PULSE STANFORD

NSF Panel on Light Source Facilities
AMO Physics Applications:
a fruitful partnership

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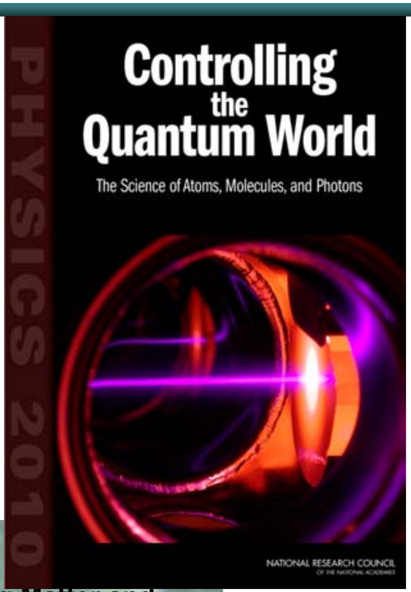
Wednesday, January 10, 2008

Resources on AMO Research in 2010 and Beyond

- AMO 2010: Controlling the Quantum World
  - National Academy decadal survey



- Controlling Matter and Energy: Five Challenges for Science and the Imagination
  - Report from the Basic Energy Sciences Advisory Committee (BESAC)

Frontier areas of AMO

- High precision clocks – the precision time frontier.
- Imaging quantum processes on ultrafast time scales – the attoscience frontier
- Coherent molecular dynamics – the quantum control frontier
- Quantum computing and quantum communication: the quantum information frontier
- Atomic physics in exotic environments: the high field and high energy density frontiers
- Ultralow temperature phenomena: the frontier of quantum degenerate atomic gases

Areas that make use of light source facilities

- High precision clocks – the precision time frontier.
- Imaging quantum processes on ultrafast time scales – the attoscience frontier
- Coherent molecular dynamics – the quantum control frontier
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- Atomic physics in exotic environments: the high field and high energy density frontiers
-

The facilities of interest for AMO frontier physics

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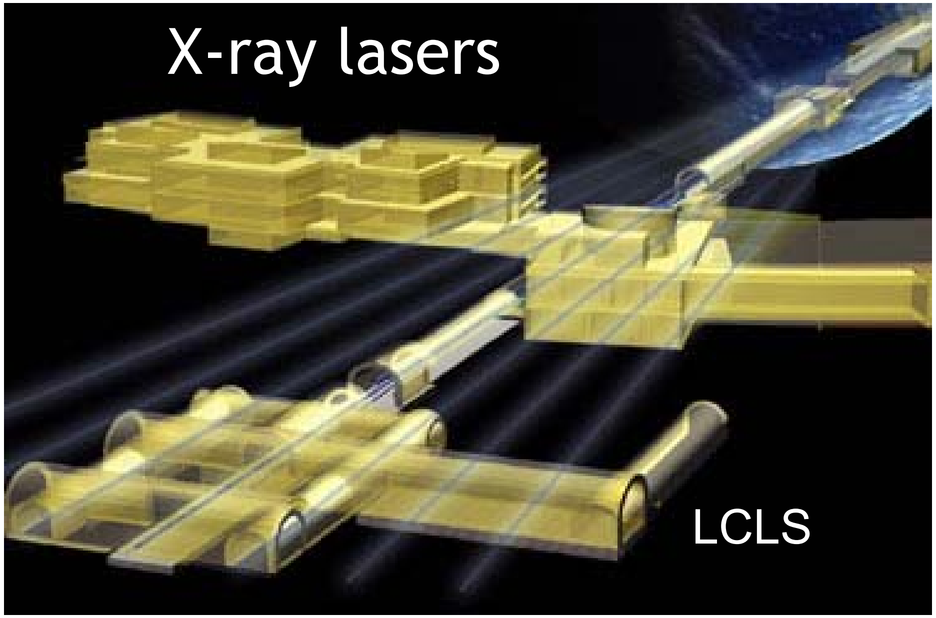
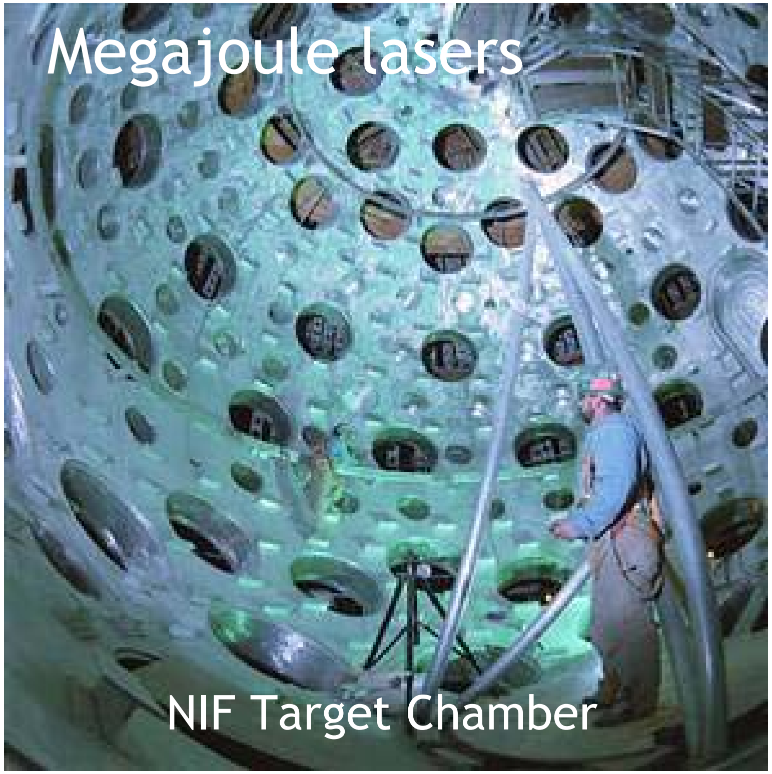
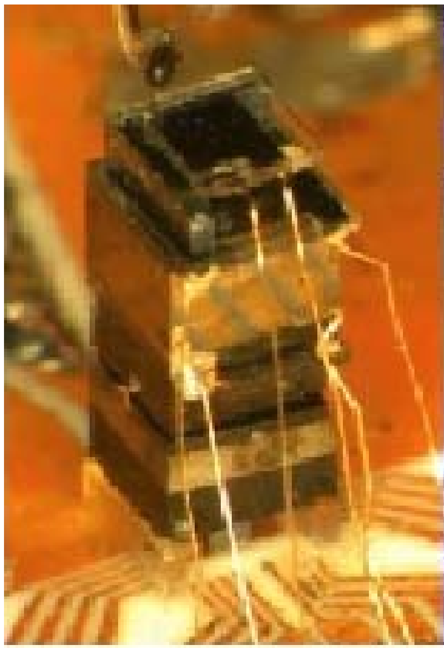




Smaller centers also contribute petawatt lasers for collaborative use (Texas Petawatt, FOCUS)

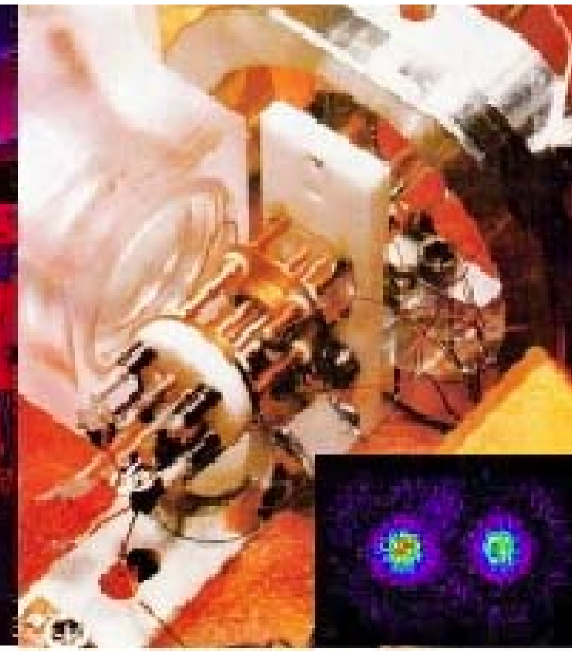
Atomic Clocks

From military navigation to fundamental physics, atomic clocks are central.



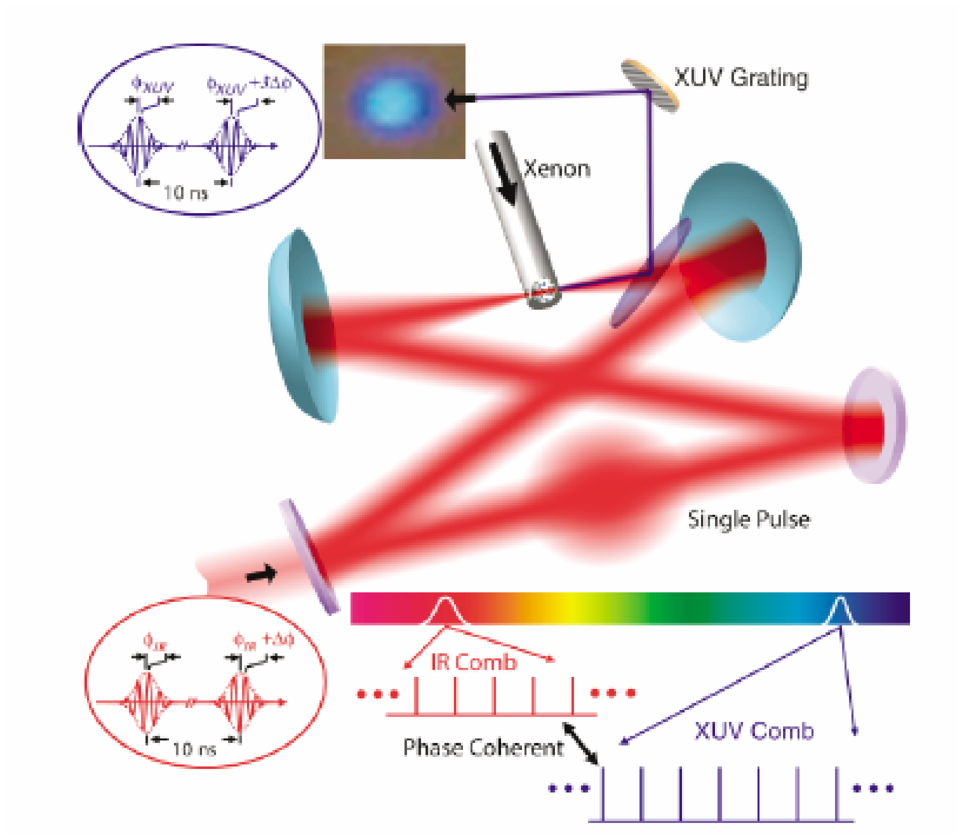
Atomic clock in a 1 mm^3 volume

U.S. primary frequency standard: Cs atomic fountain clock, accurate to 5×10^{-16} or 1 second in 60 million years



Optical frequency standards (Nobel ’05) are the future of atomic clocks

Connection I: Precision VUV Metrology



Jones et al. PRL 94, 193201 (2005)

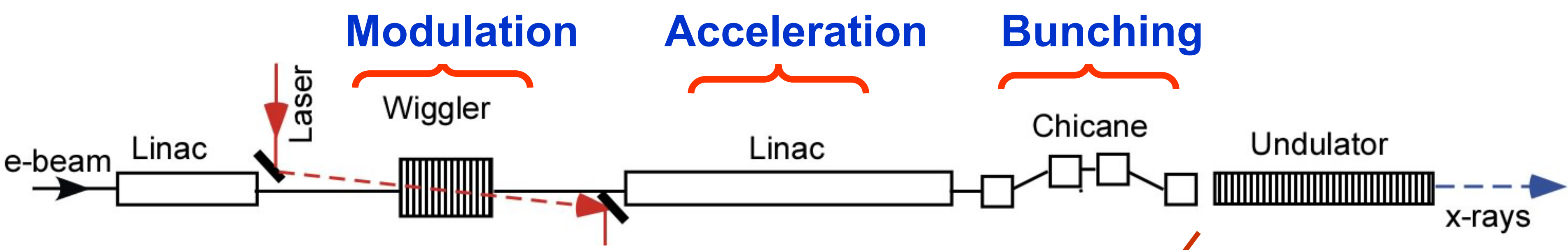
Applications:

Precision vuv atomic spectroscopy

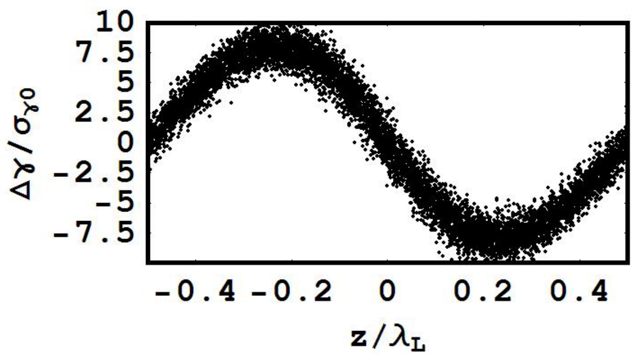
Optical time standard

Time variations of fundamental processes

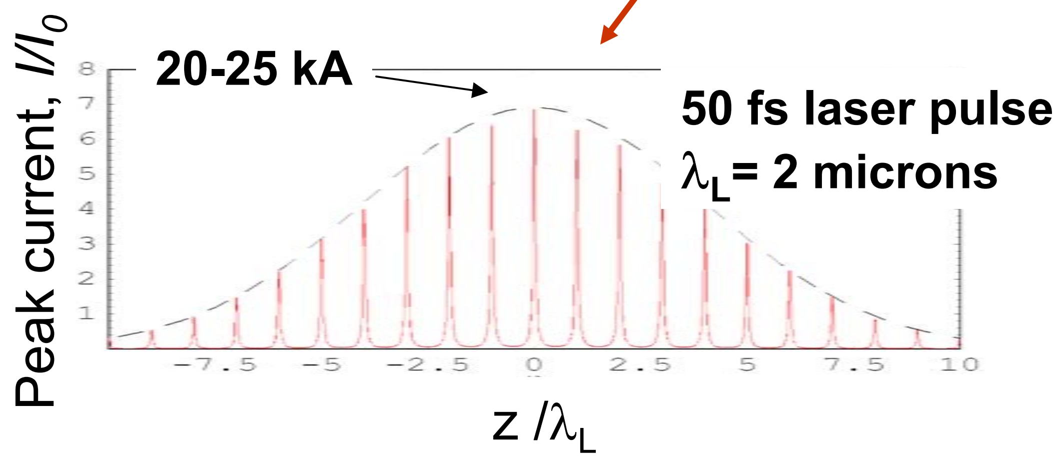
Connection II: Attosecond precision to tame the SASE FEL



Energy modulation in the wiggler at ~ 4 GeV



Only one optical cycle is shown

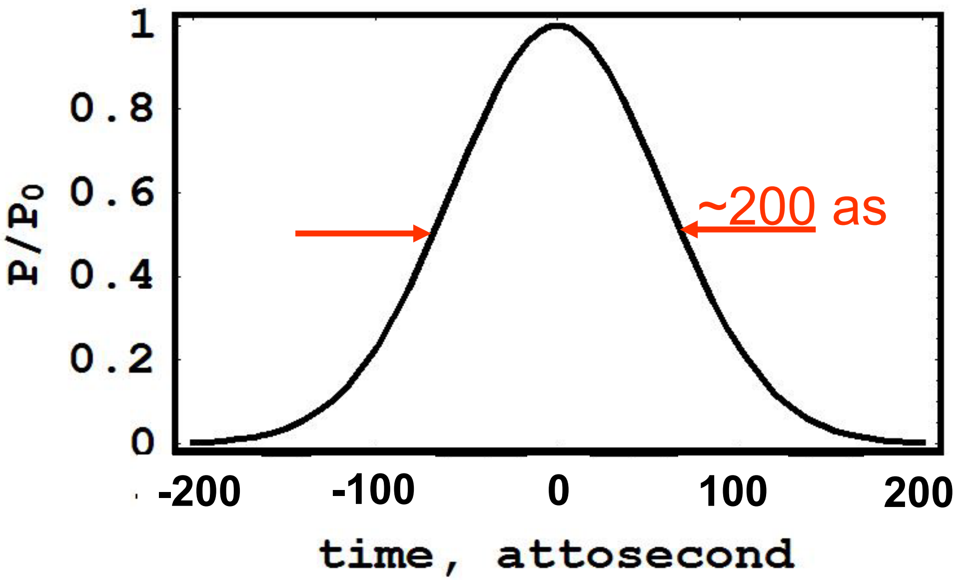


- **Laser peak power ~ 10 GW**
- **Wiggler with ~ 10 periods**

- **Electron beam after bunching at optical wavelength**

P. Emma, W. Fawley, Z. Huang, S. Reiche, G. Stupakov, A. Zholents

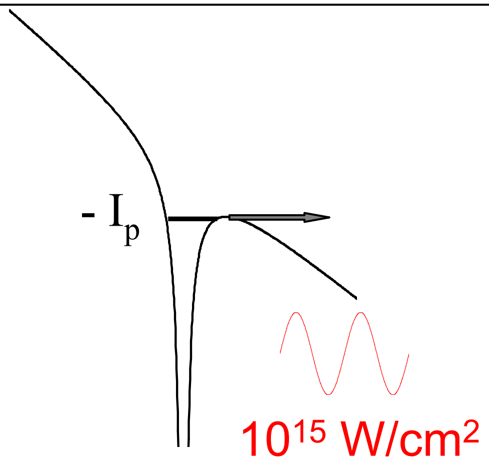
The output x-ray radiation from a single micro-bunch



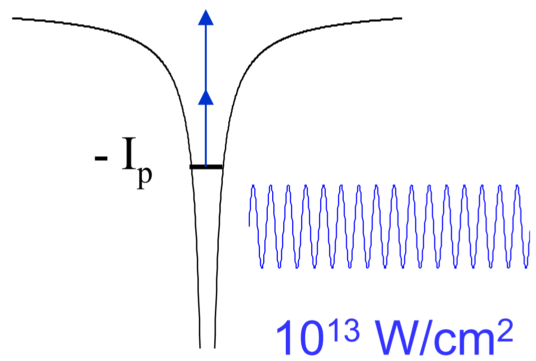
- Each spike is nearly temporally coherent and Fourier transform limited
- Carrier phase for an x-ray wave is random from spike to spike, but HGHG injection schemes could overcome this
- Pulses less than 100 attoseconds may be possible with 800 nm laser

High Field Frontier: Changing Strong Field Regimes Inside Atoms

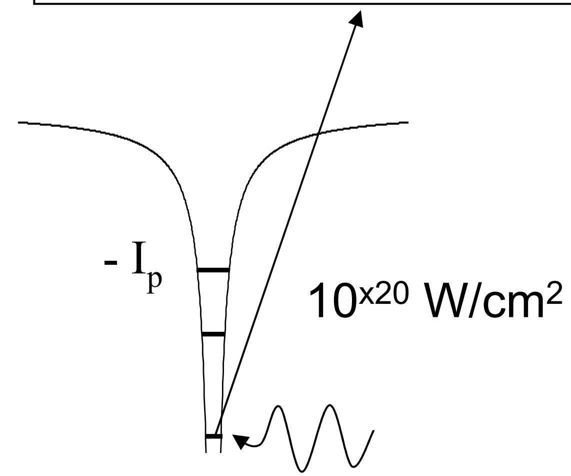
IR: Low frequency regime	VUV FEL: Intense photon source	X-RAY FEL: Highly ionizing source



$$\Gamma_{e-A+} > \omega_{laser}$$
$$U_P > \hbar\omega_{laser}$$
$$\Gamma_{n\gamma\to e-A+} \approx \Gamma_{n+1\gamma\to e-A+}$$
ATI, HHG

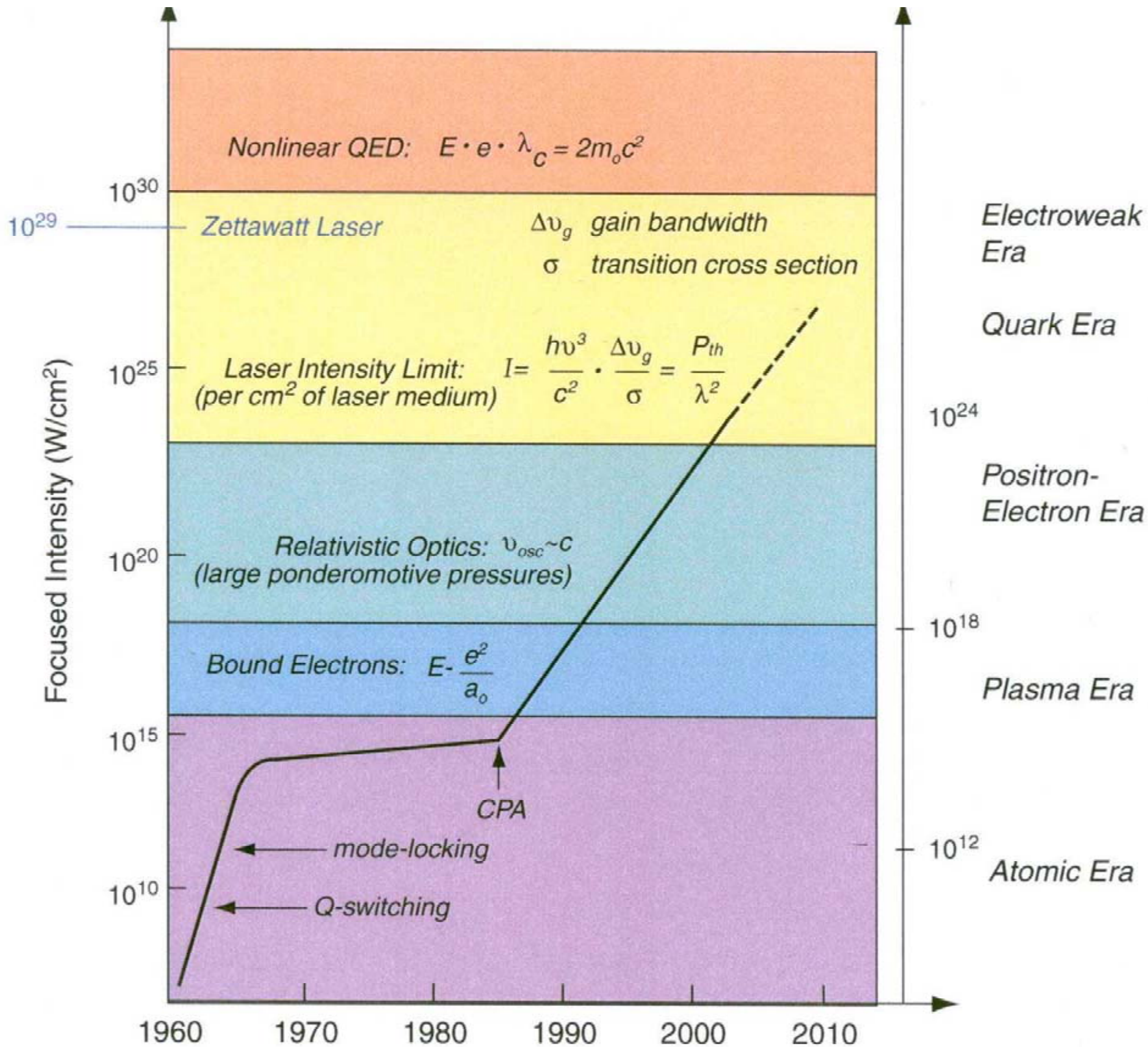


$$\Gamma_{e-A+} < \omega_{laser}$$
$$U_P << \hbar\omega_{laser}$$
$$\Gamma_{e-A+} \approx \Gamma_{2e-A++}\ ?$$
sequential vs. non-sequential



$$\Gamma_{e-A+} << \omega_{laser}$$
$$U_P << \hbar\omega_{laser}$$
$$\Gamma_{e-A+} \approx \Gamma_{Auger}, \Gamma_{2e-A++}$$
Hollow atoms?

Laser Power Beyond a Petawatt can access Relativistic Strong Field Physics



Relativistic photoionization and rescattering of photoelectrons and ions

Can the LCLS get to its own type of strong-field regime?

- impose a Keldysh parameter of one

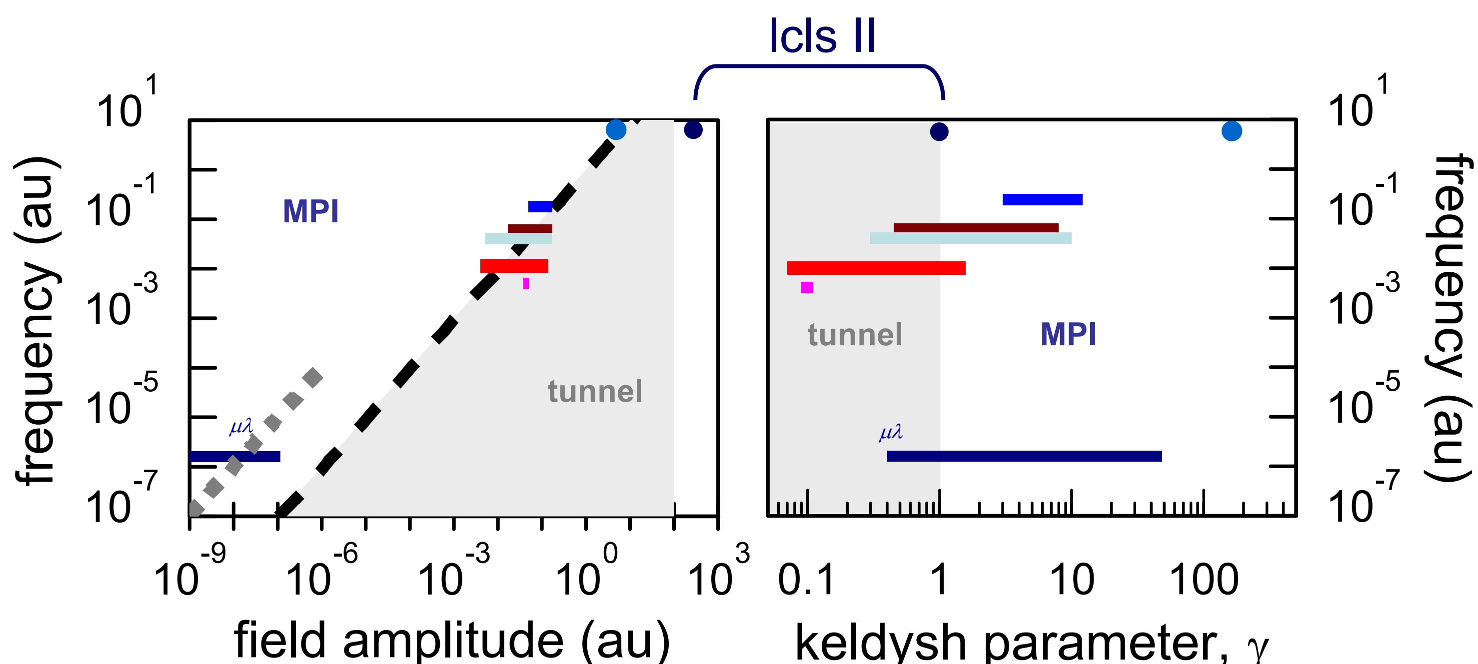
  $\gamma \equiv 1 = (I_p/2U_p)^{1/2} \Rightarrow U_p \cong 400$ eV (8 eV)

  @ 800 eV, intensity needed is 10^{21} W/cm^2 (10^{14} W/cm^2)

  number of photons is fixed, require tighter focus and shorter pulse

  τ_{lcls} ~ 10 fs (*very possible*)

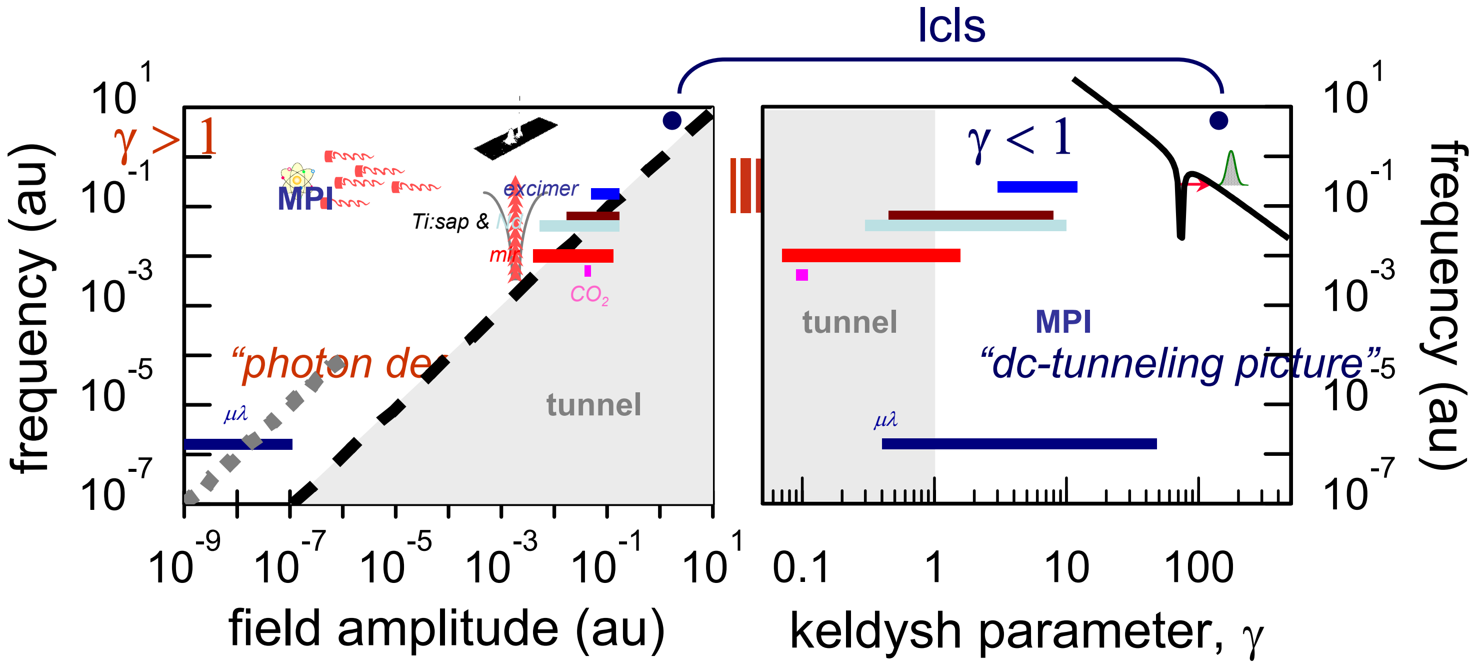
  thus require a beam waist of 50 nm (in principle possible)



Strong field wavelength scaling:

Keldysh picture

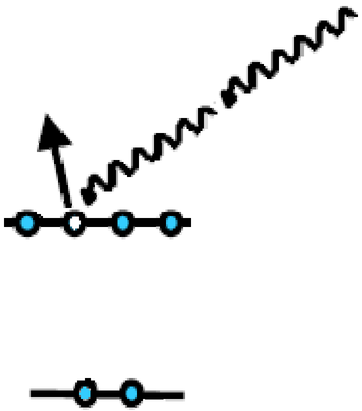
$$\gamma \equiv \frac{\text{optical frequency}}{\text{tunneling frequency}} = (I_p/2U_p)^{1/2} \propto \lambda^{-1}$$



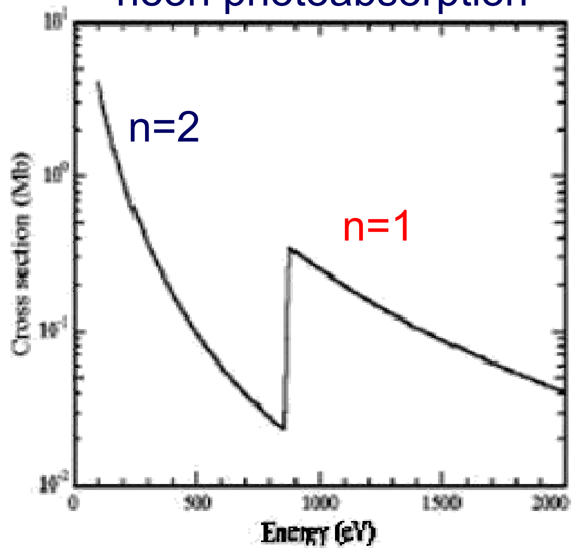
- data compiled based on both electron and ion experiments

Physics comes from inner shells

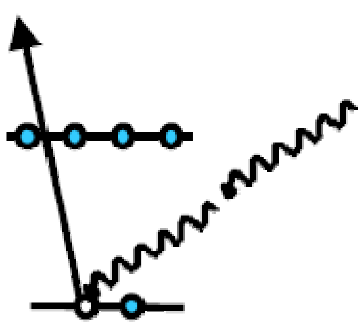
- laser multiphoton ionization



neon photoabsorption

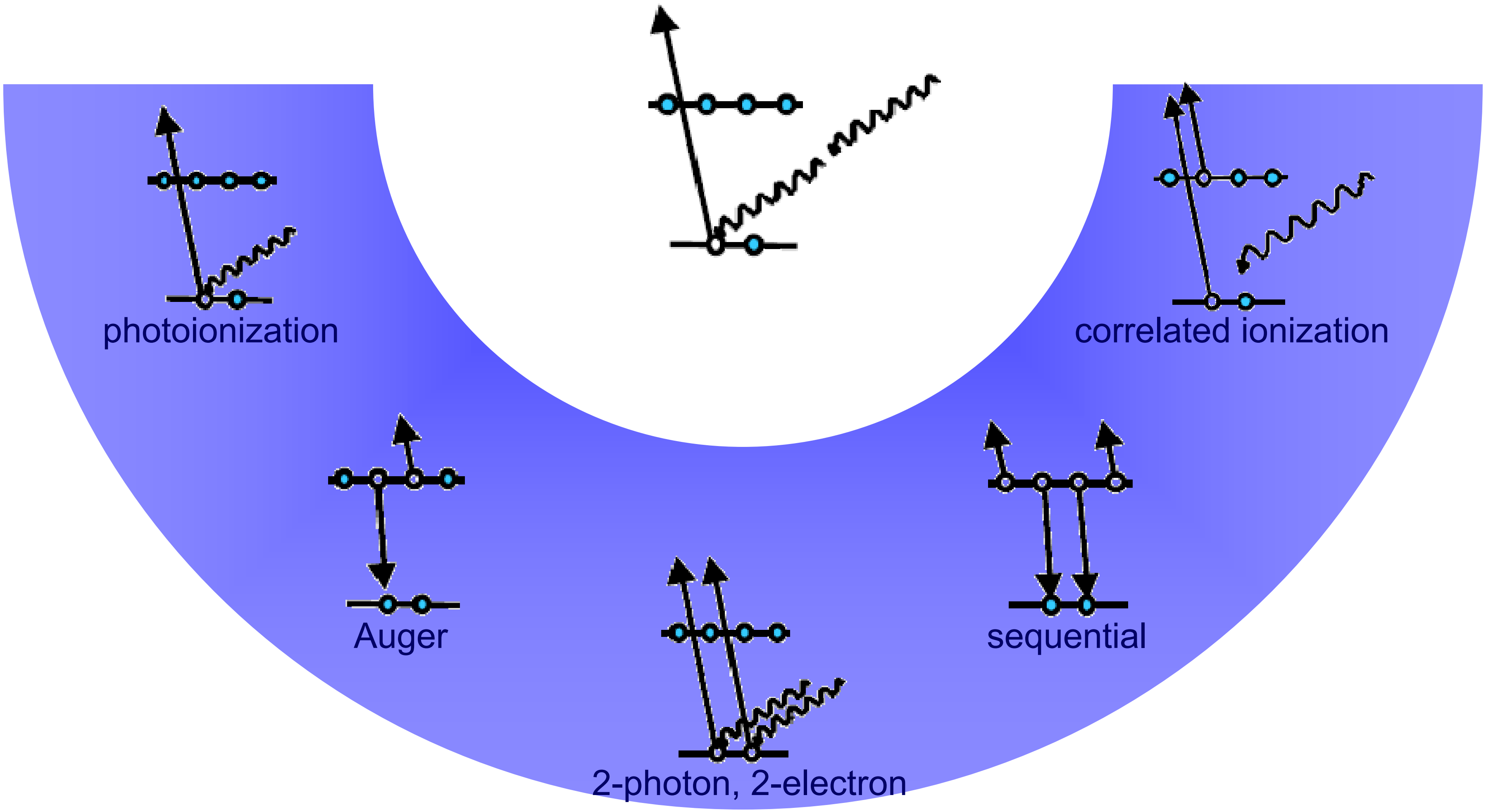


- x-ray multiphoton ionization



x-ray strong field experiment

x-ray multiphoton ionization



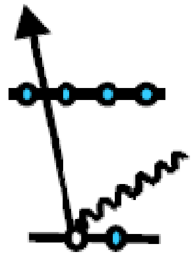
1-photon, 1-electron ionization

consider a 1-photon K-shell transition:

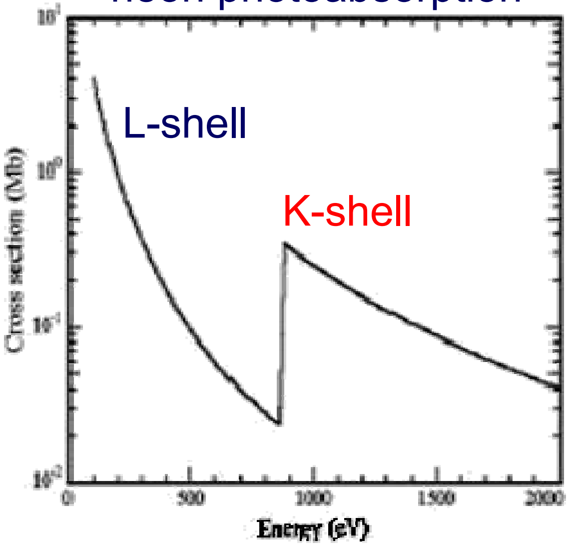
$\sigma_K \approx 10^{-18}$ cm^2

$\Gamma_K = \sigma_K F_{lcls} \approx 10^{15}$ s^{-1} (*saturated*)

$t_K = 1/\,\Gamma_K = 1$ fs



- rapid enough to ionize more than one electron!
- fast enough to compete with atomic relaxation?



2-photon, 2-electron ionization

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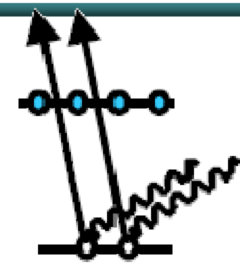
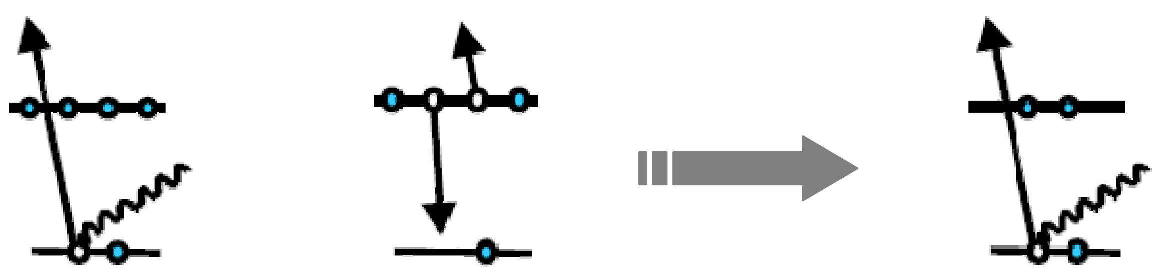


2-photon, 2-electron

- are the electrons correlated?
- in a strong optical field single electron dynamics dominate.

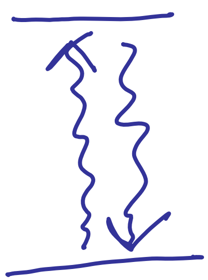
i.e. is it sequential ionization?



photoionization Auger photoionization

Coherent effects?

- 3d generation x-ray sources have << 1 photon per mode; LCLS will have coherence “spikes” containing a billion photons or more, in ~femtoseconds! What about coherent excitation?



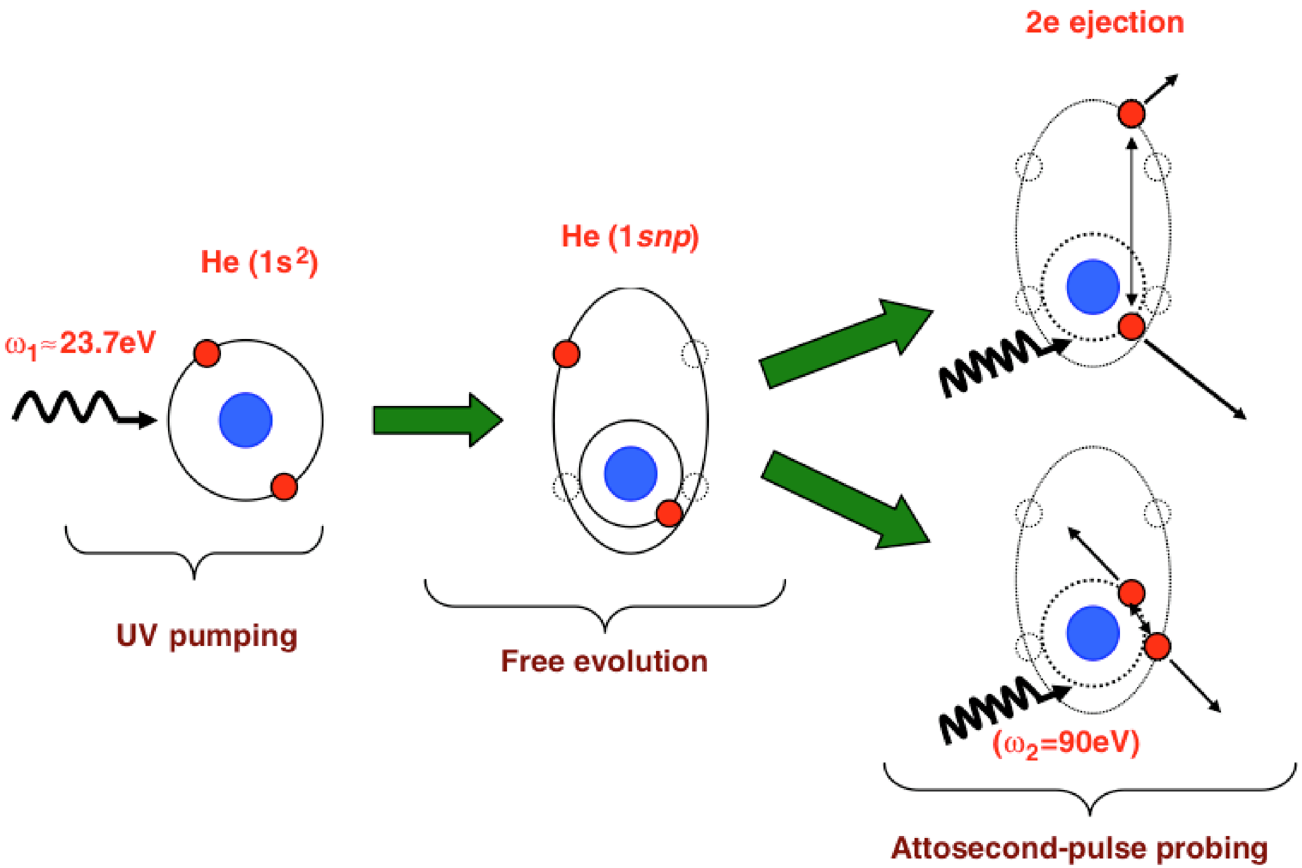
$$\text{Rabi rate } \Omega \approx \mu F_0$$

$$\mu = \langle f | ex | i \rangle \approx E_{binding}^{-1} \approx 0.01 \text{ for } 1\,\text{keV}$$

$$\mathrm{F}_0 \approx 1 \text{ then implies } \Omega^{-1} \approx 2.5 \text{ fsec}$$

Attosecond pump-probe?

fundamental time scale electron dynamics Atomic time unit = 24 attoseconds

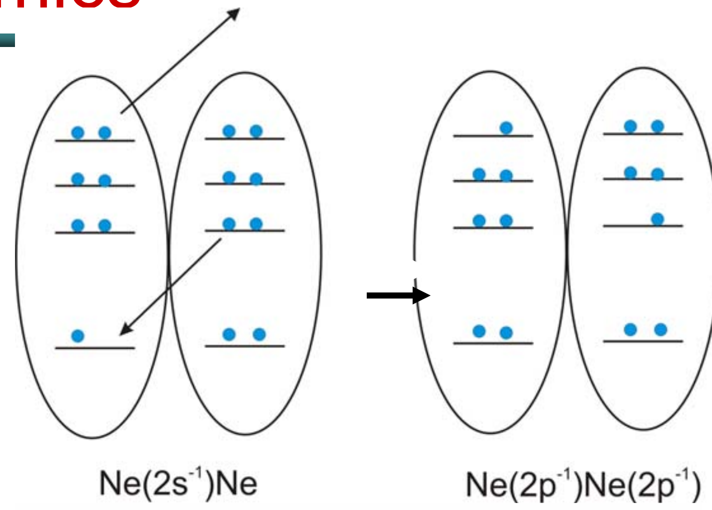


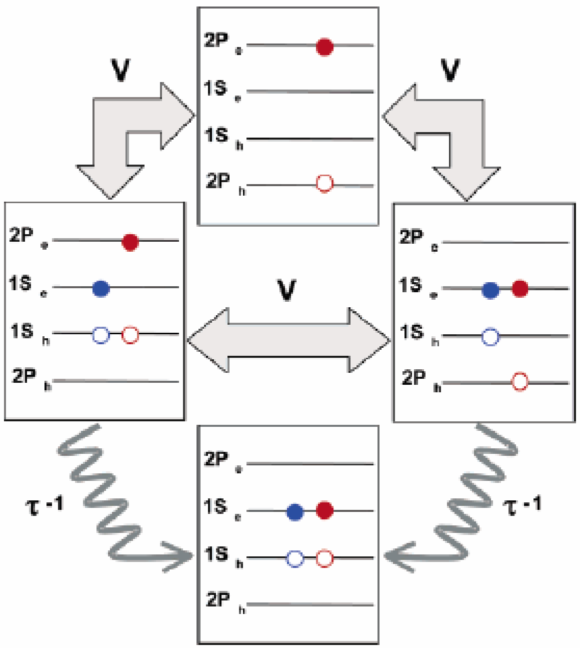
Direct attosecond probe of atomic electron correlation Hu and Collins, PRL (2006)

Theory

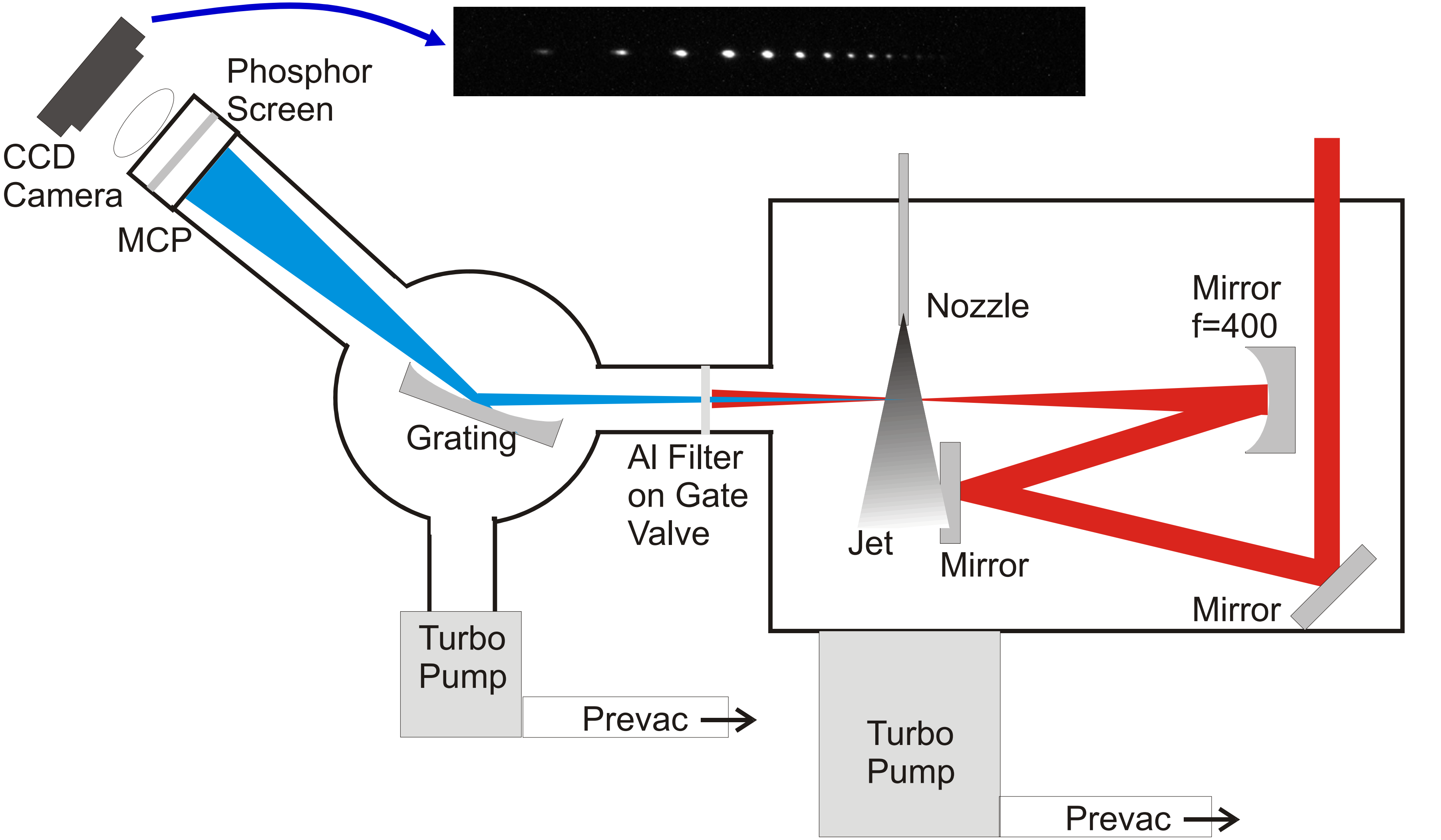
Observing the inner workings of an atom: Auger dynamics

- Dynamics driven by electron correlation effects
- Time-scale important in atoms, molecules, nano-particles (i.e. multiple-exciton generation)
- Attosecond pump-probe expts proposed for NGLS (Berkeley workshop, 2007)

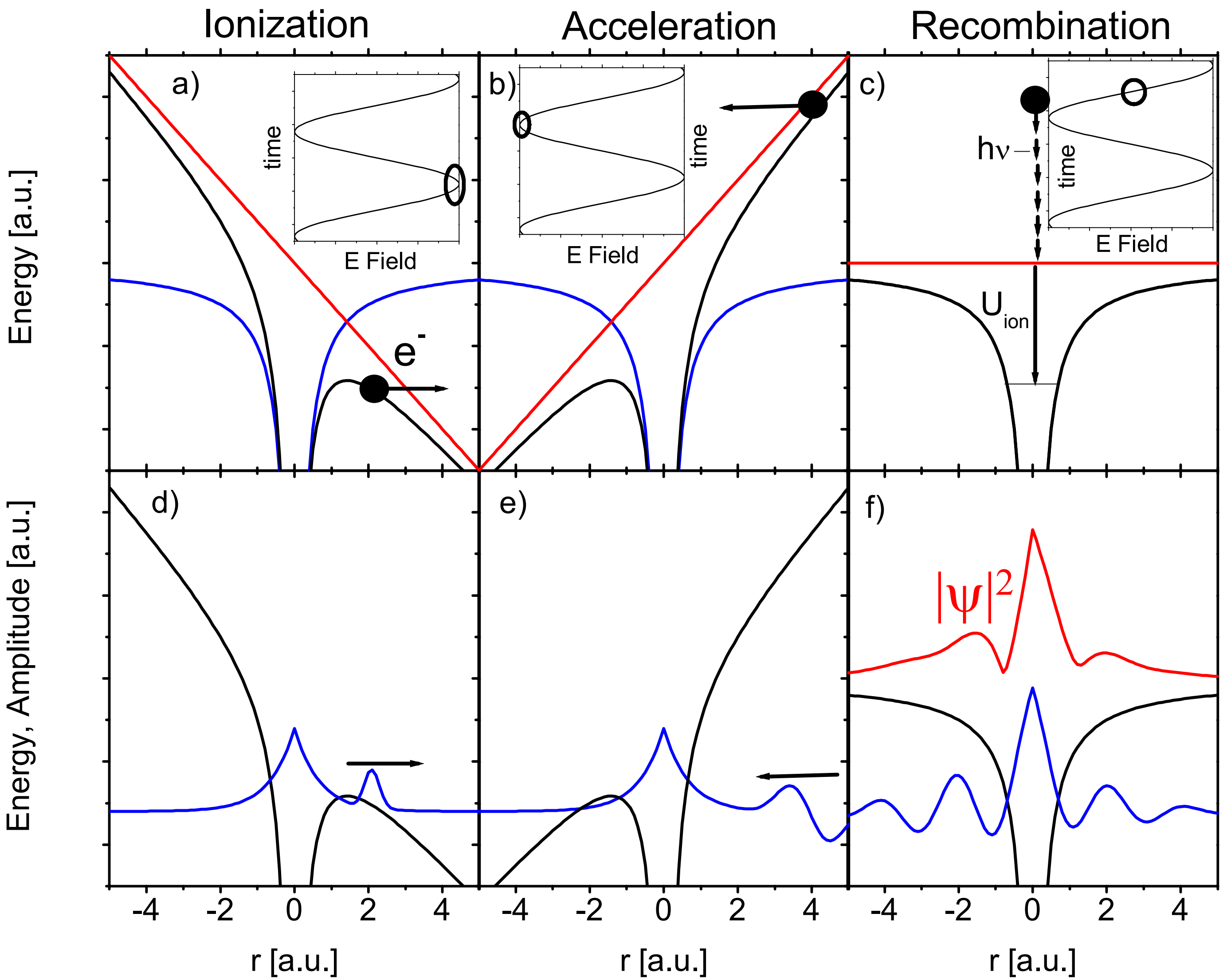




The competition for attoscience: HHG, a source of controllable vuv radiation



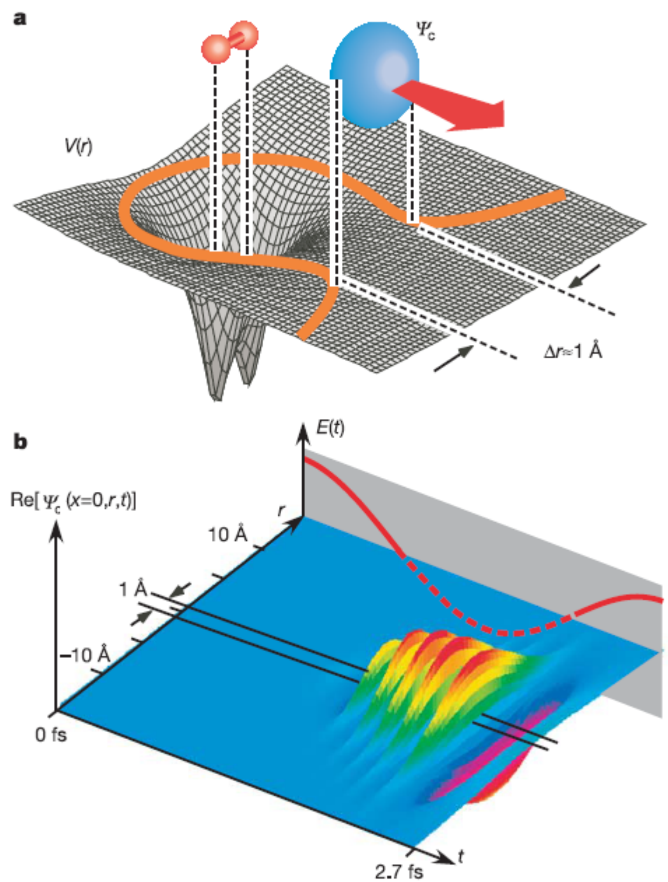
HHG mecanism involves rescattering, and so is limited to the atomic scale

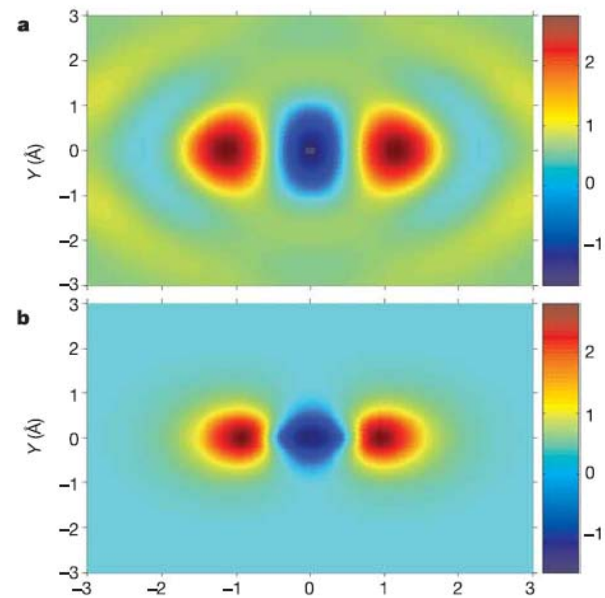


classical

quantum

Imaging the Inner Workings of a Molecule



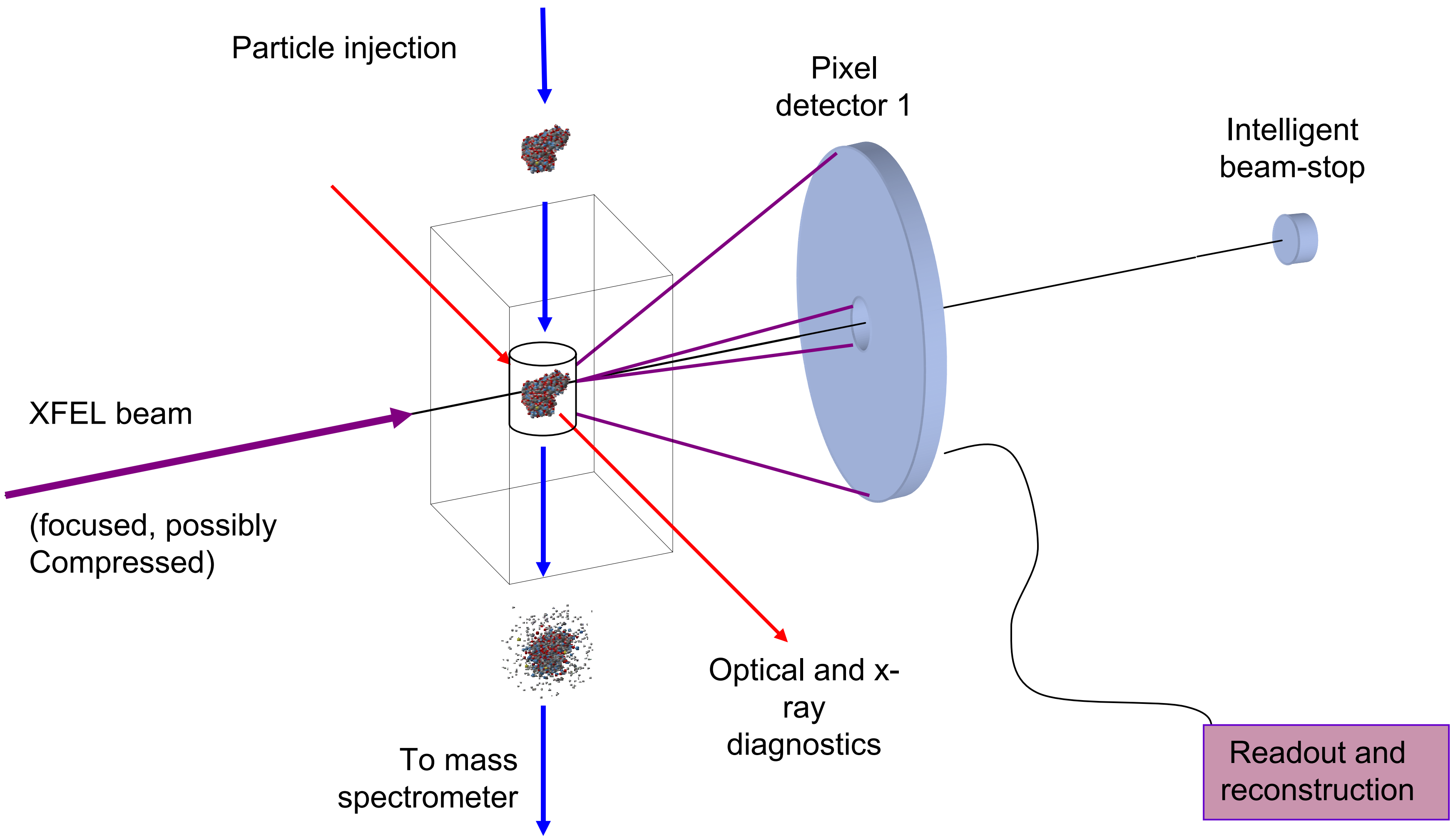


A snapshot image of a molecule

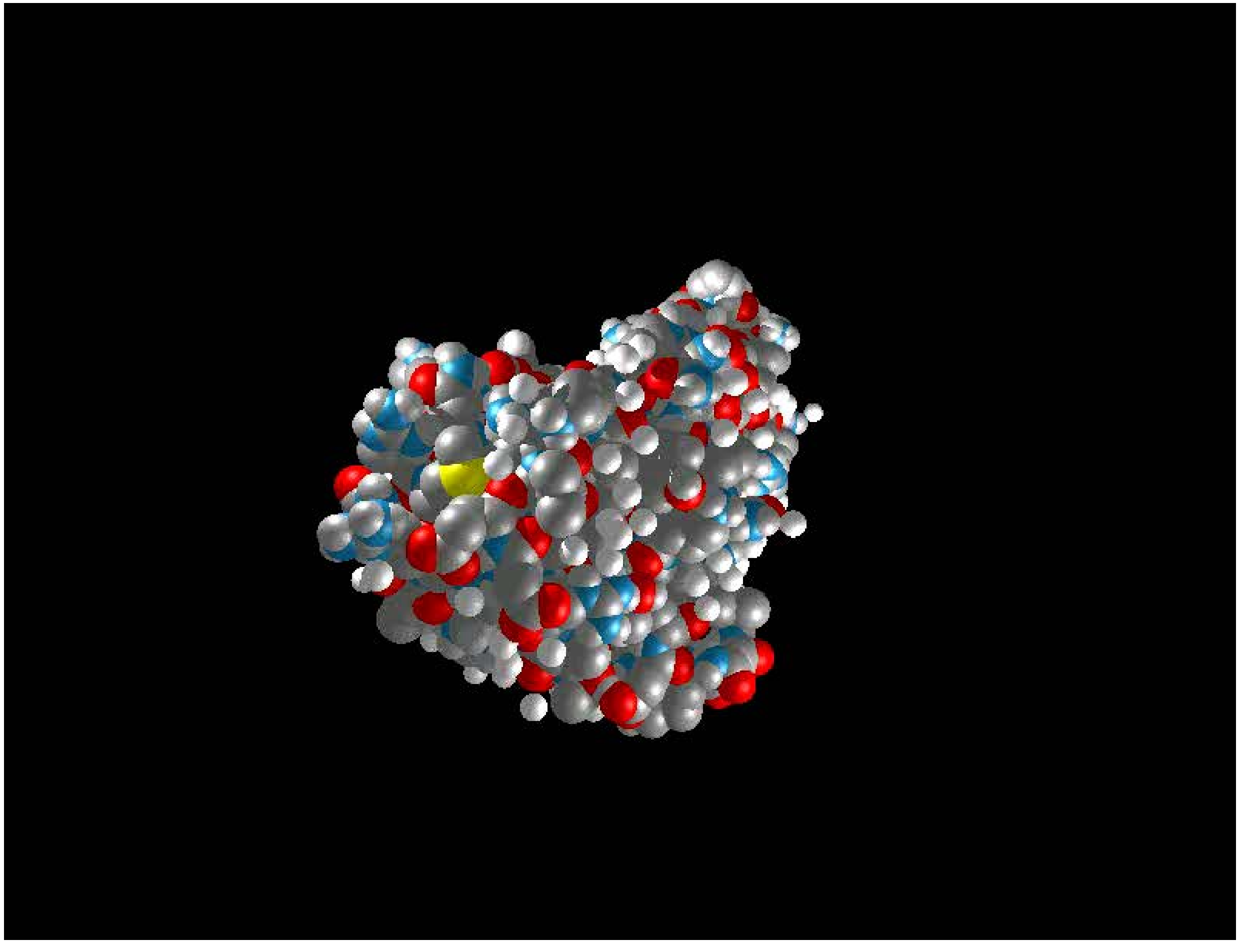
obtained from field ionization and electron-molecule recollision

Can we get this degree of control with radiation from a facilitiy?

Diffraction imaging with x-rays at LCLS



Exploding T4 Lysozyme: Short pulses and high power are essential

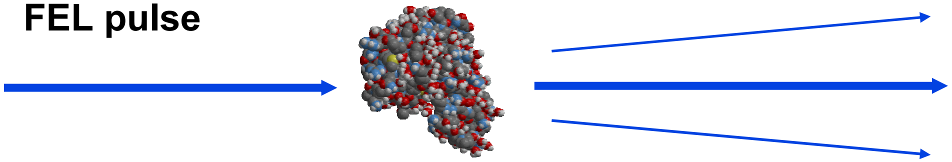


$1 \times 10^{11} W/cm^2$ irradiation for 200 fs by LCLS pulse in 1mm spot (unfocused)

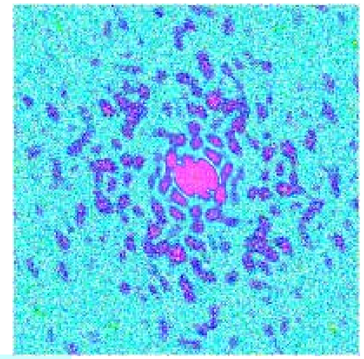
A 3D dataset can be assembled from diffraction patterns in unknown orientations

Diffraction from a single molecule:

FEL pulse



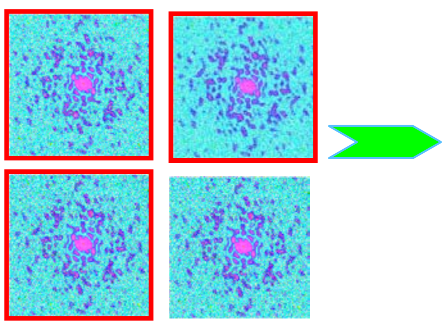
Unknown orientation



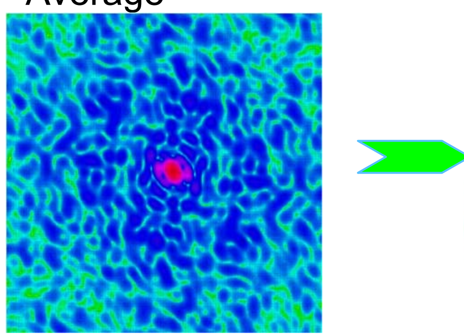
Noisy diffraction pattern

Combine 10^5 to 10^7 measurements into 3D dataset:

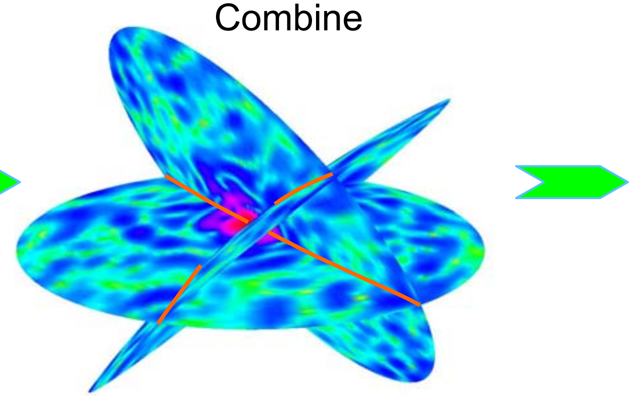
Classify



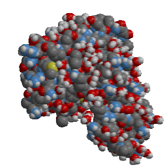
Average



Combine



Reconstruct



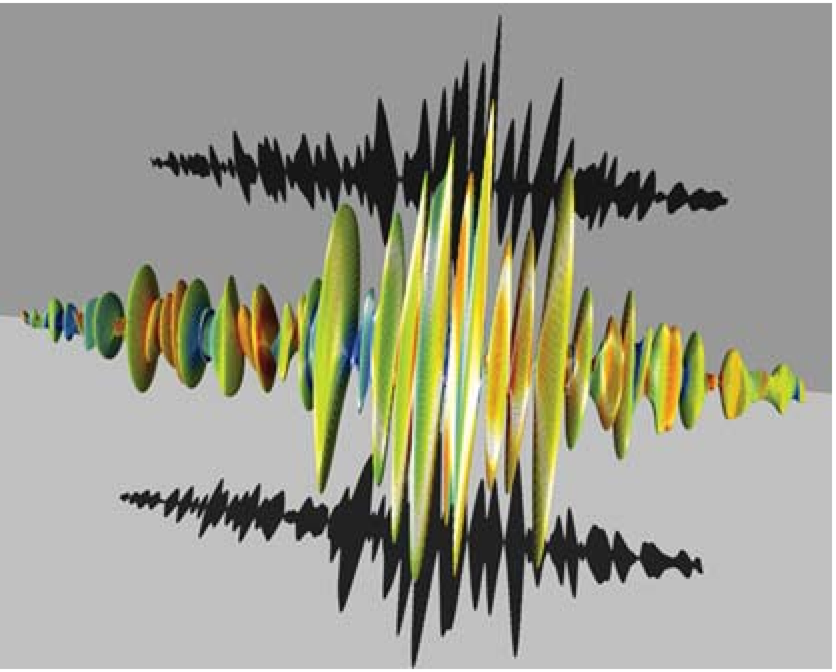
The highest achievable resolution is limited by the ability to group patterns of similar orientation

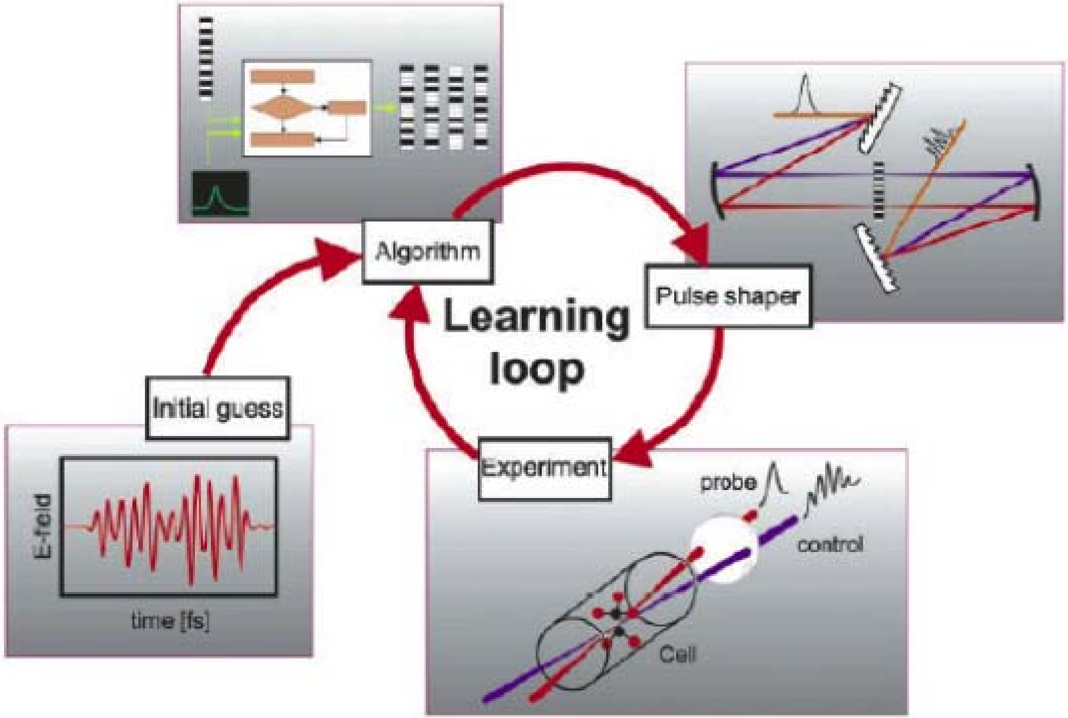
Gösta Huldt, Abraham Szöke, Janos Hajdu (J.Struct Biol, 2003 02-ERD-047)

Miao, Hodgson, Sayre, PNAS 98 (2001)

Beyond imaging: Controlling quantum evolution

tools for control





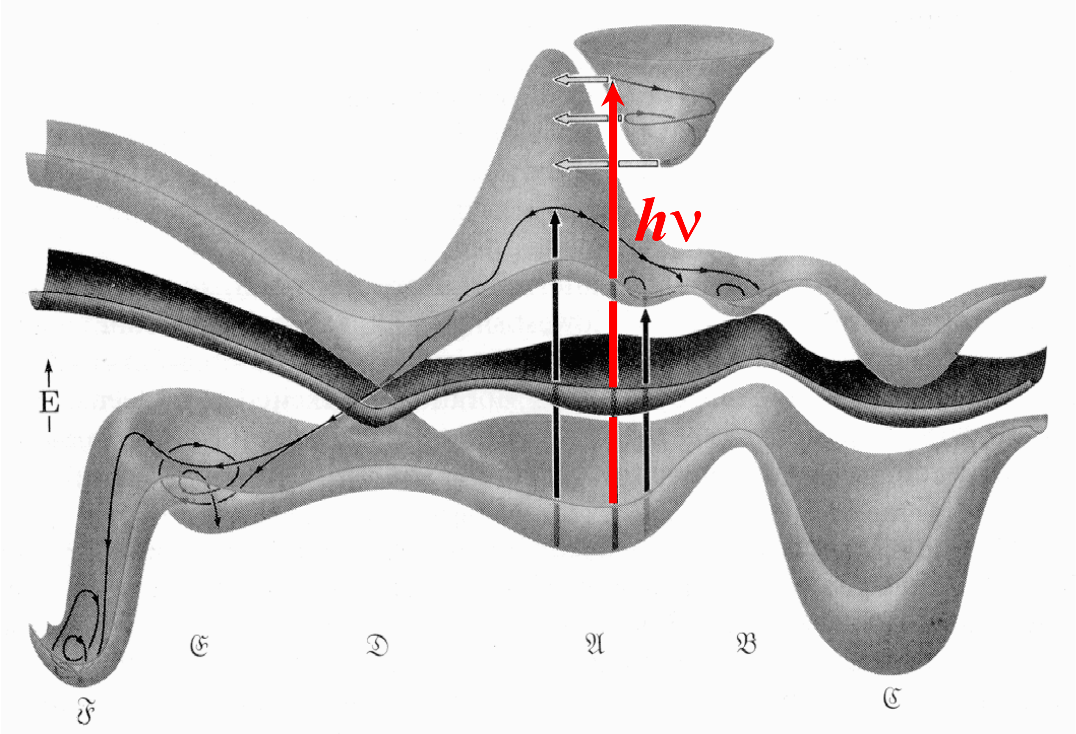
Total field control

- -Ultrafast studies (1999 Nobel)
- -Carrier envelope phase control (2005 Nobel)
- -Pulse shapers

Learning feedback

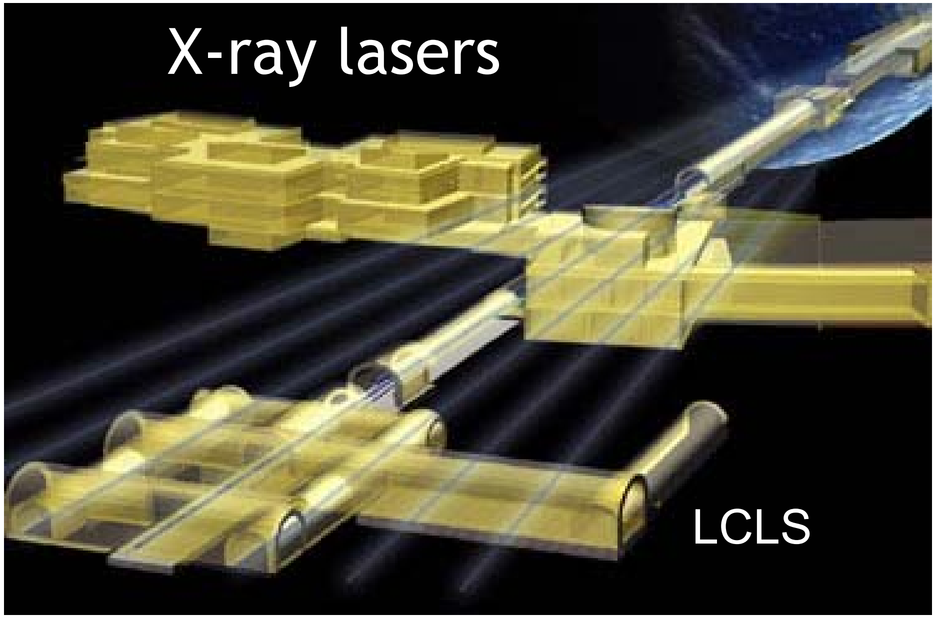
Ultrafast vuv control will involve extreme non-Born-Oppenheimer dynamics

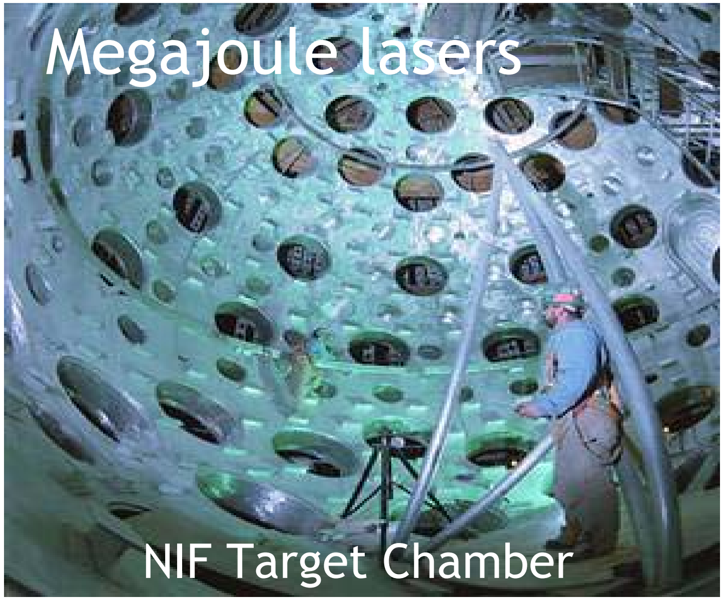
Launch dynamics on multiple potential energy surfaces



Create electronic wavepacket: superposition on several electronic surfaces

Partnership: Light sources will contribute richly to AMO Science…





…and AMO will contribute techniques and technology to utilize these sources for science.

Thanks to…

- Lou DiMauro
- Linda Young
- Markus Guehr
- Bill McCurdy
- Joe Stohr
- Janos Hajdu
- Many others…