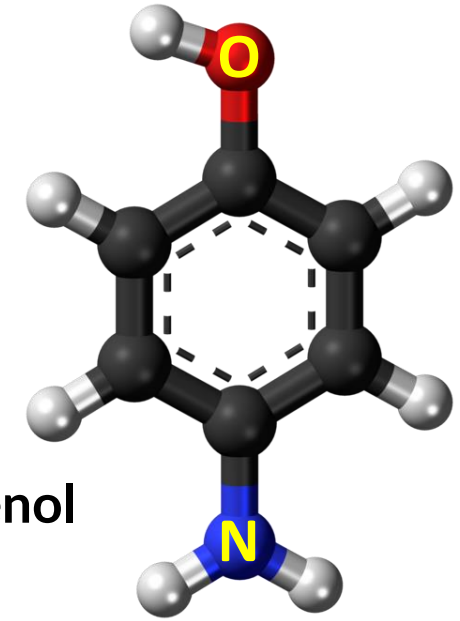
- Transition through virtual state detuned by keV provides instantaneous response
- Fluorescence intensity provides autocorrelation of X-ray pulse





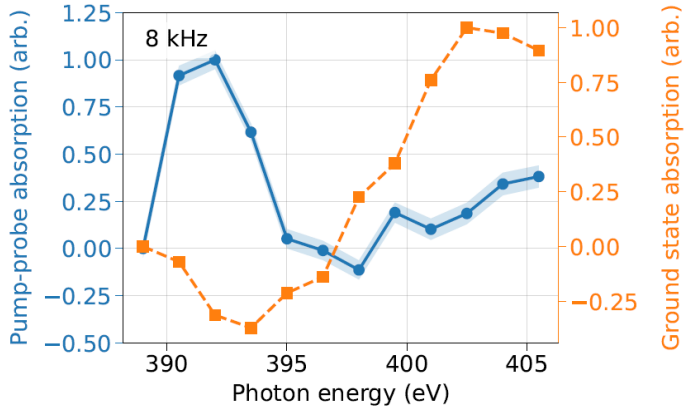
3. Fostering an integrated research ecosystem:
Attosecond science at high repetition rate

Electron dynamics initiated by inner valence ionization captured with X-ray absorption spectroscopy

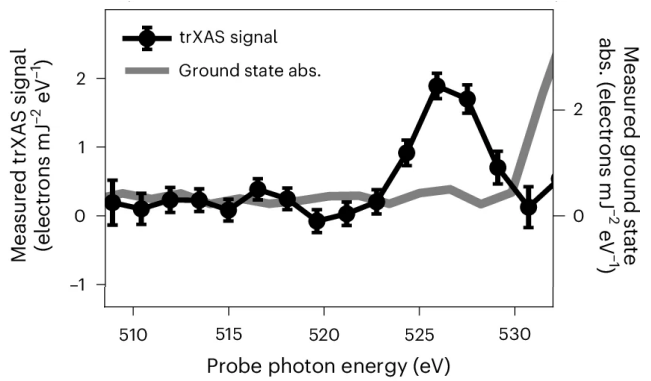


aminophenol

~5 minutes with SC-LCLS at the N K-edge



Many hours with NC-LCLS at the O K-edge



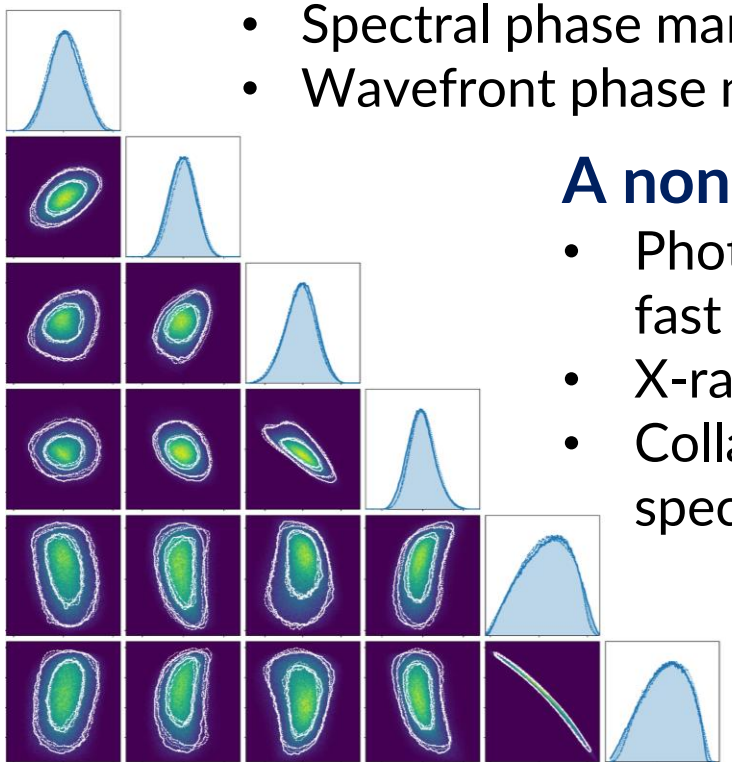
Taran Driver *et al. Nature Phys.* DOI: /10.1038/s41567-026-03360-x

High repetition rate SC-LCLS will transcend demonstration experiments

3. Fostering an integrated research ecosystem:
Accelerator & X-ray science R&D collaboration essential

Ever increasing control over the six-dimensional phase space of the X-ray beam

- Improvements in e^- beam brightness to extend the photon energy reach to harder X rays
- Spectral phase manipulation for novel X-ray spectroscopies
- Wavefront phase manipulation for X-ray imaging applications



Science Reports **15**, 43049 (2025)

A non-experts view of research priorities

- Photoinjectors: photocathode design, optical laser pulse shaping, fast feedback for optimization
- X-ray cavity & seeding methods for enhanced spectral brightness
- Collaboration between FEL science and X-ray optics for non-linear spectroscopy & imaging applications

A non-experts view of development priorities

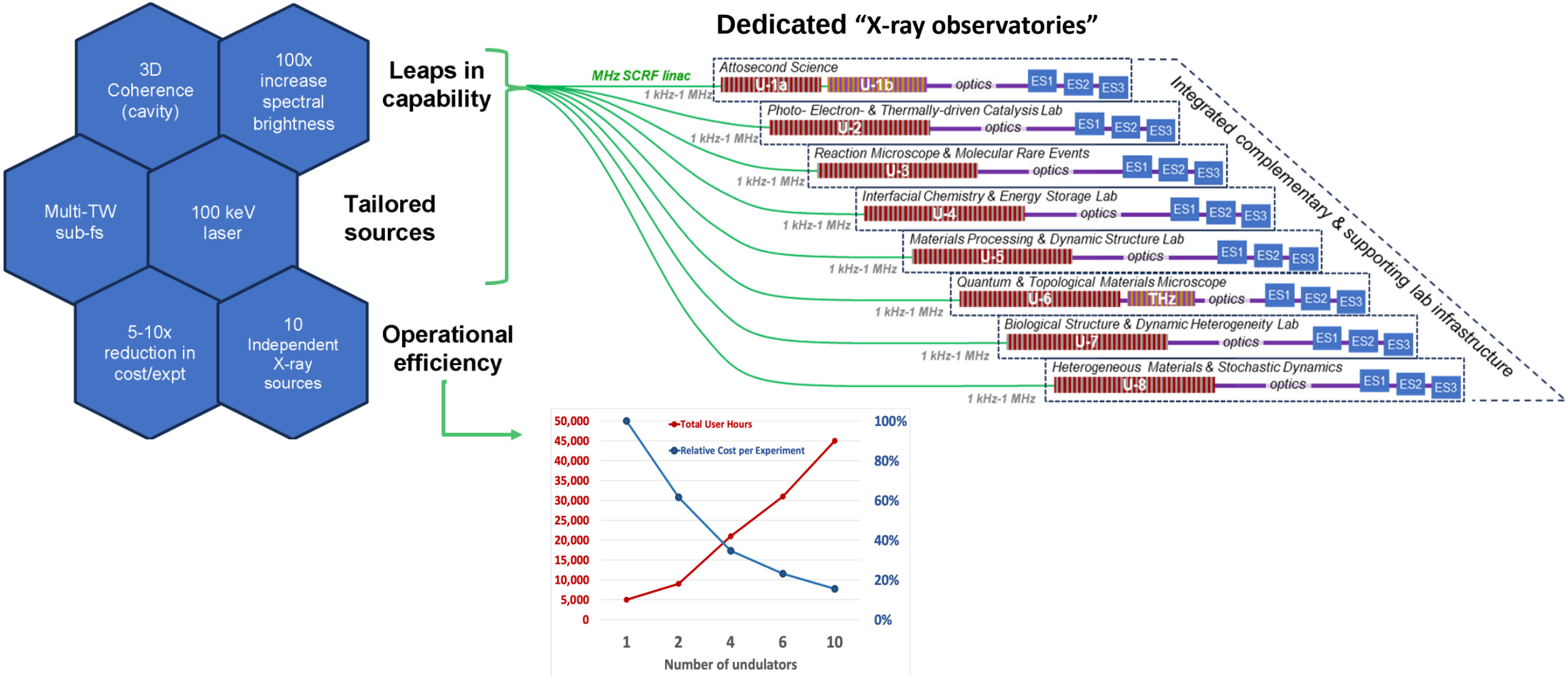
- AI enabled feedback focused on stability: spectral, temporal, & intensity stability

The opportunity to develop the '*next thing*' dependent on robust delivery of the '*present thing*'

Thank you and questions

4. Multiplexed X-ray Laser:

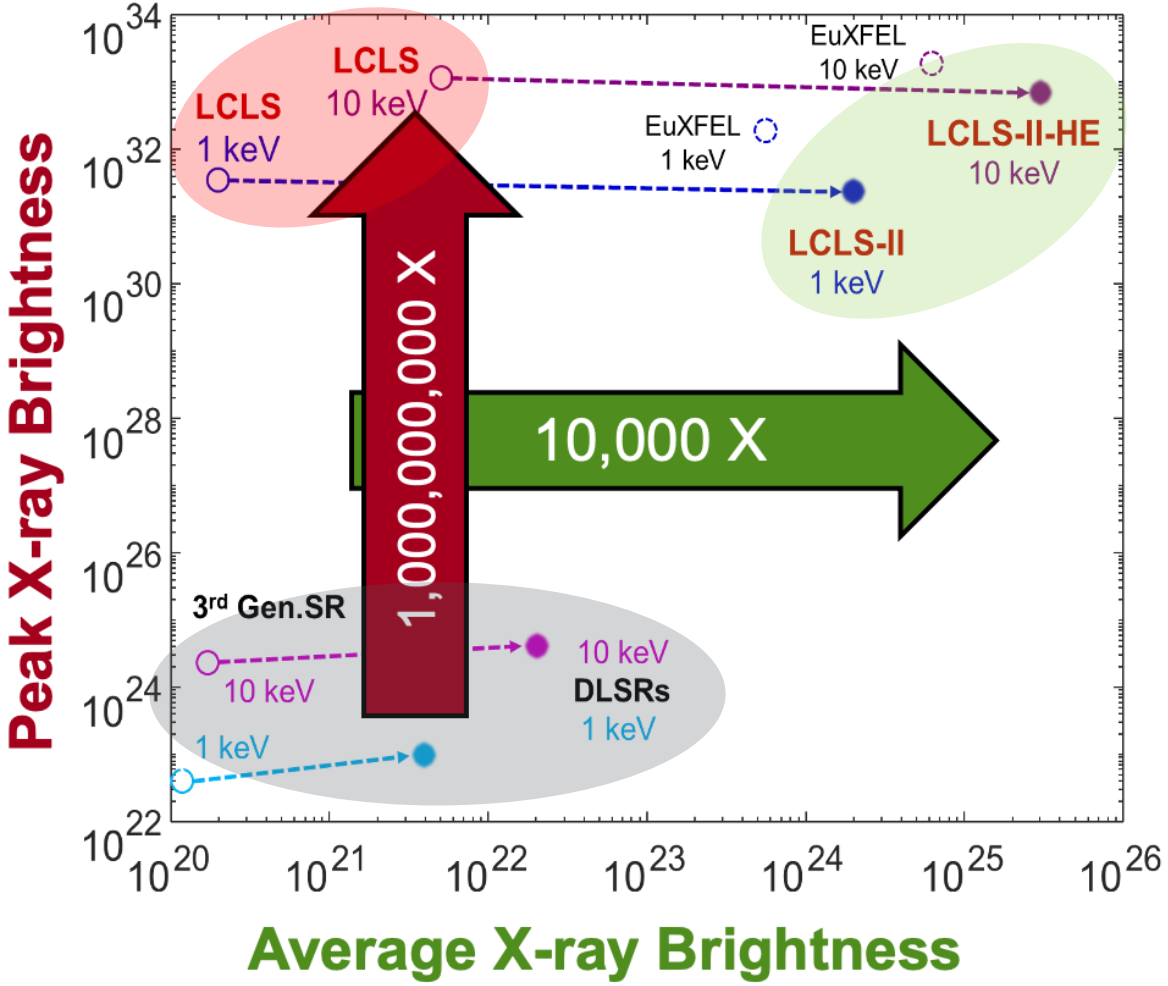
Dedicated, specialized XFEL beamlines operated in parallel



Multiplexed delivery of dedicated & specialized instrumentation: Necessary for the efficient delivery of scientific impact only achievable with X-ray lasers

2. Leaps in LCLS capabilities:

High repetition rate X-ray laser game changer for science discovery



Phase 1 (2020): LCLS-II variable gap dual undulators

Phase 2 (2023-2025): LCLS-II 4 GeV SC accelerator

- 0.25 to 1.5 keV with up to 100 kHz (CW, programmable)
- Instruments: TMO IP1 + IP2, qRIXS, ChemRIXS

Phase 3 (2026-2029): LCLS-II-HE 8 GeV SC accelerator

- 0.25 to 10 keV with up to 100 kHz
- Instruments: upgrades to XPP & MFX, plus RIX3 & TXI

Phase 4: LEI and Instrument Upgrades

- 0.25 to 20 keV with up to 1 MHz
- Instruments: upgrades to CXI & XCS)

Commissioning of high repetition rate hard X-rays scheduled for Fall 2027