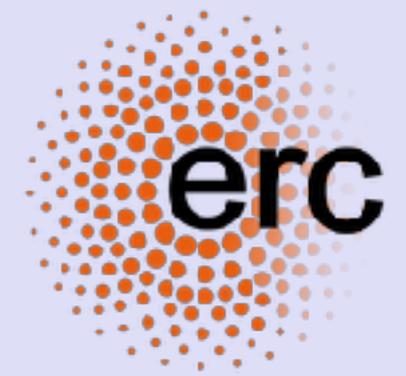


**X-ray absorption spectroscopy with X-rays
from a laser wakefield accelerator**

Stuart Mangles

Acknowledgements



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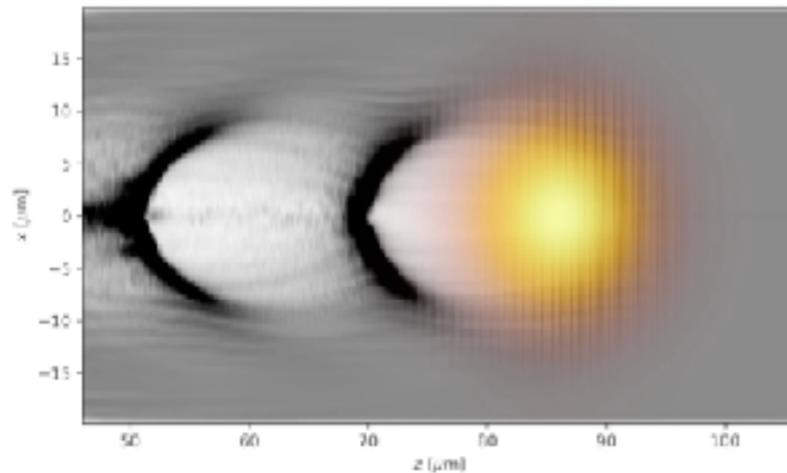
⁷Lawrence Livermore National Laboratory, USA

⁸Queens University Belfast, UK

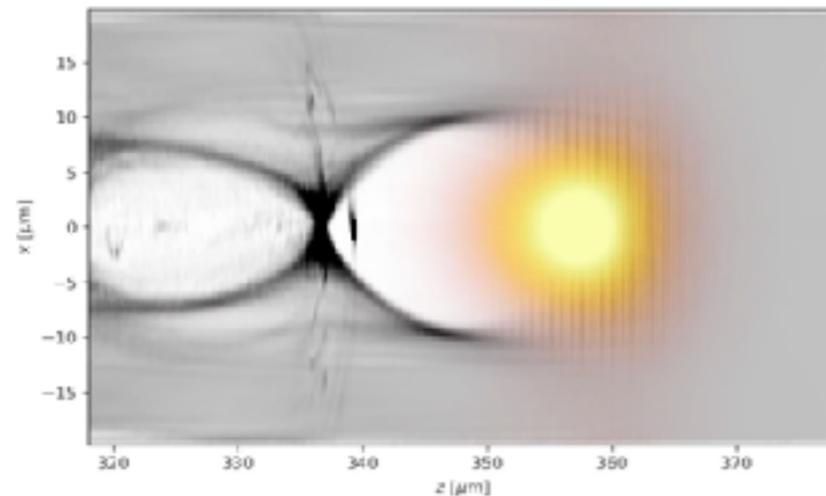
**Imperial College
London**



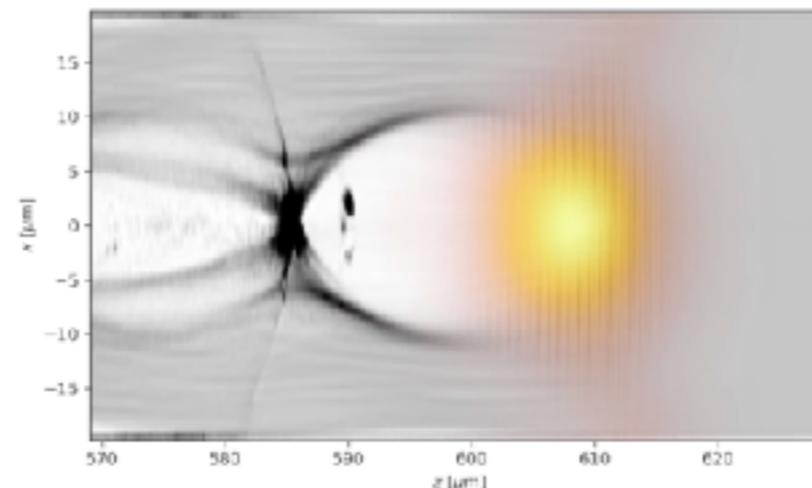
When a high power laser enters a plasma, something amazing happens...



- Laser enters plasma, driving a plasma wave in its wake

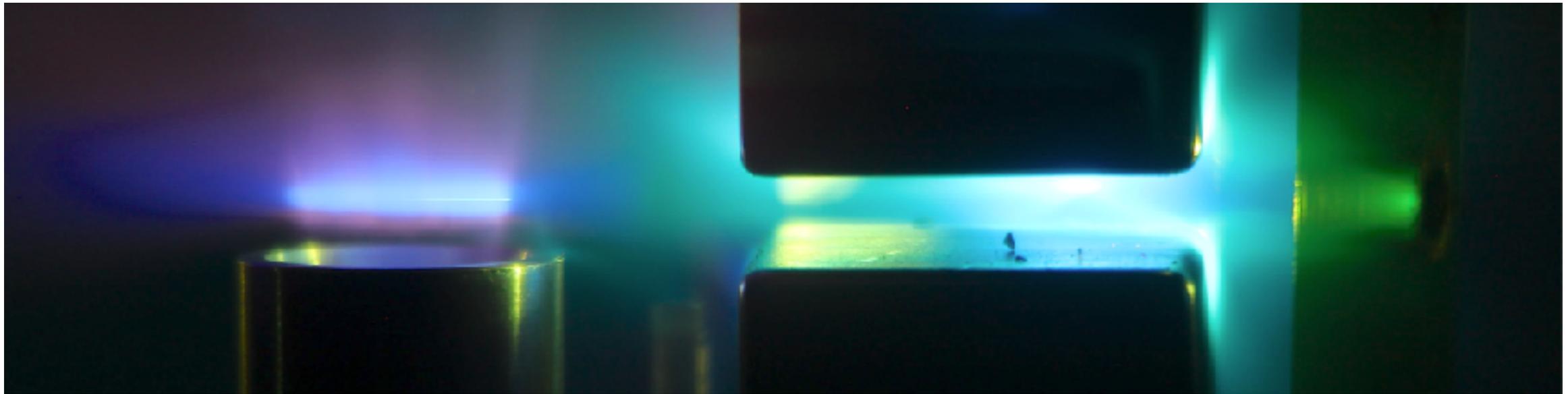


- Wake amplitude grows and electrons from background plasma are swept up and accelerated by the wake

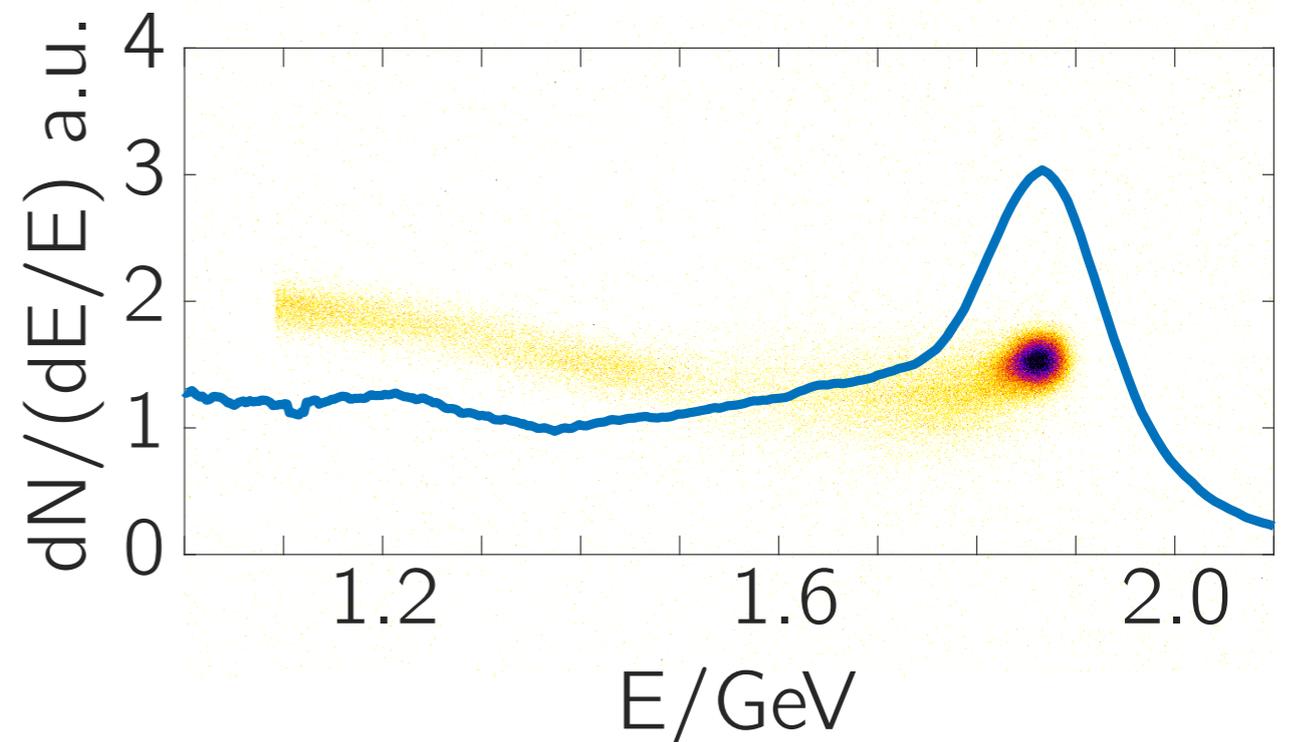


- Electrons undergo betatron oscillations in the wake, generating X-rays

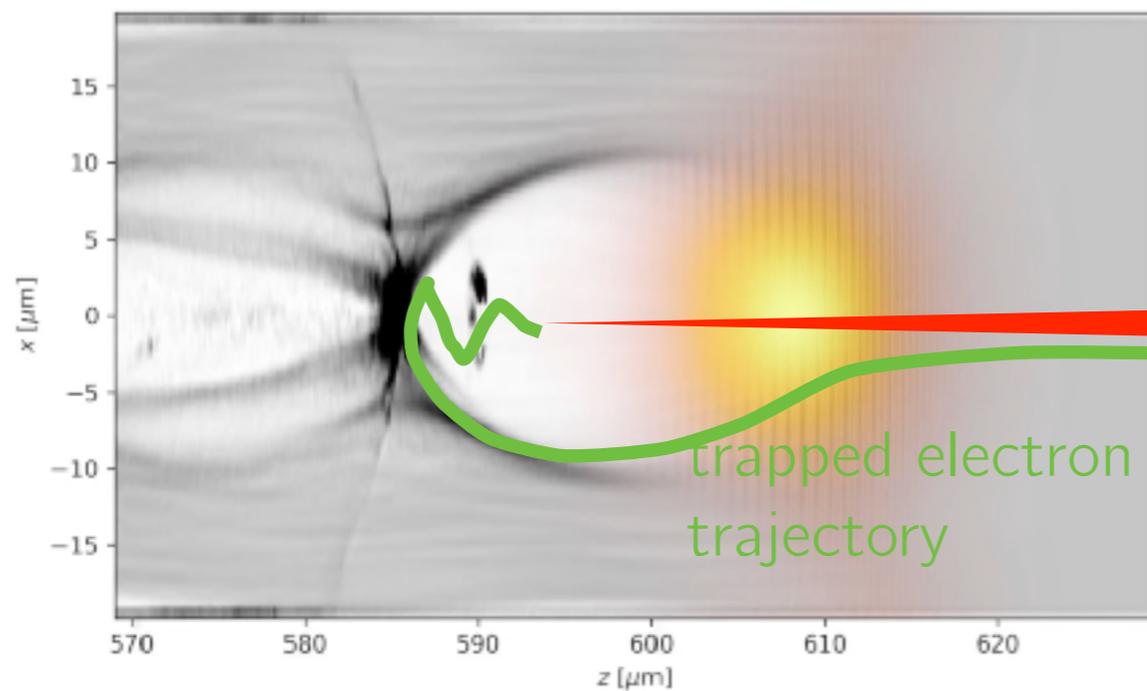
Laser wakefield accelerators are a source of interesting electron beams



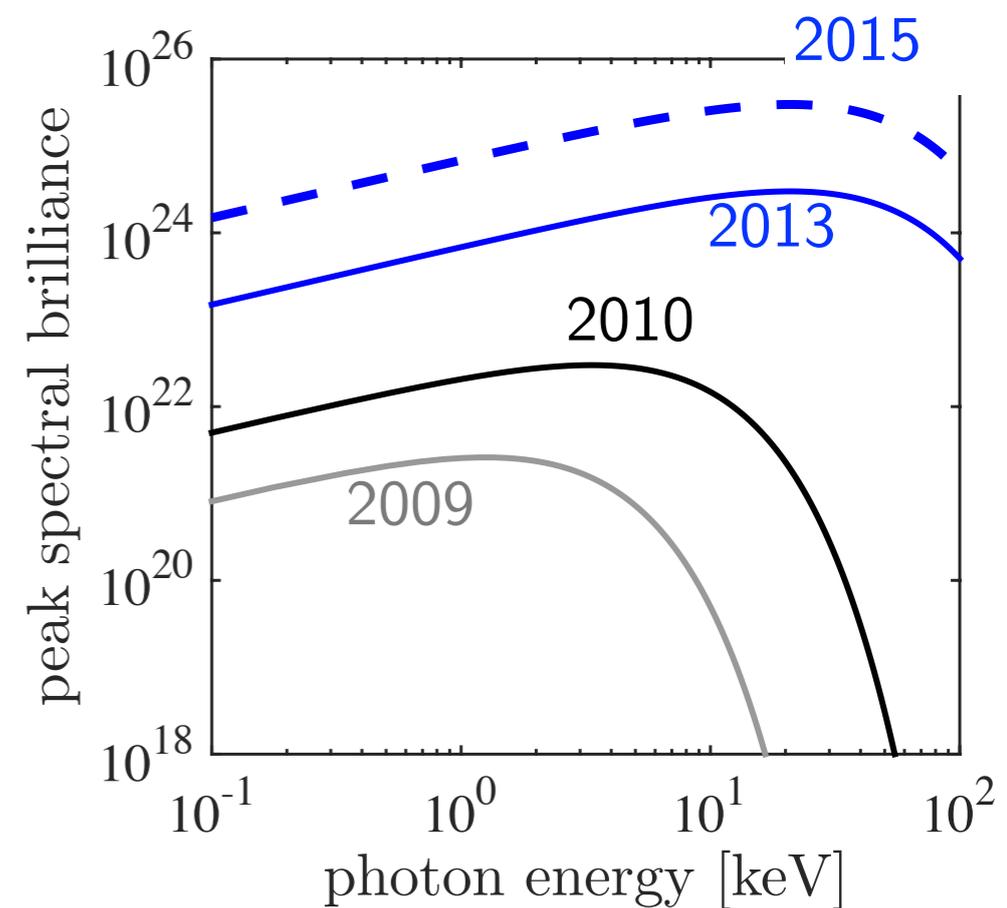
- Laser wakefield accelerators produce electron beams
 - high charge (100 pC)
 - high energy (> 1 GeV)
 - short duration (~ 10 fs)



Laser wakefield accelerators are a source of interesting X-ray beams



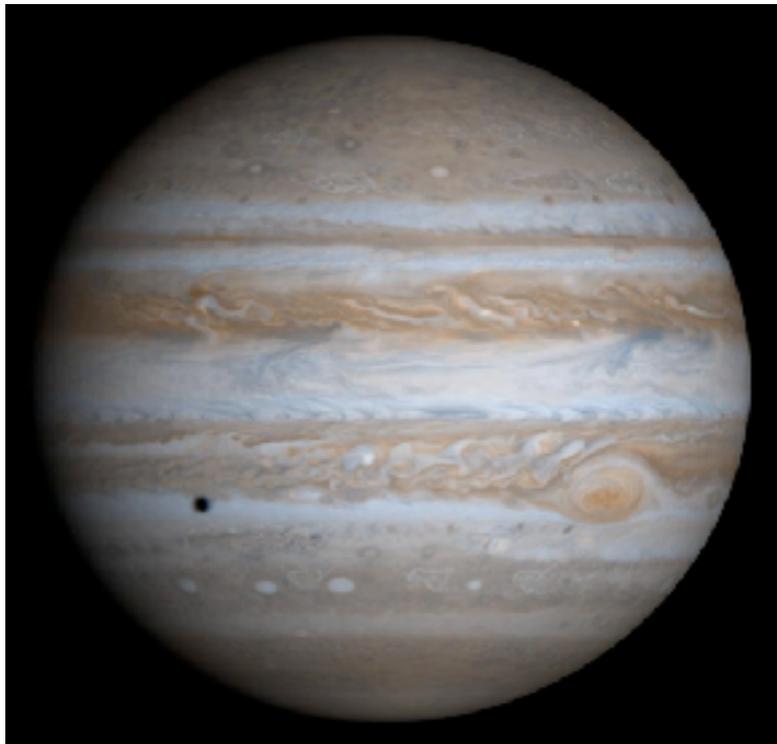
bright X-ray flash



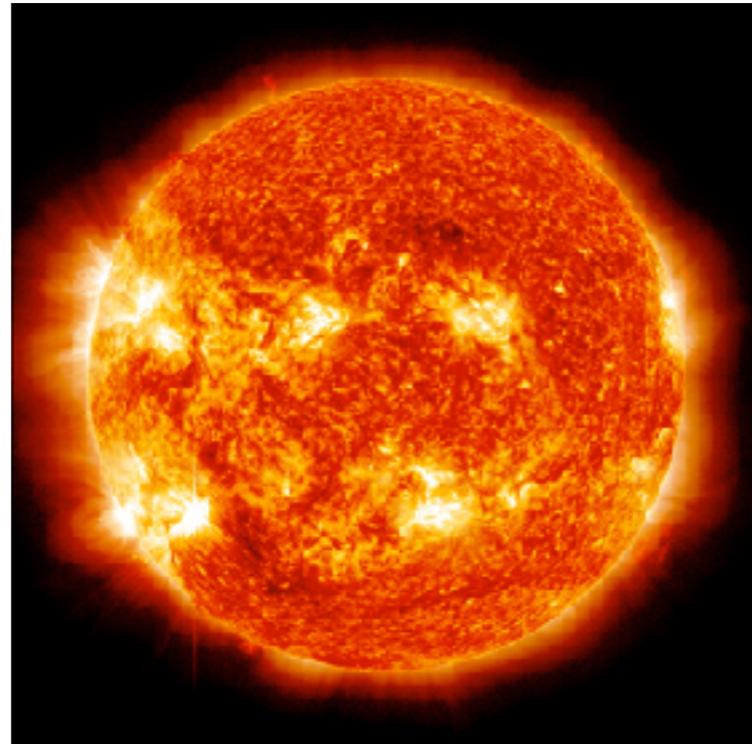
- LWFA produce X-rays “betatron radiation”
 - high-energy (10s keV);
 - broadband (synchrotron spectrum)
 - ultra-fast (femtosecond duration);
 - bright ($> 10^9$ photons per shot)

High power lasers can be used to create extreme conditions

- *nanosecond*: shock compress material to high pressure
- *picosecond*: create hot, dense matter and high flux X-rays
- *femtosecond*: very strong electromagnetic fields



high pressures

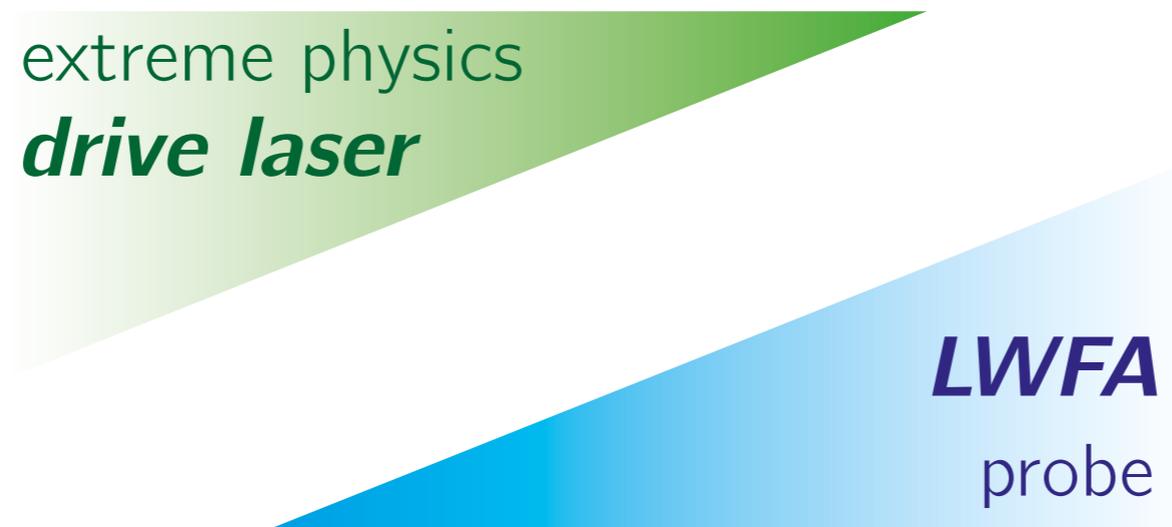


high temperatures



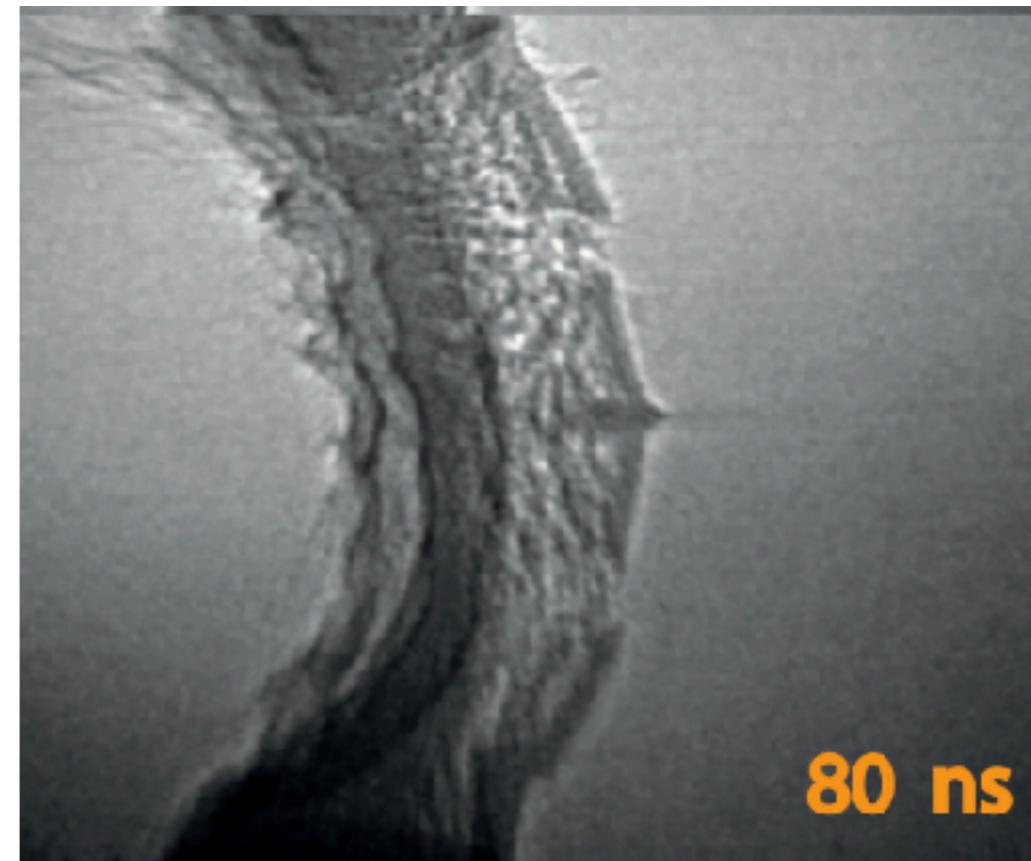
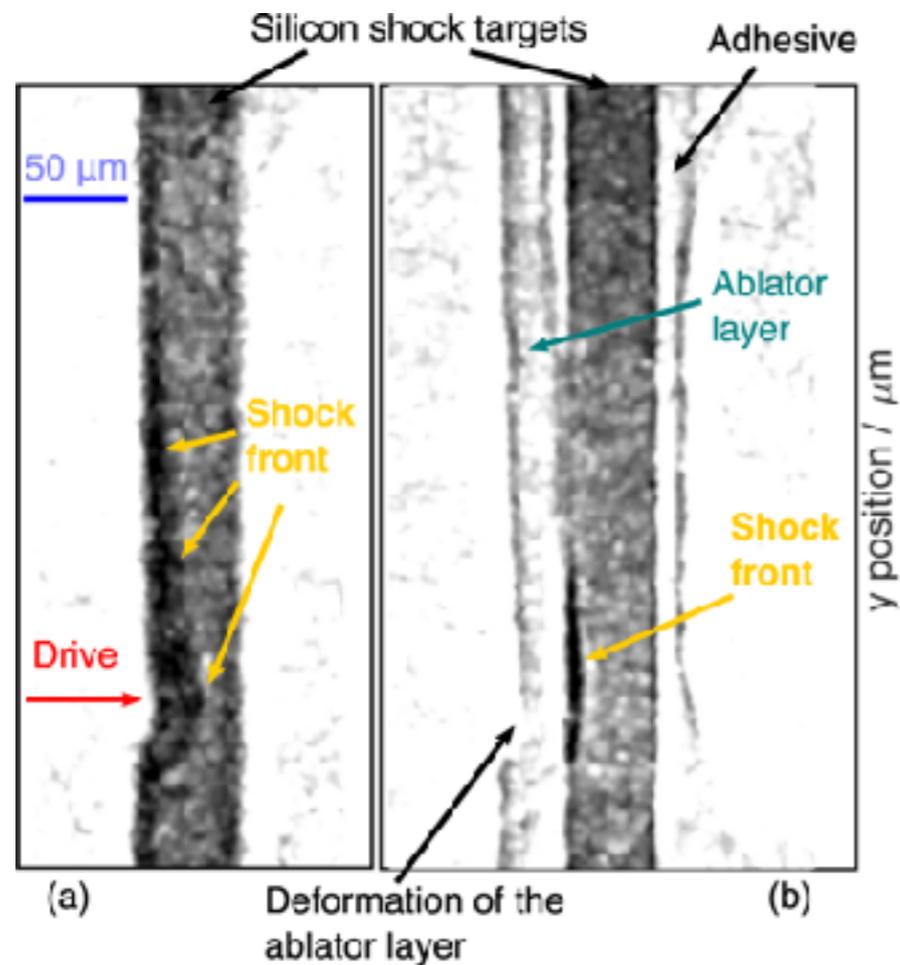
high flux X-rays
high electromagnetic fields

Using Laser Wakefield Accelerators to probe extreme conditions



- Co-location of wakefield based sources with other drivers
 - Good spatial and temporal overlap between sources
 - » 5 μm and 10 fs achievable
- Laser wakefield sources could be used to probe extreme states of matter

Laser Wakefield Accelerators for Dynamic Imaging



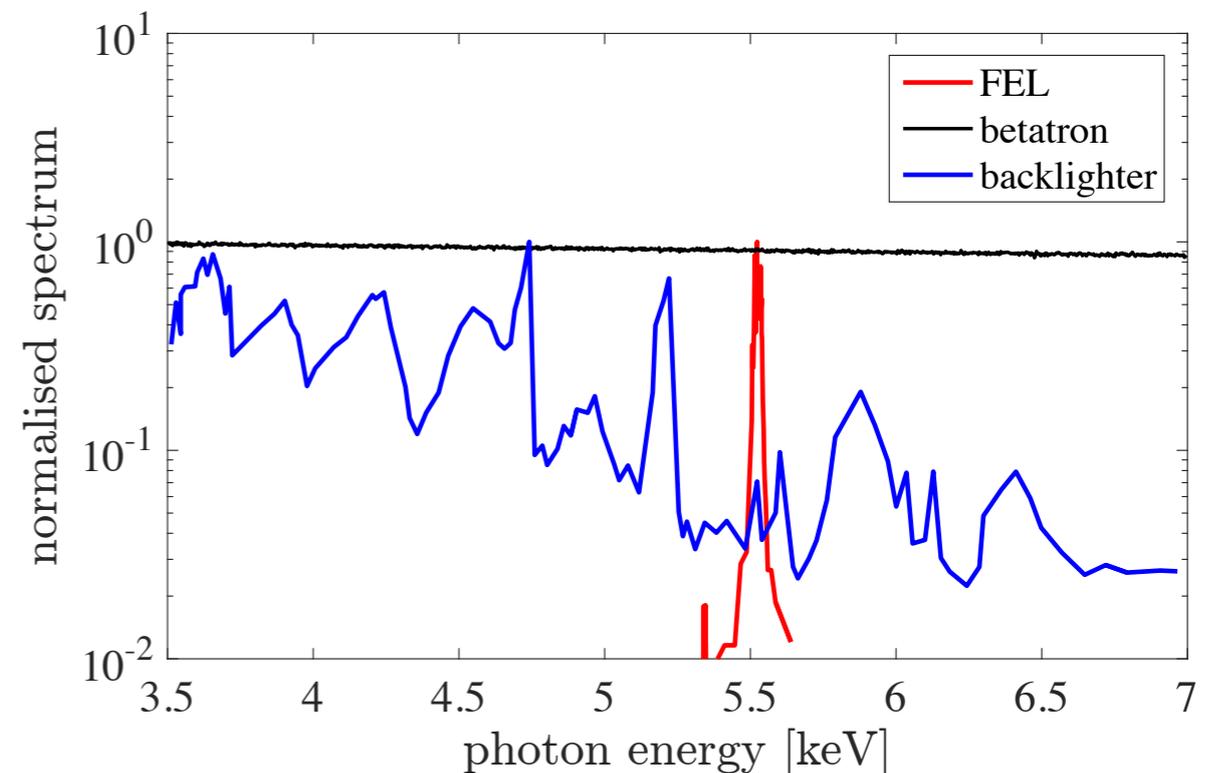
J Wood et al Sci Rep 8, 11010 (2018)

J Wood PhD Thesis, Imperial 2017

- Small ($1\ \mu\text{m}$) source size enables use to make high resolution imaging of laser driven shocks

X-rays from LWFA are well suited to Absorption Spectroscopy

- At LPAW2013 the plasma accelerator community identified XAS for as a possible application of wakefield accelerator based light sources

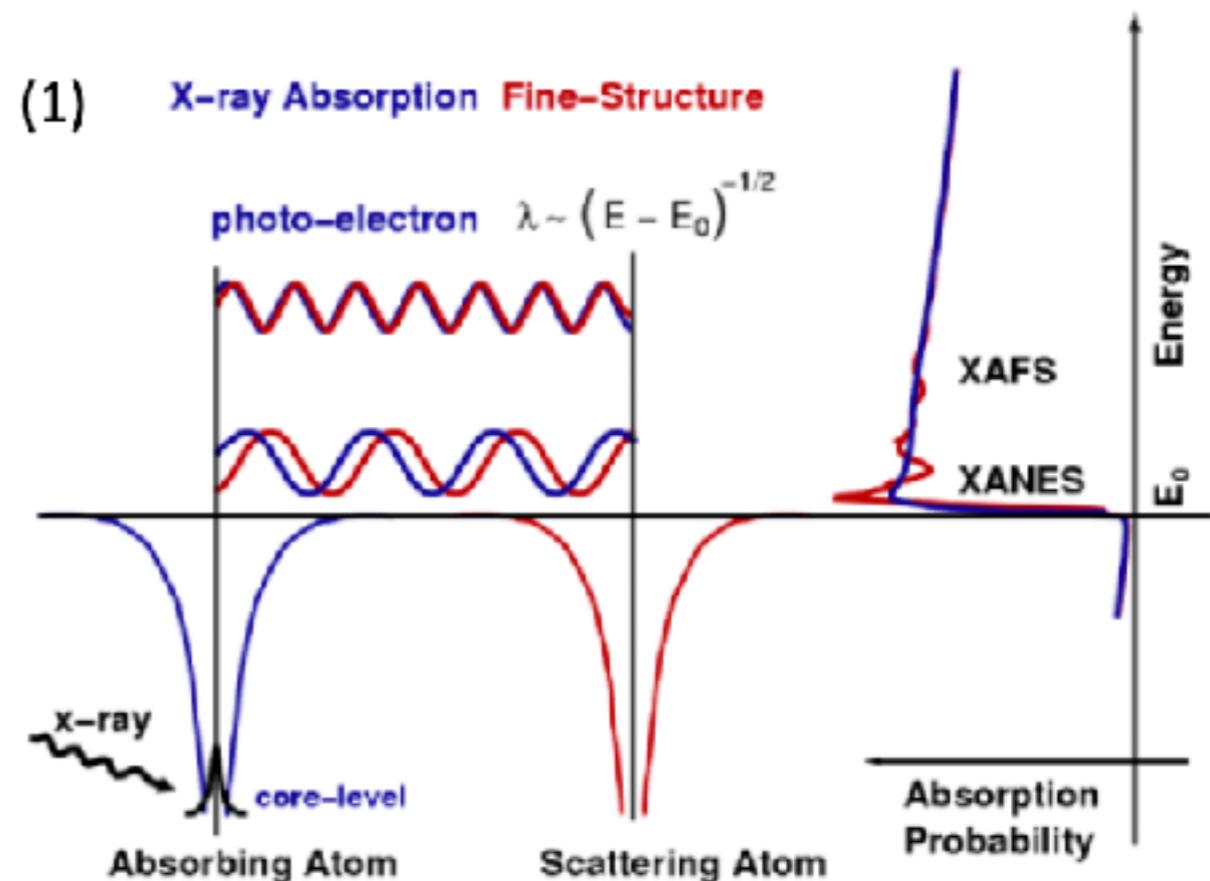


*“Due to its broad, continuous spectrum, femtosecond pulse duration and synchronization with the drive laser, there is wide recognition that betatron radiation has the potential [in time resolved X-ray absorption spectroscopy] , but several improvements have to be made to the source in order to achieve this
..... $N_{ph} > 10^6 \text{ eV}^{-1}$ must be fulfilled to realize an EXAFS experiment with good statistics .”*

F. Albert et al PPCF 2014

XANES: X-ray Absorption Near Edge Spectroscopy

- X-ray absorbed by atom → emits photo-electron → photo-electron scatters from nearby atoms
- Interference between incident and scattered photo-electrons affects the probability of X-ray absorption
- This encodes information about both electronic energy levels and local ion structure of material

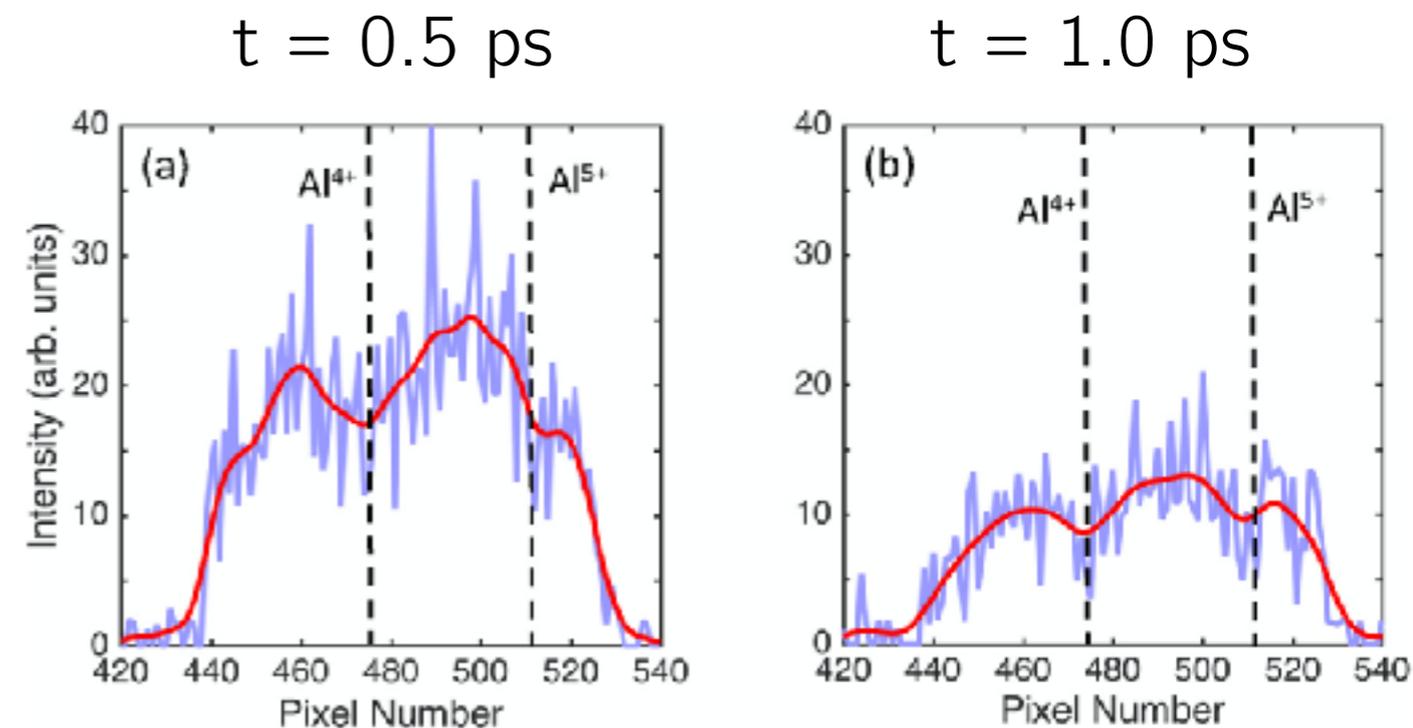


A Practical Introduction to Multiple Scattering Theory, Bruce Ravel, 2005

Progress in X-ray Absorption Spectroscopy using LWFA

- At ALLS, Canada, MZ Mo et al., performed XAS of laser heated Warm Dense Aluminium

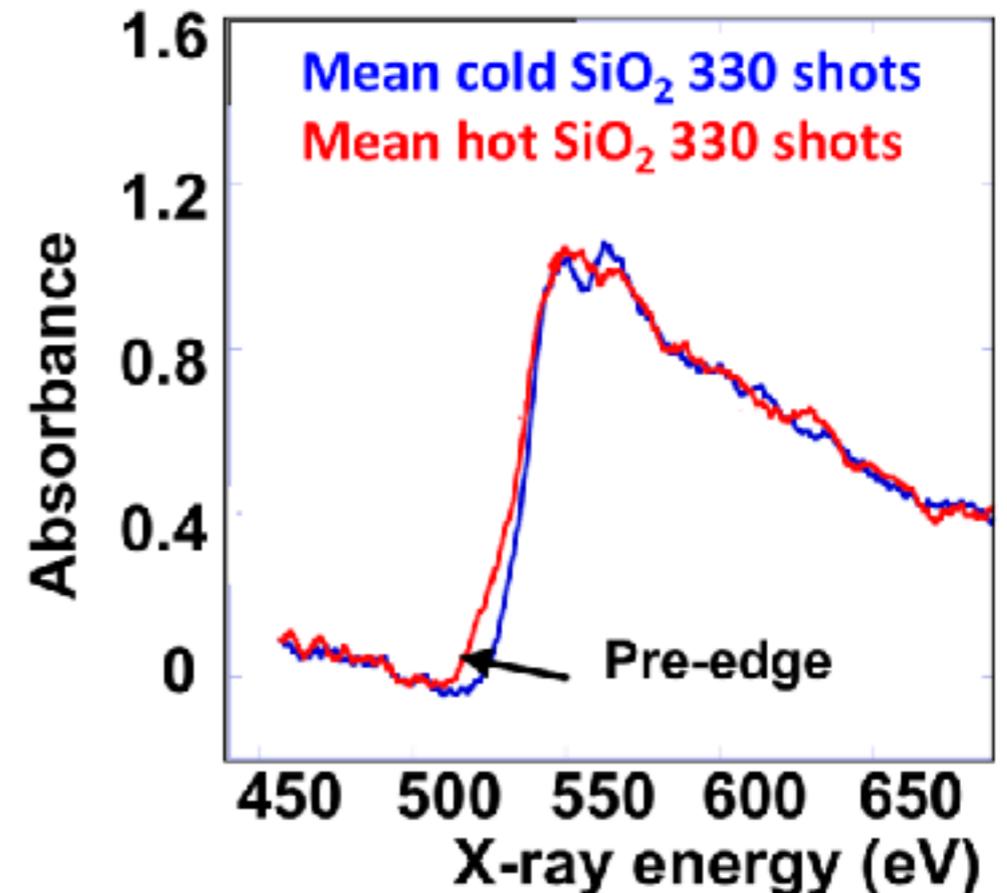
- 80 TW laser pulse
- More than 150 shots per spectrum



MZ Mo PRE 2017

Progress in X-ray Absorption Spectroscopy using LWFAs

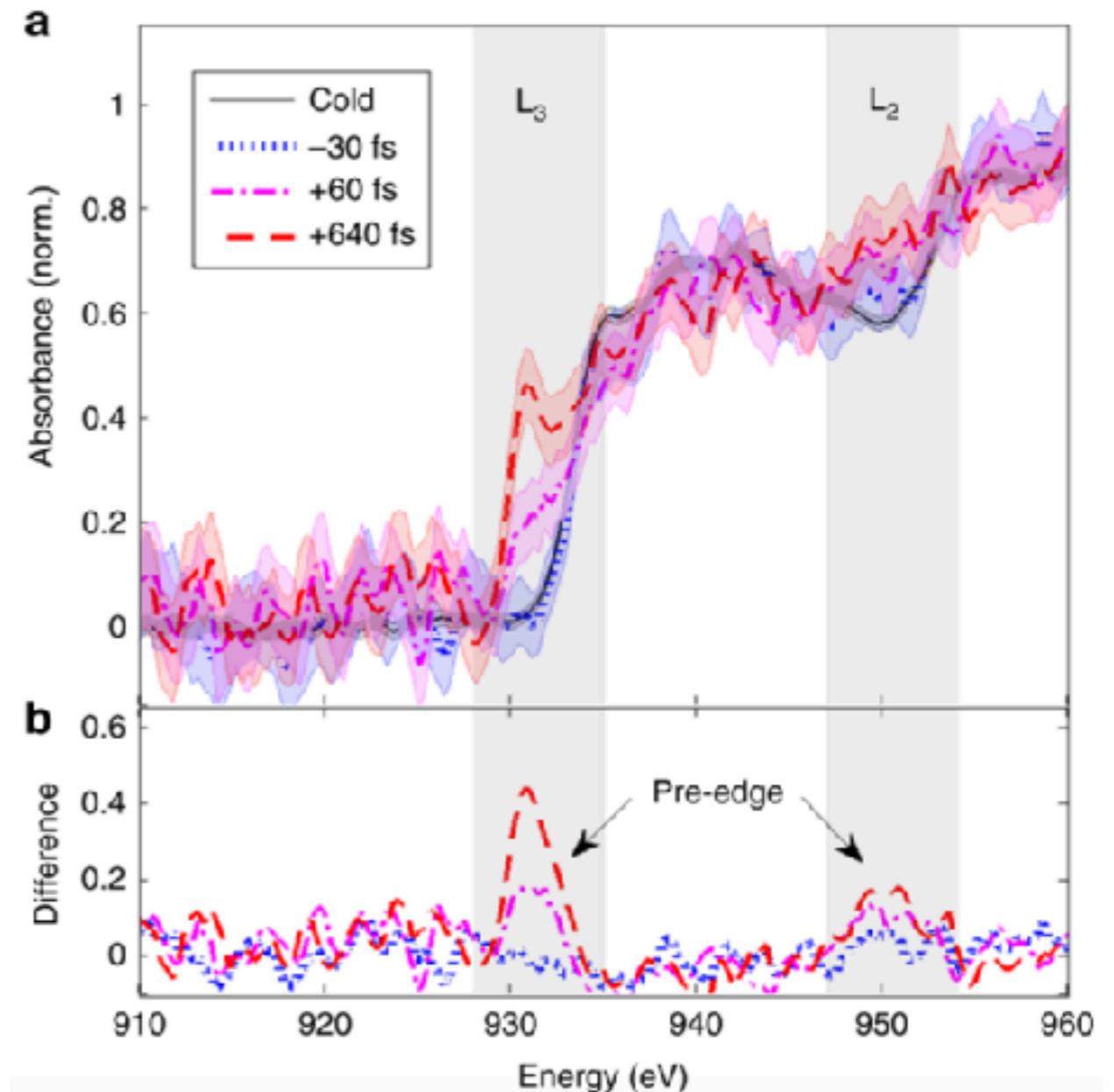
- At LCLS, F Albert et al., performed XAS of XFEL heated SiO_2
 - 20 TW laser pulse
 - More than 300 shots per spectrum



F Albert, “Applications of light sources driven by laser wakefield acceleration”
IPAC 2018

Progress in X-ray Absorption Spectroscopy using LWFAs

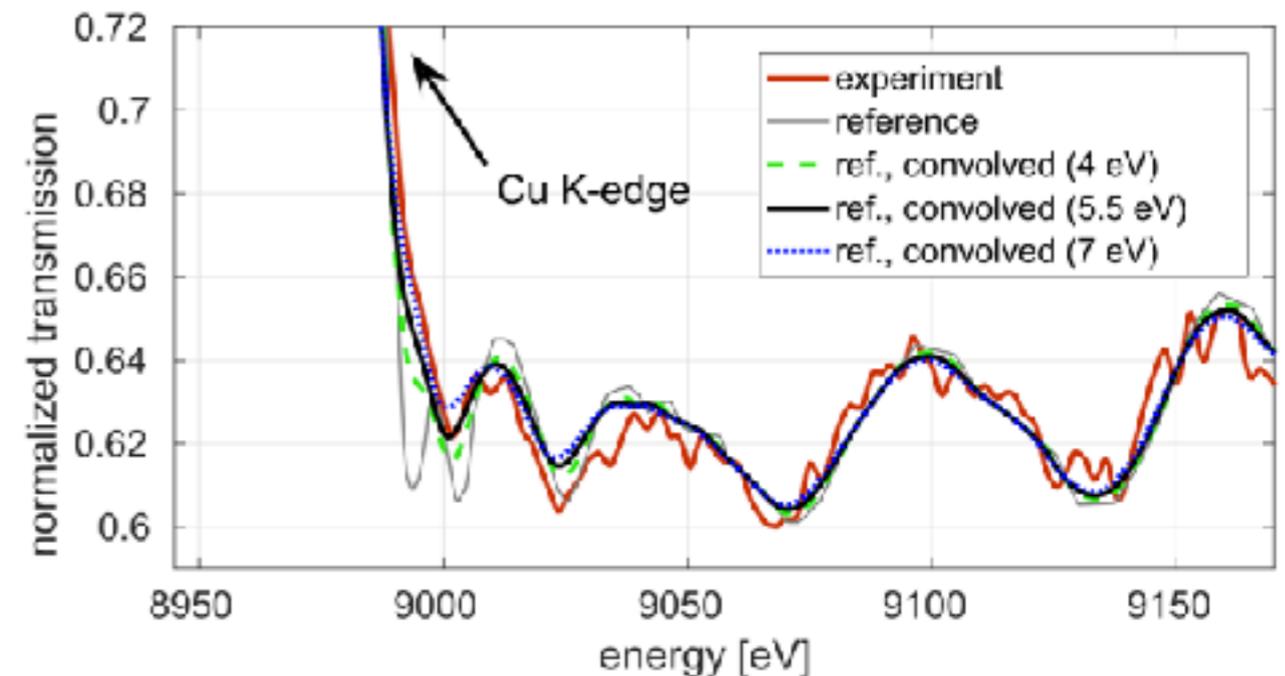
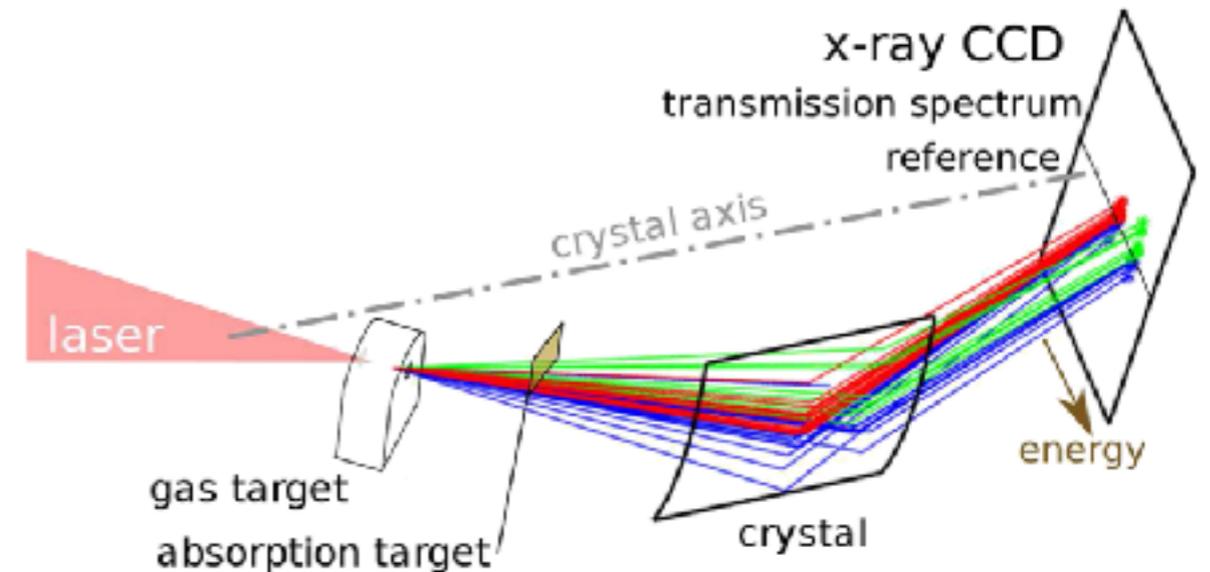
- At LOA, Mahieu et al observed sub-100 fs electron heating of warm dense copper observed (L-edge XANES)
 - 50 TW laser
 - 50 laser shots per spectrum



Mahieu Nature Communications 2018

Progress in X-ray Absorption Spectroscopy using LWFAs

- At Lund, M Smid et al., developed a high efficiency HOPG crystal spec
 - 20 TW laser pulse
 - 150 shots per spectrum

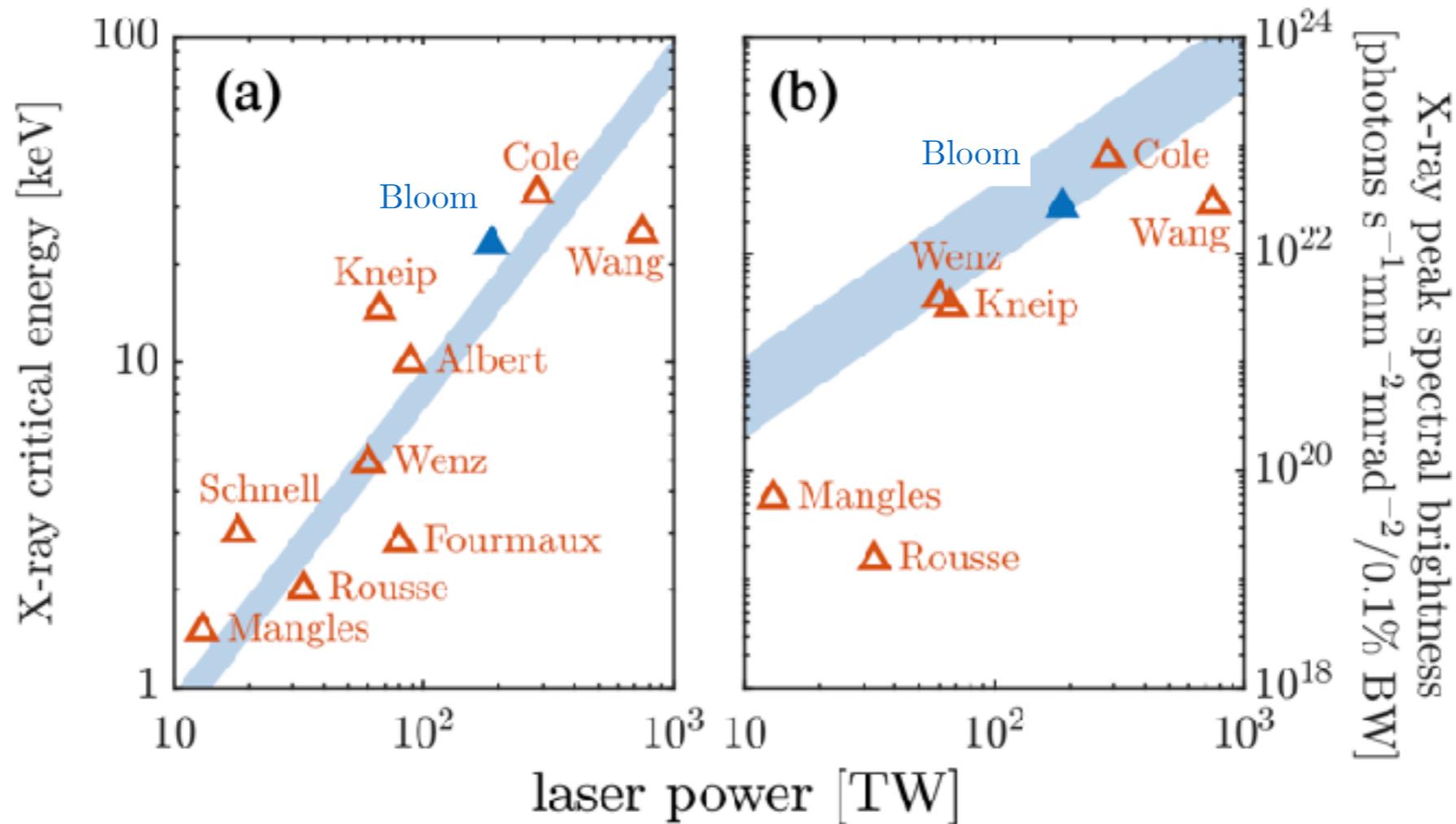


M Smid et al RSI 2017

Is single shot XANES possible?

- XANES using betatron radiation from LWFA sources shown so far are limited by:
 - Low X-ray energy (≈ 1 keV) : limits choice of material/thickness
 - Low X-ray flux : many shots required for one spectrum
- Can we increase photon energy and flux to achieve single shot XANES?
 - This will open up possibility of doing XANES on lower rep rate, high-energy laser systems better suited to creating extreme conditions
 - e.g. VOPPEL project on Vulcan Laser at CLF will combine 30 J/30 fs betatron beam line with 500 J/ 500 fs and 300 J / 8 ns pulses

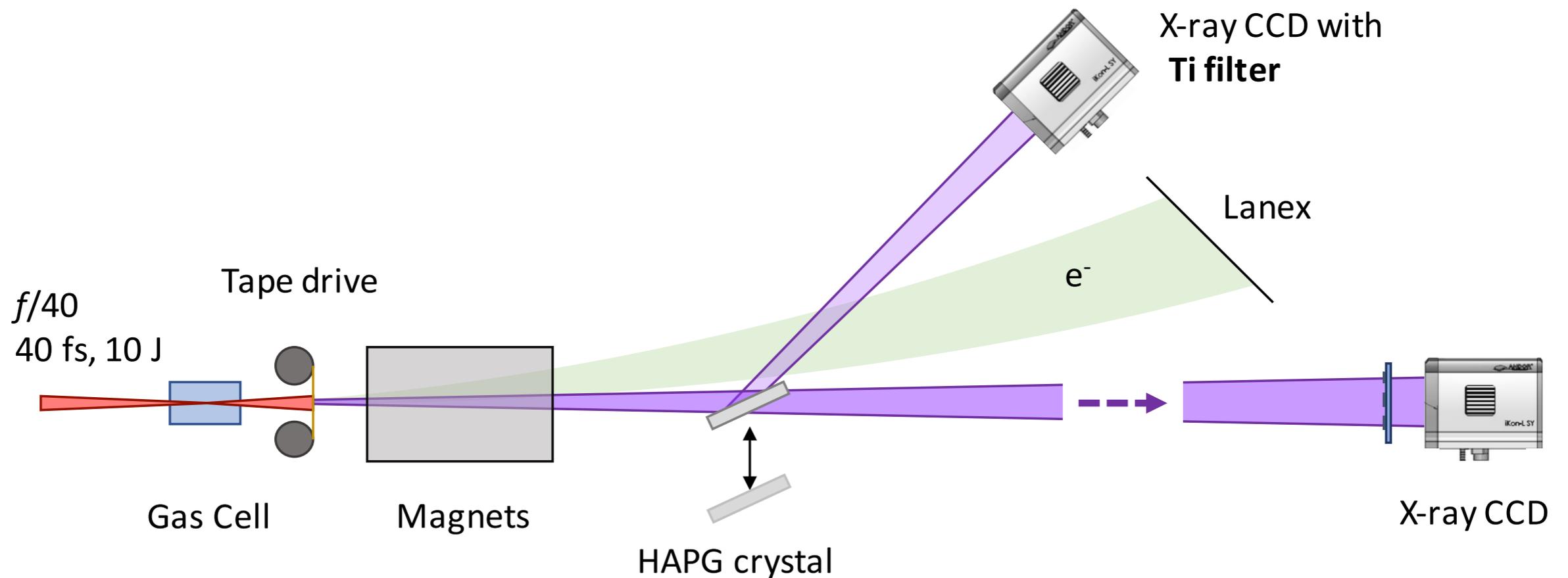
Is single shot XANES possible?



Bloom PRAB 2020

- Increasing laser power increases X-ray energy and brightness
 - Use Gemini 250 TW laser

XANES on Gemini

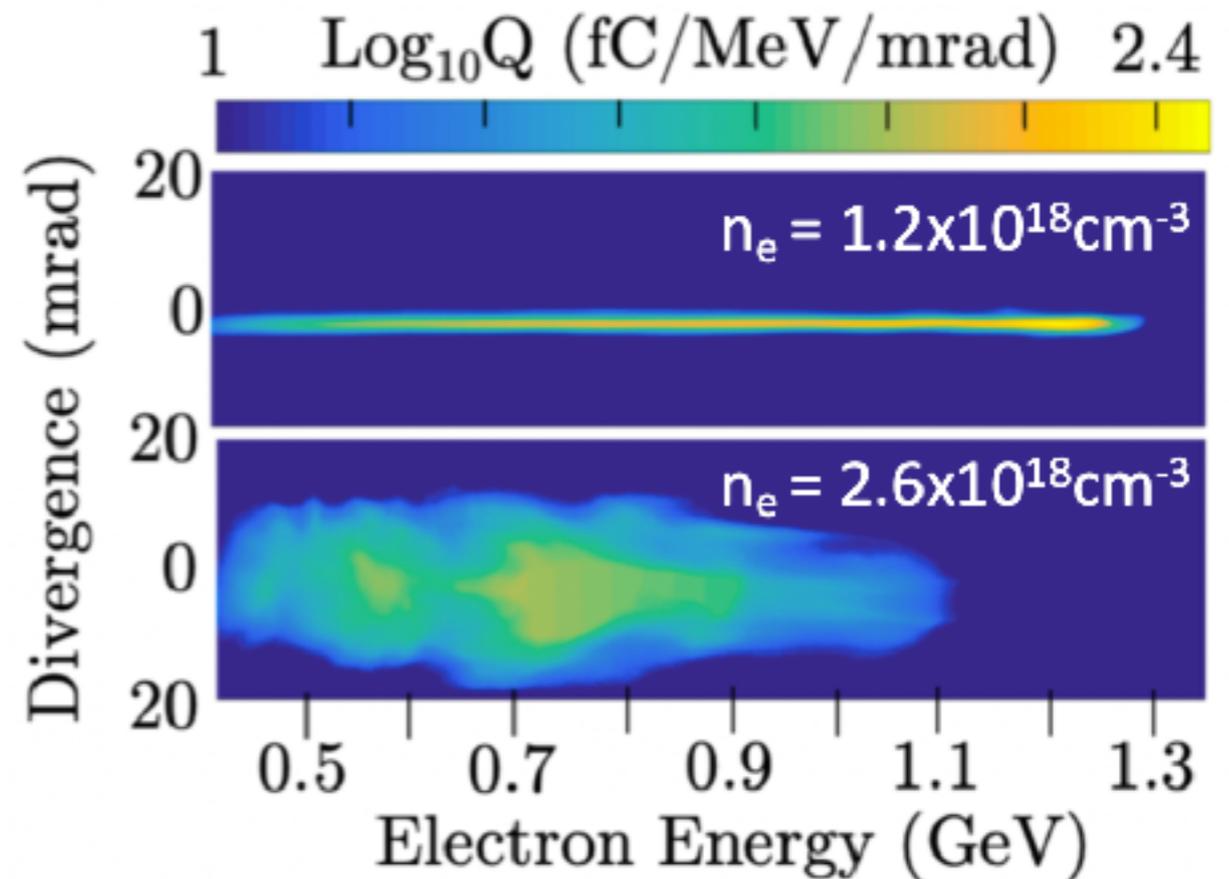


- Gemini Drive laser:

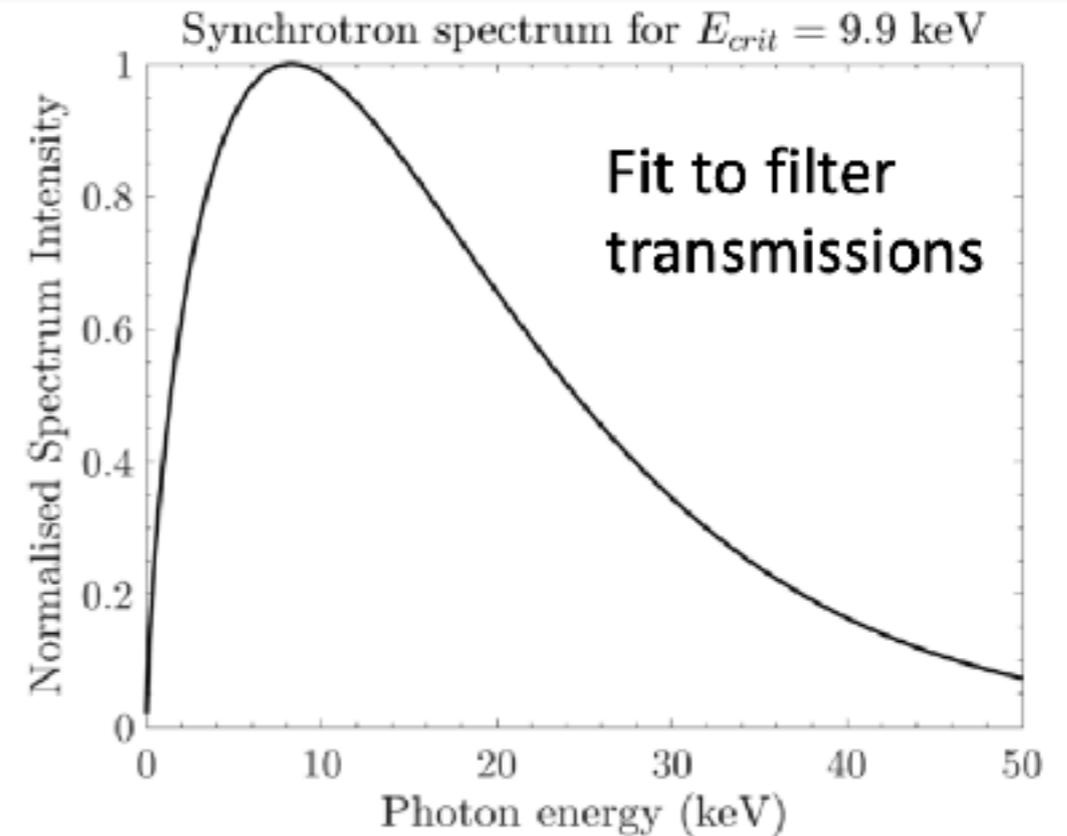
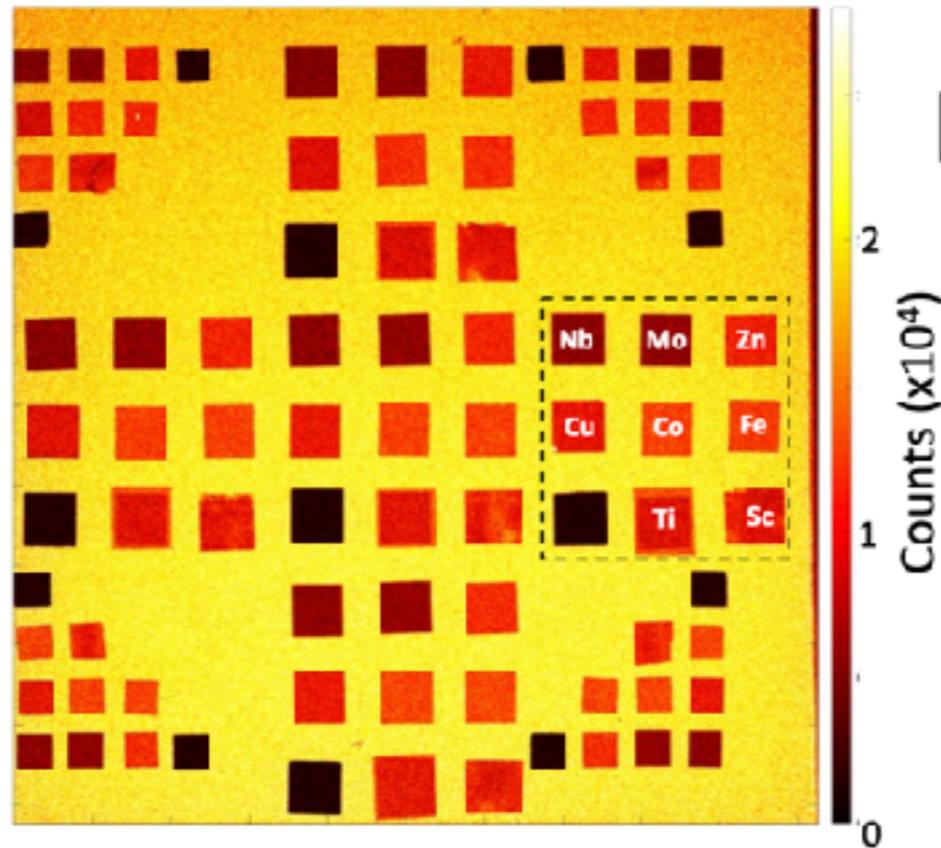
- duration 47 ± 5 fs
- Energy 9.0 ± 0.3 J (40% in fwhm)
- Intensity $4.9 \pm 0.6 \times 10^{18}$ Wcm⁻²

Optimising accelerator performance for X-rays

- Accelerator operated in regime that maximised multi-keV X-rays
- Electron beams with
 - Lower energy
 - Higher charge
 - Higher divergence



X-ray beam characterisation



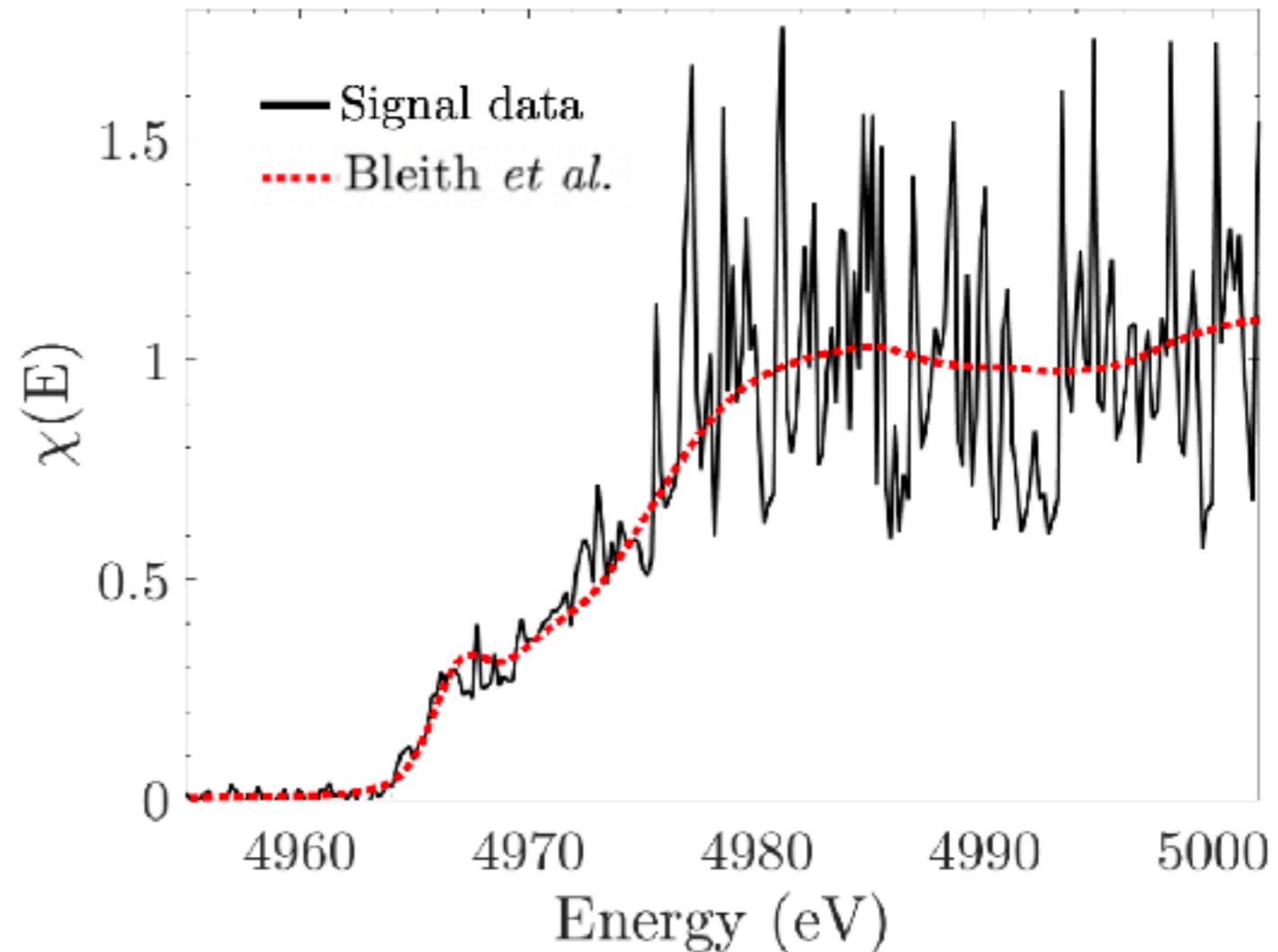
$$\left. \frac{d^2 I}{dE d\Omega} \right| \propto \gamma_e^2 \left(\frac{E}{2E_{crit}} \right)^2 \mathcal{K}_{2/3}^2 \left(\frac{E}{2E_{crit}} \right)$$

- Spectrum characterised by measuring transmission through array of metallic filters

- $E_{crit} = 9.9 \pm 1.5$ keV,
- $7.2 \pm 2.8 \times 10^5$ photons/eV at 5 keV

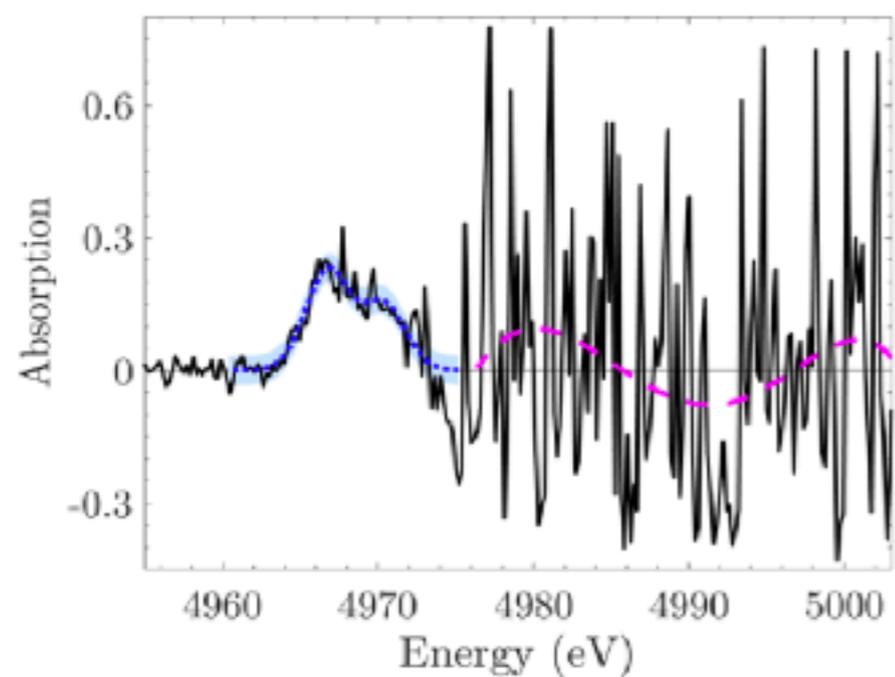
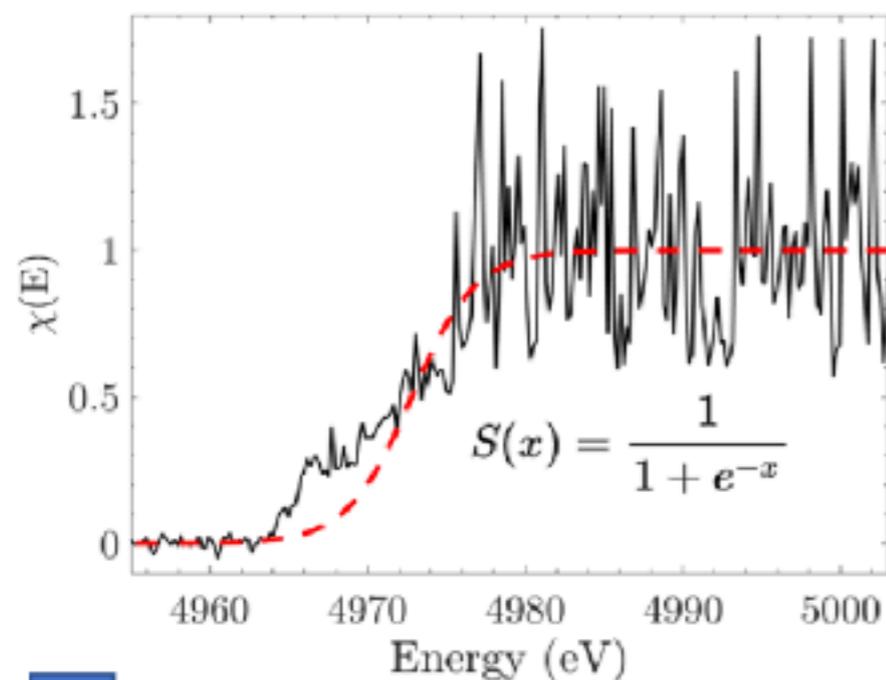
Titanium K-edge XANES measurements

- HAPG flat crystal spectrometer
 - 10 μm Ti foil (cold)
- Sufficient flux for **single shot** XANES over an 80 eV window
 - instrument function of 2.2 eV

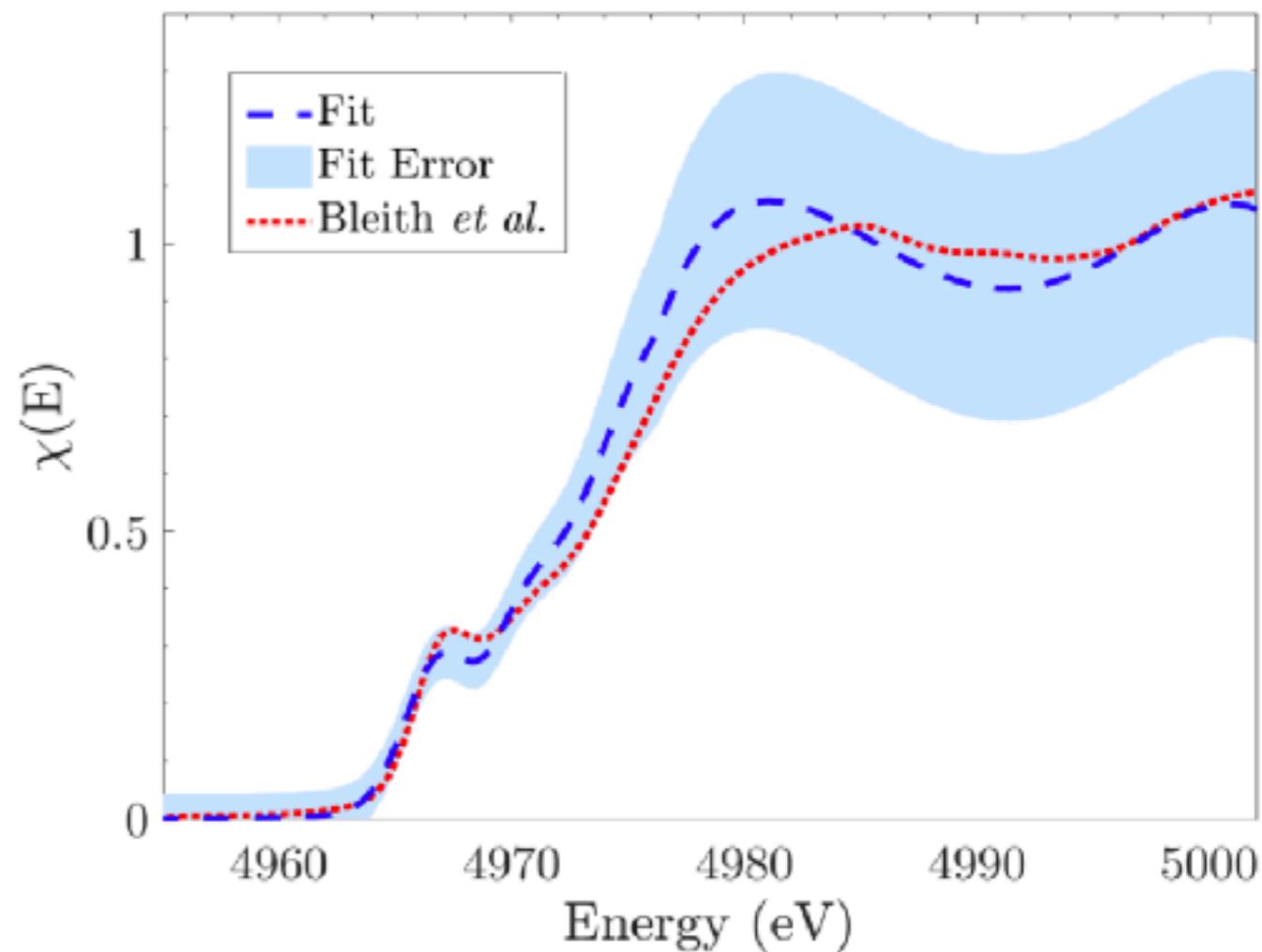


Main noise source identified as radiation produced in electron beam dump - improvements possible

Some fitting....

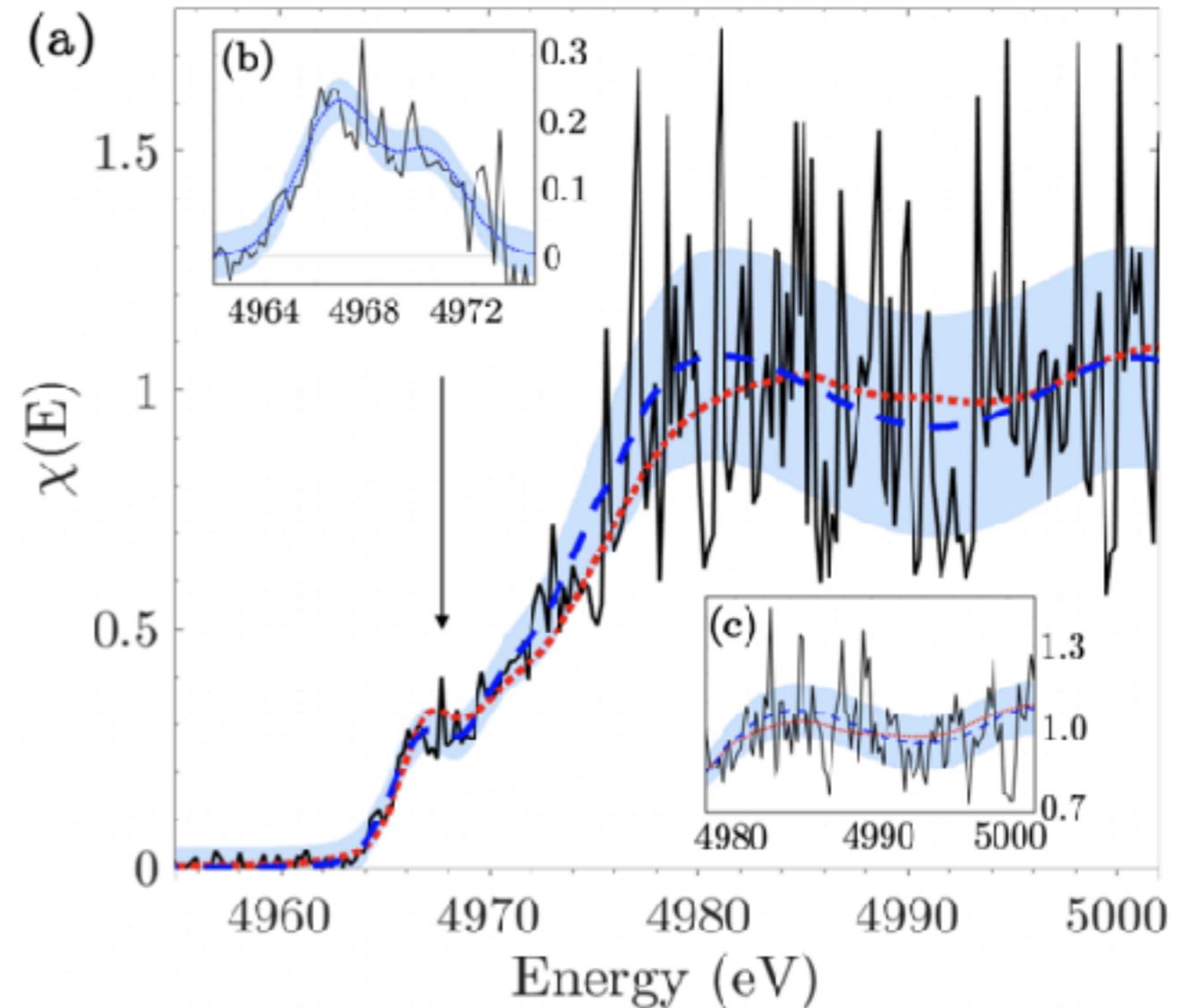


Reconstructed fit



Single shot XANES using betatron radiation from a LWFA

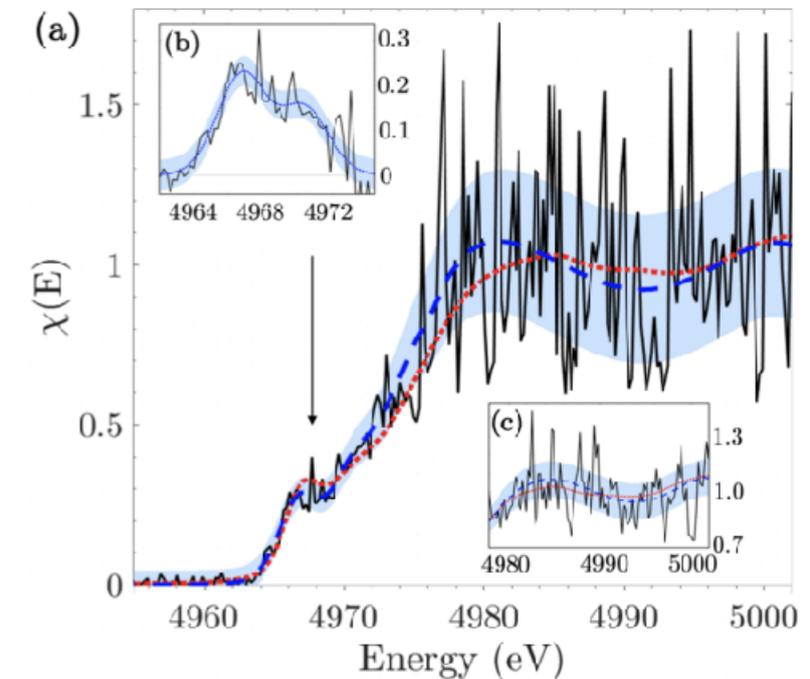
- Pre-edge feature and edge slope → electron temperature
 - fitting confidence intervals correspond to
$$\Delta T_e \approx 0.4 \text{ eV}$$
 - ion features (EXAFS) still poorly resolved



B Kettle PRL, 123, 254801 (2019)

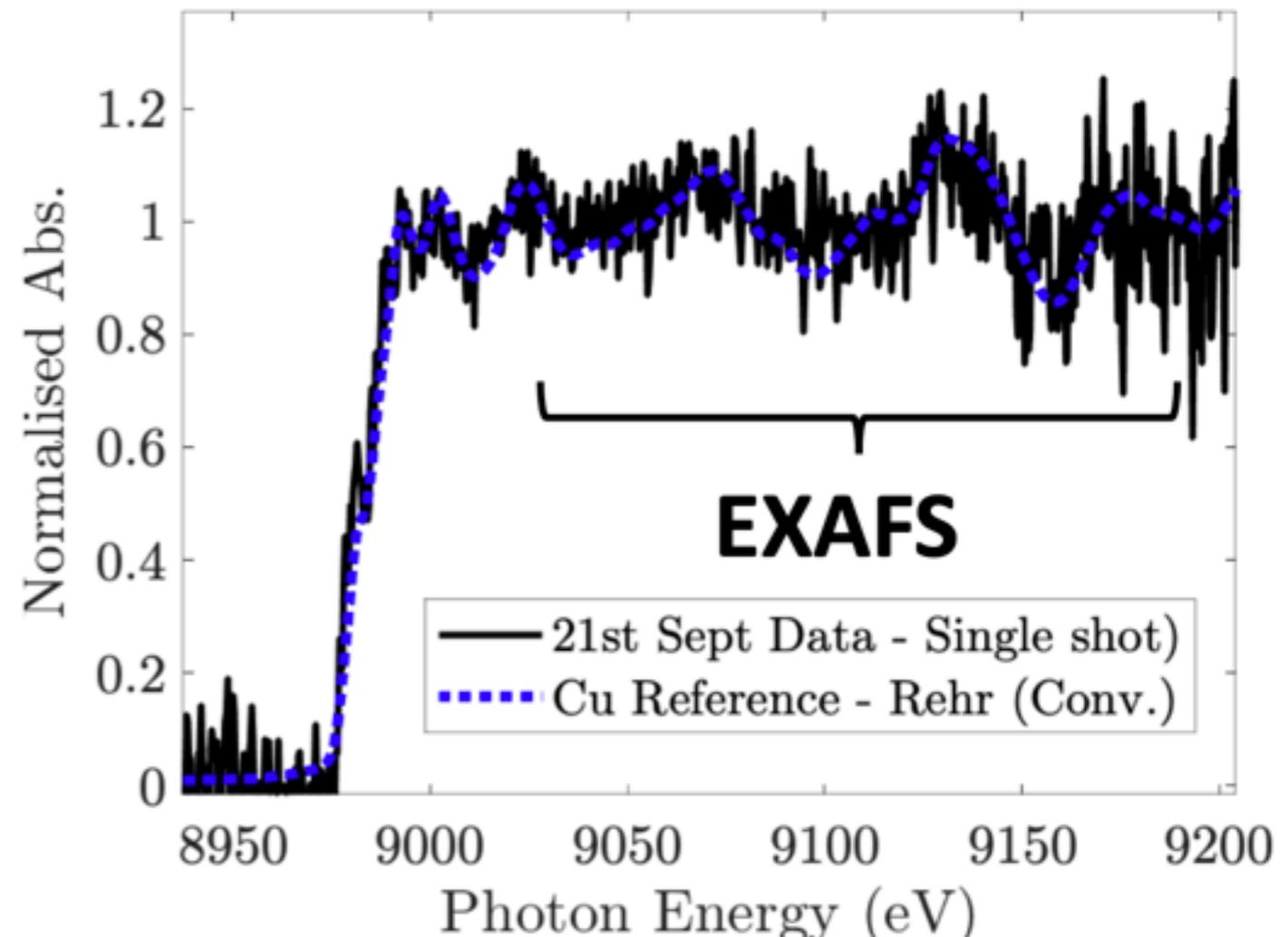
Summary

- X-rays from laser wakefield accelerators as a tool for ultrafast X-ray absorption spectroscopy
 - increased flux on Gemini enables single shot XANES
- What is next?
 - single shot EXAFS



2020 experiment: single shot XANES in Copper

- Improved shielding
 - lower noise
- Focussing crystal spectrometer
 - improved signal to noise
- XANES and EXAFS clearly resolved in a single shot



Summary

- X-rays from laser wakefield accelerators as a tool for ultrafast X-ray absorption spectroscopy
 - Increased flux on Gemini enables single shot XANES
- What is next?
 - Single shot EXAFS
 - Dynamic measurements of rapidly heated matter:
 - e.g simultaneous measurements of electron and ion temperatures in non equilibrium warm dense matter to measure equilibration rates

