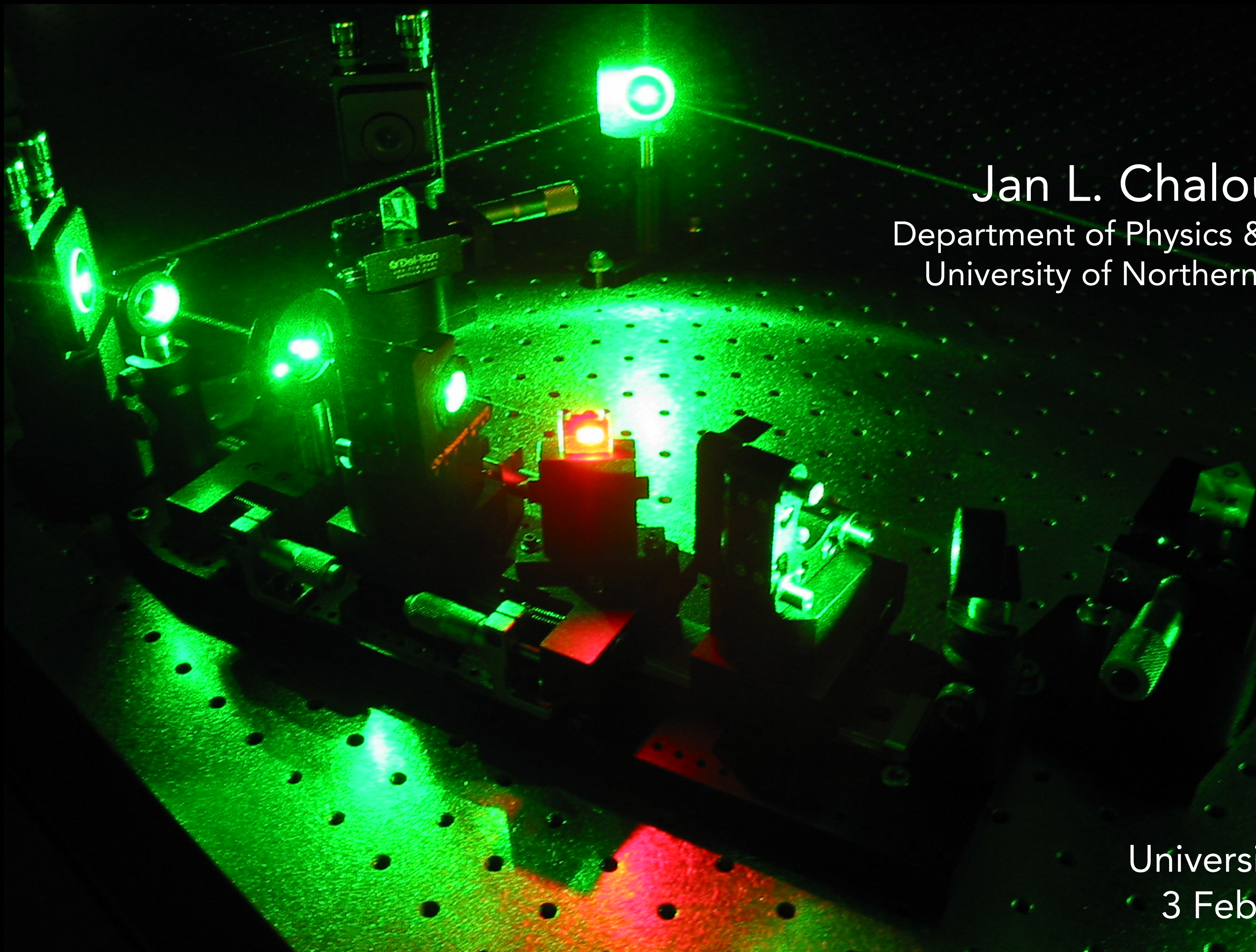
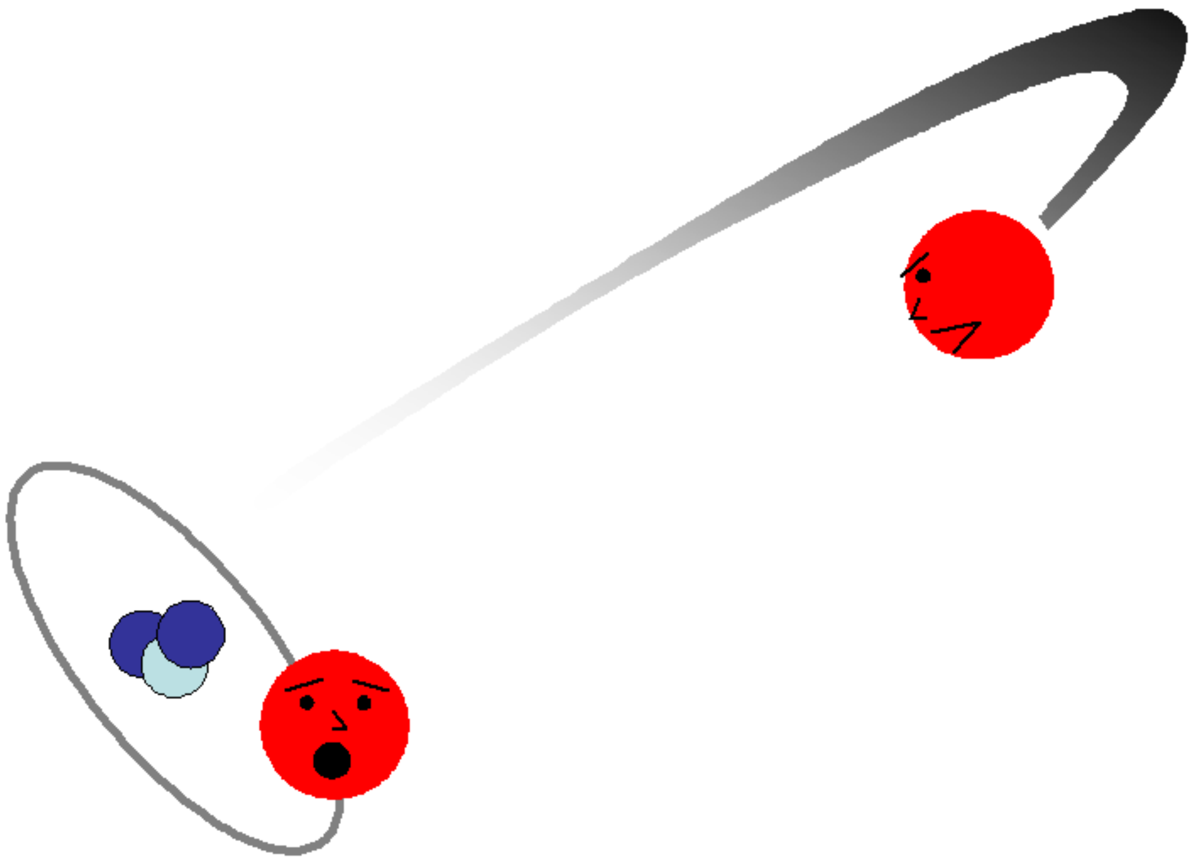
Atoms in Intense Laser Light: Classical Models & Two-Color Fields

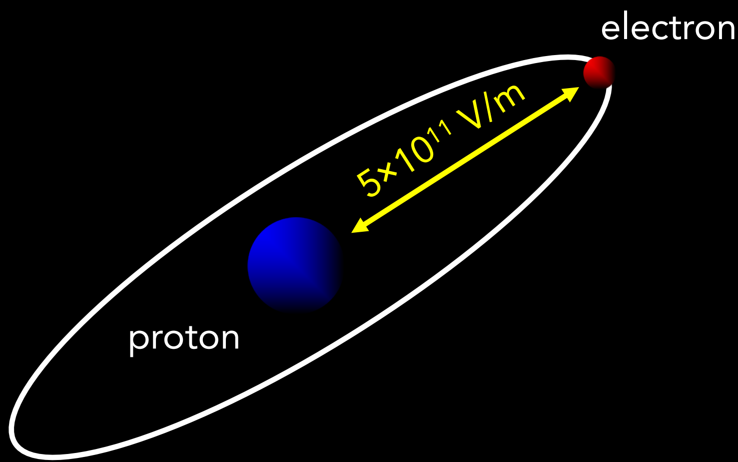


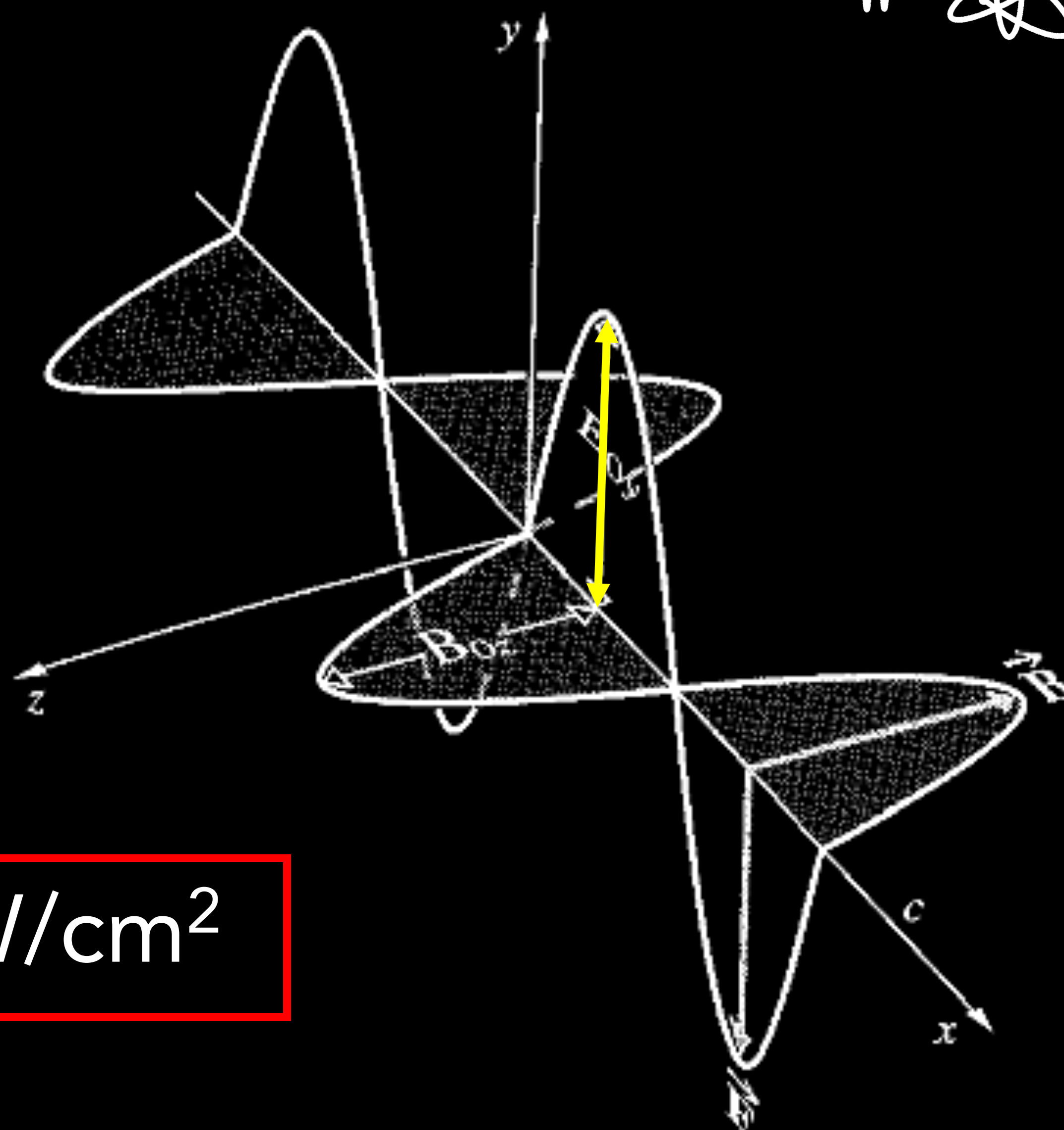
Jan L. Chaloupka
Department of Physics & Astronomy
University of Northern Colorado

University of Denver
3 February 2016



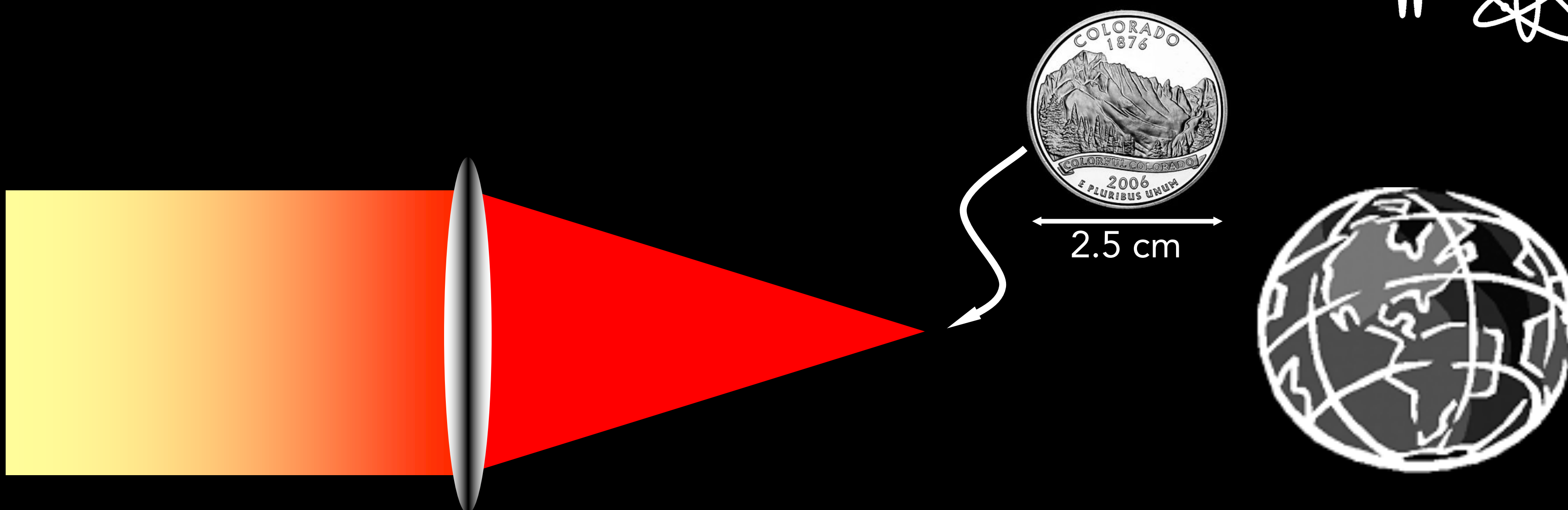
atomic unit of intensity





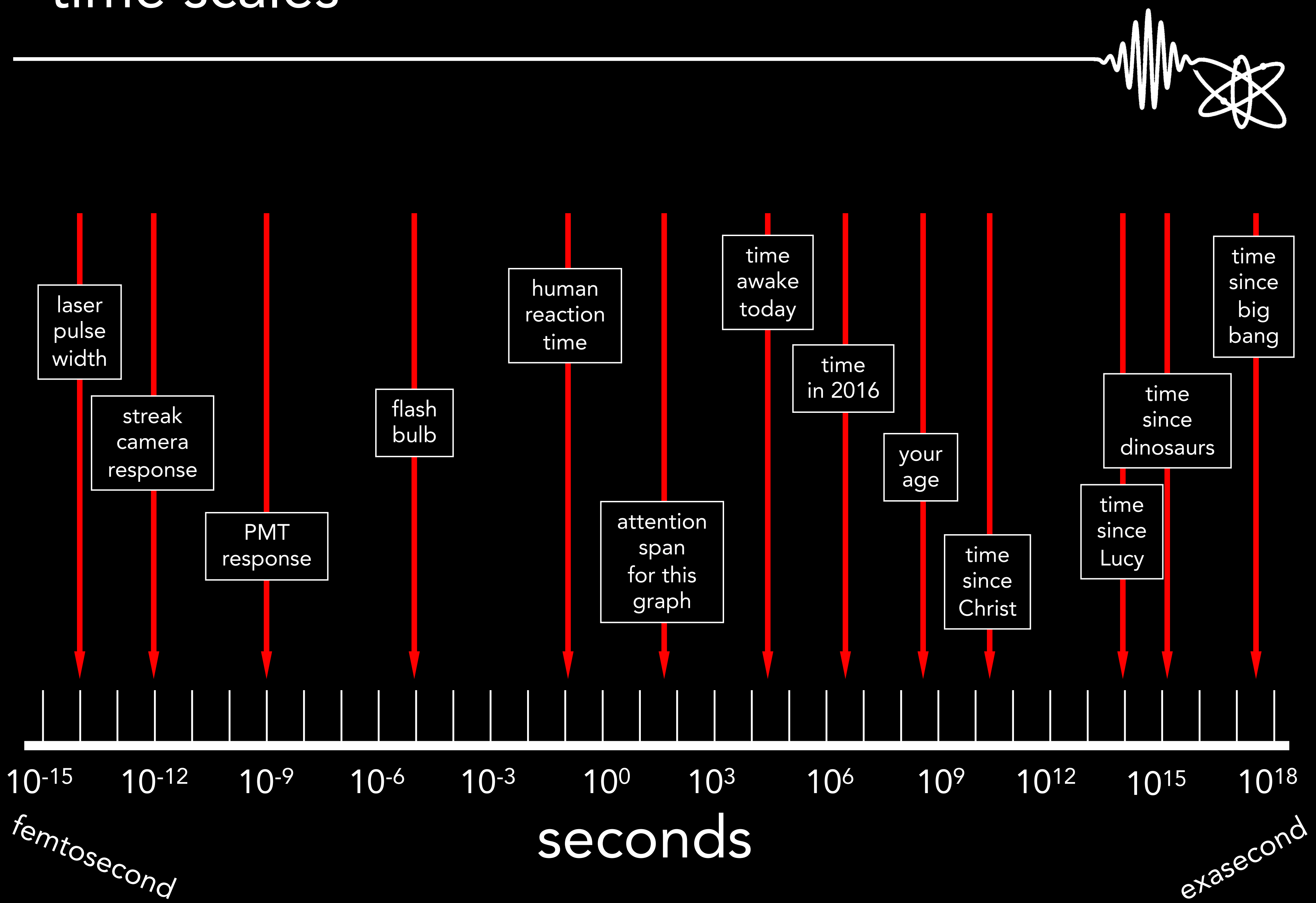
3.5×10^{16} W/cm^2

intense fields with sunlight

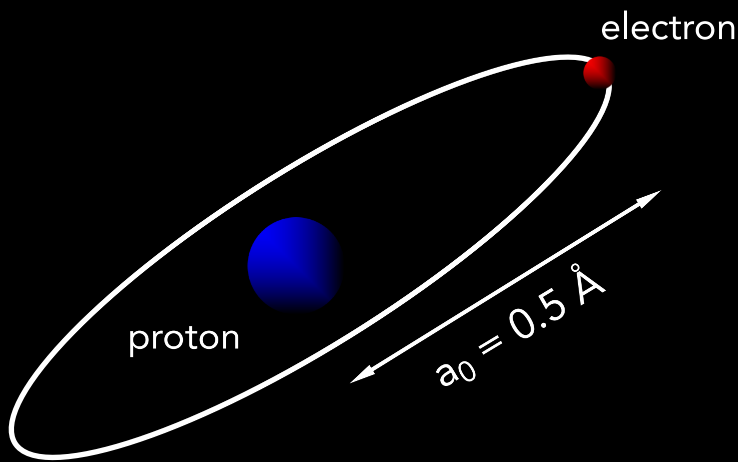


$$\frac{1\ \mathrm{mJ}}{(10\ \mathrm{fs}) \cdot \pi\, (5\ \mu\mathrm{m})^2} \approx 10^{17}\ \mathrm{W/cm^2}$$

time scales

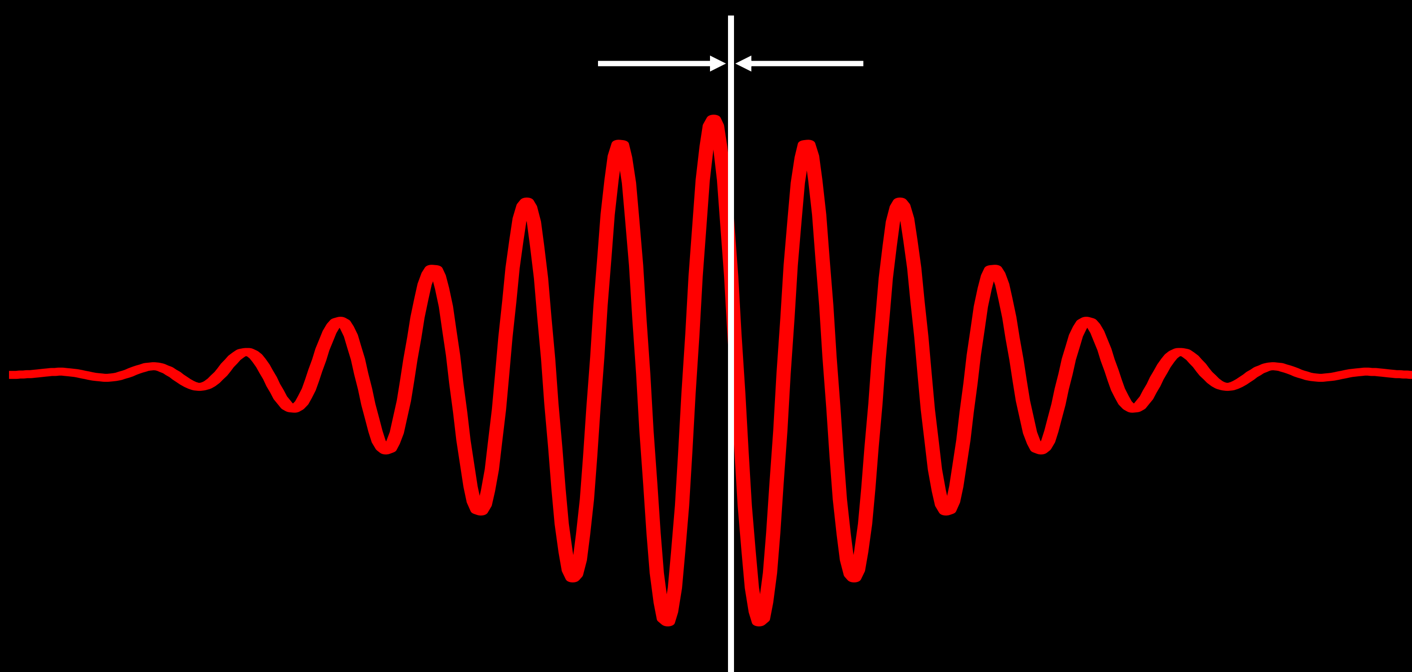

laser pulse width
streak camera response
PMT response
flash bulb
human reaction time
attention span for this graph
time awake today
time in 2016
your age
time since Christ
time since Lucy
time since dinosaurs
time since big bang
10^{-15}
10^{-12}
10^{-9}
10^{-6}
10^{-3}
10^{0}
10^{3}
10^{6}
10^{9}
10^{12}
10^{15}
10^{18}
seconds
femtosecond
exasecond

atomic unit of time

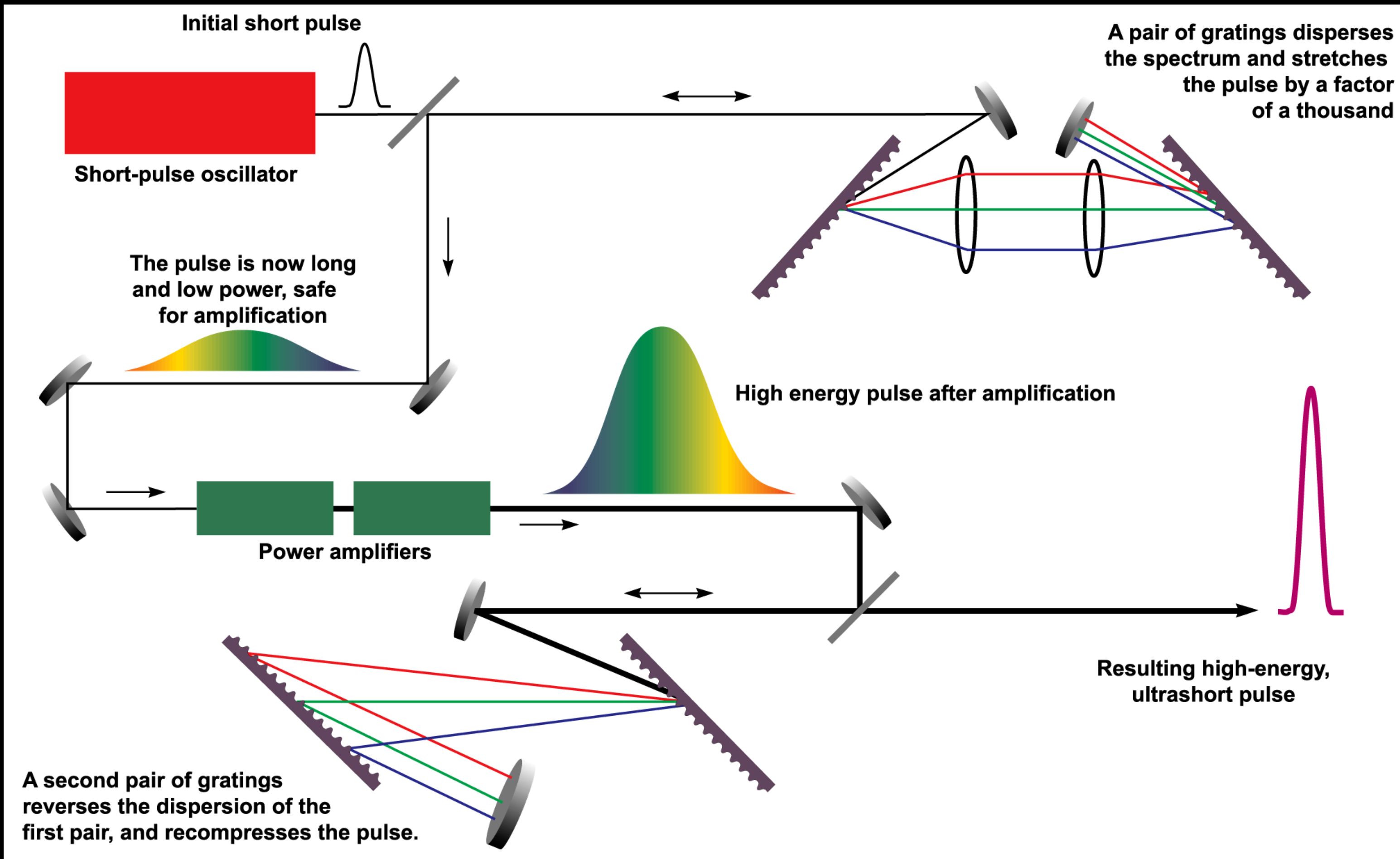


$$t = \frac{2\pi a_0}{\sqrt{2E/m}}$$

$\approx$ 150 attoseconds
(10^{-18} sec)



chirped-pulse amlification

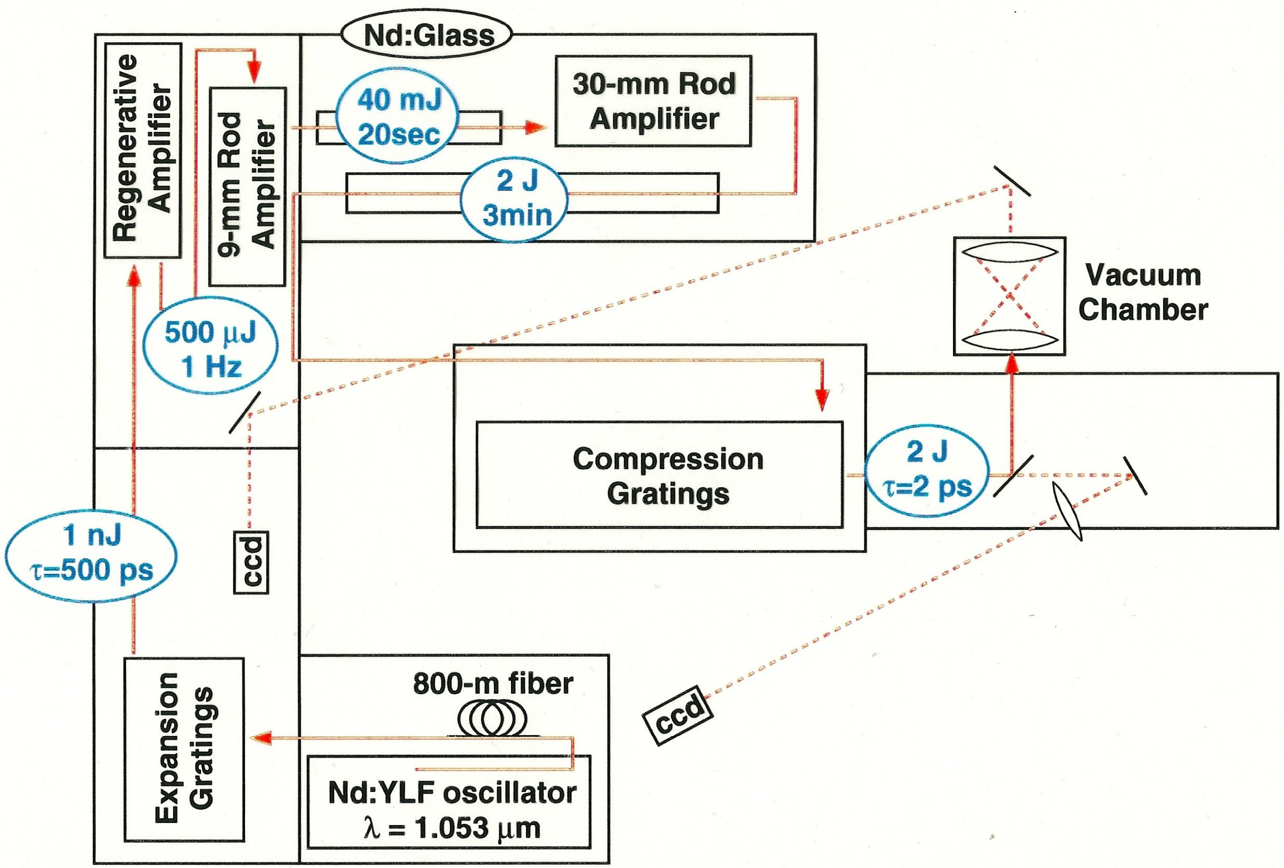


Wikipedia!

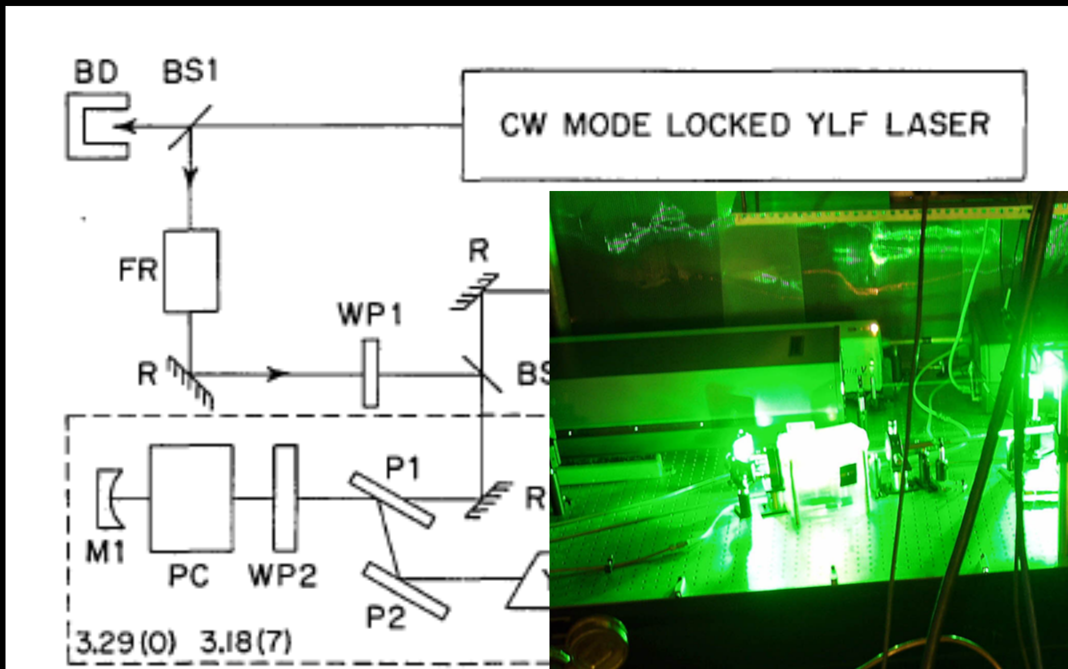
original table-top terawatt (T^3)

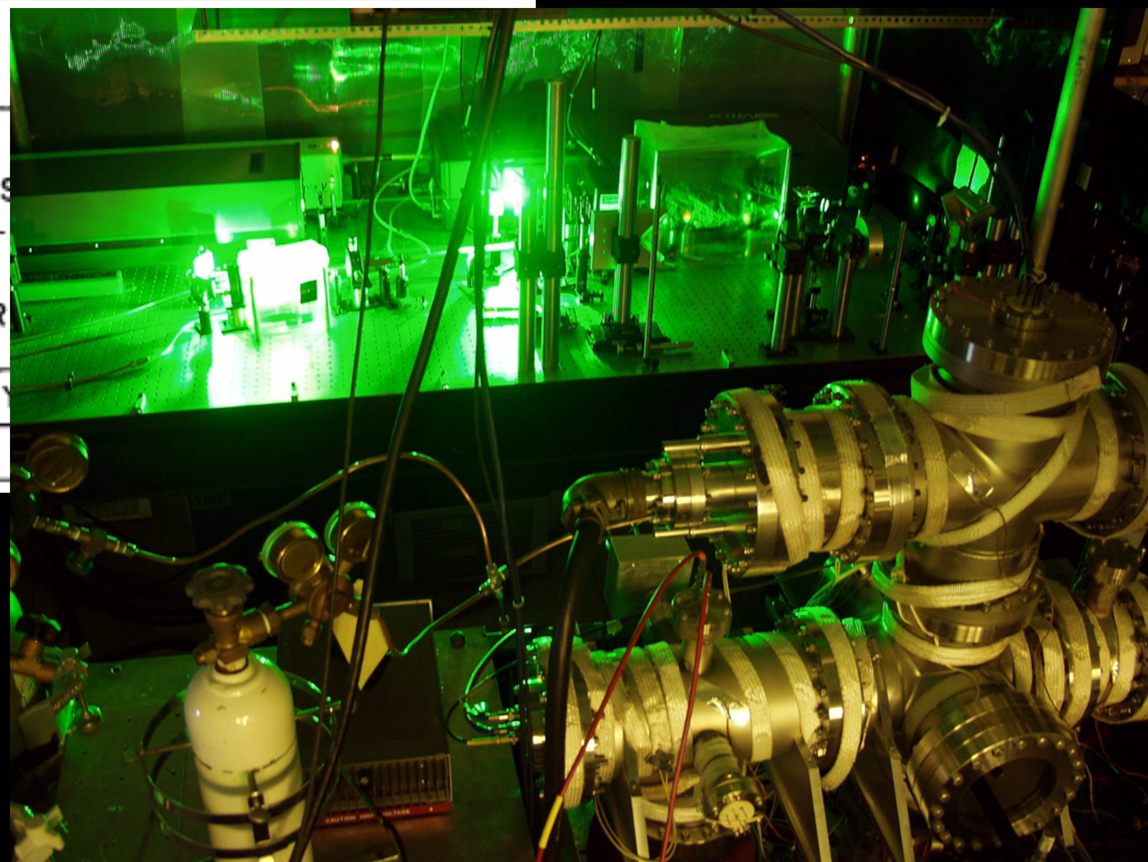
The chirped-pulse amplification table-top terawatt laser system produces a single 2-psec, 2-Joule, 1-micron pulse every three minutes

UR LLE



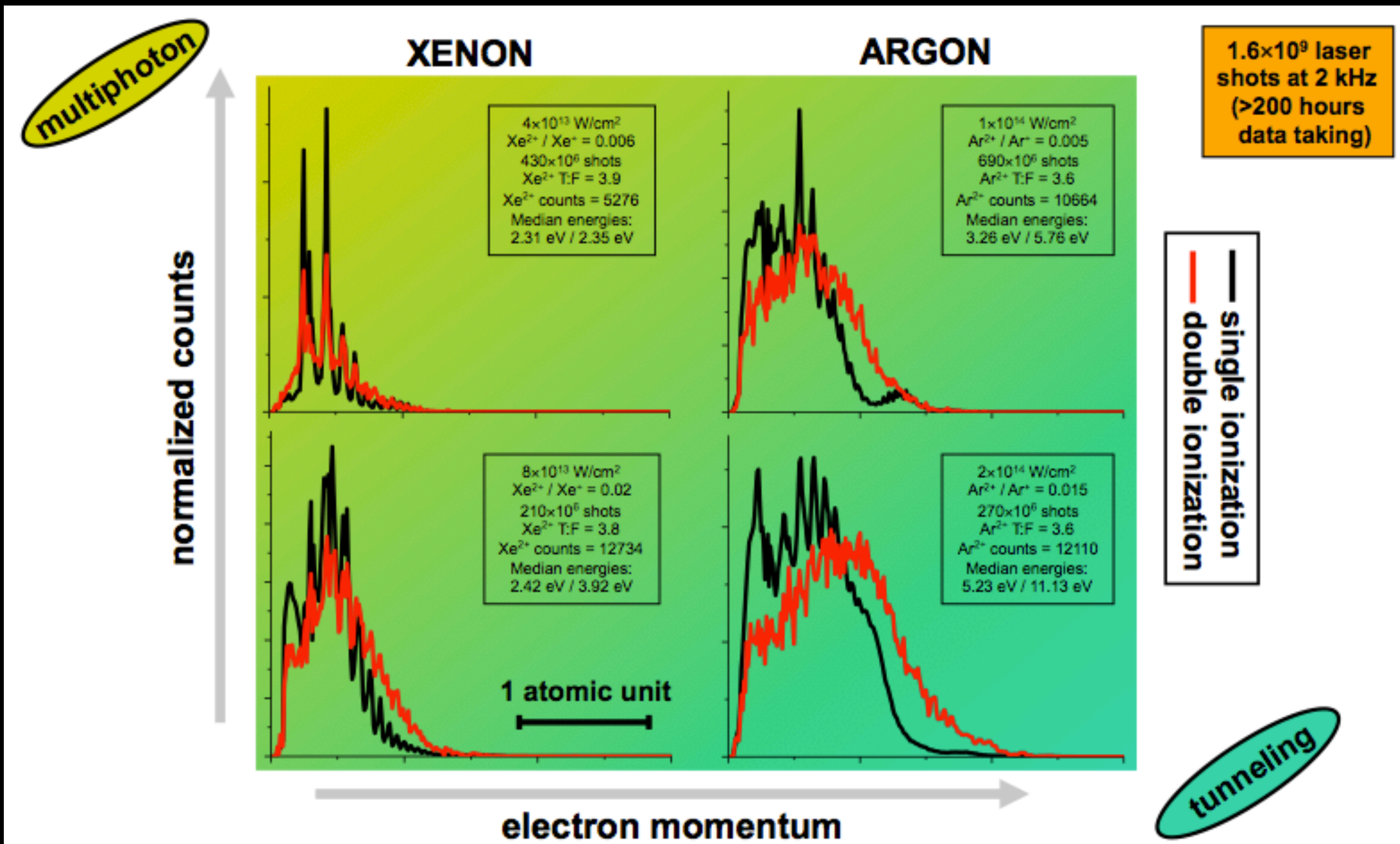
high-repetition-rate lasers





M. Saeed, D. Kim, L. F. DiMauro, Applied Optics 29 1752, 1990

lots of data!



JLC et al, PRL 90 033002, 2003

ultra-intense lasers

$$\boxed{\frac{9\ \mathrm{J}}{30\ \mathrm{fs}} = 300\ \mathrm{TW}}$$

$$\boxed{2\times10^{22}\ \mathrm{W/cm^2}}$$

at 10^{18} W/cm^2

$E_{quiver} \approx 60$ keV

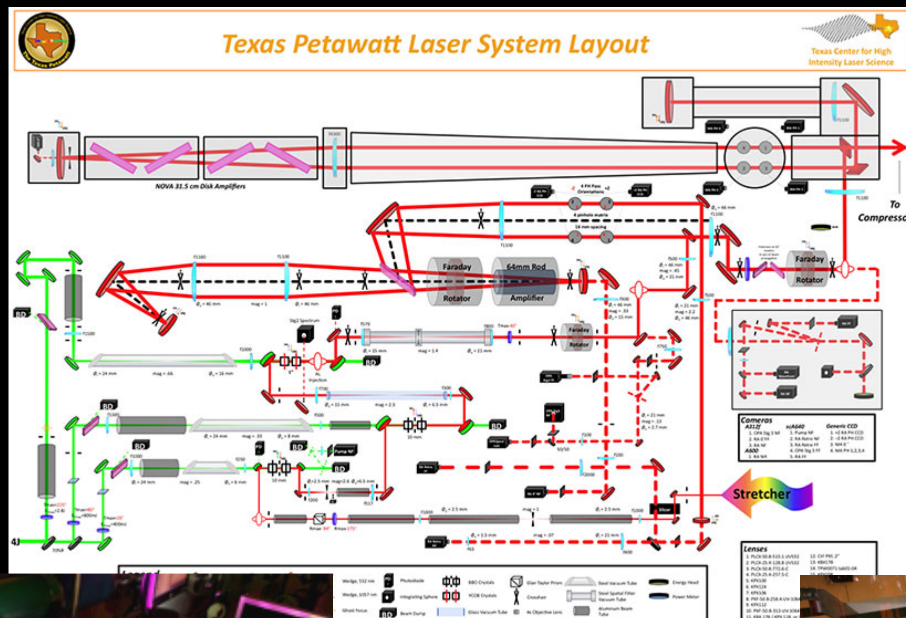
at 2×10^{22} W/cm^2

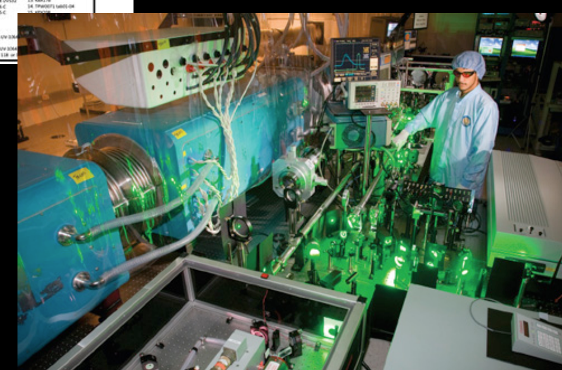
$E_{quiver} \approx 1$ GeV

ultra-relativistic !!!

University of Michigan, 300TW at 0.1 Hz

petawatt laser systems





University of Texas, 200J at 150fs gives 1.1PW

national ignition facility

attosecond pulses

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6 September 2012 Last updated at 05:16 ET

458 Share

Shortest laser pulse lasts just 67 attoseconds

Researchers in the US have produced the shortest-ever laser pulses: just 67 billionths of a billionth of a second.

The feat surpasses the prior record of 80 attoseconds, set in 2008.

Like a camera with an ever-shorter flash, these 67-attosecond pulses will allow researchers to examine the very fastest natural processes.

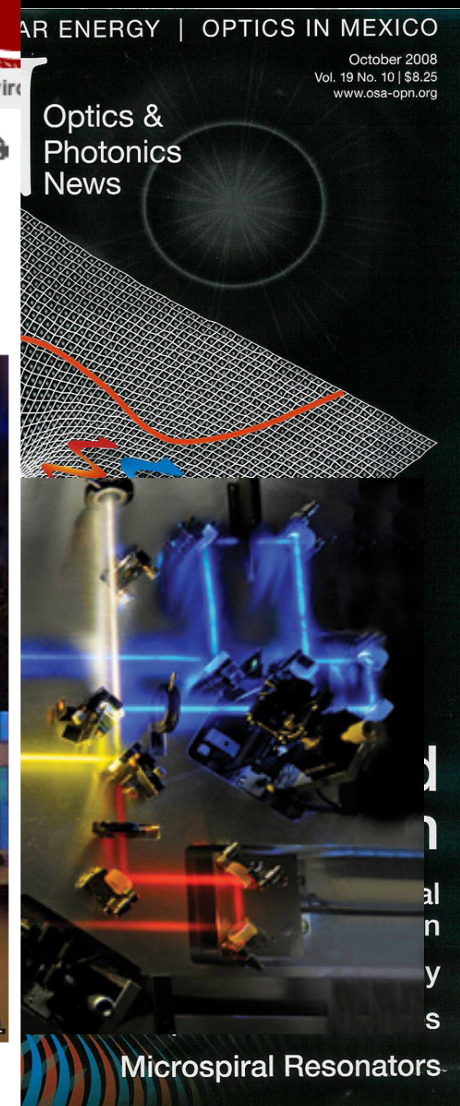
The team behind the pulses, reporting in Optics Express, have also developed a novel detector to capture them - like a camera with a shutter speed to match.

The quest for the shortest laser pulse has been underway since the laser's first demonstration in 1960; the very first laser created pulses of about a thousandth of a second.

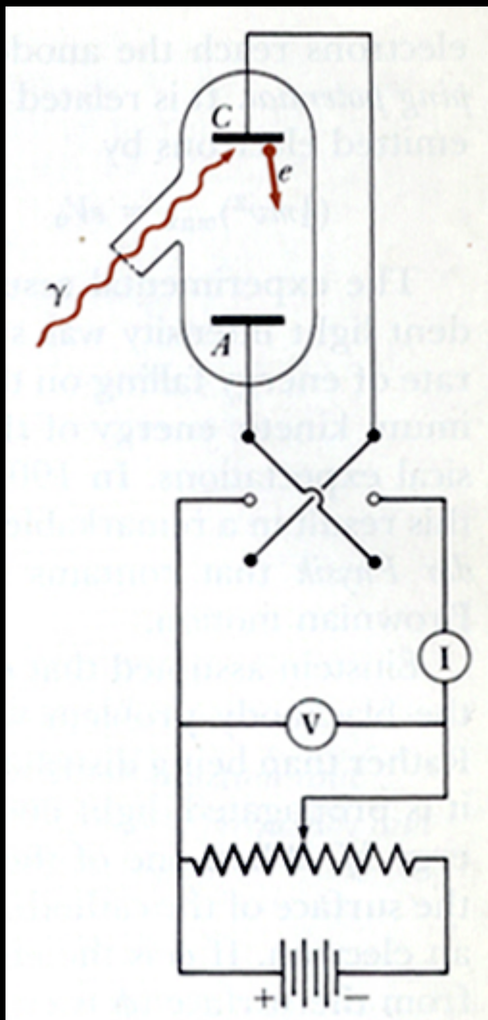
In recent years the field of "femtosecond" lasers - producing pulses lasting just millionths of a billionths of a second - have become widespread research tools.

SPL

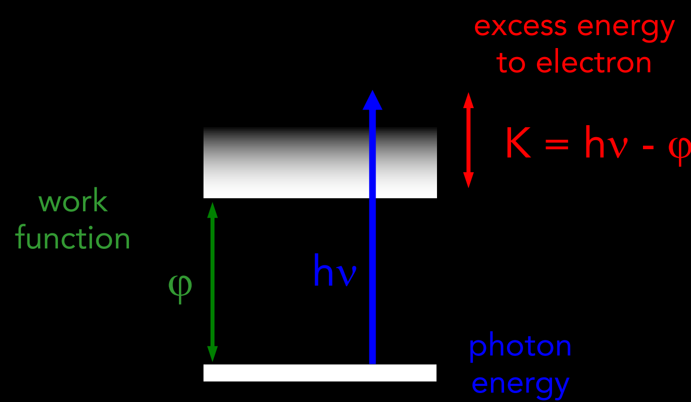
The quest for the shortest pulse has been ongoing since the laser's invention



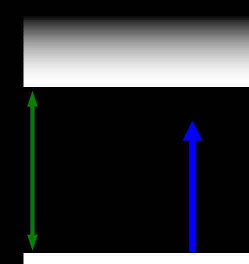
photoelectric effect



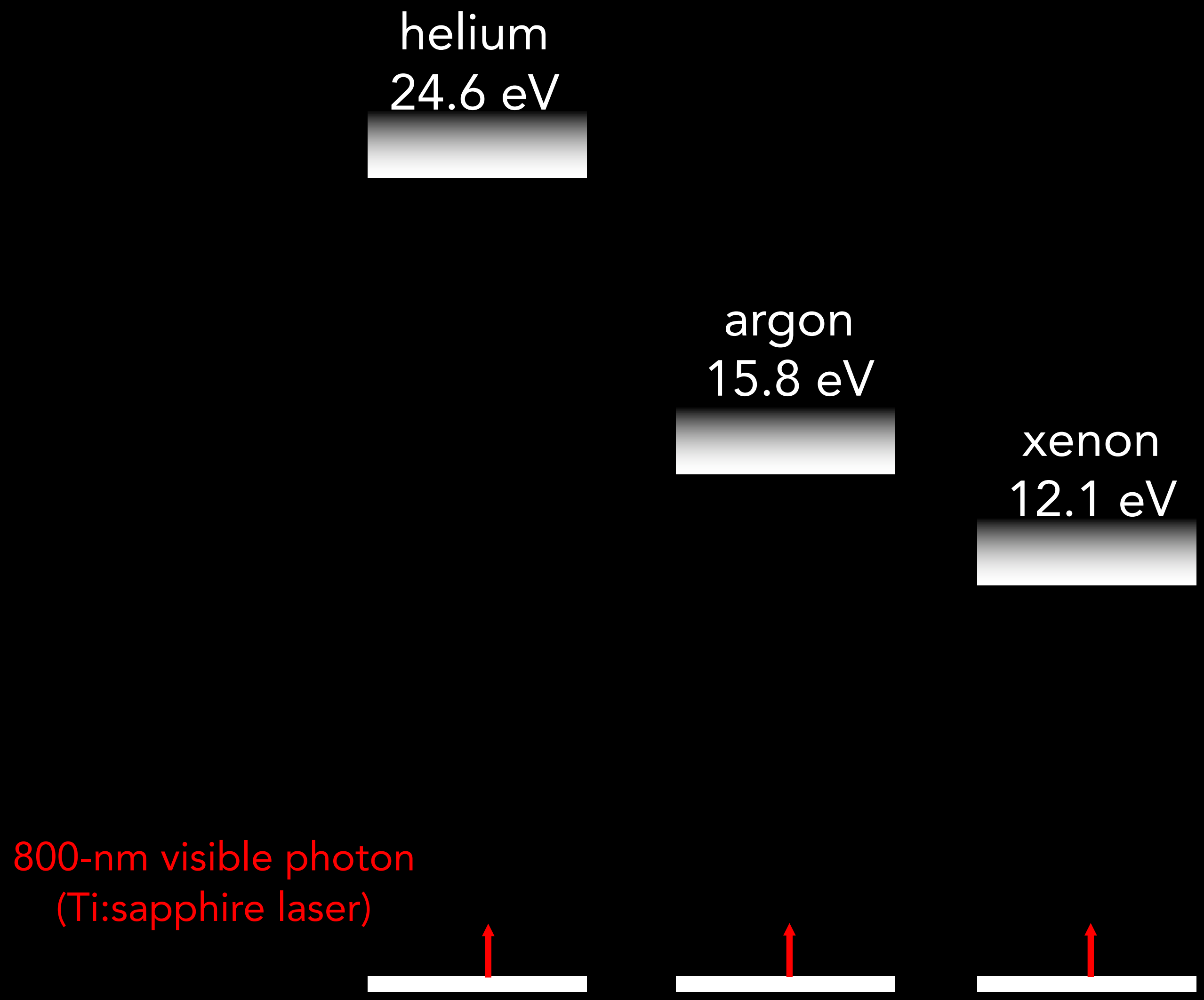
(Tippler, Modern Physics)



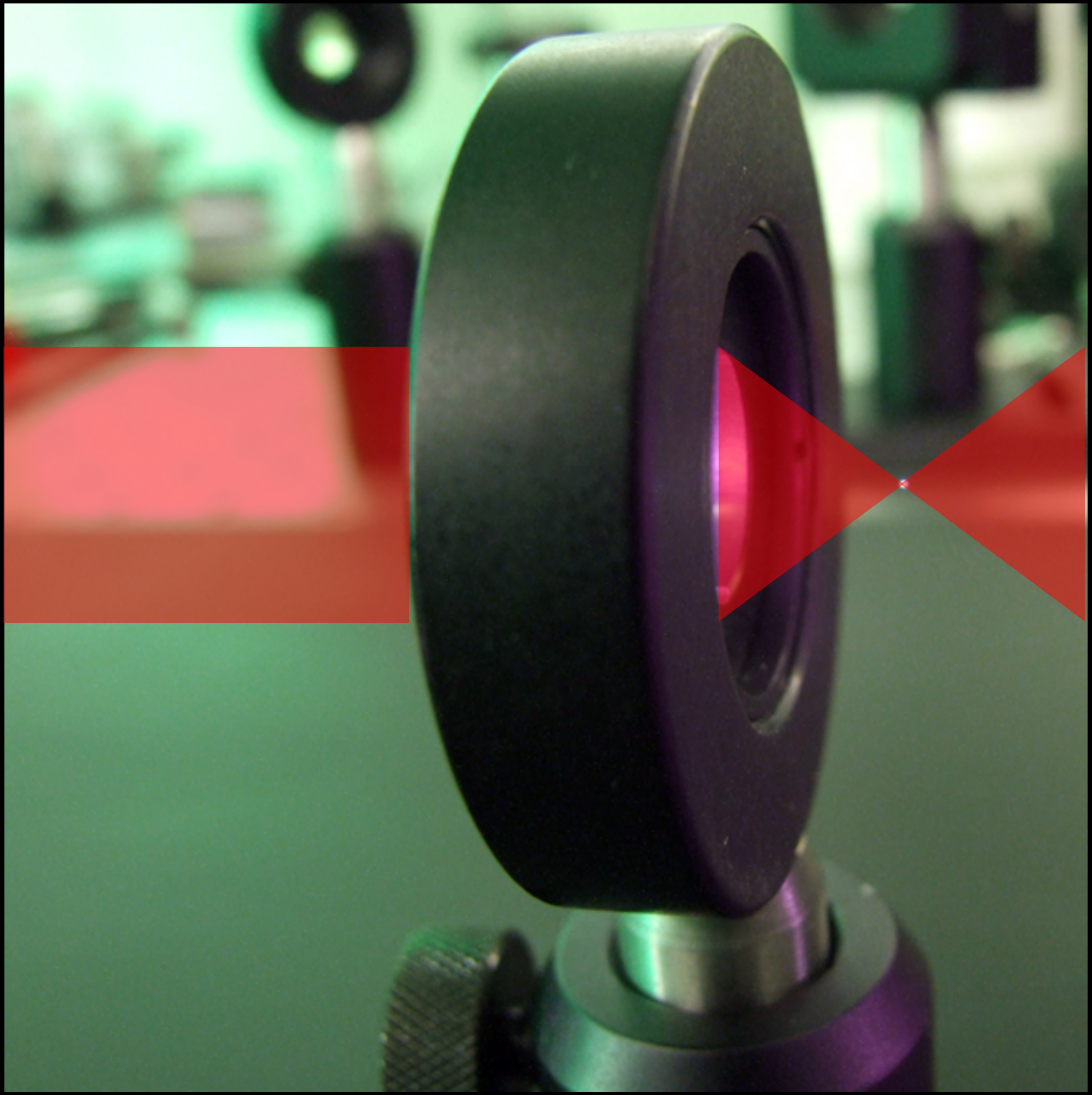
No ionization for $h\nu < \varphi$:



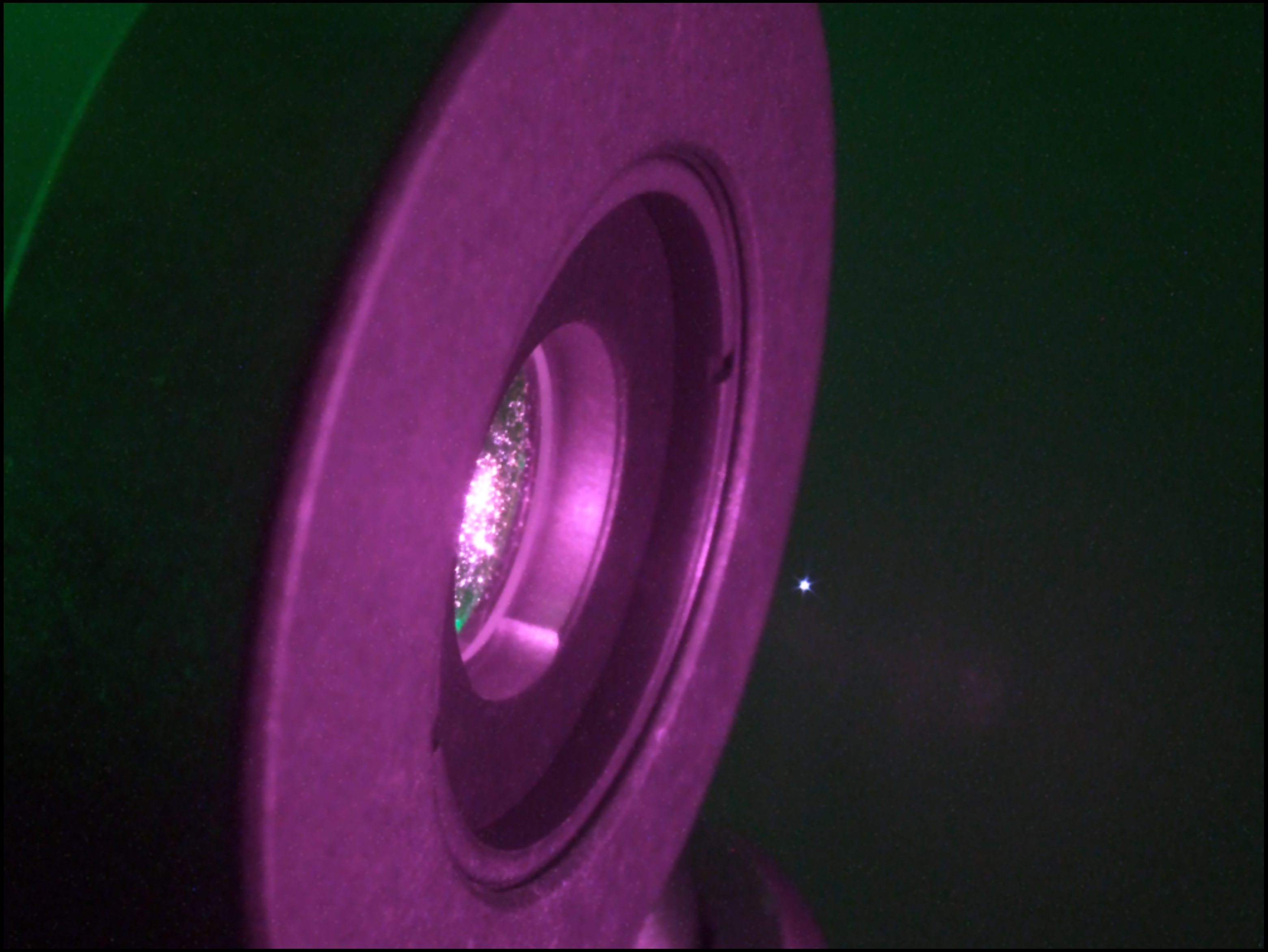
photoelectric effect



ionization of air



ionization of air



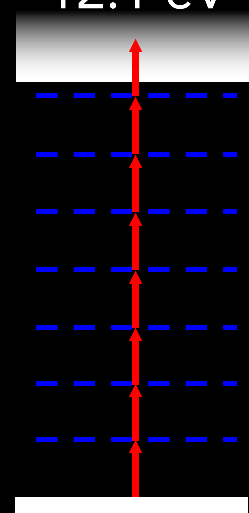
multiphoton ionization

Typical Laser Parameters:

energy/pulse: 10 μJ
spot diameter: 10 μm
pulse width: 100 fsec

10^{14} W/cm^2

xenon
12.1 eV



virtual levels

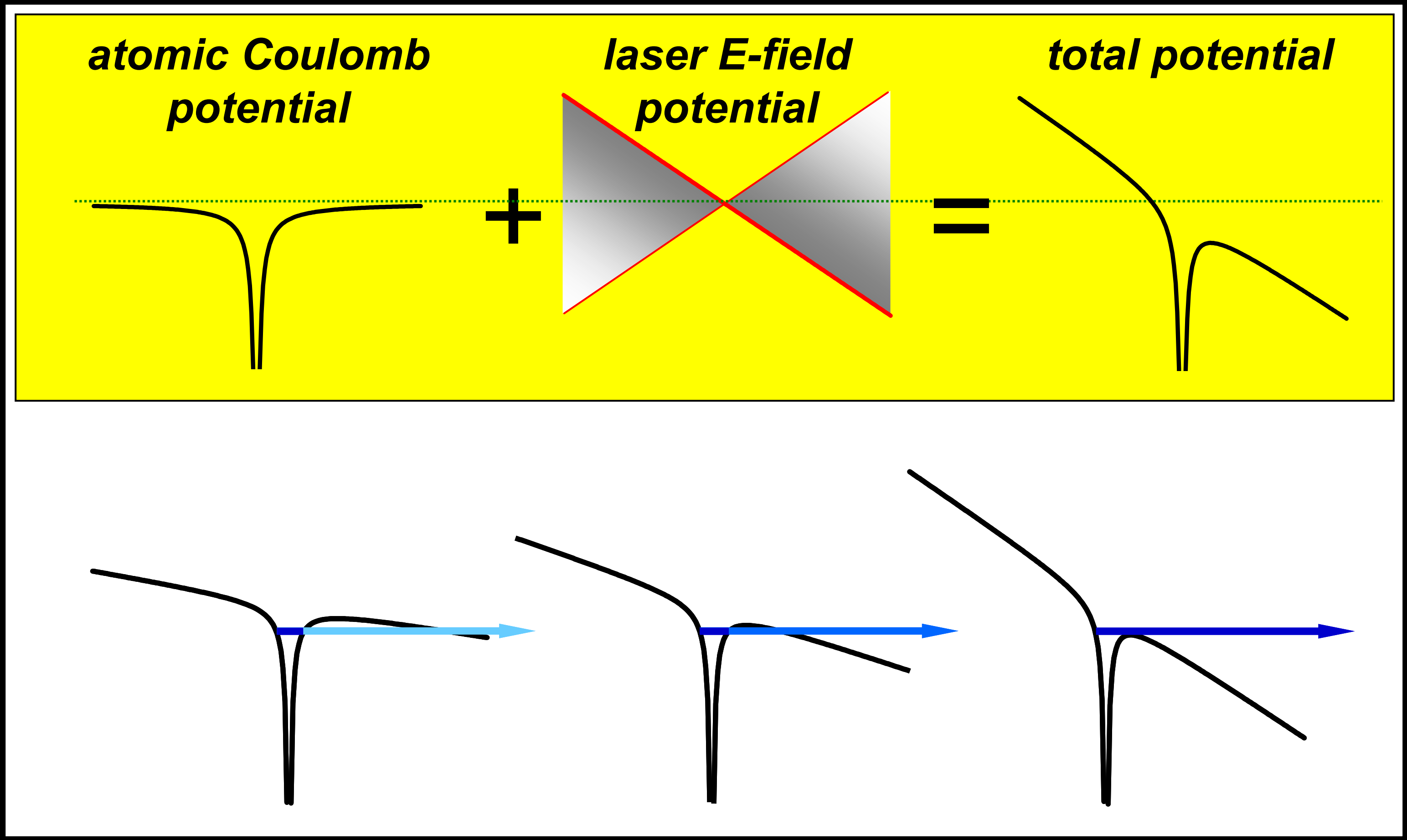
eight 780-nm photons
= 8×1.6 eV = 12.8 eV

Photon Density:

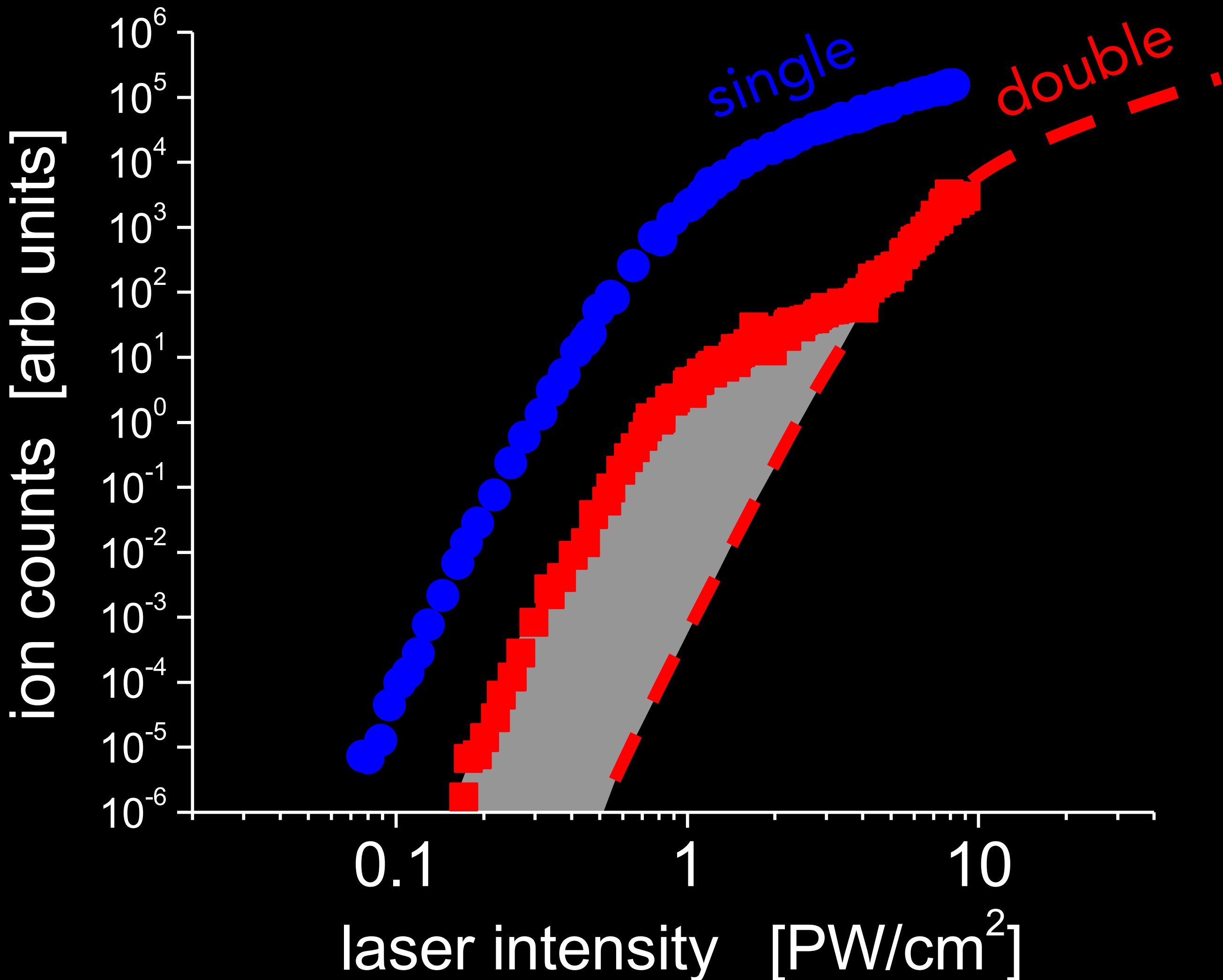
sunlight
2×10^{7} photons/cm^3

intense laser
4×10^{24} photons/cm^3

tunnel ionization

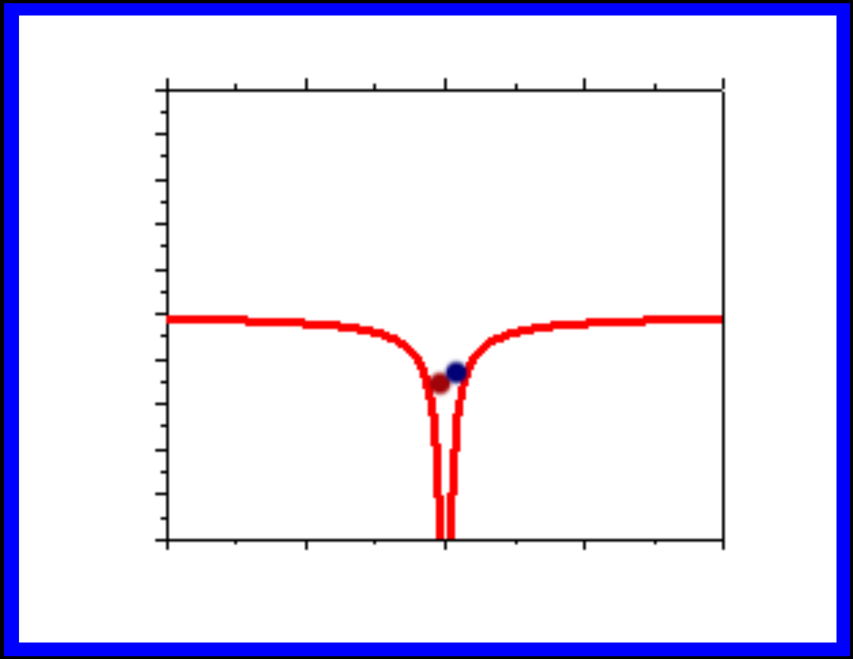


ionization yield curves



B. Walker, B. Sheehy, L. F. DiMauro, P. Agostini, K. J. Schafer, and K. C. Kulander, PRL 73, 1227 (1994)

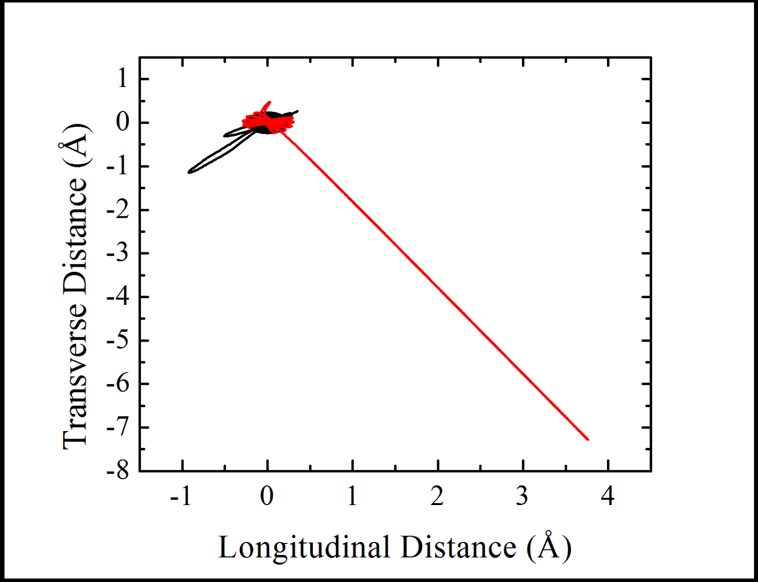
rescattering



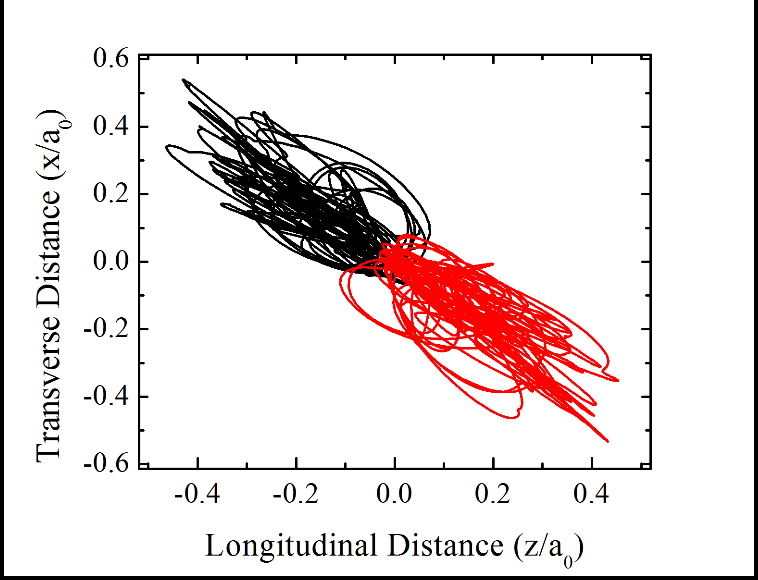
classical model atom

$$H = \frac{p_1^2}{2} + \frac{p_2^2}{2} - \frac{2}{r_1} - \frac{2}{r_2} + \frac{1}{|\vec{r_1} - \vec{r_2}|}$$

$$H = \frac{p_1^2}{2} + \frac{p_2^2}{2} - \frac{2}{\sqrt{r_1^2 + .825^2}} - \frac{2}{\sqrt{r_2^2 + .825^2}} + \frac{1}{\sqrt{|\vec{r_1} - \vec{r_2}|^2 + .05^2}}$$

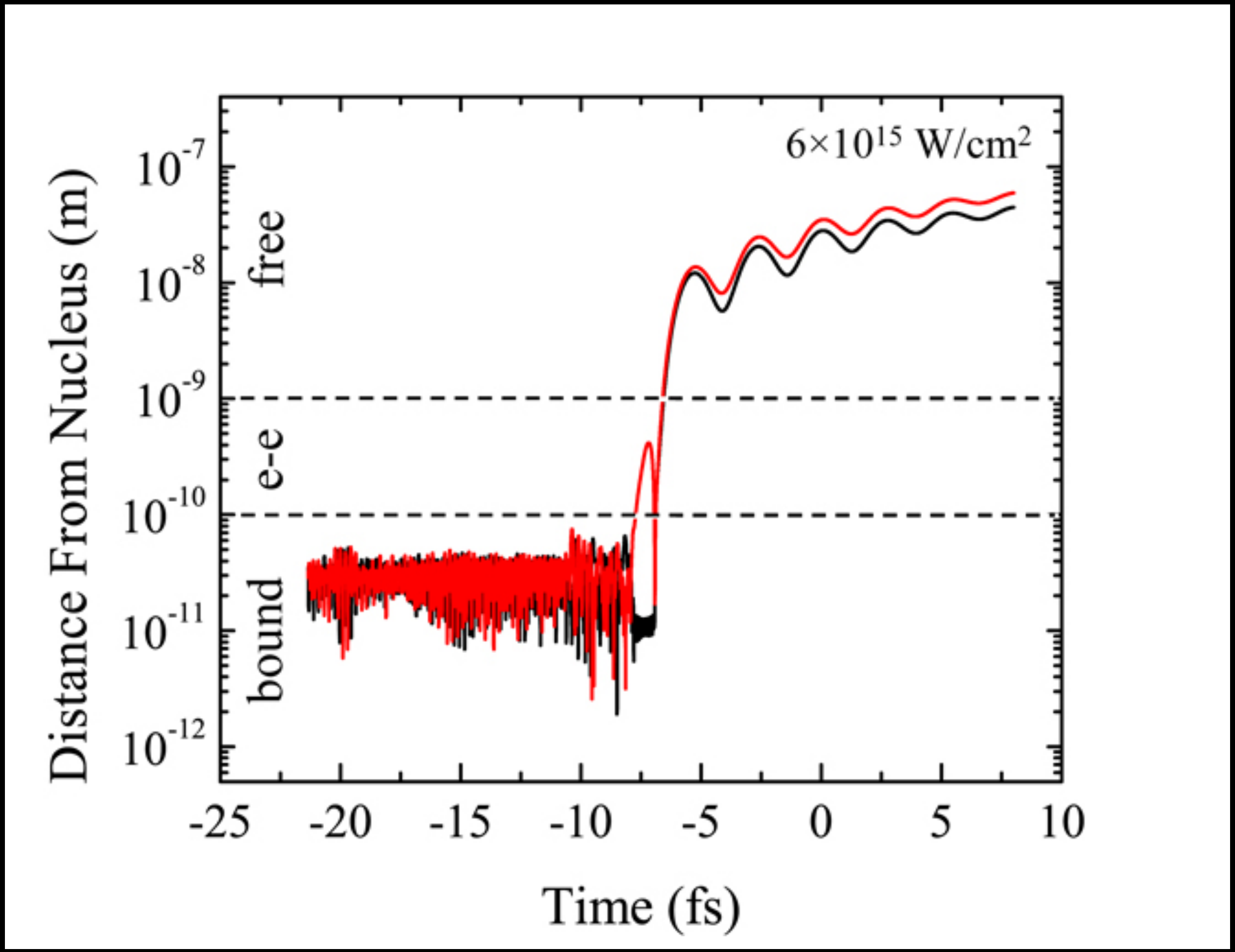


Classical Atom → Autoionization

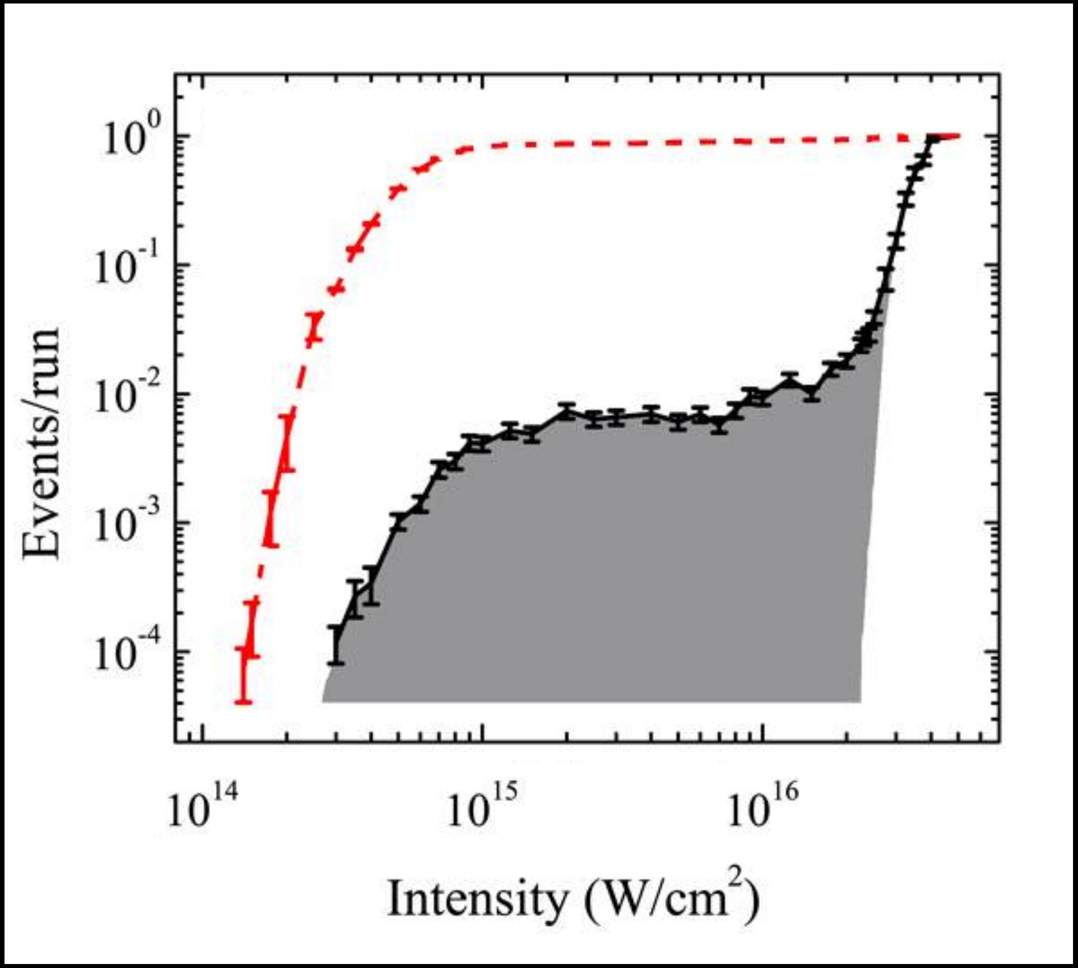


Softened Potential → Stable Atom

rescattering with linear polarization

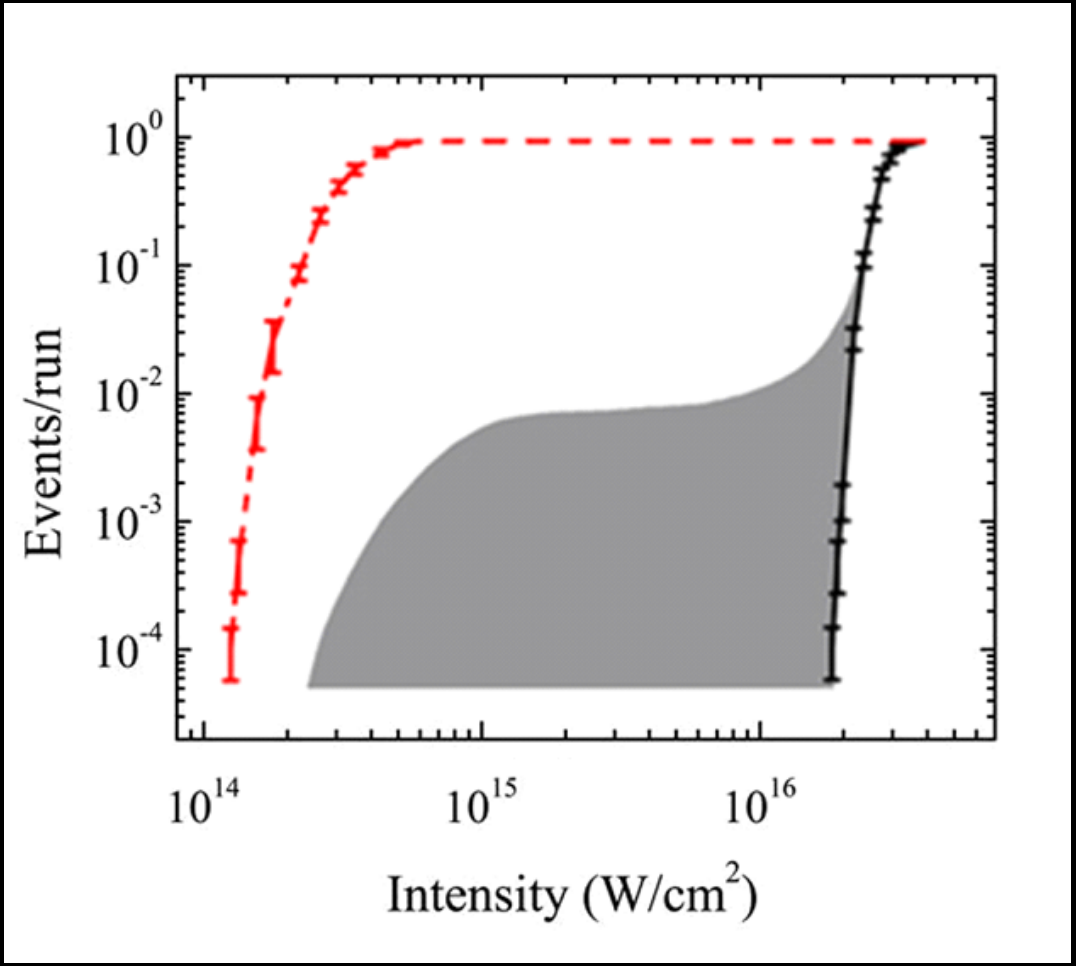


yield curves with linear polarization



JLC and J.P. Paquette, PRA 79 043410, 2009

yield curves with circular polarization



HHG with two-color, counter-rotating fields

nature photonics

ARTICLES

PUBLISHED ONLINE: 8 DECEMBER 2014 | DOI: 10.1038/NPHOTON.2014.293

Genera
polariz

Ofer Kfir[1]*, Pa
Tenio Popmint
Margaret Mur

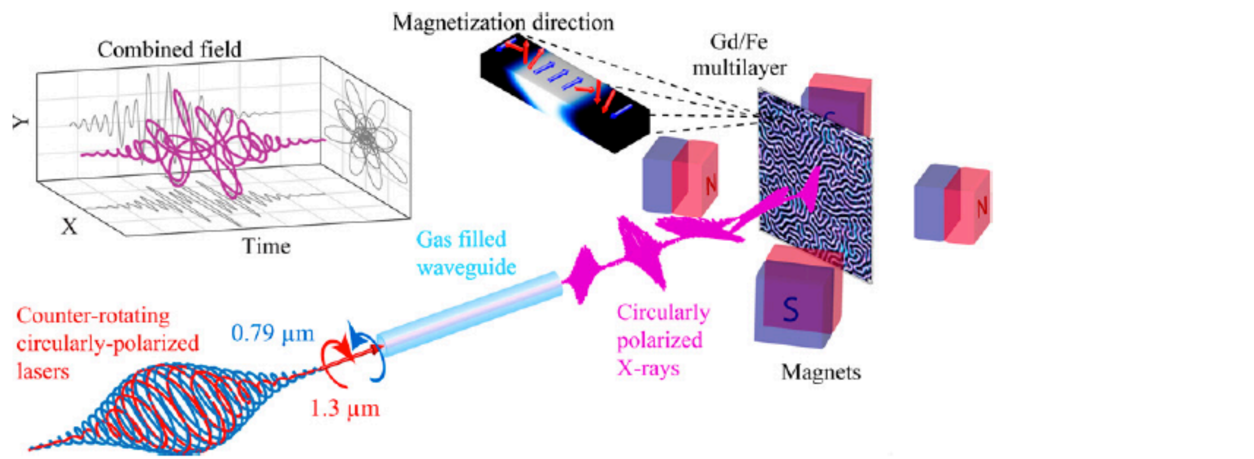
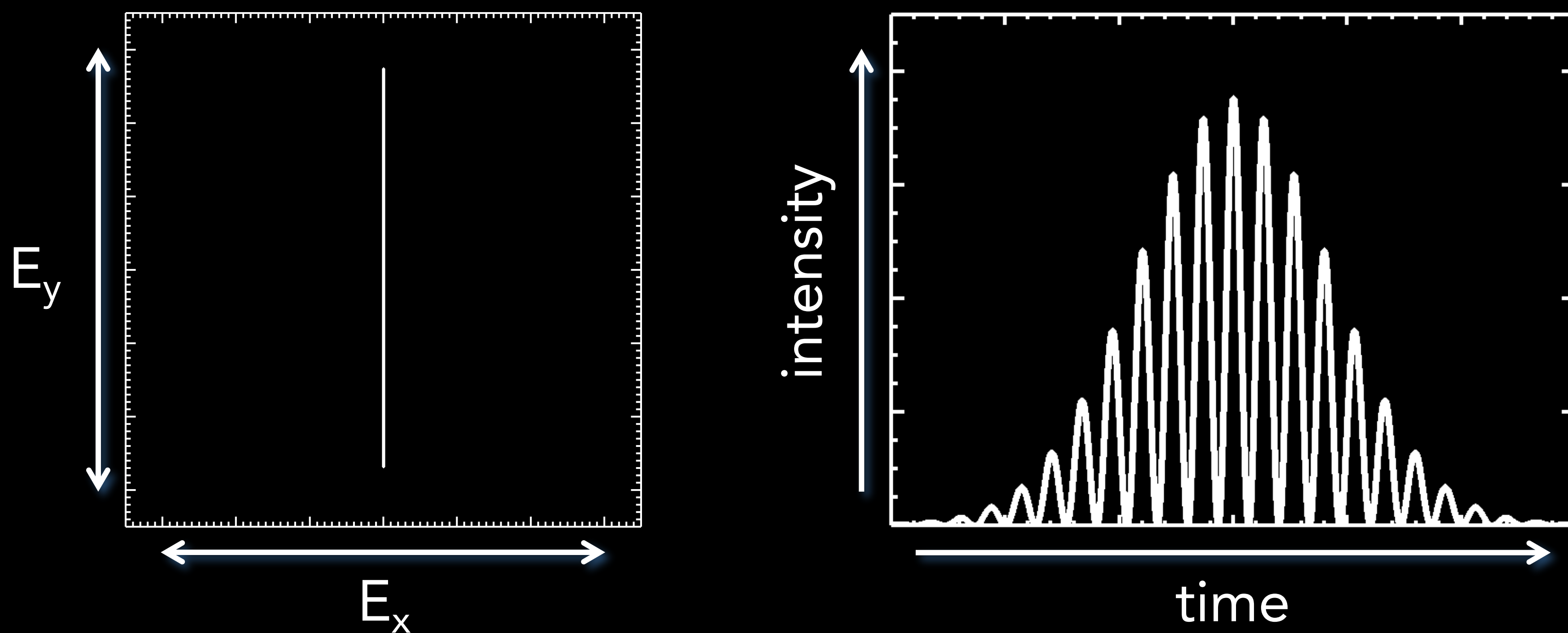


Fig. 1. Experimental scheme. Bright, circularly polarized, soft X-ray beams were generated by focusing 0.79- and 1.3-µm counterrotating circularly polarized laser fields into a gas-filled waveguide; they are then used for XMCD measurements at the $N_{4,5}$ absorption edges of Gd as well as the $M_{2,3}$ absorption edge of Fe from an out-of-plane magnetized Gd/Fe multilayer sample. (*Left Inset*) Combined field of the two drivers.

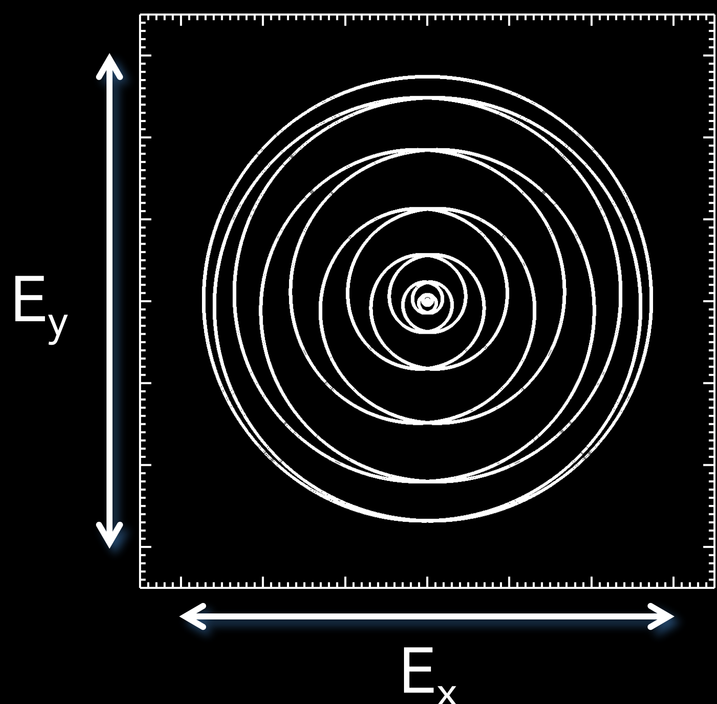
Bright circularly polarized soft X-ray high harmonics for X-ray magnetic circular dichroism

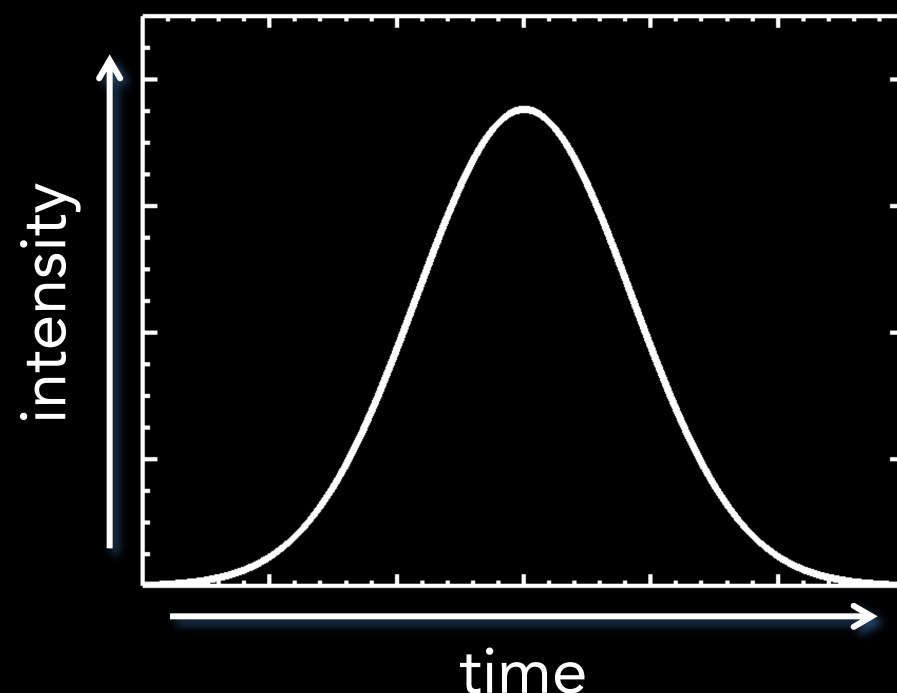
Tingting Fan[a,1], Patrik Grychtol[a], Ronny Knut[a], Carlos Hernández-García[a,b], Daniel D. Hickstein[a], Dmitriy Zusin[a], Christian Gentry[a], Franklin J. Dollar[a], Christopher A. Mancuso[a], Craig W. Hogle[a], Ofer Kfir[c], Dominik Legut[d,e], Karel Carva[e,f], Jennifer L. Ellis[a], Kevin M. Dorney[a], Cong Chen[a], Oleg G. Shpyrko[g], Eric E. Fullerton[h], Oren Cohen[c], Peter M. Oppeneer[f], Dejan B. Milošević[i,j,k], Andreas Becker[a], Agnieszka A. Jaroń-Becker[a], Tenio Popmintchev[a], Margaret M. Murnane[a,1], and Henry C. Kapteyn[a]

single-color linear polarization

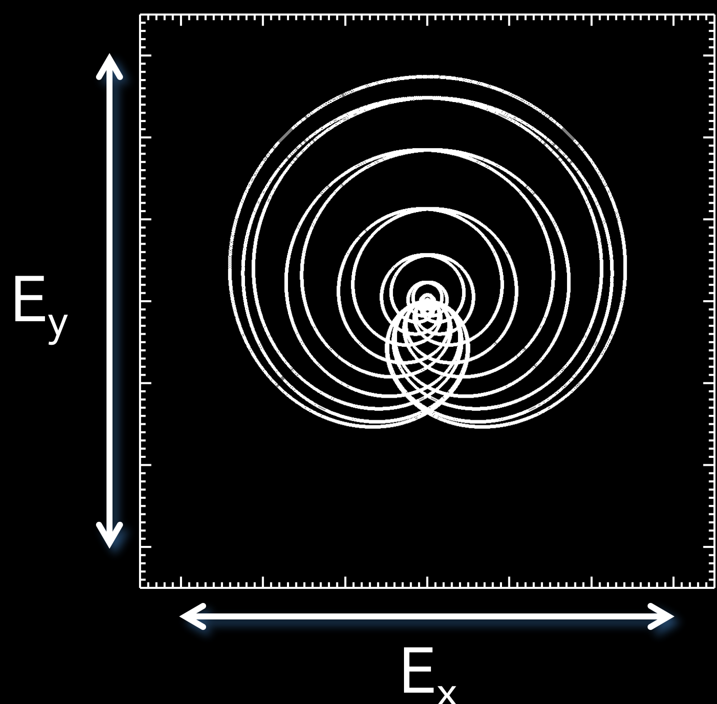


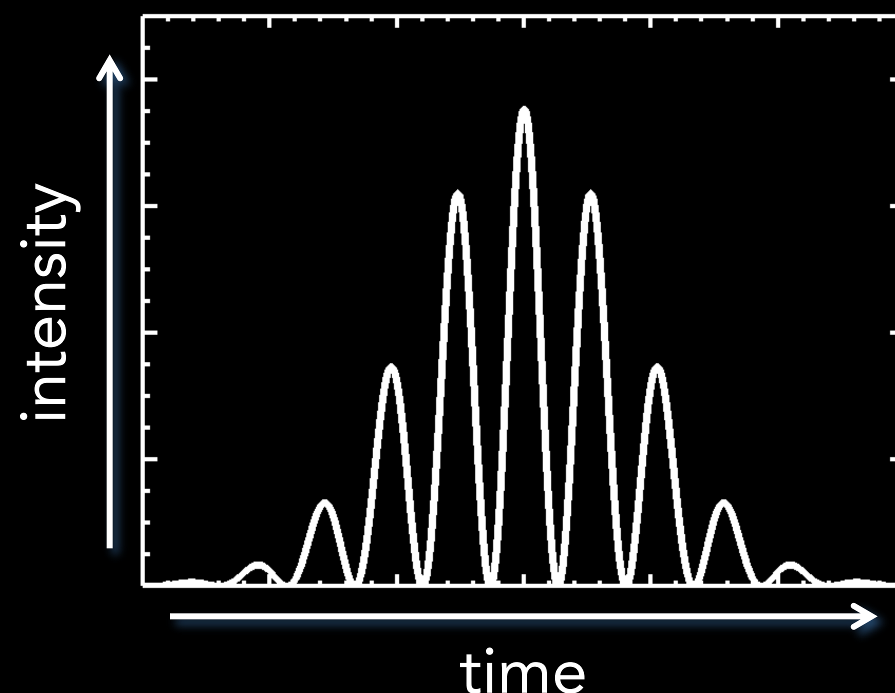
single-color circular polarization



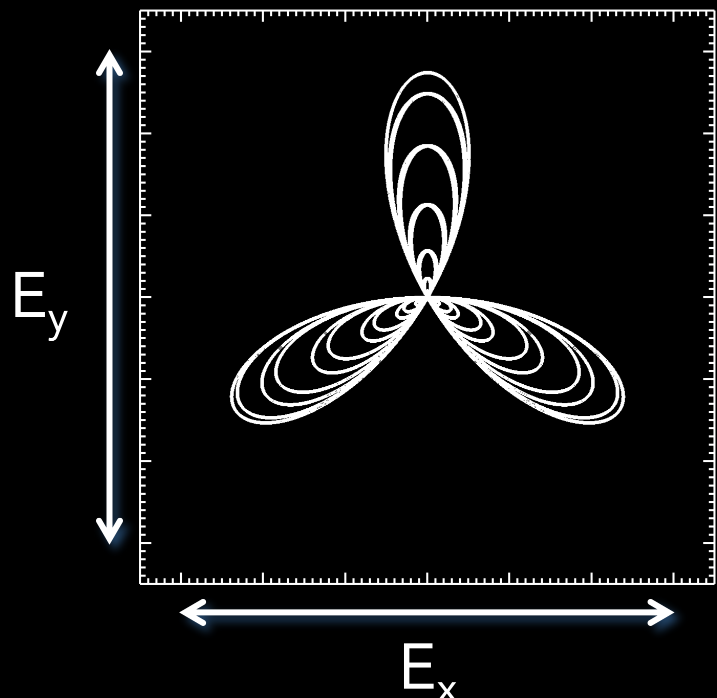


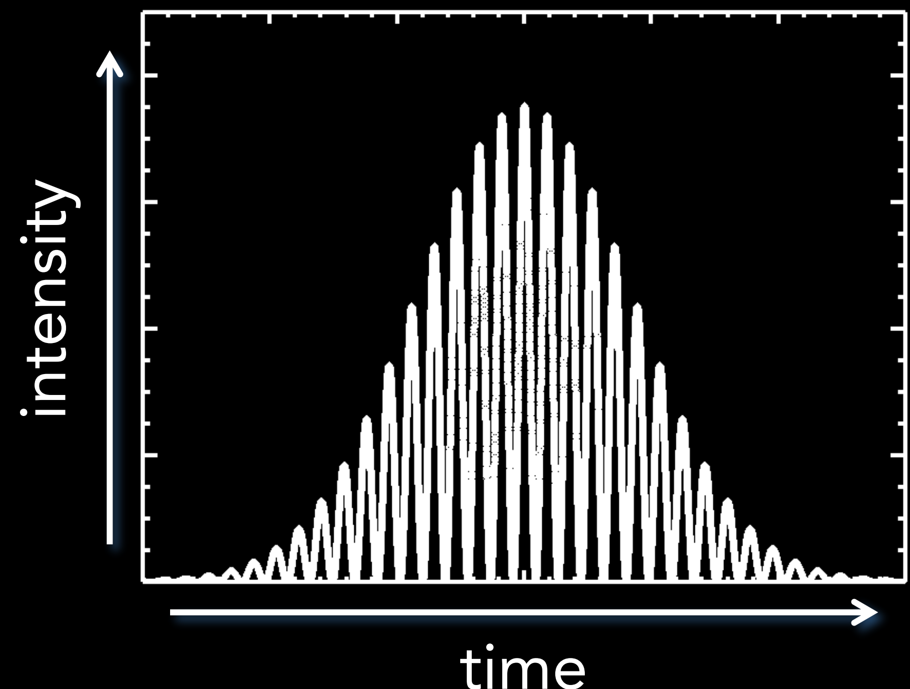
two-color co-rotating fields





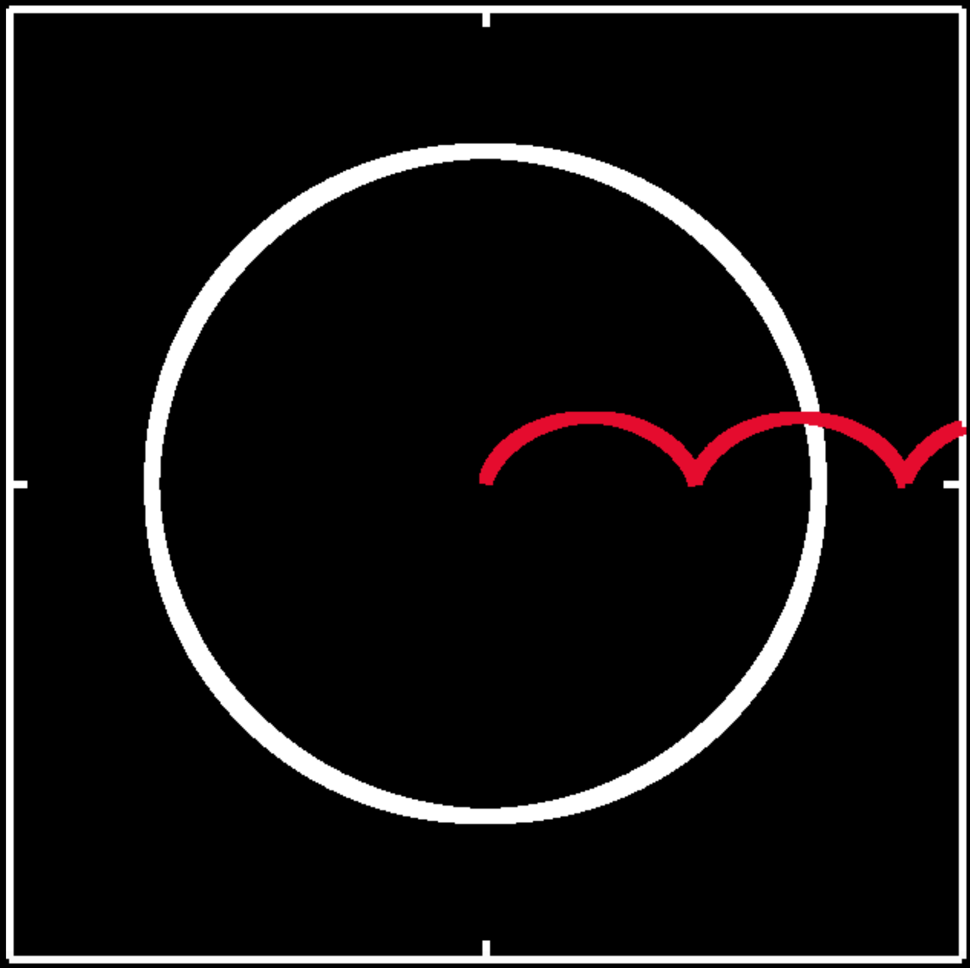
two-color counter-rotating fields





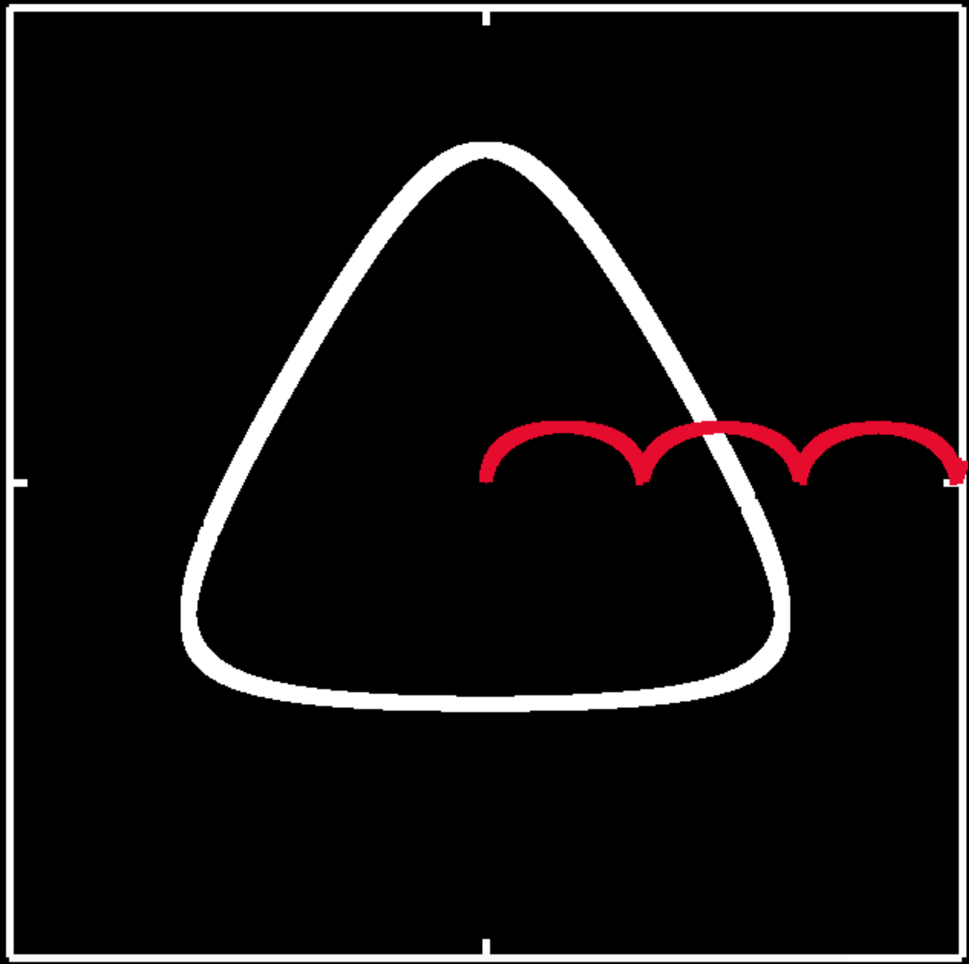
simple trajectories

circular polarization



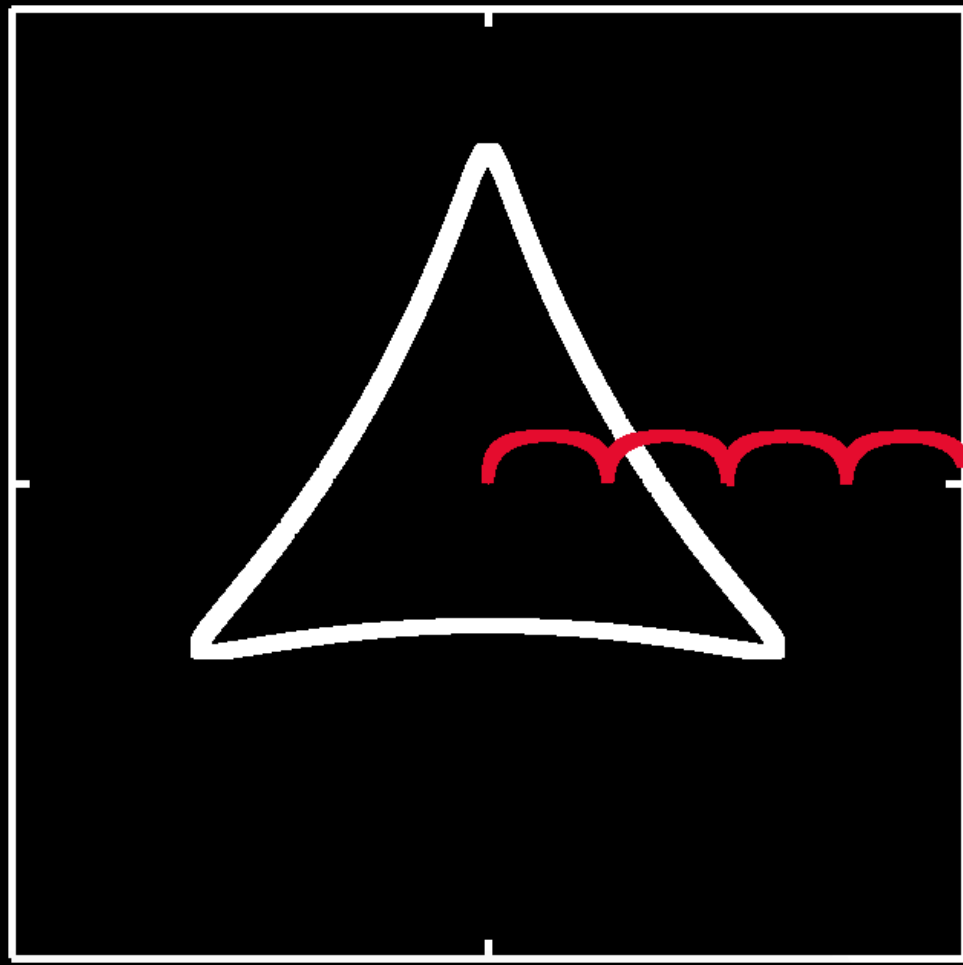
simple trajectories

0.2:1 counter-rotating ω:2ω



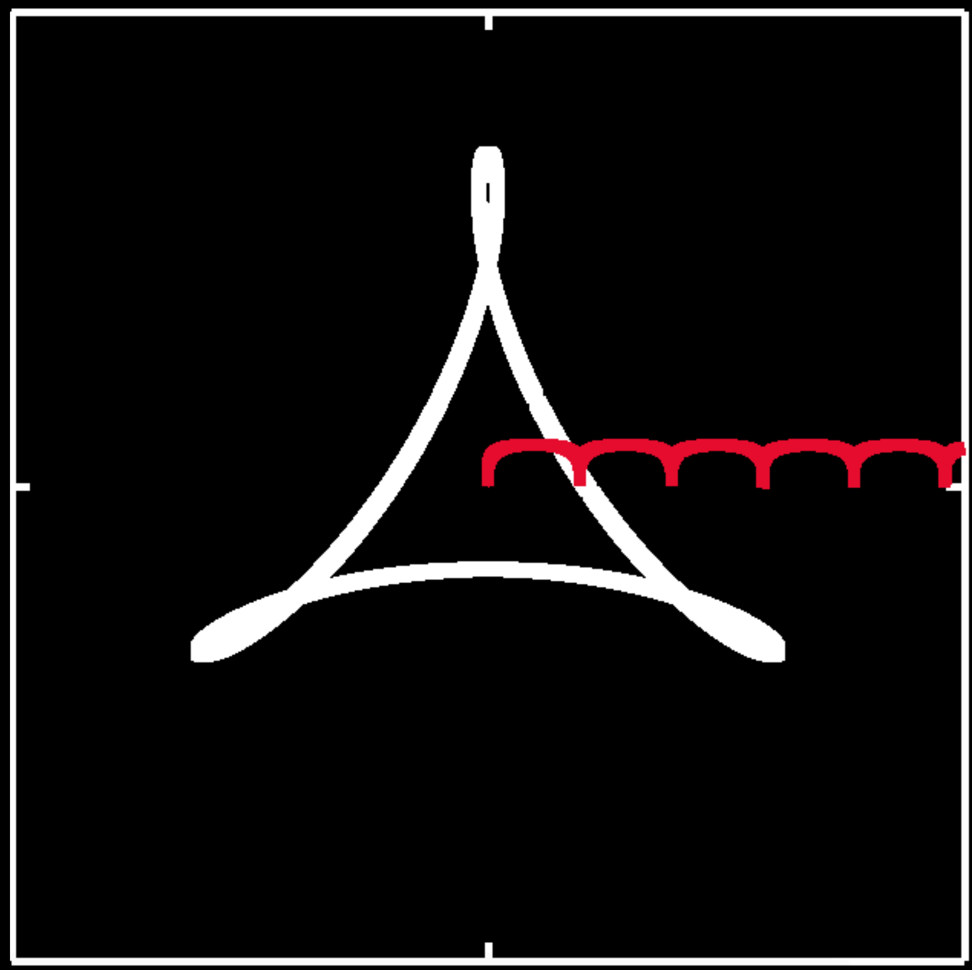
simple trajectories

0.4:1 counter-rotating ω:2ω



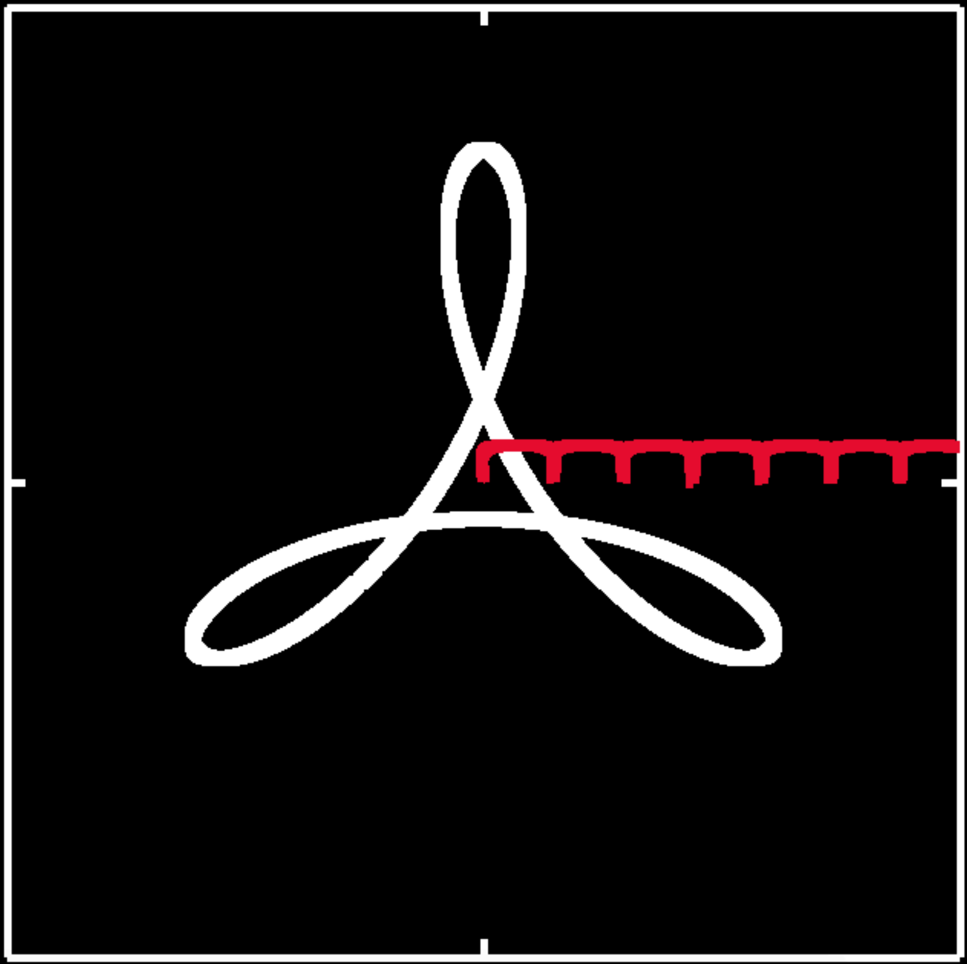
simple trajectories

0.6:1   counter-rotating ω:2ω



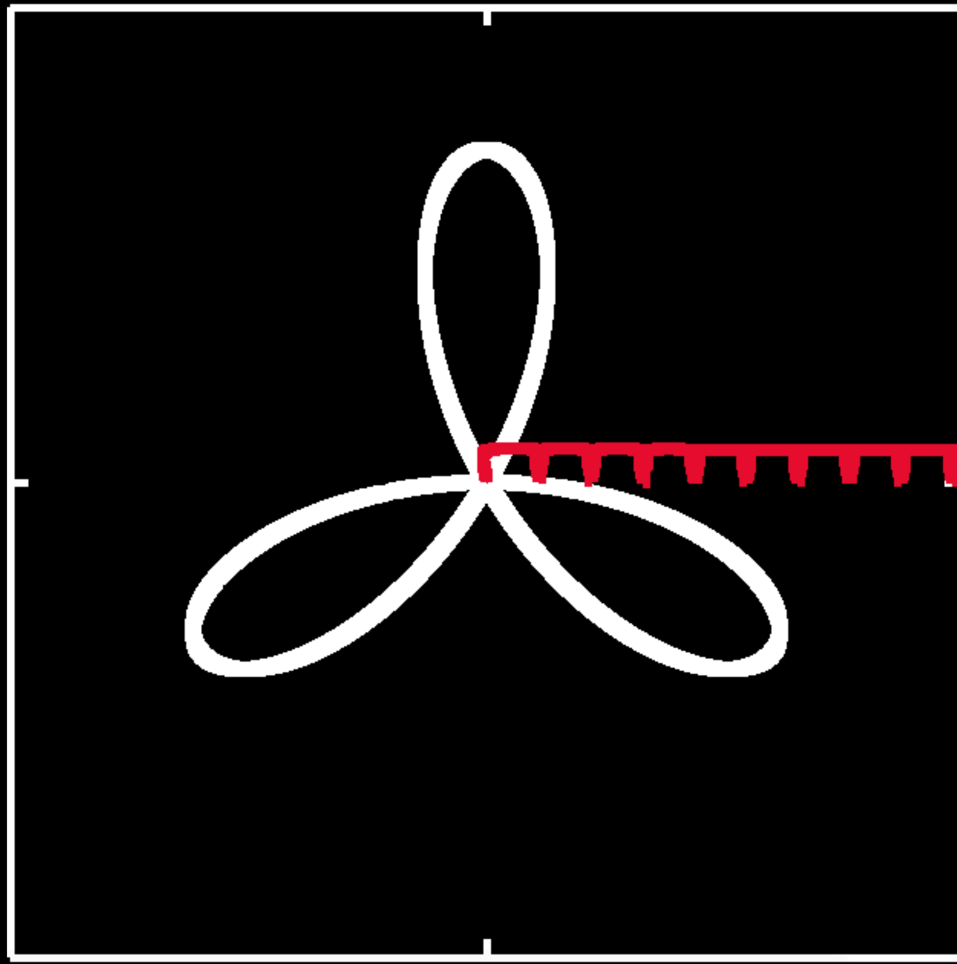
simple trajectories

0.8:1   counter-rotating ω:2ω



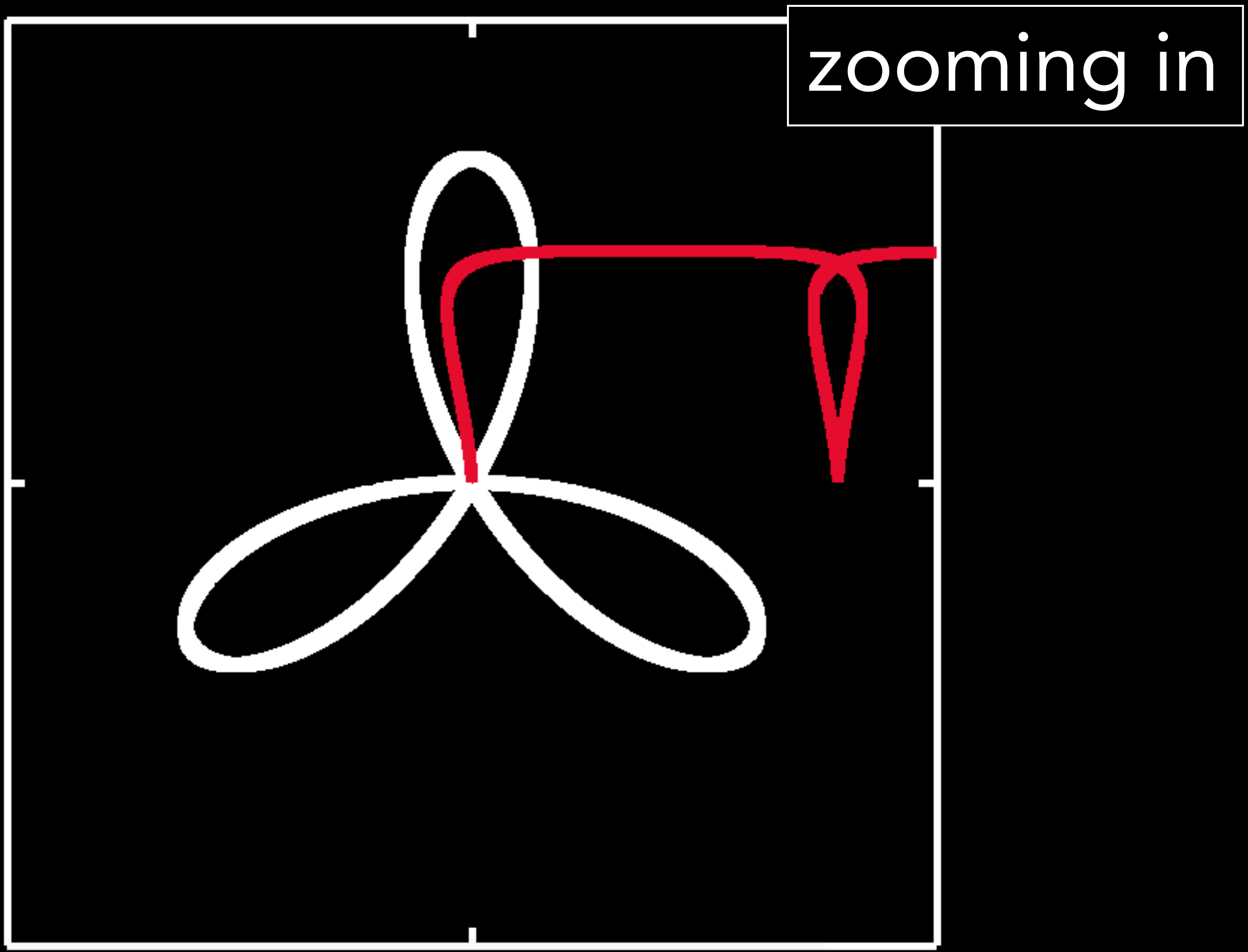
simple trajectories

1.0:1 counter-rotating ω:2ω



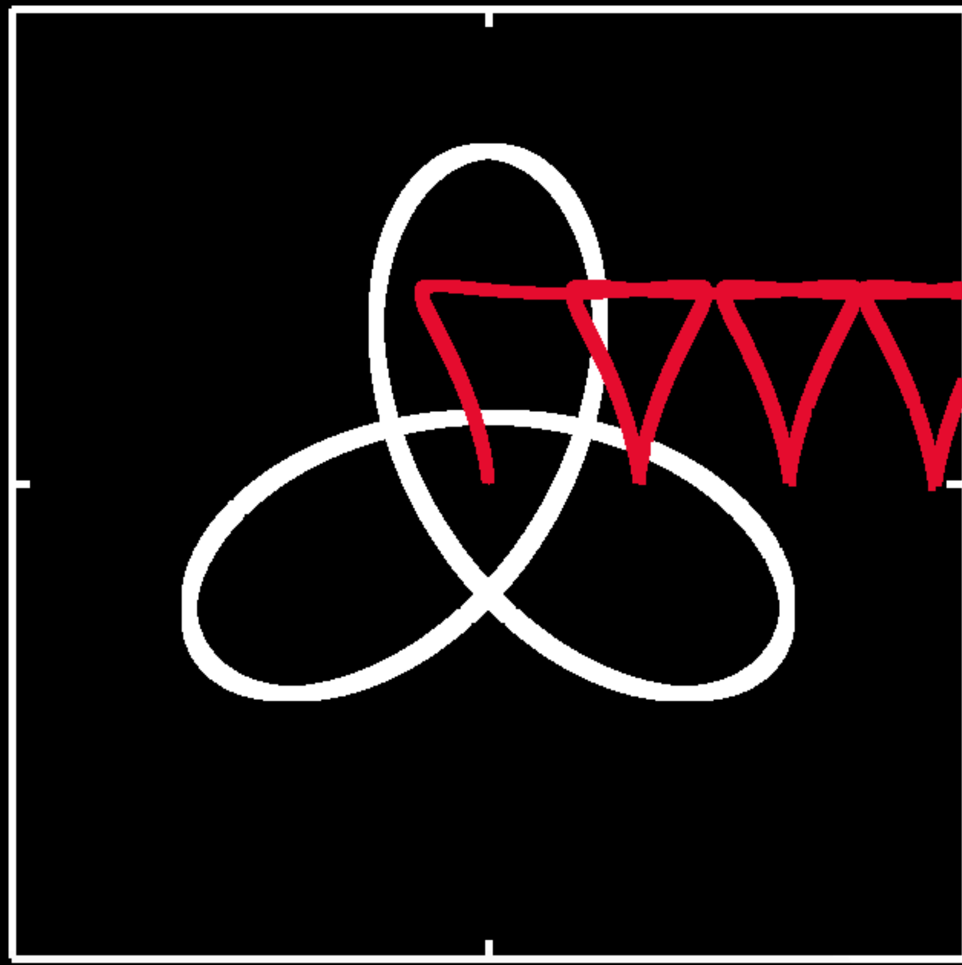
simple trajectories

1.0:1 counter-rotating ω:2ω



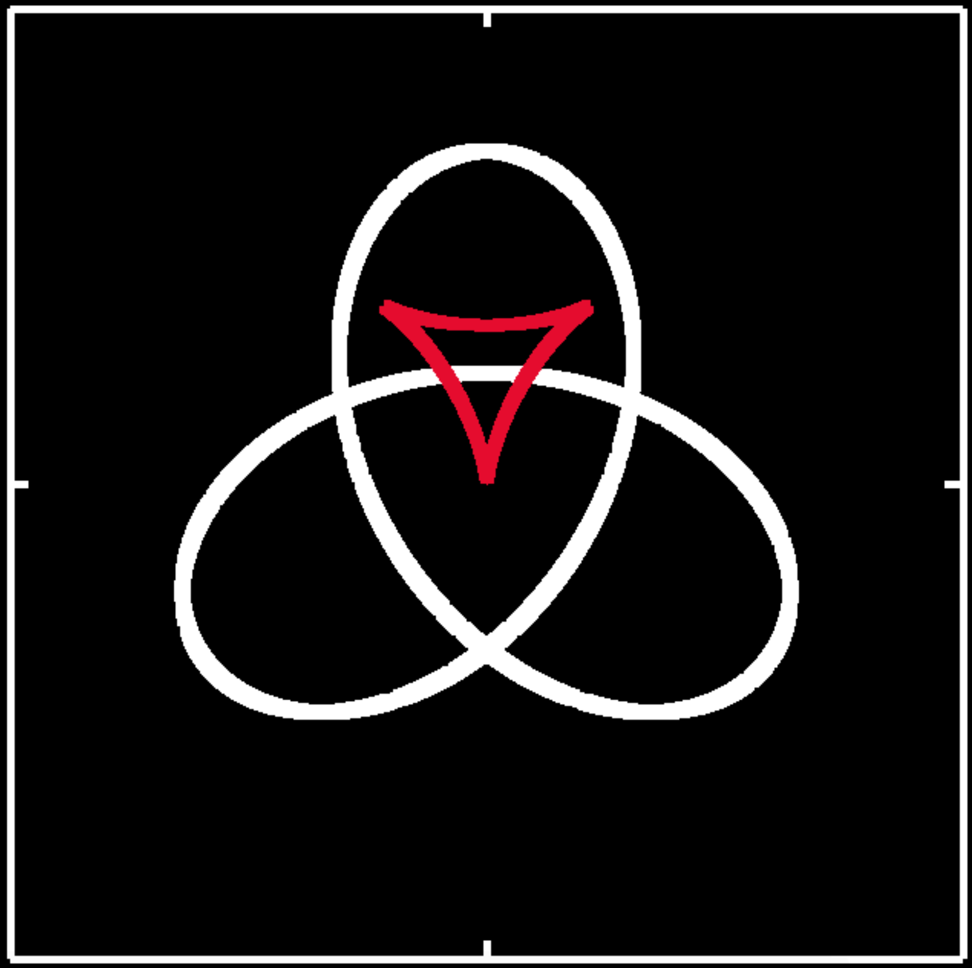
simple trajectories

1.5:1 counter-rotating ω:2ω



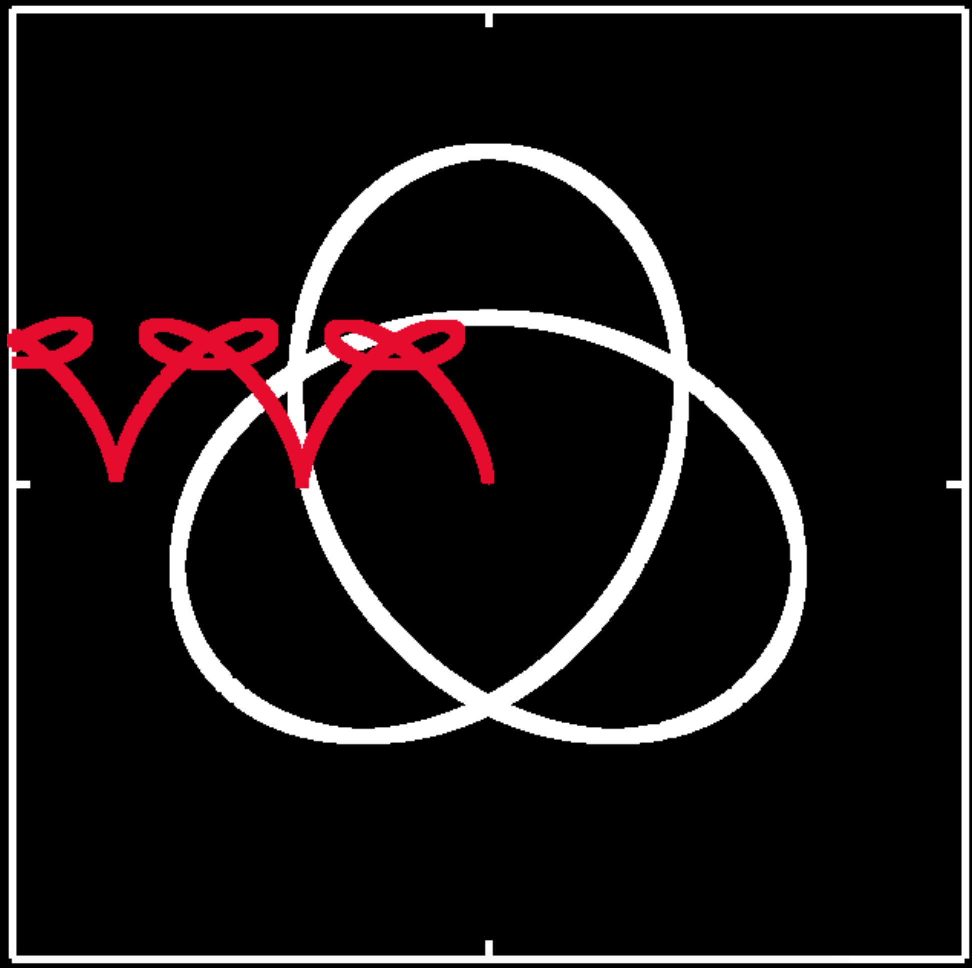
simple trajectories

2.0:1 counter-rotating ω:2ω

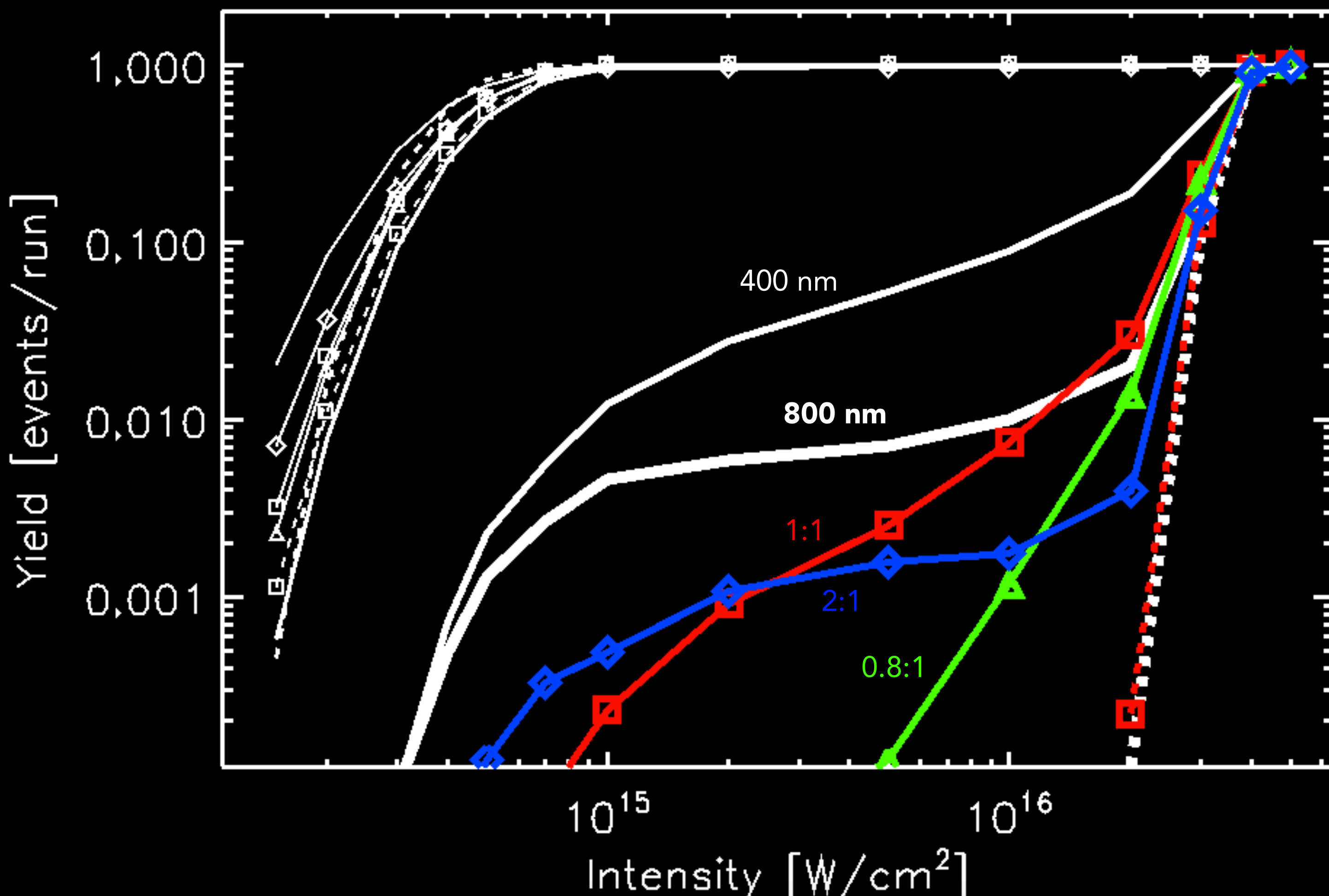


simple trajectories

3.0:1   counter-rotating ω:2ω

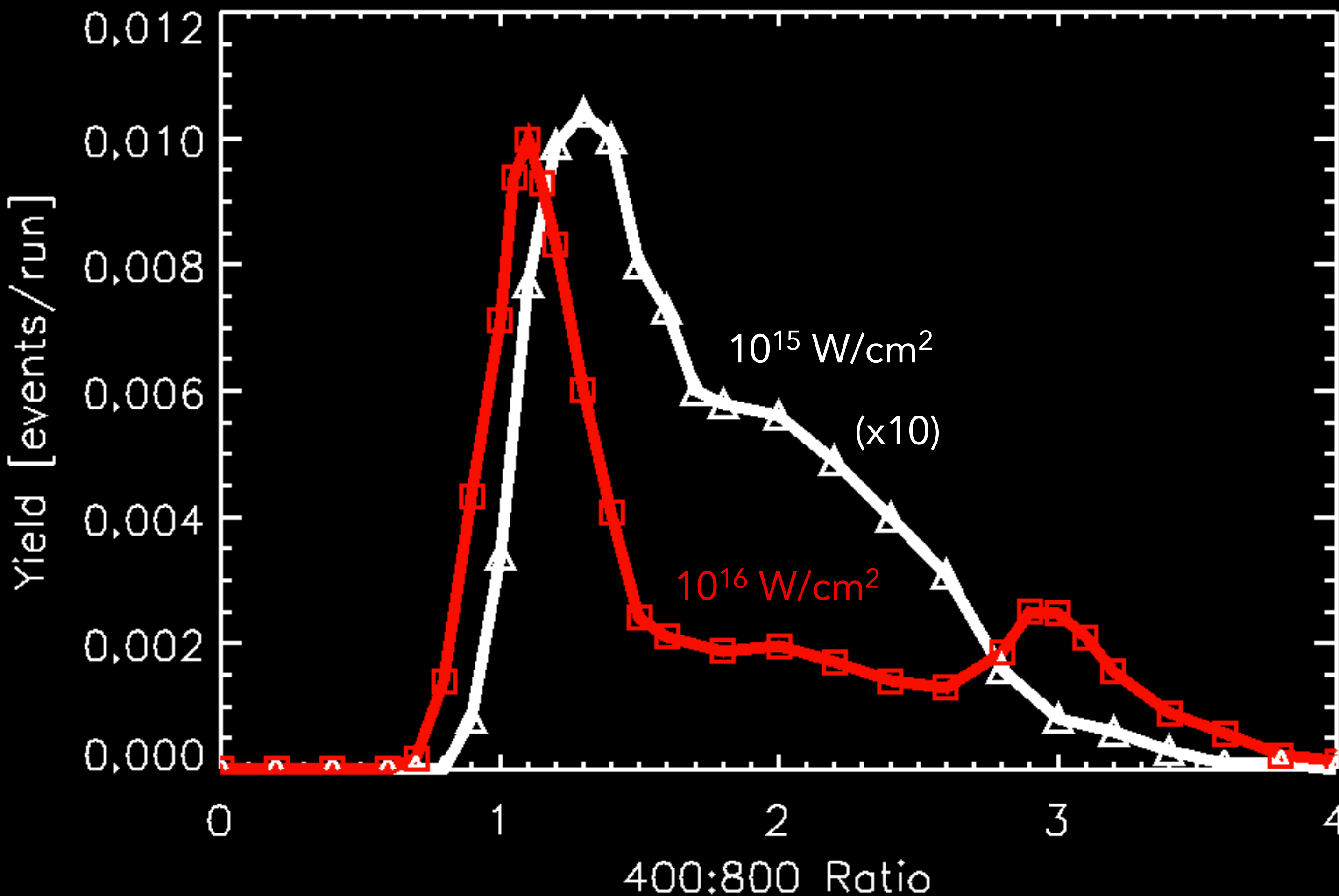


ionization yield curves



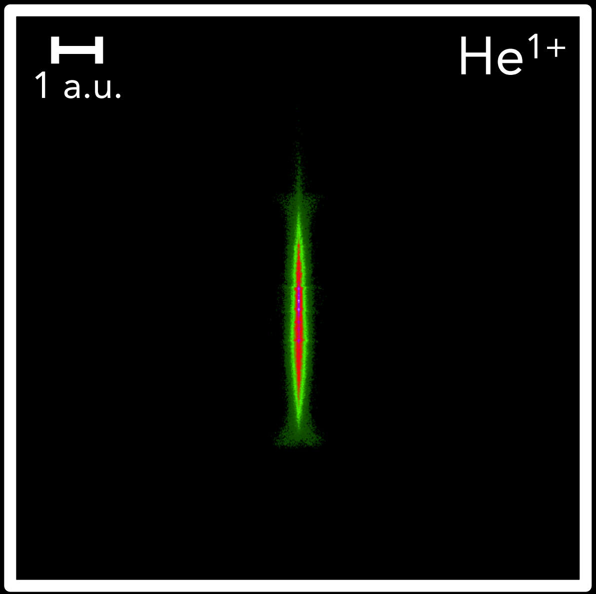
JLC and D.D. Hickstein, submitted to PRL, 2016

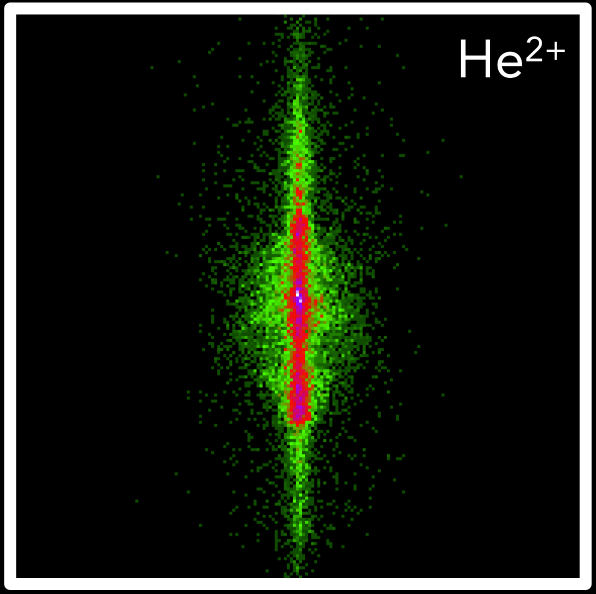
yield vs 400:800 ratio



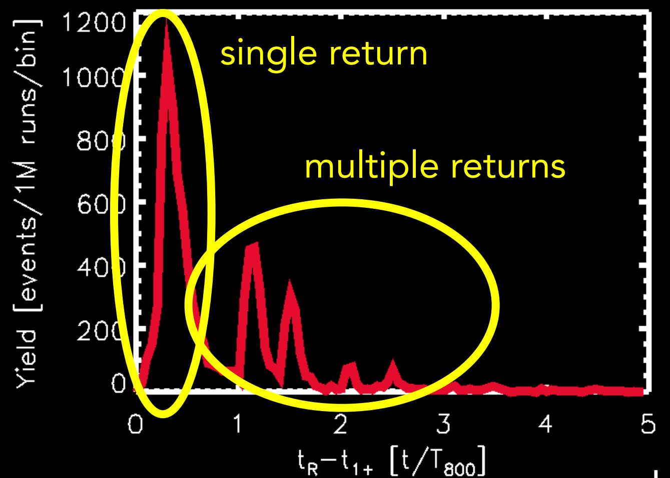
electron momenta & timing (linear 800nm)

transverse electron momenta

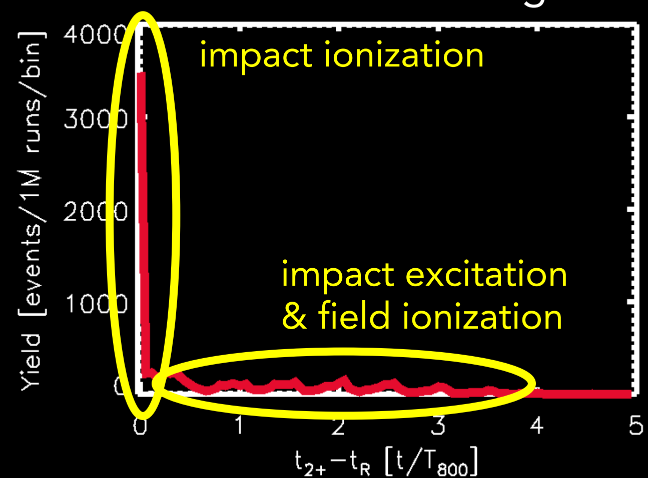




rescattering timing

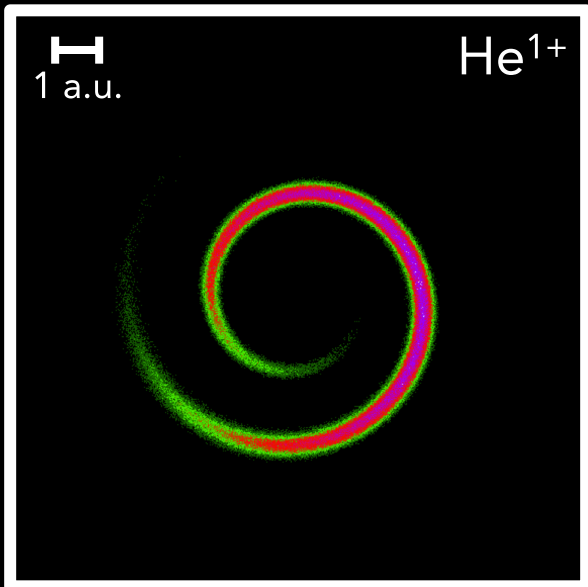


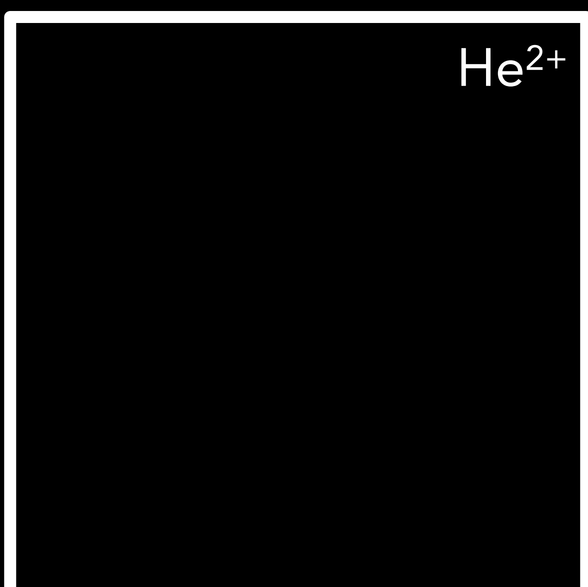
double
ionization timing



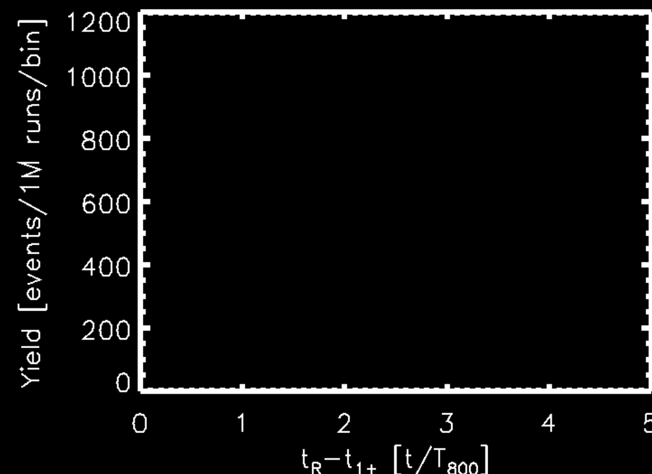
electron momenta & timing (circular 800nm)

transverse electron momenta

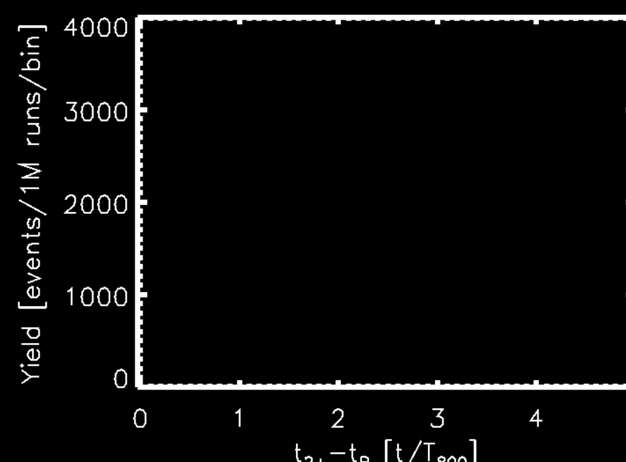




rescattering timing

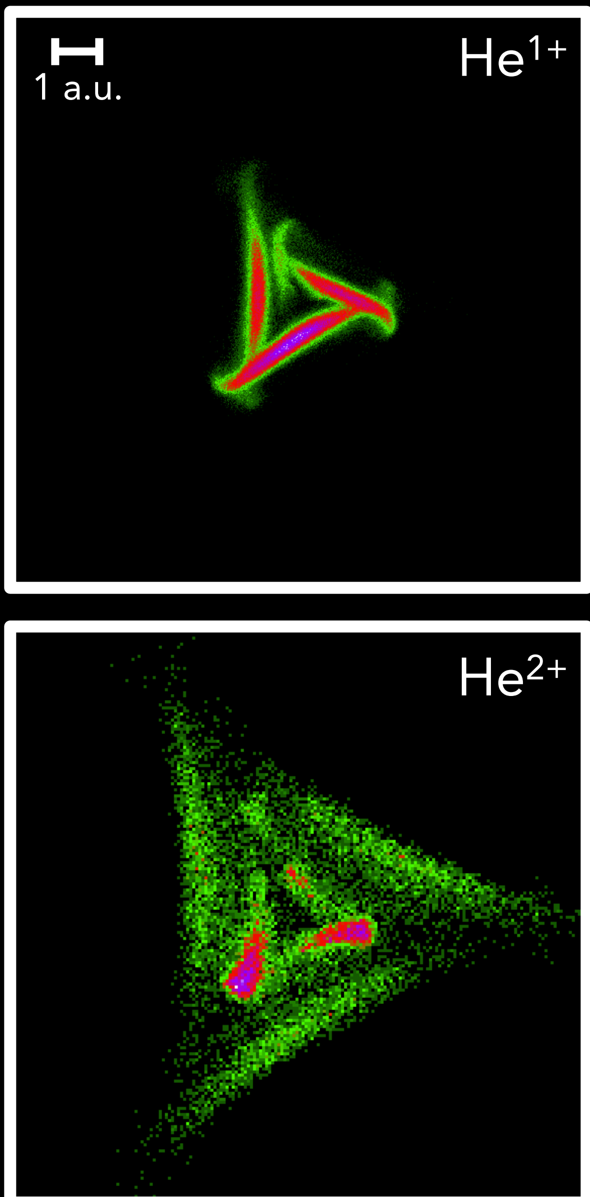


double
ionization timing

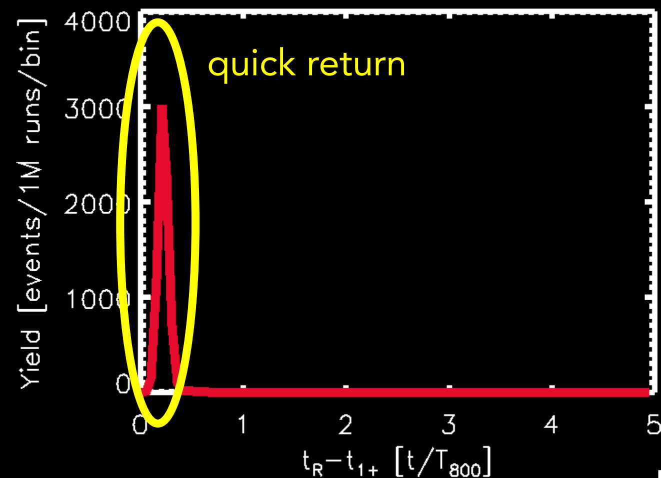


electron momenta & timing (400:800 1:1)

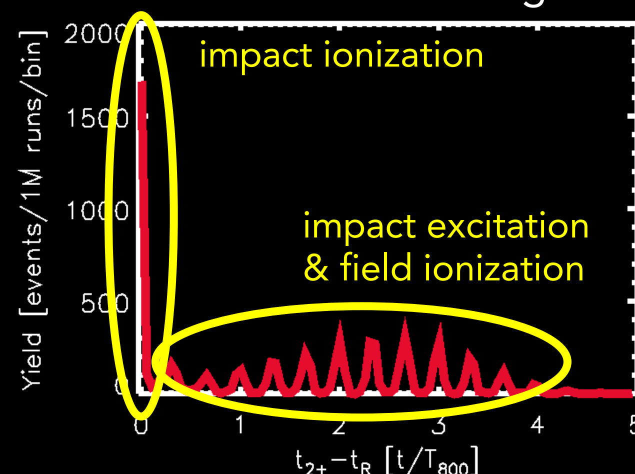
transverse electron momenta



rescattering timing

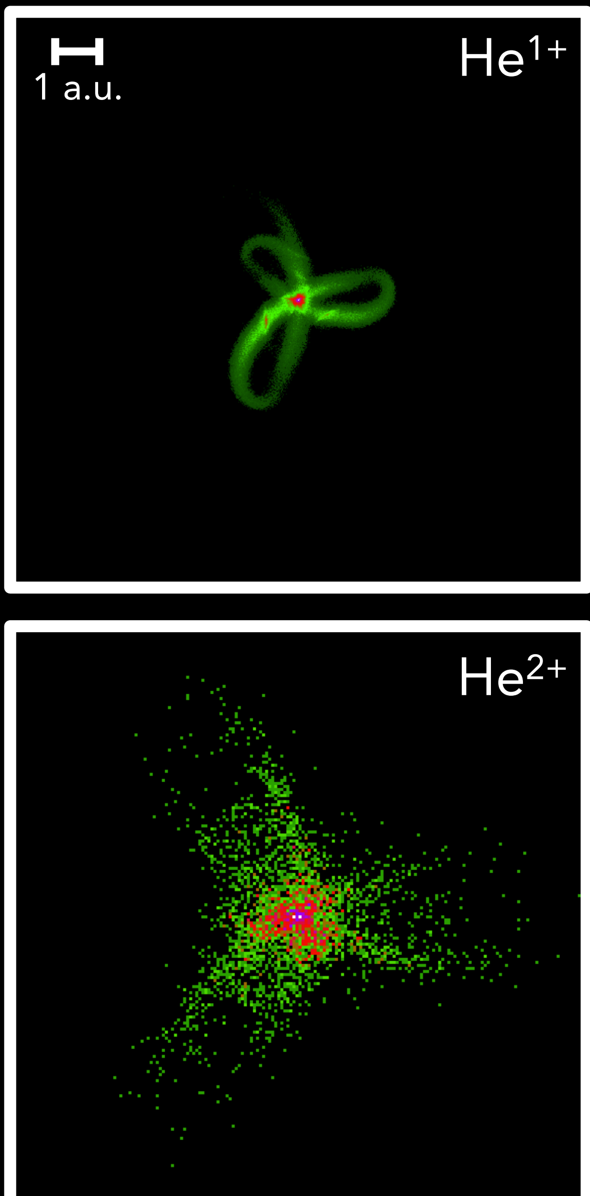


double ionization timing

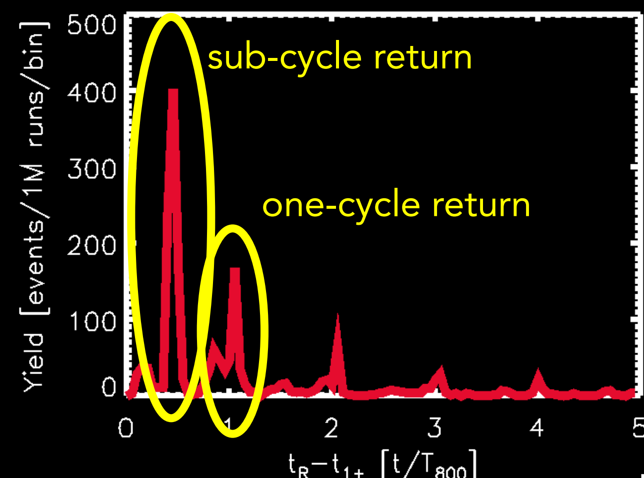


electron momenta & timing (400:800 2:1)

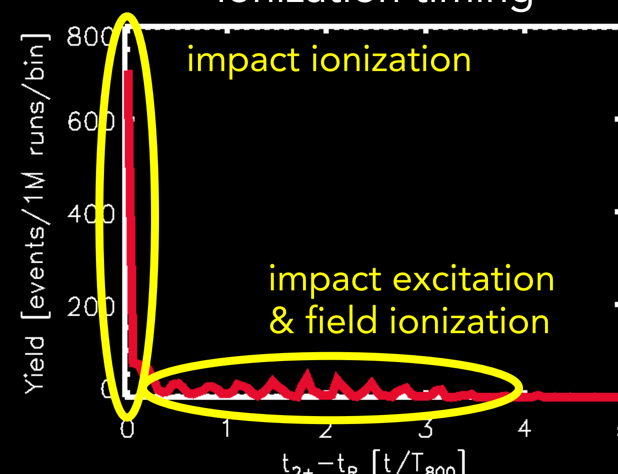
transverse electron momenta



rescattering timing

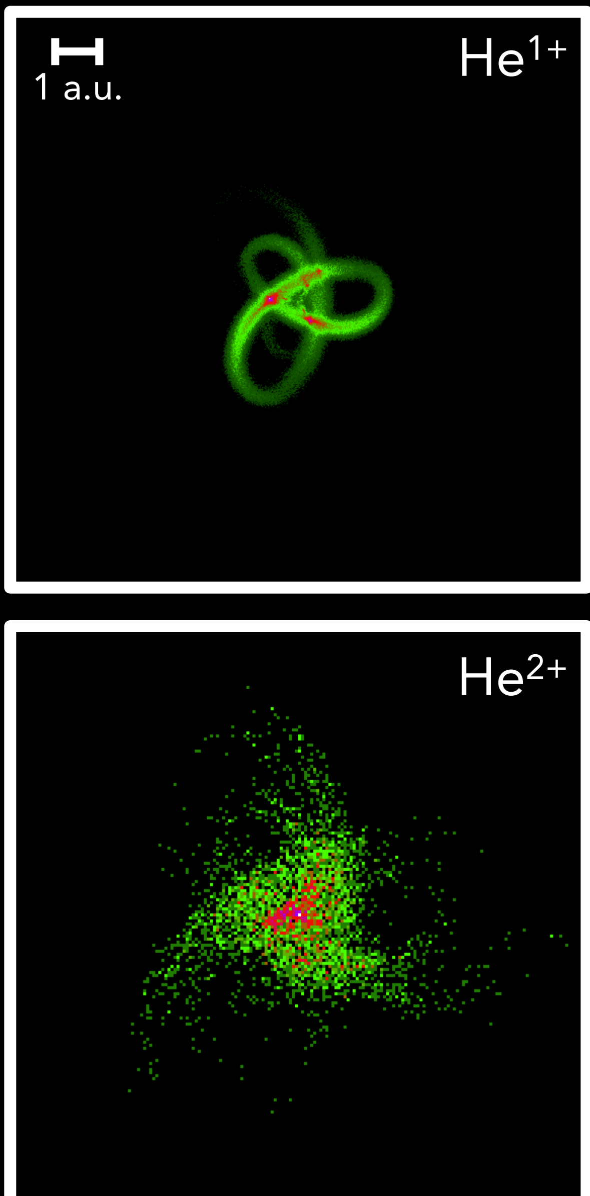


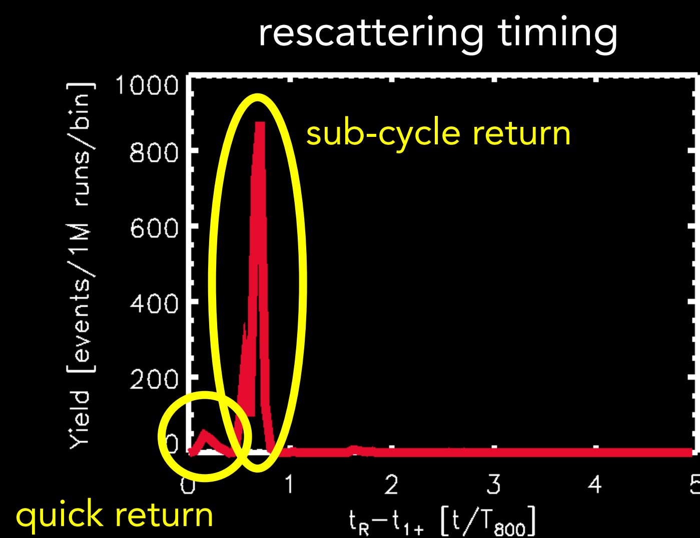
double
ionization timing

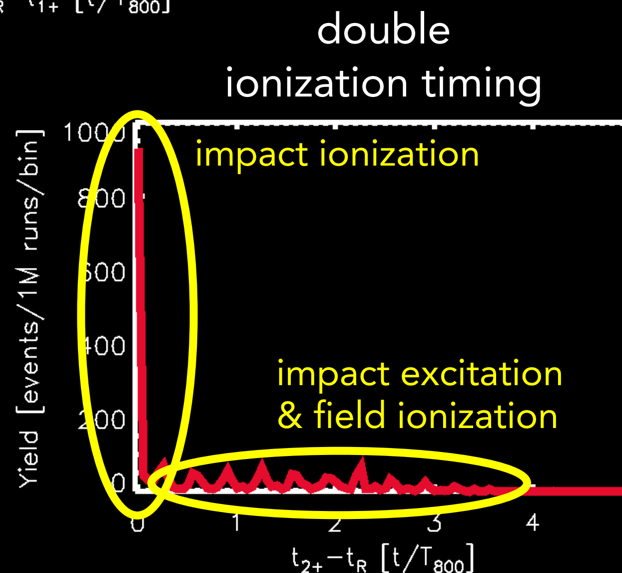


electron momenta & timing (400:800 3:1)

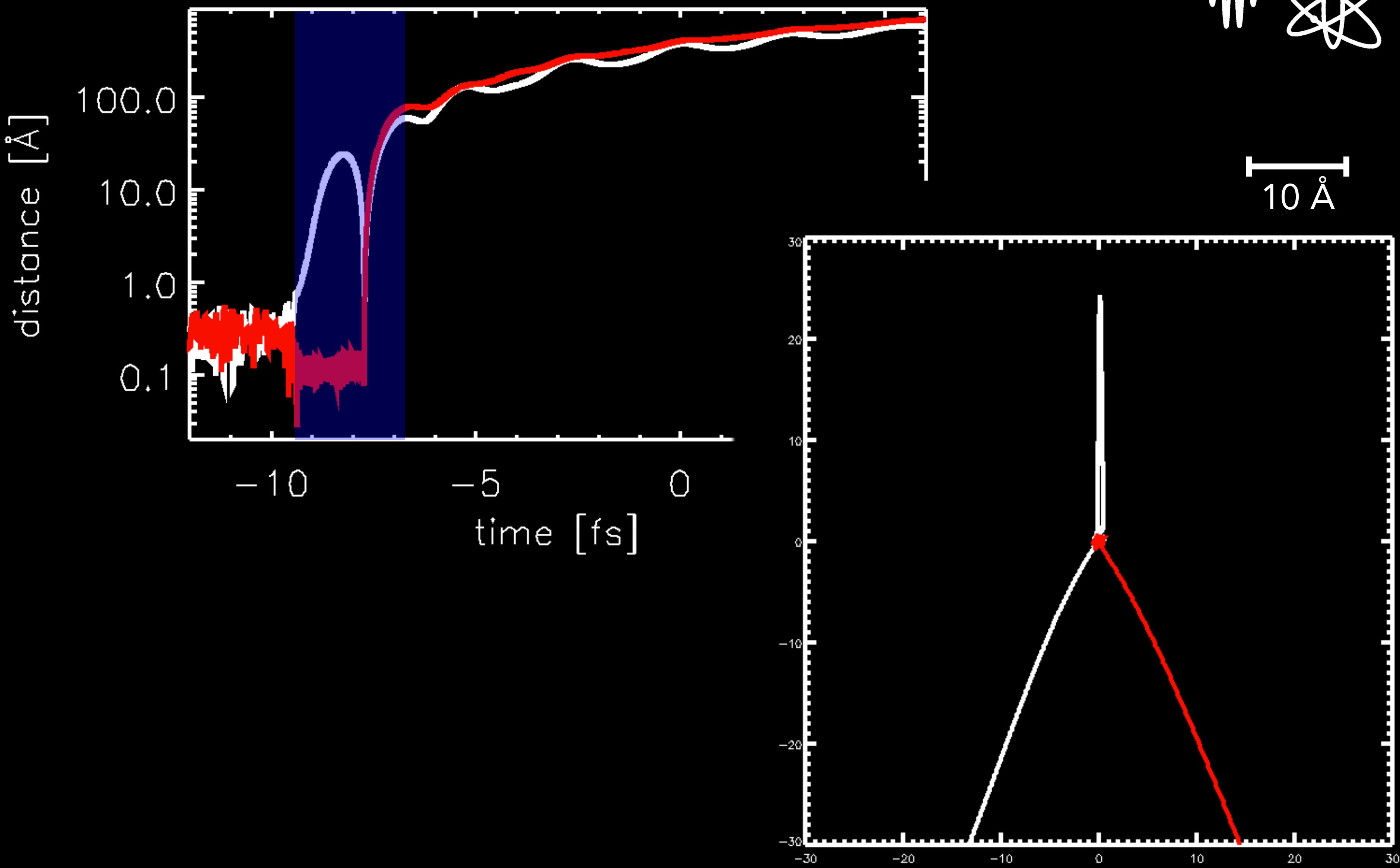
transverse electron momenta



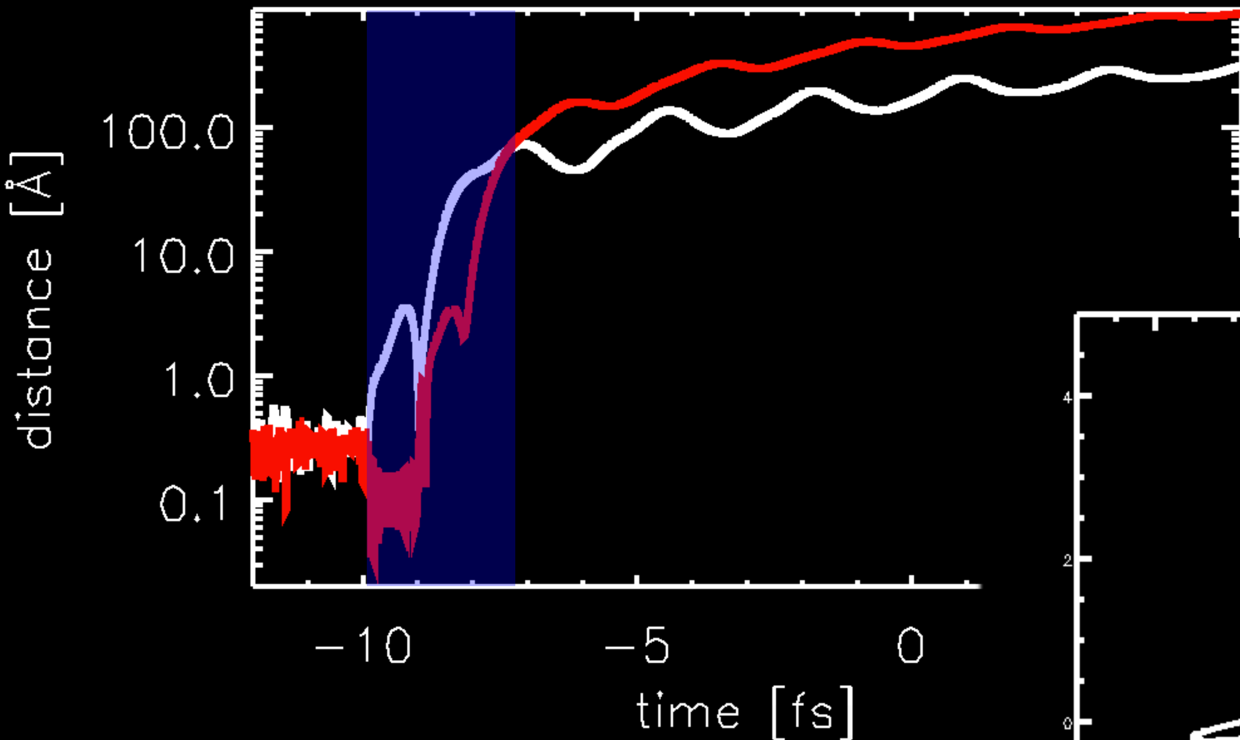


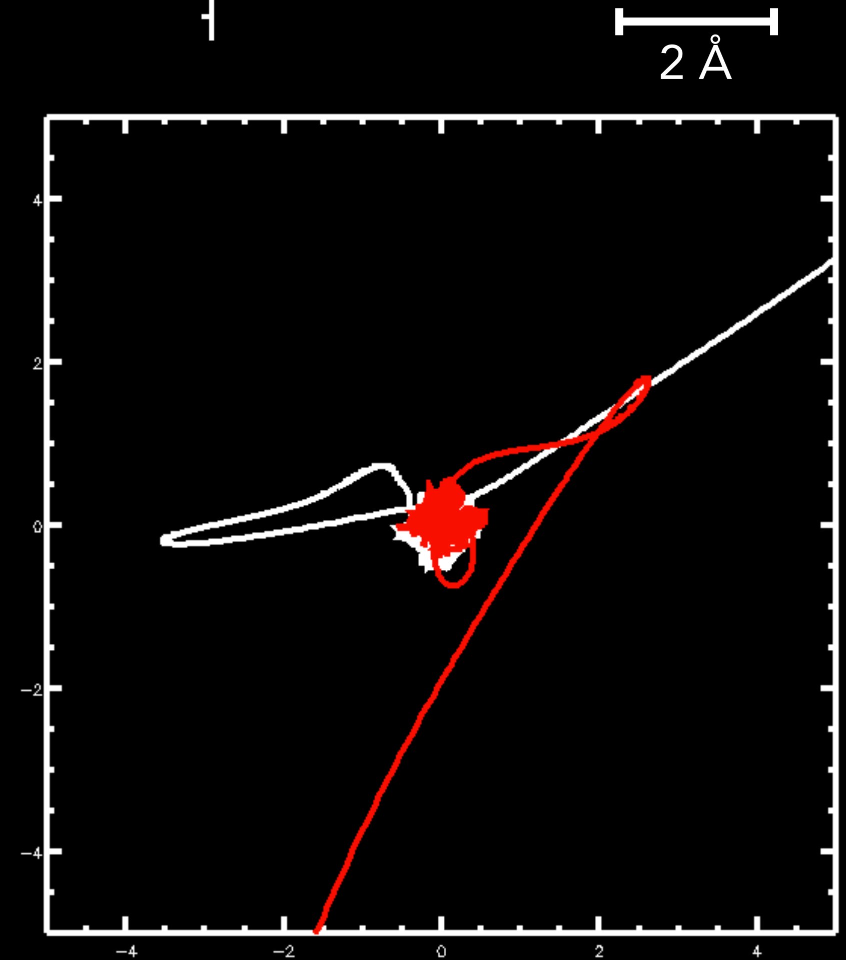


sample trajectories (linear 800nm)

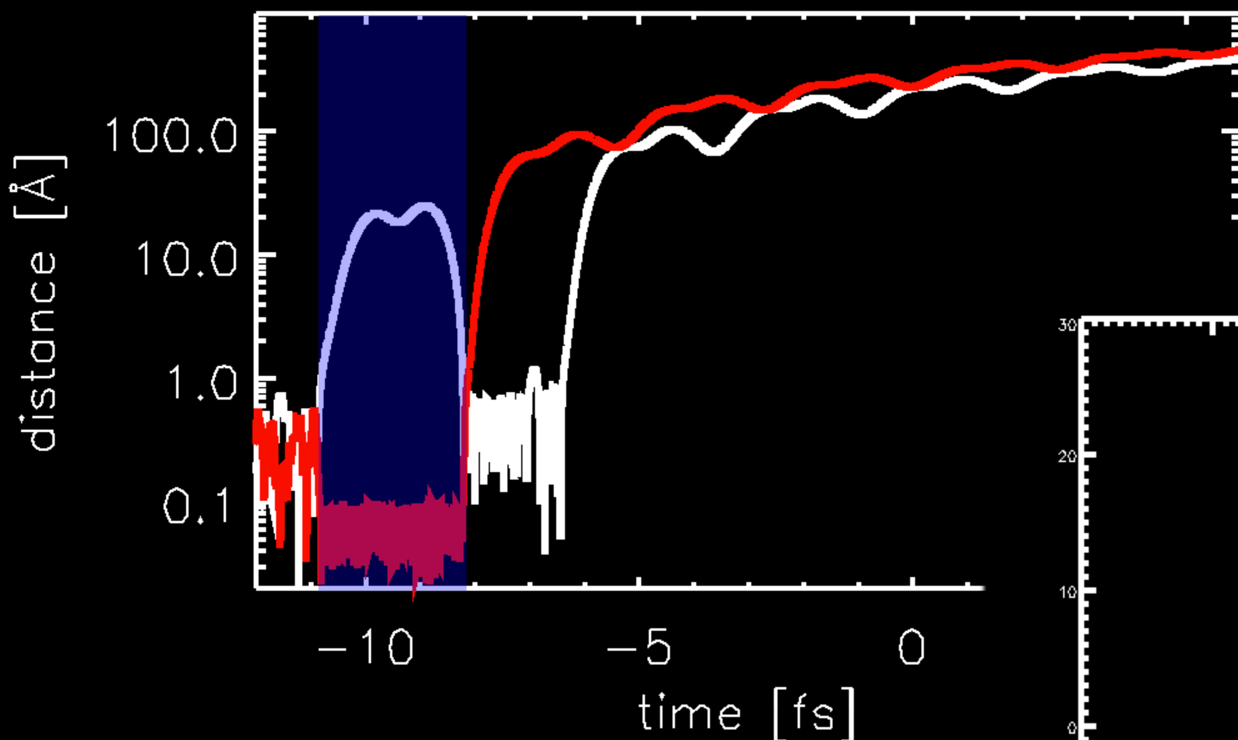


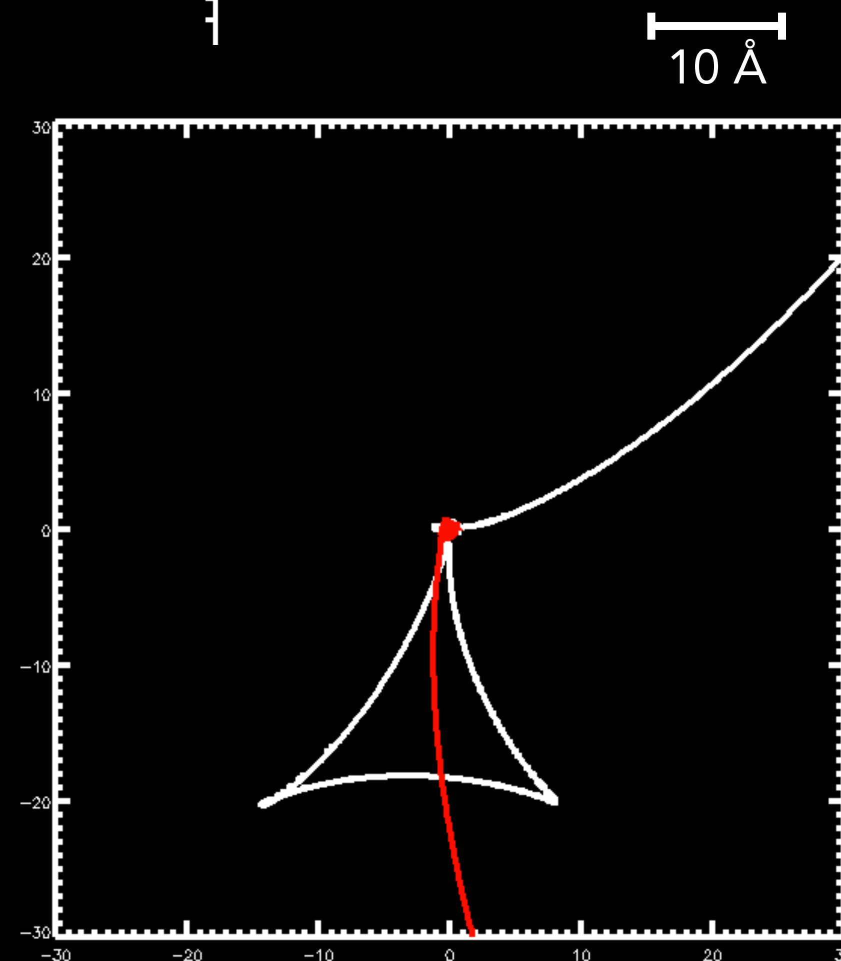
sample trajectories (800:400 1:1)





sample trajectories (800:400 2:1)



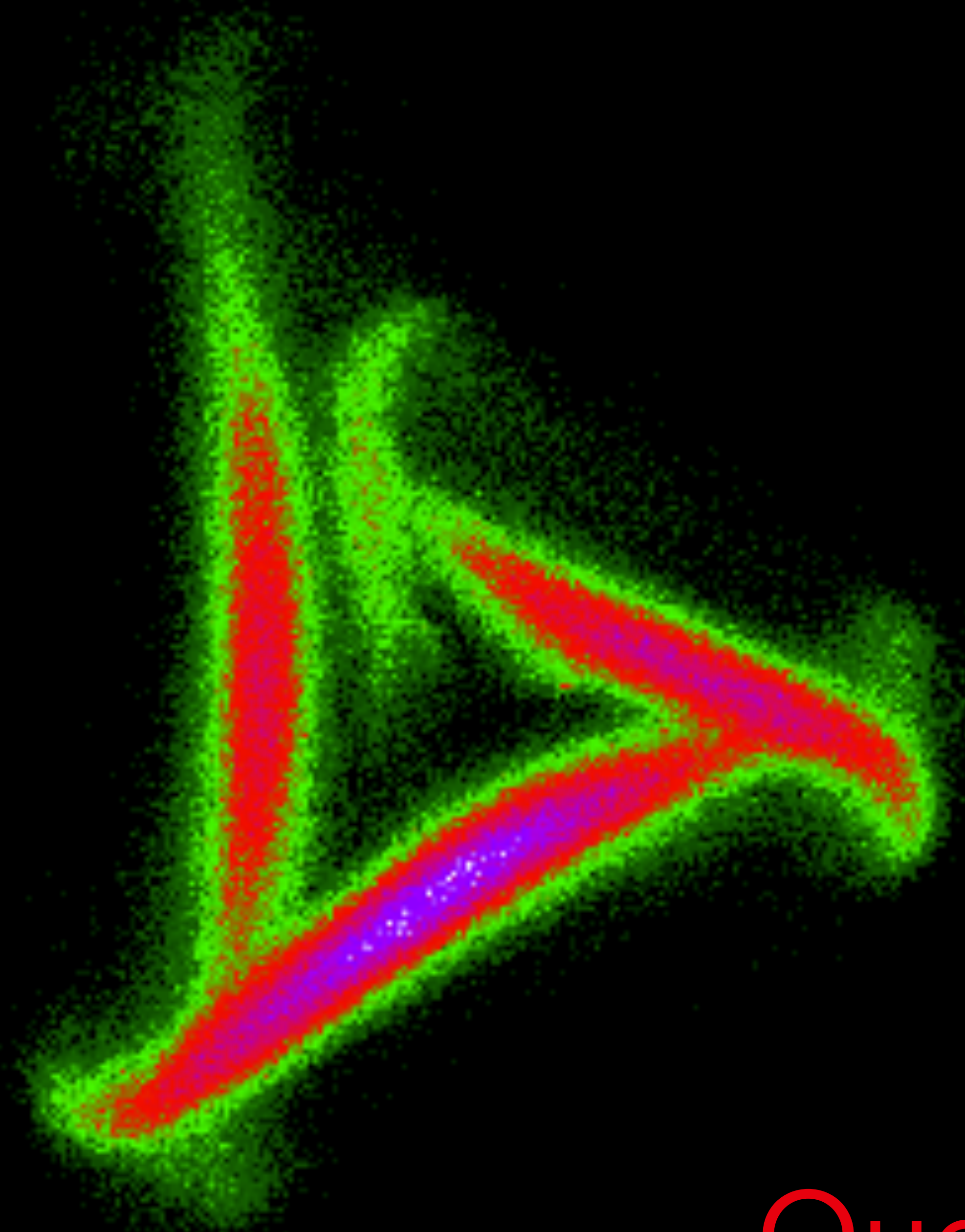


conclusions

- Simulations with classical model atoms were used to perform the first analysis of strong-field ionization in two-color, counter-rotating fields

- Electrons exhibit complex trajectories leading to non-sequential double ionization in novel ways

- The observed diversity of rescattering timing and impact angles should play a role in high-harmonic generation, photoelectron spectroscopy, and attosecond pulse generation



Questions?