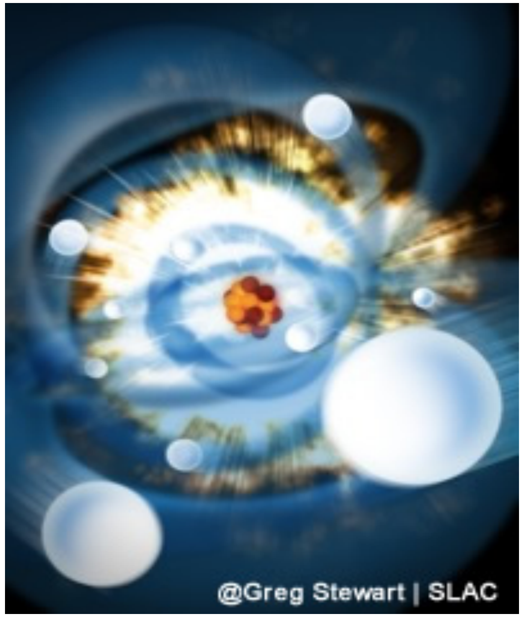
Harnessing ultra-intense x-rays for dynamic imaging

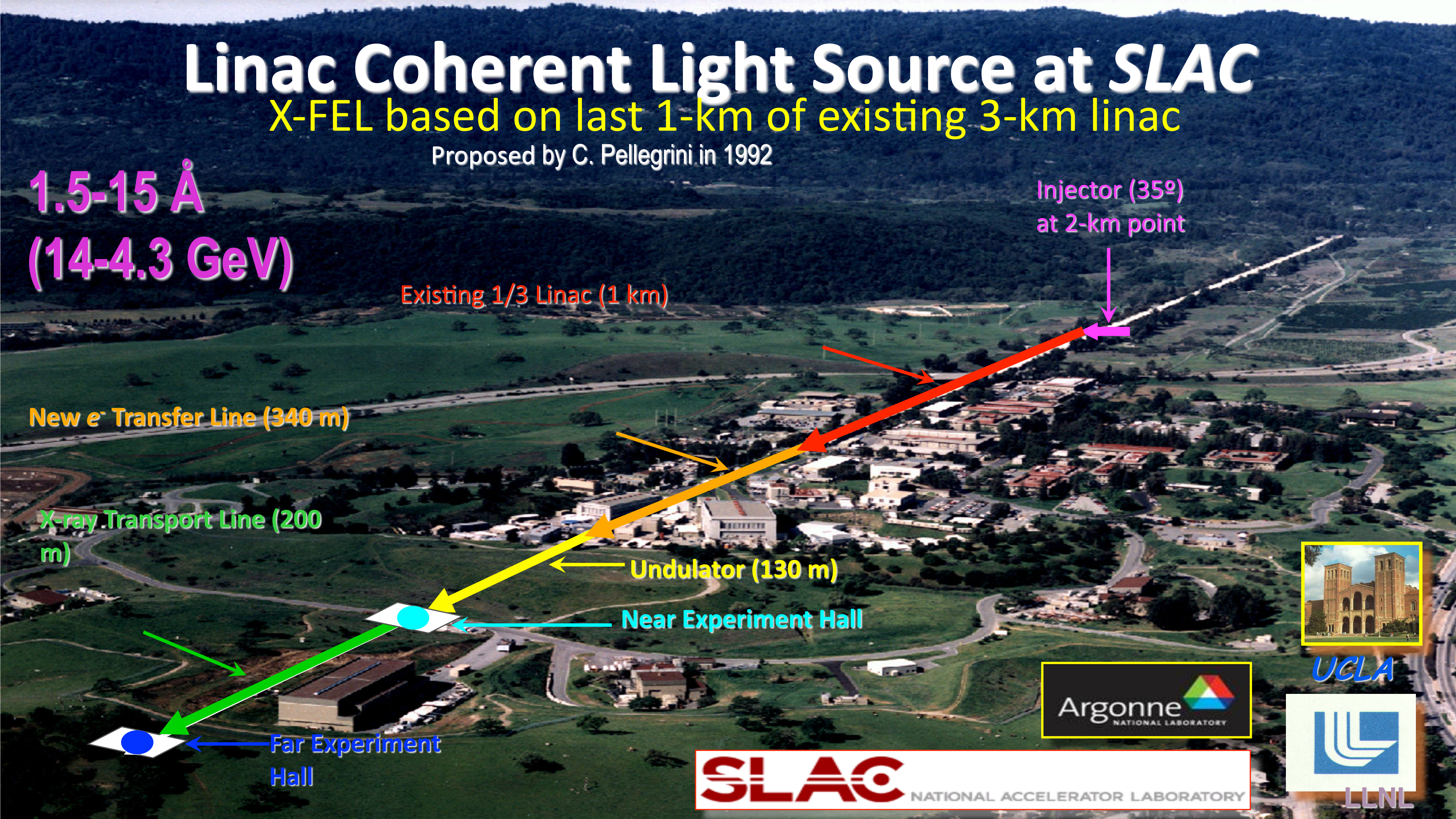


Linda Young

30th International Conference on Photonic, Electronic and Atomic Collisions
Cairns, Queensland, Australia
26 Jul - 1 Aug 2017

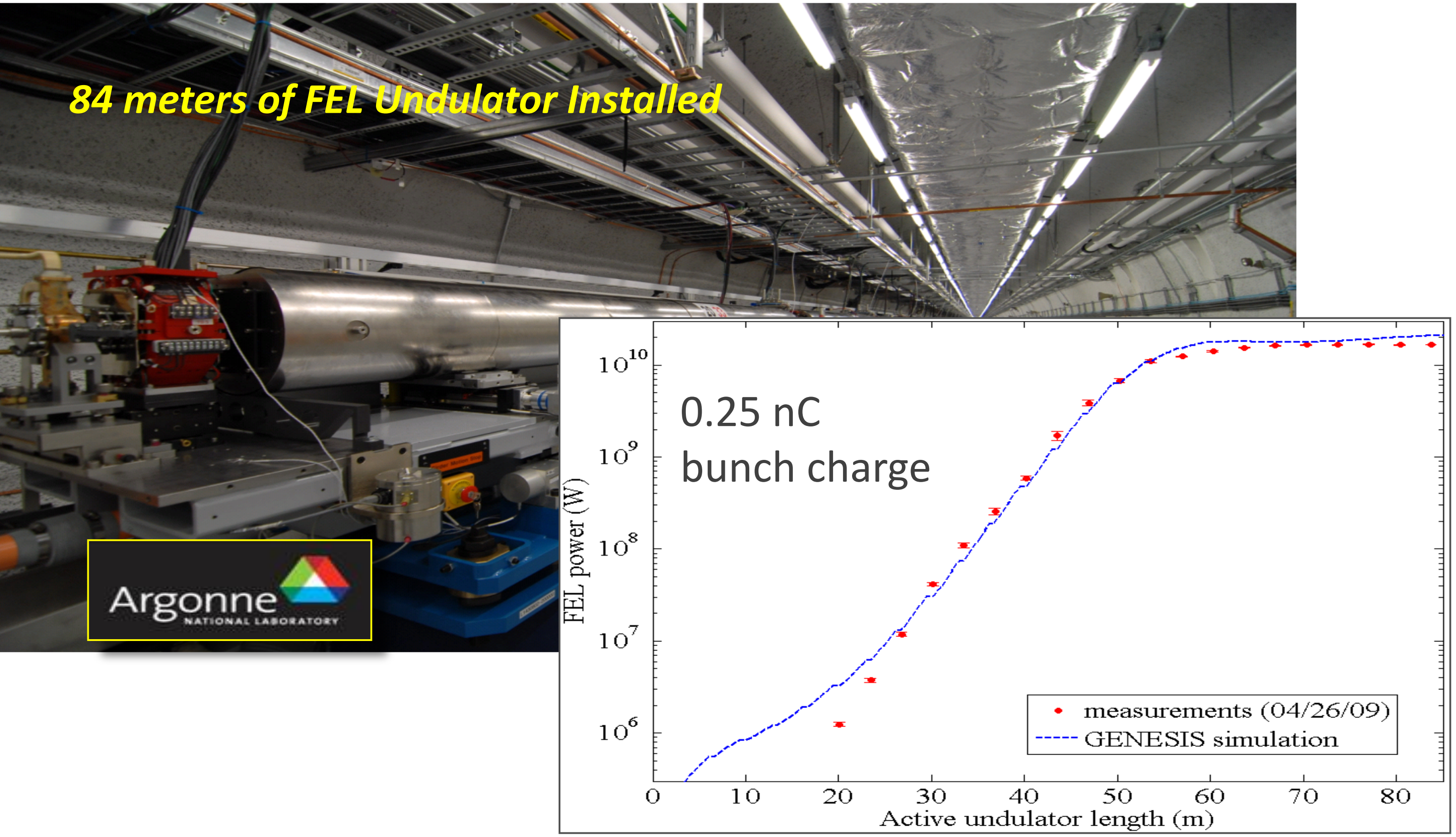
Outline

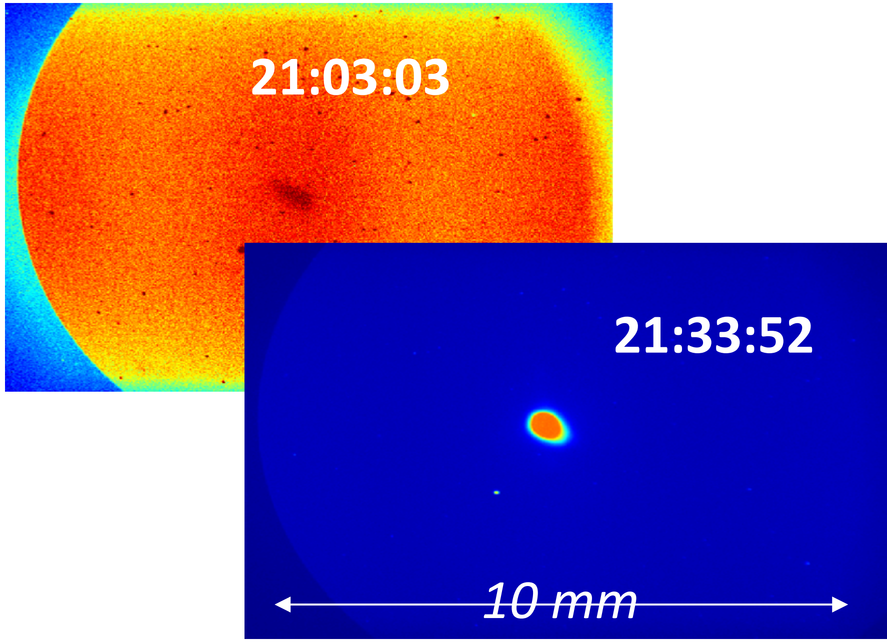
- Birth of world’s first hard x-ray FEL - LCLS
- Non-resonant high intensity x-ray phenomena
  - Atoms: Ne, Ar, Kr, Xe
- Resonant high intensity x-ray processes
  - Rabi flopping, stimulated Raman
- Towards single particle imaging --- with hard x-rays & also water window
- New XFEL capabilities



Linac Coherent Light Source at SLAC
X-FEL based on last 1-km of existing 3-km linac
Proposed by C. Pellegrini in 1992
1.5-15 Å
(14-4.3 GeV)
Injector (35º)
at 2-km point
Existing 1/3 Linac (1 km)
New e⁻ Transfer Line (340 m)
X-ray Transport Line (200 m)
Undulator (130 m)
Near Experiment Hall
Far Experiment Hall
UCLA
Argonne NATIONAL LABORATORY
SLAC NATIONAL ACCELERATOR LABORATORY
LLNL

April 10, 2009: LCLS lases at 1.5Å

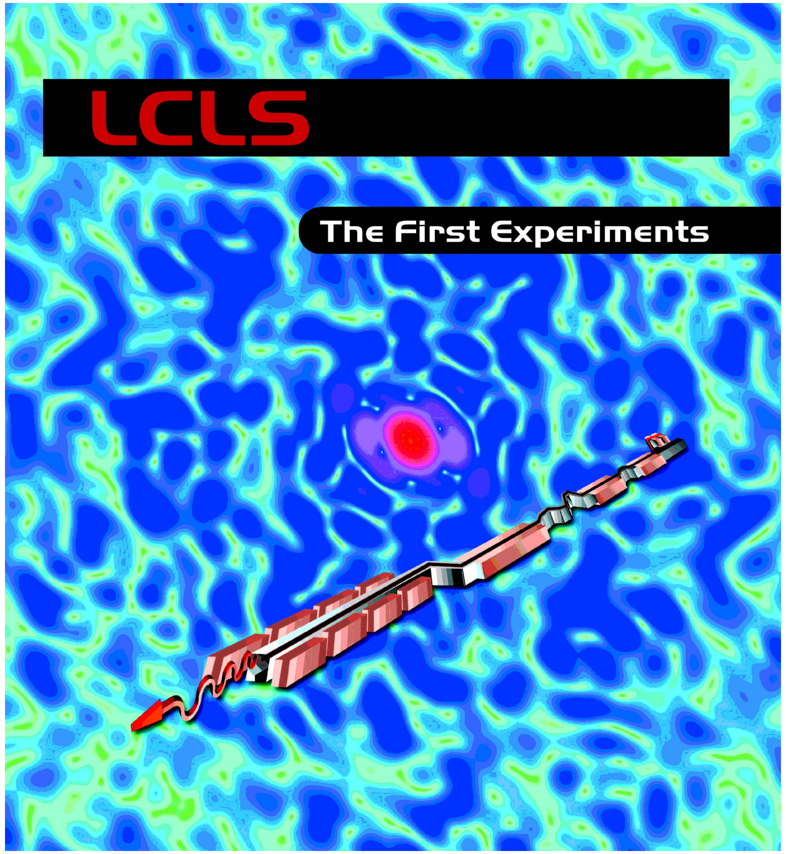




- Saturation after ~65 meters of undulator!
- Alignment req'd 5 microns over 100 m

Yes I Do Smile on Occasion

Science Drivers for LCLS



AMO: Atomic Molecular and Optical

SXR: Soft X-ray Materials Science

XPP: X-ray Pump-Probe

XCS: X-ray Correlation Spectroscopy

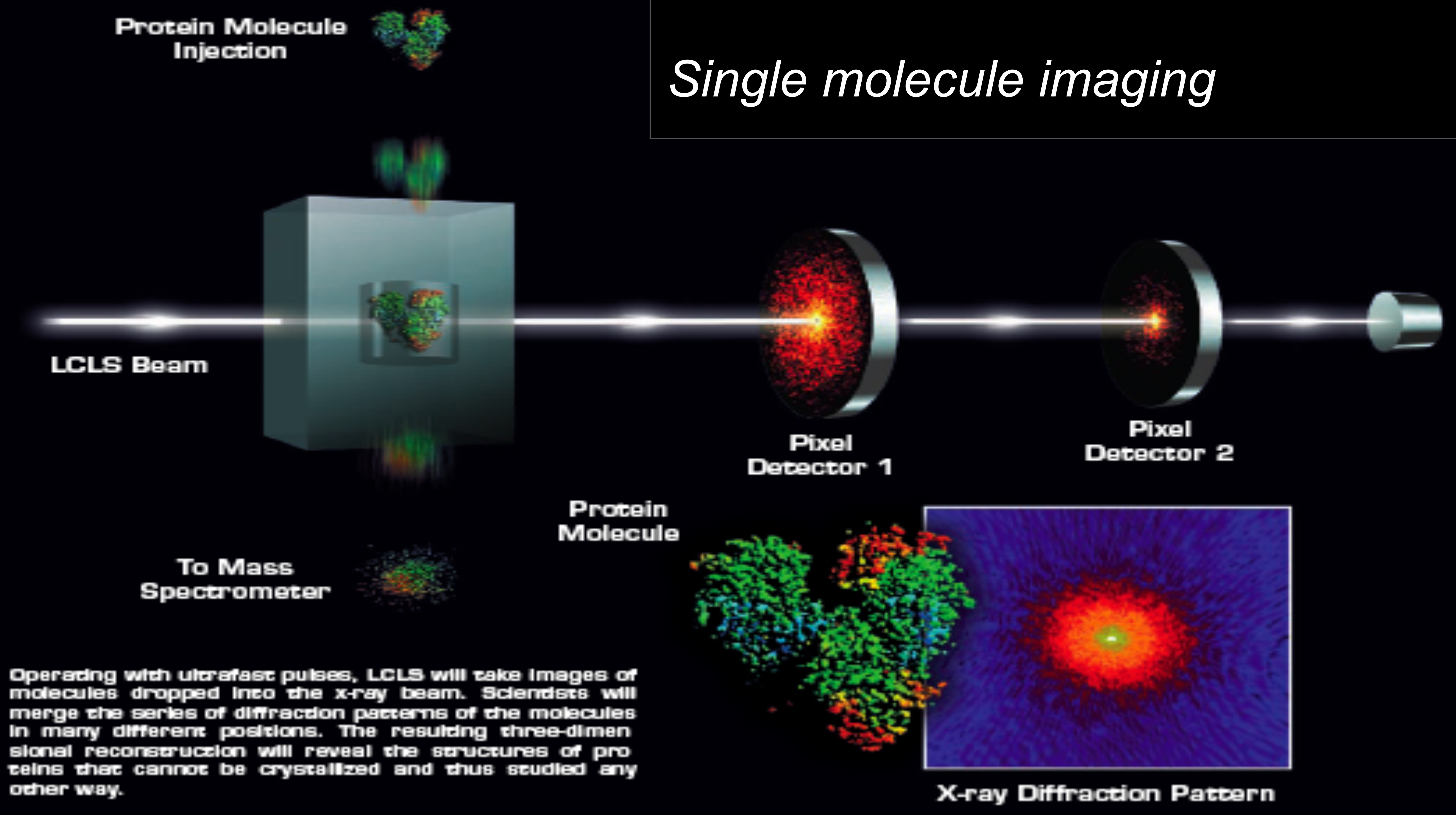
CXI: Coherent X-ray Imaging

MEC: Materials in Extreme Conditions

AMO

- Understand and control x-ray atom/molecule interactions at ultrahigh x-ray intensity as a foundation for other applications.
- Provide diagnostics of the LCLS radiation

Single molecule imaging

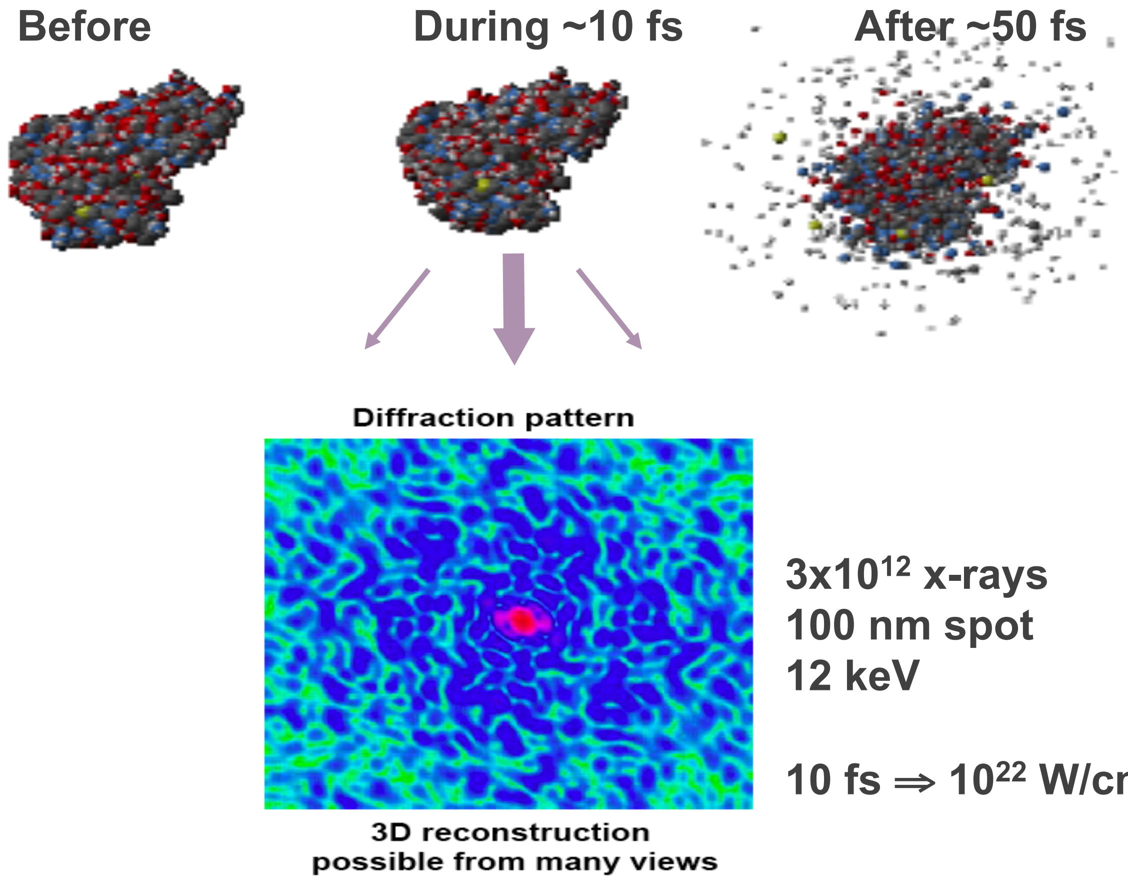


AMO questions at the ultraintense x-ray frontier

- fundamental nature of x-ray damage at high intensity
  - -Coulomb explosion
  - -electronic damage
  - -behavior at 10^{22} W/cm^2 - 1Å

- nonlinear x-ray processes
  role of coherence

- quantum control of inner-shell processes



$3\text{x}10^{12}$ x-rays
100 nm spot
12 keV

10 fs $\Rightarrow 10^{22}$ W/cm^2

Neutze, Wouts, van der Spoel, Weckert, Hajdu   Nature 406, 752 (2000)

LCLS Experiment 1 - Oct 1, 2009

Nature of the electronic response to

10^5 x-rays/Å^2

80 - 340 fs

800 - 2000 eV

$\sim 10^{18}$ W/cm^2

Original single molecule imaging parameters, Neutze et al. Nature (2000)

3×10^{12} x-rays/(100 nm)^2 = 3×10^6 x-rays/Å^2

10 fs

$\sim 10^{22}$ W/cm^2

Our approach to understanding ultraintense x-ray interactions

- Start with a well-characterized target

Binding energies in neutral neon

2p : ~21 eV

2s : ~48 eV

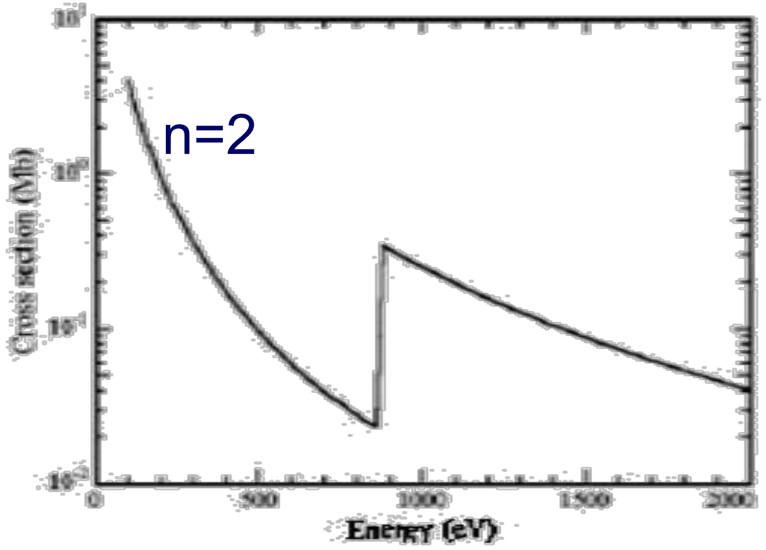
1s : ~870 eV

Inner-shell excitation

Auger yield 98%

Auger clock - τ_{1s}: 2.4 fs

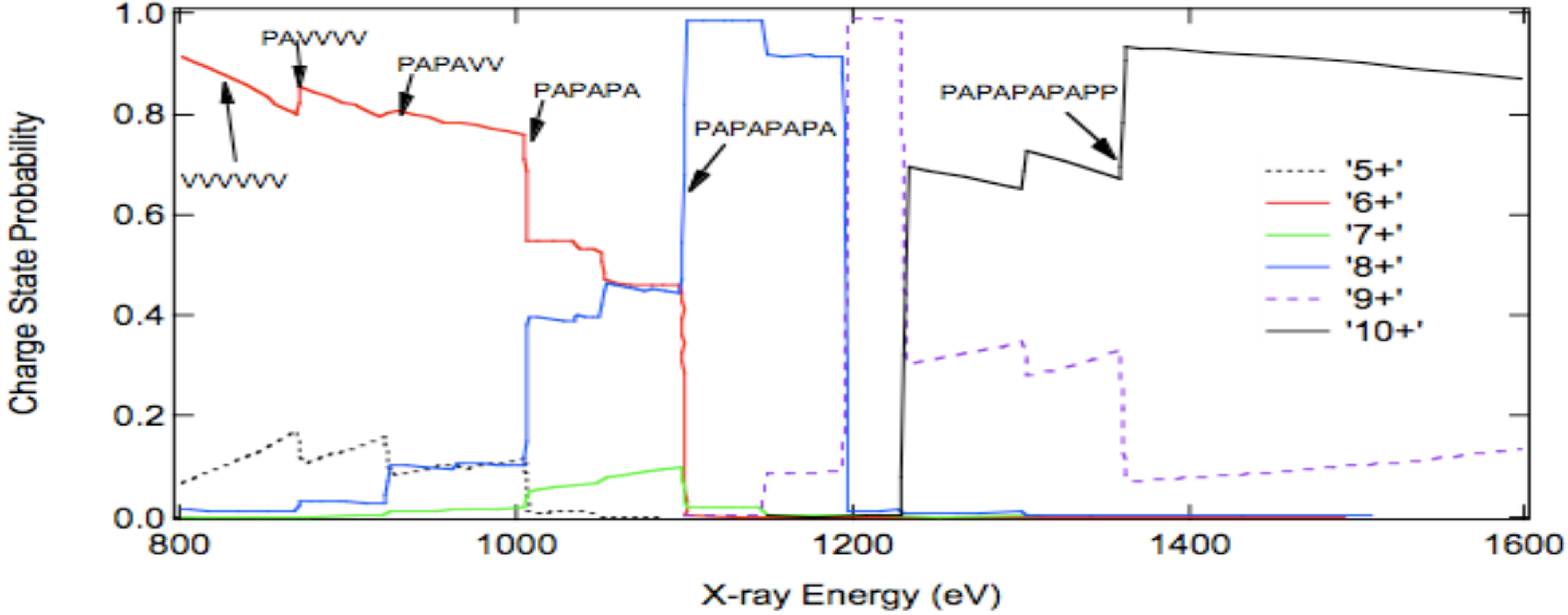
neon photoabsorption



- Probe changes in interaction from outer- to inner-shell between 800-2000 eV

Guided by theory

Theory: Rohringer & Santra, PRA 76, 033416 (2007)



LCLS specs

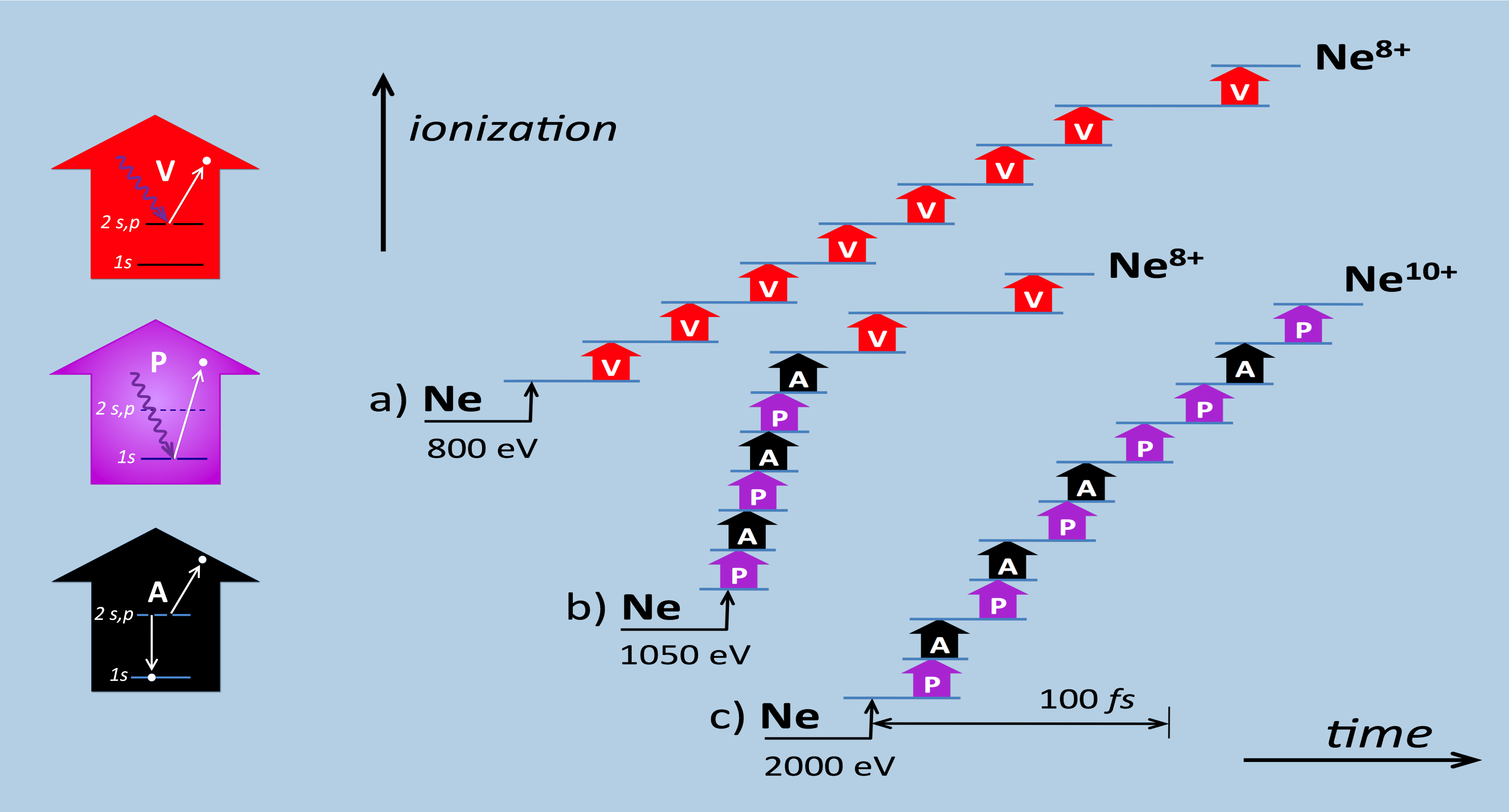
10^{13} x-rays

230 fs

1 μm spot

Three target energies: 800 eV, 1050 eV, 2000 eV

Valence ionization, core ionization and Auger decay

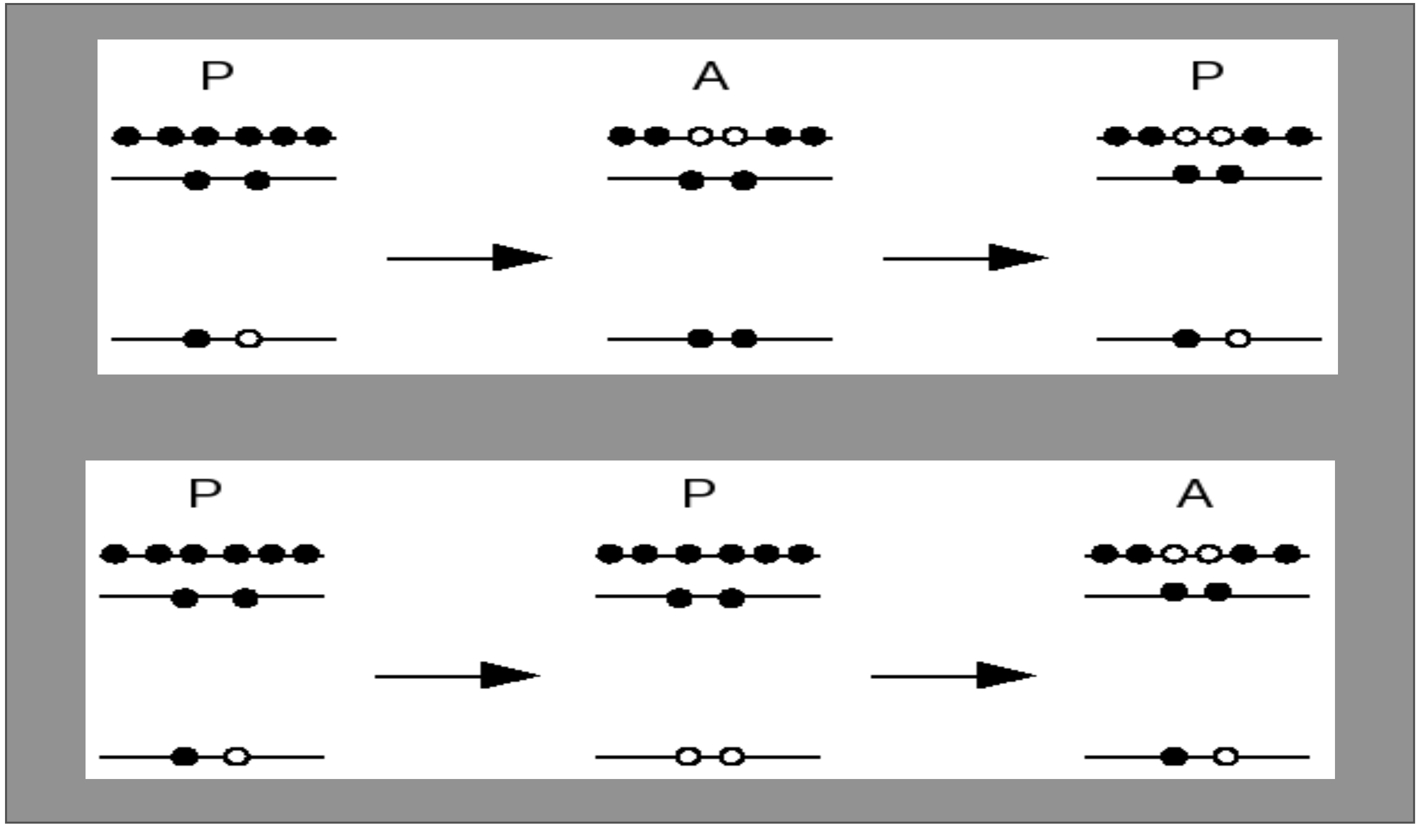


Sequential single photon processes dominate the interaction

How does one arrive at a particular charge state?

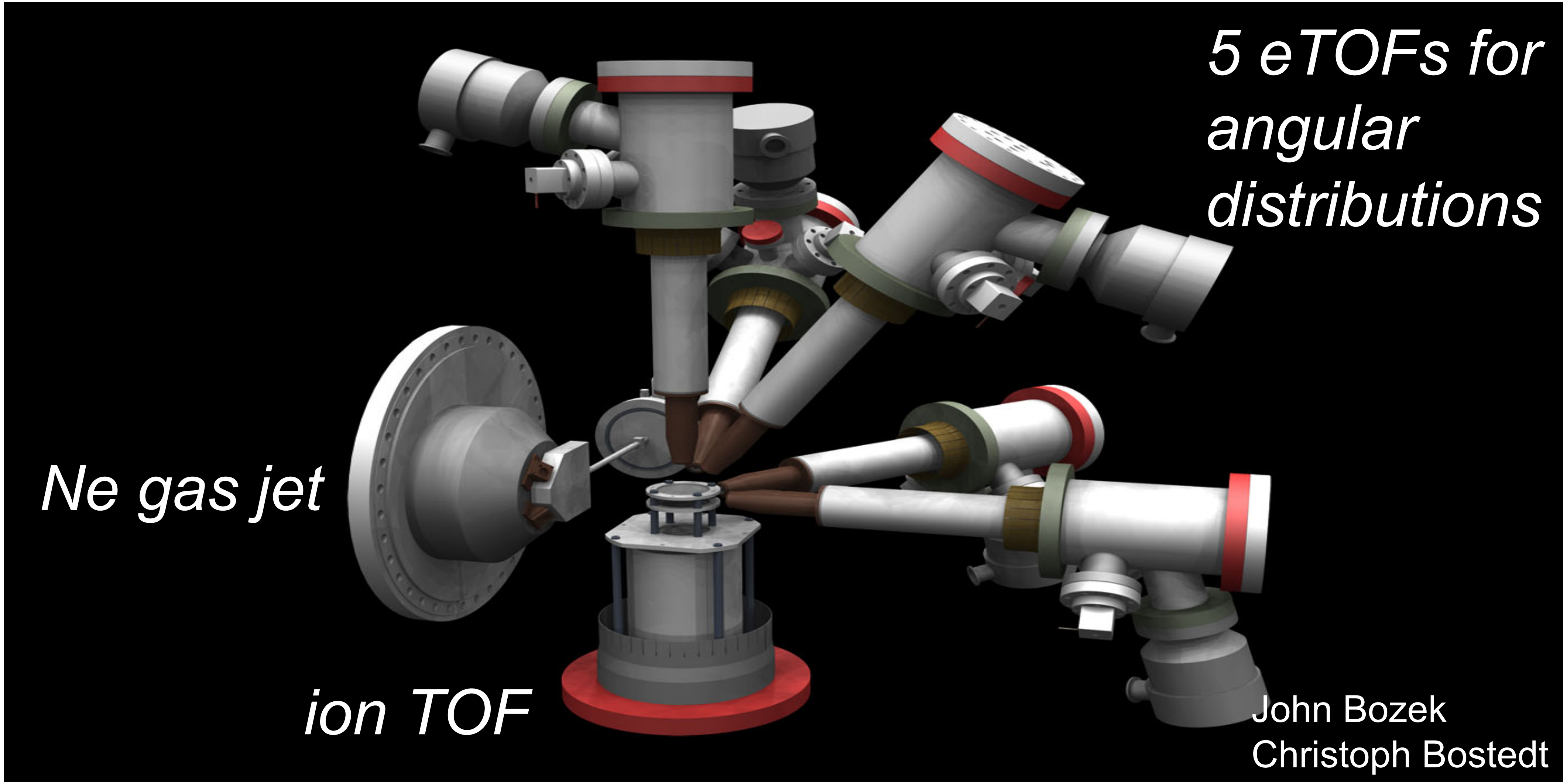
Low Intensity
PAP

High Intensity
PPA



- Hollow atoms produced at high x-ray intensity
- Electron spectroscopy can define the mechanism

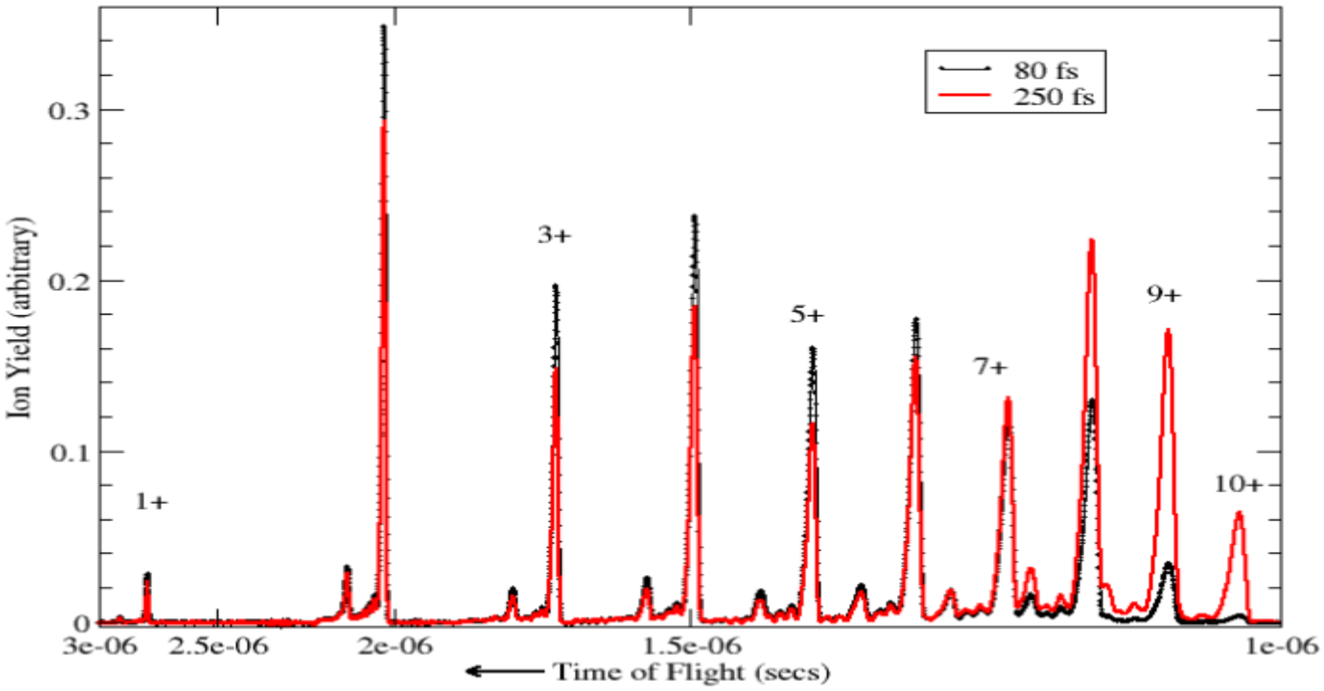
High field physics chamber



Day 1 – two interesting observations

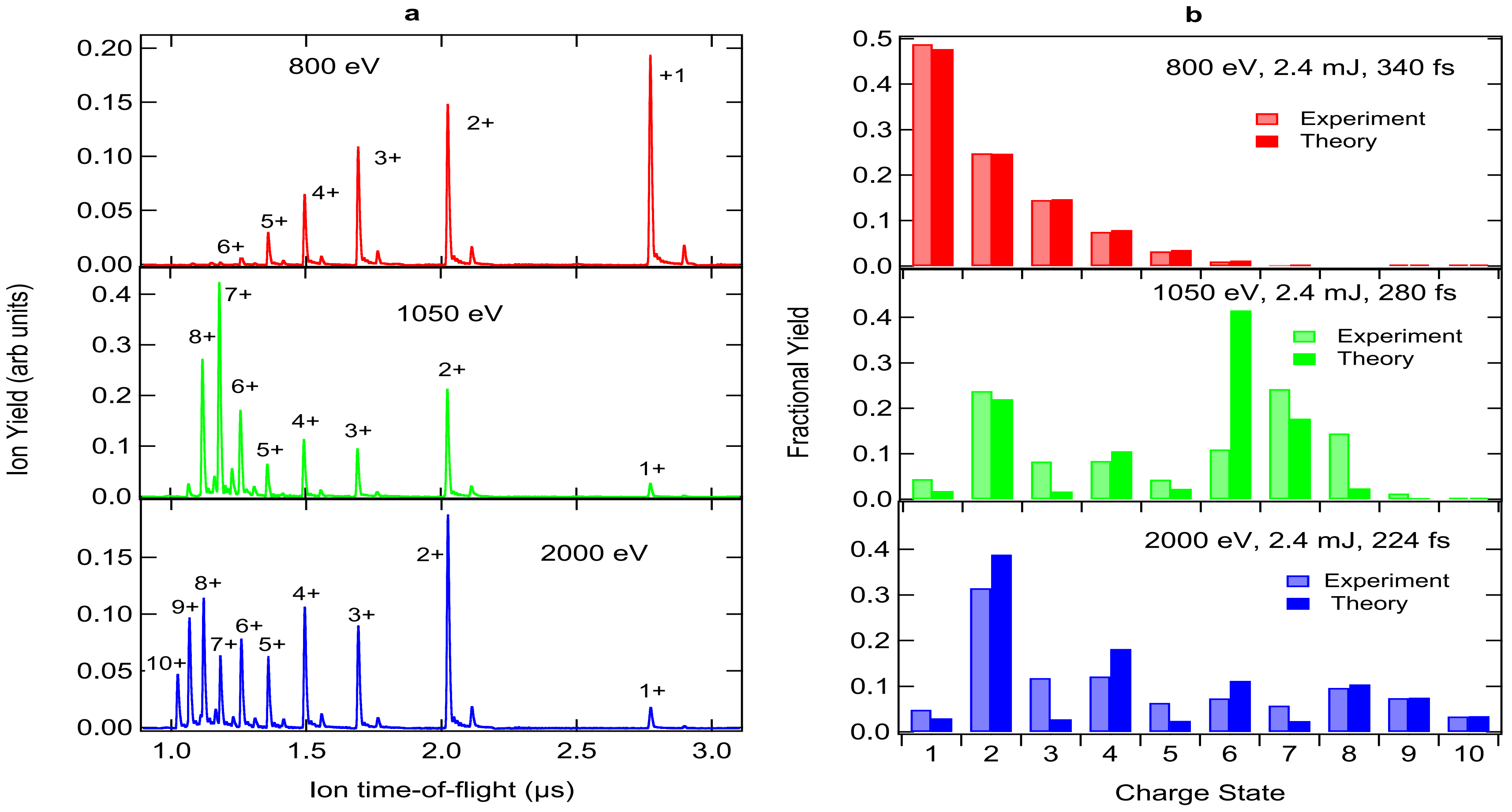
- Single ~100 fs pulse at 2000 eV fully strips neon

  6-photon, 10-electron process



- Shorter pulses with equal pulse energy & fluence suppress absorption & damage.

Theory can model ultraintense x-ray-induced electronic damage in neon



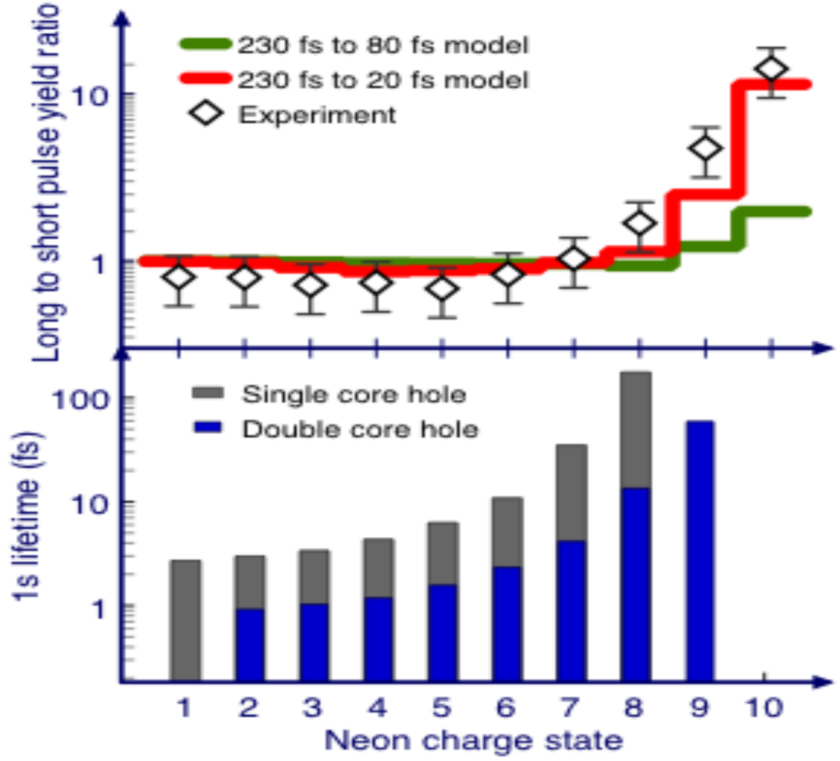
Theory

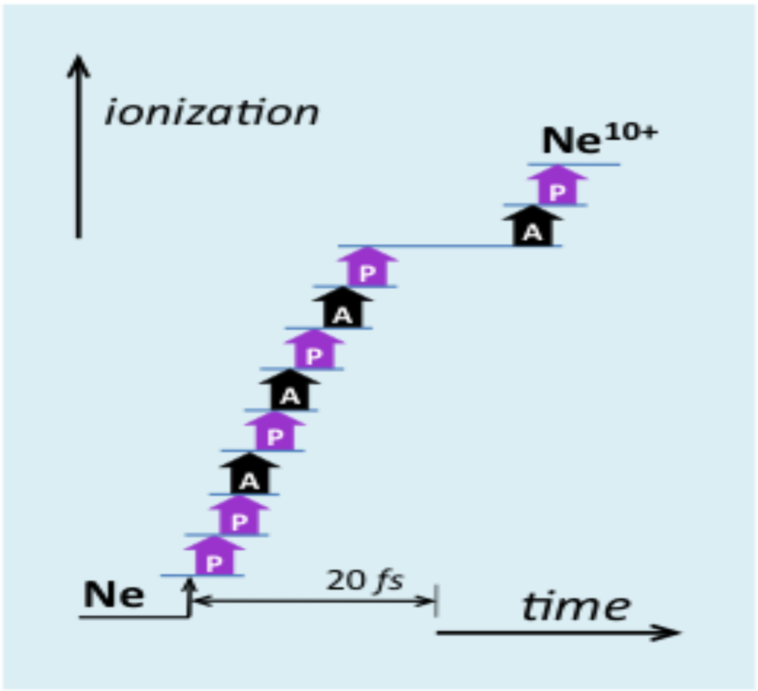
- Intensity averaged
- Fluence determined by experiment

Consistent with "measured" pulse energy and focus.

Sang-Kil Son, Robin Santra – refined calcs include shakeoff – G. Doumy et al, PRL 2011

Atoms become transparent at high x-ray intensity !

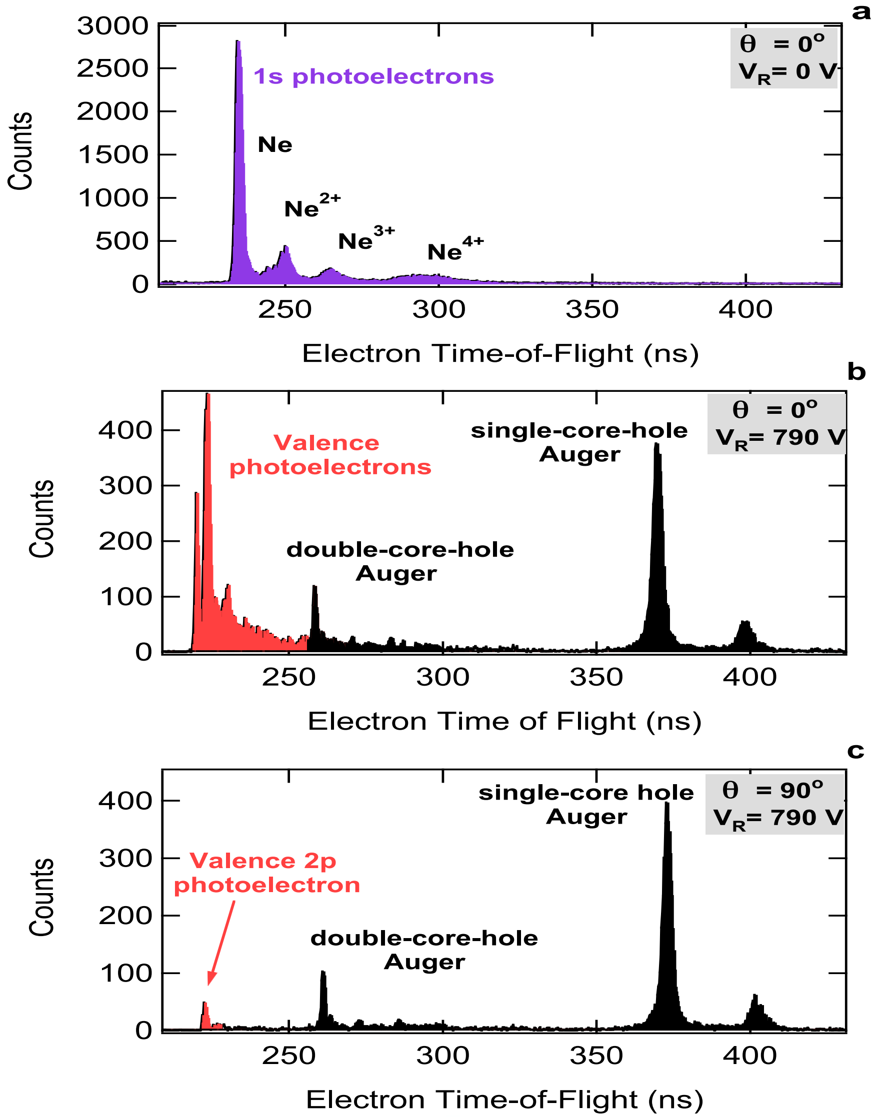




- x-ray absorption is due to the presence of 1s electrons
- high x-ray intensities eject both 1s electrons rendering the atom transiently transparent
- slowing atomic clocks create transparency at surprisingly long timescales

Electron spectrometers track ionization mechanism

X-ray energy 1050 eV



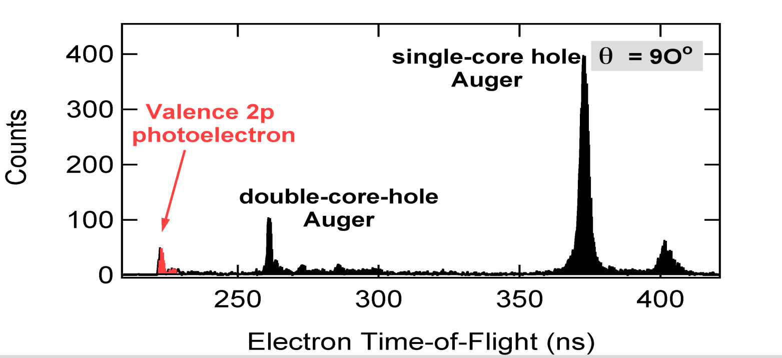
"Slow" 1s photoelectrons along x-ray polarization axis

"Fast" valence photoelectrons and Augers along polarization axis

Clean hollow atom signature double-core-hole Auger

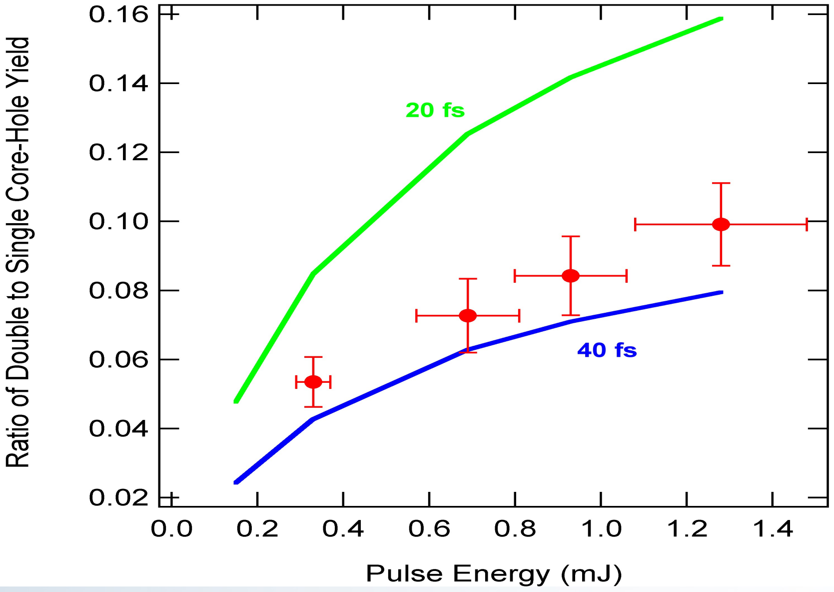
$\theta = 90^{o}$

Hollow atom production: deliberate, huge and an a an indicator of x-ray pulse duration



Hollow atom yield
@ LCLS ~10%
@ synchrotron ~0.3%
due to electron correlation

1050 eV,
nominal electron bunch duration ~80 fs



Summary: non-resonant ultraintense x-ray interactions

- Ultraintense x-ray interactions – nonlinear multiphoton processes rule!

  - establish sequential single photon absorption as dominant ionization mechanism

    fully stripped neon: six-photon, ten-electron (~$10^{12}/\mu m^2$)

  - multiple photon absorption probability high when fluence > $1/\sigma$

  - controlled electron stripping (outer v inner shells)

- X-ray induced transparency – a general phenomena

  - transient x-ray transparency caused by ejection of inner-shell electrons

  - induced transparency = frustrated absorption = core-level bleaching

    molecules: Hoener *et al.*, PRL **104**, 253002 (2010)

    clusters: Schorb *et al.*, PRL **108**, 233401 (2012)

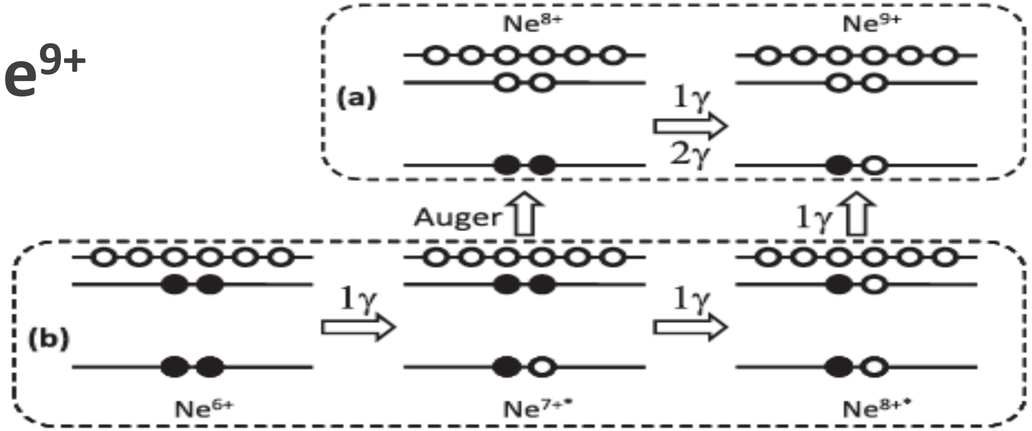
    solids: Yoneda *et al.*, Nat. Comm. (2014), Rackstraw *et al.*, PRL (2015)

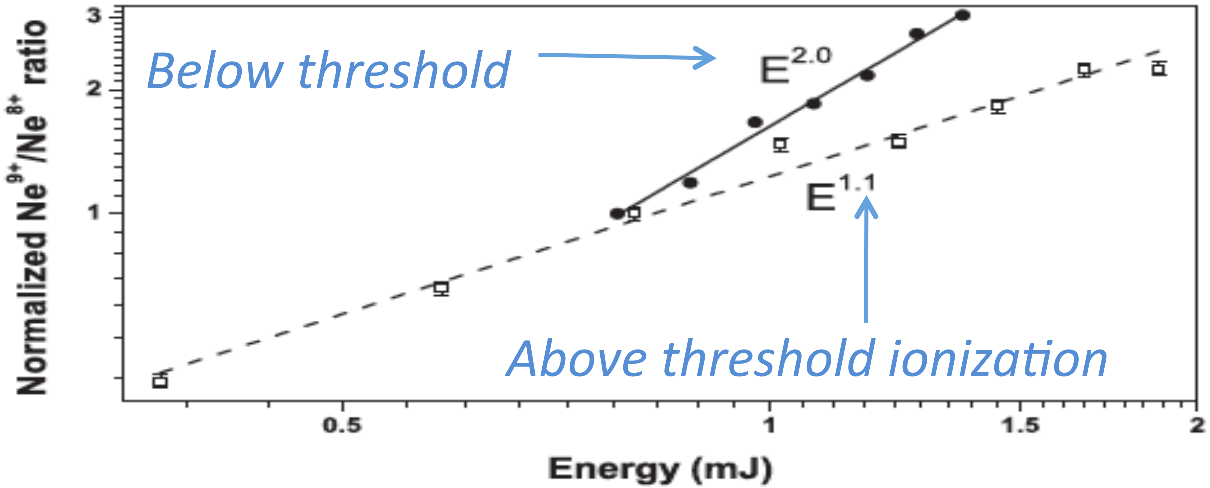
  - implications for imaging: $\sigma_{scatt}/\sigma_{abs}$ is increased

- Femtosecond time-scale atomic processes provide FEL diagnostics

Direct two-photon absorption cross section small He-like neon

Two pathways for production of Ne^{9+}





Signature of 2γ absorption

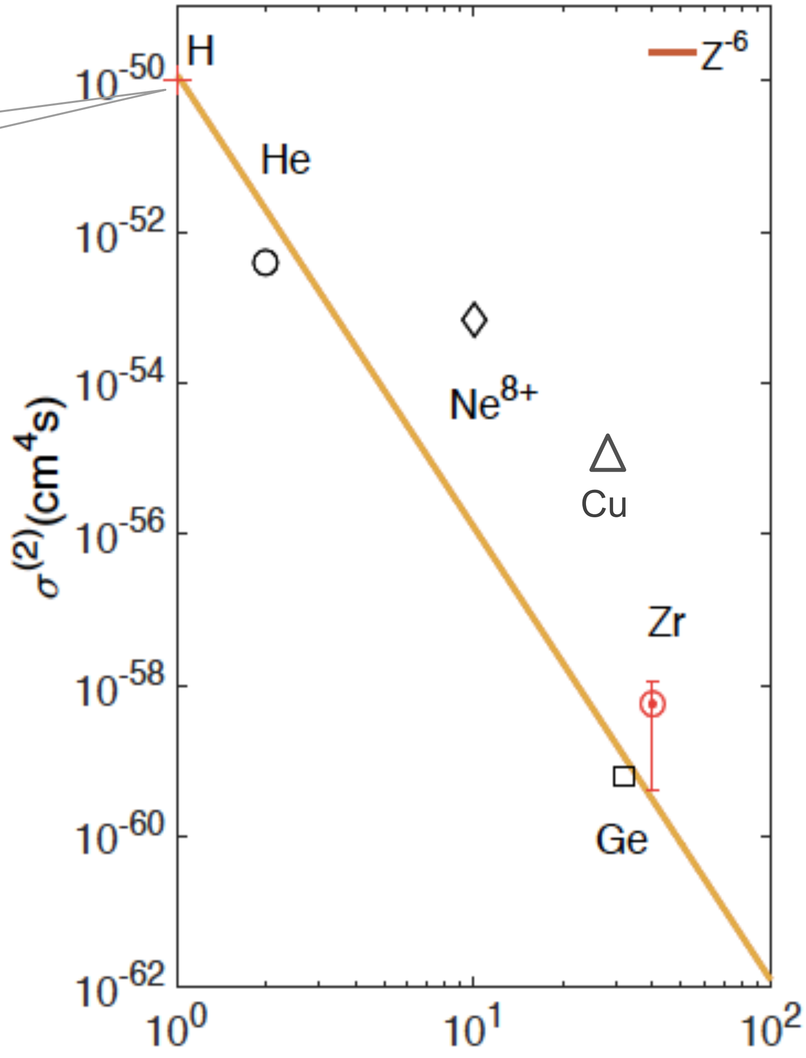
Absolute value of $\sigma^{(2)}$ enhanced by nearby 1s -> 4p resonance

G. Doumy *et al.*, PRL **106**, 083002 (2011).

Two-photon absorption cross-sections v Z

Maria Goeppert-Mayer

1GM



Atomic number

Ge: Tamasaku *et al.*, Nat Phot (2014)
Zr: Ghimire *et al.*, PRA **94**, 043418 (2016)
Cu: Szchlactko *et al*, Sci Rep (2016)

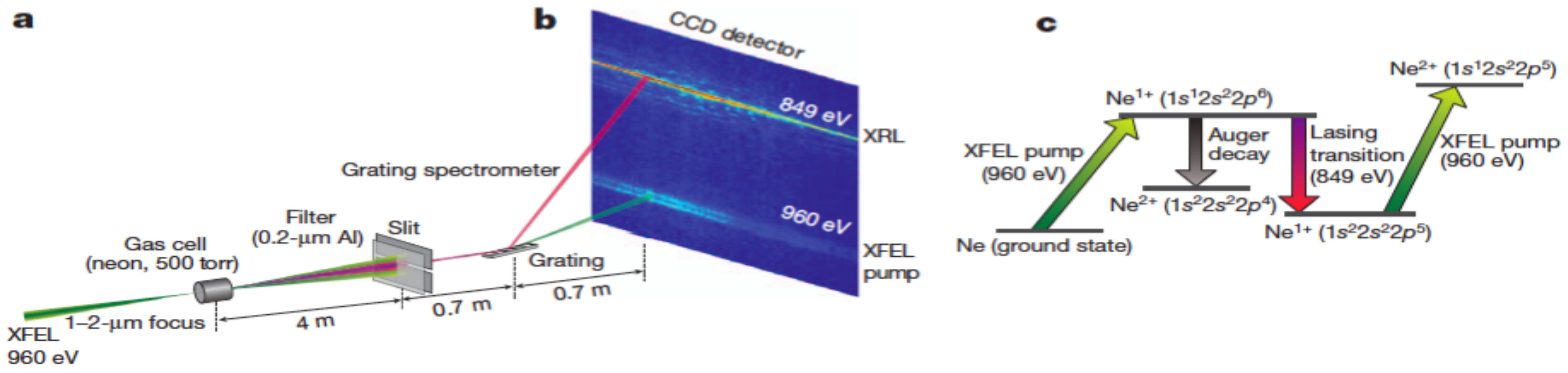
LETTER

Nature **481**, 488 (2012)

doi:10.1038/nature10721

Atomic inner-shell X-ray laser at 1.46 nanometres pumped by an X-ray free-electron laser

Nina Rohringer[1]†, Duncan Ryan[2], Richard A. London[1], Michael Purvis[2], Felicie Albert[1], James Dunn[1], John D. Bozek[3], Christoph Bostedt[3], Alexander Graf[1], Randal Hill[1], Stefan P. Hau-Riege[1] & Jorge J. Rocca[2]



Gain medium: 500 torr neon, 1.5 cm, LCLS focused to ~1-2 µm

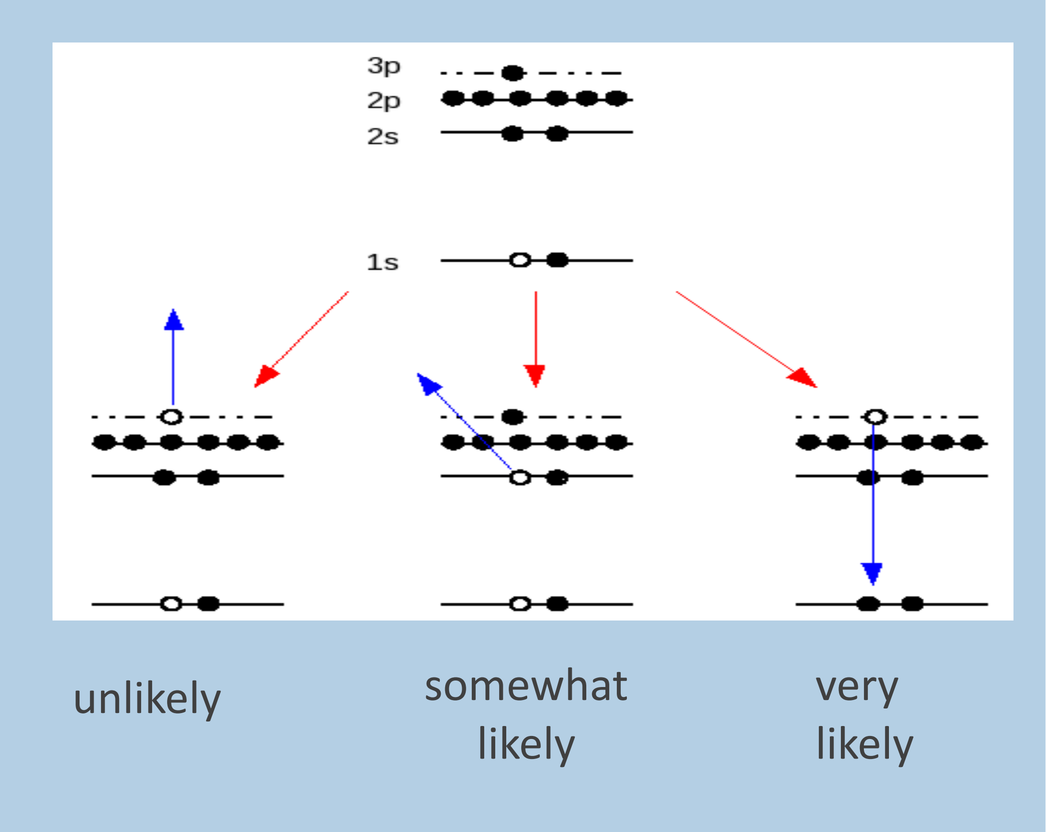
Stable wavelength, same divergence as XFEL pump, 10000x increase output for 2x increase pump power

Resonant x-ray processes at high intensity

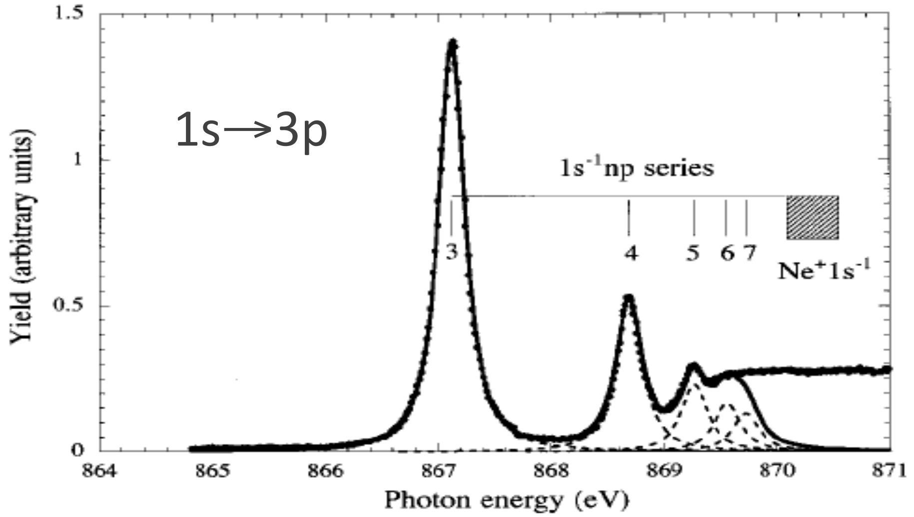
LCLS Expt 5

Can we control inner-shell electron dynamics?

"Rabi flopping" may inhibit Auger decay & x-ray damage.



But LCLS linewidth ~ 8 eV!



- **Strong 1s→3p resonance**

$\mu_{Ne\ 1s\text{-}3p} = 0.01\ ea_0$

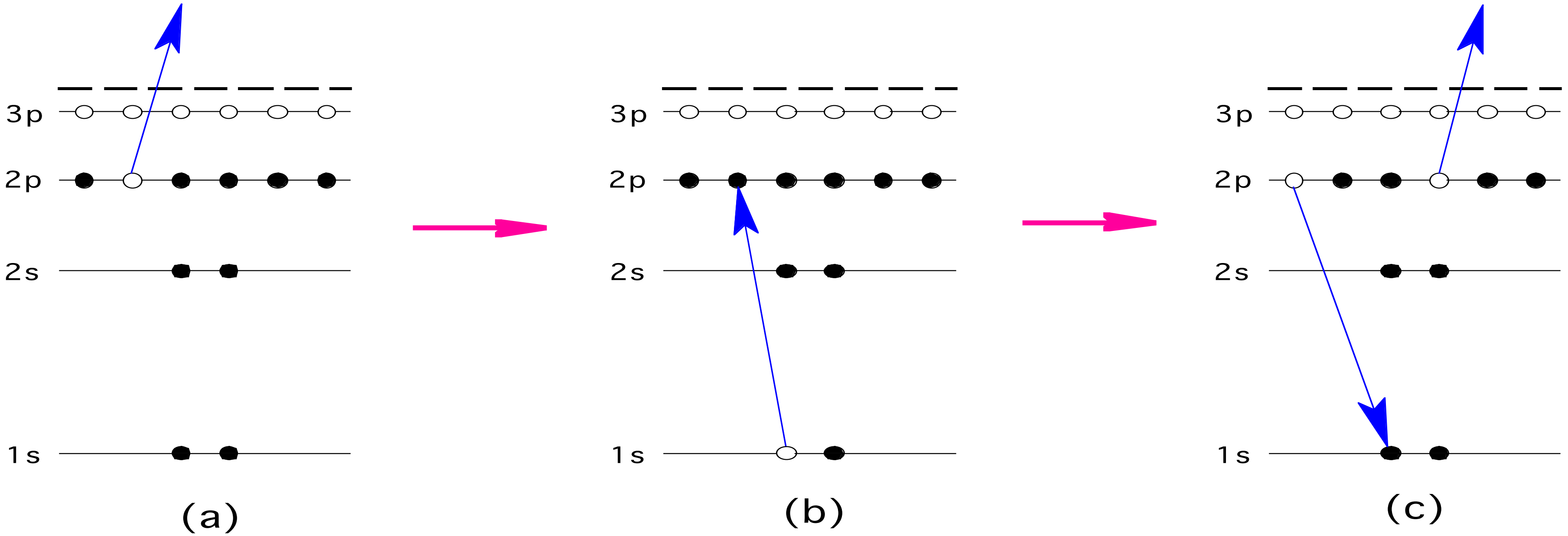
$\tau_{Ne\ 1s^{-1}} = 2.4\ fs = 100\ a.u.$

- **Rabi flopping possible**

$E_{Ne} \sim 6.3\ a.u.$

$I_{Ne} \sim 1.4\ x10^{18}\ W/cm^2$

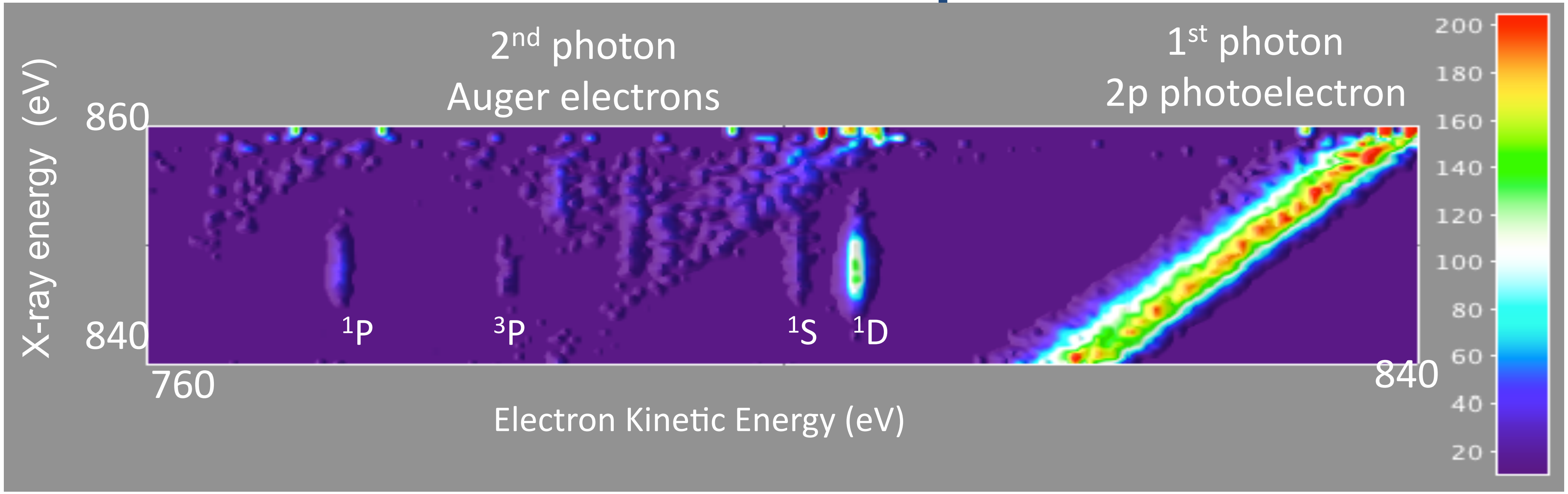
Rabi-flopping on 1s - 2p resonance more feasible



$E_{x\text{-}ray} = 848.6\ eV$
$\sigma_{1s\text{-}2p} = 500\sigma_{2p\text{-}\infty} = 30\ \sigma_{1s\text{-}3p}$

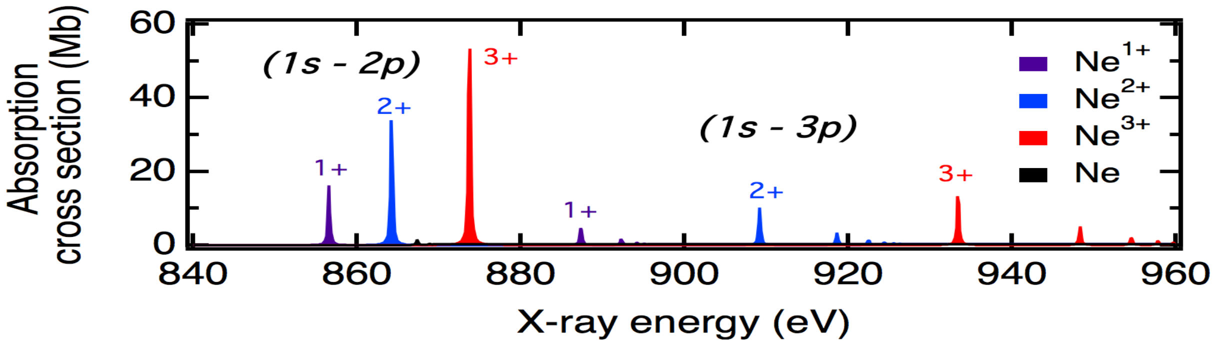
Observe Auger yield when x-rays scanned over 1s - 2p resonance.
Observe broadening at resonance to indicate Rabi flopping
Theory: Rohringer & Santra PRA (2008).

Looking for Rabi flopping: unveiling and driving hidden resonances with LCLS pulses



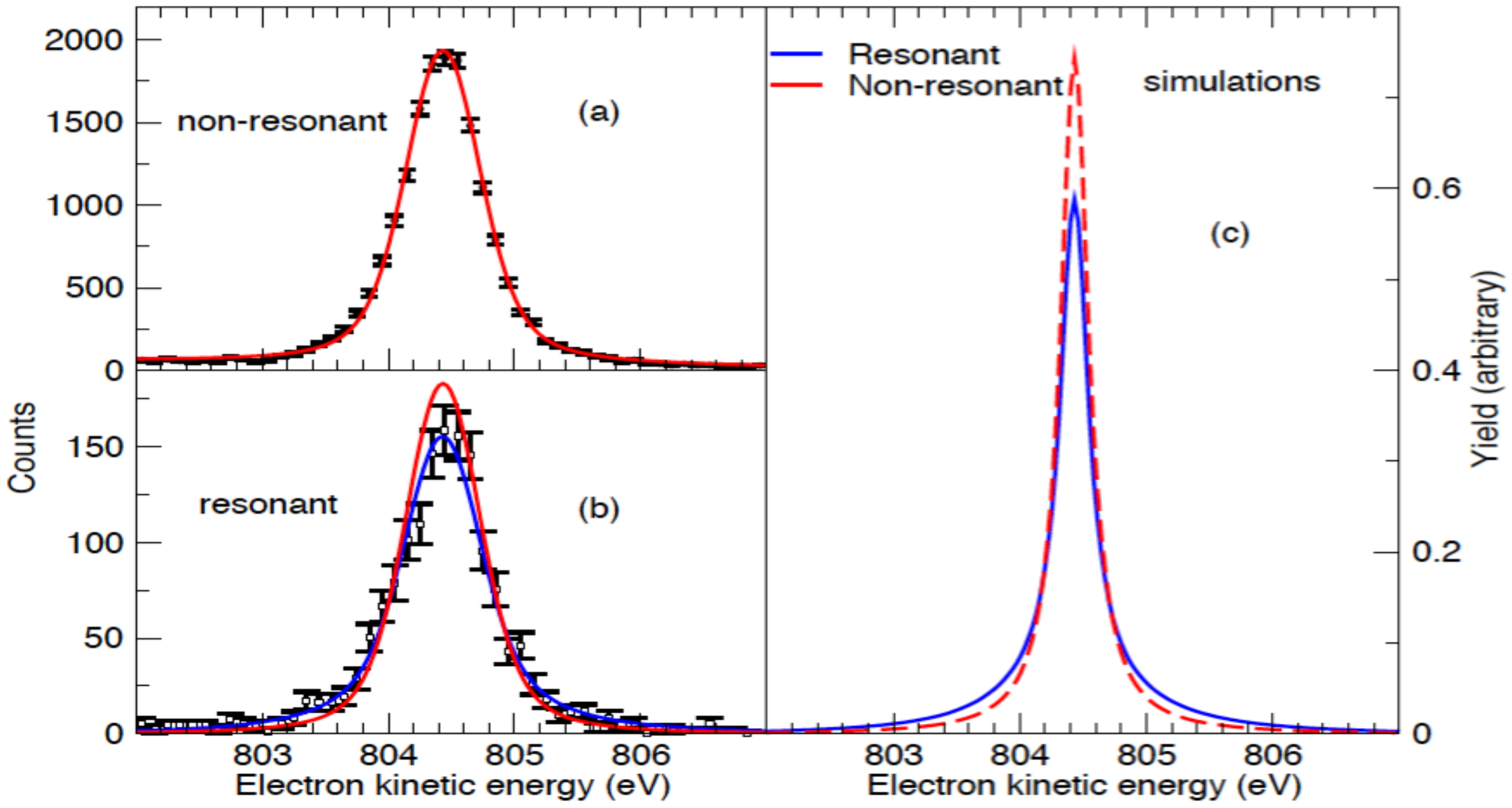
- High fluence pulse alters target to reveal enormous “hidden” resonances ~1000x larger than background

- X-ray absorption spectrum changes rduring the fs duration pulse



E. P. Kanter et al., PRL (2011)

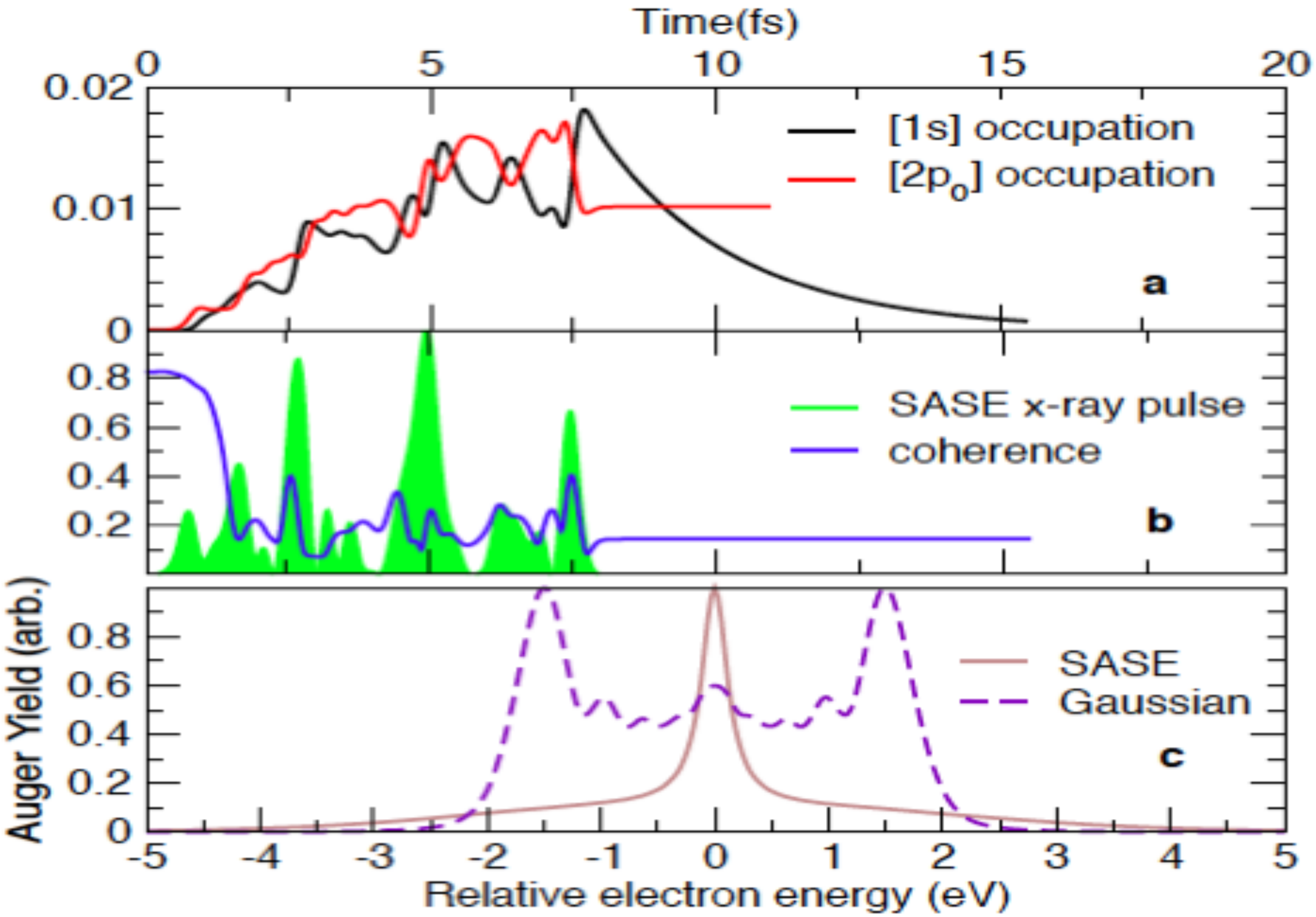
Is the ^1D Auger line broadened on 1s-2p resonance?



E.P. Kanter *et al.*, PRL (2011)

Theory from N. Rohringer and R. Santra

SASE vs Gaussian pulse for Rabi flopping



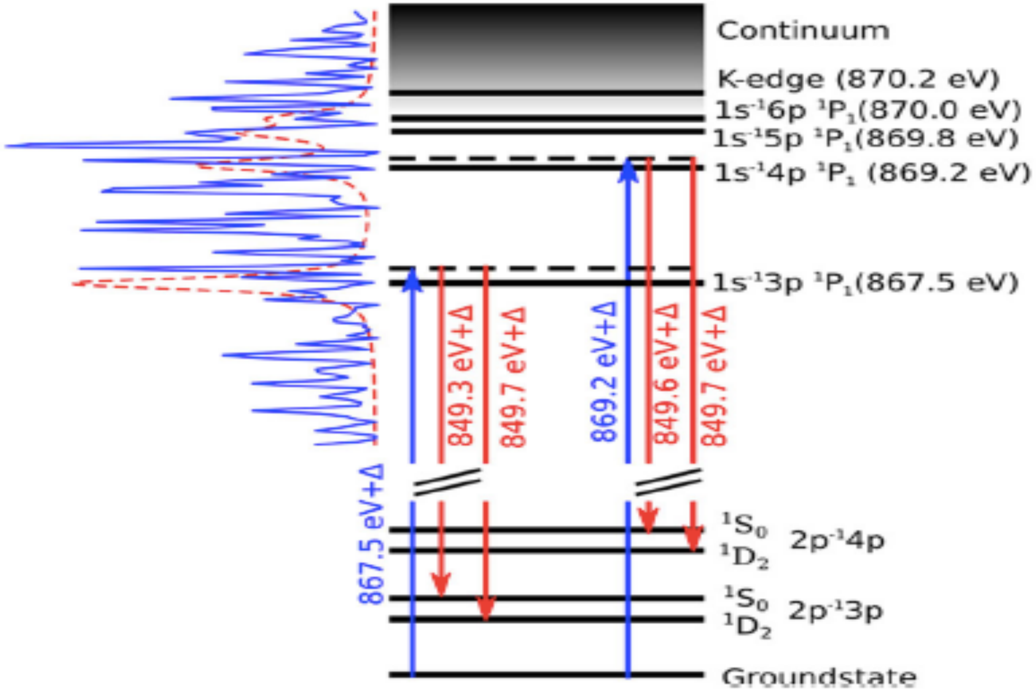
Summary: resonant x-ray processes at high intensity

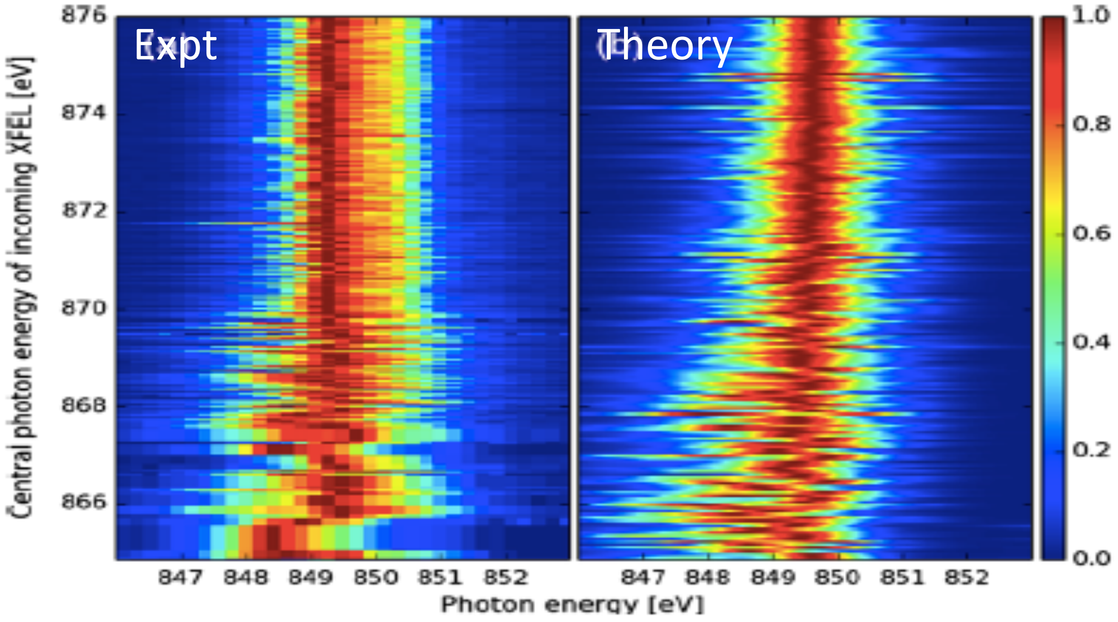
- First hint of Rabi cycling for inner-shell electrons: Ne 1s – 2p resonance

- Need XFEL with improved longitudinal coherence – SEEDING
  - Quantum control – multidimensional spectroscopies
  - Single particle imaging (reduced radiation damage & increased x-ray intensity)

- "Hidden" resonances critical in atomic response to ultraintense x-rays
  - Enhanced two-photon absorption probability
    - Doumy *et al.*, PRL **106**, 083002 (2011)
  - Ionization beyond sequential single photon model
    - Schorb *et al.*, PRL **108**, 233401 (2012) - Ar
    - Rudek *et al.*, Nat. Phot. **6**, 858 (2012) – Xe
    - Rudek *et al.*, Phys. Rev. A **87**, 023413 (2013) – Kr

Stimulated Raman scattering in Ne with SASE pulse





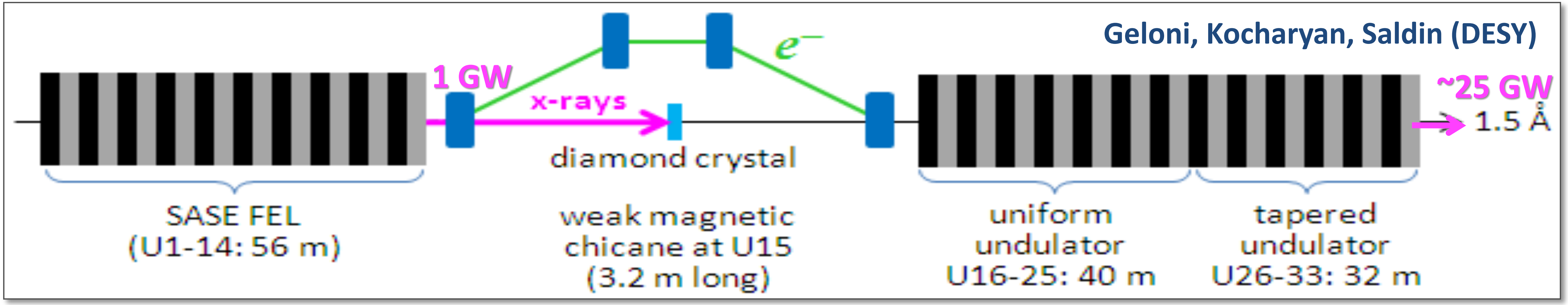
Small overlap of SASE pulse w/resonances
Tail of SASE pulse used to stimulate Raman

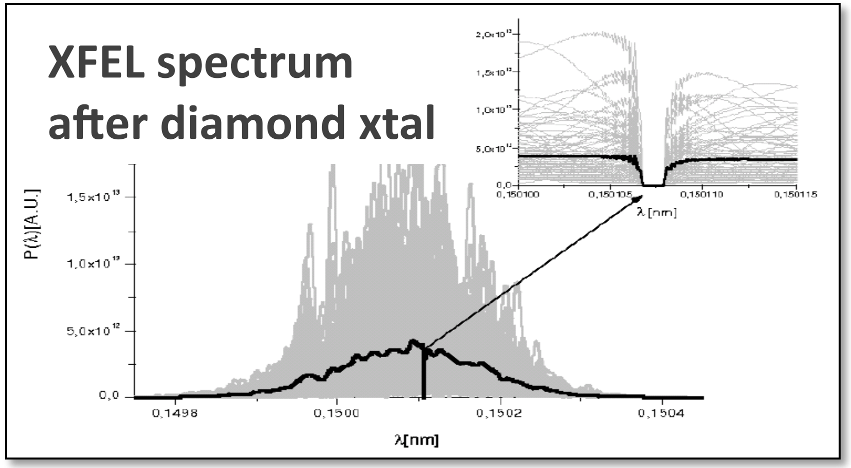
SRS Signature:
Stochastic scattering intensity below edge

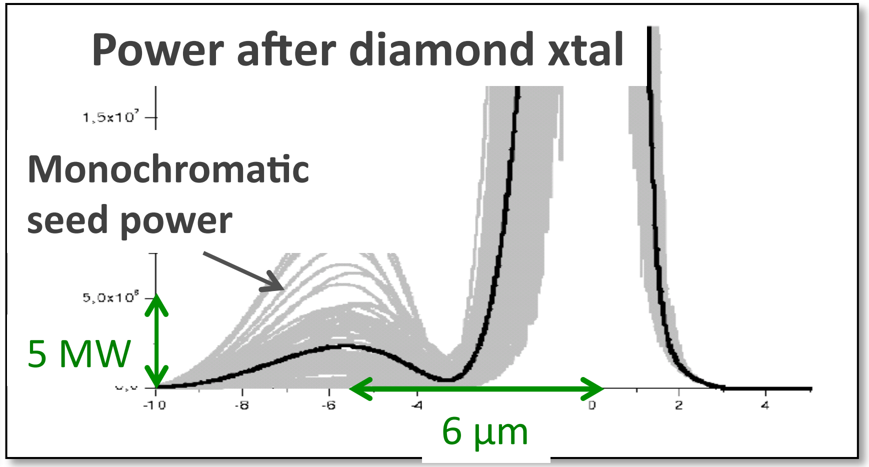
Weninger *et al*, PRL 111, 233902 (2013)
Weninger & Rohringer, PRA **88,** 053421 (2013)

Improving the X-ray Laser

Hard x-ray self-seeding proposed 2010



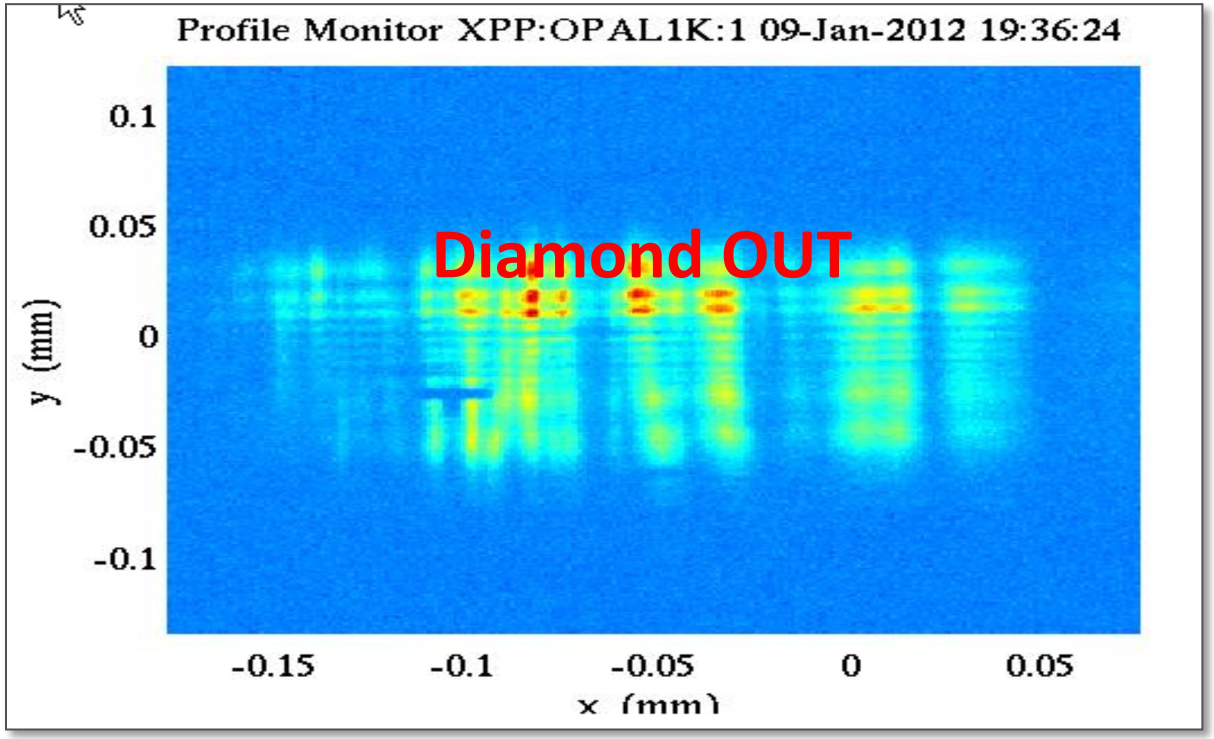


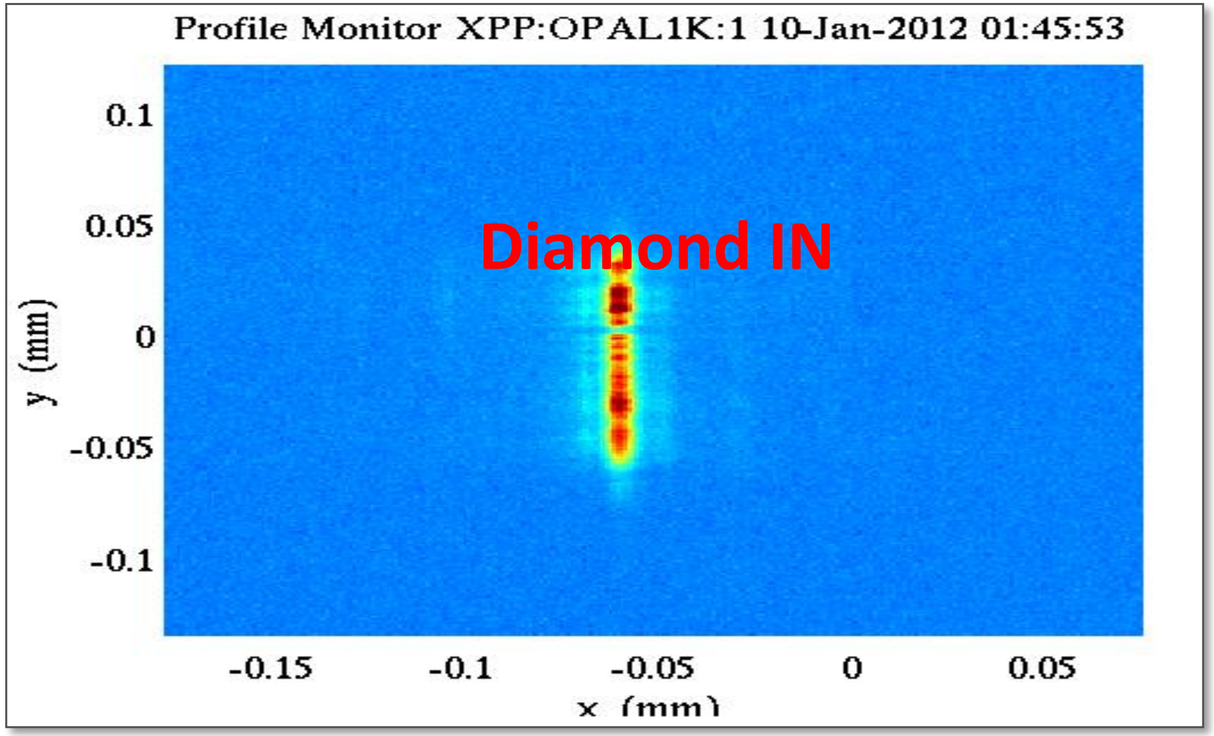


Diamond C(004): 100μm
λ = 0.15 nm, θ_B = 57°

arXiv:1008.3036v1 Geloni

Hard x-ray self seeding realized Jan 2012 – P. Emma et al.





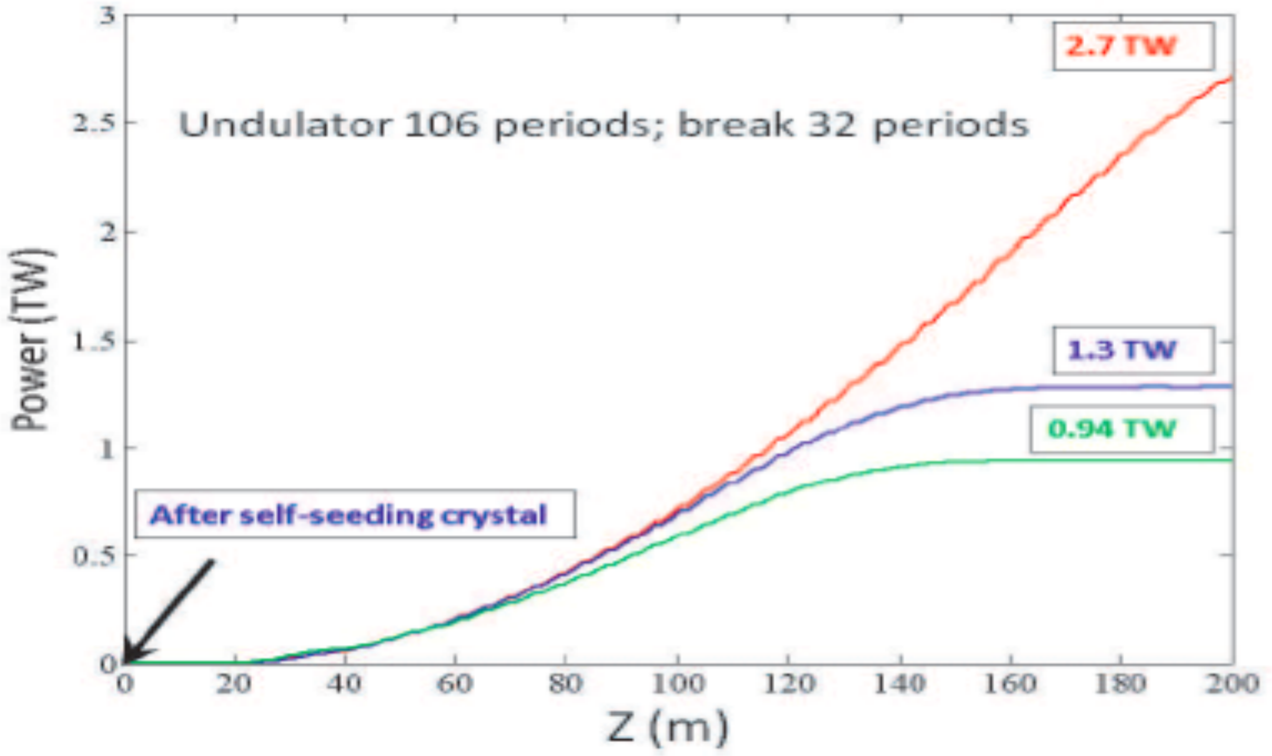
Bandwidth $<10^{-4}$ at 8-9 keV and tunable

But … did not achieve saturation and power jitter still present

J. Amann *et al.*, Nature Photonics 6, 693 (2012)

On the road to a TW FEL :   LCLS-TN-11-3

GENESIS simulation



200 m undulator tapered

10^{13} x-rays @ 8-10 keV
10 fs

W.M. Fawley[1], J. Frisch[1], Z. Huang[1], Y. Jiao[1], H.-D. Nuhn[1], C. Pellegrini[1,2], S. Reiche[3], J. Wu[1†]
[1]SLAC National Accelerator Laboratory, Menlo Park, CA 94025, USA
[2]Department of Physics and Astronomy, UCLA, Los Angeles, CA 90095-1547, USA
[3]Paul Scherrer Institute, Villigen PSI, 5232, Switzerland

Also arXiv Jun 2013: S. Serkez *et al.* 10 TW FEL, 10^{14} x-rays, 10 fs @ 3.5 keV

Towards single particle imaging

LETTER

doi:10.1038/nature09748

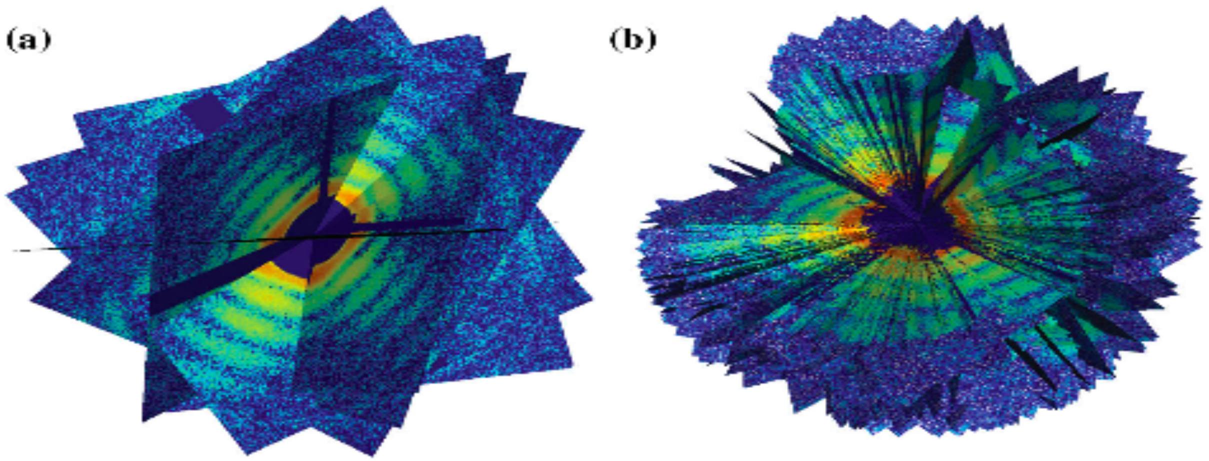
Single mimivirus particles intercepted and imaged with an X-ray laser

Seibert et al., Nature 470, 78 (2011)

Selected for a Viewpoint in *Physics*
PRL **114,** 098102 (2015) PHYSICAL REVIEW LETTERS week ending 6 MARCH 2015

Three-Dimensional Reconstruction of the Giant Mimivirus Particle with an X-Ray Free-Electron Laser

Ekeberg et al., PRL (2015)



Mimivirus

-Largest known virus – 0.75 µm

-Does not crystallize

-Large for 3D cryoelectron microscopy

Single Shot Scattering Pattern

2D: 32 nm resolution

Set of 198 scattering patterns

3D: reconstruction to 120 nm

Physics

on Ekeberg et al., PRL (2015)

Viewpoint

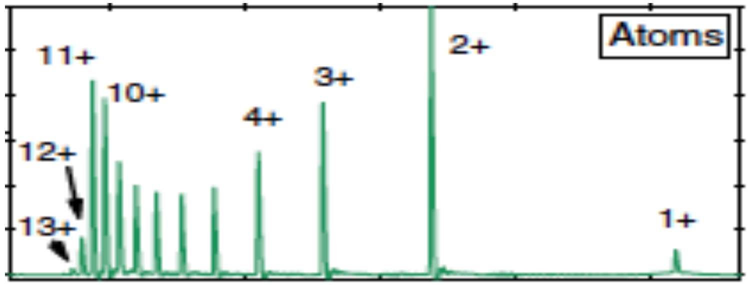
X-Ray Imaging of a Single Virus in 3D

"And there are still open questions on the impact of electronic damage on x-ray scattering on femtosecond time scales: The above-mentioned work by Neutze et al. tracked the movements of the atomic nuclei of the biomolecule, showing they don't move on the few-femtosecond timescale of an x-ray pulse. Electrons, however, move faster than nuclei. Since electrons are what scatters x rays, it is yet to be confirmed that few-femtosecond pulses can probe an unperturbed electronic structure." - Keith Nugent

March 2, 2015

Beyond the sequential single photon ionization model

Argon



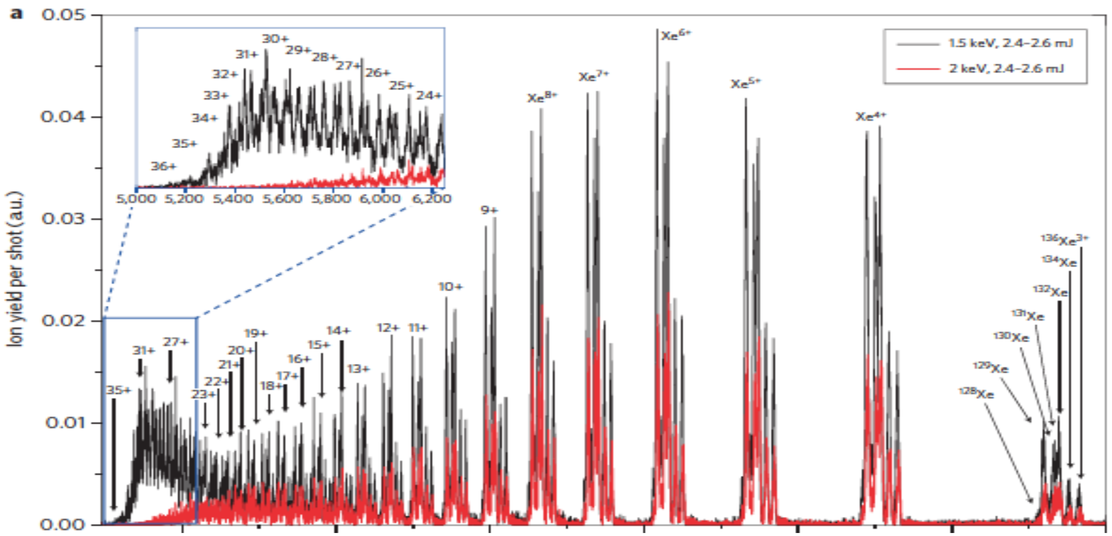
@ 480 eV

sequential single photon limit 10+

observe 13+

Schorb et al., PRL (2012)

Xenon



@1500 eV

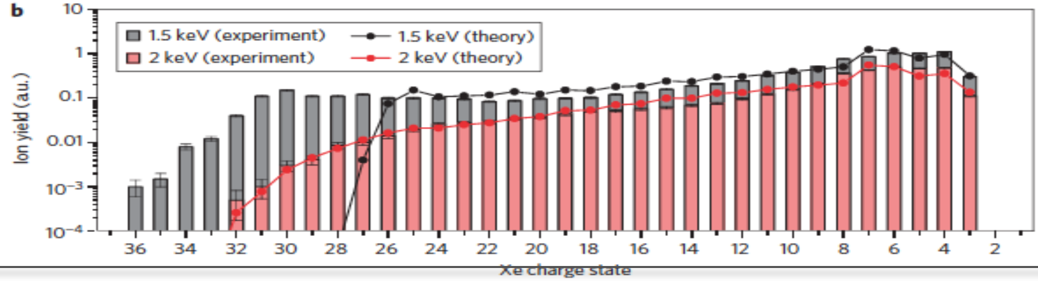
sequential single photon limit 27+

observe 36+

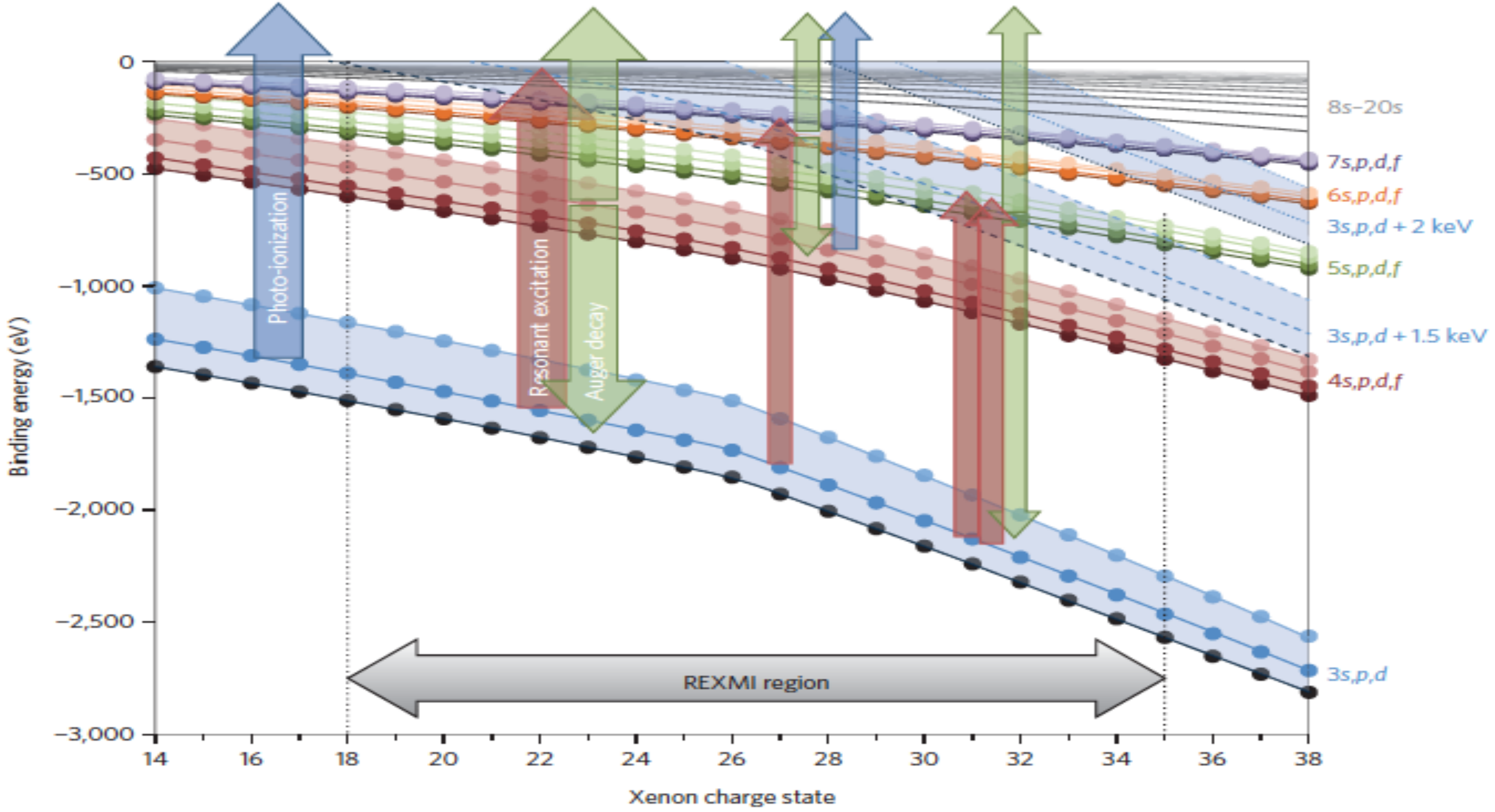
@2000 eV

sequential single photon limit 32+

observe 32+



Resonance-enabled x-ray multiple ionization

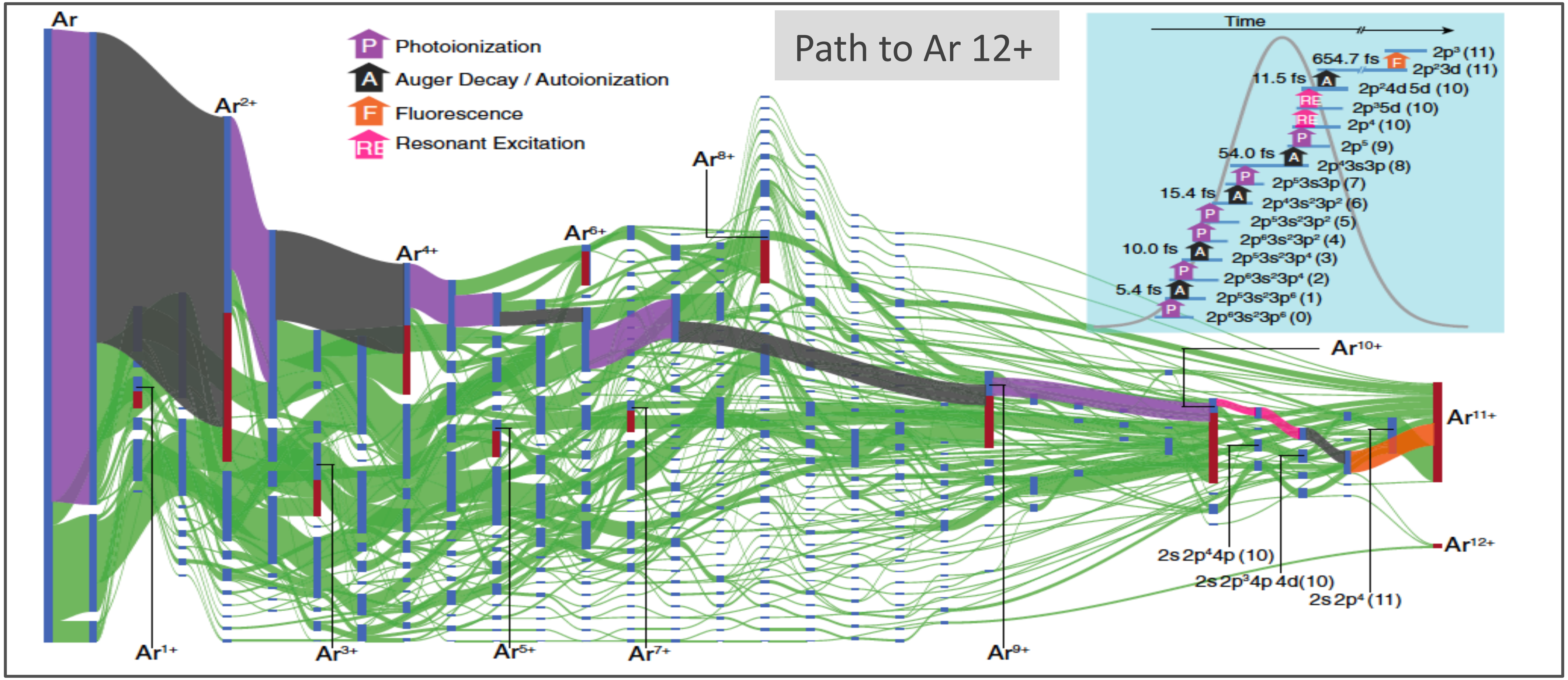


B. Rudek *et al.*, Nat. Phot. (2012)

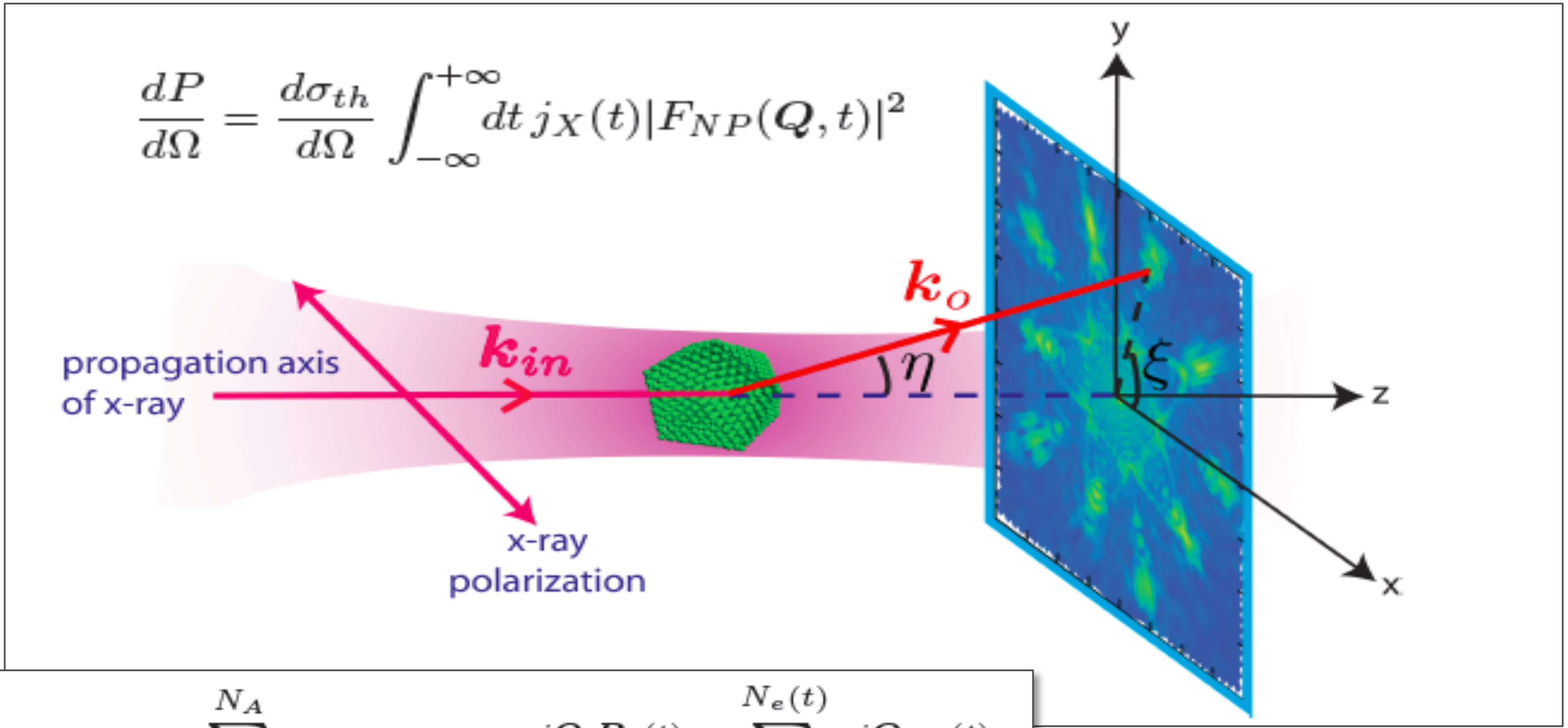
Tracking electronic configurations during XFEL pulse including resonances!

Monte Carlo Rate Equation Approach

	# of ECs with no RE	# of ECs with RE
Ar	1.33×10^{3}	2.85×10^{13}
Kr	3.05×10^{5}	2.08×10^{19}
Xe	7.06×10^{7}	9.05×10^{22}



X-ray diffraction image - electronic & structural damage

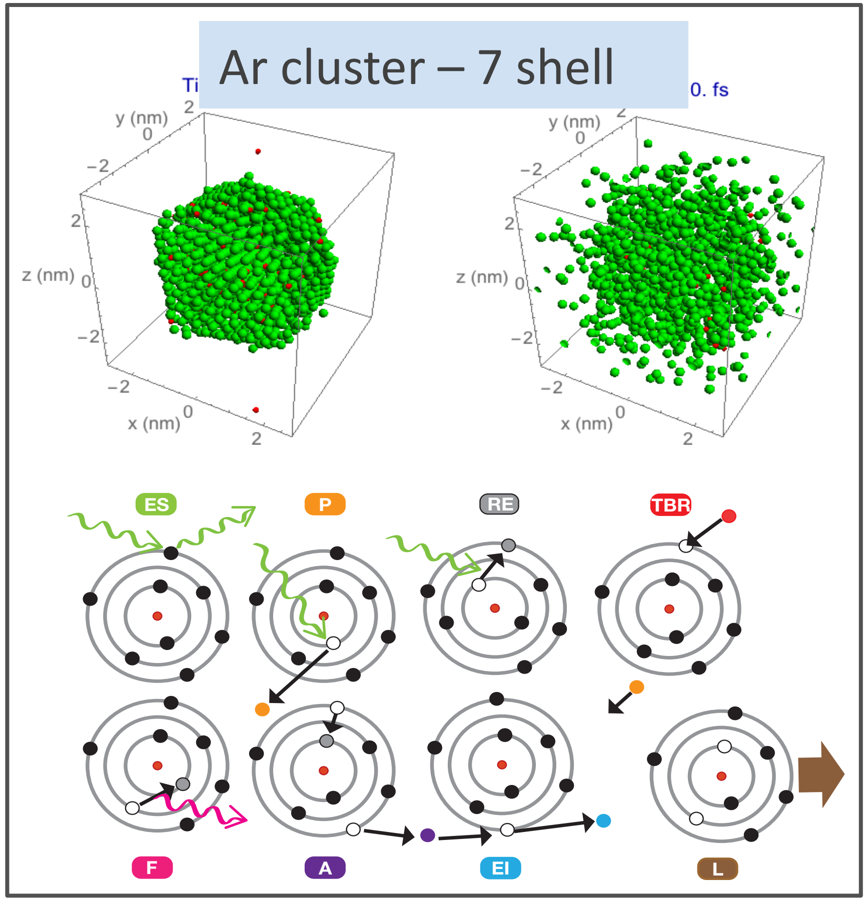


$$F_{NP}(\boldsymbol{Q}, t) = \sum_{j=1}^{N_A} f_j(\boldsymbol{Q}, C_j(t)) e^{i\boldsymbol{Q}\cdot\boldsymbol{R}_j(t)} + \sum_{j=1}^{N_e(t)} e^{i\boldsymbol{Q}\cdot\boldsymbol{r}_j(t)}$$

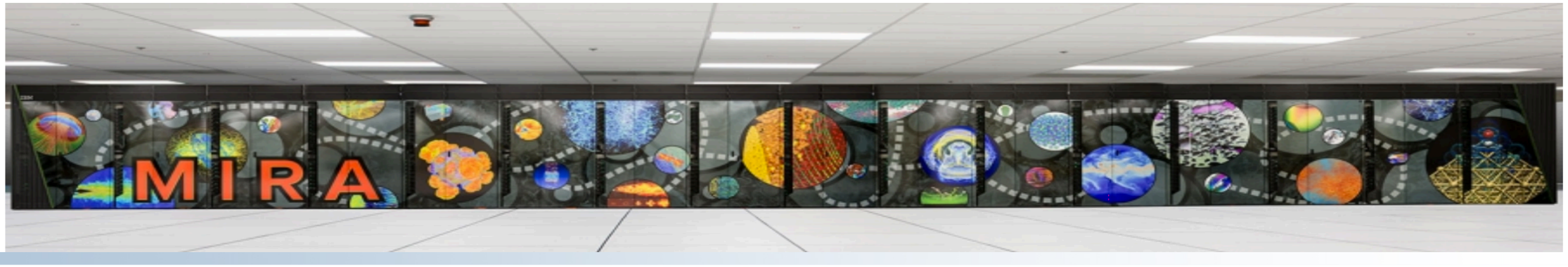
$$f_j(\boldsymbol{Q}, C_j(t)) = \int_{-\infty}^{+\infty} d\boldsymbol{r}\, \rho(\boldsymbol{r}, C_j(t)) e^{i\boldsymbol{Q}\cdot\boldsymbol{r}}$$

AMO approach to the ultraintense x-ray frontier

- Complete simulation of experimental observables w/ atomistic detail (MC/MD)
  - -Monte Carlo for quantum processes
  - -Molecular dynamics to follow ions and electrons
- Expt'l AMO observables:
  - Ion, photoelectron, Auger, fluorescence and x-ray diffraction pattern
- Computations on large scale systems



Phay Ho
Chris Knight



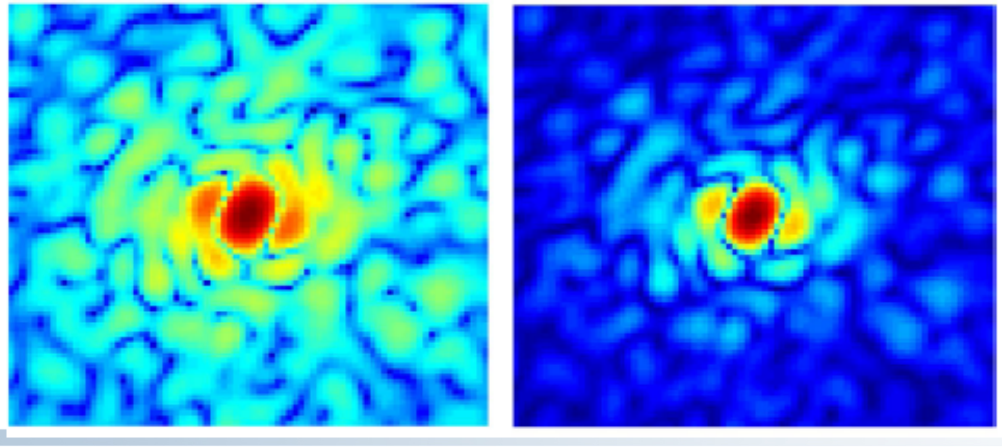
748kcores
786 TB memory
10 PetaFLOPS

Electronic damage: from atoms to complex systems

- Electronic damage effect on biological systems considered
  - H. Quiney & K. Nugent, NatPhot (2011) – frozen lattice, no Compton
  - U. Lorenz *et al.*, PRE (2012) – frozen lattice, no Compton Scattering
  - J. Slowik *et al.*, NJP (2014) – Compton Scattering considered for carbon atom
  - O. Yu. Gorobtsov *et al.*, PRE (2015) w/ Compton Scattering on

    27 nm, 200,000 non-hydrogen atoms
    - Frozen lattice appx – (typically assumed valid for pulses <5 fs)
    - Compton scattering substantial contribution in hard x-ray region 1A
    - Compton scattering limits resolution to 4 Å
  - C. H. Yoon *et al.*, Sci. Rep. (2016) – full start-to-end XFEL simulation

No damage



30 fs w/damage

5×10^{11}/pulse @ 5keV
250 x 160 nm^2
64 kD protein
5.3 Å half-period resolution

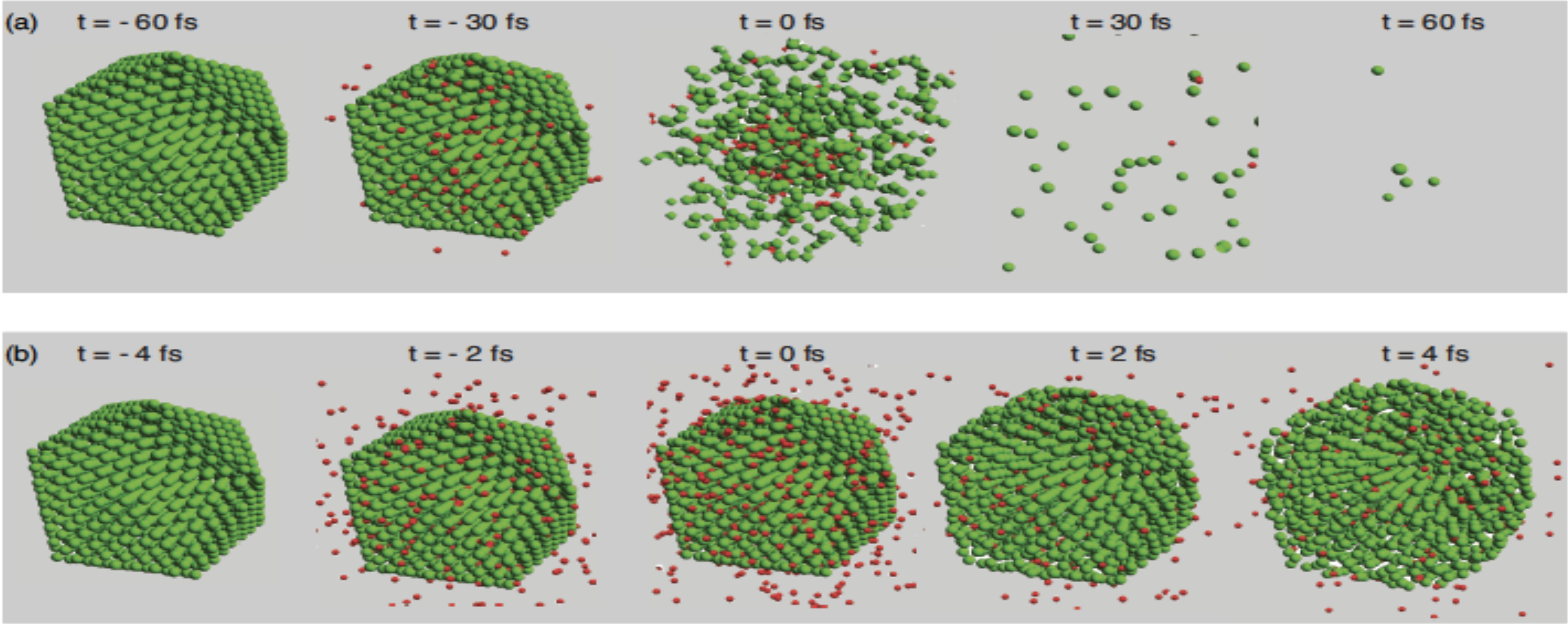
Simulations on a non-biological, high-Z system

7-shell Ar cluster electron and ion dynamics

10^{14} photons/μm^2 @ 8 keV

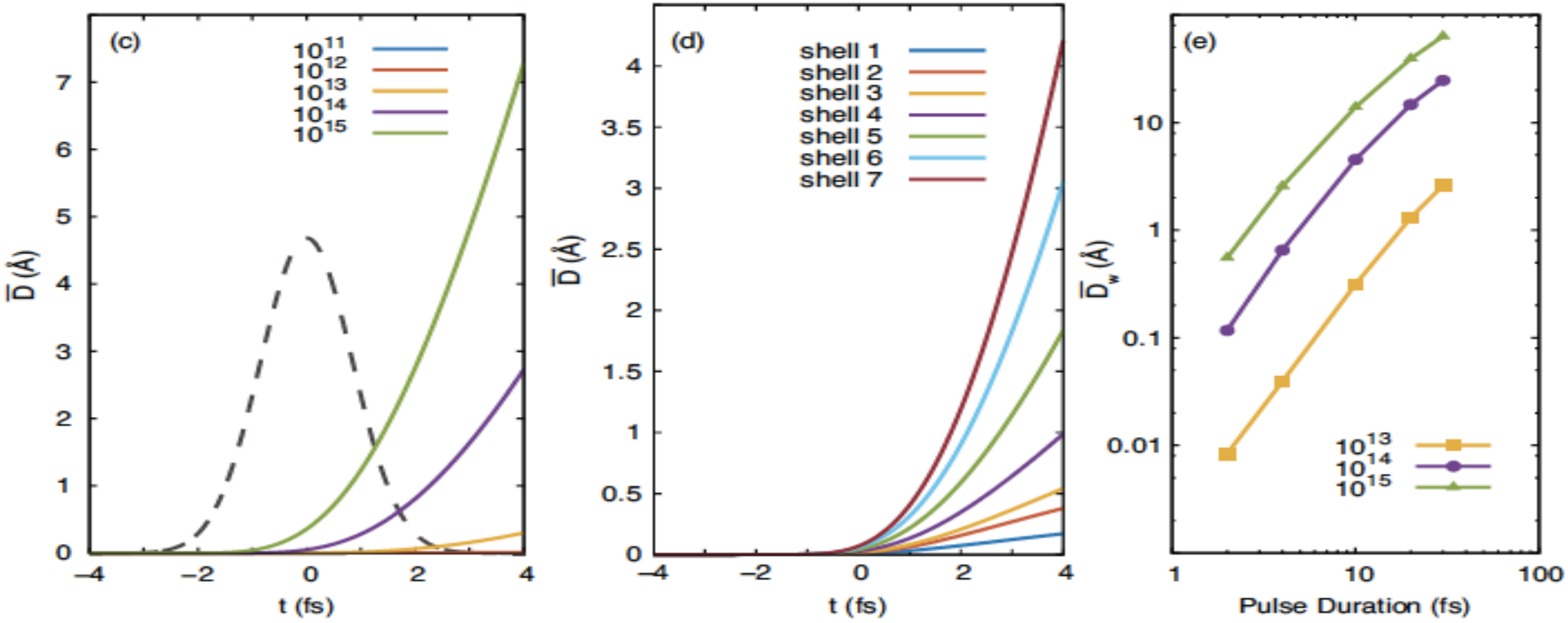
30 fs FWHM

2 fs FWHM



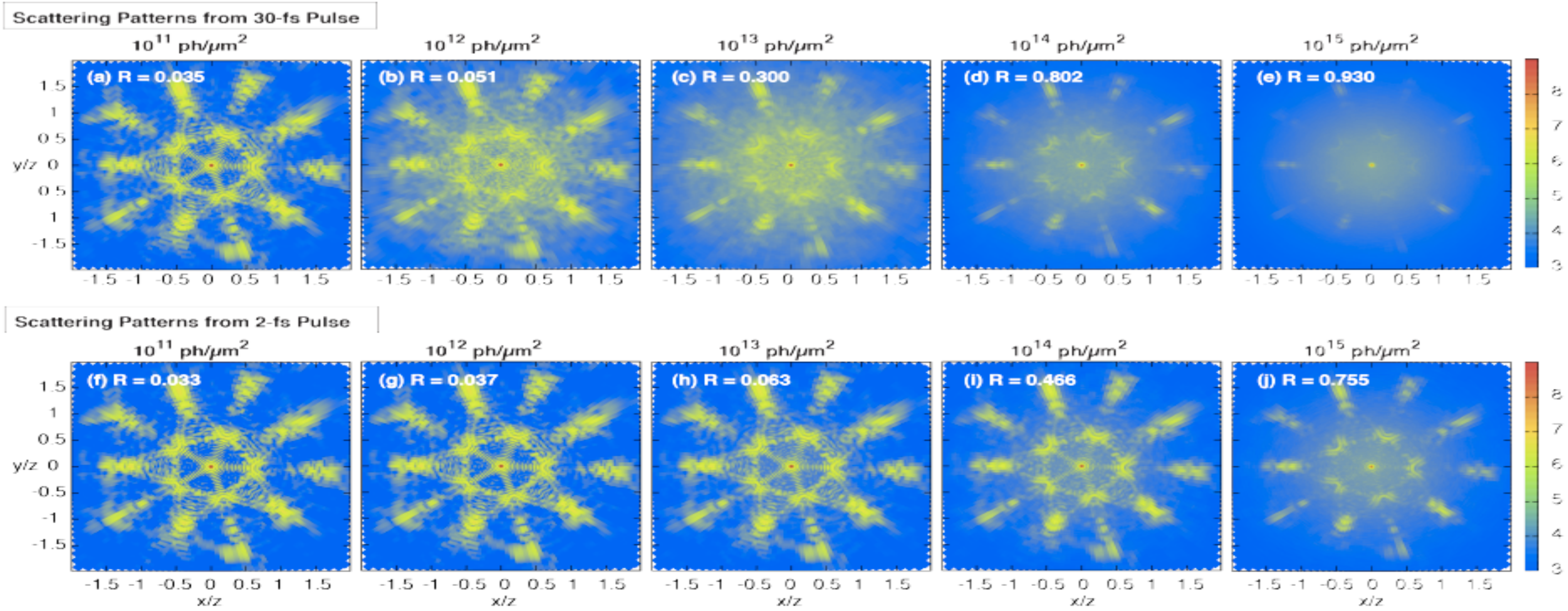
P. Ho *et al*. PRA (2016)

Cluster expansion - but pulse weighted average



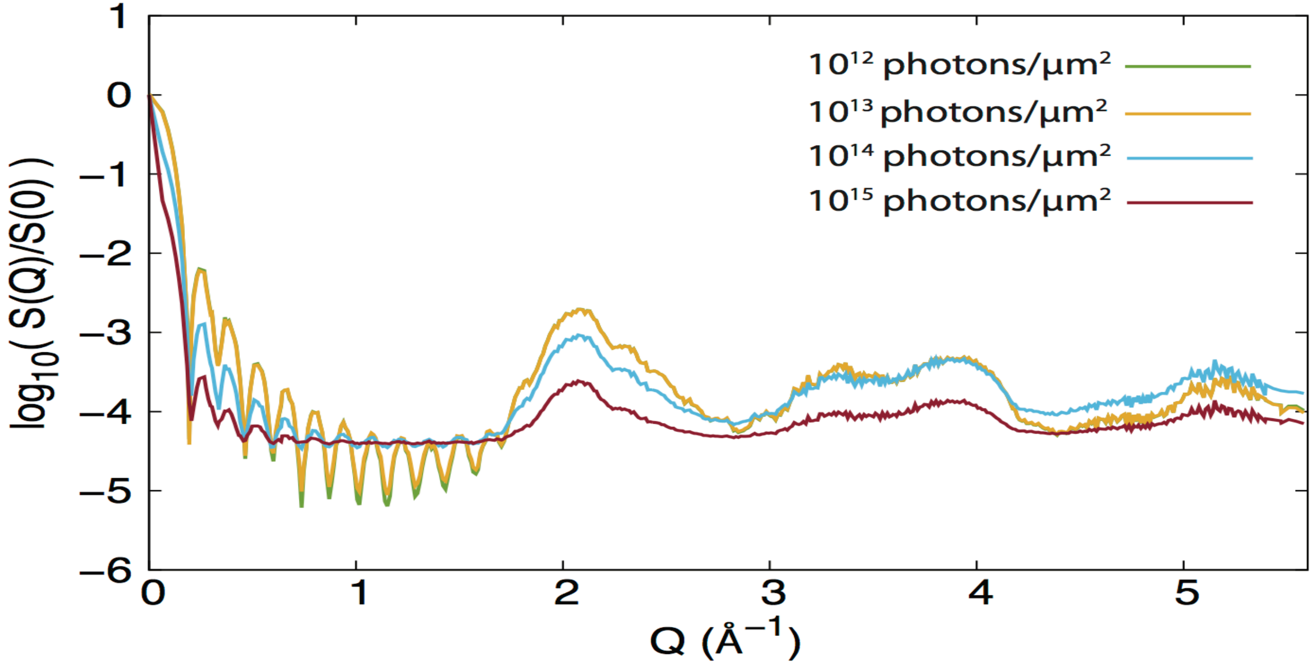
"Original" structure recoverable despite substantial atom movement
Analogous to "self-terminating Bragg gates" in XFEL crystallography

Scattering patterns for 7-shell Ar
8 keV, 30 fs and 2 fs pulses



Three major contributions: nanoparticle, free electron & Compton scattering

Reconstruction in the face of radiation damage-ideal case



7-shell Ar cluster, ~ 5nm

1415 atoms , 25470 e-

8 keV, 2 fs

Ideal case reconstruction

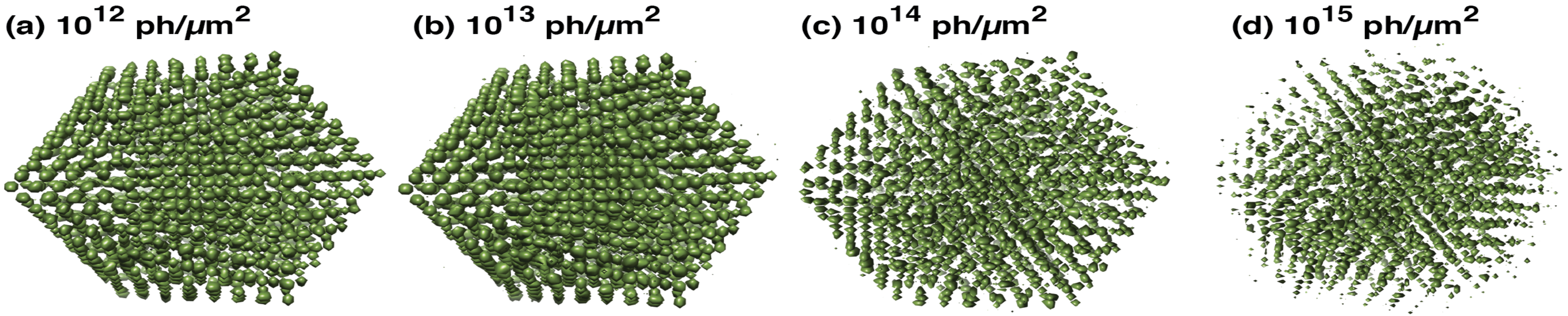
Complete Q-space info in 3D available

1-D: Qmax = 3.24 Å^{-1}, dQ = 0.065Å^{-1}

No noise

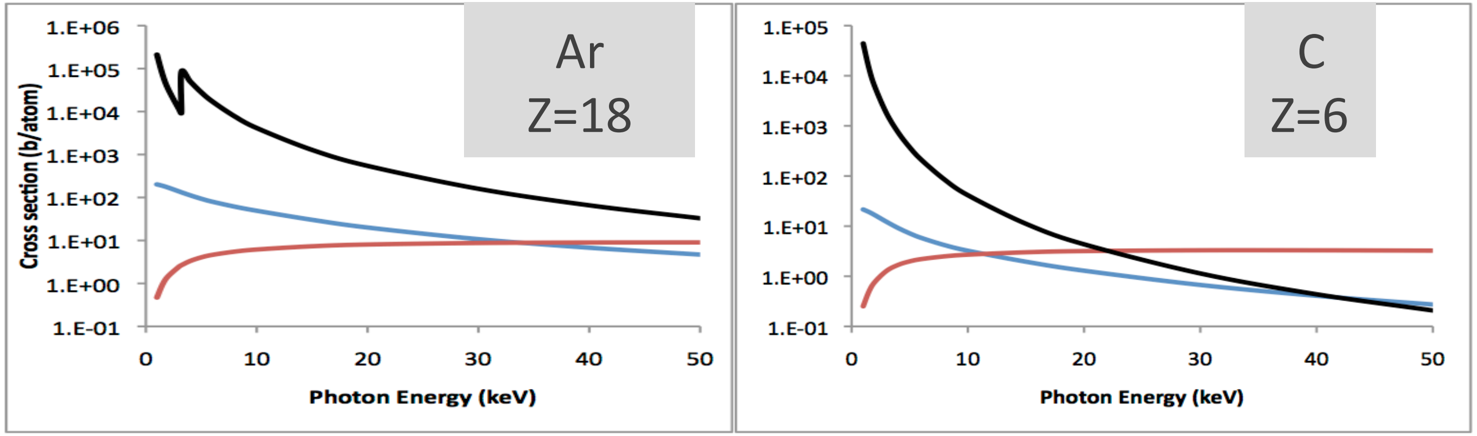
Atomic level info still visible @ 10^{14}/μm^2

With Miklos Tegze & Gyula Faigel



Single particle imaging: bio v non-biological systems

- Compton scattering plays a smaller role



- High-Z systems require shorter pulses

  Inner-shell lifetimes: Carbon ~10 fs, Argon ~1 fs

- Two effects analogous to serial femtosecond crystallography:

  Pulse-weighted scattering allows structure recovery despite atomic movement

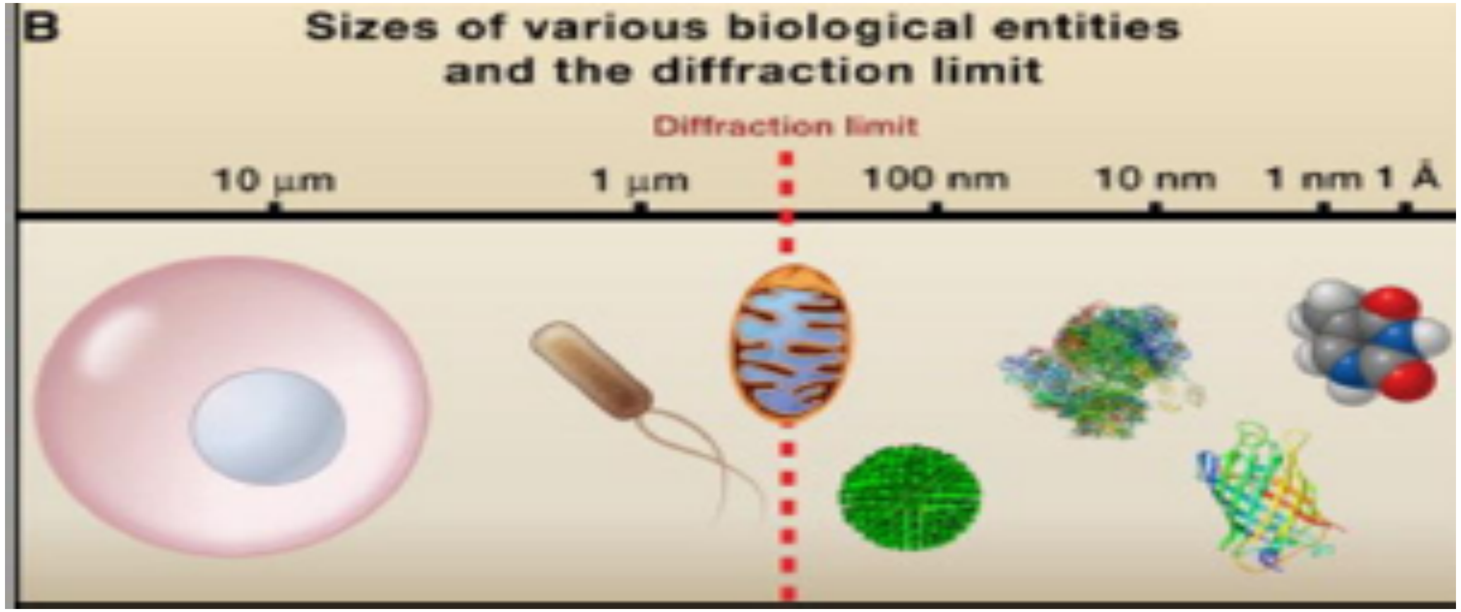
  -- self-terminating Bragg gates

  Distribution of radiation damage favors larger samples

P. Ho *et al.*, PRA (2016)

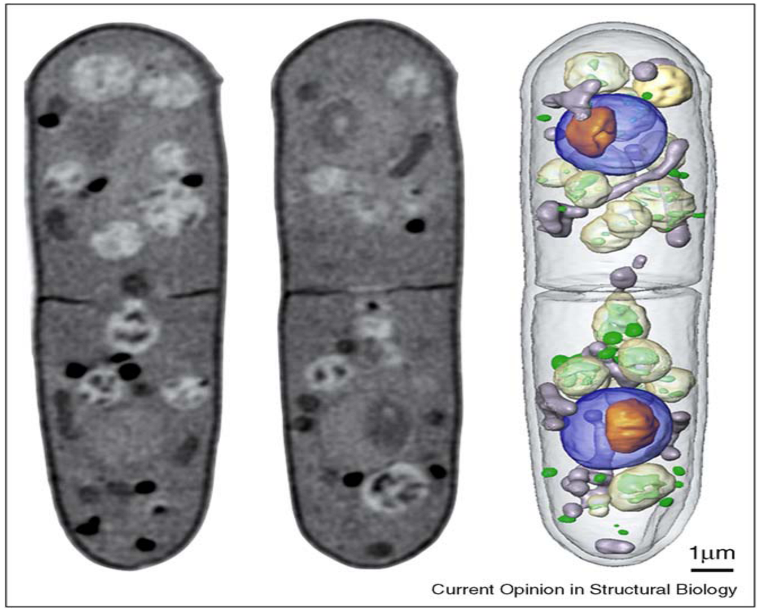
Why water window flash imaging at XFELs?

Optical microscopy: superresolution imaging



Chemical labelling

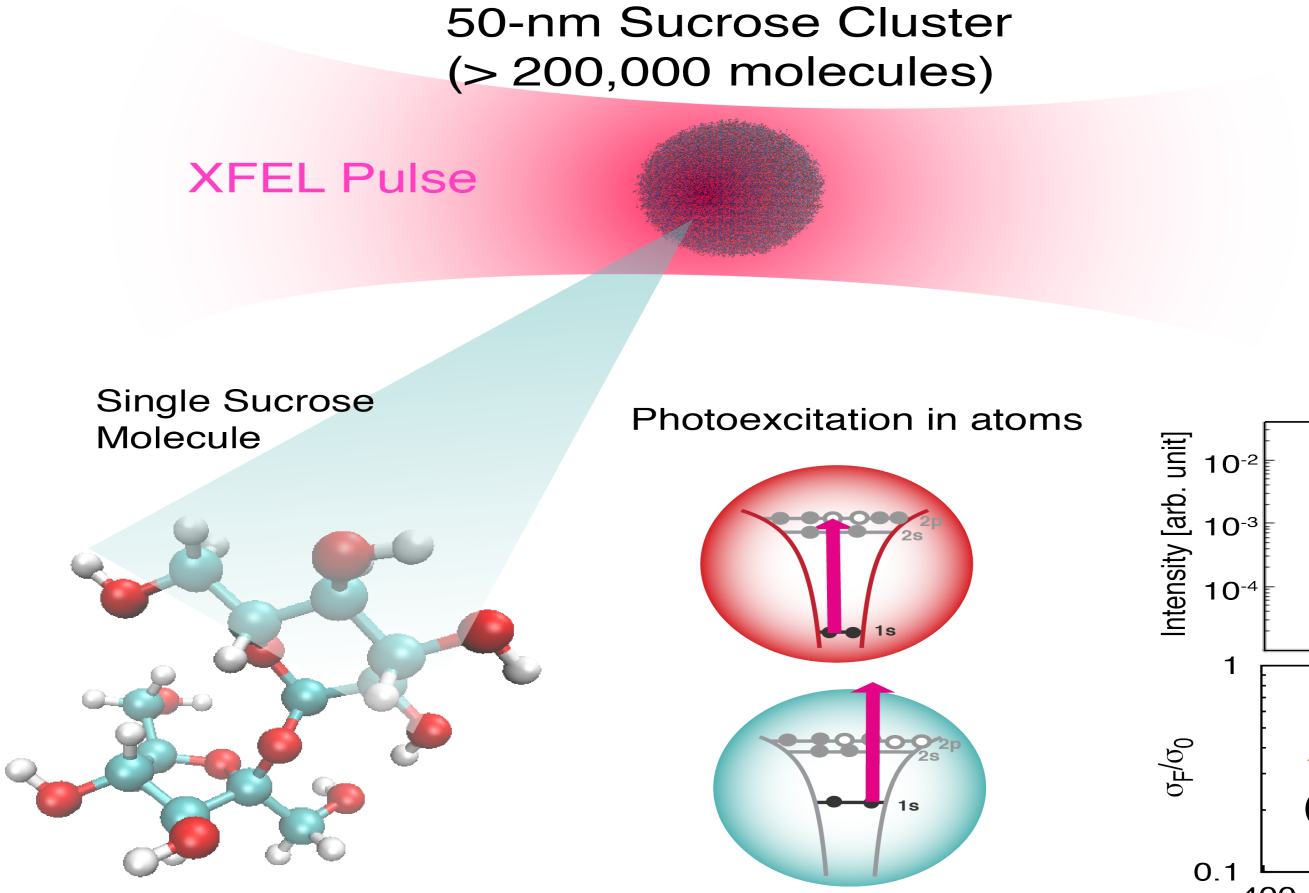
Soft x-ray tomography

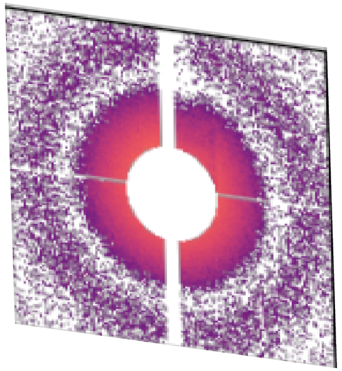


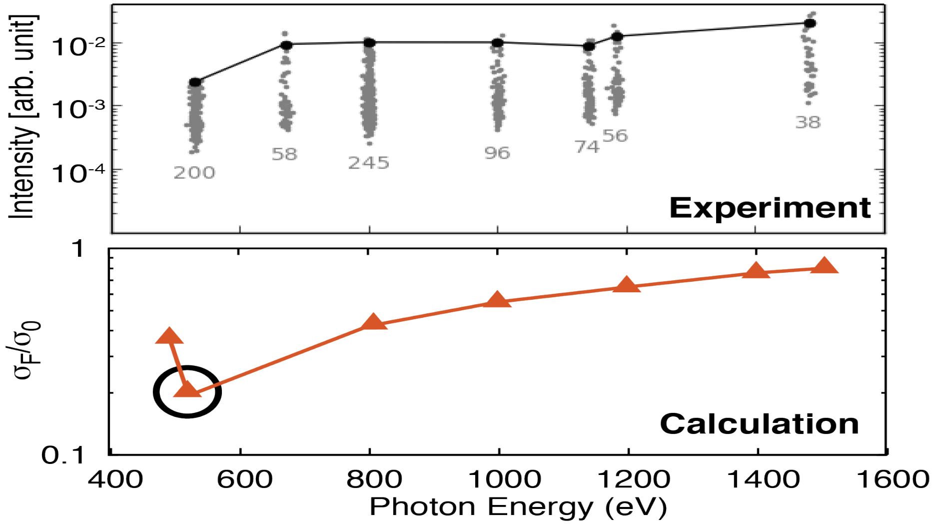
Cryo fixation

XFEL flash imaging has the potential to interrogate cells, viruses .. in native state with nanometer resolution – Janos Hajdu

Imaging just below the oxygen K-edge w/FELs



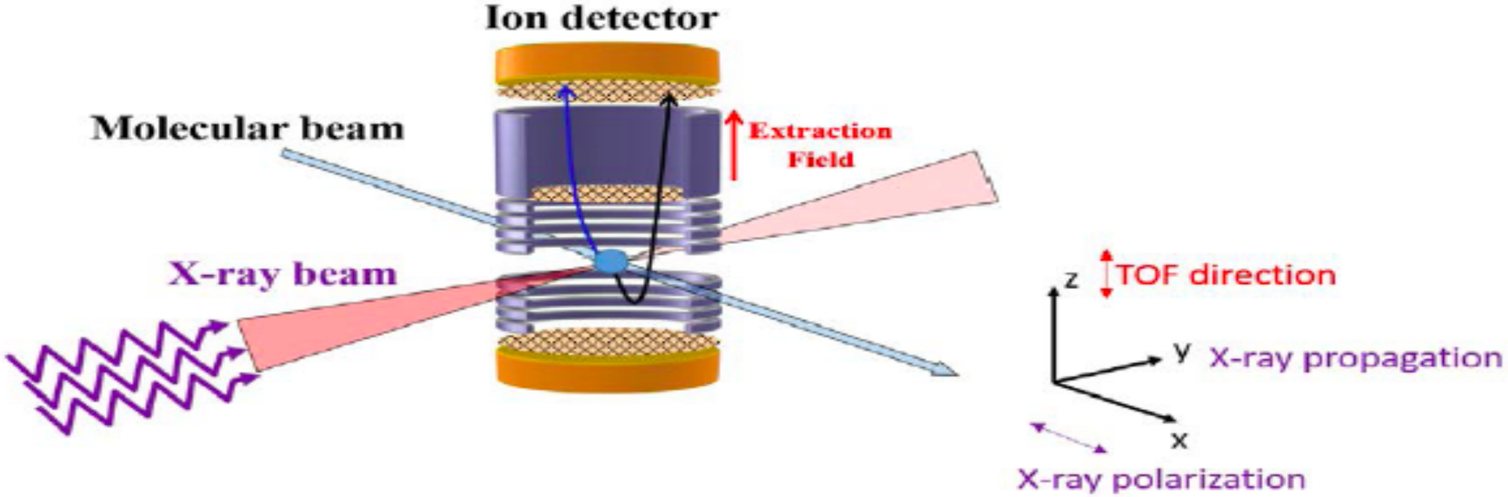




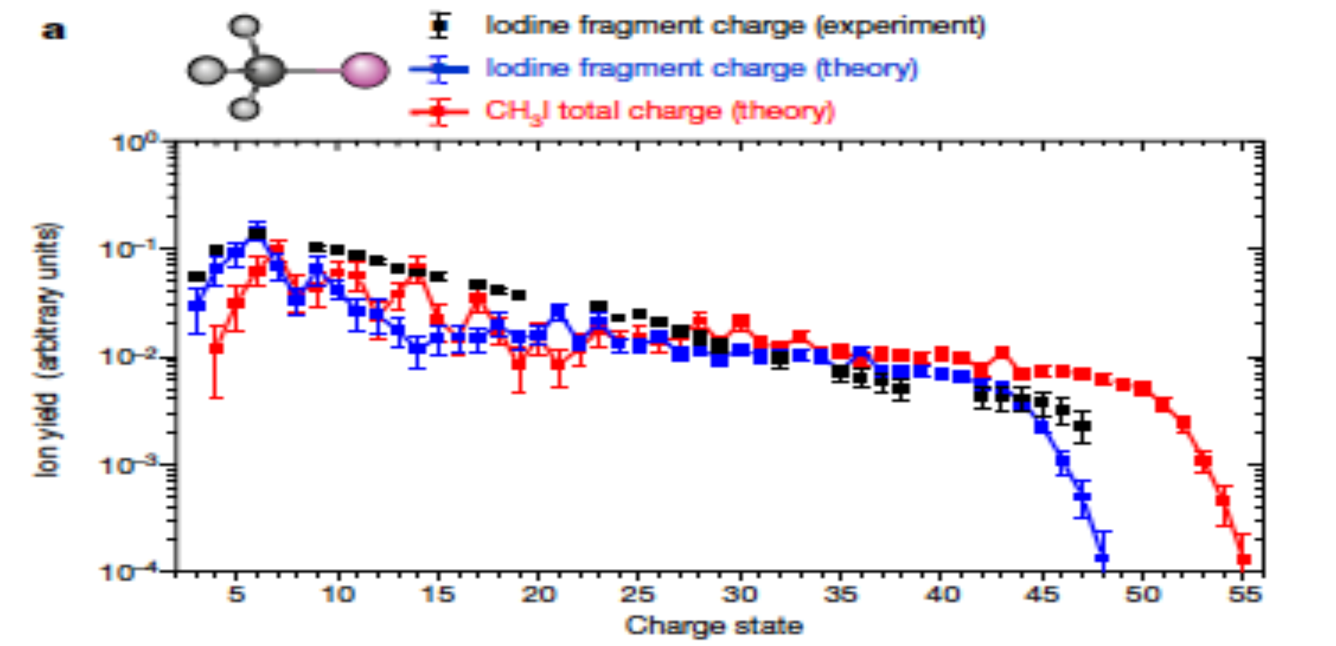
- Resonances just below the oxygen K-edge increase ionization & decrease scattering power
- Pulse duration dependence: 10x decrease scattering power between 2 and 180 fs.

Uppsala expt'l data & Phay Ho calcs

Ultra-intense x-ray interactions in molecules - CH_3I hard x-rays at 10^{20} W/cm^2



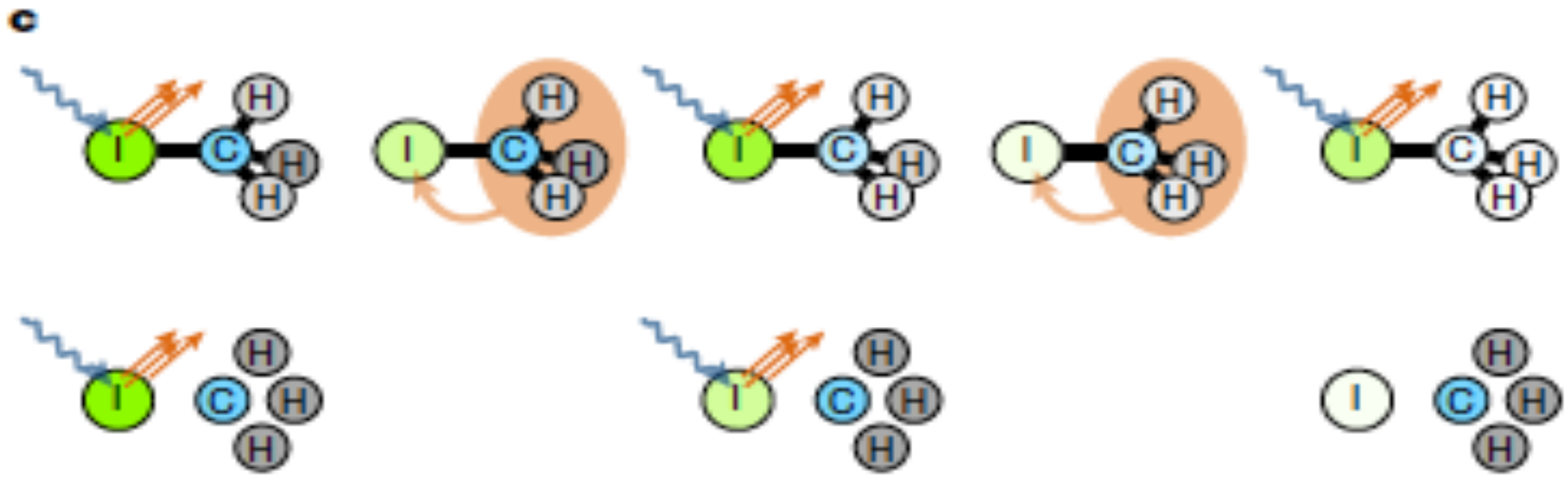
LCLS: CXI instrument
8.3 keV, 30 fs, 1.1 mJ, 0.1 μm^2
10^{20} W/cm^2



- Maximum total charge 54+
- Greater than analogous atom Xe 48+
- Greater than analogous SACLA expt which obtains 22+ w/ 50x less pulse energy

Nature June 1, 2017
Artem Rudenko
Sang-Kil Son

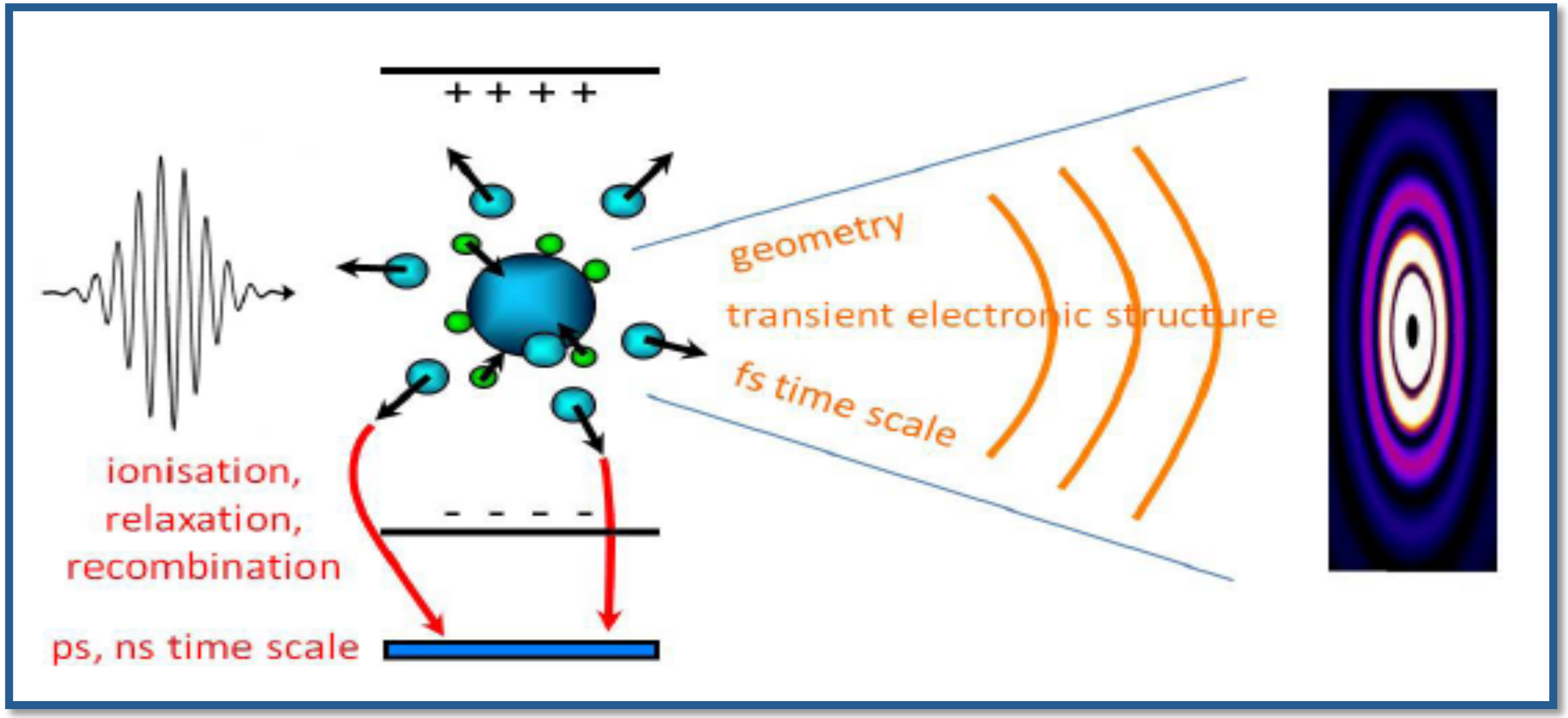
Charge rearrangement enhanced x-ray ionization of molecules: "CREXIM"



- Sequential single photon processes dominate - now with nearby reservoir of electrons.
- XMOLECULE calculates the **molecular** electronic structure – unlike XMDYN
- CREXIM mechanism may be more important in larger molecules and clearly important for radiation damage

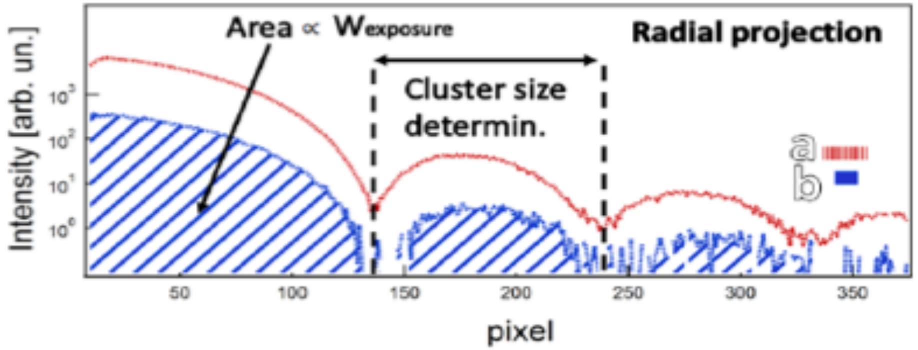
A. Rudenko et al.
Nature **546** 129 (2017)

Expt'l Strategy: spectroscopy + imaging



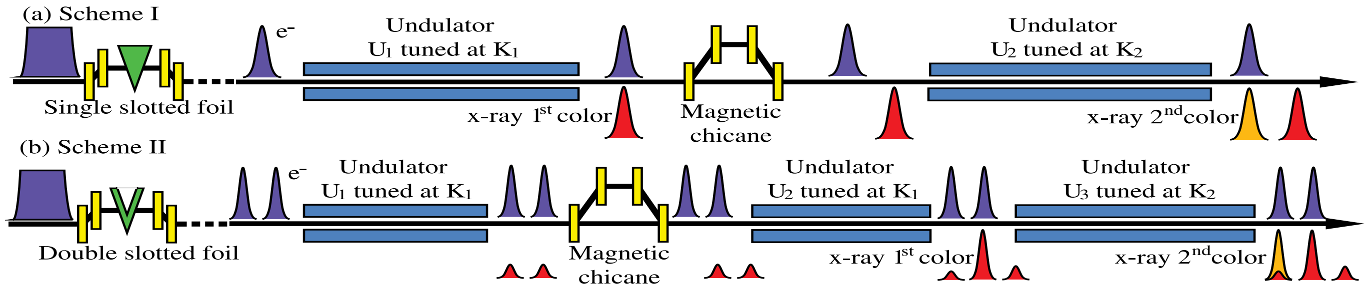
Simultaneous ion yield and x-ray diffractive image
- Ion & electron yields sensitive to pulse integral
- X-ray imaging probes only during the pulse

Cluster size from small angle scattering
Pulse intensity from integral of scattering

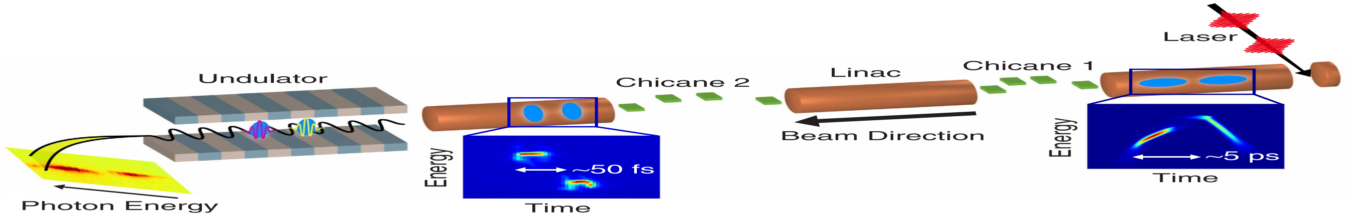


X-ray pump/x-ray probe capabilities at LCLS - I

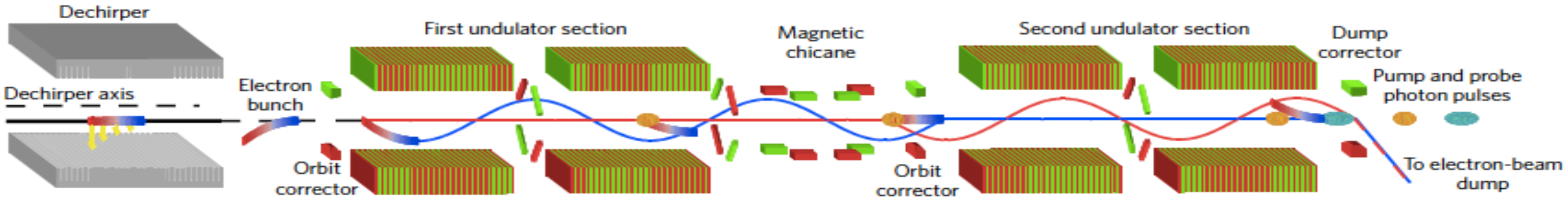
One e-bunch – two x-pulse – two color (Lutman *et al.*, PRL **110**, 134801 (2013))



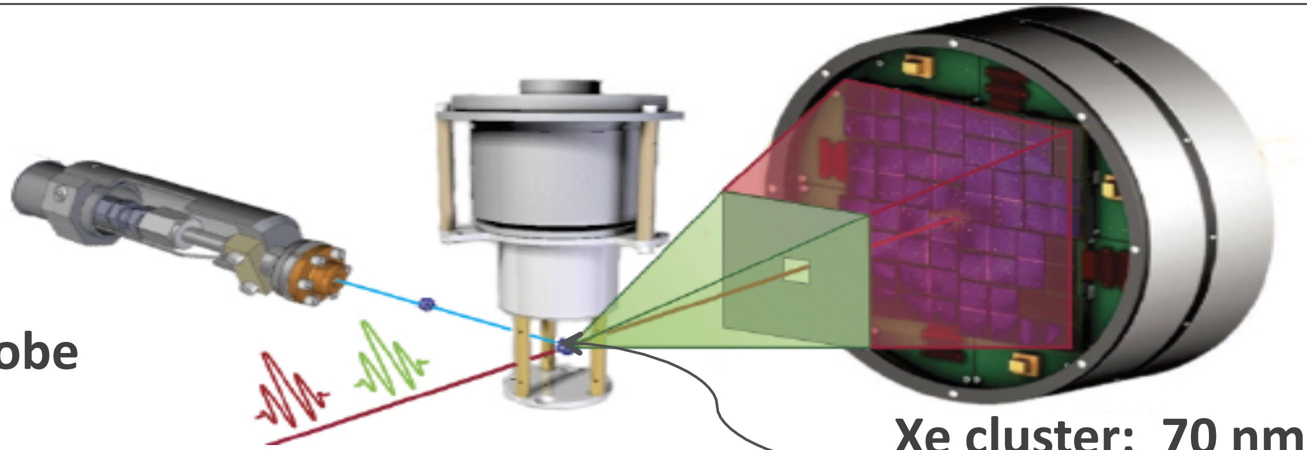
Two e-bunch – two x-pulse – two color (Marinelli *et al.*, Nat. Comm. **6**, 6369 (2015))



Fresh-slice multicolor (Lutman *et al.*, Nat. Photon. **10**, 745 (2016))



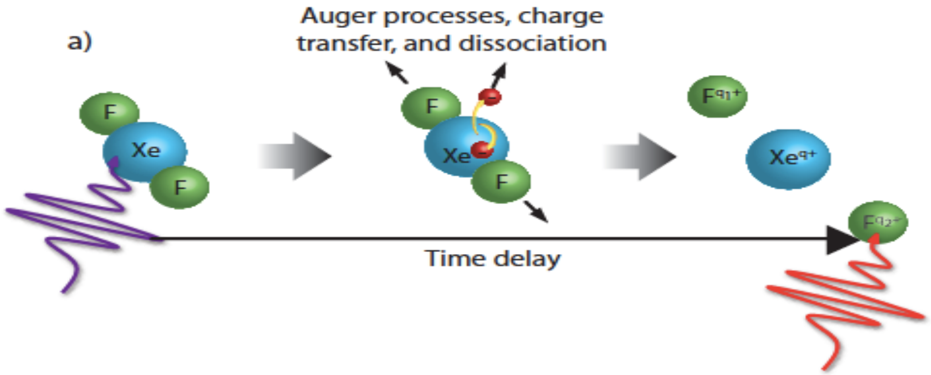
Expt'l strategy II: x-ray pump / x-ray probe



Ferguson … Bostedt
Science Adv. (2016)

X-ray pump / x-ray probe
8.39 keV / 8.31 keV
~10^{12} photons/(200 nm)^2, 10 fs
Δt = 15-80 fs

Xe cluster: 70 nm, 3 x 10^6 atoms
Solid-to-nanoplasma transition
Observed lattice contraction of 3% in 80 fs...



Picon … Southworth
Nat. Comm. (2016)

X-ray pump / x-ray probe
690 eV / 683 eV
~10^{12} photons/5µm^2, 10 fs
Δt = 4, 29, 54 fs

XeF_2
Monitor inner-shell hole dynamics
Observed appearance of F ions following Xe 3d hole creation

Evolution of ultrafast x-ray pump/x-ray probe

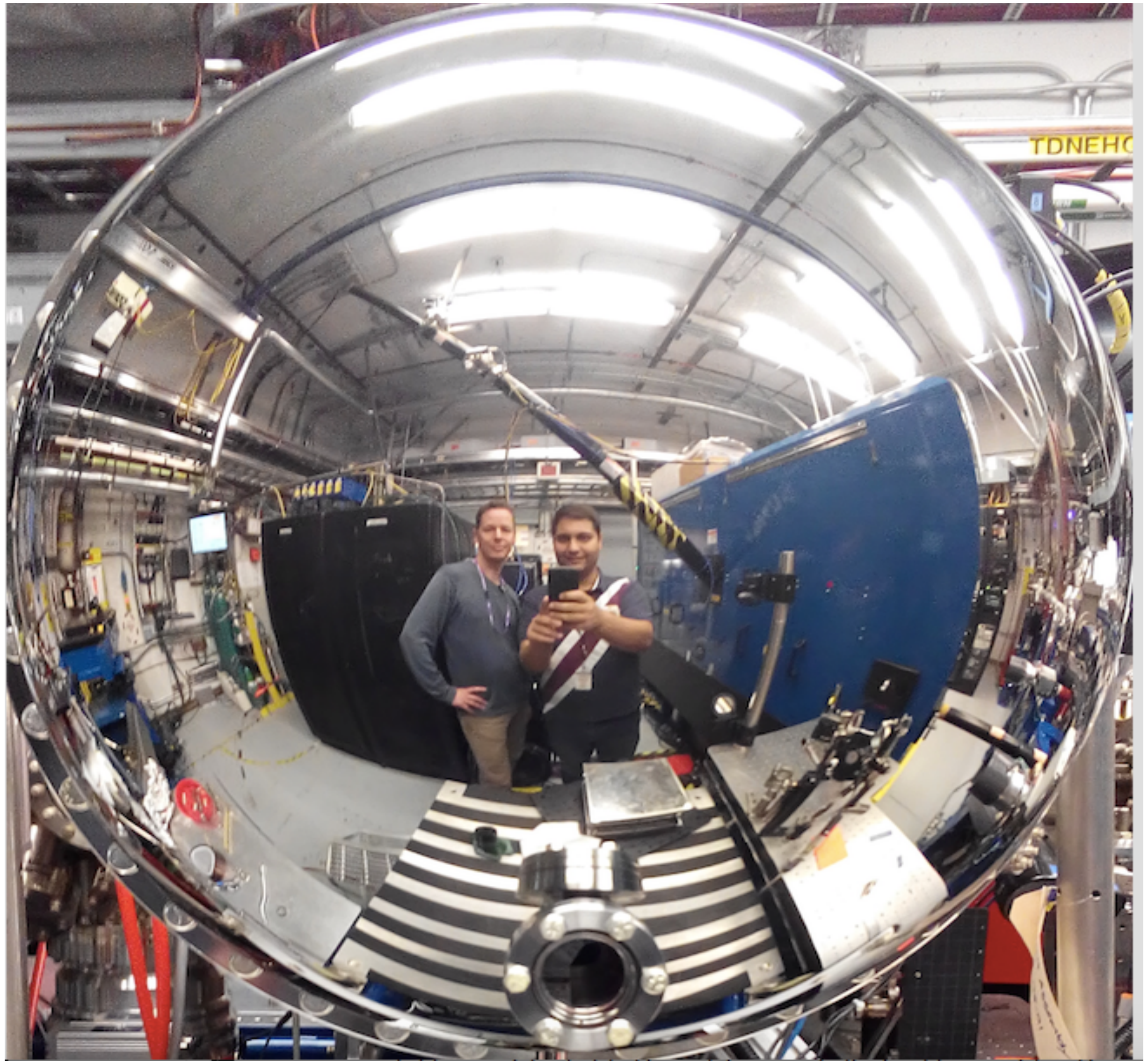
- Two-color -> fresh slice
- Recoil ion -> PES

April 2014: XeF_2 Recoil Ion

690 eV, 683 eV
~30 μJ, 10 fs
Δt = 4, 29, 54 fs

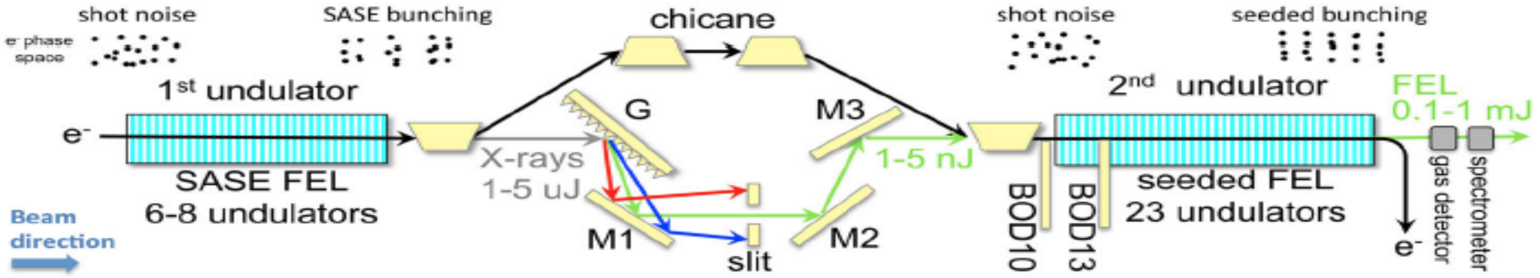
Nov 2016: CO Photoelectron Spec

535 eV, 525 eV
~500 μJ, pump 5-10 fs, probe 5 fs
Δt = -10, +10, +40 fs

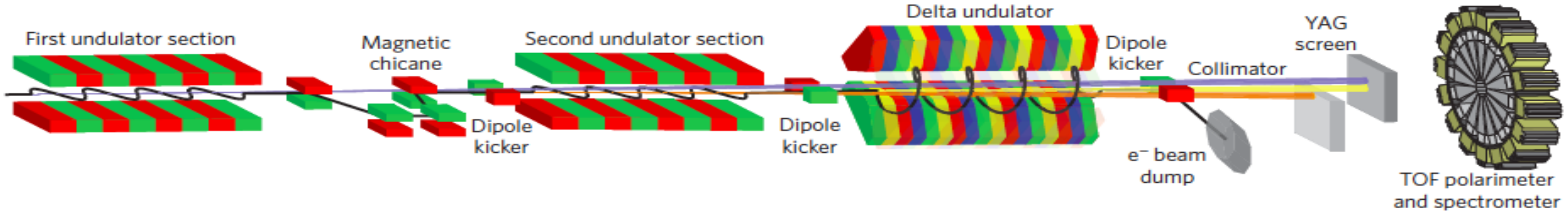


More XFEL capabilities becoming available

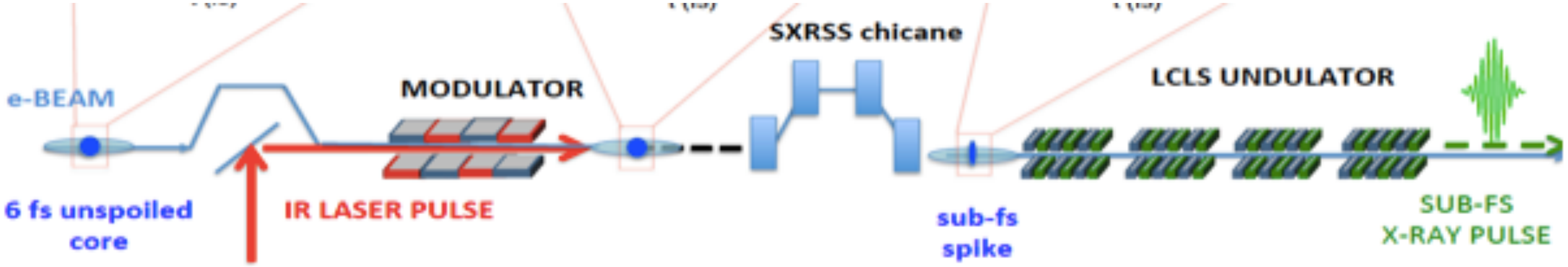
Seeded soft x-ray beam (Ratner *et al.*, PRL **114**, 054801 (2015))



Polarization control: 2 pulse – 2 color (Lutman *et al.*, Nat. Phot. **10**, 468 (2016))



Attosecond pulses : XLEAP --- A. Marinelli, A. Zholents ...



International hard X-ray FELs here and on the horizon

SACLA Image Gallery

PAL POHANG ACCELERATOR LABORATORY

SwissFEL

European XFEL

Summary

- AMO physics expts & theory have established fundamental understanding of the response of matter to ultraintense XFEL irradiation

  - sequential single (multi) photon ionization dominates
  - intensity-induced x-ray transparency (frustrated absorption)
  - intense x-rays can "control" inner-shell electron dynamics
  - resonances can be critical in XFEL interactions

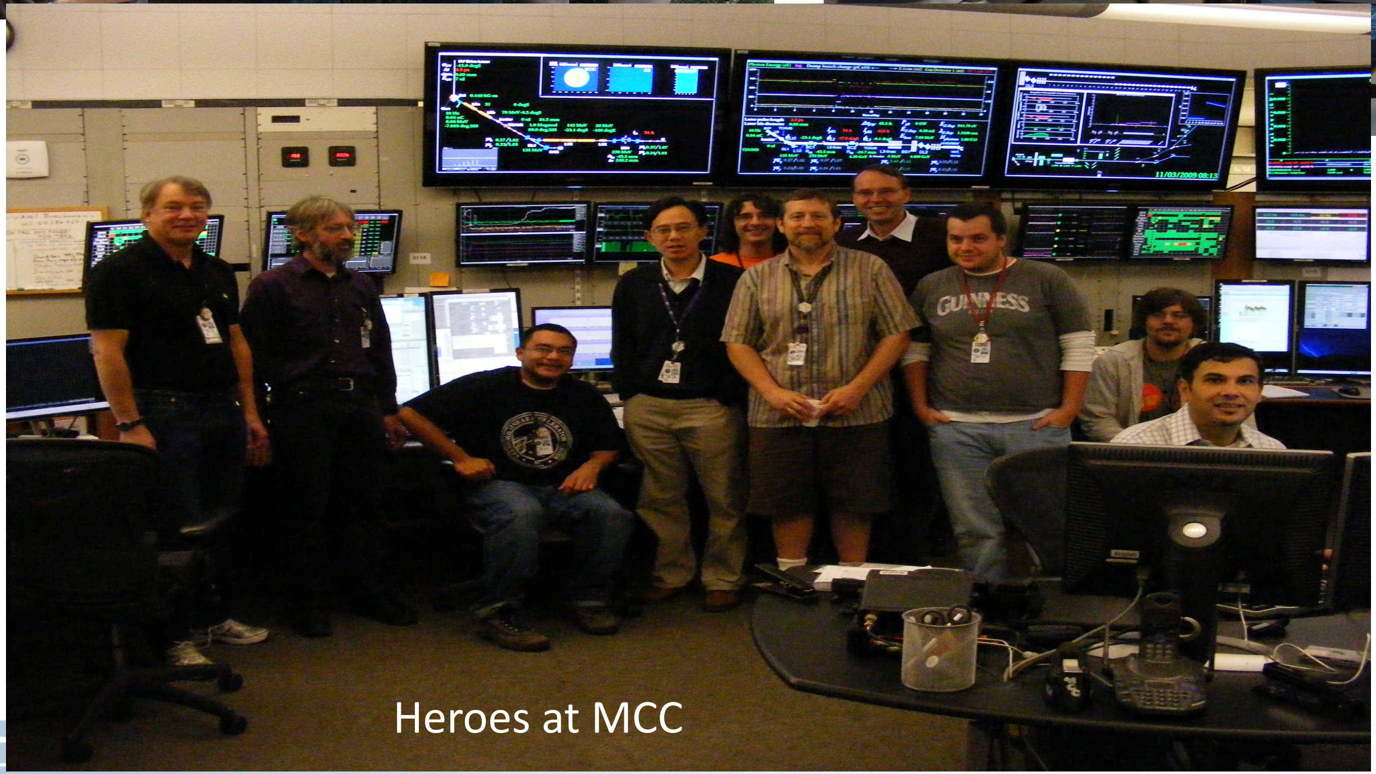
- This understanding will aid in the quest for single molecule imaging and other applications, e.g. high energy density matter

  -AMO methods (ion, electron, photon) in concert with theoretical & computational studies promise fuller understanding of radiation damage in extended systems

- Future is bright with better-characterized ultraintense x-ray lasers, multiple pulse configurations, attosecond pulses, high repetition rates …


Argonne AMO group Oct 2009


Heroes at AMO Control


Heroes at MCC

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Jacek Krzywinski
Dipanwita Ray
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Sang-kil Son
Ludger Inhester
Nina Rohringer

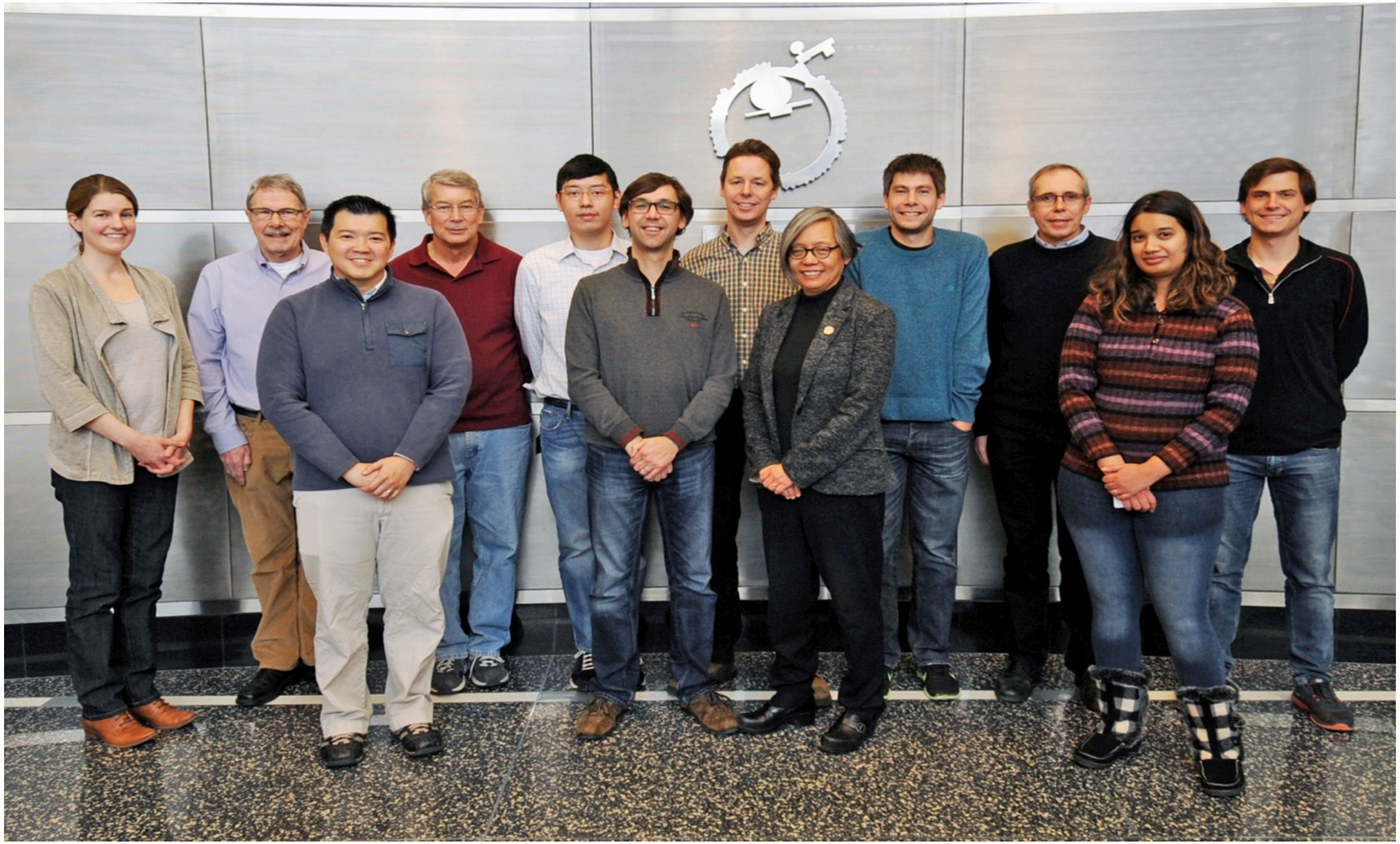
KSU
Artem Rudenko
Daniel Rolles

UConn
Nora Berrah

OSU
Lou DiMauro

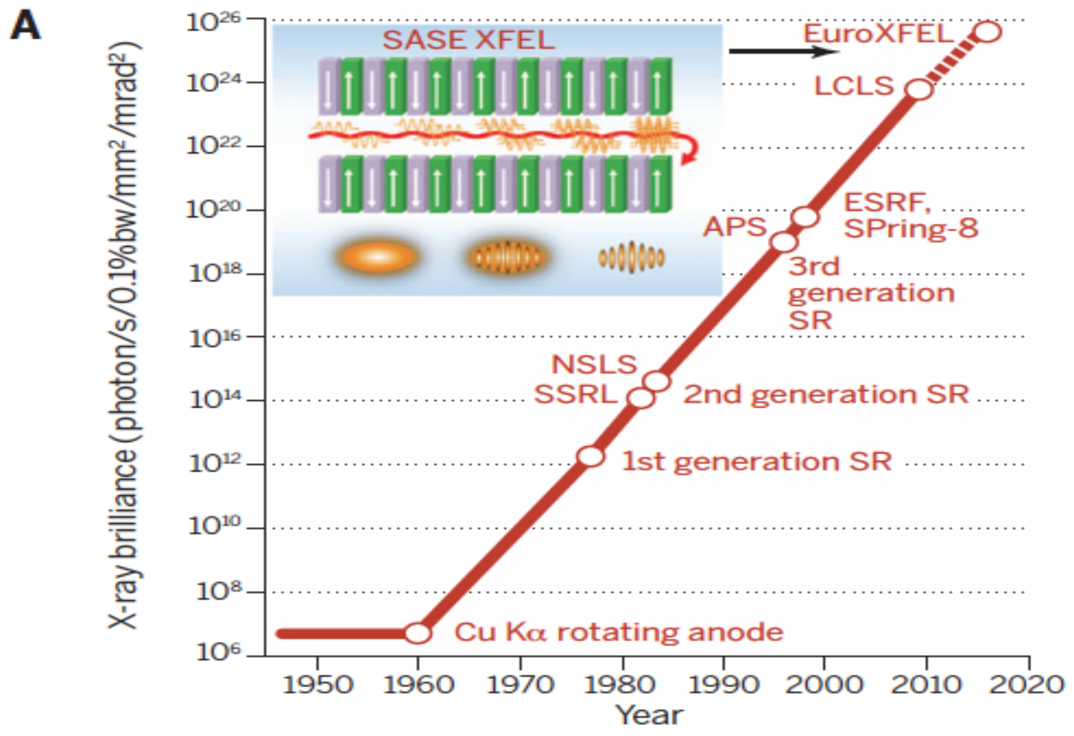
And many others …

Argonne AMO Group

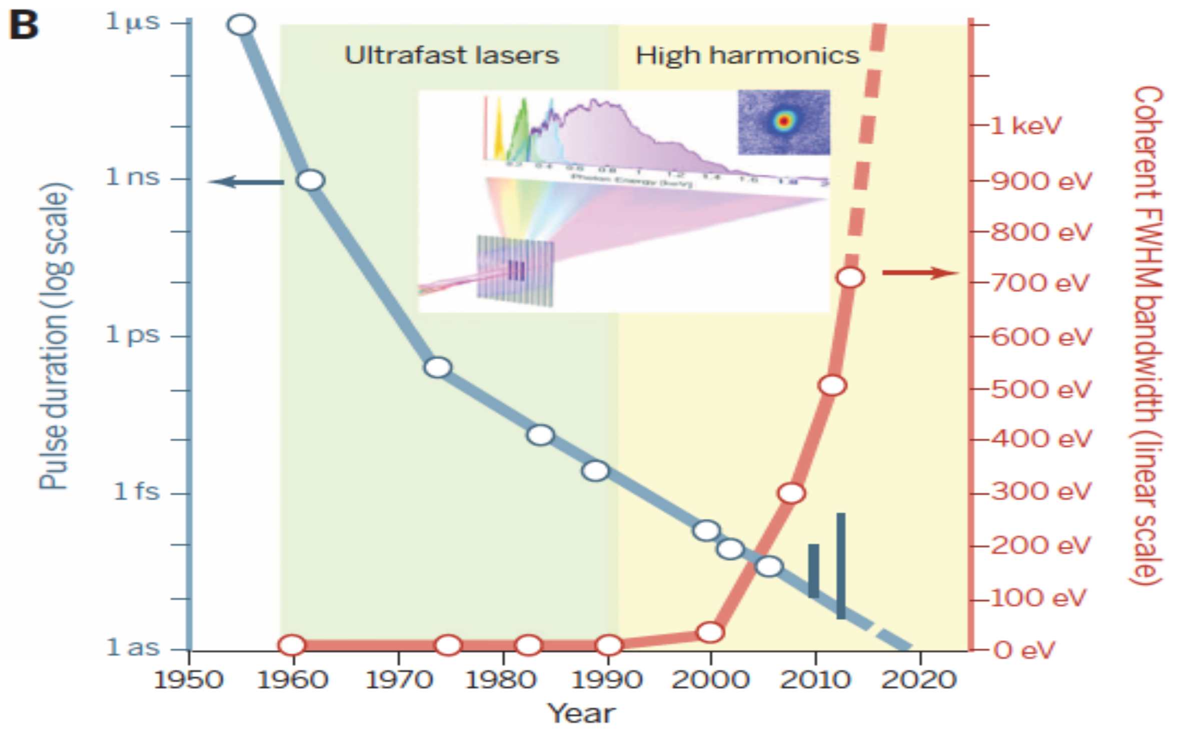


Christoph Bostedt, Gilles Doumy, Bob Dunford, Phay Ho, Elliot Kanter, Bertold Krässig, Anne Marie March, Antonio Picon, Steve Southworth, Linda Young, Max Bucher, Yuan Gao, Dooyshaye Moonshiram

X-ray sources: accelerator-based vs laser-based HHG



10^{13} x-rays/pulse/1% BW @ 1 keV
~100 fs



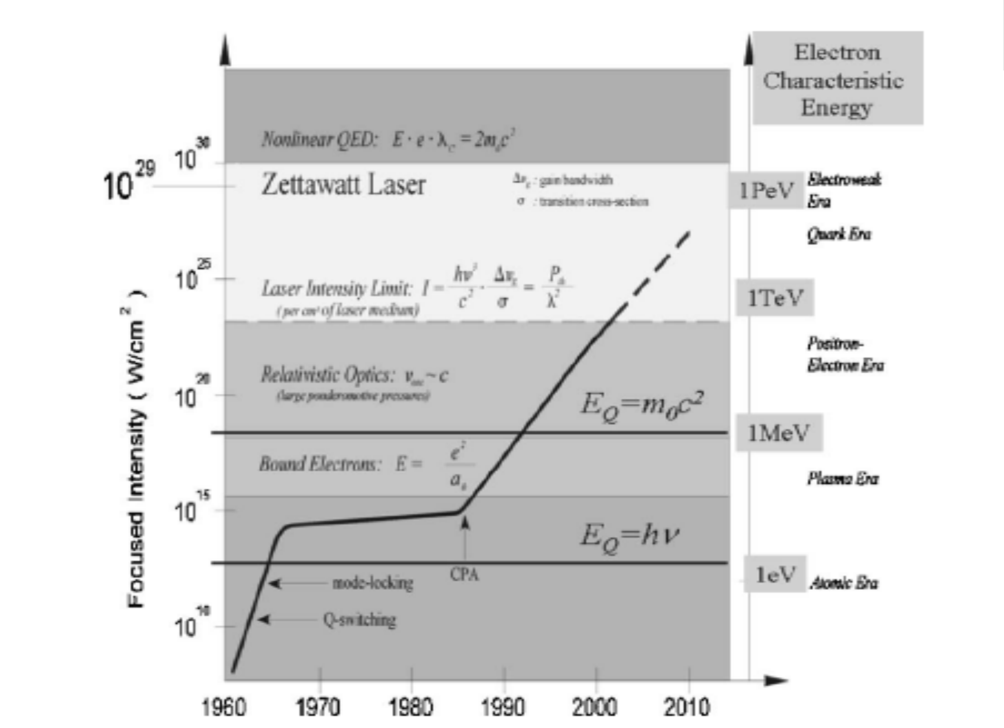
10^5 x-rays/pulse/1% BW @ 1 keV
~1 fs

XFELs 10^8 “brighter” than HHG sources
HHG pulses 100x shorter & self-synchronized w/pump laser

From: Miao, Ishikawa, Robinson, Murnane, Science **348**, 530 (2015)

Compare ultraintense optical and x-ray sources

Hign-intensity at optical wavelengths
- high harmonic generation
- tabletop coherent x-ray radiation
-



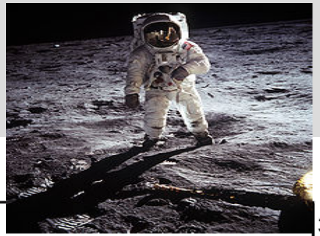
G. Mourou RMP 2006

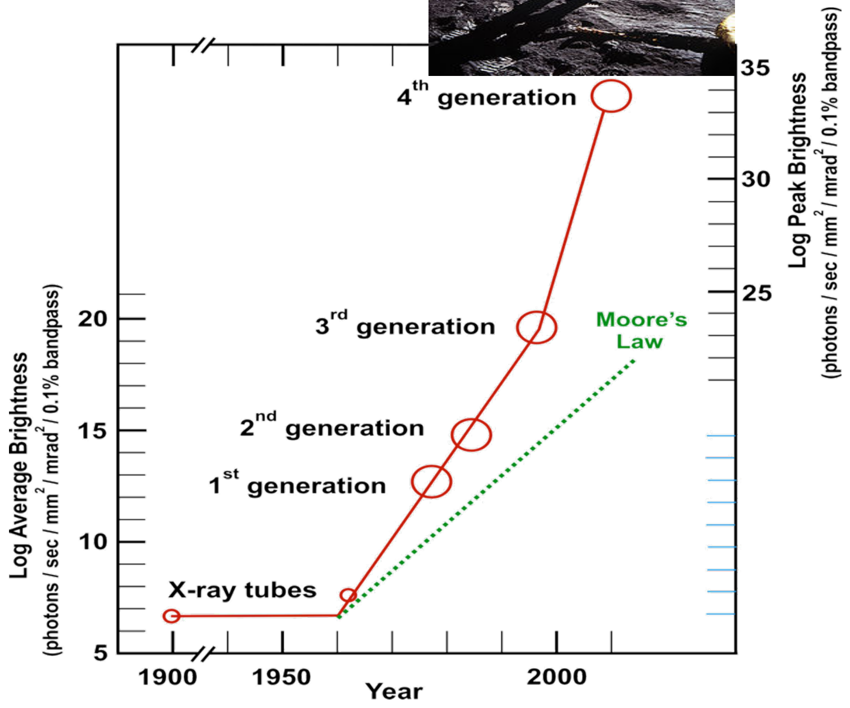
High-intensity at x-ray wavelengths

?

?

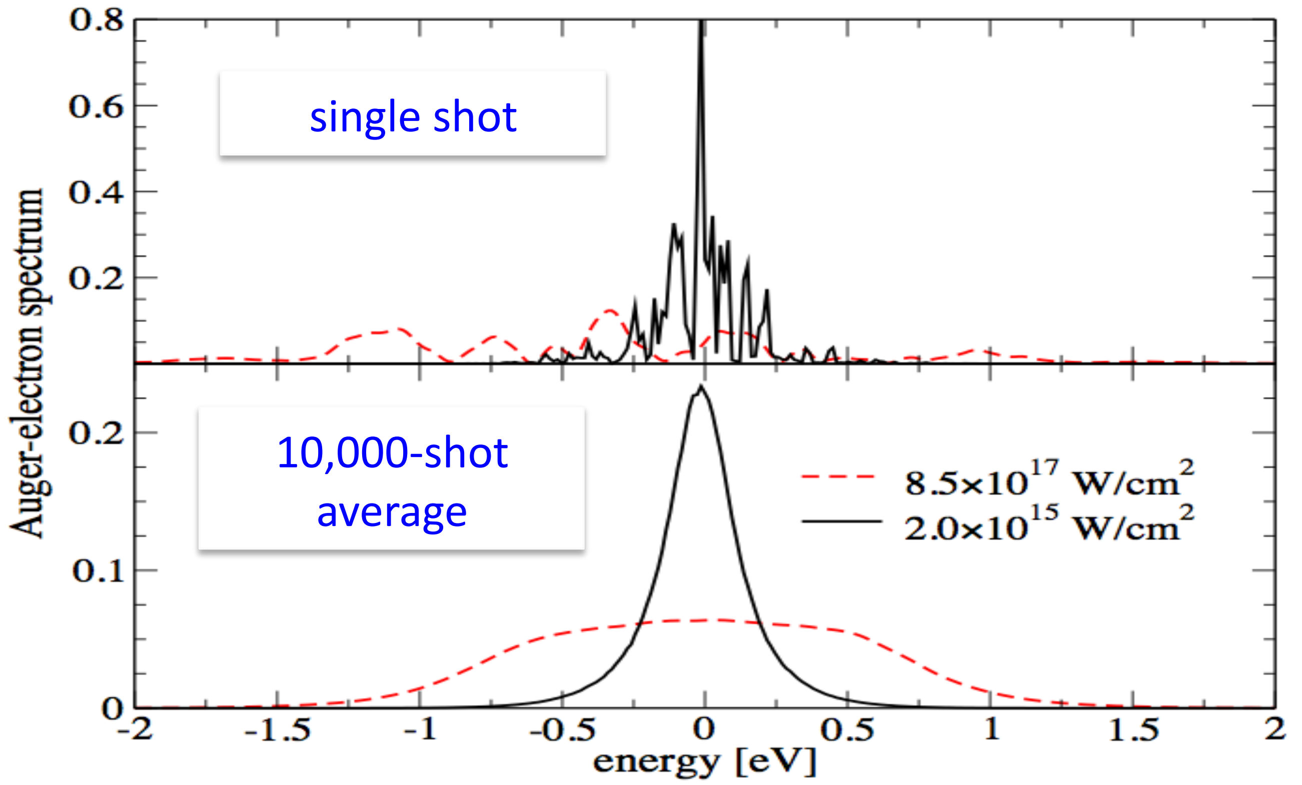
?





D. Moncton, George Brown

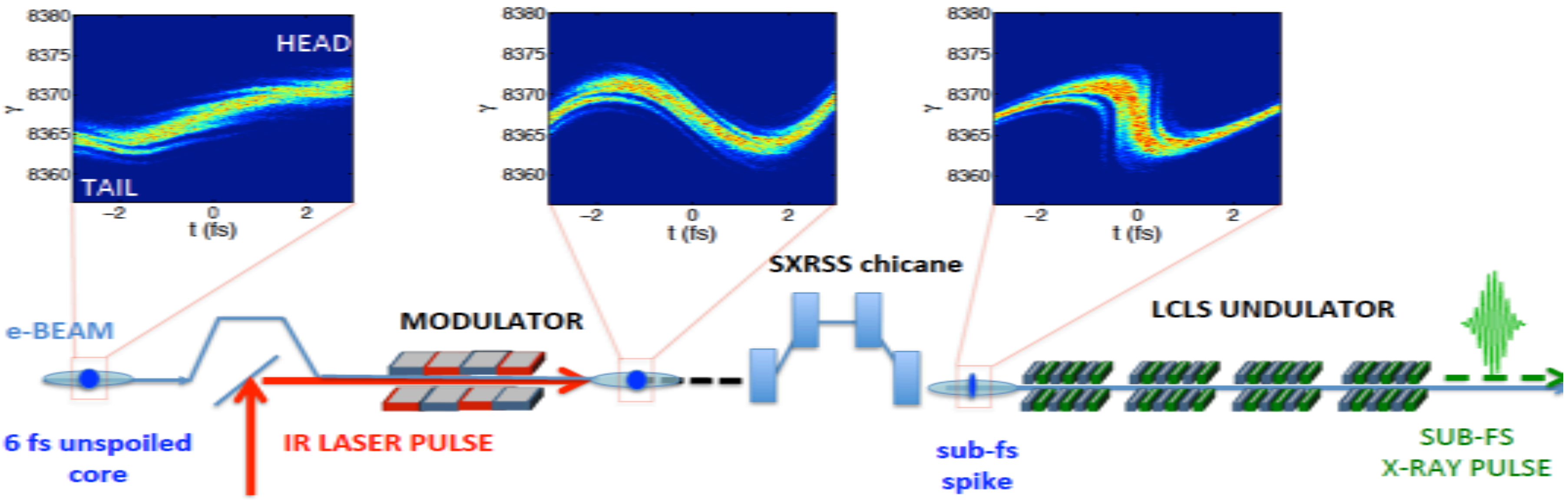
Calculated "Resonant Auger effect at high x-ray intensity"



-> Look for Auger line broadening on resonance

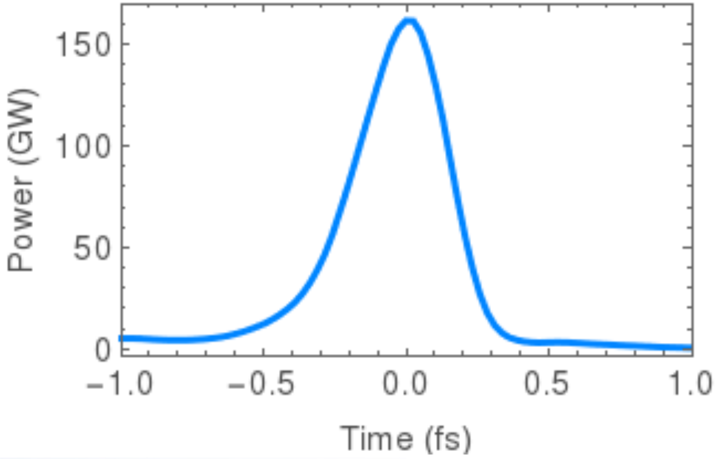
N. Rohringer & R. Santra, PRA 77, 053404 (2008)

XLEAP



Enhanced SASE
Use intense IR pulse in a wiggler to compress a fraction of the electron beam.
(A. Zholents, 2005)

DT = ~0.5 fs FWHM, E_{pulse} ~ 20 to 50 uJ
- 10x shorter than fastest pulse measured at LCLS.
- 4 times shorter than typical cooperation length.



From R. Schoenlein – atto @ LCLS initiative