# Femtosecond X-ray diffraction at megahertz repetition rates

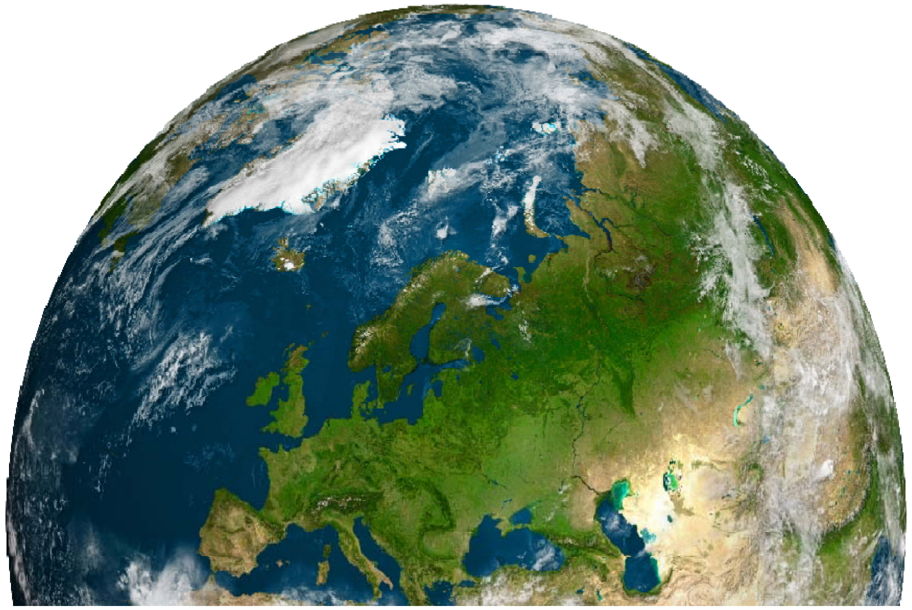
Anton Barty
Center for Free Electron Laser Science
(overview talk presenting results on behalf of many, many people)

# The European XFEL in Hamburg is 3 kilometres long

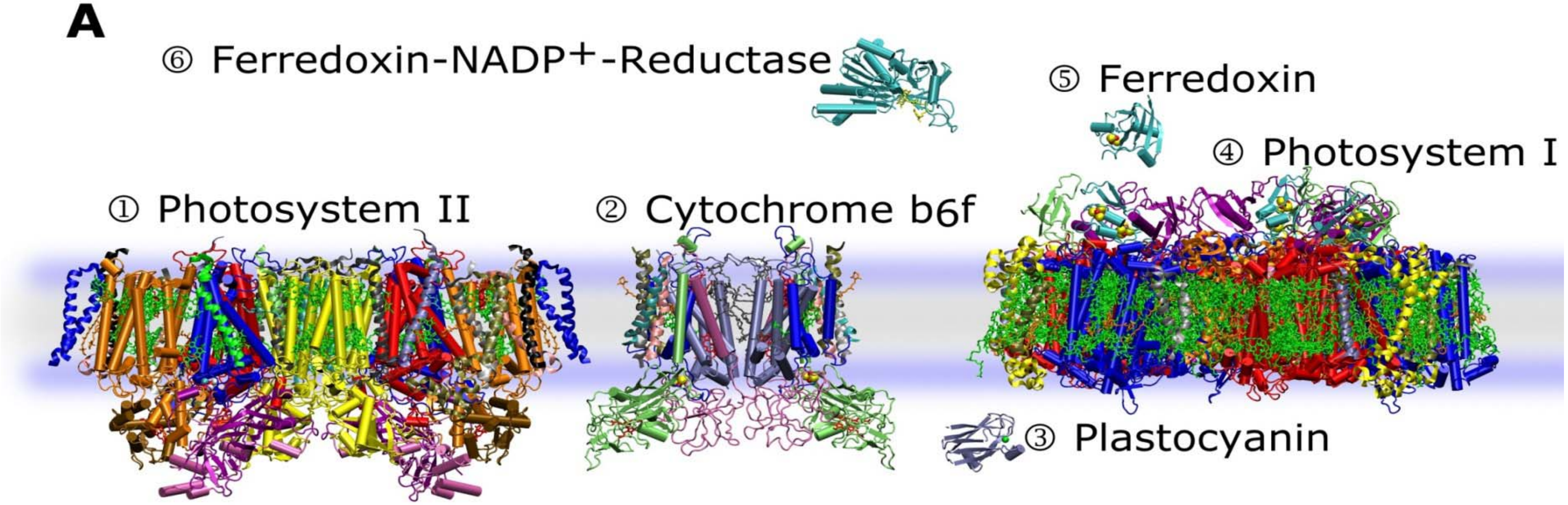
# Why?



## Scientific Background

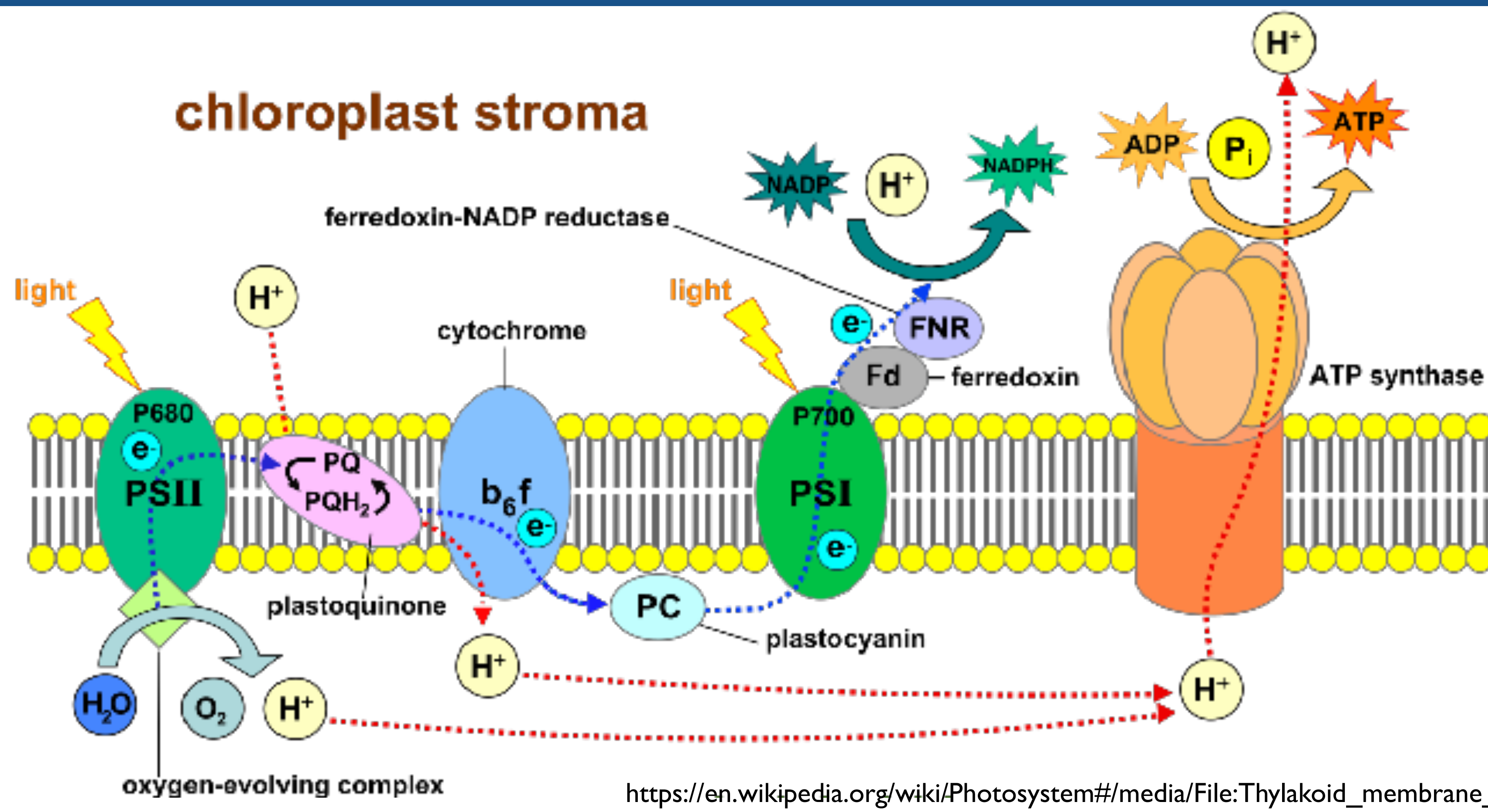


**Photosynthesis transformed our planet 2.5B years ago producing oxygen, capturing solar energy and $CO_2$, that slowly converted to fossil fuels.**

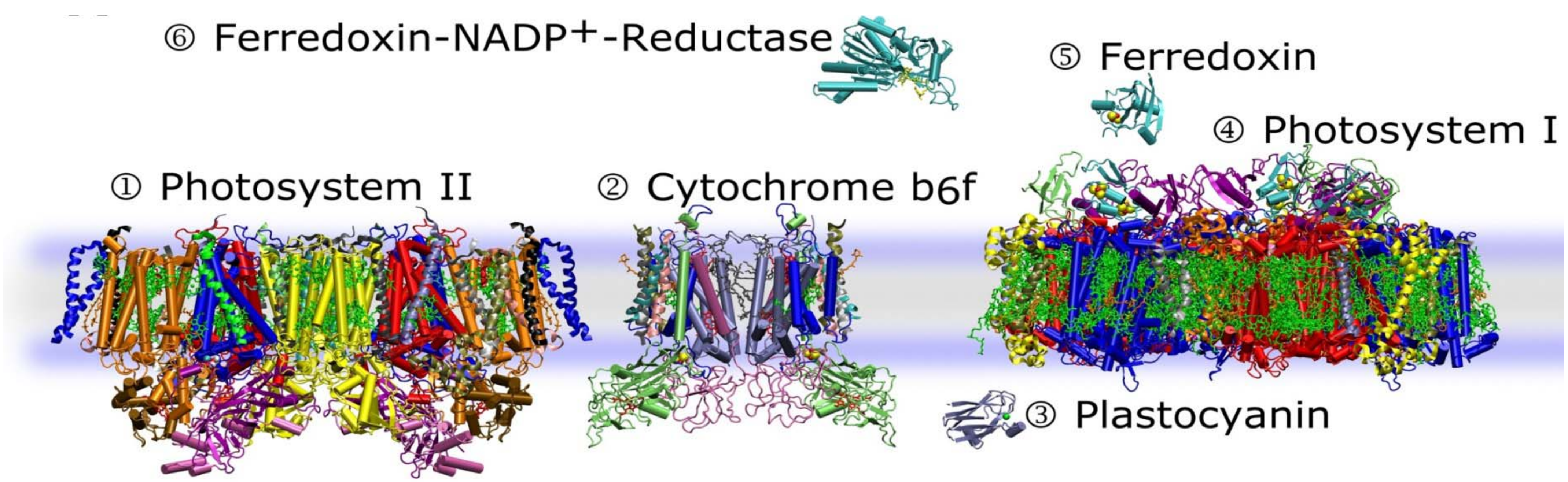



*Source: Petra Fromme, ASU*

# Why?

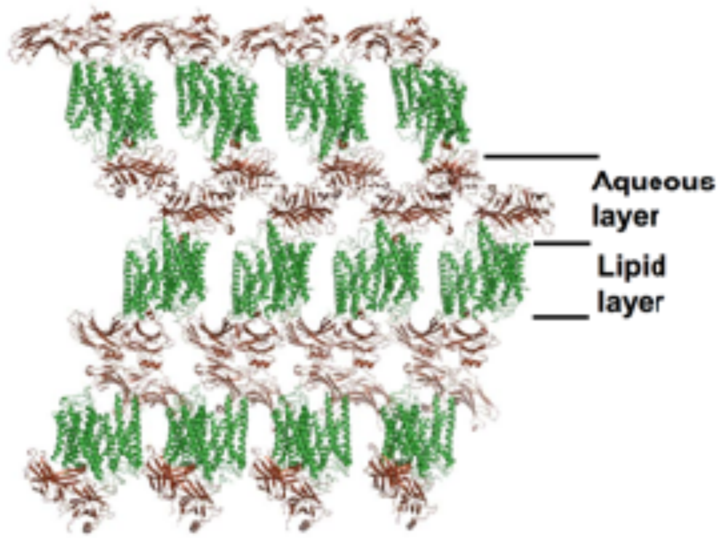


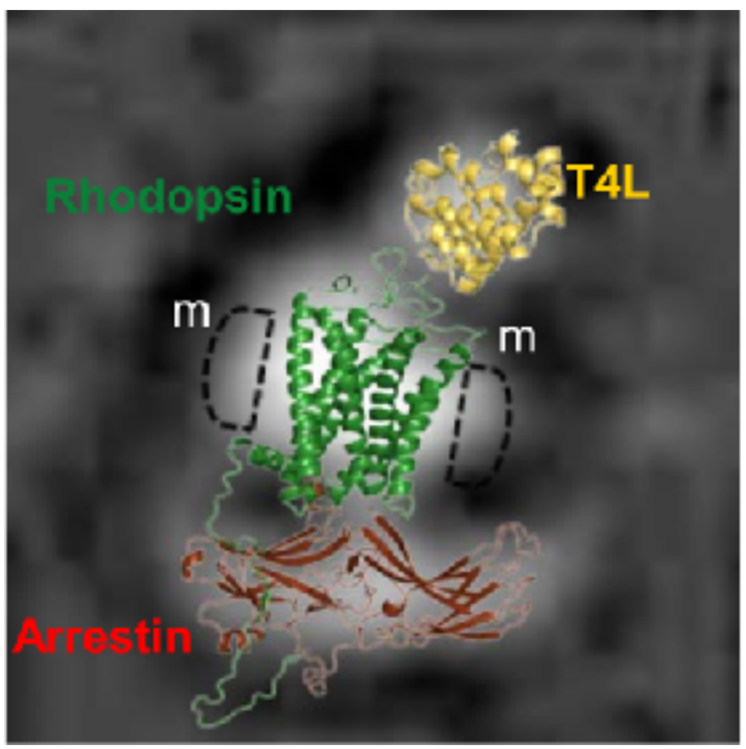

https://en.wikipedia.org/wiki/Photosystem#/media/File:Thylakoid_membrane_3.svg

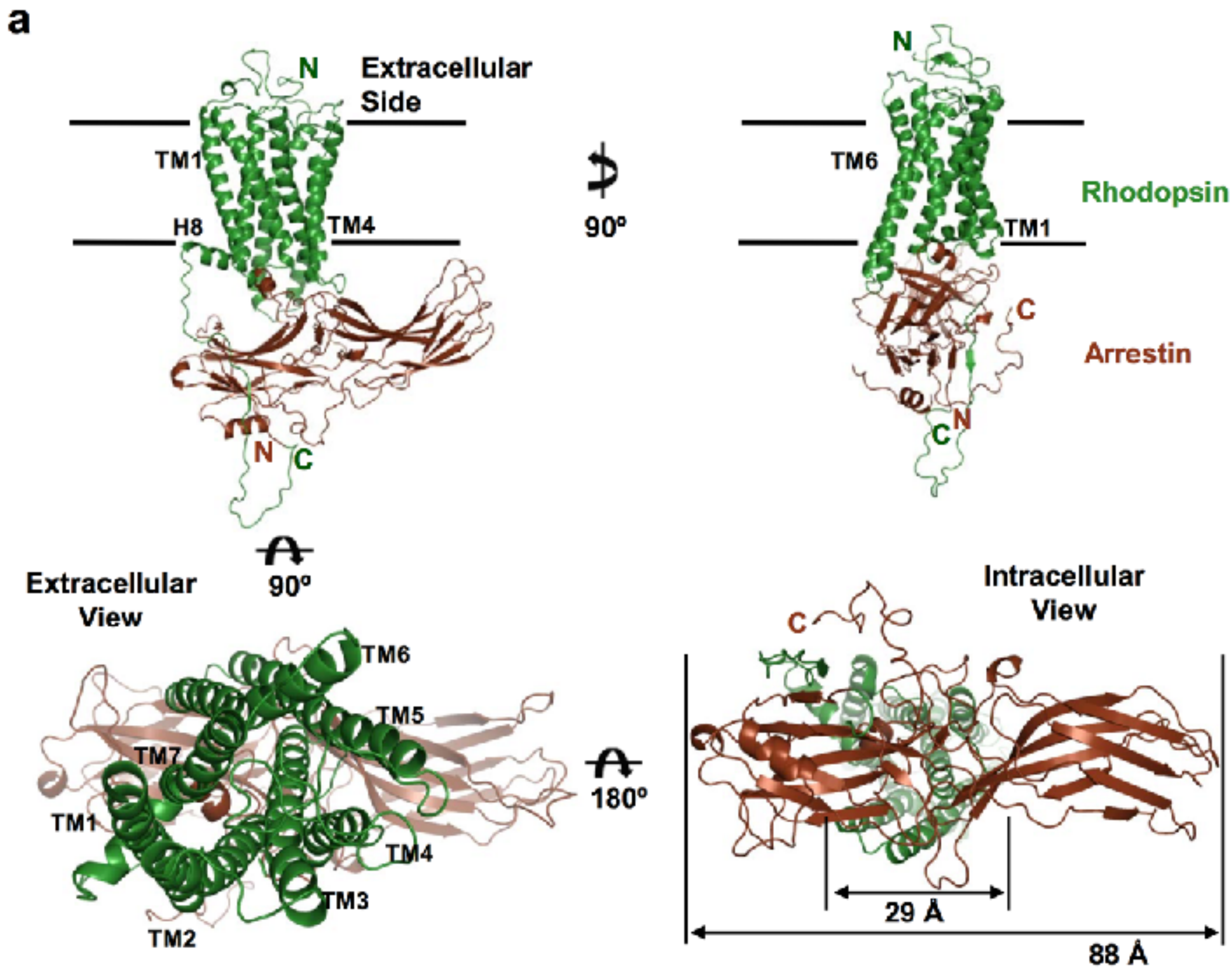



*Source: Petra Fromme, ASU*

# Rhodopsin-Arrestin complex solved at LCLS



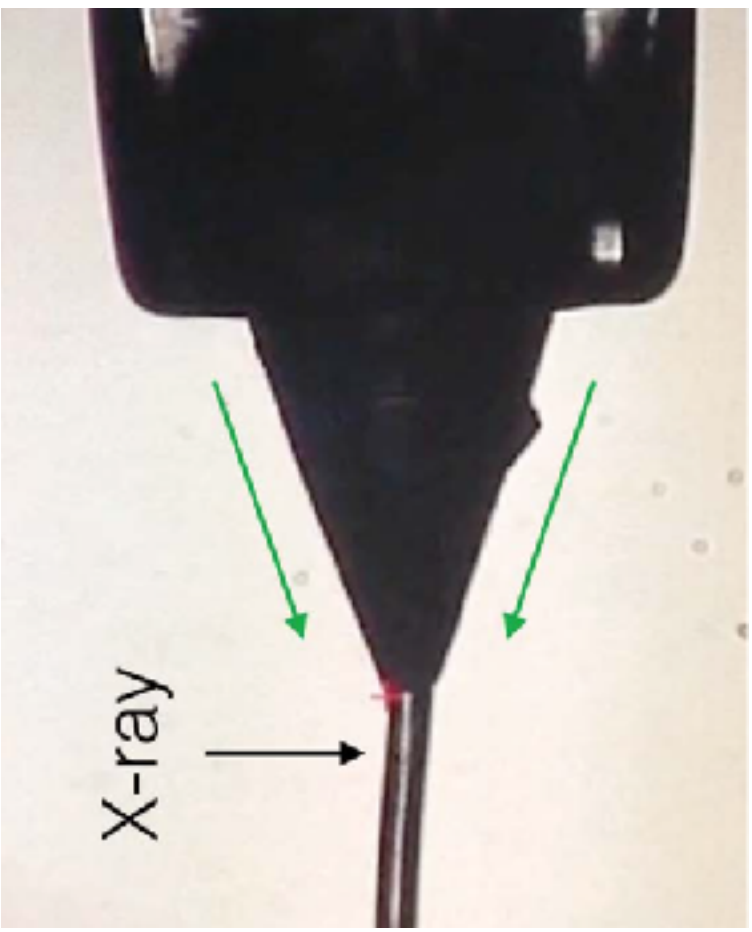



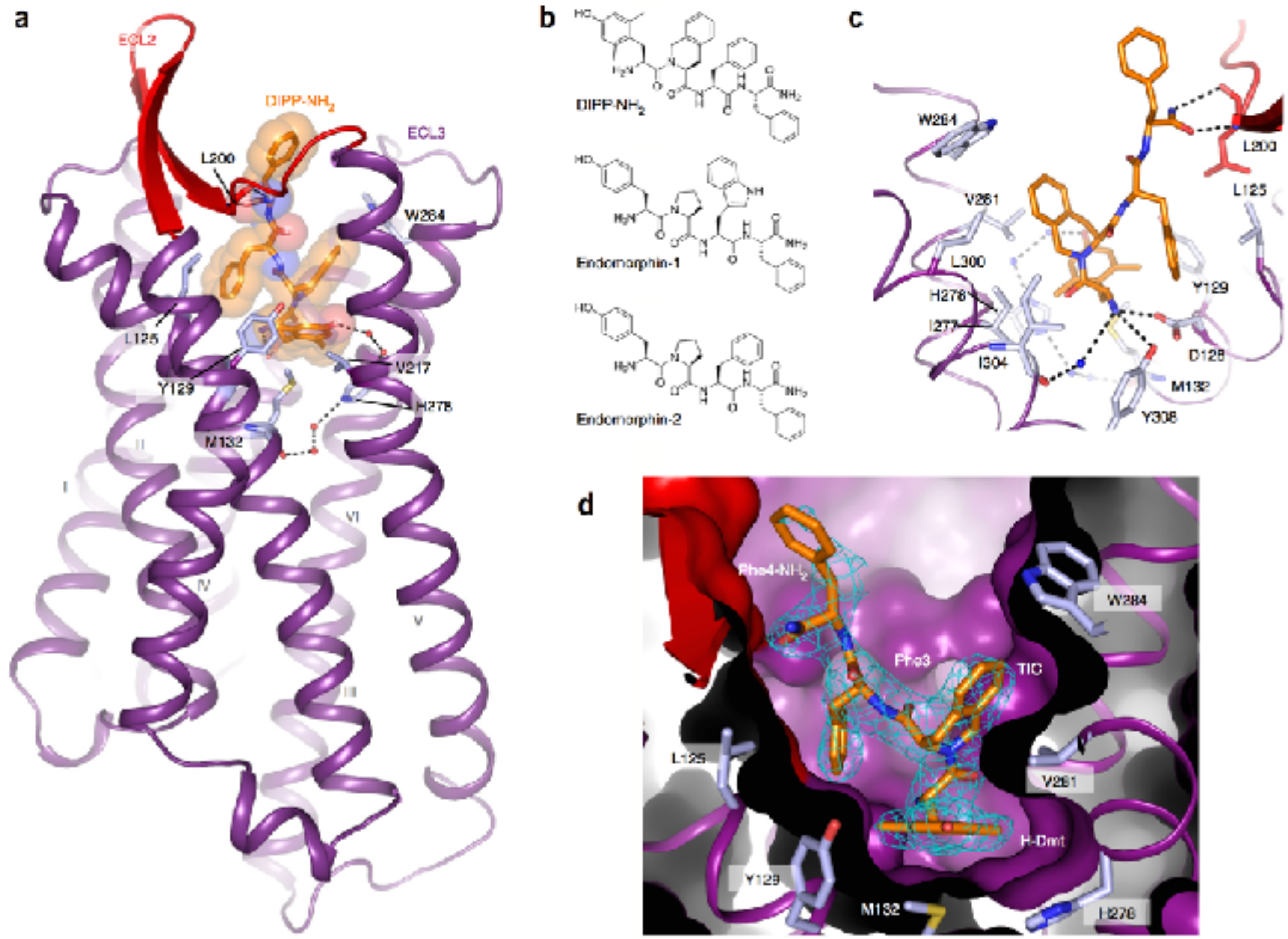

Unit cell: a=b=109.2 Å, c=452.6 Å
Resolution: 3.8 Å (a*/b*) and 3.3 Å (c*)
physically twinned, pseudo-merohedrally twinned
diagonal pseudo-translation in *a/b* plane
two fold rotational pseudo-symmetry parallel to *a*

Y. Kang, … E. Xu et.al.
“Crystal structure of rhodopsin bound to arrestin by femtosecond X-ray laser.,” Nature, vol. 523, no. 7562, pp. 561–567, Jul. 2015.

# δ-opioid receptor crystals delivered in LCP showed superior diffraction at room temperature compared to synchrotron data

Structural basis for bifunctional peptide recognition at human δ-opioid receptor

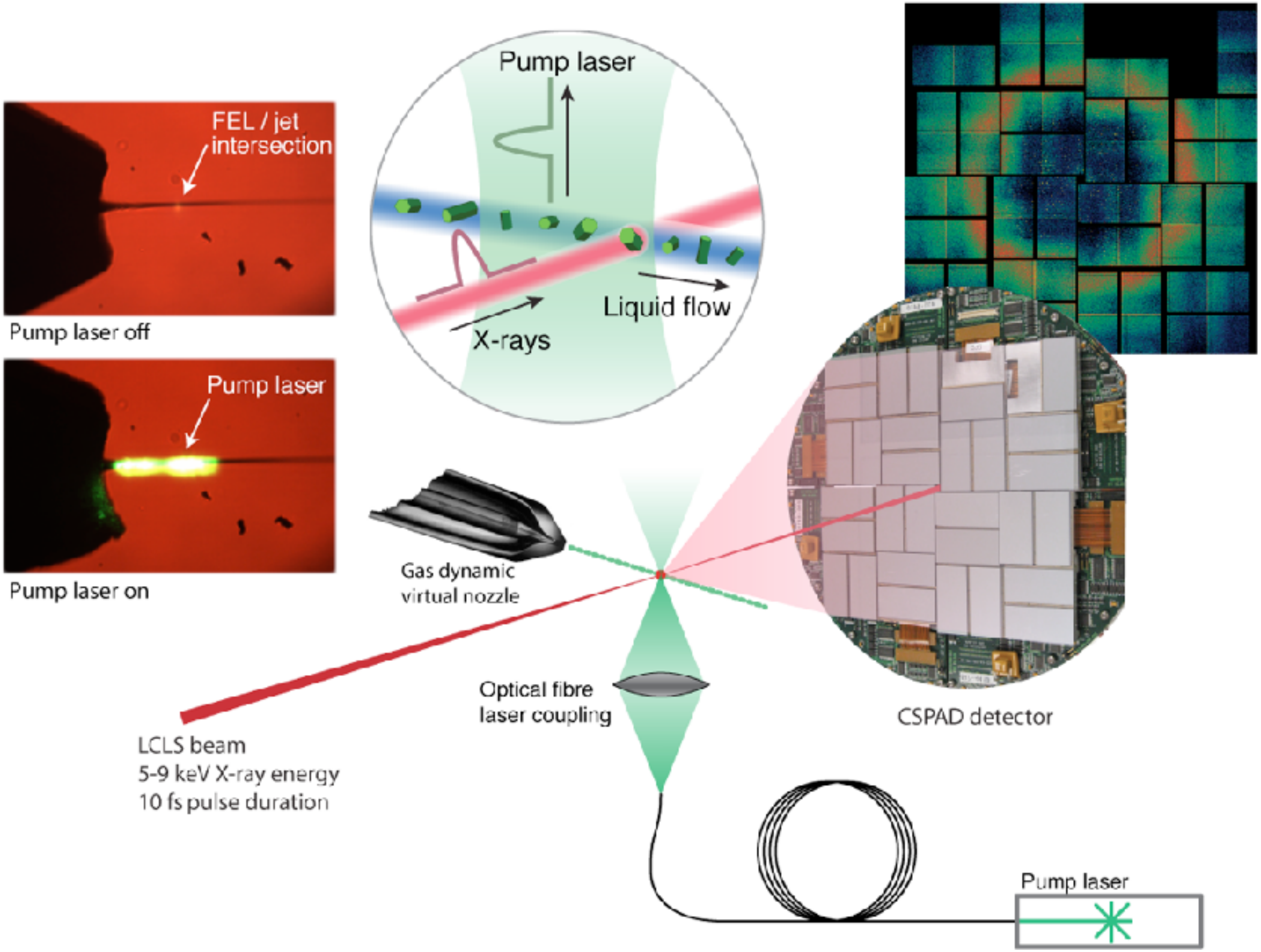



Crystal size: 1 to 10 µm (average size of 5 × 2 × 2 µm)
Dose: 46 MGy/crystal (room temperature)
Flow rate: 0.17 µL/min
Resolution (synchrotron): 3.3 Å (cryo)
Resolution (LCLS): 2.7 Å (room temperature)

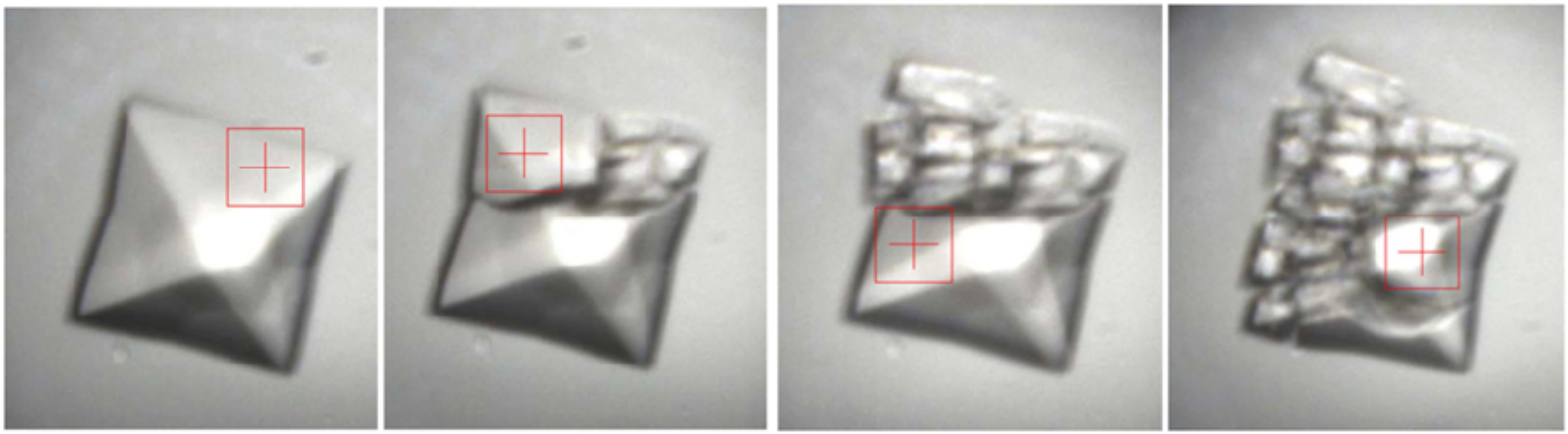
G. Fenalti, … V. Cherezov et al. (2015).
Structural basis for bifunctional peptide recognition at human delta-opioid receptor
Nature Structural & Molecular Biology, 22(3), 265–268.

# Data is merged from thousands of separate crystals



# X-ray radiation destroys protein crystals during exposure

Before exposure | 1st 0.5 sec exposure | 2nd 0.5 sec exposure | 3rd 0.5 sec exposure



Axford et.al.
*Acta Cryst (2012). D68, 592-60,* pp. 1–9, Apr. 2012.

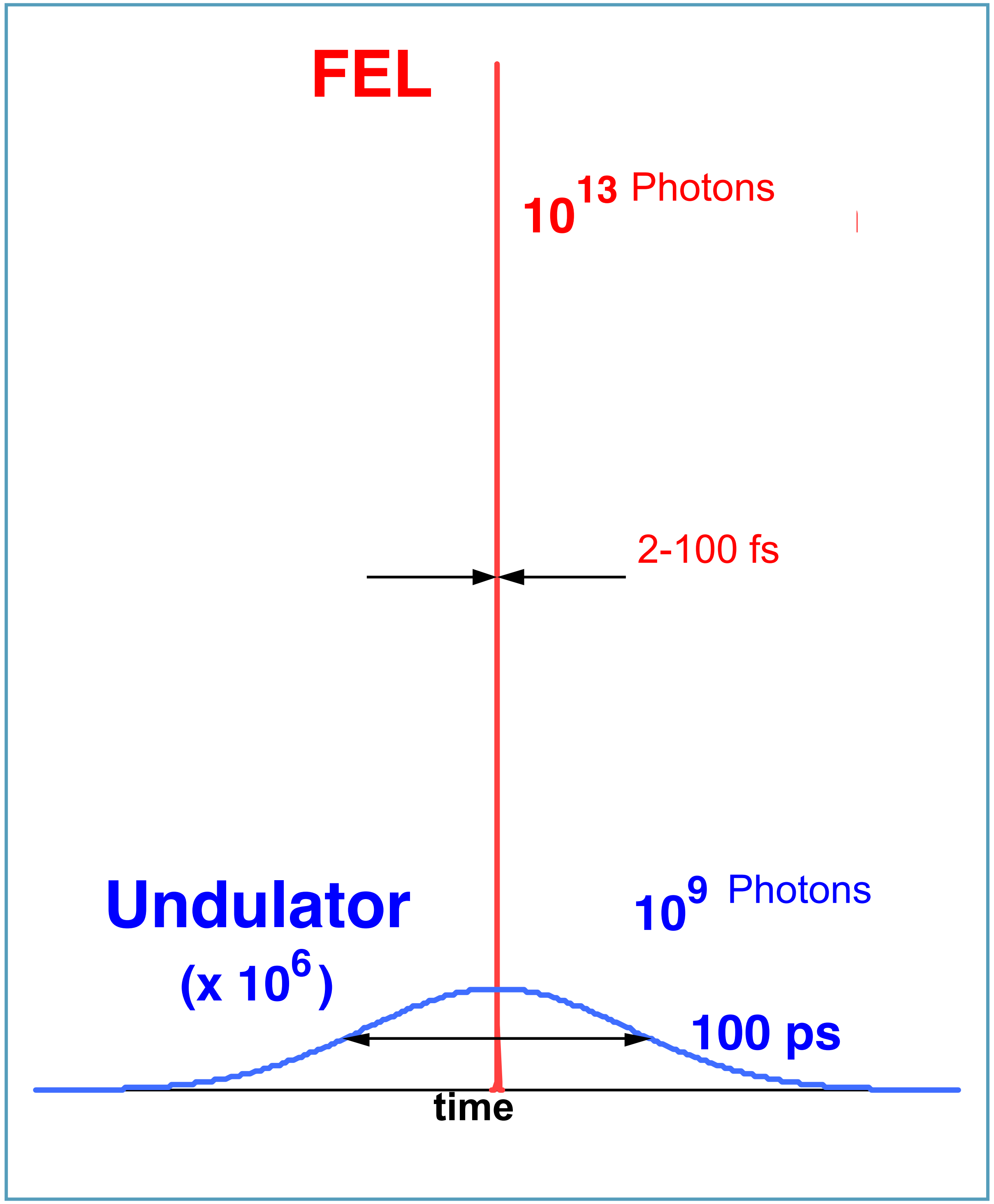
Crystal of Bovine enterovirus 2 (BEV2)
after subsequent exposures of 0.5 s, at $6 \times 10^8$ ph/$\mu m^2$
300 kGy dose, room temperature

Cryogenic cooling extends dose limit to 30 MGy

1 Gy = 1 J/kg

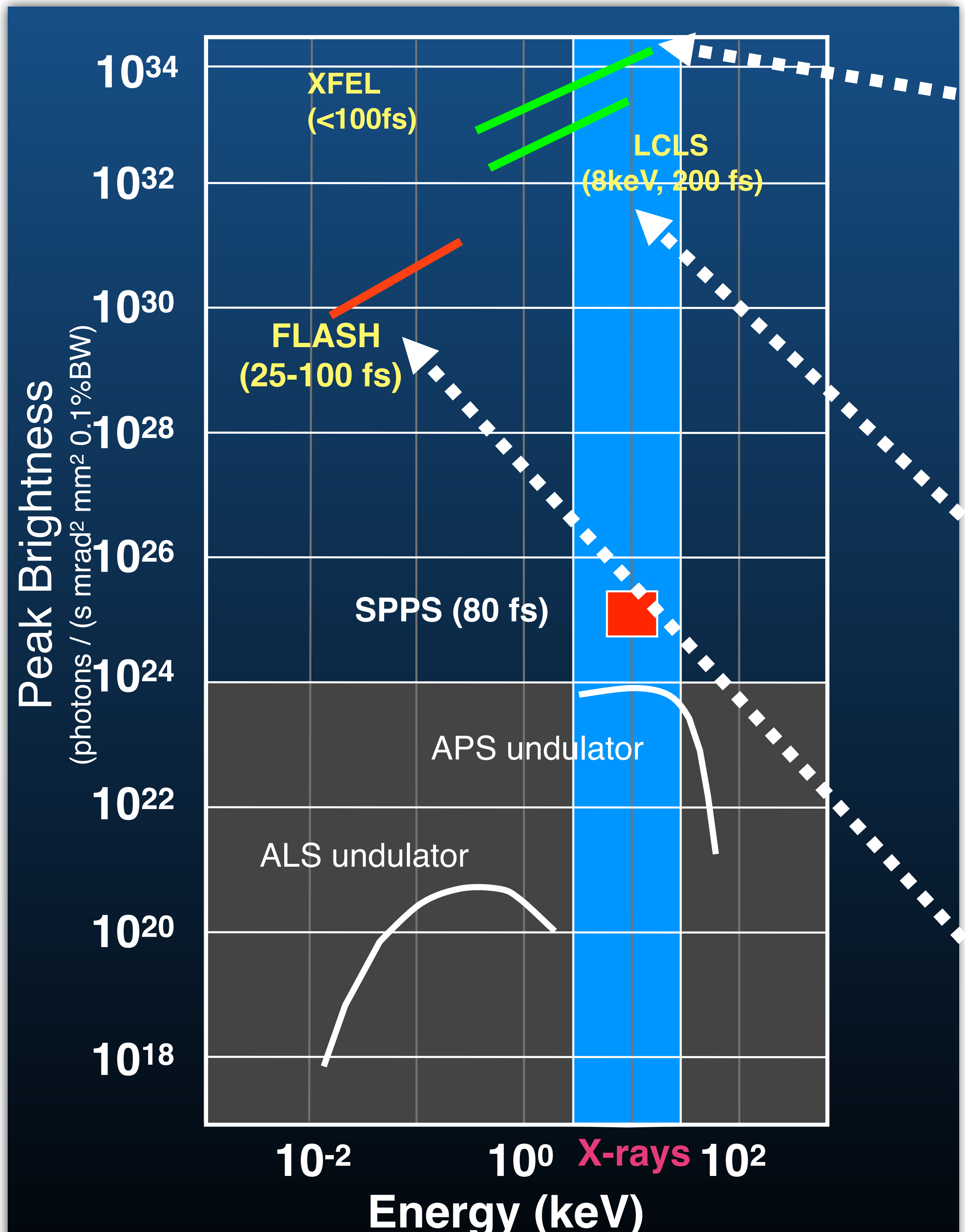
1MGy ≈1eV/Da absorbed
≈ 0.16 eV / atom!
≈$2 \times 10^9$ ph/$\mu m^2$
(about one ionisation per 10 amino-acid residues)

# The gain in peak brightenss at an FEL is several orders of magnitude


*Source: Robert Feidenhans'l*

# X-ray free electron lasers are a unique class of X-ray source




APS=Advanced Photon Source (ANL)
ALS=Advanced Light Source (LBNL)


operational ~~2013~~ 2017
1-12 keV
20-50 fs
$10^{13}$ photons/pulse

European X-ray FEL,
DESY, Hamburg


operational 2009
0.8-8 keV
100 fs
$10^{12}$ photons/pulse

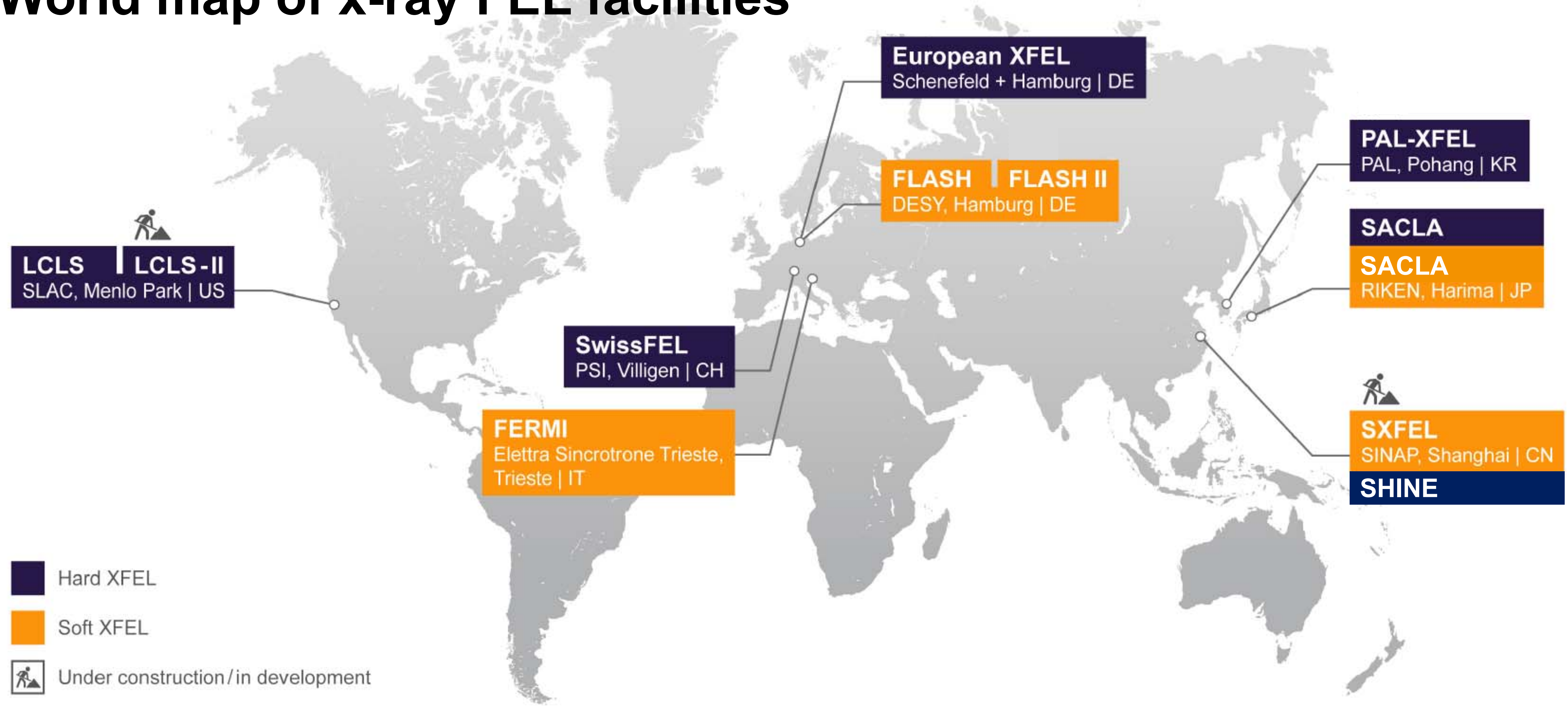
Linac Coherent Light Source,
SLAC, Stanford


operational 2006
50-400 eV (7-50 nm)
25 fs
$10^{12}$ photons/pulse

FLASH
DESY, Hamburg

# The number of X-ray free electron lasers worldwide is growing

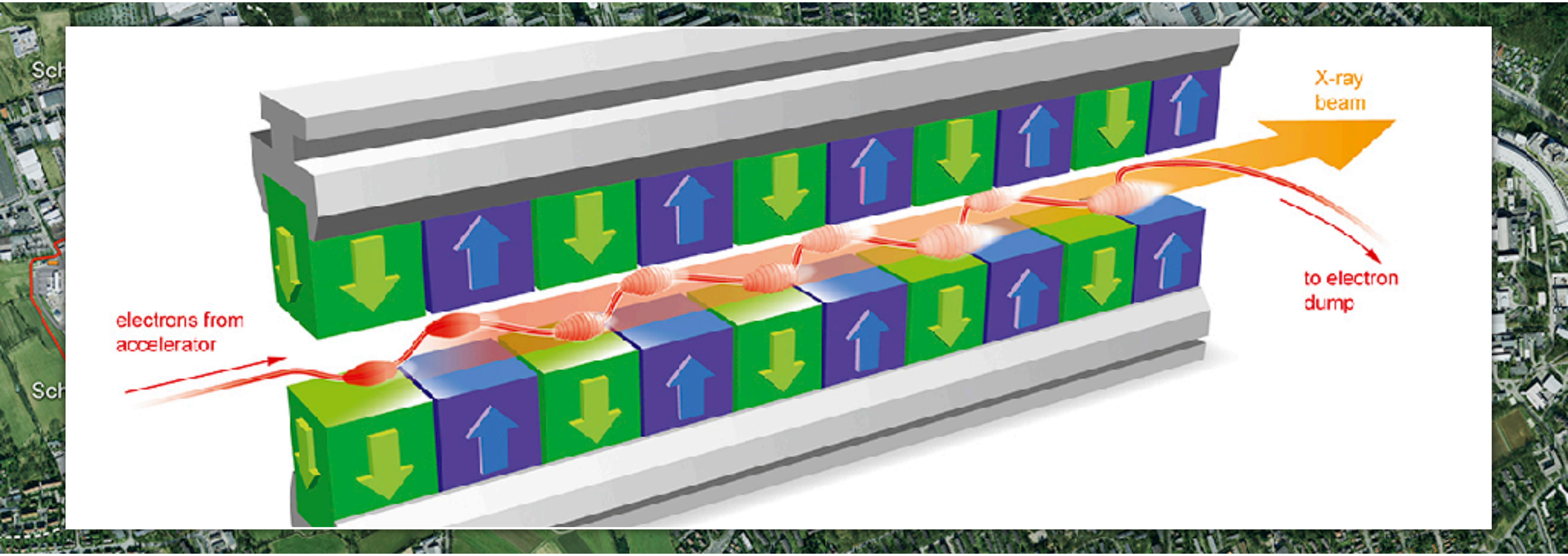
## World map of x-ray FEL facilities

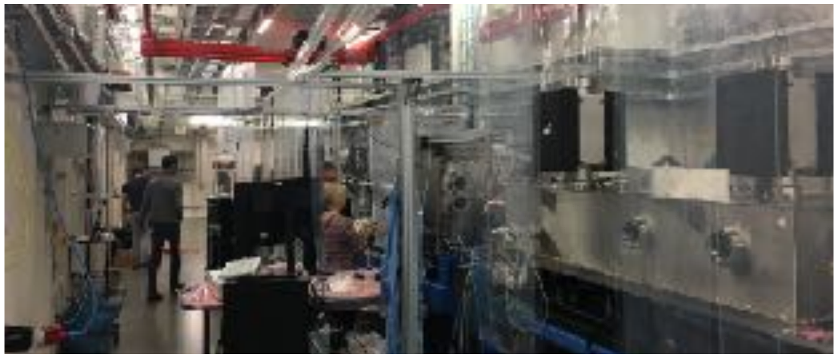


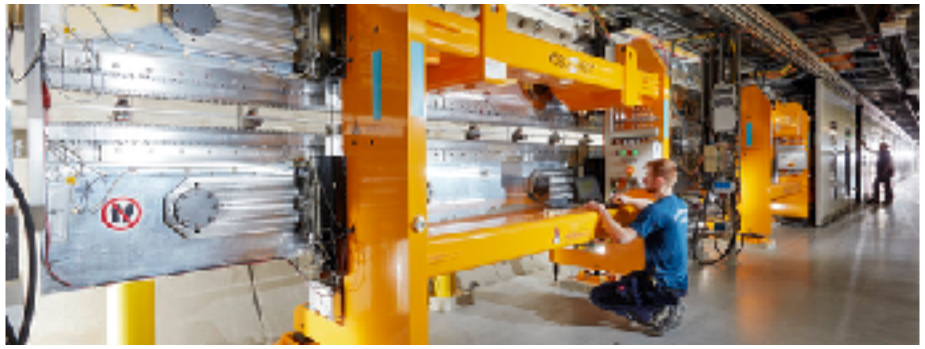

*Source: Thomas Tschentscher*

# The European XFEL free electron laser facility in Hamburg opened for users in 2017

58% 27%

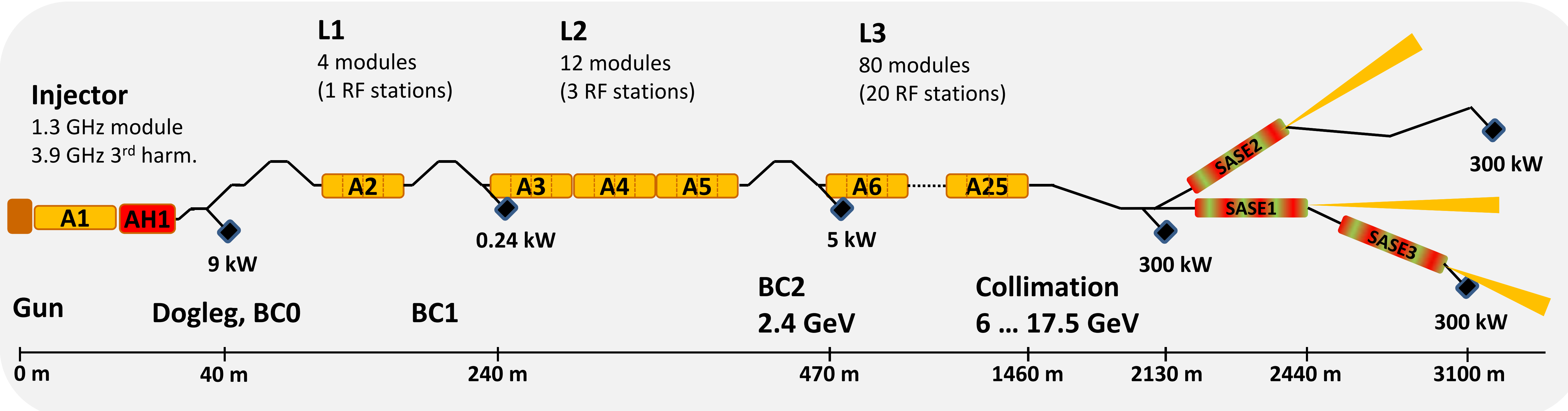


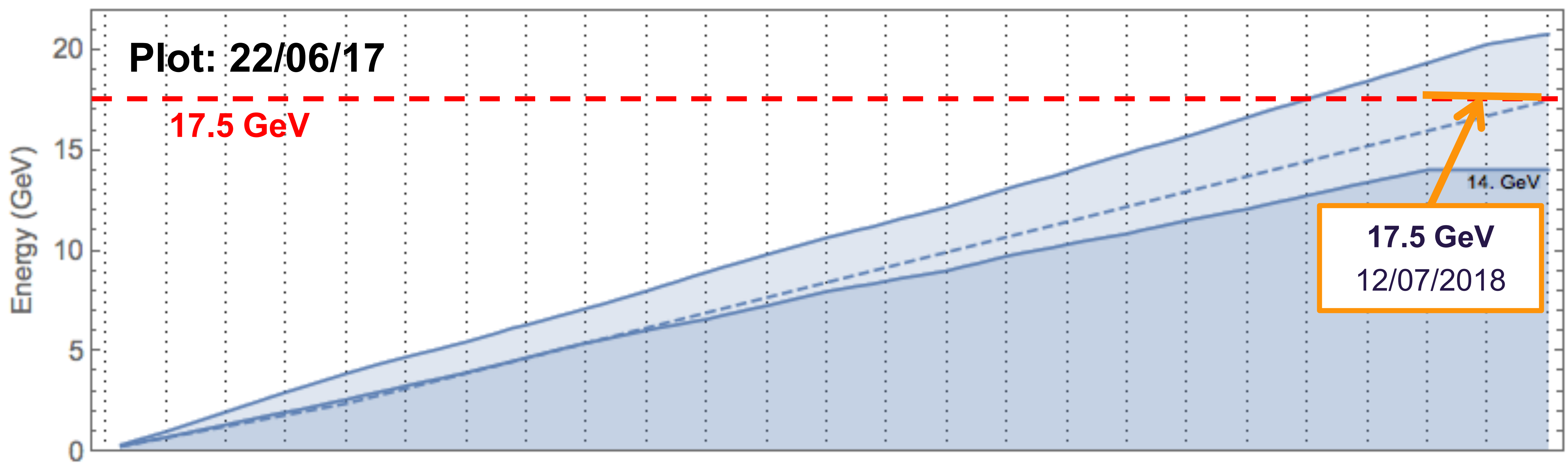


17.5 GeV
27,000 pulses per second

# A brief overview of the EuXFEL accelerator



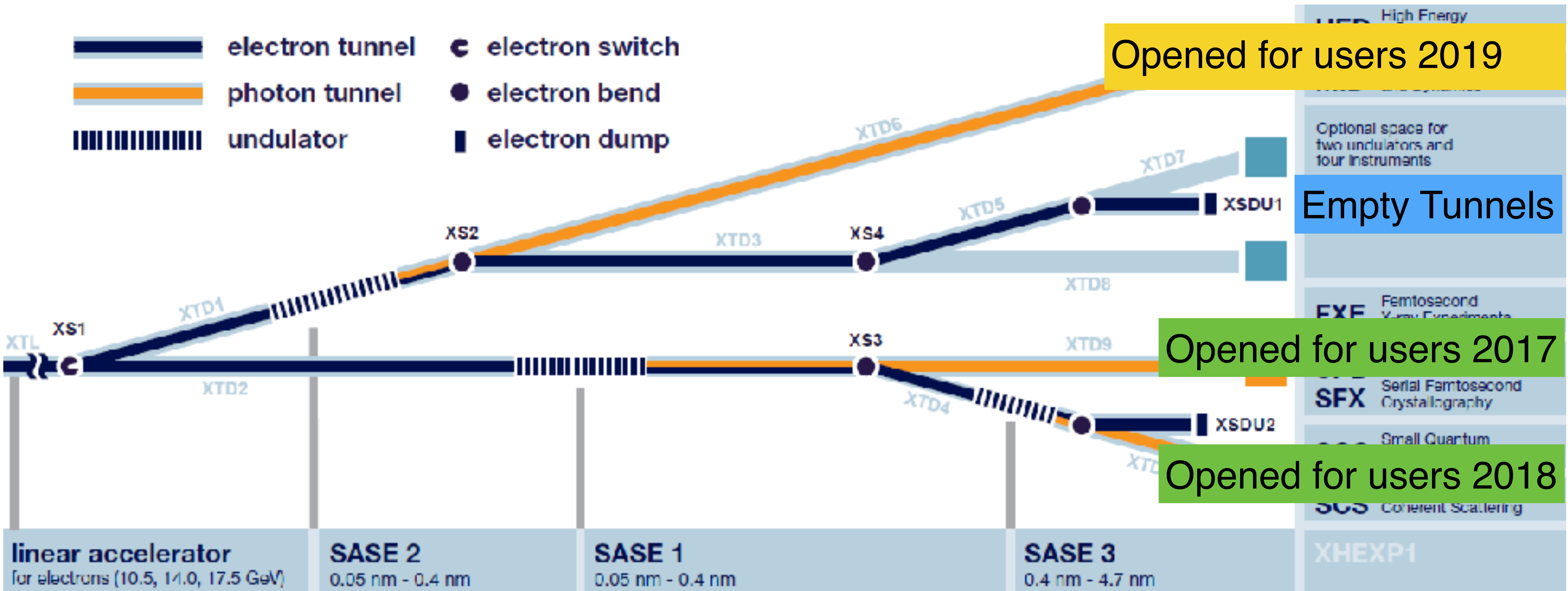

*Source: Winni Decking*




*Source: Thomas Tschentscher*

800 Nb cavities, 100 cryo modules, ~1000m long accelerator, 17.5 GeV,

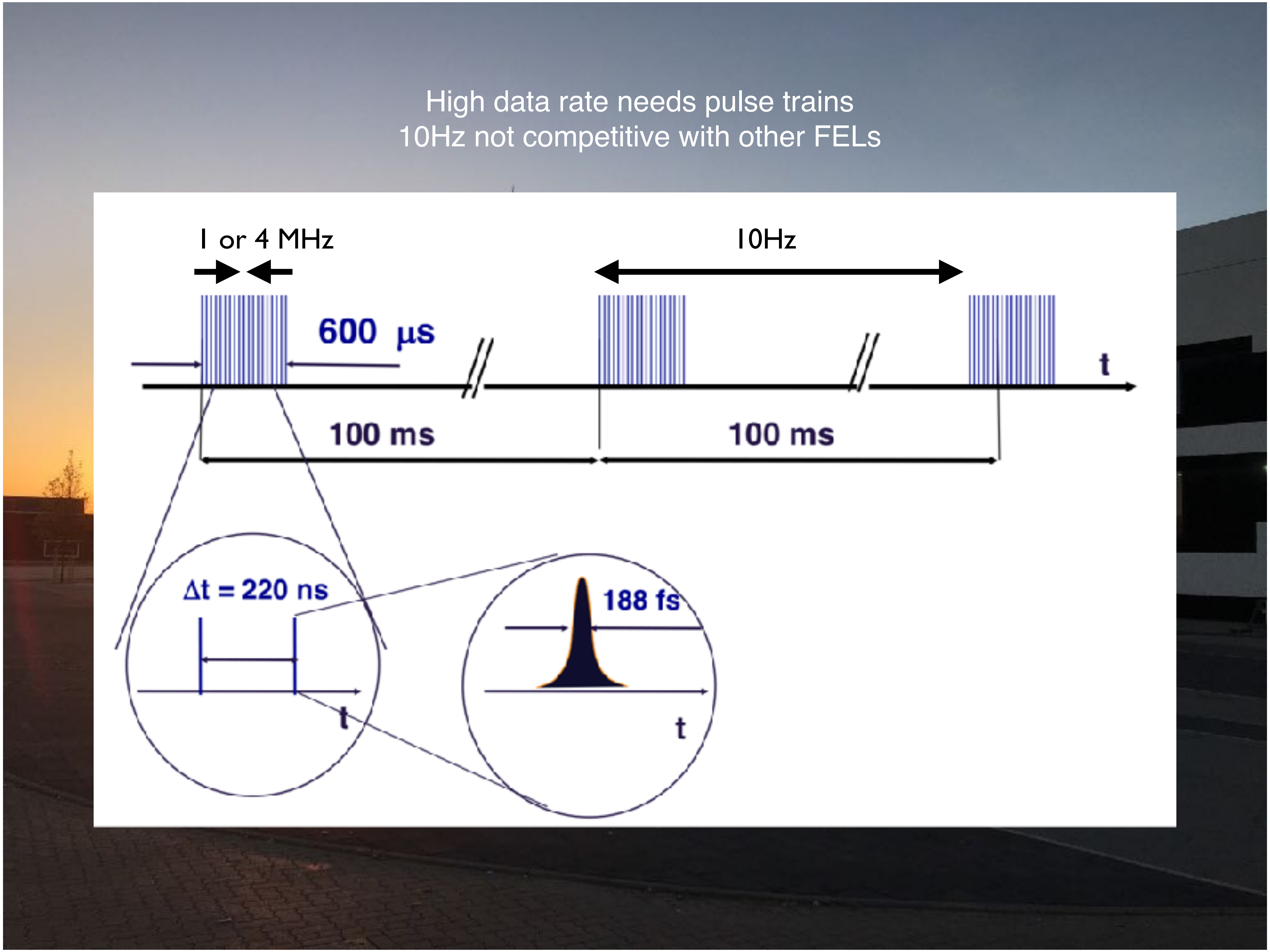
# Experimental Hall



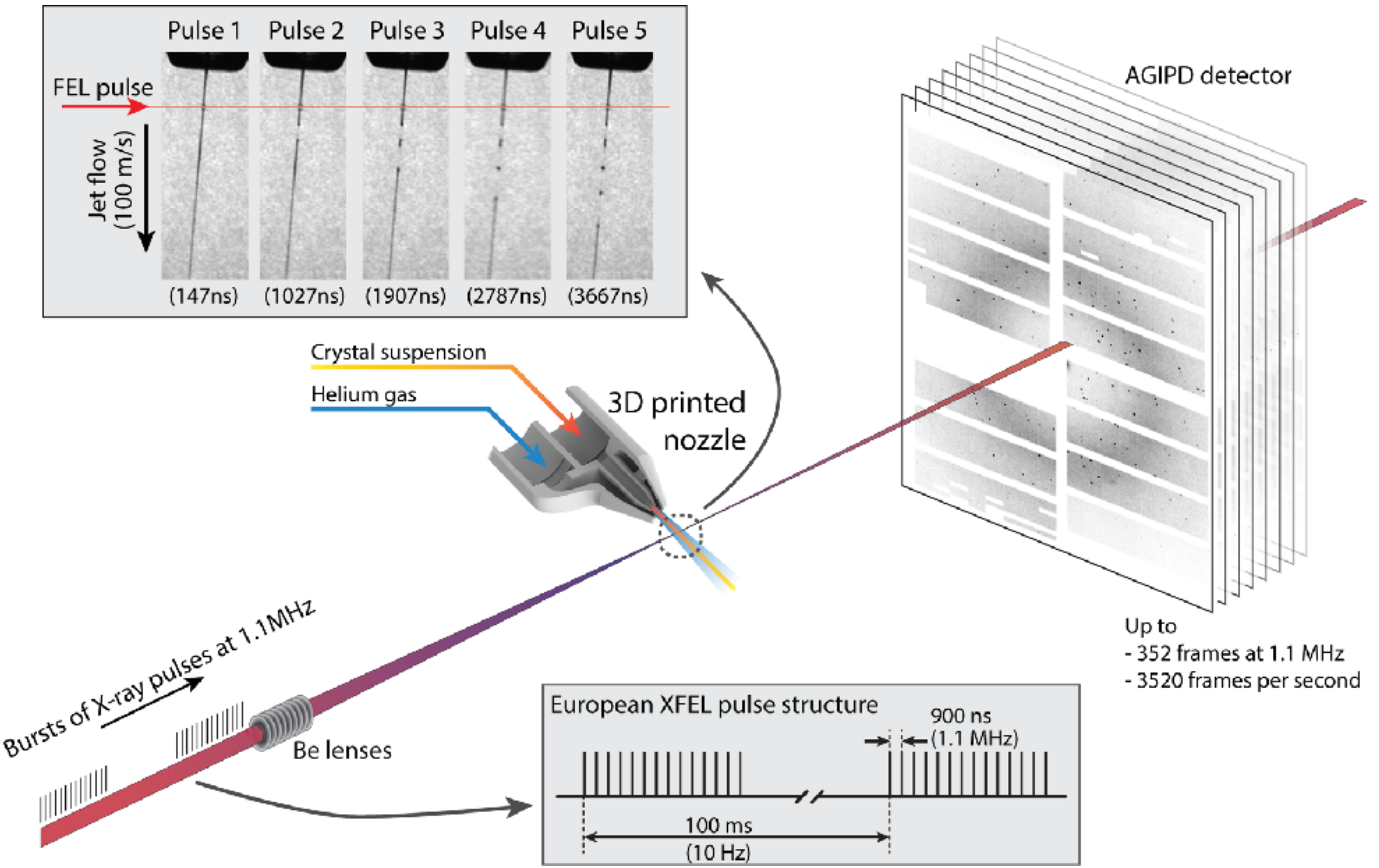

European XFEL

*Source: Thomas Tschentscher*

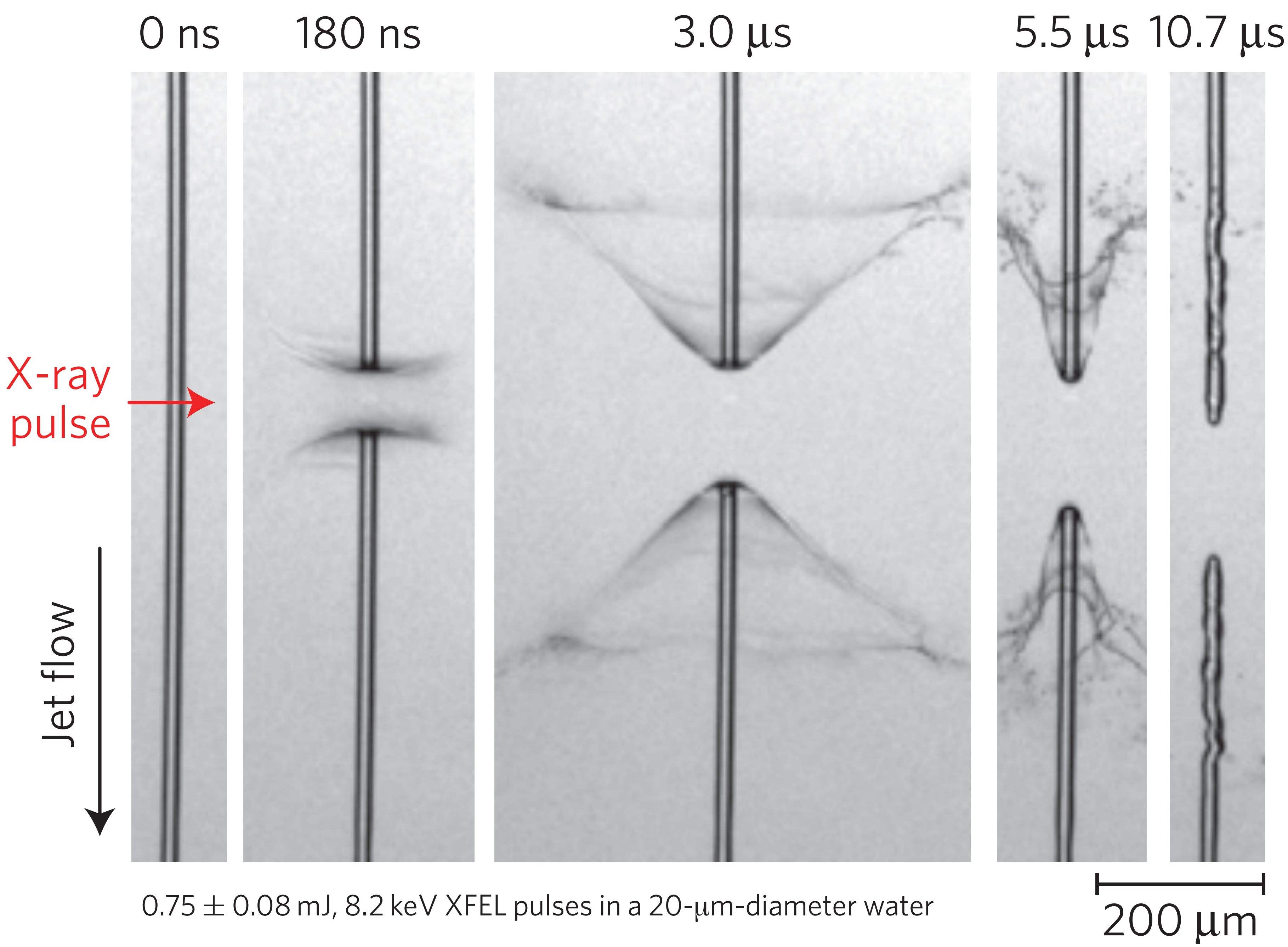
# First user experiments at the European XFEL started on 14 September 2017



# SFX at the European XFEL



# Liquid jets explode in the X-ray beam and need to recover before the next pulse

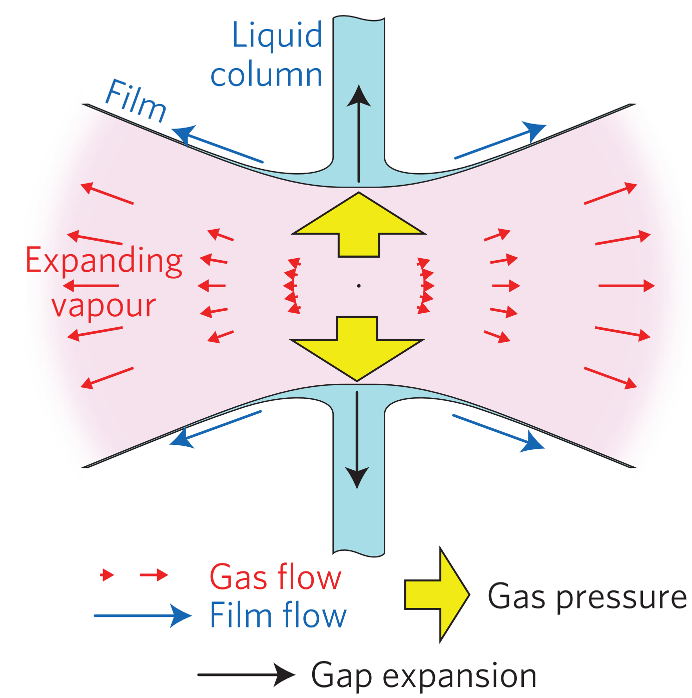



0.75 ± 0.08 mJ, 8.2 keV XFEL pulses in a 20-µm-diameter water


nature physics | ARTICLES

**Liquid explosions induced by X-ray laser pulses**

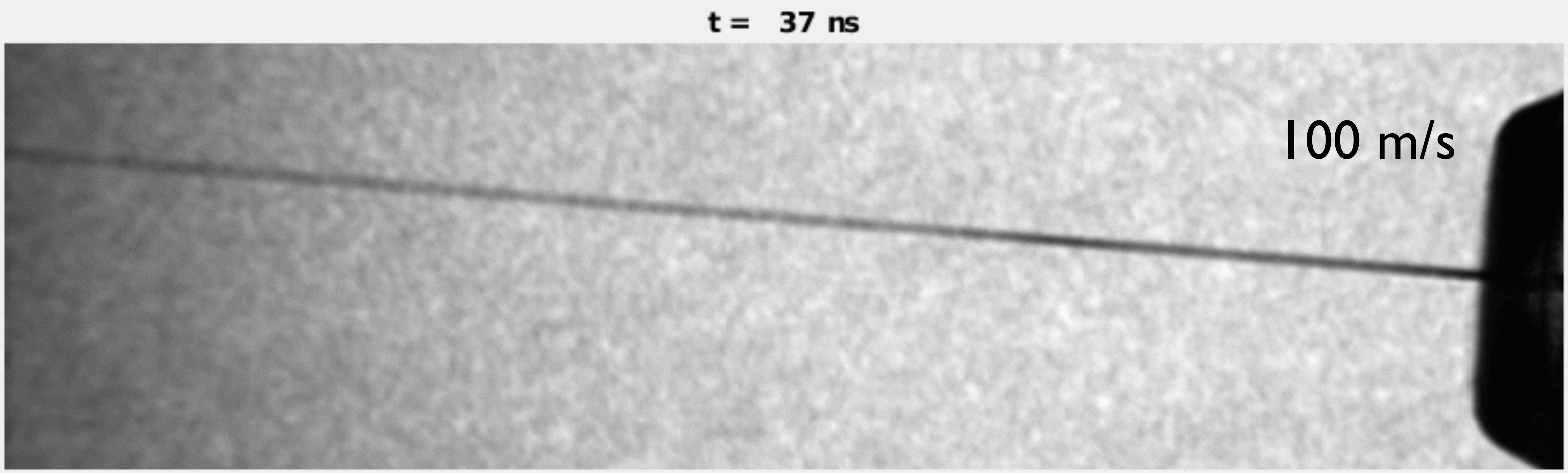
Claudiu A. Stan[1*], Despina Milathianaki[2], Hartawan Laksmono[1], Raymond G. Sierra[1], Trevor A. McQueen[2], Marc Messerschmidt[2†], Garth J. Williams[2†], Jason E. Koglin[2], Thomas J. Lane[2], Matt J. Hayes[2], Serge A. H. Guillet[2], Mengning Liang[2], Andrew L. Aquila[2], Philip R. Willmott[2,4], Joseph S. Robinson[2], Karl L. Gumerlock[2], Sabine Botha[5‡], Karol Nass[5], Ilme Schlichting[5], Robert L. Shoeman[5], Howard A. Stone[6] and Sébastien Boutet[2]




Shock waves propagate even faster

Claudiu Stan, SLAC, Nature Physics, 2016

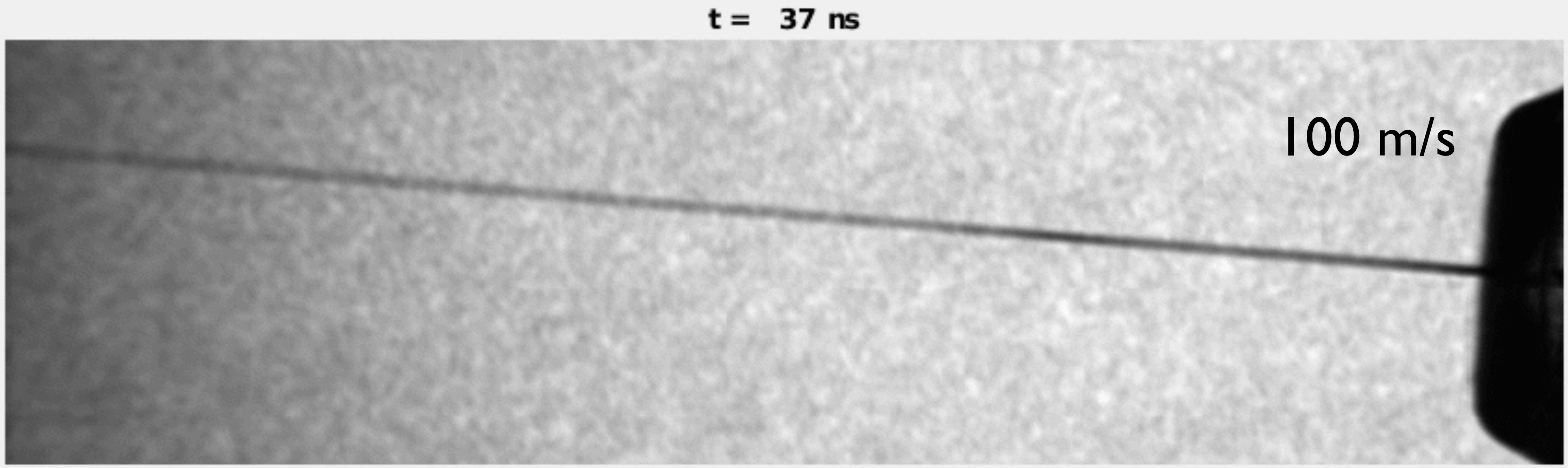
# Fast jets recover in time for the next pulse at 1.1 MHz repetition rate

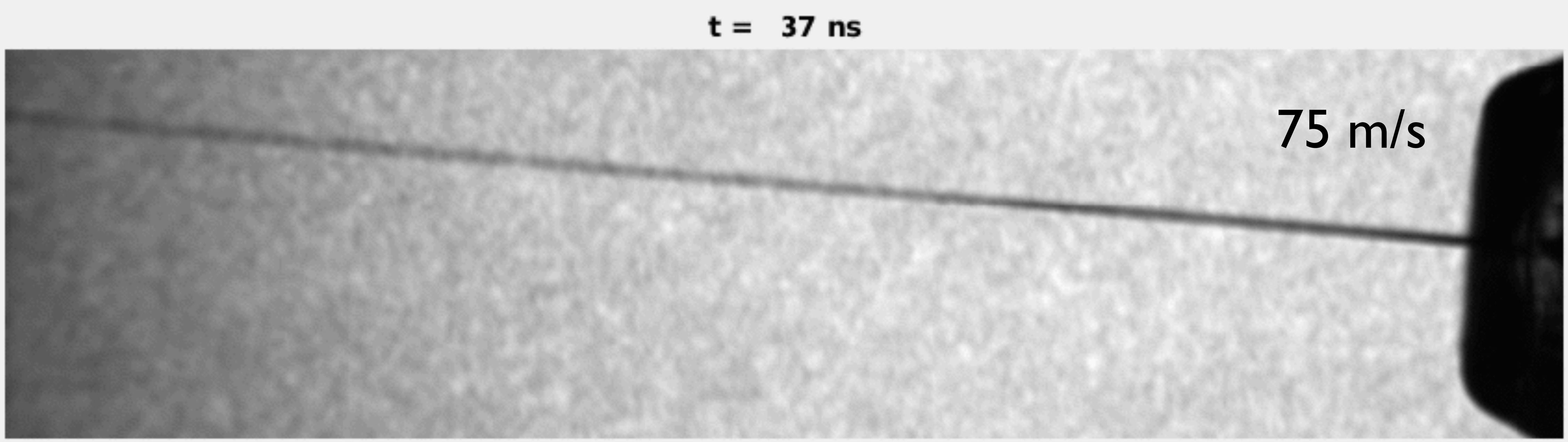



9.3 keV
580 mJ XFEL pulses
10 μm FWHM focus (or smaller)
1.1 MHz repetition rate

Max Wierdorn, Claudio Stan

# Fast jets recover in time for the next pulse at 1.1 MHz repetition rate

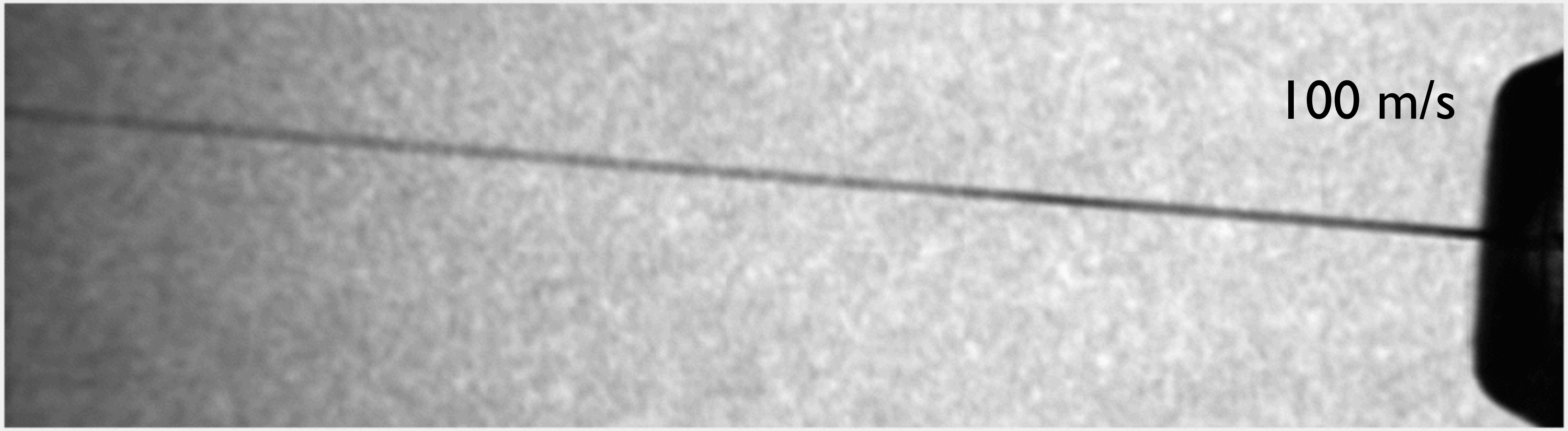


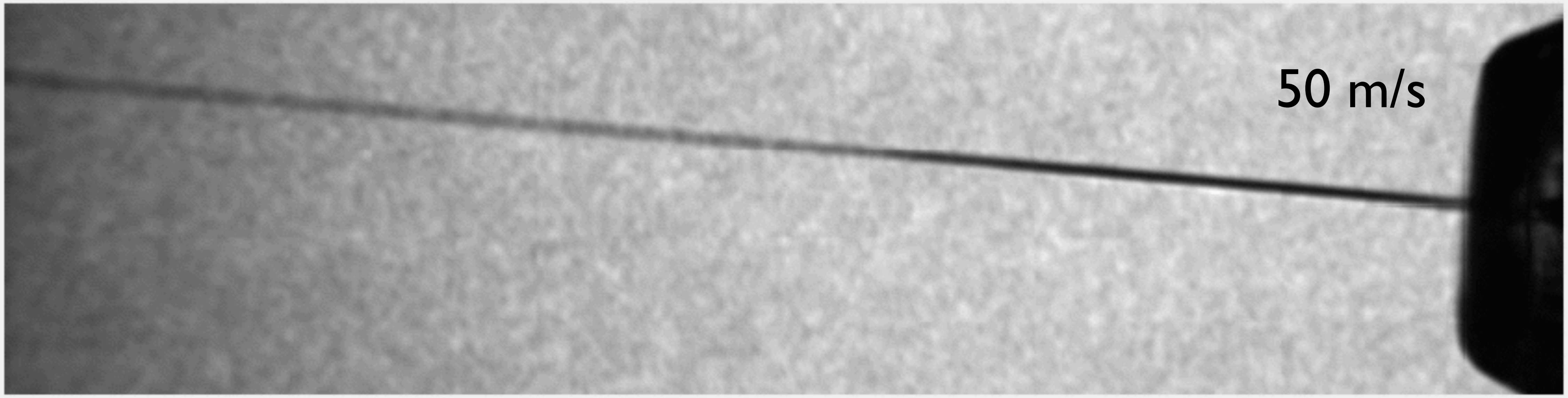

Max Wierdorn, Claudio Stan

# Fast jets recover in time for the next pulse at 1.1 MHz repetition rate

t = 37 ns



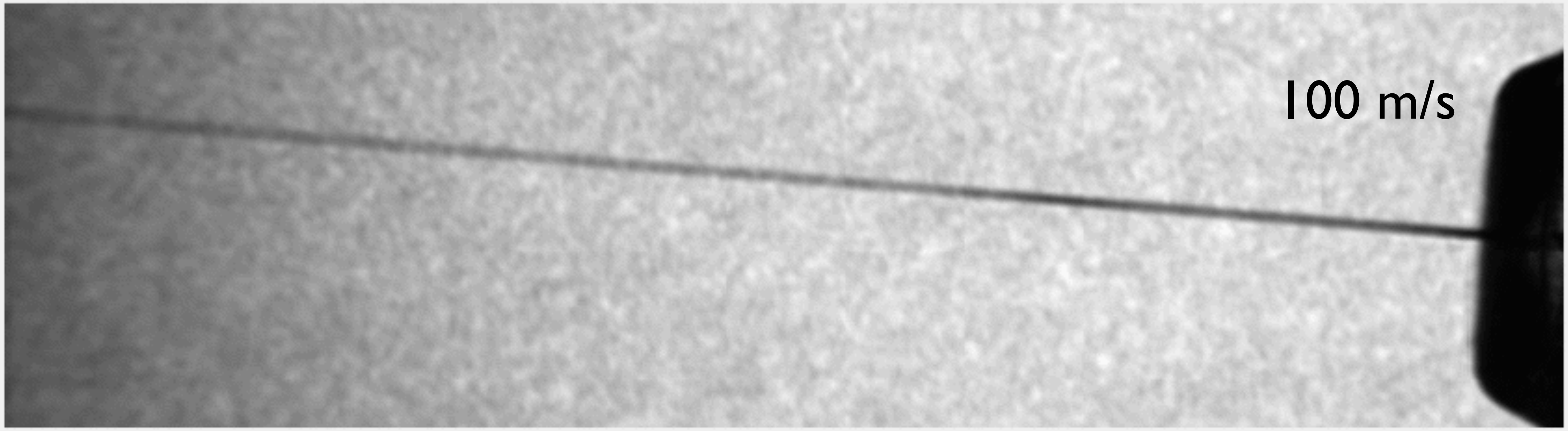

t = 37 ns



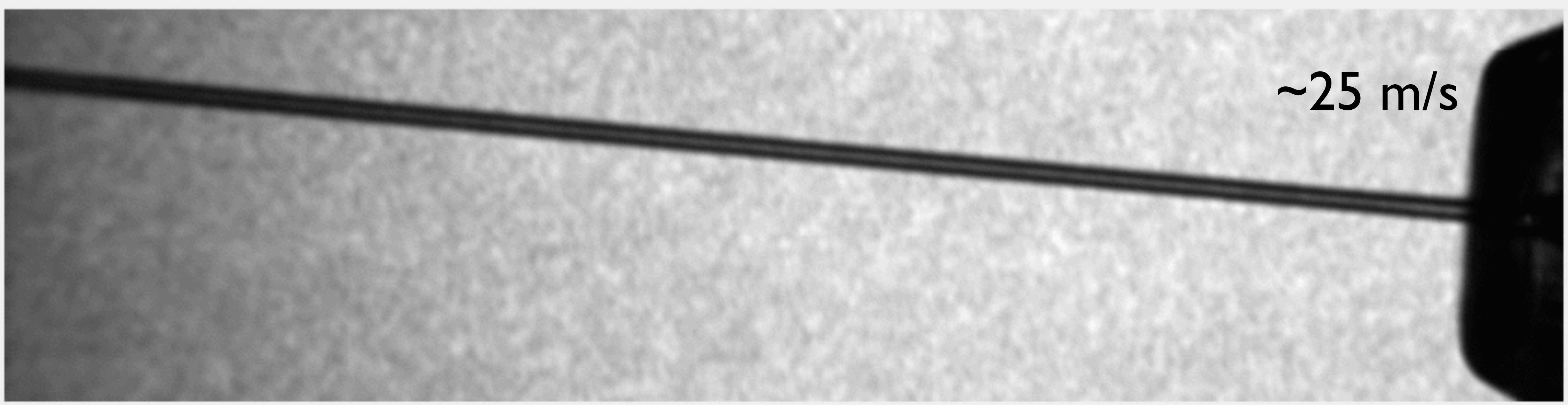

Max Wierdorn, Claudio Stan

# CFEL-designed fast jets recover in time for the next pulse at 1.1 MHz repetition rate

t = 37 ns

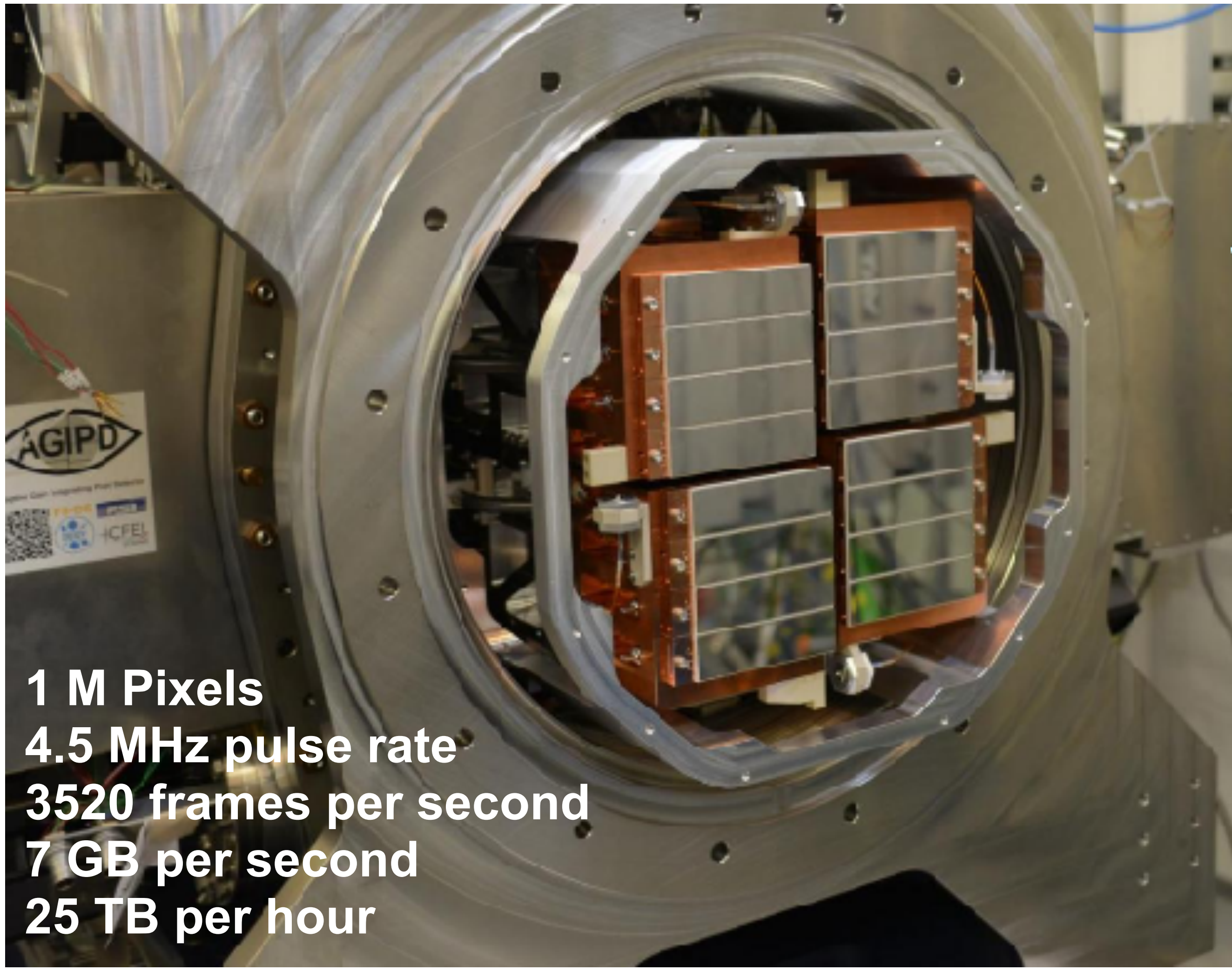



t = 37 ns



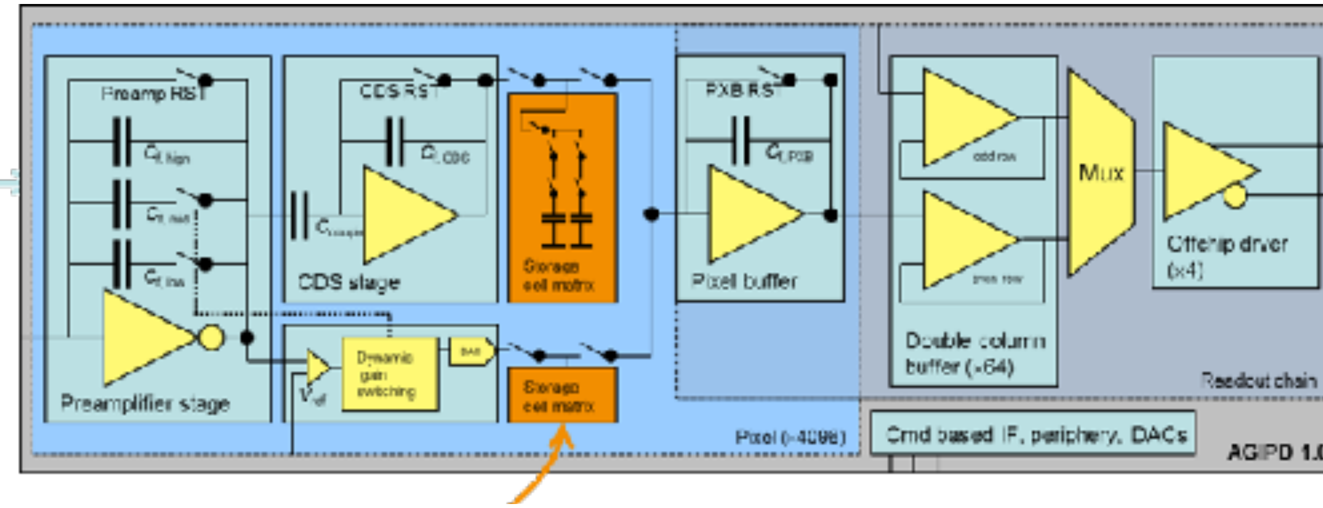

Max Wierdorn, Claudio Stan

# The Adaptive Gain Integrating Pixel Detector (AGIPD) can read out 3520 frames per second with MHz pulse spacing

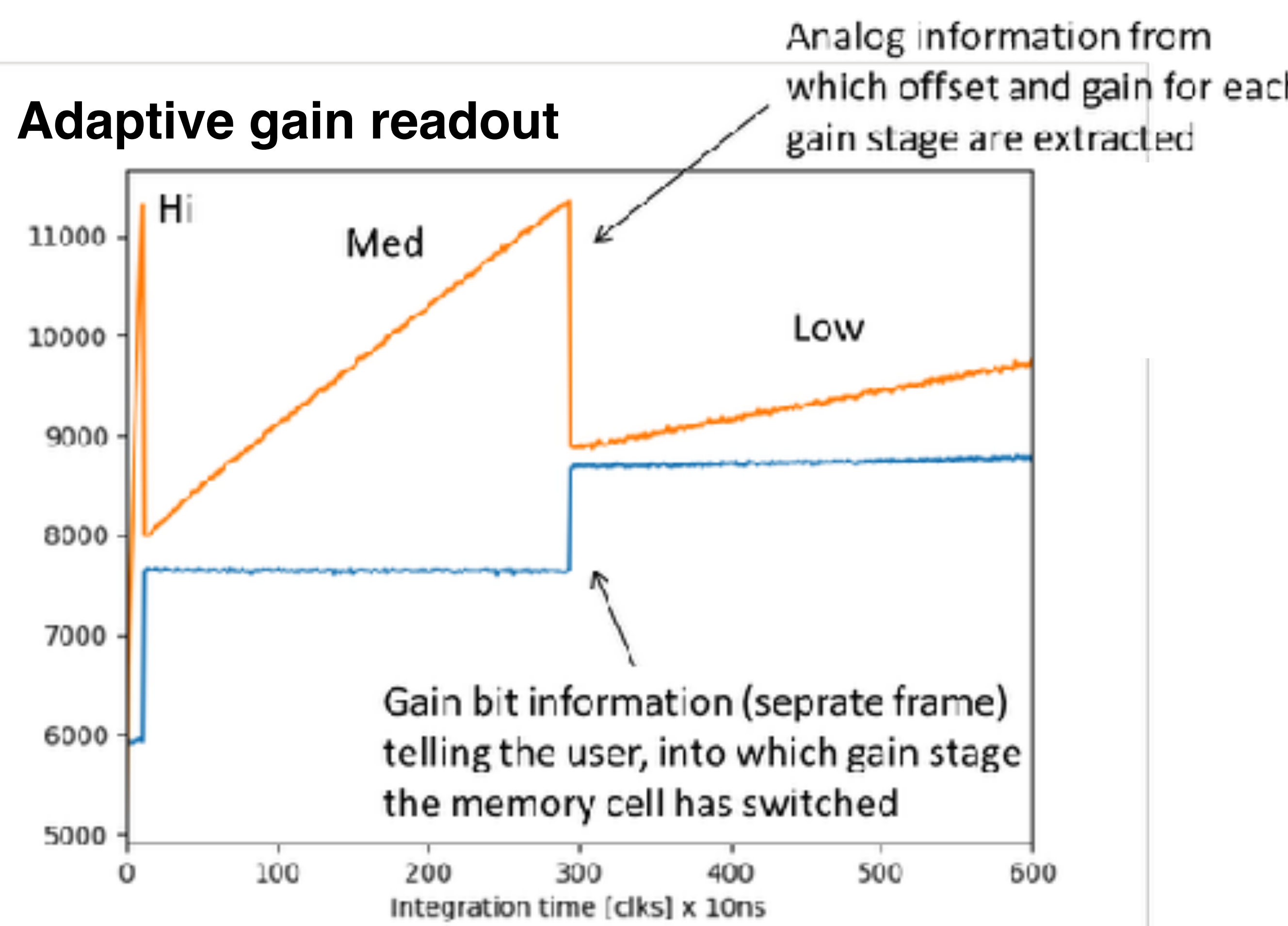



| | |
|---|---|
| Energy range | **3keV-18keV** |
| Frame rate | **> 4.5MHz (burst)** |
| Memory depth | **352 frames** |
| Dynamic range | **1 to $10^4$ photons/pixel/frame at 12.4 keV** |
| Pixel size | $(200\mu m)^2$ |
| Operating principle | Charge integrating |
| Dynamic gain switching | Yes (3 gains) |
| Single Photon sensitivity | Yes |

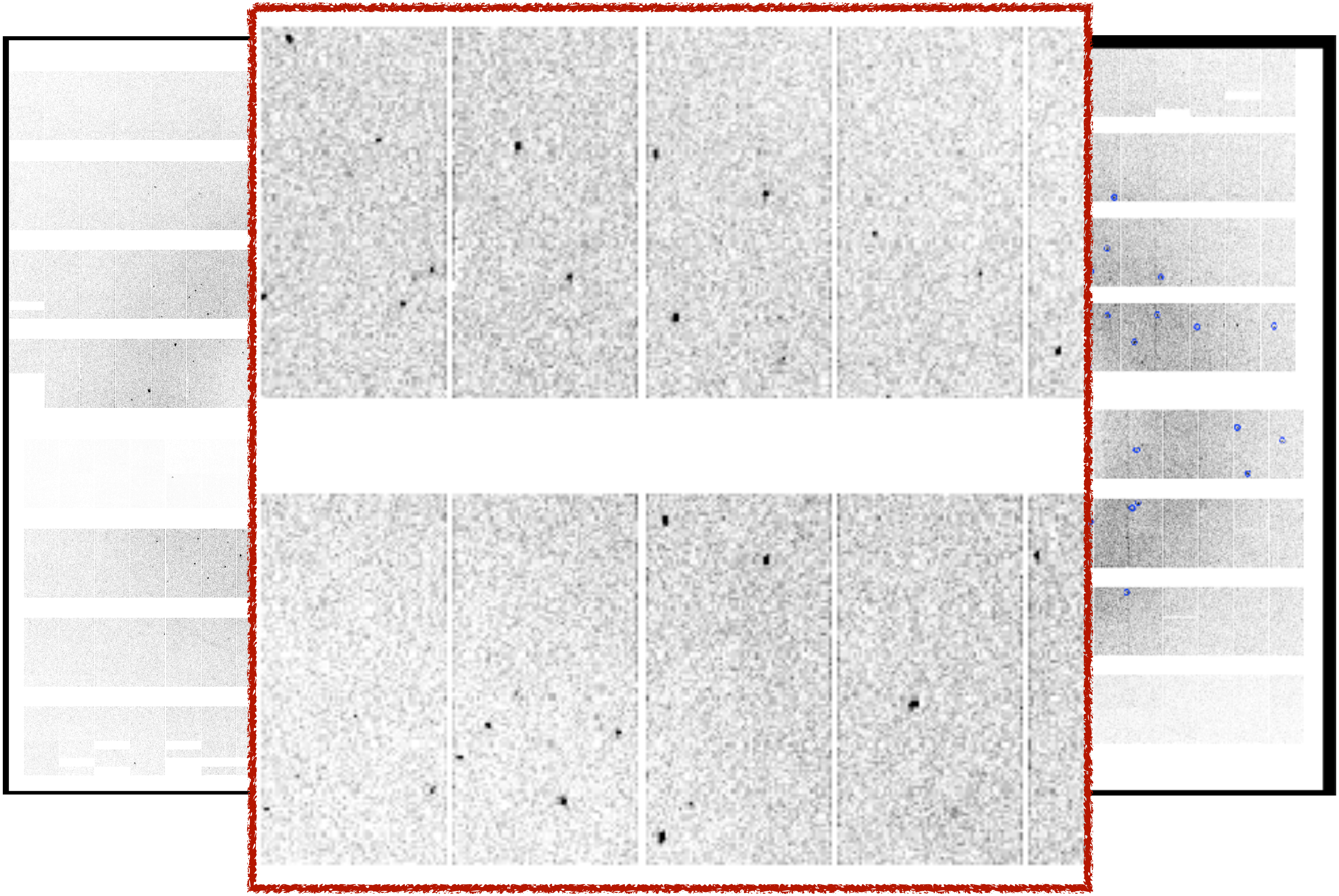
## Pixel circuit overview



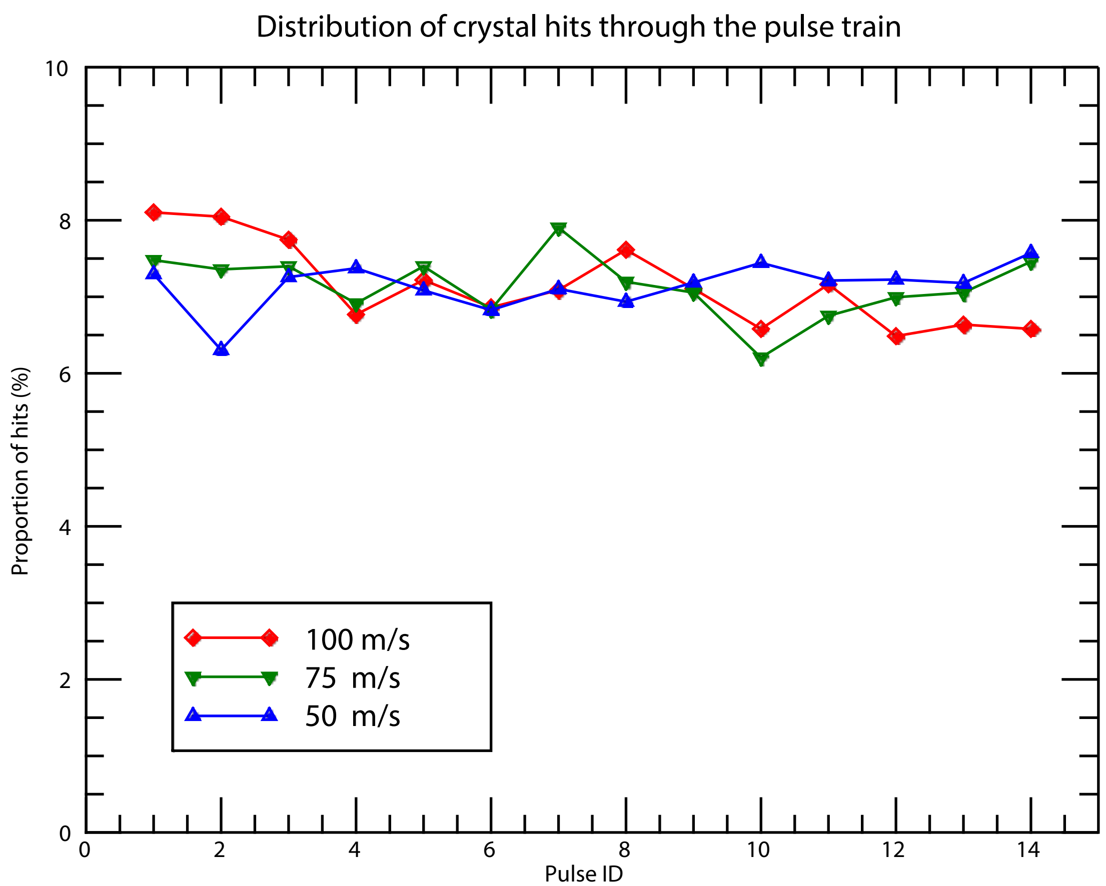

## Adaptive gain readout

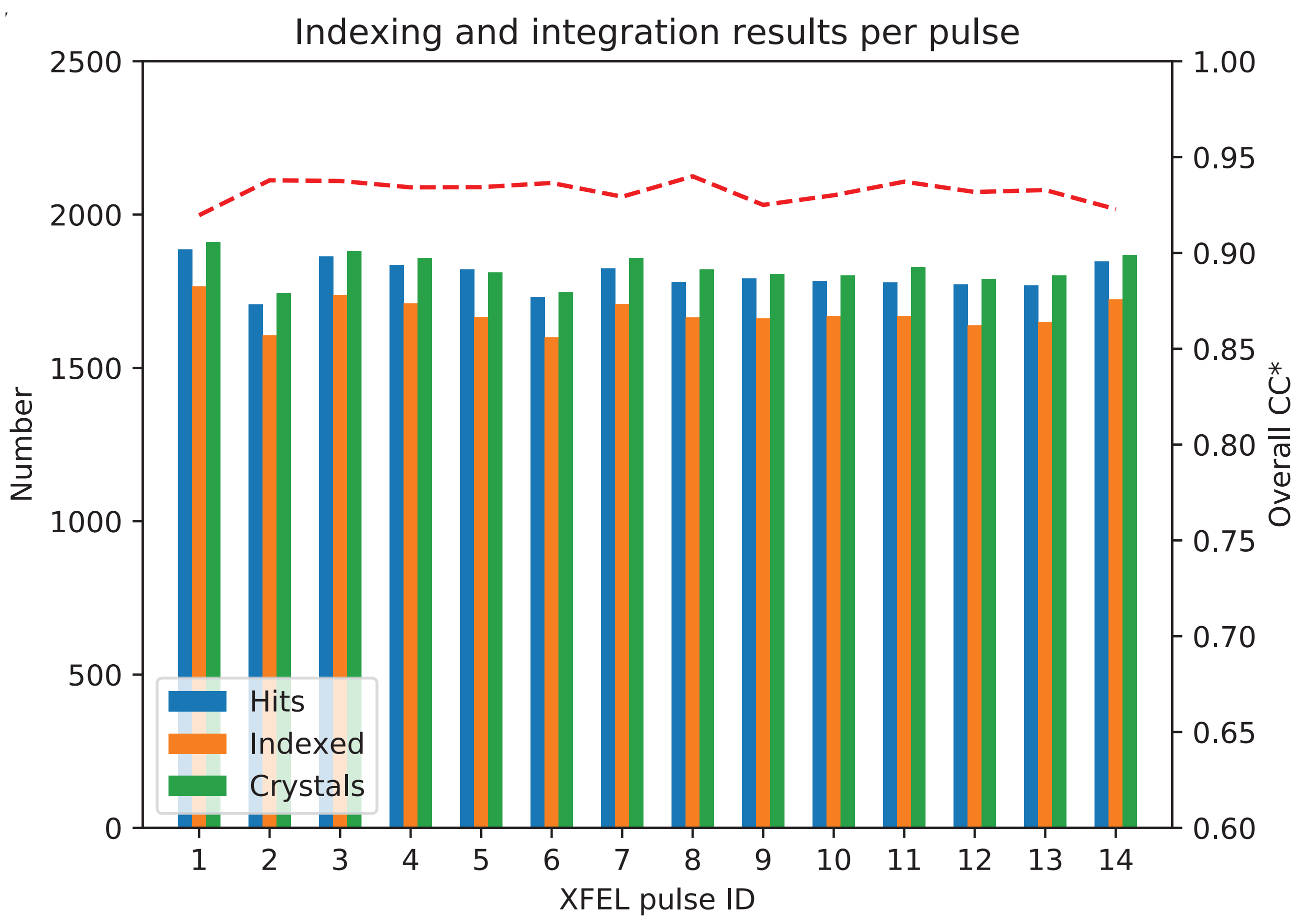


# We can extract reasonable looking diffraction patterns with low noise and high dynamic range thanks to dynamic gain switching



# Crystal hits are evenly distributed through the pulse train



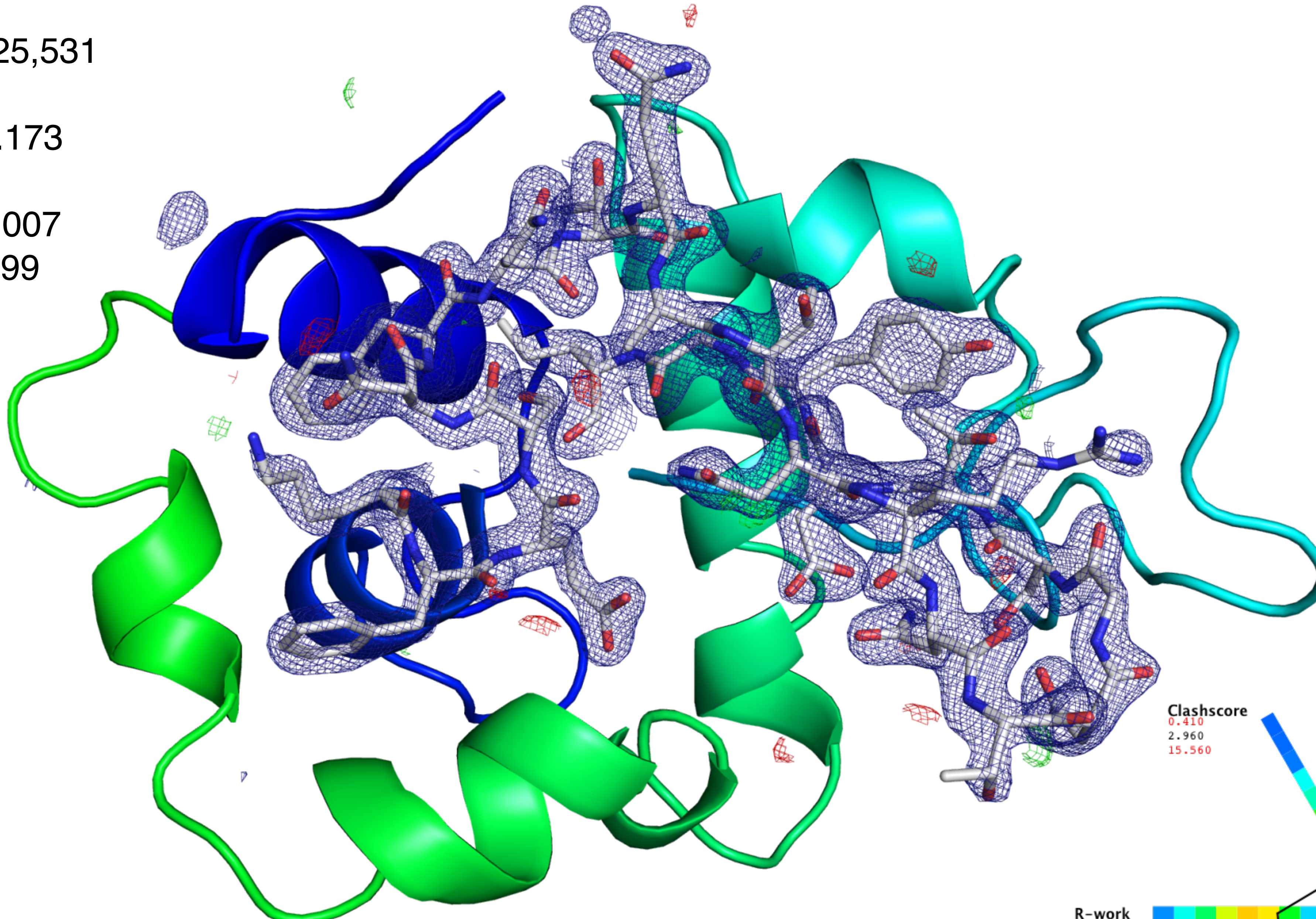

Wiedorn *et.al.* "Megahertz serial crystallography" Nat Commun. 9, 4025 (2018).

# Lysozyme data confirms an accurate structure can be measured to 1.76Å resolution using MHz pulse trains

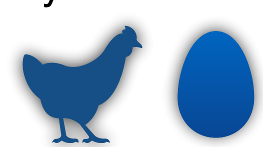
**PDB: 6FTR**

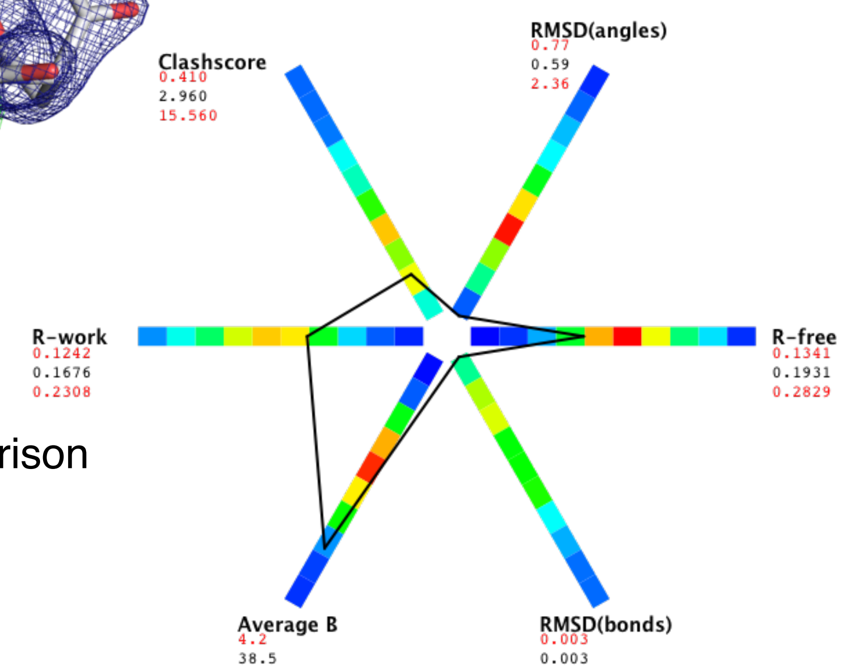
Number of lattices: 25,531
Resolution: 1.76Å
$R_{work}/R_{free}$: 0.157 / 0.173
Average $B_{ISO}$: 30 Å
RMSD bonds (Å): 0.007
RMSD angles (°): 0.99
**CXIDB: ID-80**

2mFo-DFc map (1.5σ)
and mFo-DFc map (3σ)
over residues 33-55



There are over 1800 Lysozyme PDB depositions for comparison



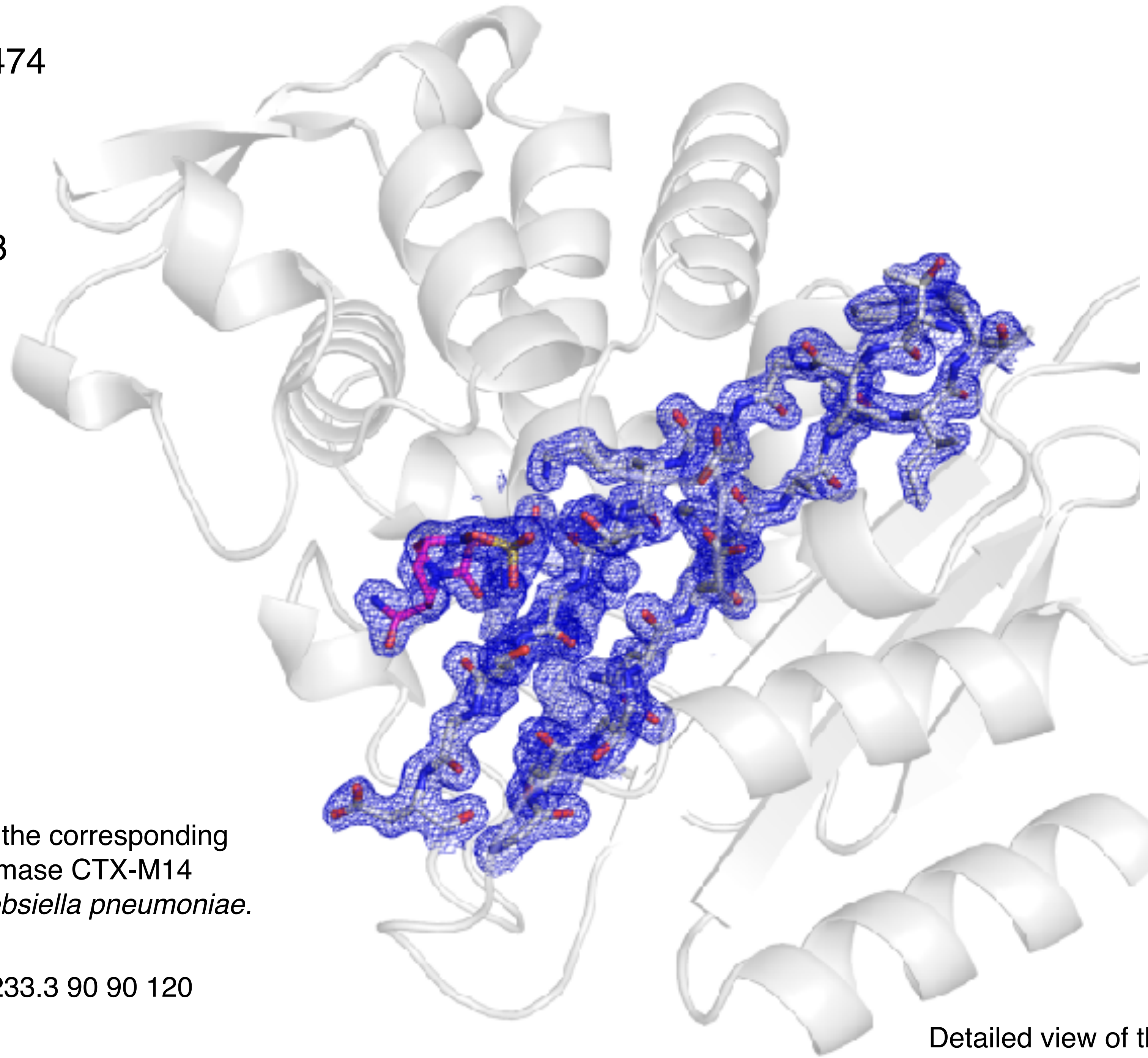



Wiedorn *et.al.* "Megahertz serial crystallography" Nat Commun. 9, 4025 (2018).

# We solved the unknown structure of Beta-lactamase CTX-M-14 to 1.7 Å using data from 12,500 indexed lattices

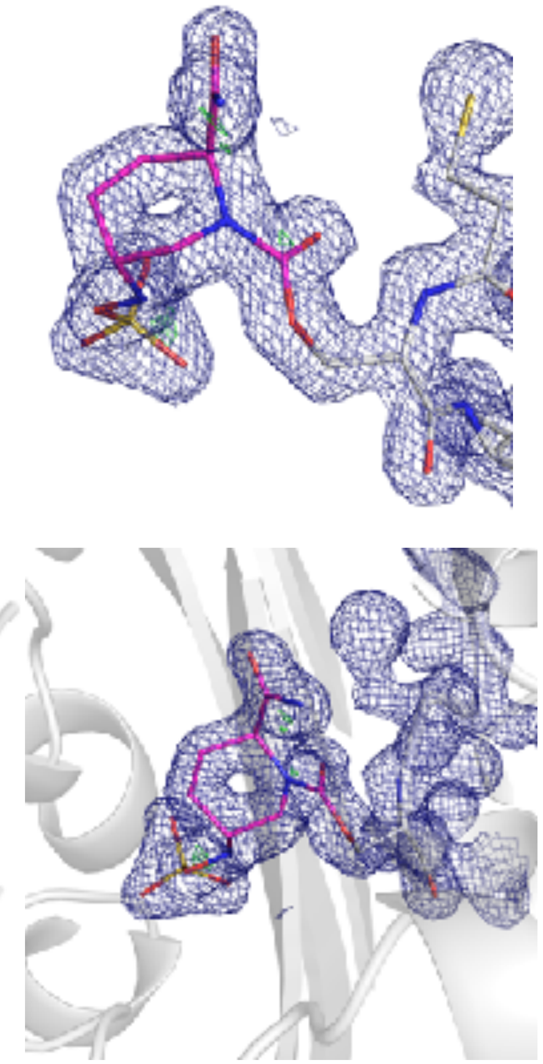
**PDB: 6GTH**

Number of lattices: 12,474
Resolution: 1.69Å
$R_{work}/R_{free}$: 0.176 / 0.21
Average B: 27.6
RMSD bonds (Å): 0.008
RMSD angles (°): 1.22
**CXIDB: ID-83**



2Fo-Fc map (at 1.5 σ) over the corresponding part of the model of ß-lactamase CTX-M14 from multidrug resistant *Klebsiella pneumoniae.*

$P3_221$ Unit Cell: 41.8 41.8 233.3 90 90 120



Detailed view of the binding of the ß-lactamase inhibitor avibactam to Ser70. The inhibitor is bound covalently to the protein (hemiacetal).

Sample: Christian Betzel, UHH

Wiedorn *et.al.* "Megahertz serial crystallography" Nat Commun. 9, 4025 (2018).

# Over 125 authors from 38 institutions contributed to this work

nature COMMUNICATIONS

NATURE COMMUNICATIONS | DOI: 10.1038/s41467-018-06156-7

NATURE COMMUNICATIONS (2018)9:4025 | DOI: 10.1038/s41467-018-06156-7

ARTICLE

DOI: 10.1038/s41467-018-06156-7 OPEN

# Megahertz serial crystallography

Max O. Wiedorn et al.[#]

Max O. Wiedorn[1,2,3], Dominik Oberthür[1], Richard Bean[4], Robin Schubert[3,5,6], Nadine Werner[5], Brian Abbey[7], Martin Aepfelbacher[8], Luigi Adriano[9], Aschkan Allahgholi[9], Nasser Al-Qudami[4], Jakob Andreasson[10,11,12], Steve Aplin[1], Salah Awel[1,3], Kartik Ayyer[1], Saša Bajt[9], Imrich Barák[13], Sadia Bari[9], Johan Bielecki[4], Sabine Botha[3,5], Djelloul Boukhelef[4], Wolfgang Brehm[1], Sandor Brockhauser[4,14], Igor Cheviakov[8], Matthew A. Coleman[15], Francisco Cruz-Mazo[16], Cyril Danilevski[4], Connie Darmanin[7], R. Bruce Doak[17], Martin Domaracky[1], Katerina Dörner[4], Yang Du[1], Hans Fangohr[4,18], Holger Fleckenstein[1], Matthias Frank[15], Petra Fromme[19], Alfonso M. Gañán-Calvo[16], Yaroslav Gevorkov[1,20], Klaus Giewekemeyer[4], Helen Mary Ginn[21,22], Heinz Graafsma[9,23], Rita Graceffa[4], Dominic Greiffenberg[24], Lars Gumprecht[1], Peter Göttlicher[9], Janos Hajdu[10,11], Steffen Hauf[4], Michael Heymann[25], Susannah Holmes[7], Daniel A. Horke[1,3], Mark S. Hunter[26], Siegfried Imlau[1], Alexander Kaukher[4], Yoonhee Kim[4], Alexander Klyuev[9], Juraj Knoška[1,2], Bostjan Kobe[27], Manuela Kuhn[9], Christopher Kupitz[28], Jochen Küpper[1,2,3,29], Janine Mia Lahey-Rudolph[1,30], Torsten Laurus[9], Karoline Le Cong[5], Romain Letrun[4], P. Lourdu Xavier[1,31], Luis Maia[4], Filipe R.N.C. Maia[10,32], Valerio Mariani[1], Marc Messerschmidt[4], Markus Metz[1], Davide Mezza[24], Thomas Michelat[4], Grant Mills[4], Diana C.F. Monteiro[3], Andrew Morgan[1], Kerstin Mühlig[10], Anna Munke[10], Astrid Münnich[4], Julia Nette[3], Keith A. Nugent[7], Theresa Nuguid[5], Allen M. Orville[22], Suraj Pandey[28], Gisel Pena[1], Pablo Villanueva-Perez[1], Jennifer Poehlsen[9], Gianpietro Previtali[4], Lars Redecke[8,30], Winnie Maria Riekehr[30], Holger Rohde[8], Adam Round[4], Tatiana Safenreiter[1], Iosifina Sarrou[1], Tokushi Sato[1,4], Marius Schmidt[28], Bernd Schmitt[24], Robert Schönherr[30], Joachim Schulz[4], Jonas A. Sellberg[33], M. Marvin Seibert[10], Carolin Seuring[1,3], Megan L. Shelby[15], Robert L. Shoeman[17], Marcin Sikorski[4], Alessandro Silenzi[4], Claudiu A. Stan[34], Xintian Shi[24], Stephan Stern[1,4], Jola Sztuk-Dambietz[4], Janusz Szuba[4], Aleksandra Tolstikova[1], Martin Trebbin[3,35,36], Ulrich Trunk[9], Patrik Vagovic[1,4], Thomas Ve[37], Britta Weinhausen[4], Thomas A. White[1], Krzysztof Wrona[4], Chen Xu[4], Oleksandr Yefanov[1], Nadia Zatsepin[38], Jiaguo Zhang[24], Markus Perbandt[3,5,8], Adrian P. Mancuso[4], Christian Betzel[3,5,6], Henry Chapman[1,2,3] & Anton Barty[1]

# A tale of two papers

nature COMMUNICATIONS

Experiments:
September 2017, March 2018

Published: 2 Oct 2018

Experiments:
June 2018

Published: 28 August 2018

ARTICLE

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## Megahertz serial crystallography

Max O. Wiedorn et al.[#]

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ARTICLE

DOI: 10.1038/s41467-018-05953-4 OPEN

## Megahertz data collection from protein microcrystals at an X-ray free-electron laser

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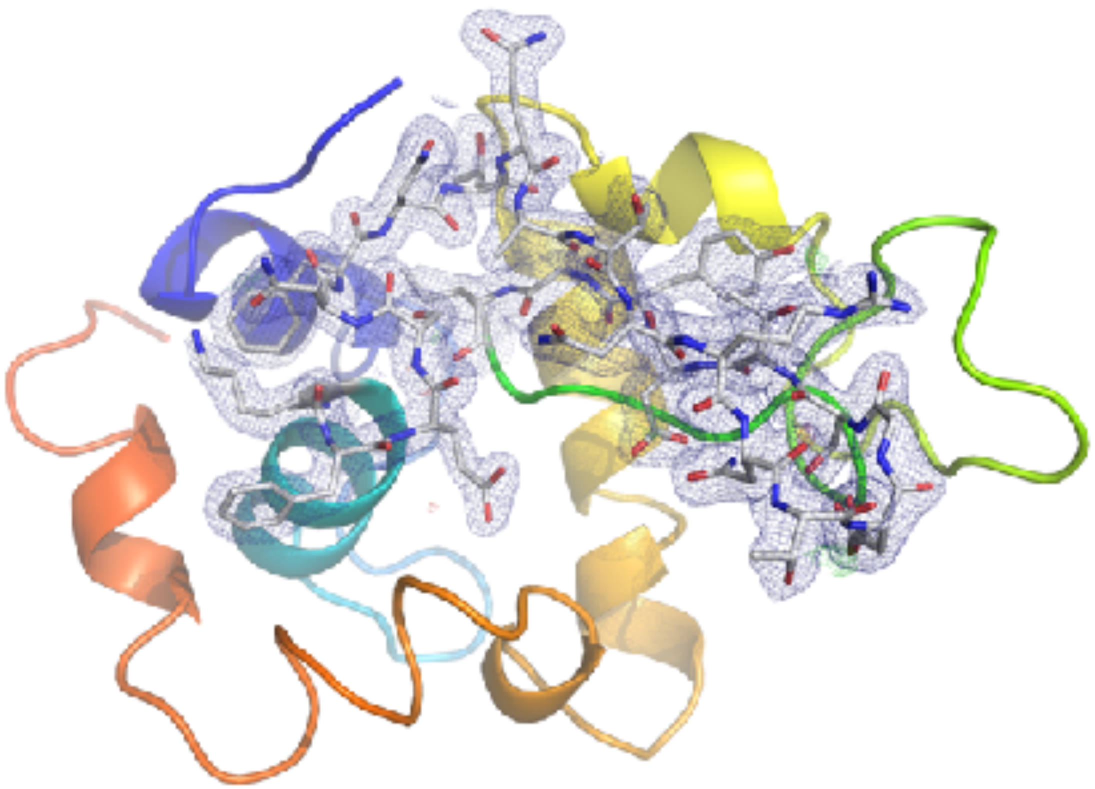
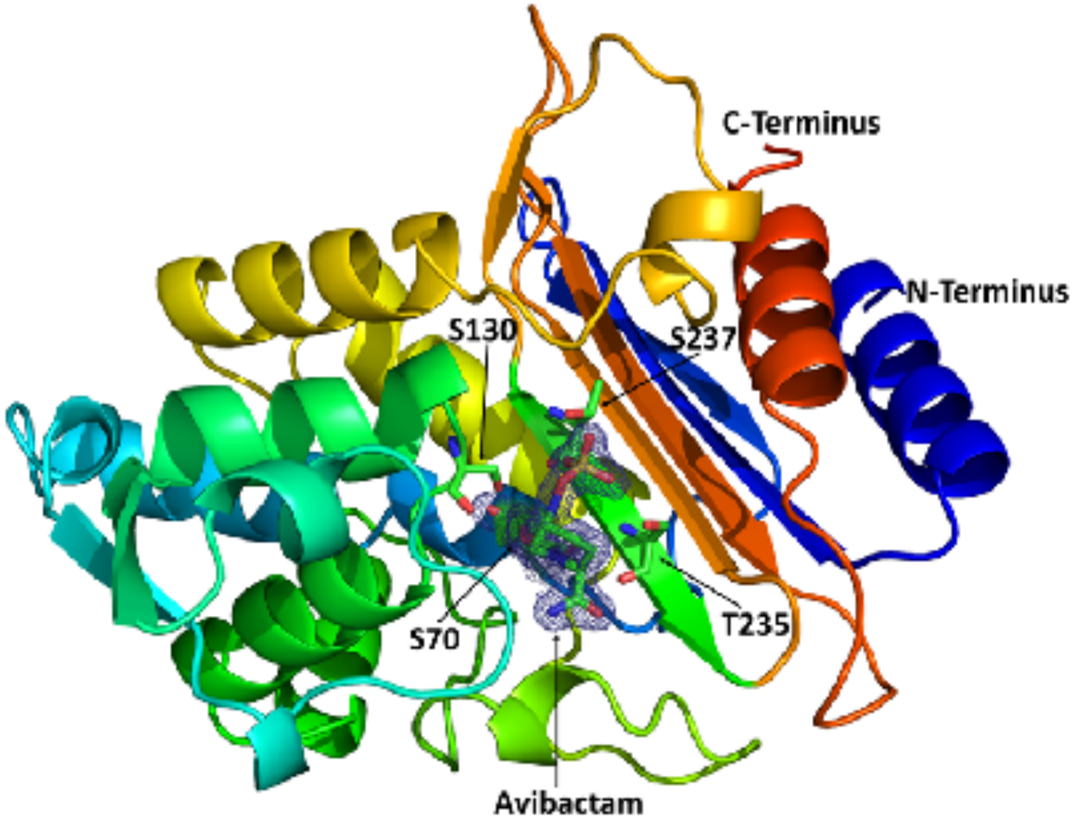
# The future of MHz SFX is very promising

**MHz SFX is a success**

The XFEL2012 data sets could be collected in 3 minutes and 15 minutes assuming no improvements other than 352 pulses per train (3520 frames per second)

| Lysozyme | CTX-M-14 $\beta$-lactamase + avibactam |
|---|---|






**Lysozyme:** 3.5 mins, 50 μL solution at 3520 frames per second

at a 4% hit fraction
September 2017

**CTX-M-14 $\beta$-lactamase + avibactam:** 15 mins at 3520 frames per second

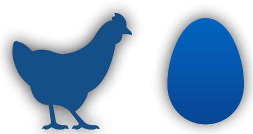
at a 0.4% hit fraction
March 2018

Wiedorn *et.al.* "Megahertz serial crystallography" Nat Commun. 9, 4025 (2018).

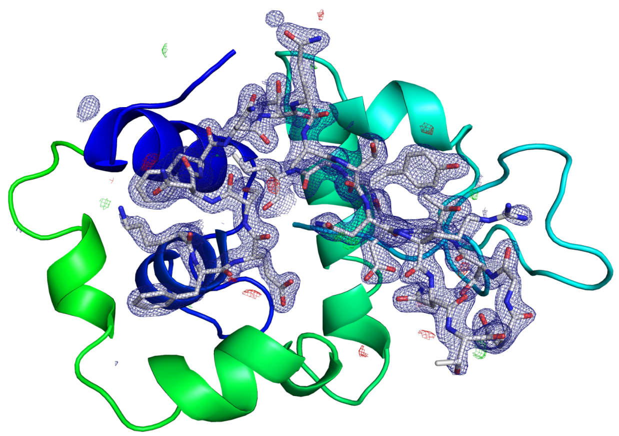
# We have measured 190,000 crystals in under 30 minutes at 1200 frames per second

## EuXFEL 2120: September 2018

Data collection:
- 120 pulses per train / 1200 per second
- 856,000 hits
- 1.4M Indexed crystals
- 11k-12k Indexed patterns per/pulse



Also lysozyme



Refinement:
- $R_{free}$ for single pulse: 19%, $R_{work}$ 16%
- $R_{free}/R_{work}$ for pulses:
  - 1 - 18.4/16.2
  - 2 - 18.9/16.1
  - 3 - 18.5/16.2
  - 20 - 19/16.1
  - 119 - 19.6/16.5
  - 120 - 19.1/16.3
- $R_{free}/R_{work}$ for all data: 15.4/13.9

Res. range for refinement: 15A - 1.6A
B-factors: 25

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**>130,000 indexed lattices in <30 minutes has been achieved**

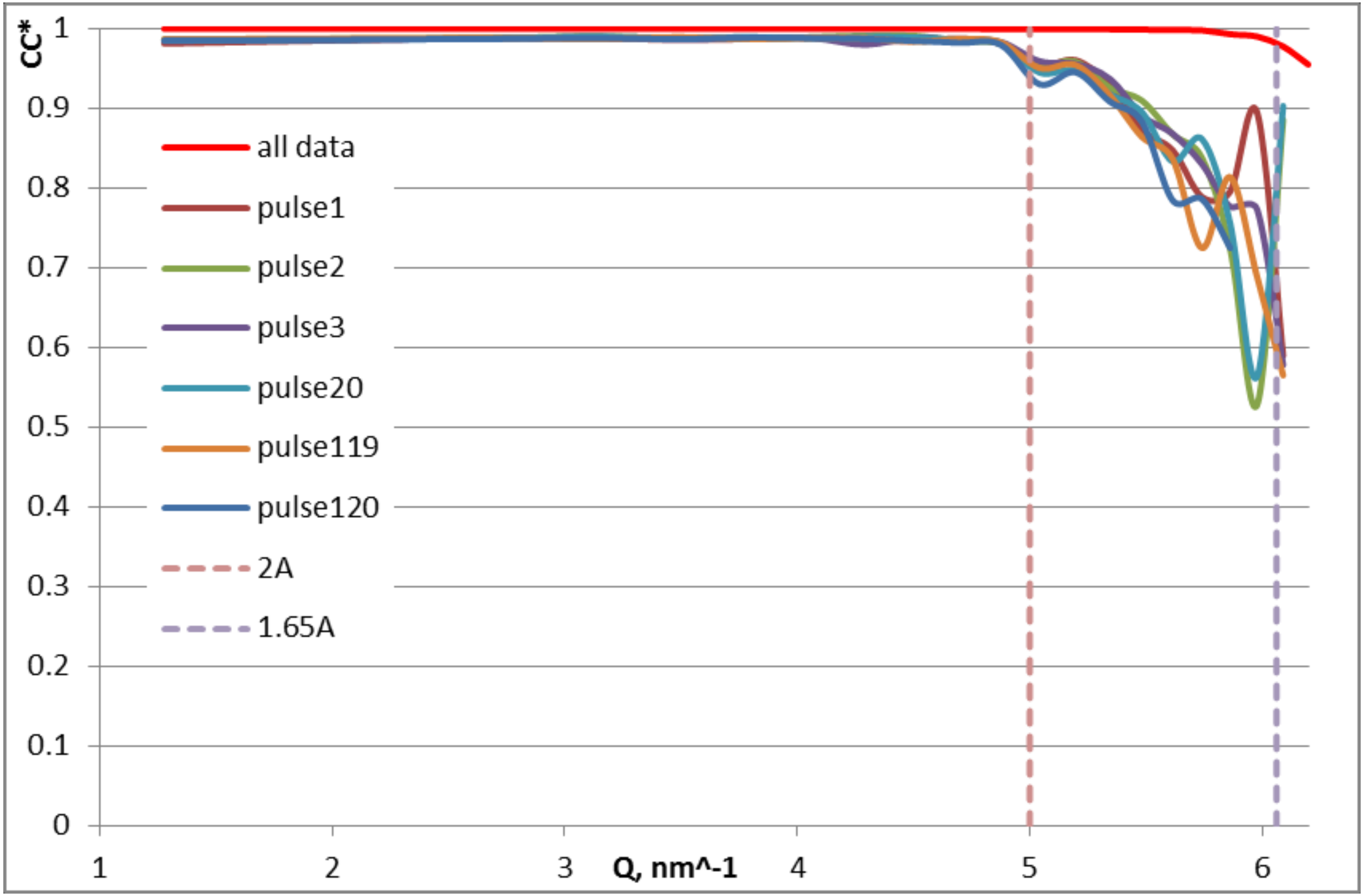
3 runs (r0096-r0098)
627,228 patterns per run, each approx. 9 minutes long
= 1.9M patterns in total measurement time of approx. 30min.
9-11% hitrate = ~ 200,000 hits in total.

Flow rate at 100 m/s:
13 µL / min
40µL in 3 mins

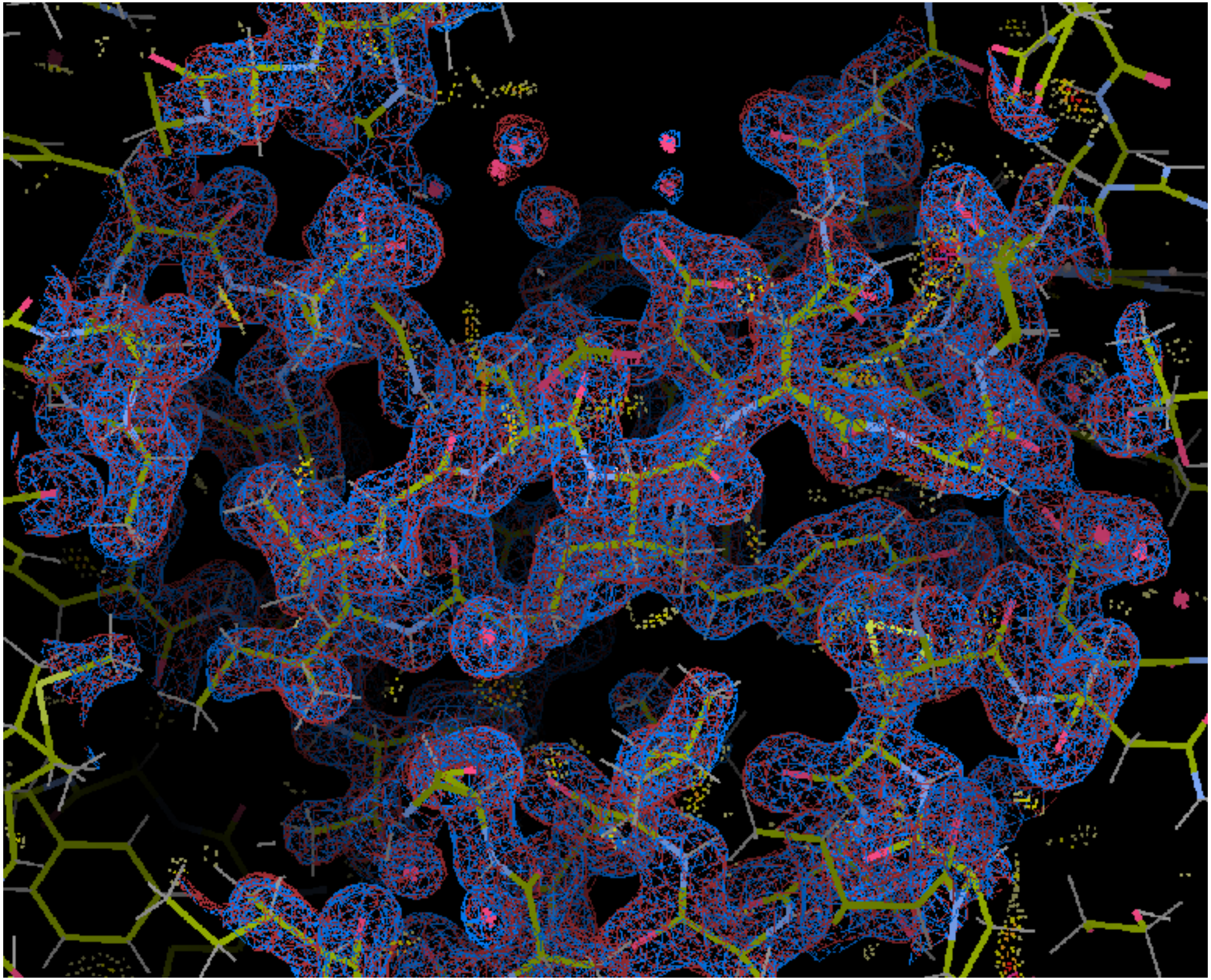
**Equivalent to 13,000 indexed lattices in 3 minutes**
**Enough for the BLAC structure in 3 minutes**

Oleksandr Yefanov
CFEL

# Data across the pulses appears self-consistent



# Electron densities appear quite similar between pulses 1 and 2

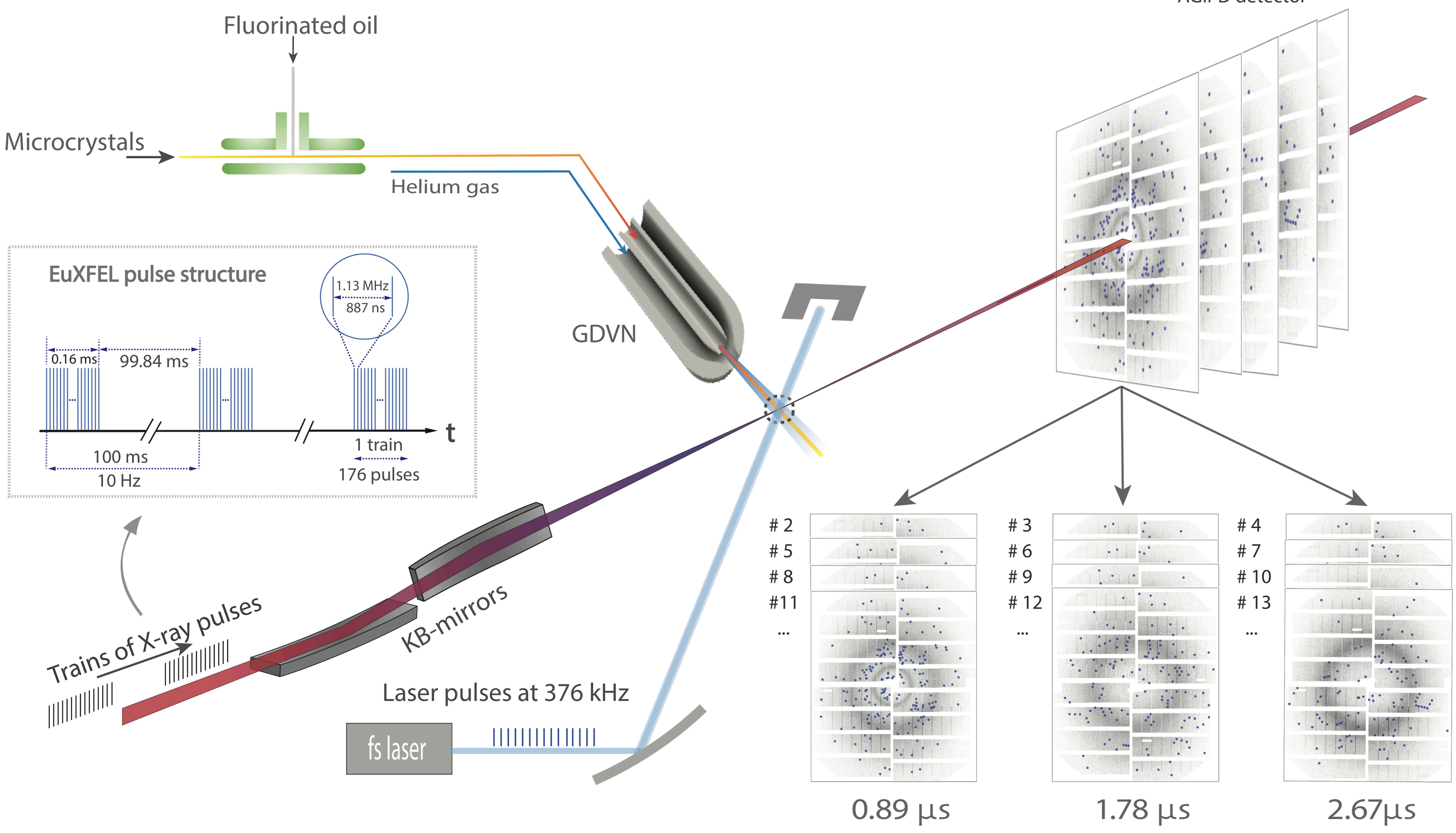


Blue:
Pulse 1

Red:
Pulse 2

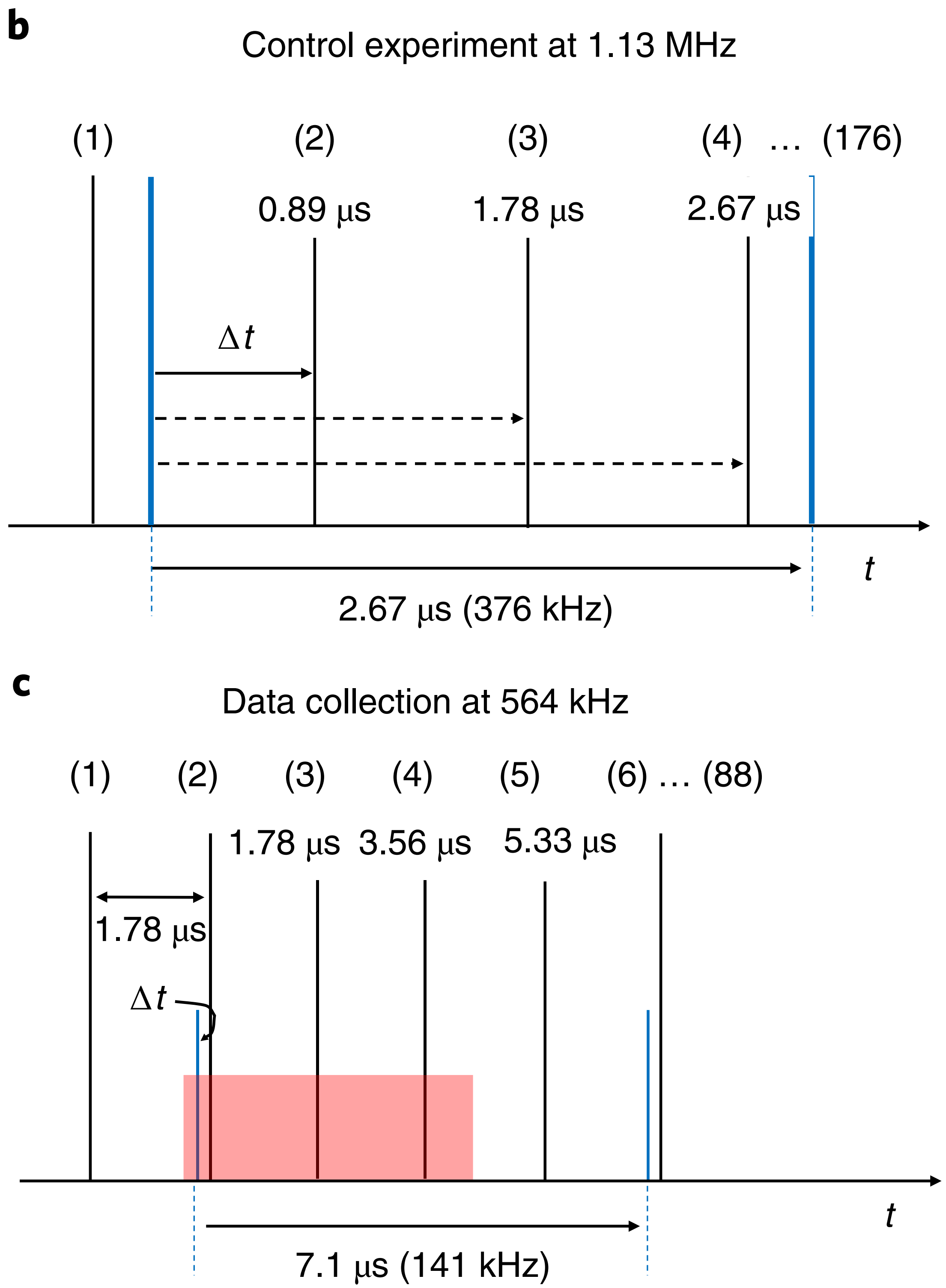
# Exploiting the EuXFEL pulse trains for time resolved studies

## Photosynthetic yellow protein (PYP)



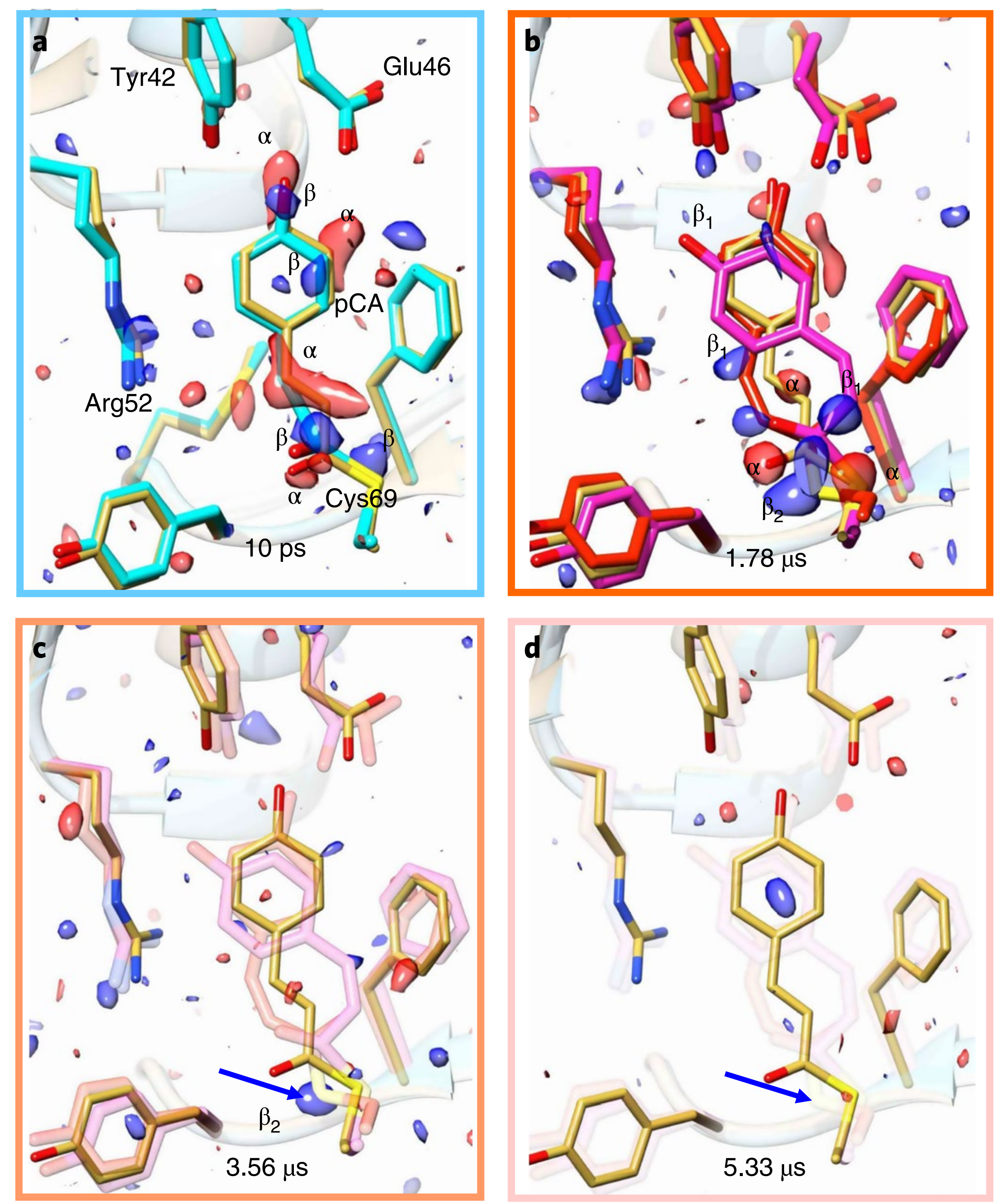

Pandey et.al. "Time-resolved serial femtosecond crystallography at the European XFEL."
Nature Methods 101, 1–11 (2019).

# Exploiting the EuXFEL pulse trains for time resolved studies



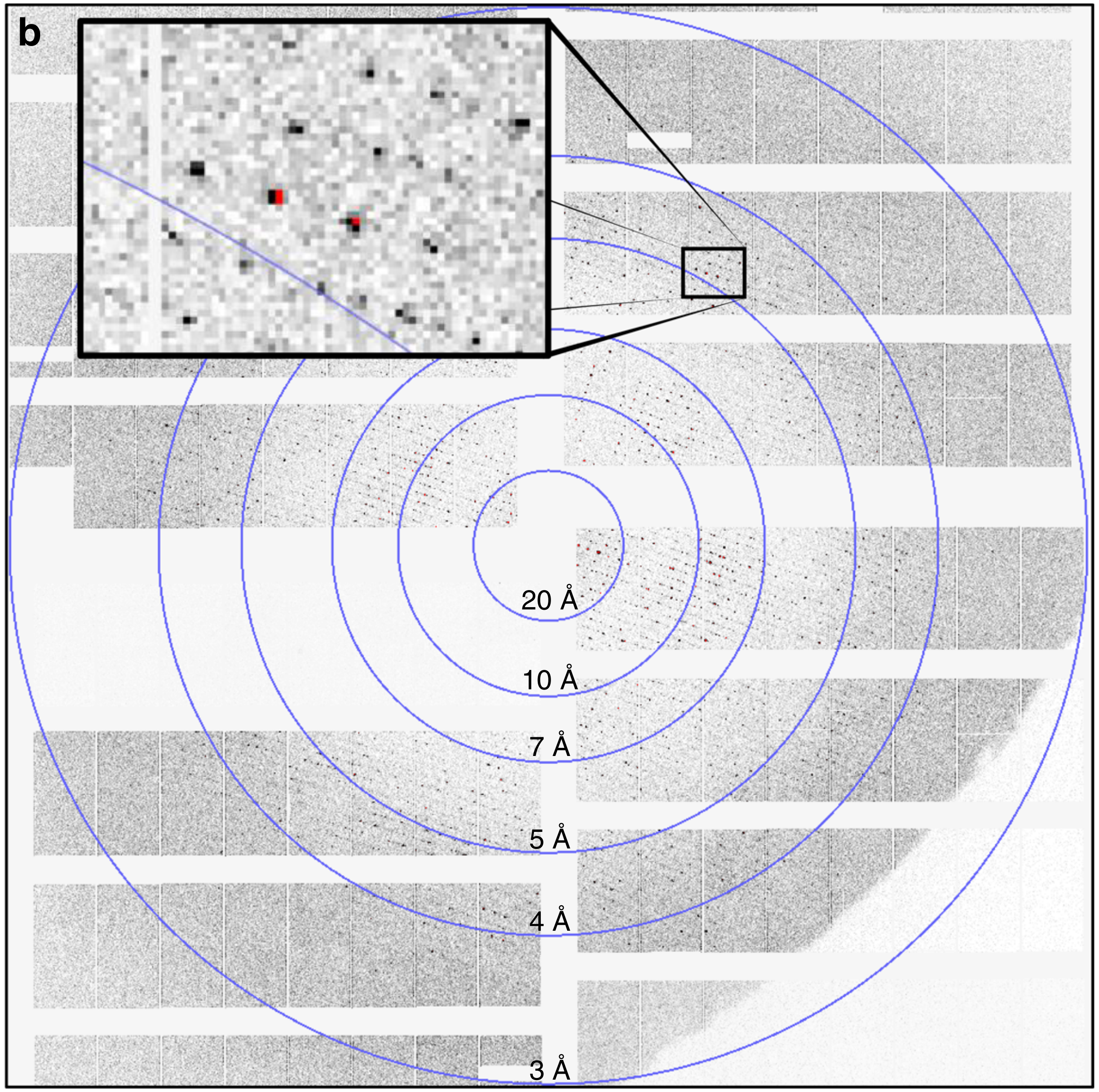

Photosynthetic yellow protein (PYP)

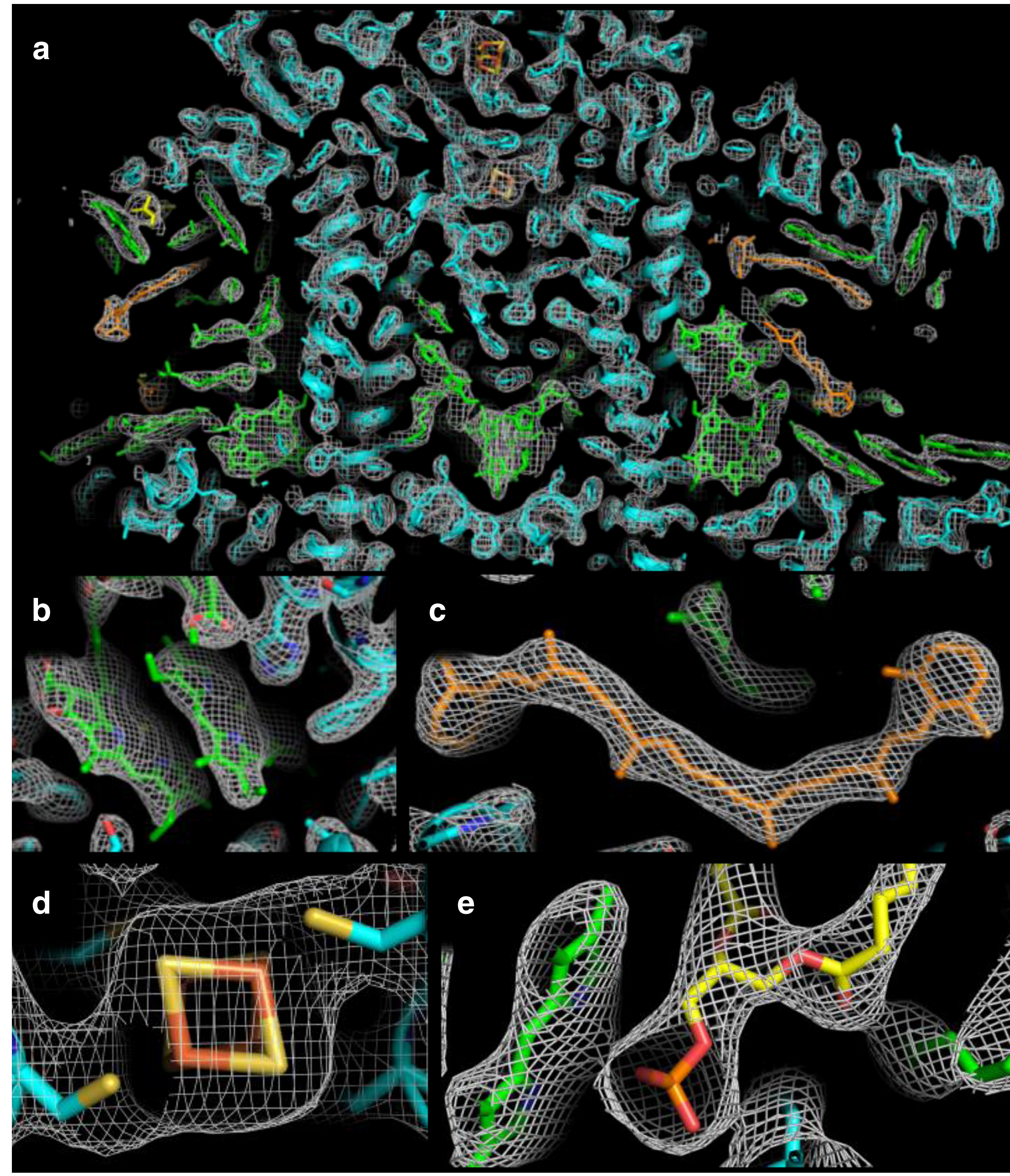
Difference electron density




Pandey et.al. "Time-resolved serial femtosecond crystallography at the European XFEL." Nature Methods 101, 1–11 (2019).

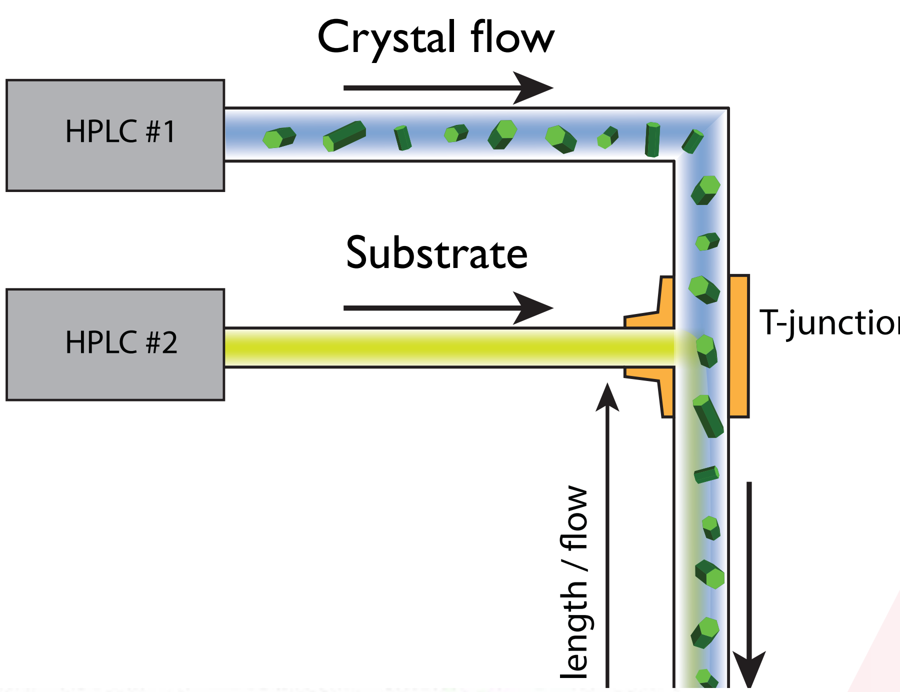
# Membrane proteins: Photosystem I at the European XFEL

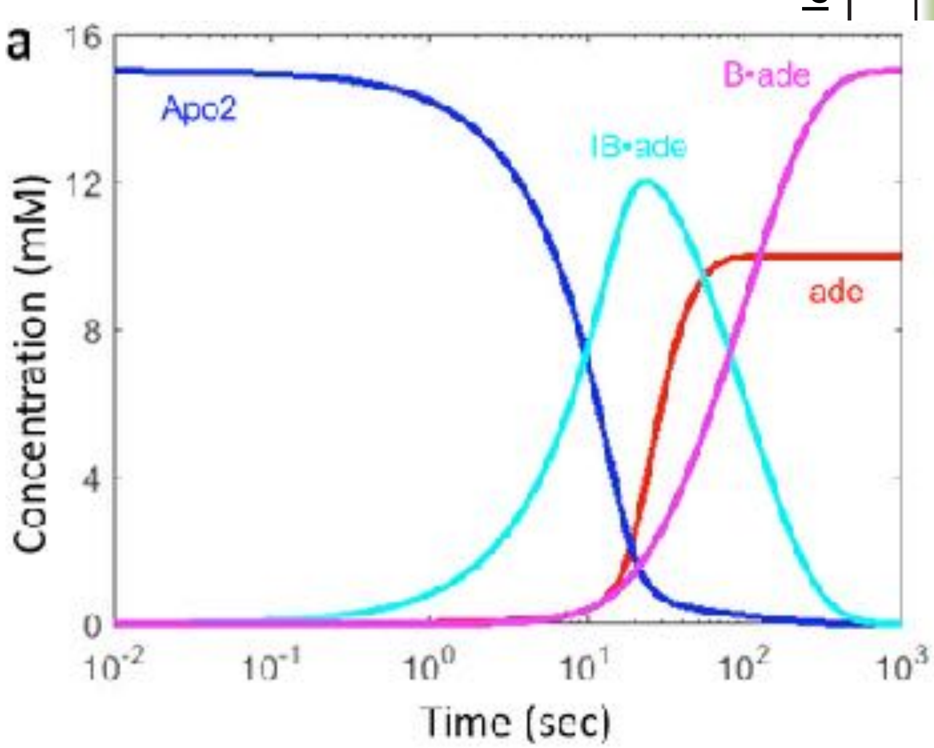


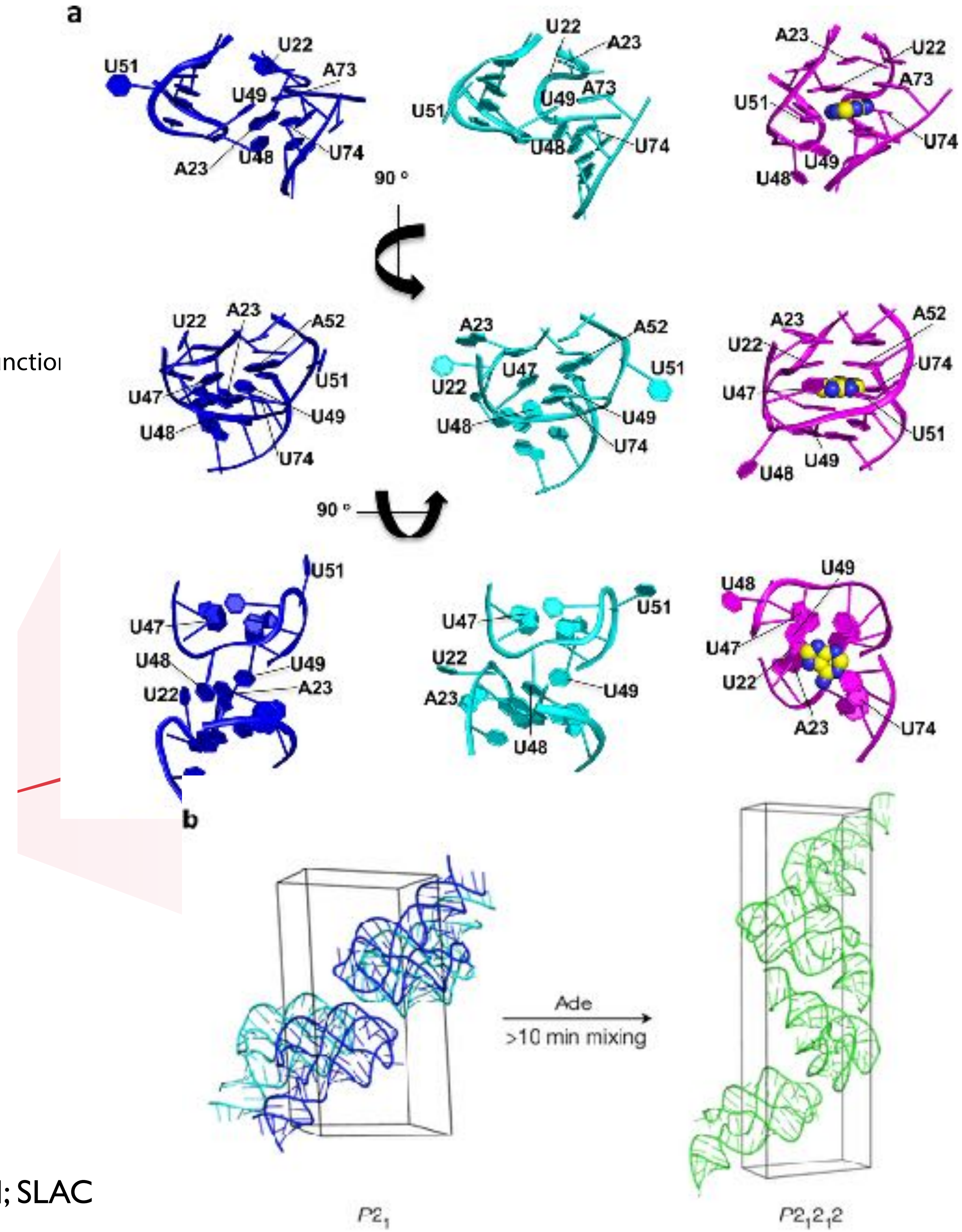




Gisriel et.al. Membrane protein megahertz crystallography at the European XFEL.
Nat Comms 10, 1–11 (2019)

# The majority of biochemical dynamics are initiated by chemical triggers, such as the RNA riboswitch measured at LCLS

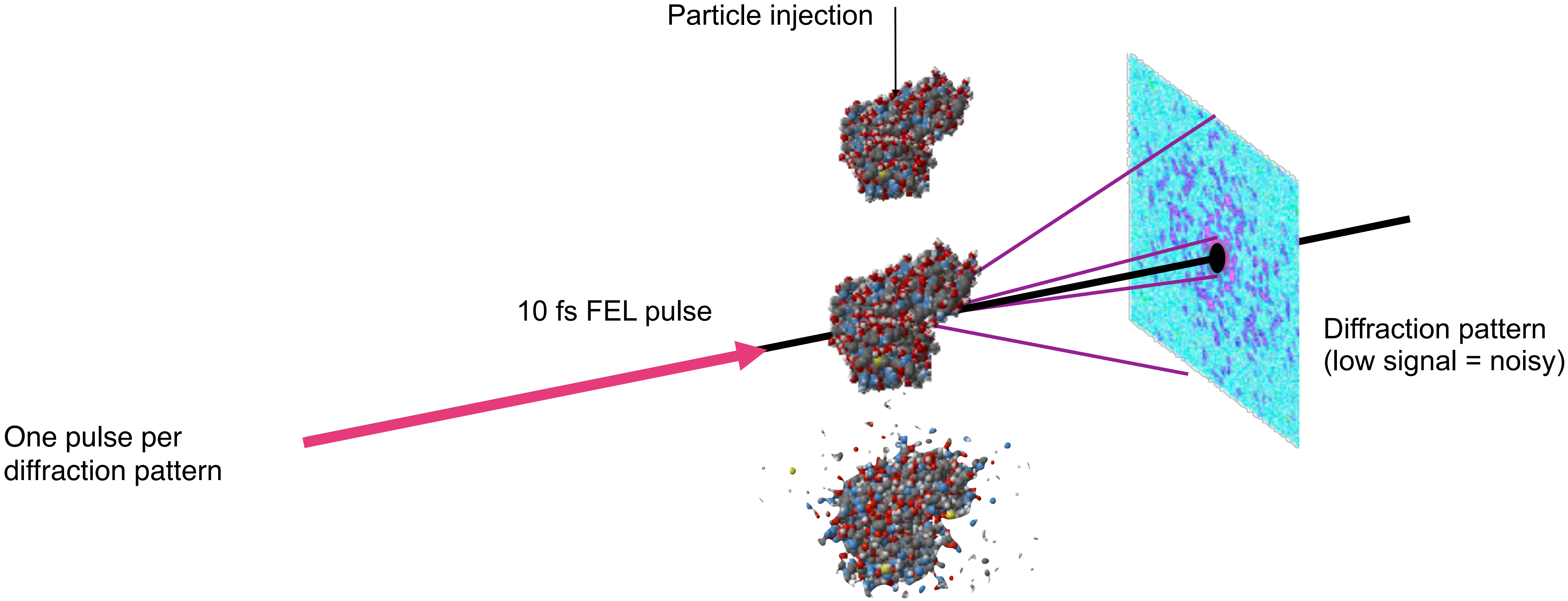


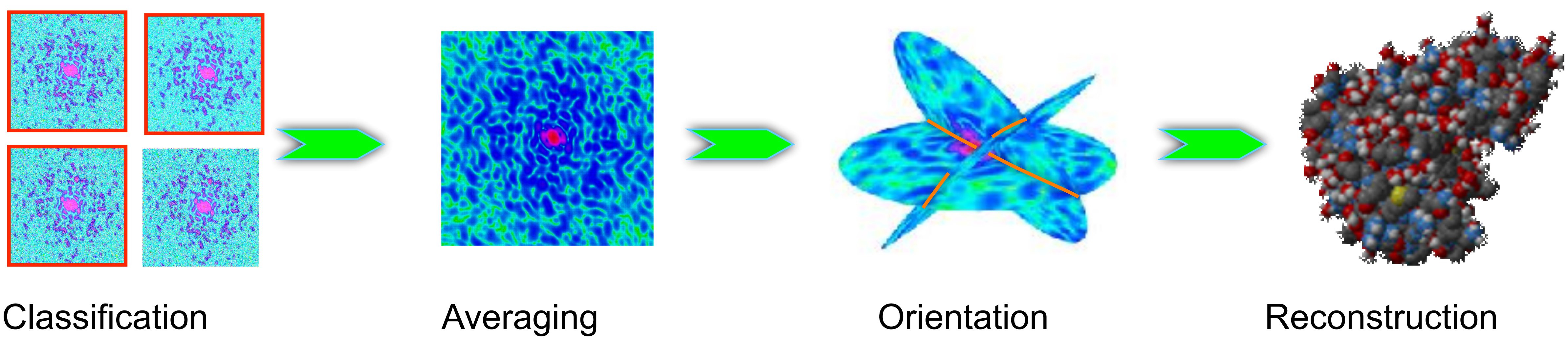




J. Stagno et al Nature 541, 242 (2017).
Y. Wang, NIH-NCI; ASU; Johns Hopkins U.; CFEL DESY; HHWI; SLAC

# What about imaging without crystals?



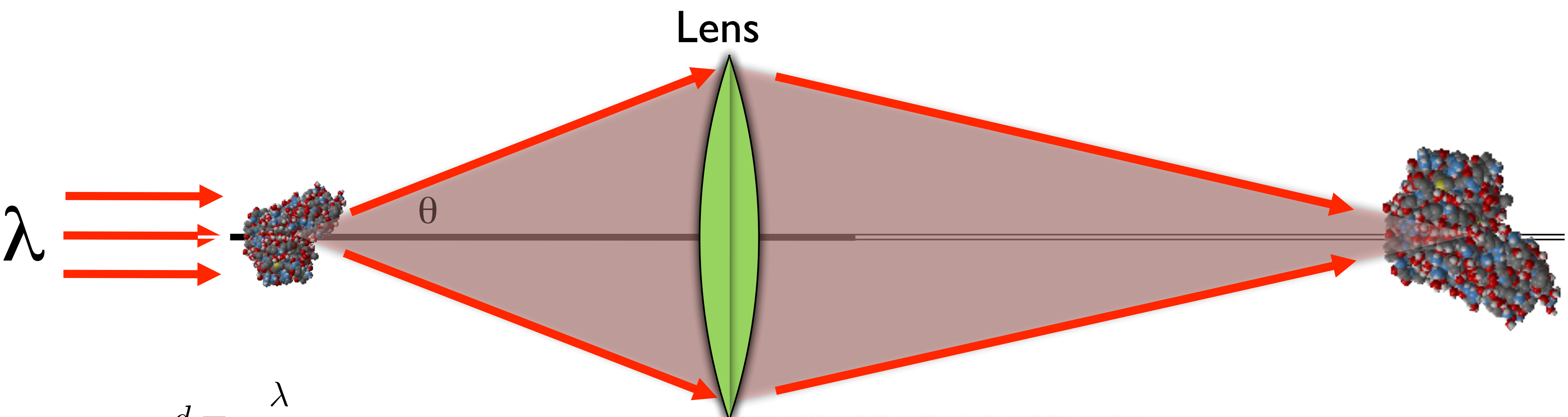

Combine $10^5$-$10^7$ weak measurements




K. Gaffney. & H. Chapman, “Imaging atomic structure and dynamics with ultrafast X-ray scattering” Science 316, 1444 (2007)

# Coherent diffractive imaging is lensless

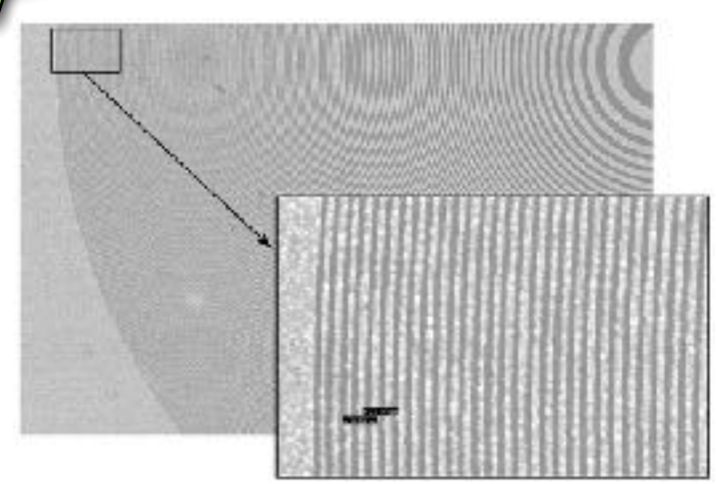
In conventional microscopy a lens is used to ‘phase’
the light and form a (magnified) real-space image of the object




$$d = \frac{\lambda}{2NA}$$

$$NA = n sin(\theta)$$

$$DOF = \frac{\lambda}{NA^2}$$



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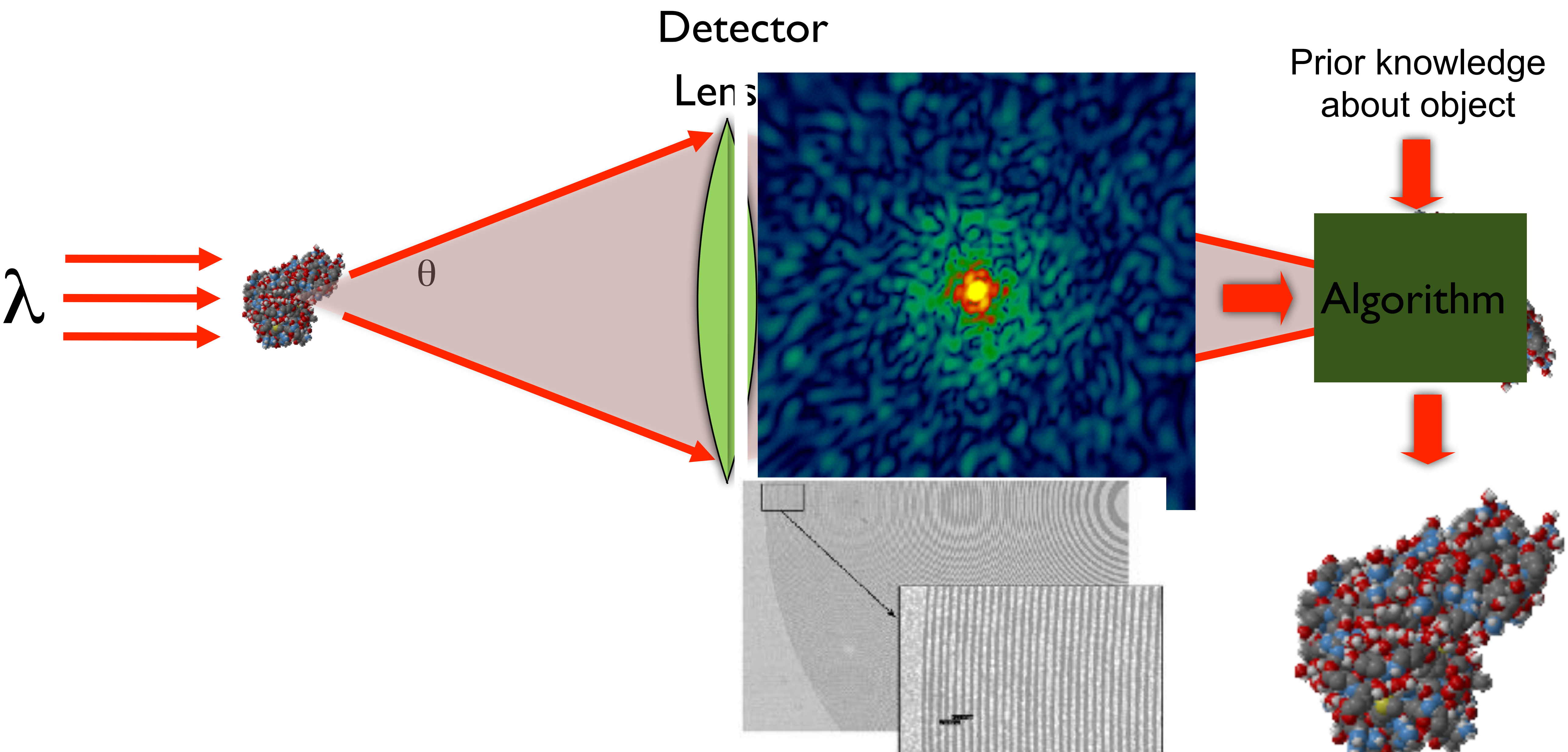
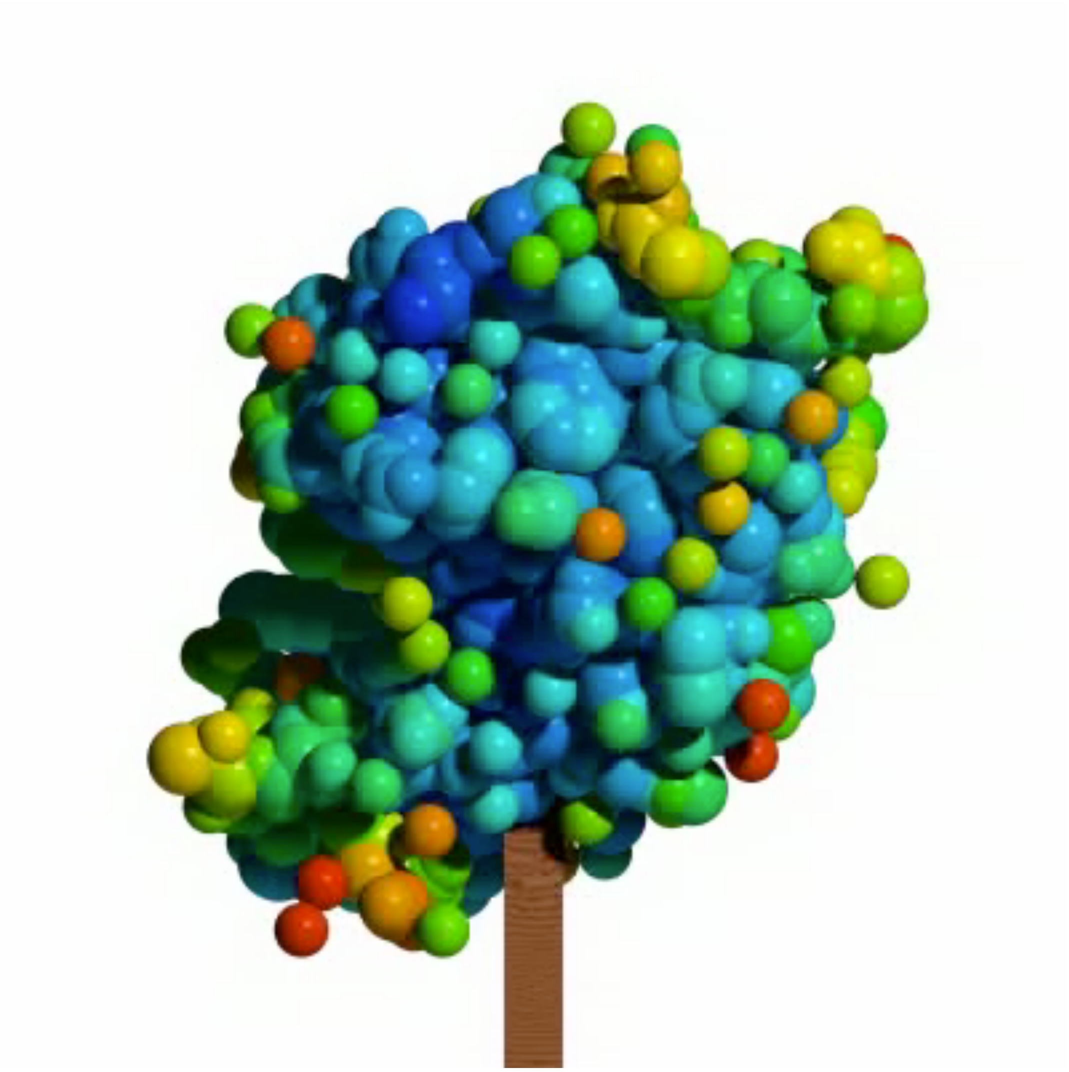
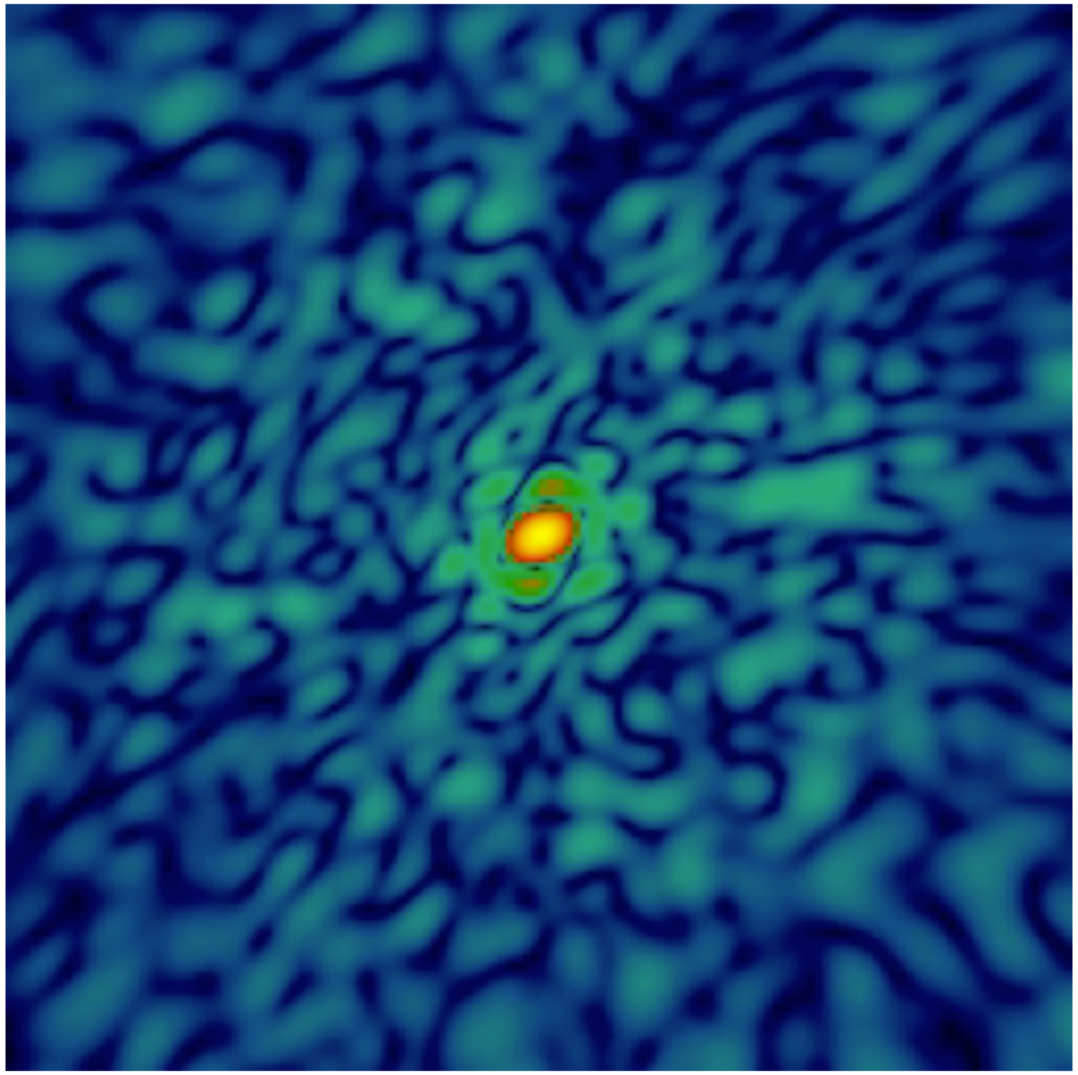



In diffractive imaging, there are no lenses
We detect light at the ‘lens’ plane and use a computer to recreate the image

# Rotating an object results in the Ewald sphere intersecting different parts of diffraction space

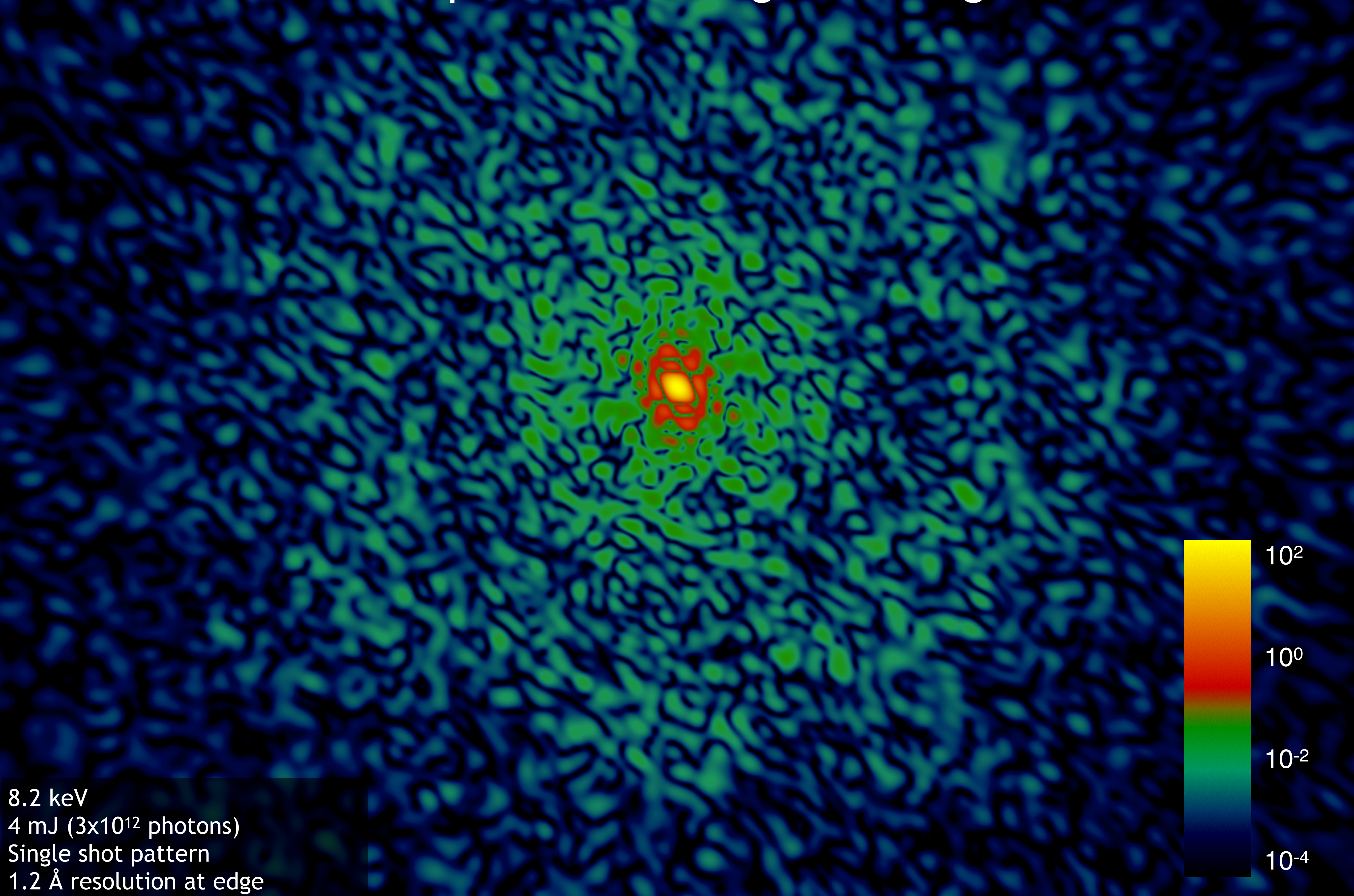




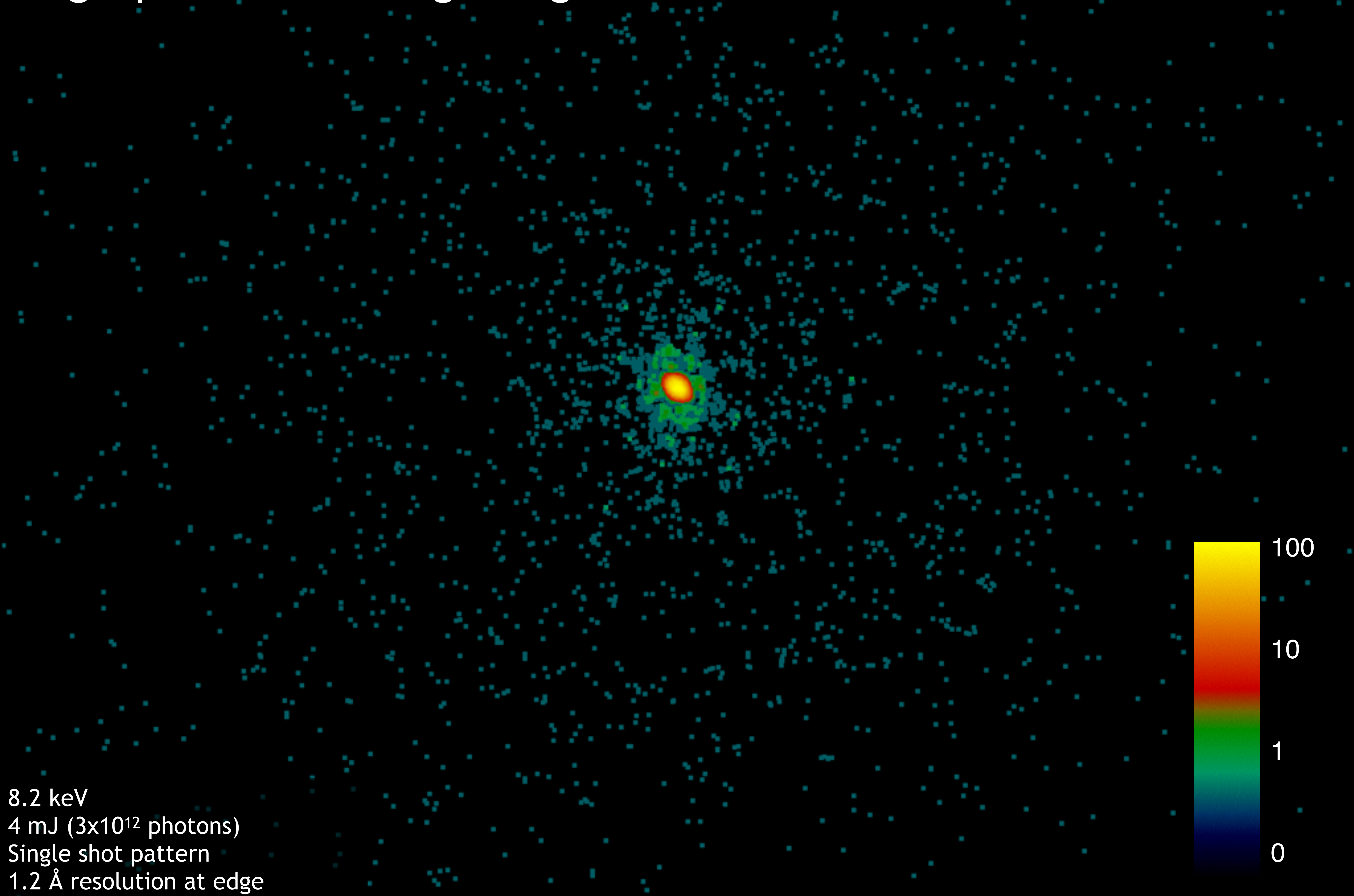
Example: simple molecule (Lysozyme, 1108 atoms, 51Å diameter, mol.wt. = 7250)

1.5Å X-rays, 84mm square detector 50mm from focus

# Diffraction from a single monomer of photosystem I shows continuous coherent speckle extending to the edge of detector



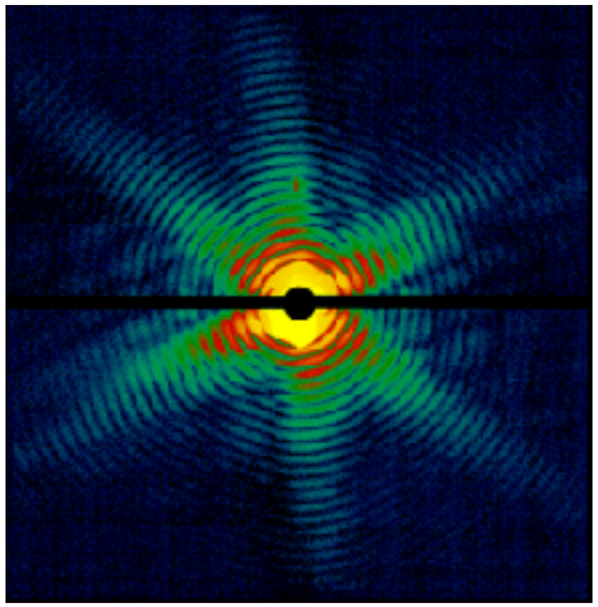
# Diffraction from a single monomer of photosystem I results in single photon counting at high resolution



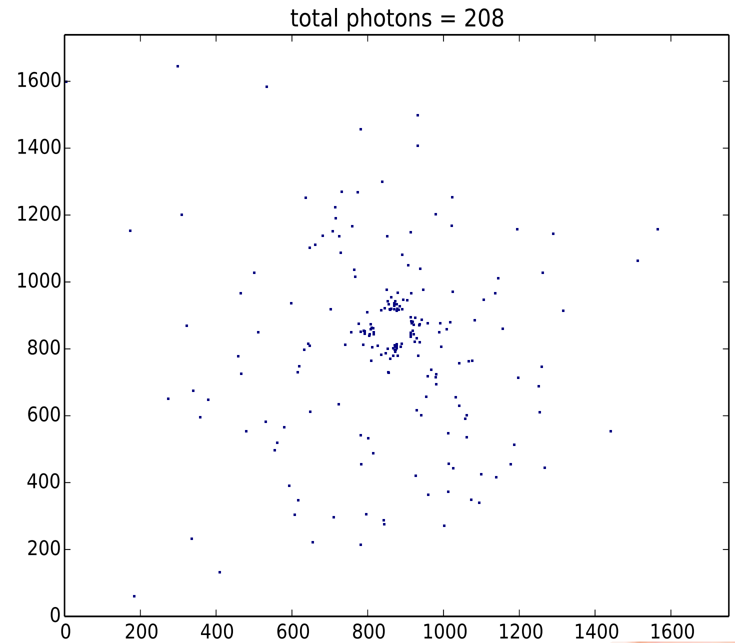

8.2 keV
4 mJ ($3 \times 10^{12}$ photons)
Single shot pattern
1.2 Å resolution at edge

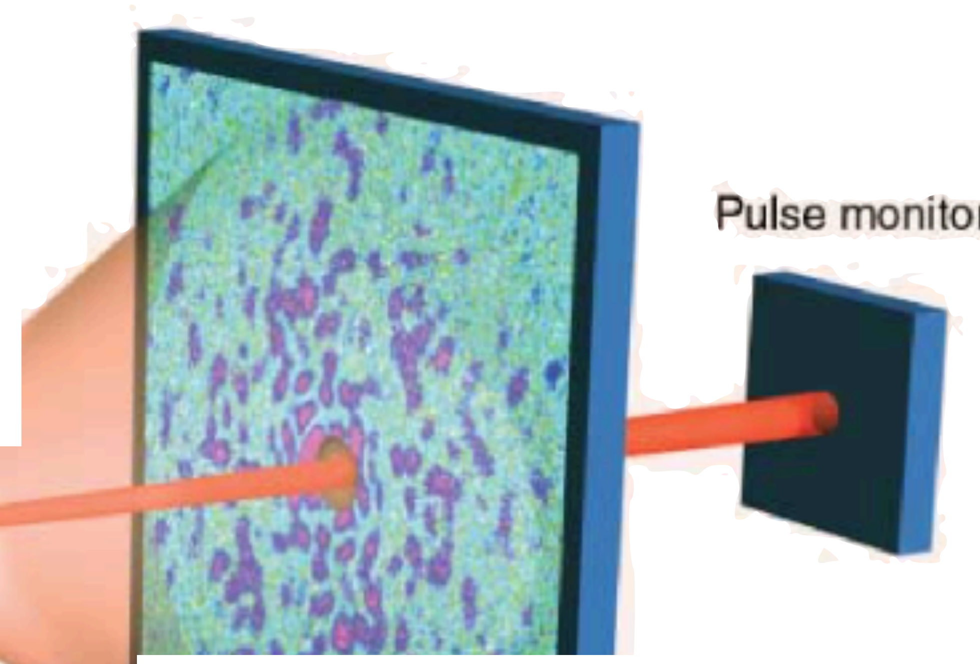
# The Single Particle Imaging initiative of LCLS is making steady progress towards realising single particle X-ray imaging at FELs

AMO (1.8 keV)



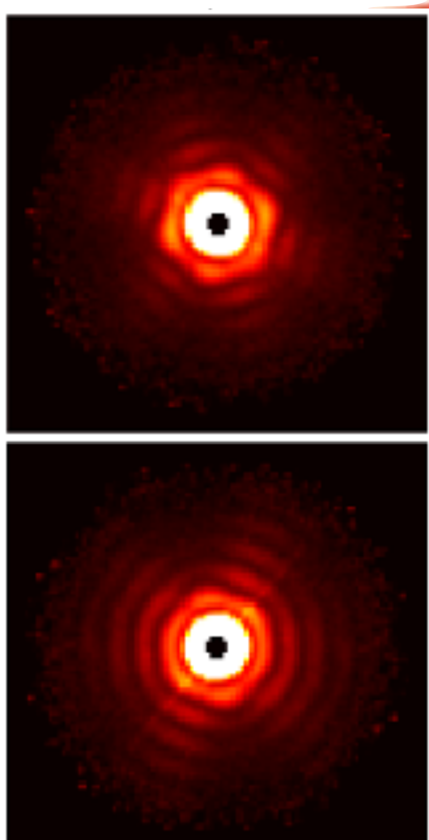
CXI (7 keV)

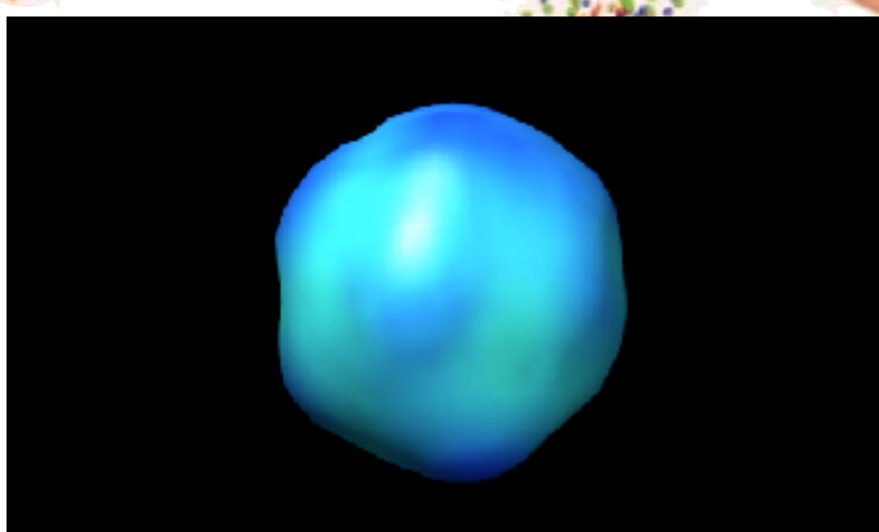


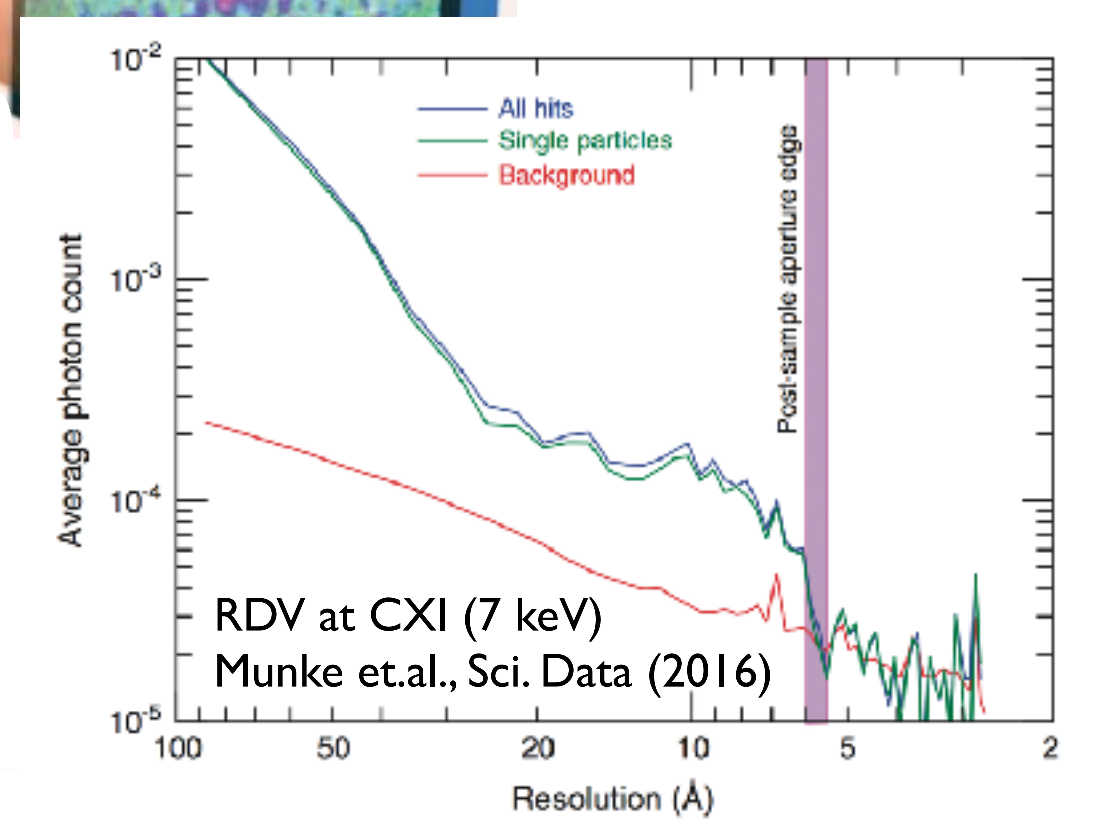

Giant Mimivirus
(450nm diameter)

Rice Dwarf Virus
(70nm diameter)





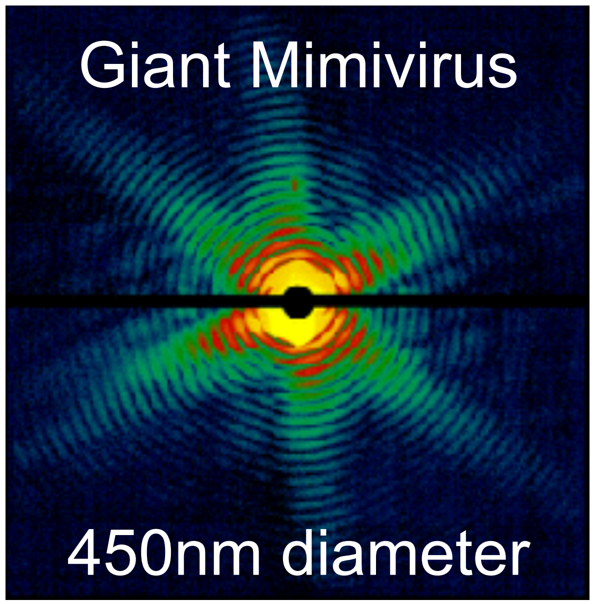
PR772 at AMO (1.6 keV)
(65-70nm diameter)
Kartik Ayyer and Andrew Morgan

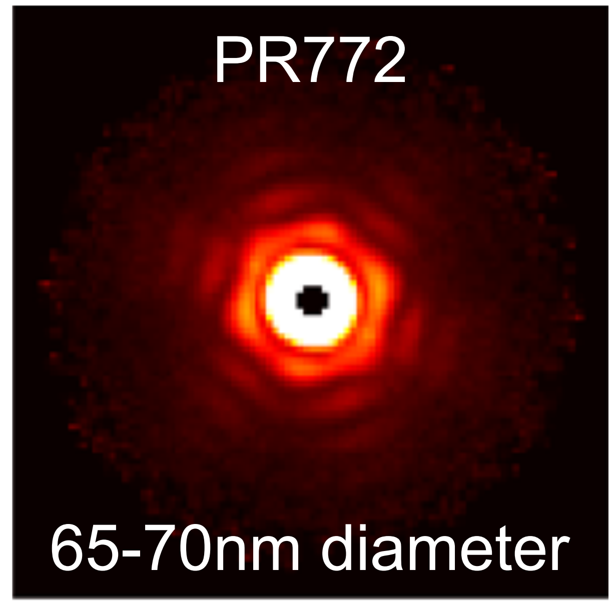



RDV at CXI (7 keV)
Munke et.al., Sci. Data (2016)

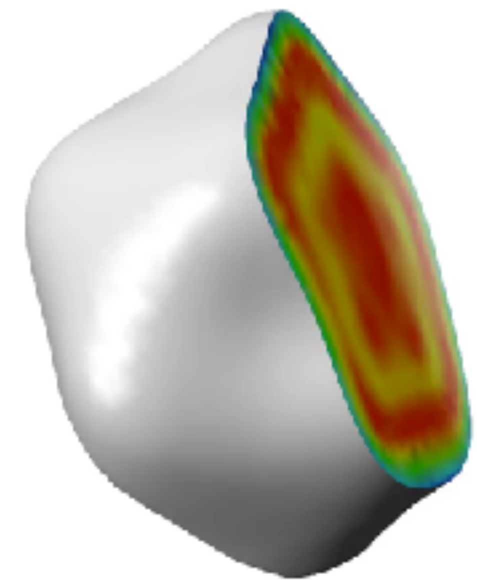
# Single molecule X-ray imaging is making steady progress

Soft X-rays
at 1.8 keV

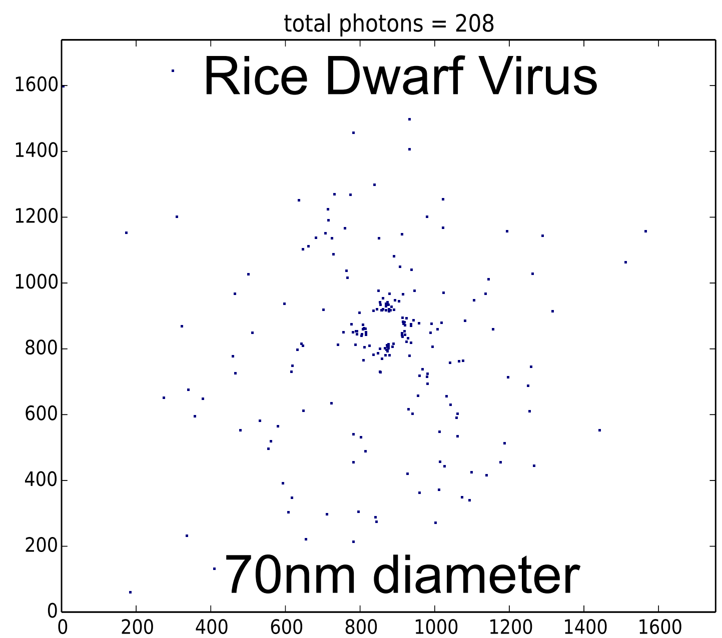


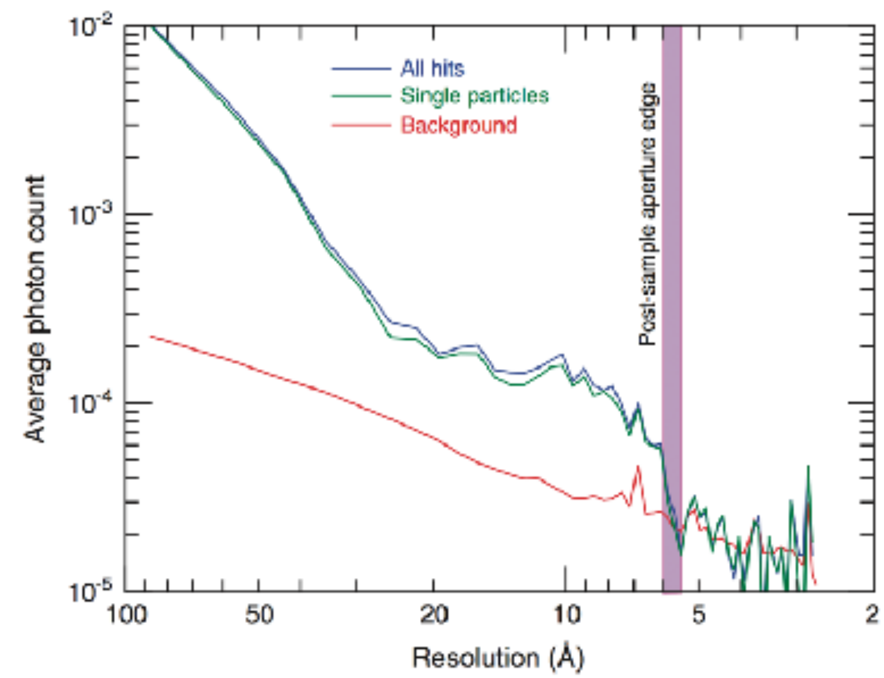




PR772

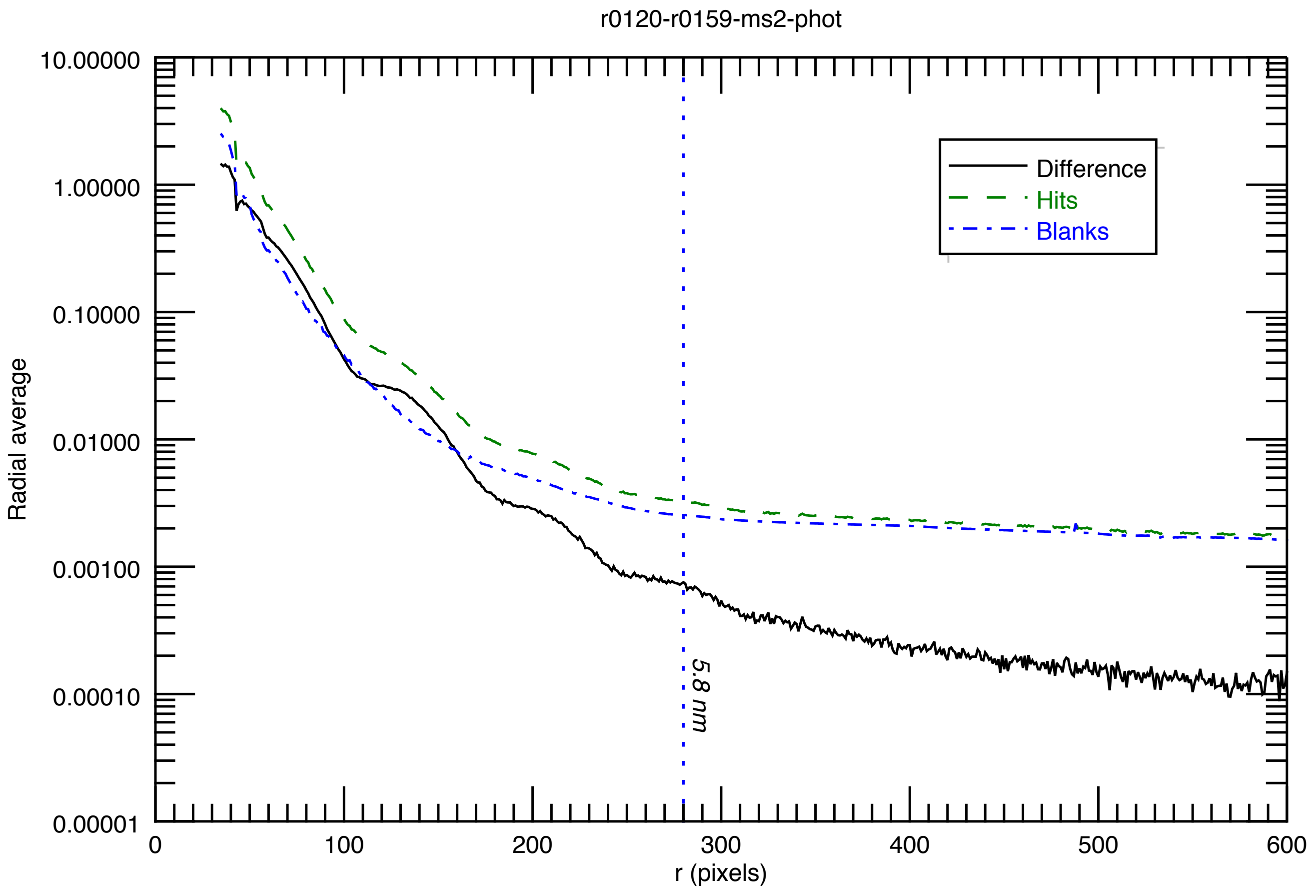


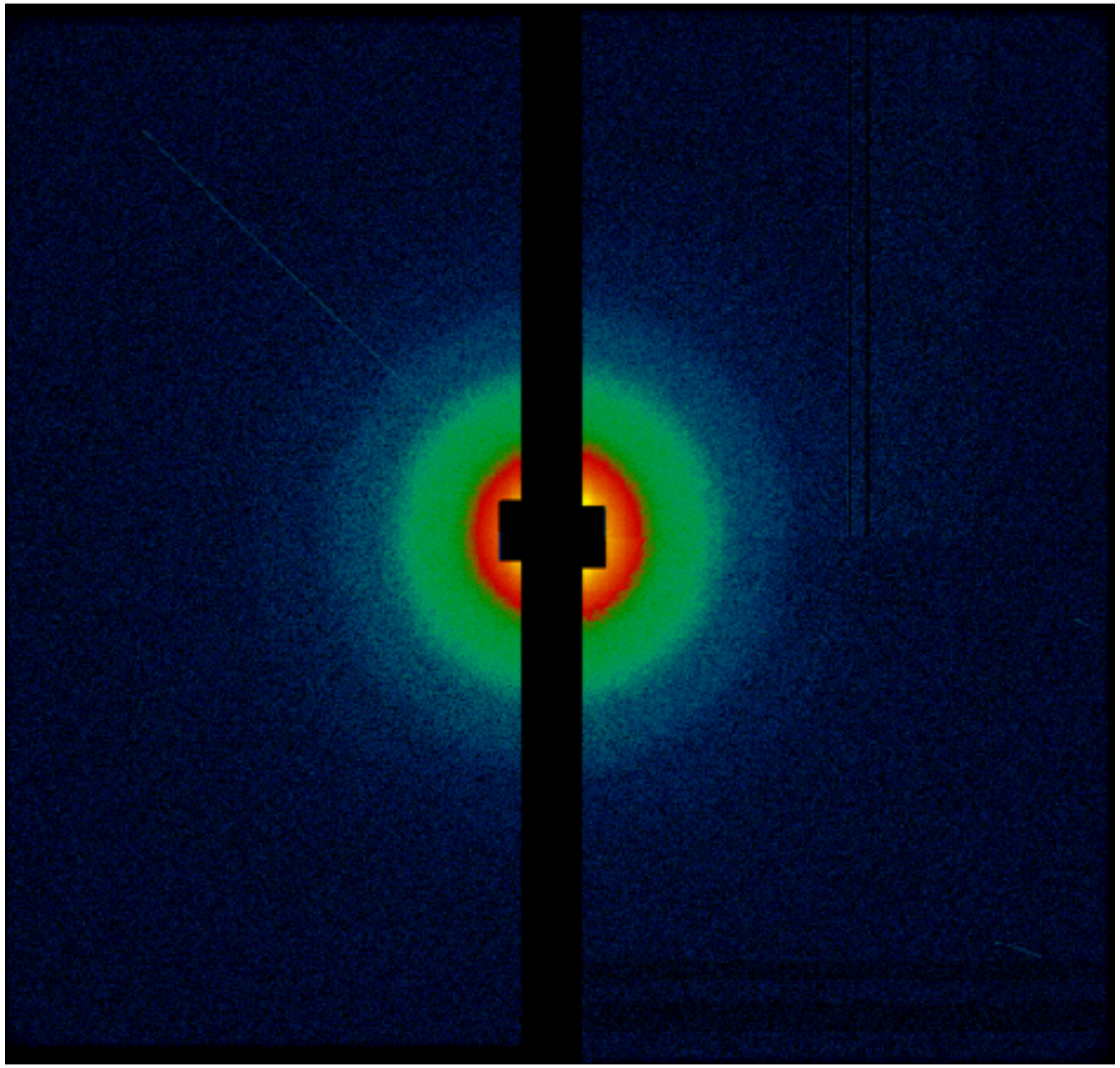
Hard X-rays
at 7 keV

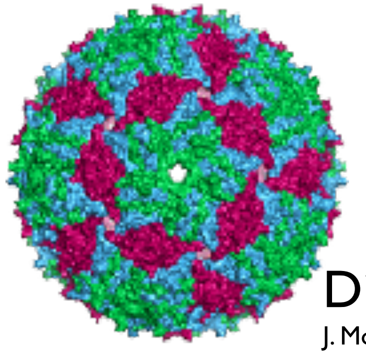


# Diffraction from MS2 virus is weak compared to background



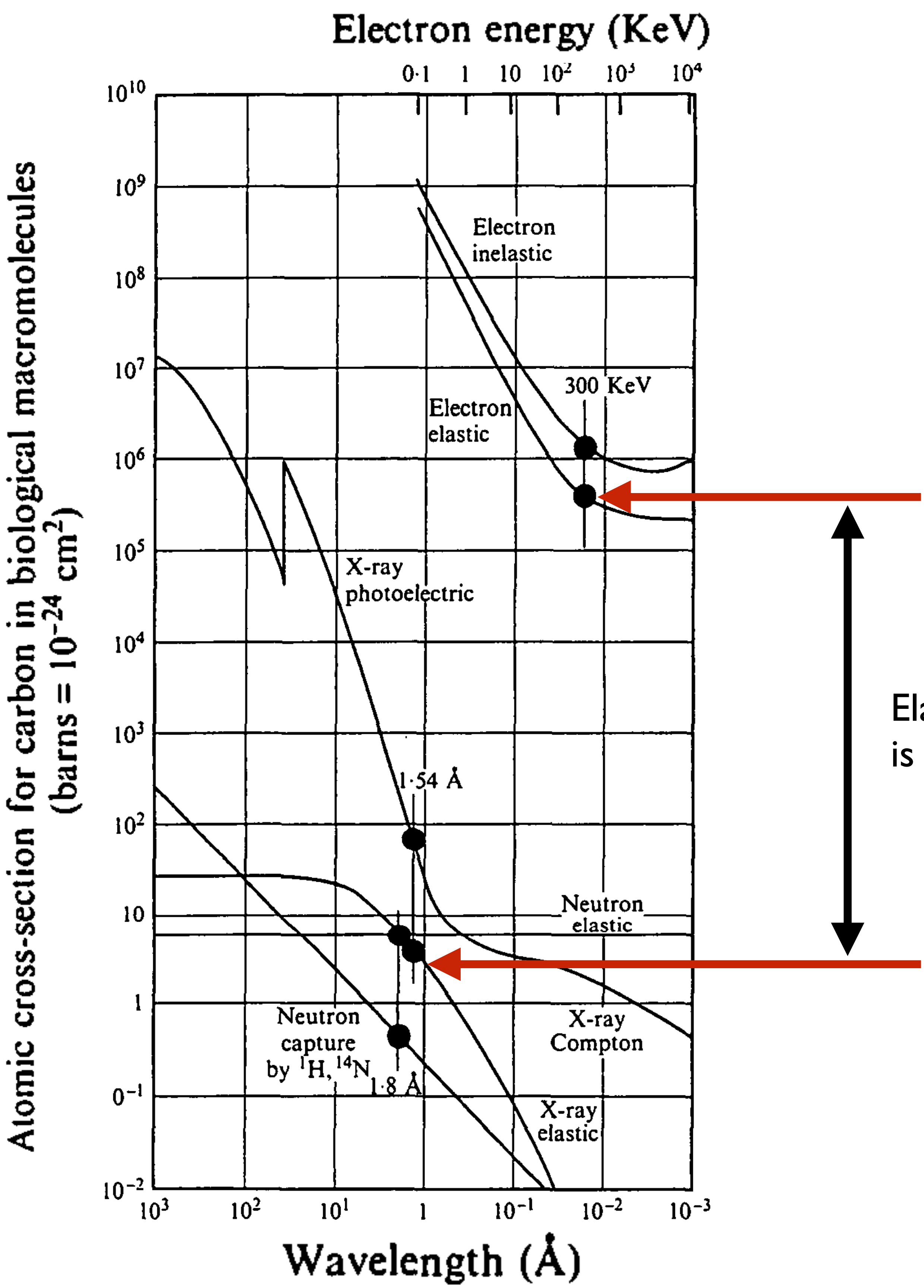


Diameter: ~27nm

J. Mol. Biol. (1963) 7, 43-54

https://en.wikipedia.org/wiki/Bacteriophage_MS2#/media/File:Ms2capsid_surface.png

# Electrons interact more strongly with matter

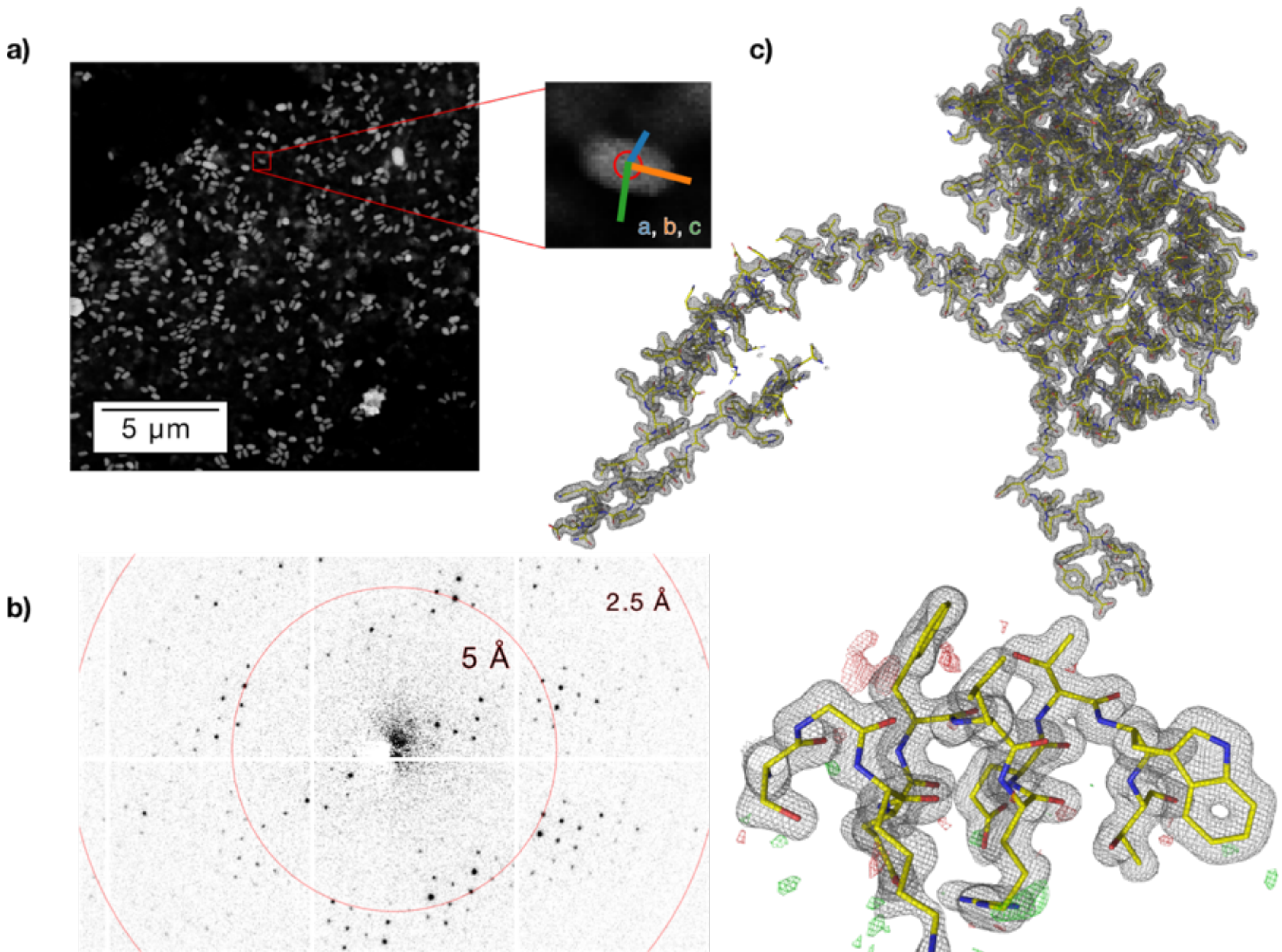



Elastic scattering cross-section is ~$10^5$ higher for electrons

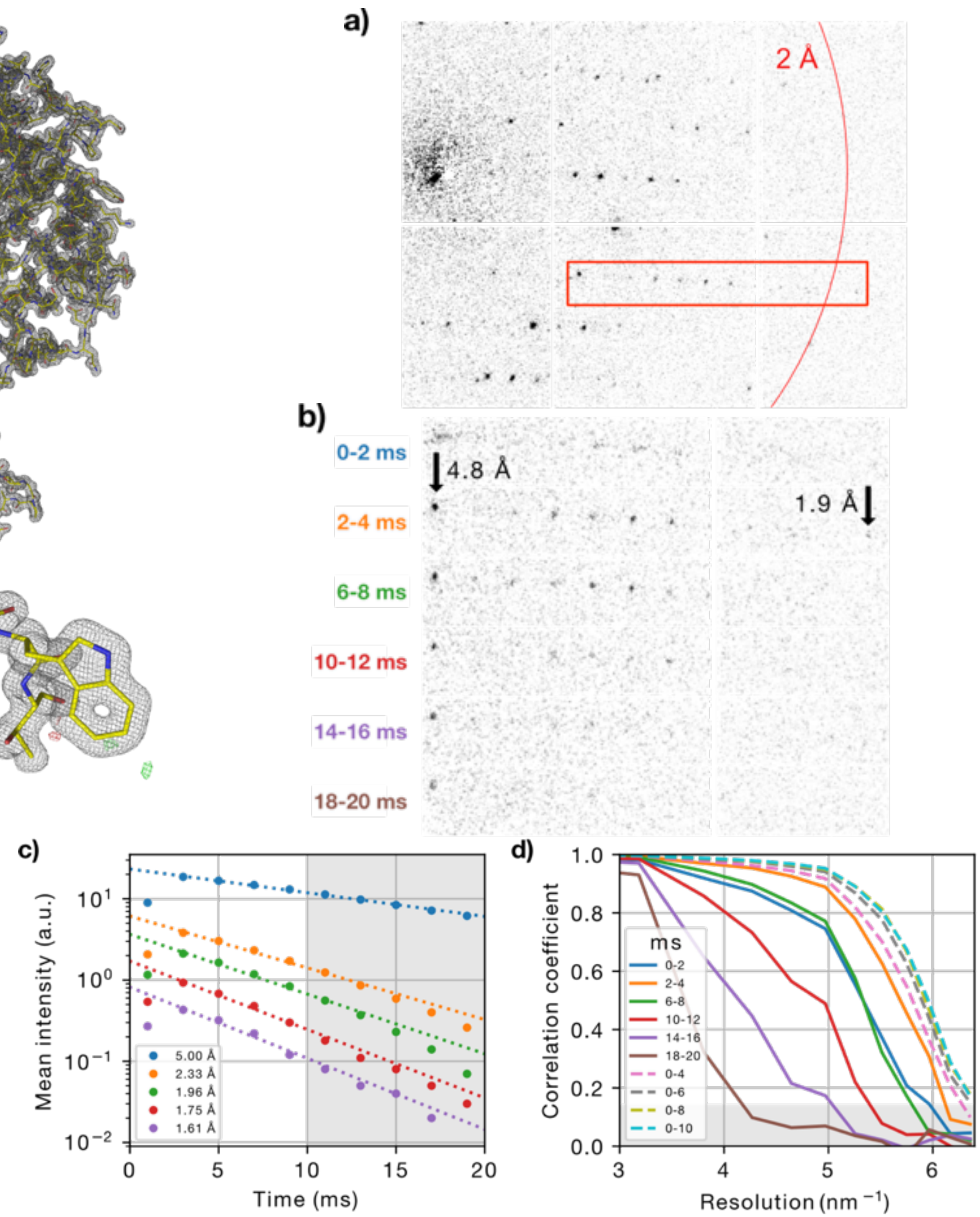
Henderson, R. "The Potential and Limitations of Neutrons, Electrons and X-Rays for Atomic-Resolution Microscopy of Unstained Biological Molecules." Quart. Rev. Biophys. 28, 171–193 (1995).

# We have demonstrated serial crystallography in an ordinary TEM

Granulovirus electron density solved to 1.55Å resolution



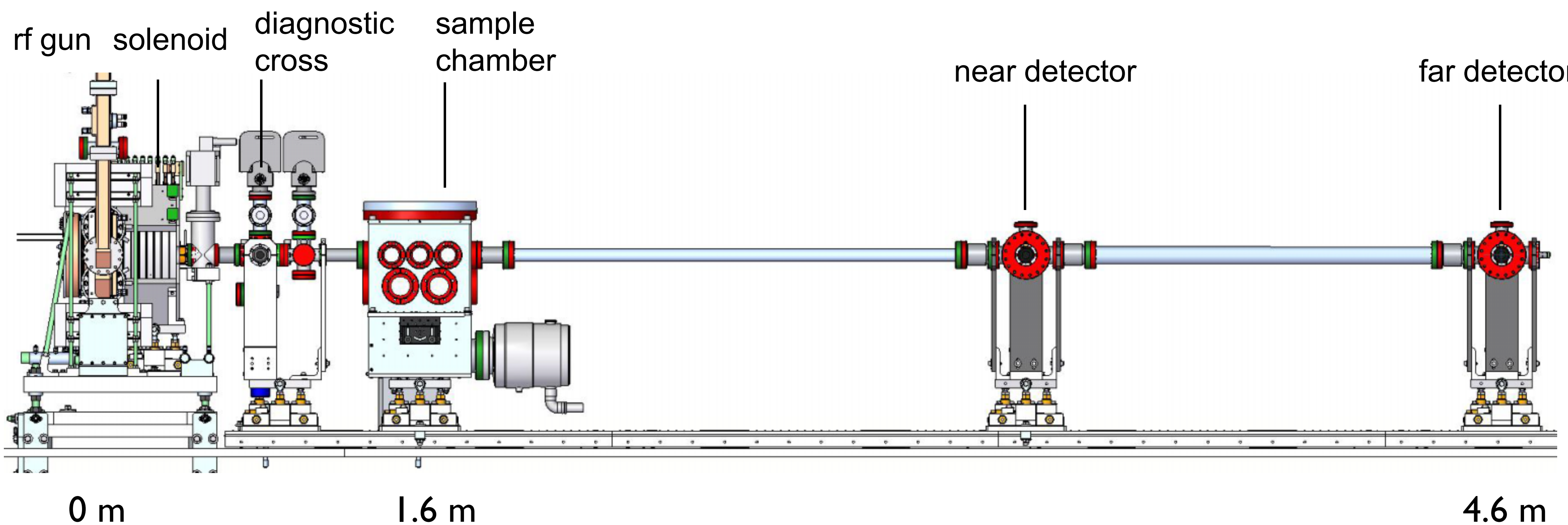

Spot fading due to accumulated dose




Optimal data quality was reached for summation of the first five movie frames, corresponding to an exposure time of 10 ms, and an integrated dose of ≈ 4.7 e-/Å$^2$

Bücker et.al., N.Comms (submitted)

# The femtosecond MeV electron diffraction facility at SLAC




**Source Parameters**

| Parameter | Value |
|---|---|
| Electron beam energy | 2 - 4 MeV |
| Repetition rate | Single shot → 360 Hz |
| Charge per pulse | 1 - 100 fC ($10^4$ - $10^6$ electrons) |
| Beam emittance | 2 - 20 nm-rad |
| Bunch length | <150 fs FWHM* |
| Momentum resolution | <0.17Å$^{-1}$ |
| Beam spot size | 100-200 um (typical), 10 um (FWHM) focused |

Estimate for single shot protein diffraction:

$10^6$-$10^7$ electrons per pulse into a ~1μm focus (crystal size)

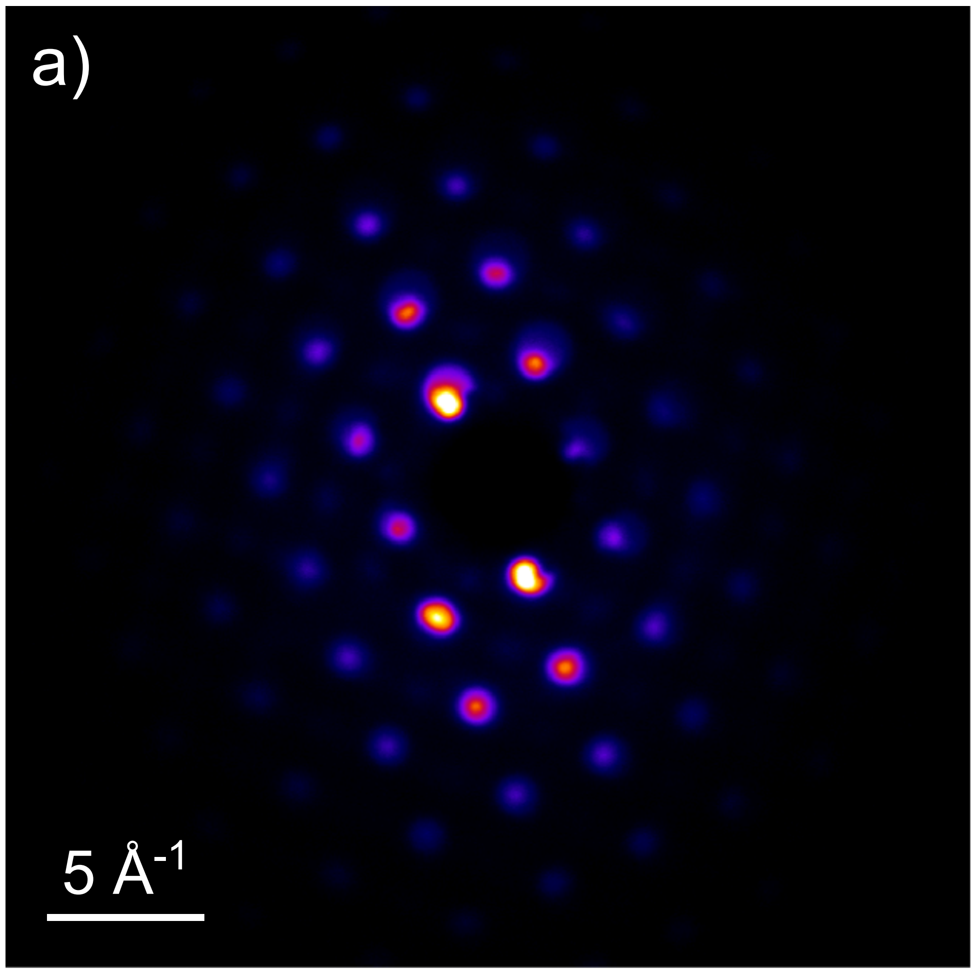
transverse coherence ~10-20nm (unit cell size)

1 C ~ 6.2 x $10^{18}$ electrons
1 fC ~ 6x$10^3$ electrons
1 pC ~ 6x$10^6$ electrons

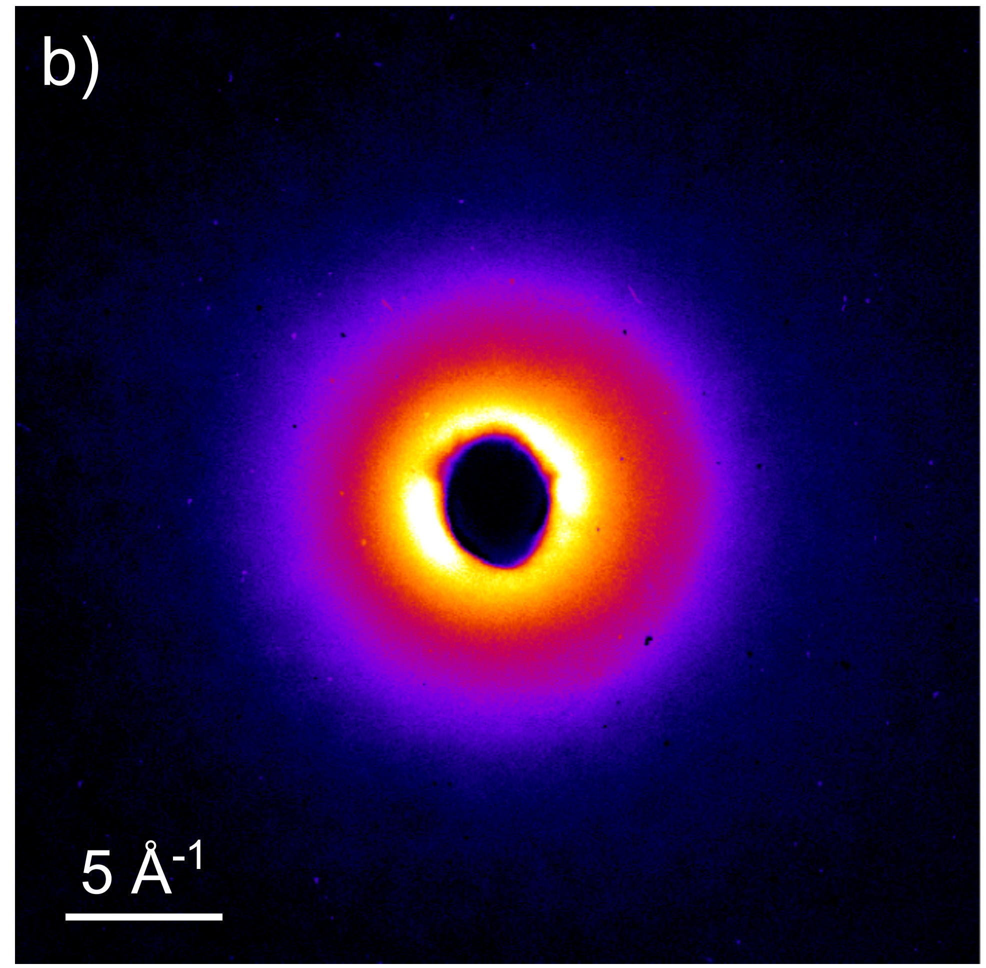
"Mega-electron-volt ultrafast electron diffraction at SLAC National Accelerator Laboratory"
Weathersby et.al. Rev.Sci.Instrum. **86**, 073702 (2015)

# First results from femtosecond MeV electron diffraction

Gold




$N_2$ Gas

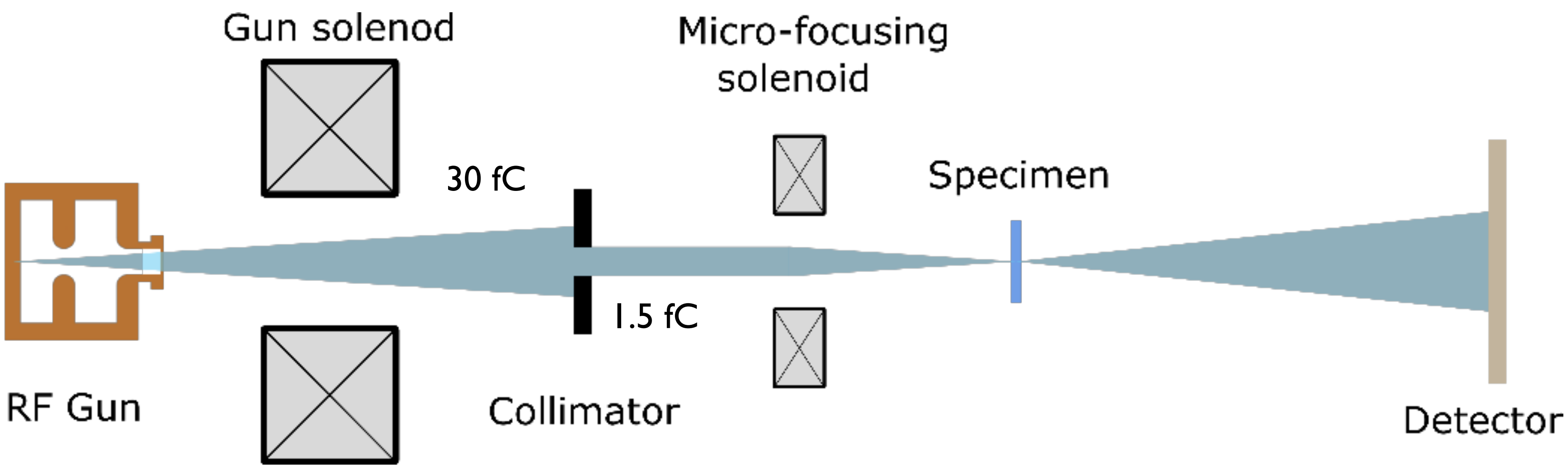



$N_2$ density: $2x10^{17}$ $cm^3$ and effective thickness of 300 μm.

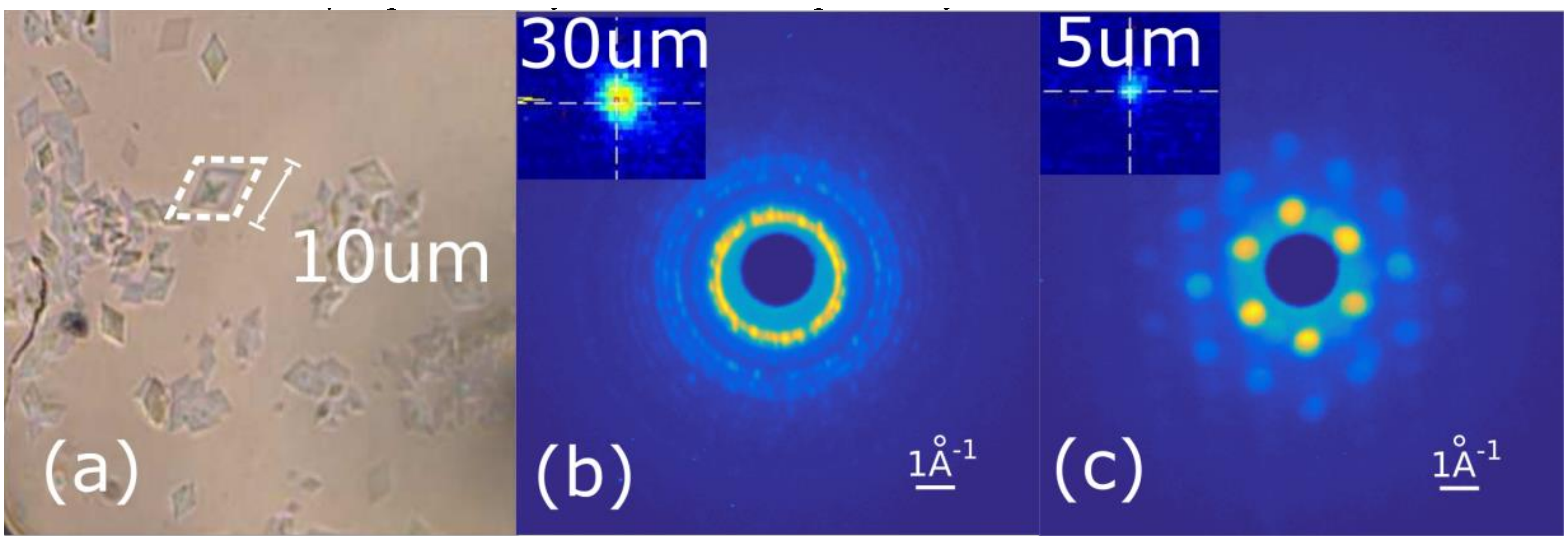
Total number of incident electrons is $2x10^9$
Total exposure time of 300 s is required at 10-fC bunch charge and 120 Hz repetition rate


"Mega-electron-volt ultrafast electron diffraction at SLAC National Accelerator Laboratory"
Weathersby et.al. Rev.Sci.Instrum. **86**, 073702 (2015)

# Spot size can be reduced by focussing at the expense of flux




UED diffraction from 10 μm paraffin crystals



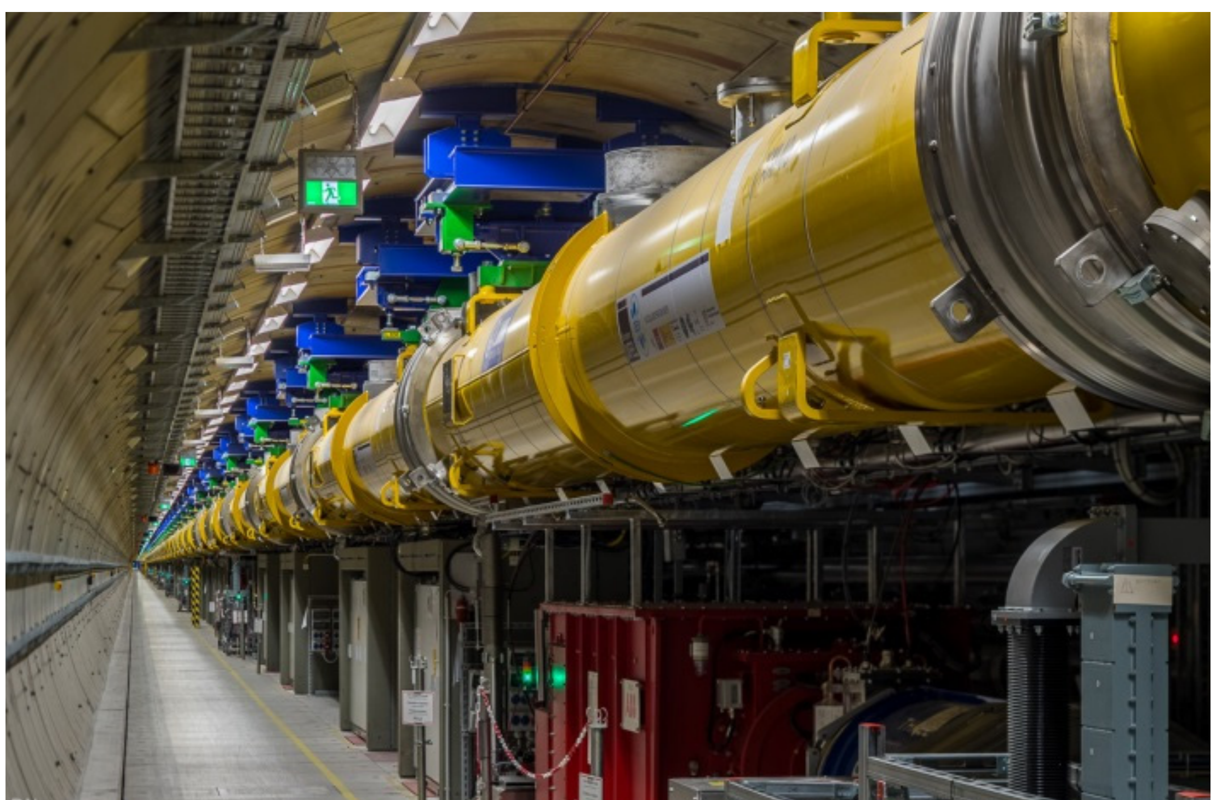

Shen et.al. "Femtosecond mega-electron-volt electron microdiffraction" Ultramicroscopy **184**, 172–176 (2018).

# The European XFEL injector is designed for higher bunch charge


Table 1: Injector Parameters

| Parameter | Design | Achieved |
|---|---|---|
| RF pulse rep. rate [Hz] | 10 | 10 |
| RF flat top [µs] | 650 | 650 |
| Bunches/RF pulse | 2700 | 2700 |
| Bunch charges [pC] | 20-1000 | 20-1000 |
| Proj. emittance @ 500 pC [mm mrad] | | 1.2 |
| Slice. emittance @ 500 pC [mm mrad] | 0.6 | 0.6[1] |

European XFEL design:
Nominal bunch charge: 20-1000 pC at 2-100 fs
$10^7$-$10^9$ electrons



W. Decking, H. Weise, "Commissioning of the European XFEL accelerator"
https://accelconf.web.cern.ch/AccelConf/ipac2017/papers/moxaa1.pdf

REGAE

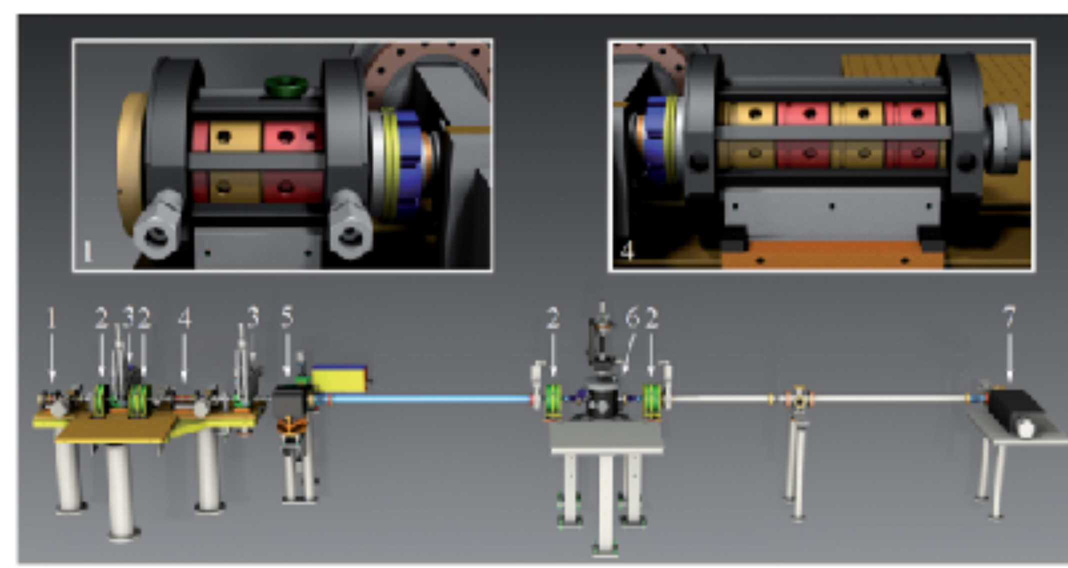
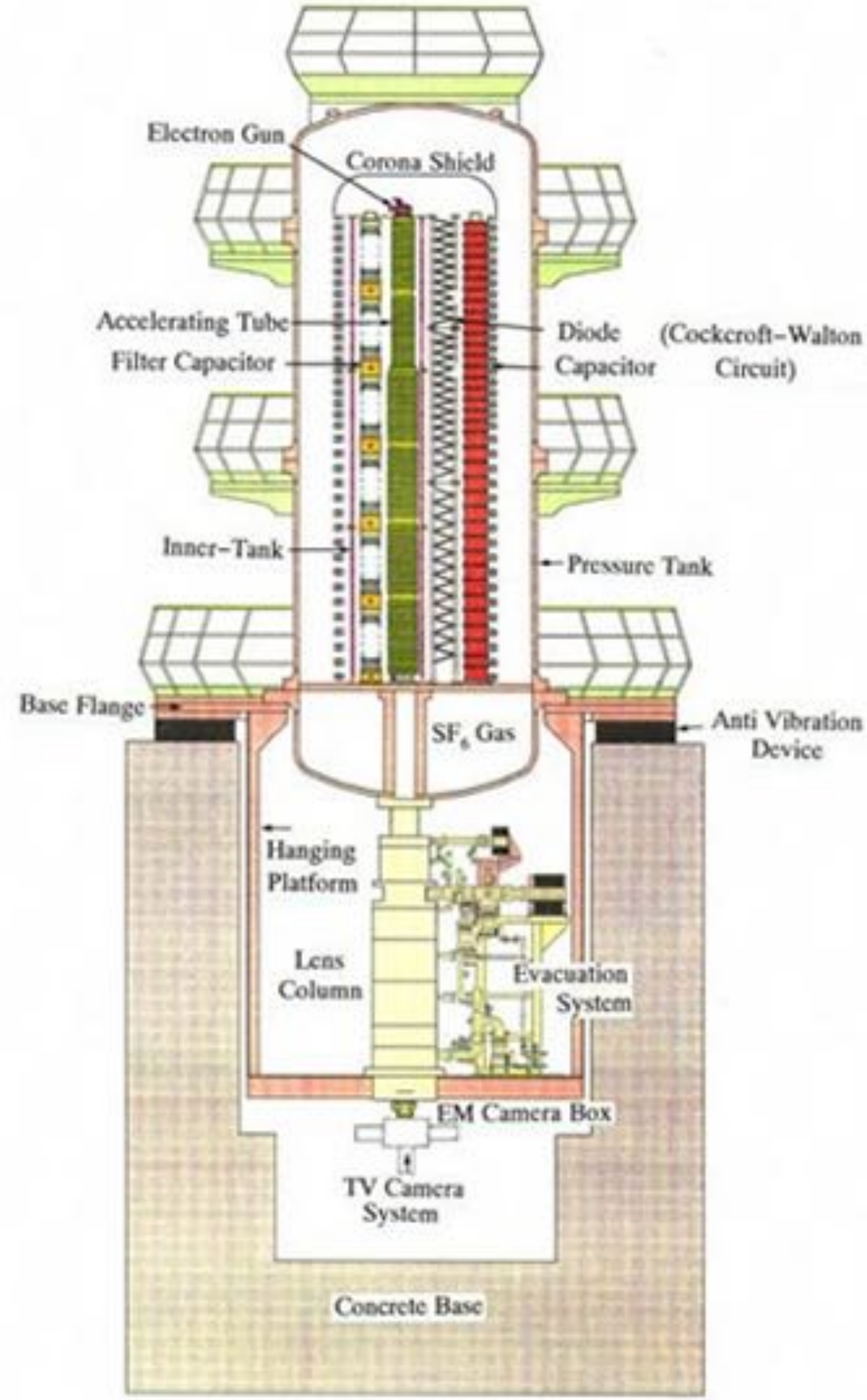


Fig. 3 REGAE scheme. Indicated with numbers are: (1) gun cavity, (2) solenoids, (3) collimators, (4) rebunching cavity, (5) dipole for electron energy measurements, (6) target interaction chamber, and (7) detector.

100 fC/pulse (<1e6 electrons)

# 3 MeV electron microscopes do exist

3 MeV TEM
Osaka University

# Acknowledgement to the fantastic staff at European XFEL




*Source: Robert Feidenhans'l*

# And to the fantastic Accelerator Staff




*Source: Robert Feidenhans'l*

# The first EuXFEL experiment at SFX/SPB was an open collaboration with over 100 participants

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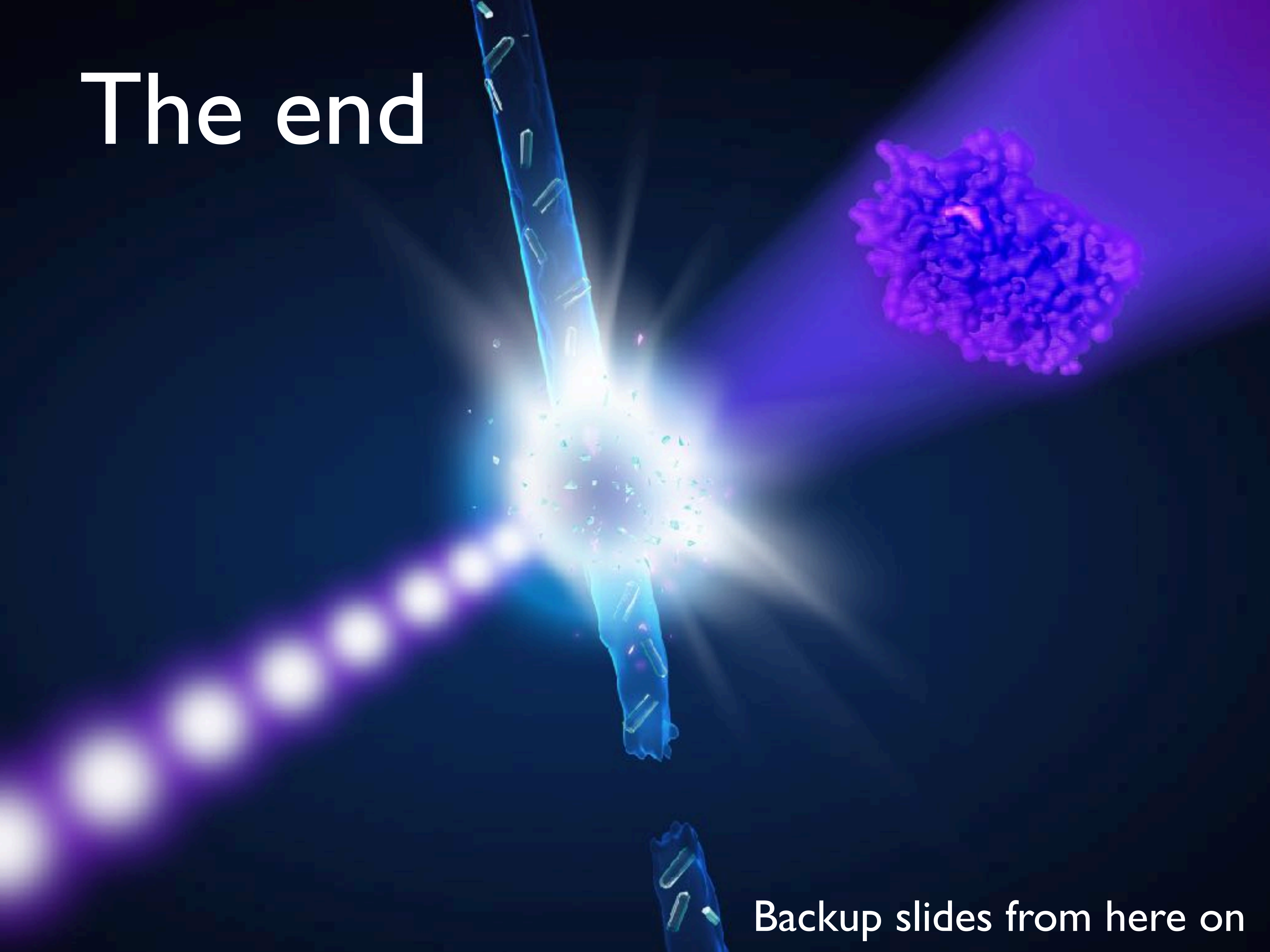
# FS-CFEL-1 group photo at DESY

# A fly through the European XFEL tunnels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