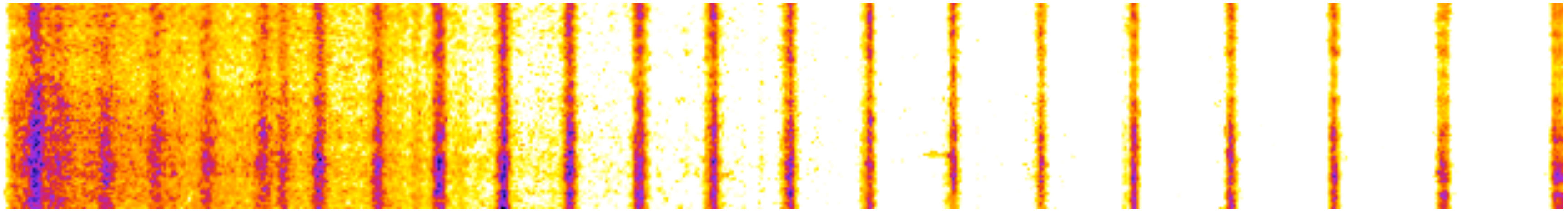
Ultrafast Laser-driven Probes for Investigating High Energy Density Physics

Franklin Dollar



High Energy Density (HED) Science Seminar Series

September 14, 2017 Lawrence Livermore

UCI University of California, Irvine

Outline

- Motivation
- MIR HHG
- UV HHG
- NC HHG
- Solid HHG
- Absorption
- MIR HHG
- Future work

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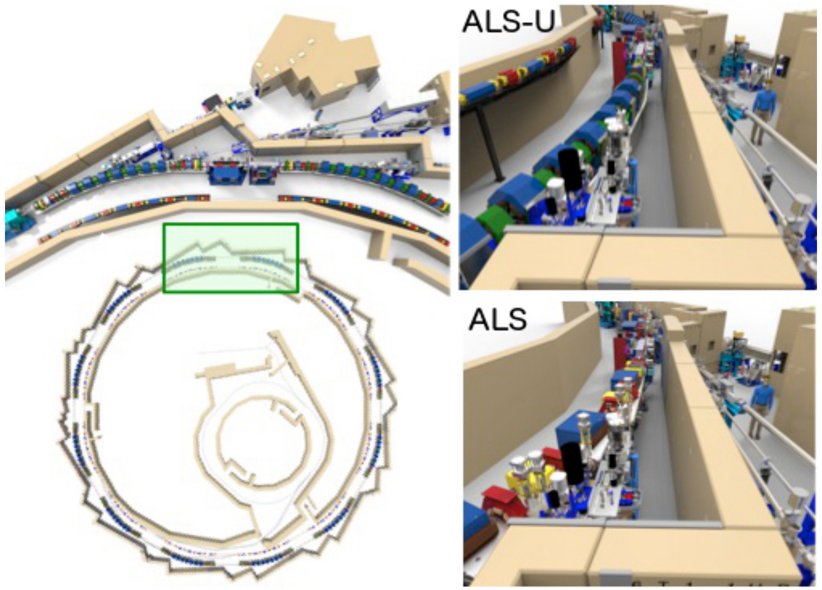
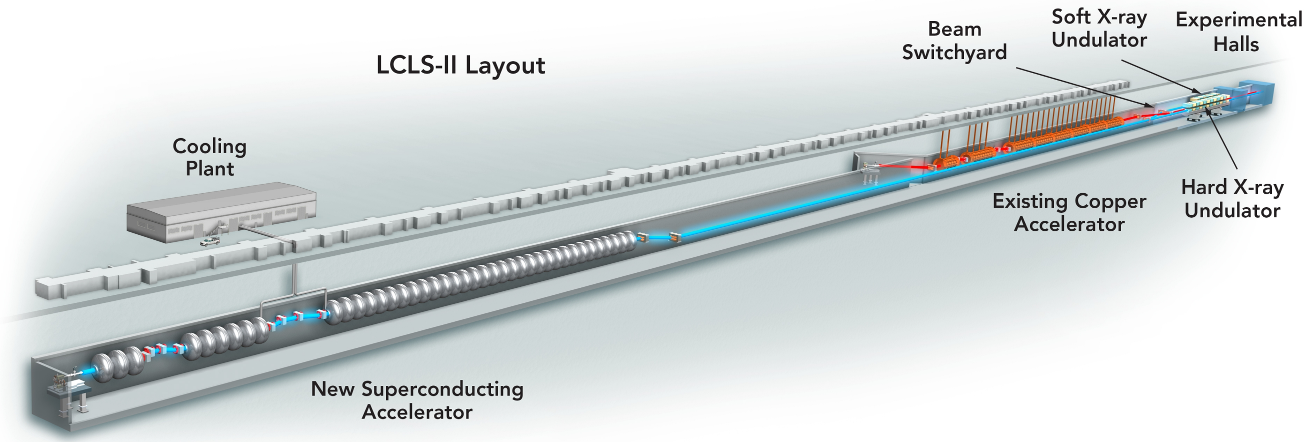
Coherent Light Sources

- Major infrastructure for coherent x-ray generation being developed
- Coherence enables novel imaging





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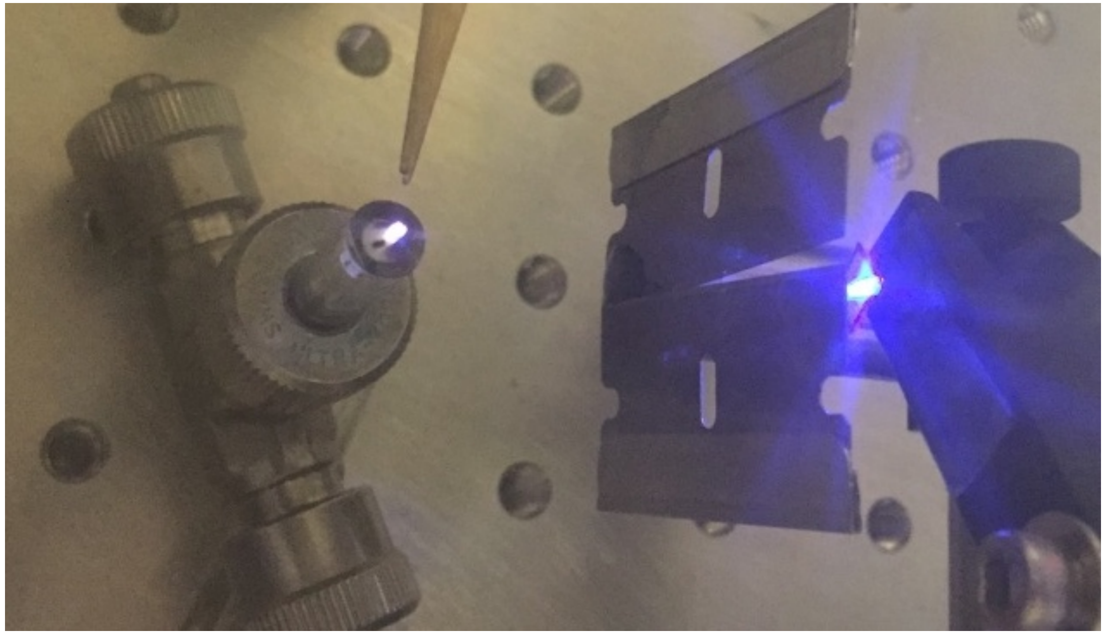
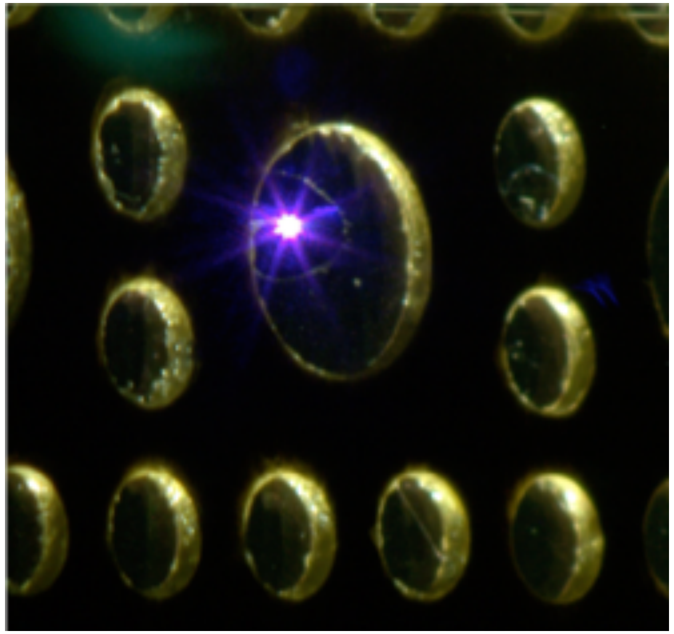
Laser Driven Coherent Light Sources

High harmonic generation (HHG)



Noble gas jet targets (Strong field HHG)



Polished solid targets (High field HHG)

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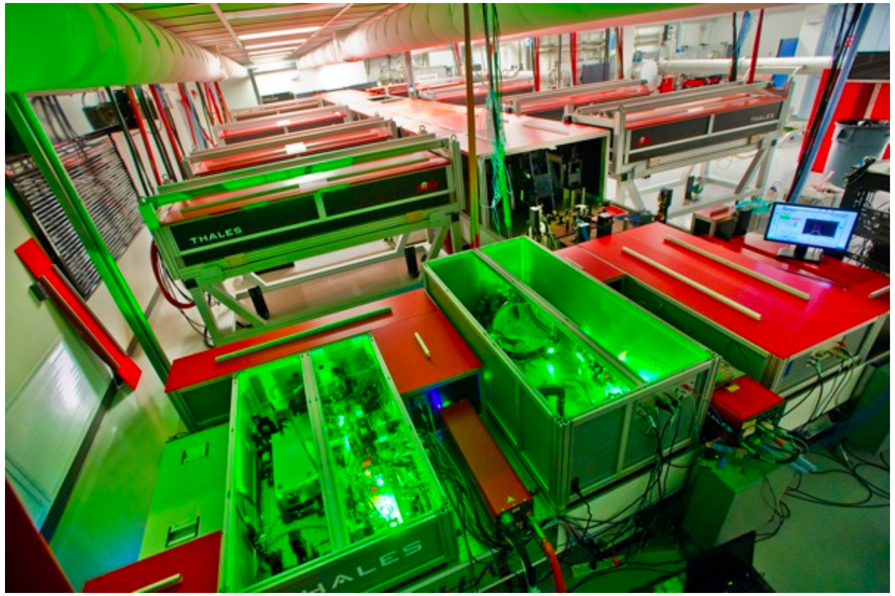
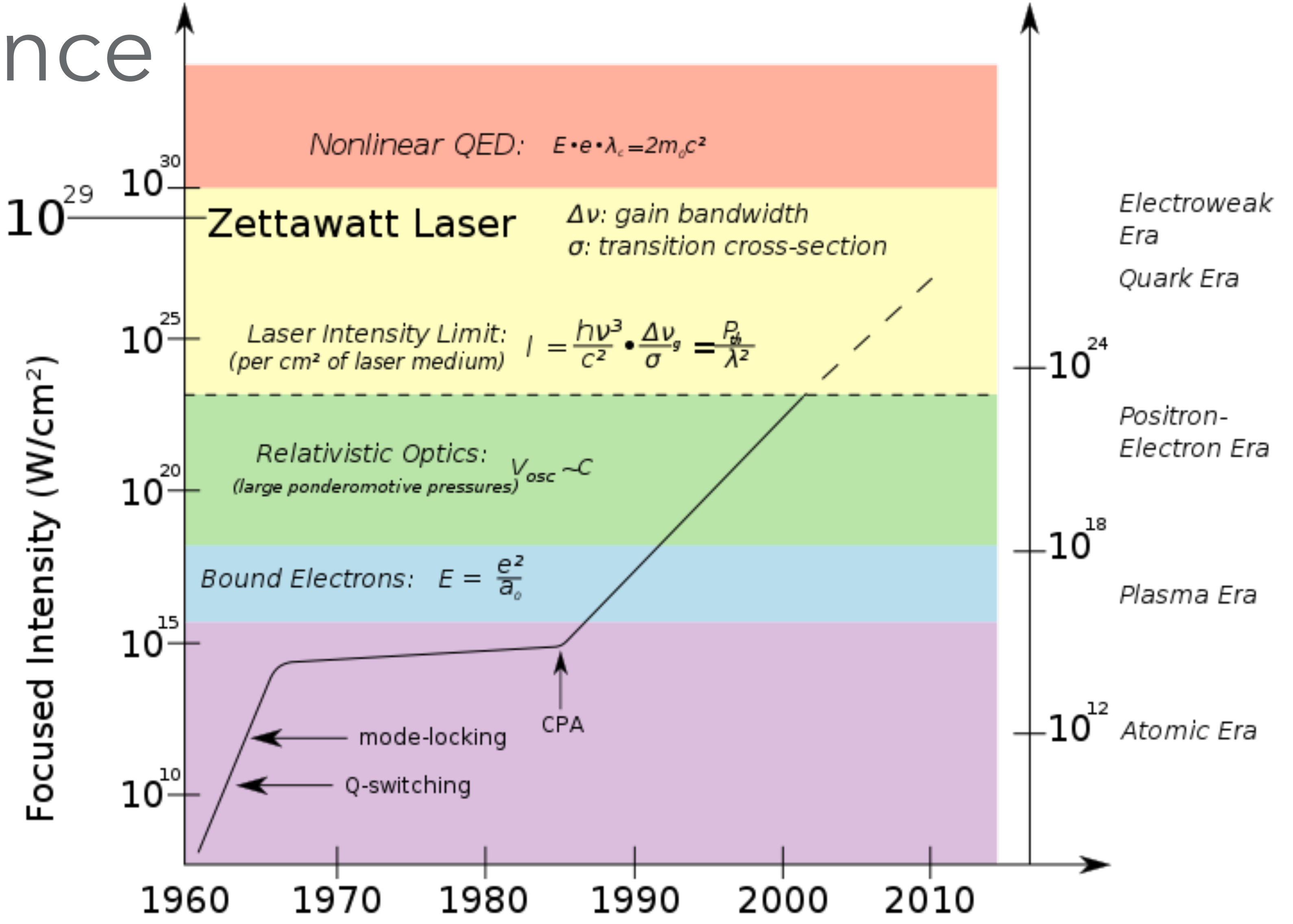
High field science





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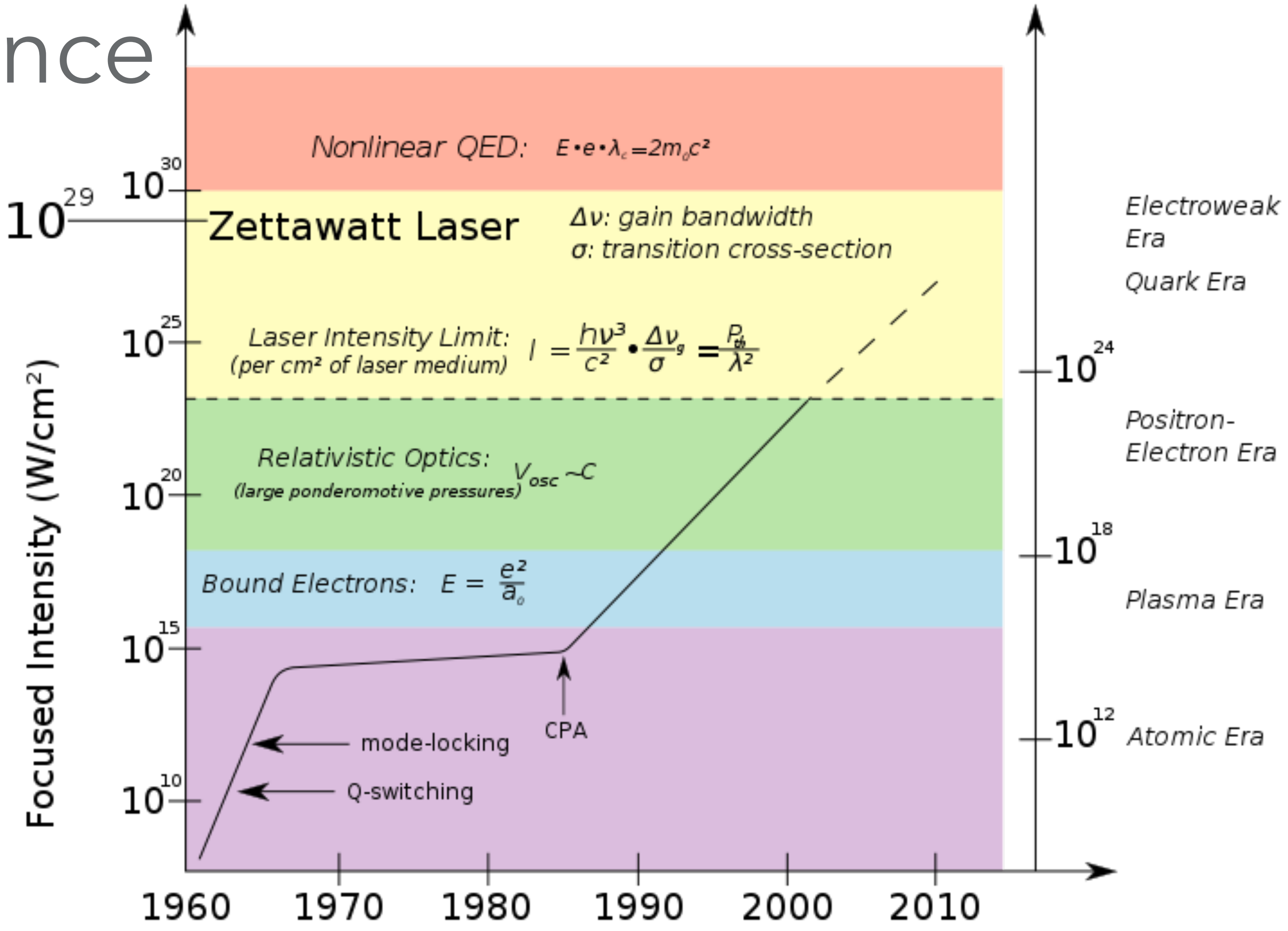
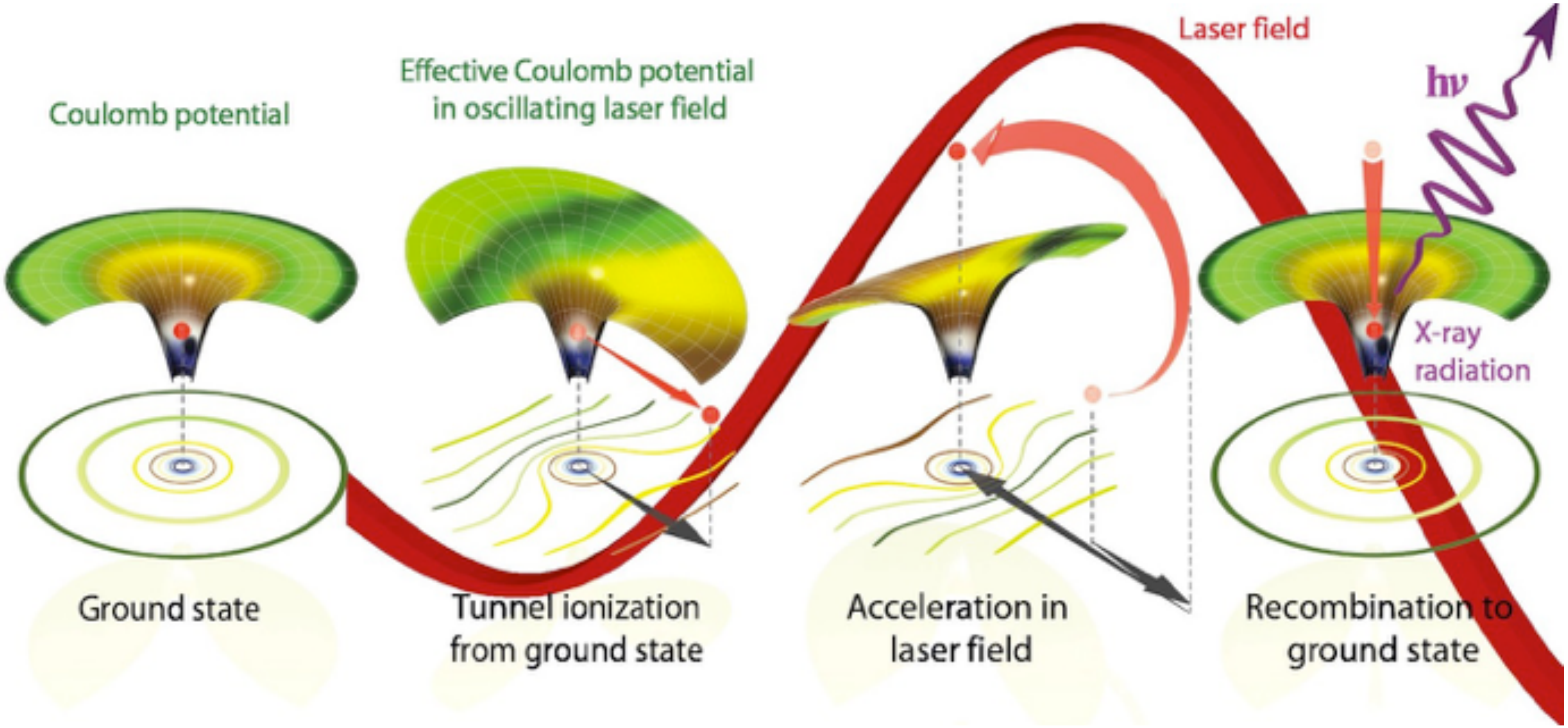
High field science

$$v_q = \frac{e_c E_0}{m_e \omega_0} \sim \lambda\sqrt{I}$$

$$U_p = \frac{1}{2} m_e \langle v_q \rangle^2$$



Single atom HHG



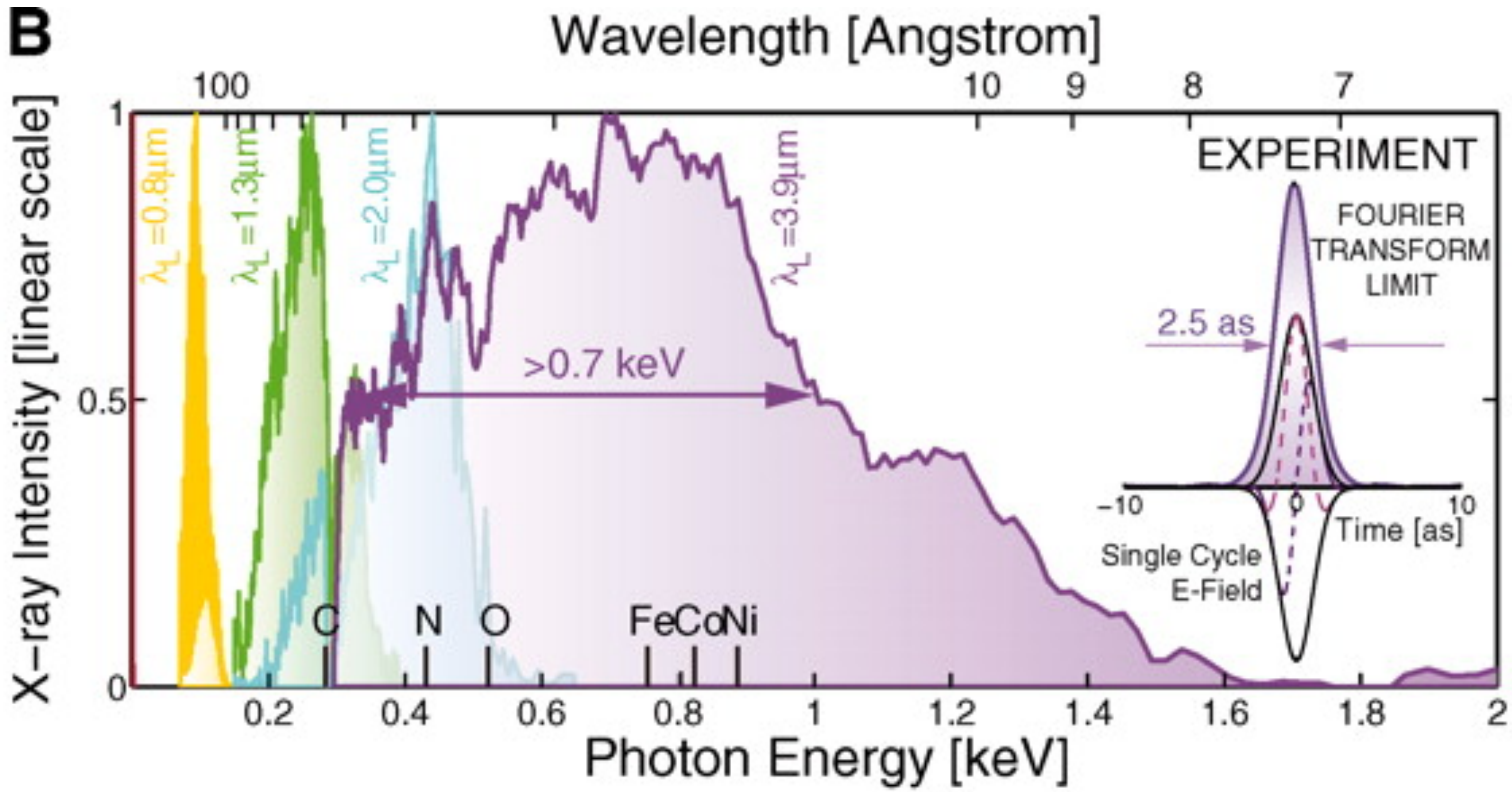
$E_{cutoff} = I_p + 3.17\ U_p$

Macroscopic HHG

- Phase matching

- Fundamental phase affected by
  - Pressure (Neutral gas index of refraction)
  - Ionization fraction (Plasma index of refraction)
  - Focusing (Gouy phase shift)

Mid-infrared HHG



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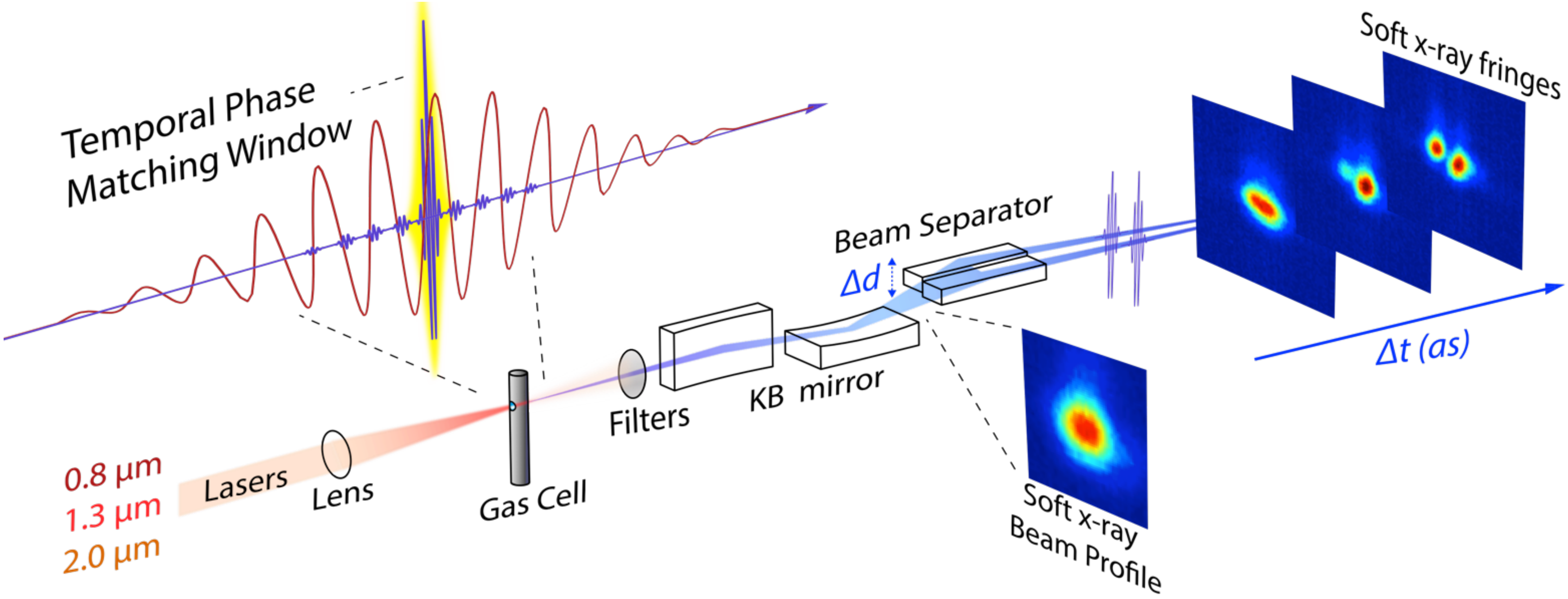
[T. Popmintchev, et al., Science (2012)]

X-ray field auto-correlation



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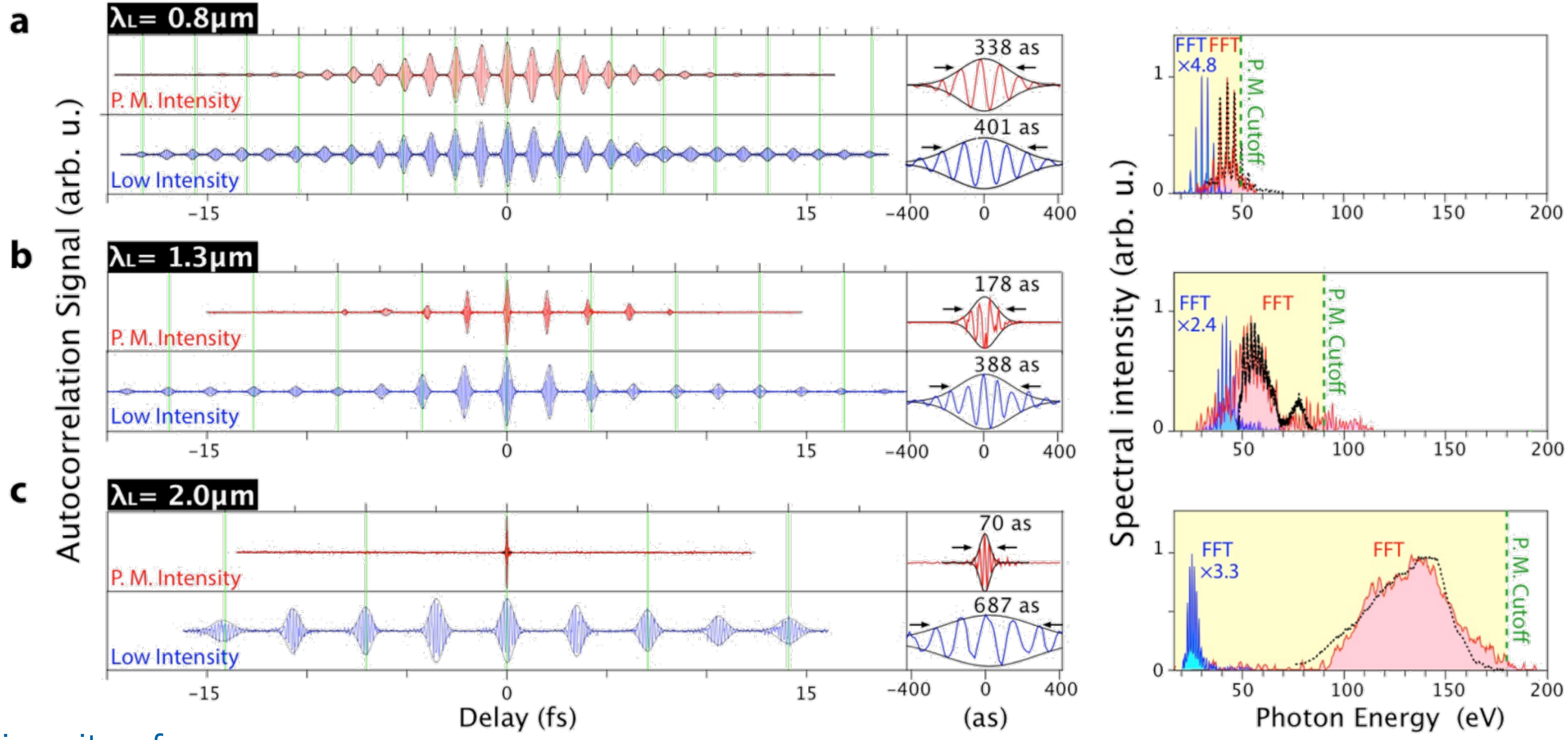
[M.-C. Chen, et al., PNAS (2016)]

Atto-interferograms



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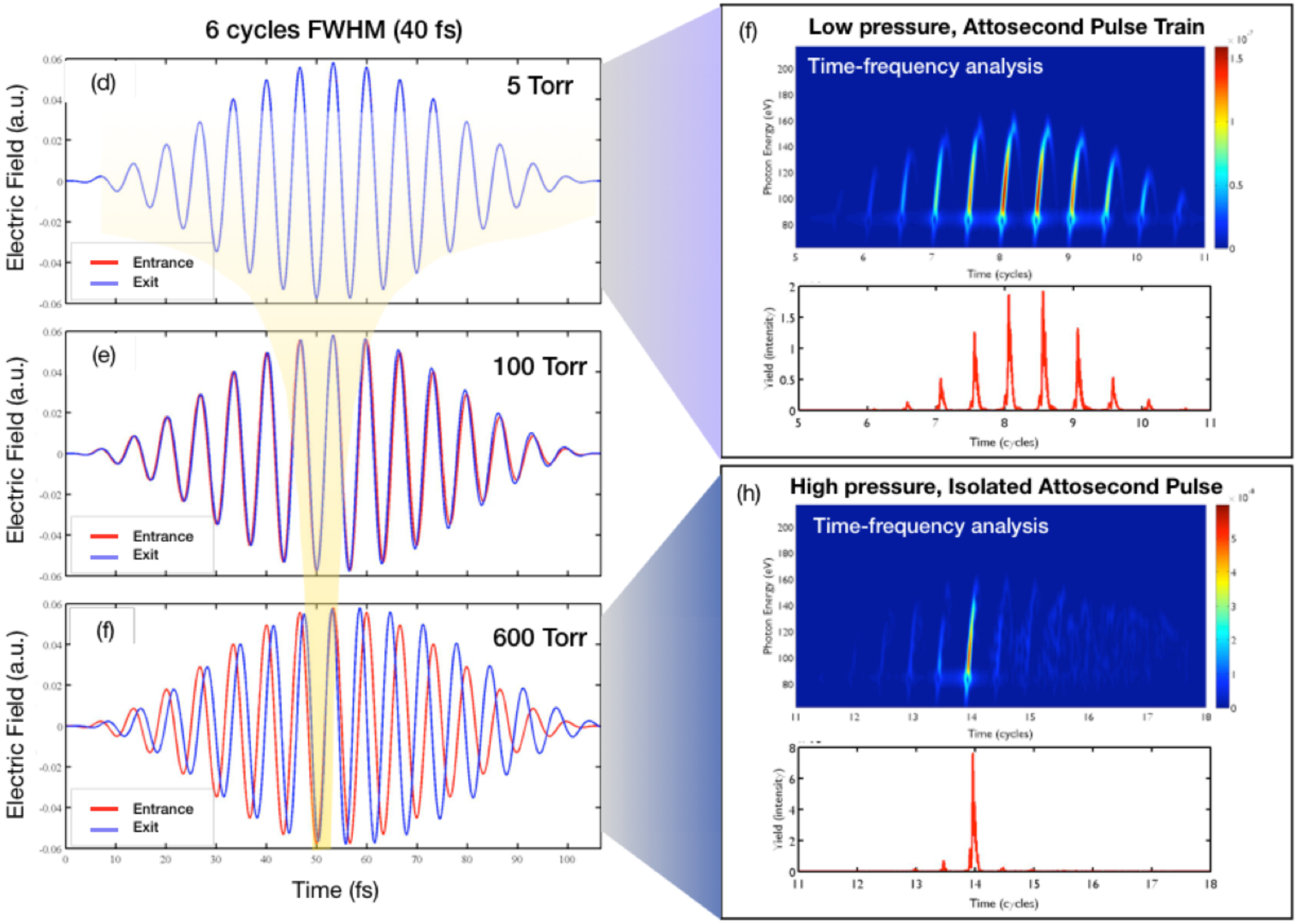
Phase matching window

- Phase matching window shrinks for longer wavelengths

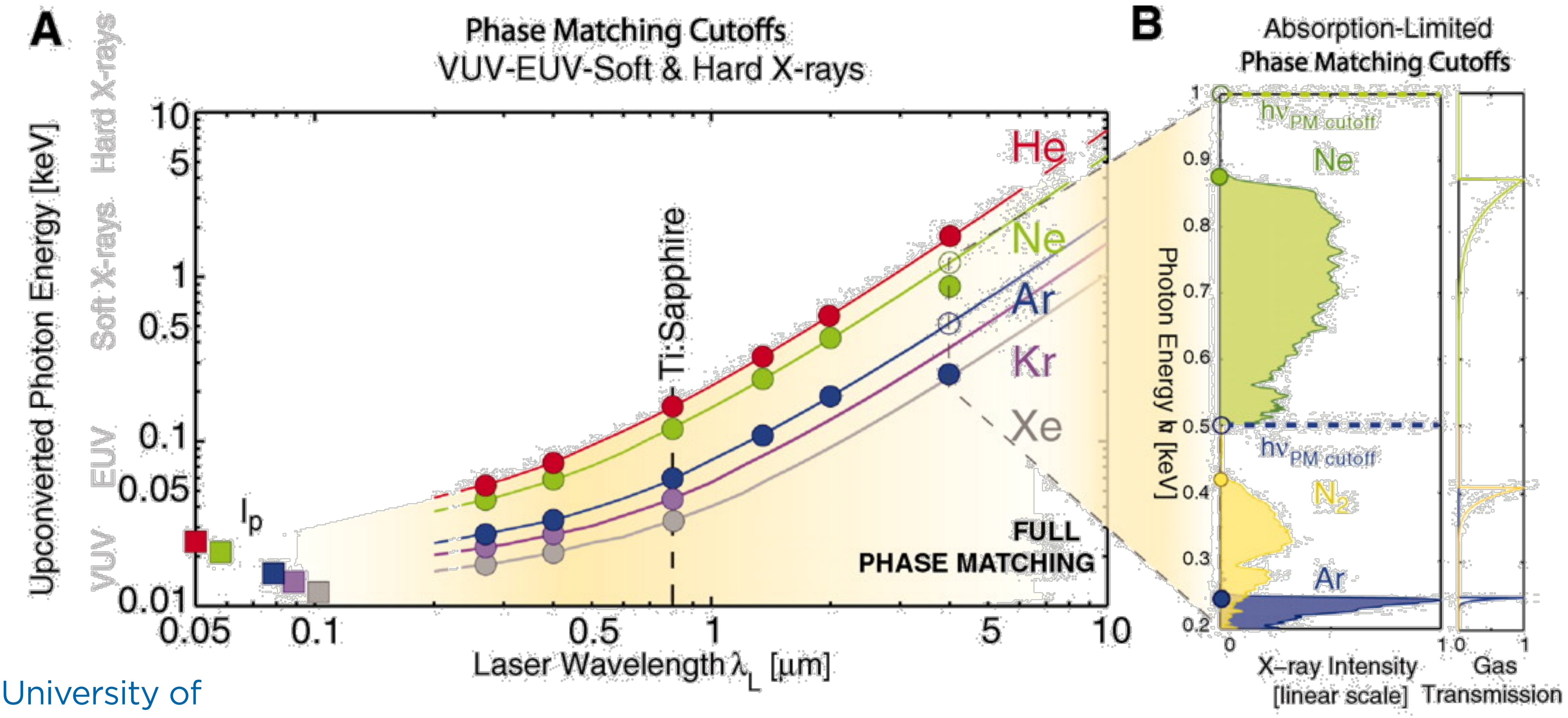
$$\Delta k(t) \approx P \cdot q \cdot \left([1-\eta(t)] \cdot \delta n \cdot \frac{2\pi}{\lambda_L} - \eta(t) \cdot N_{atm} \cdot r_e \cdot \lambda_L \right)$$

- Shrinkage occurs from
  - Increasing pressure
  - Increasing harmonic order
  - Increasing wavelength
  - Increasing period

Phase matching



Spectrum of strong field HHG



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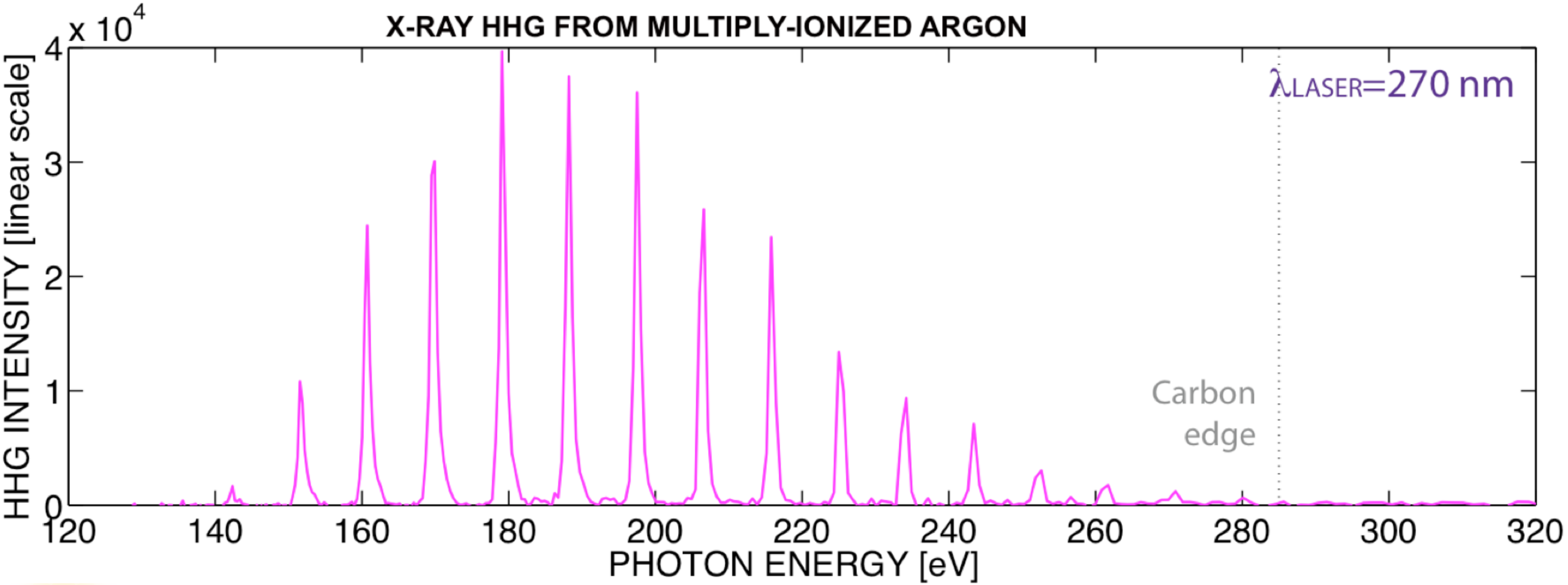
267 nm HHG



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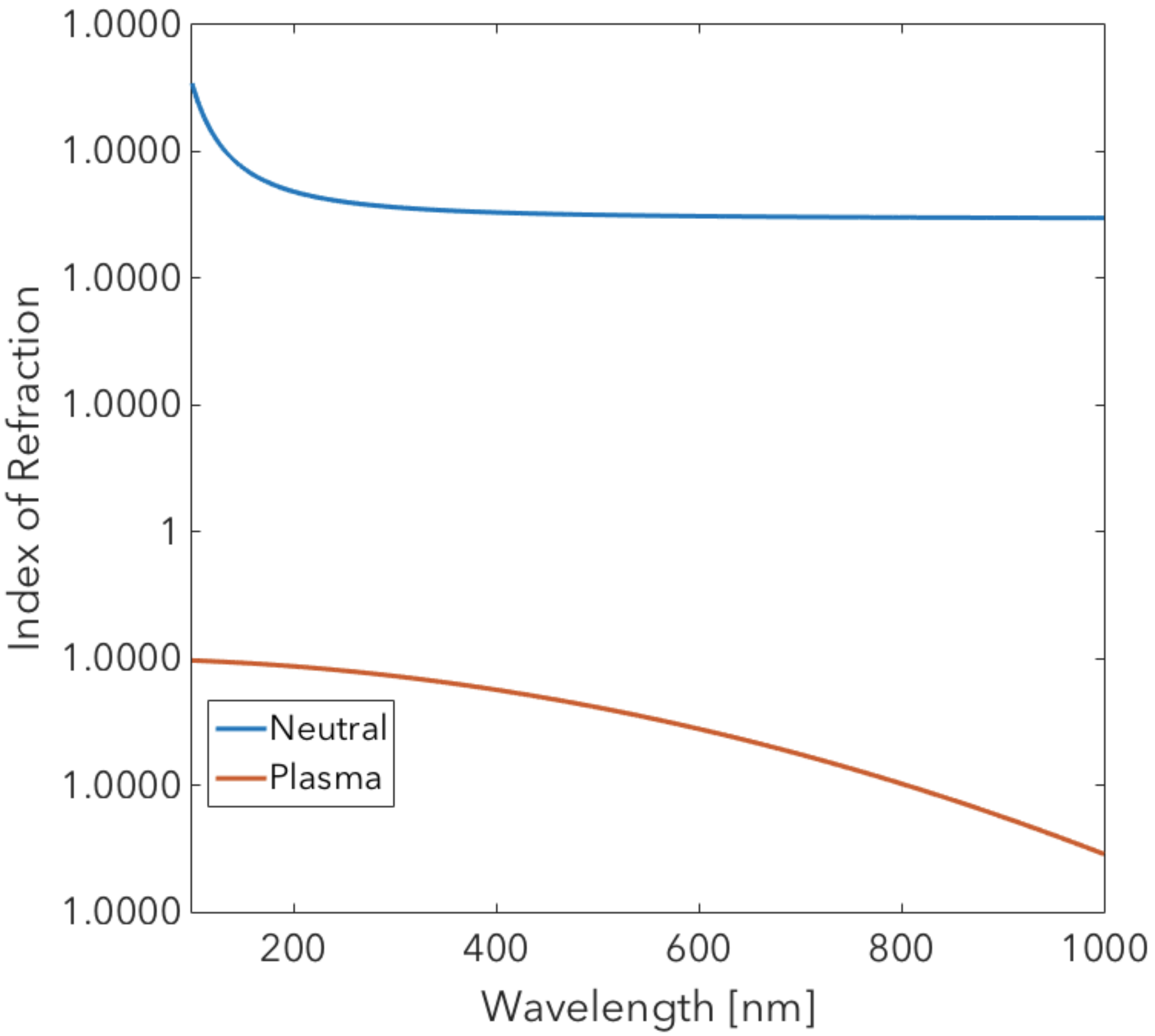
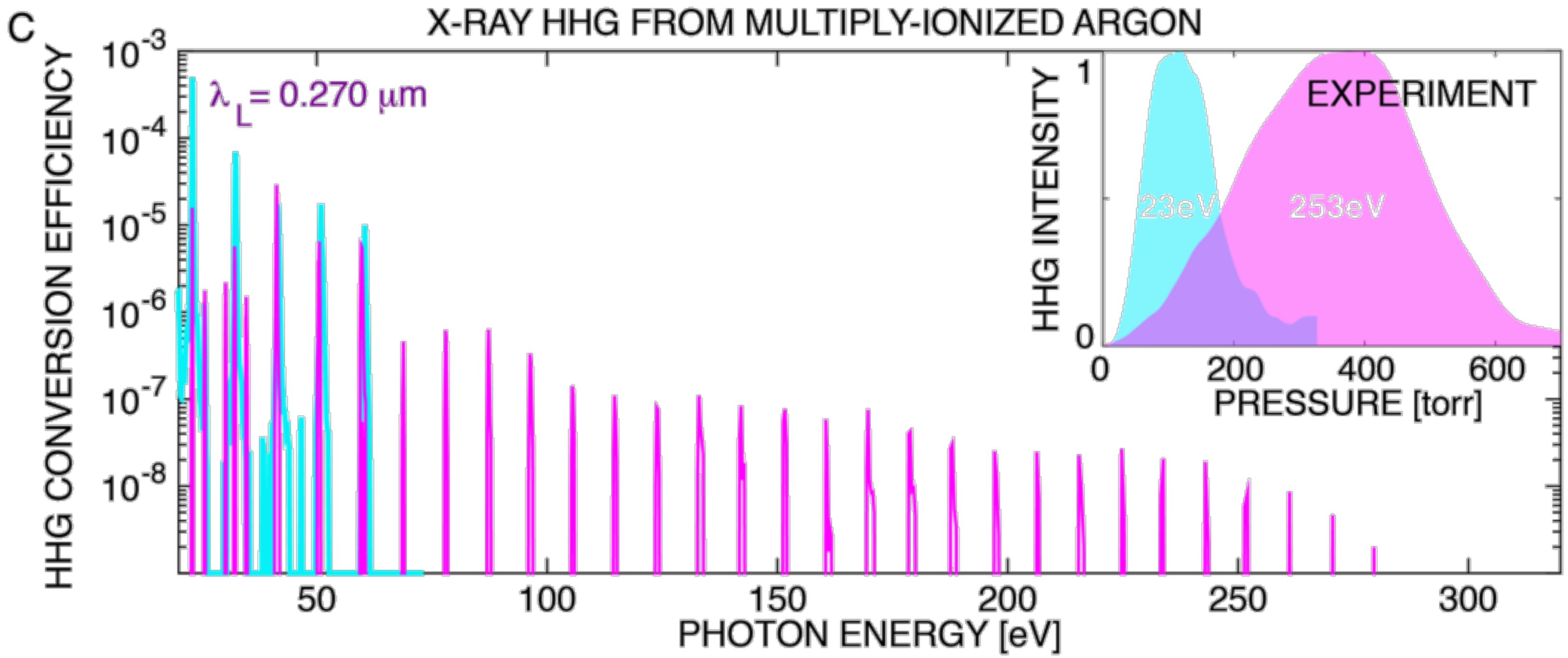
[D. Popmintchev, et al., Science (2015)]

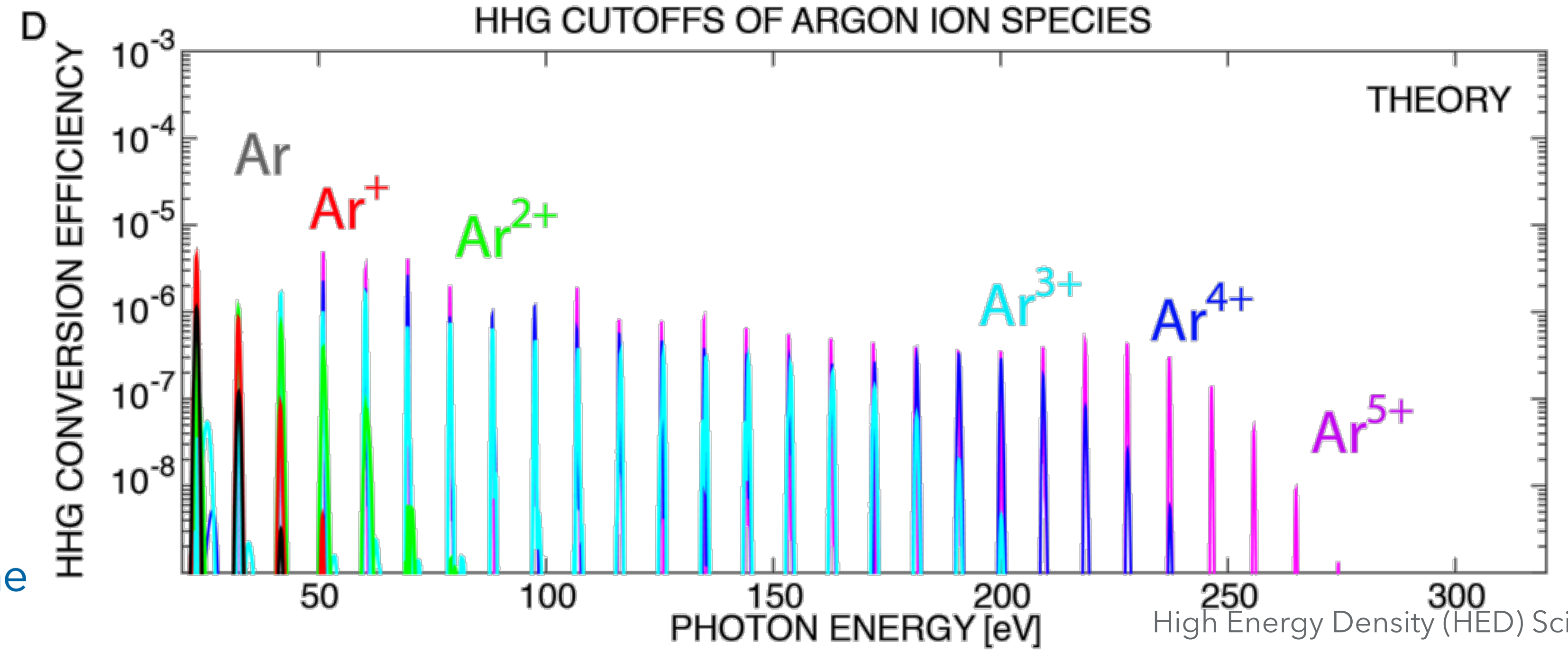
UV Phase matching

- Neutral index of refraction scales inversely with wavelength
- Plasma index of refraction scales with wavelength



TDSE





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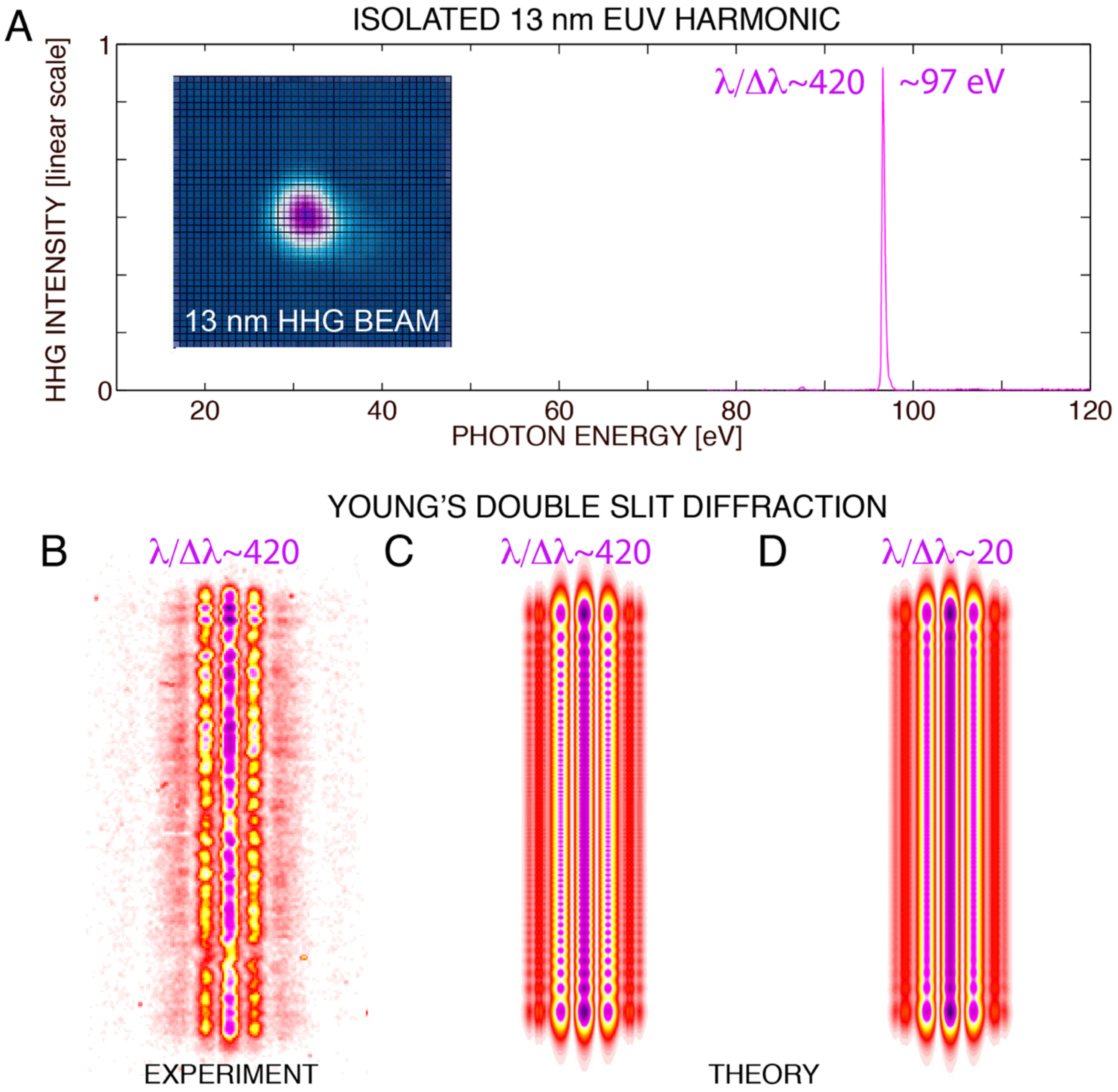
Isolated harmonics

- Notch filters enable spectrally pure wavelengths
- Rh + Be + Si filtering



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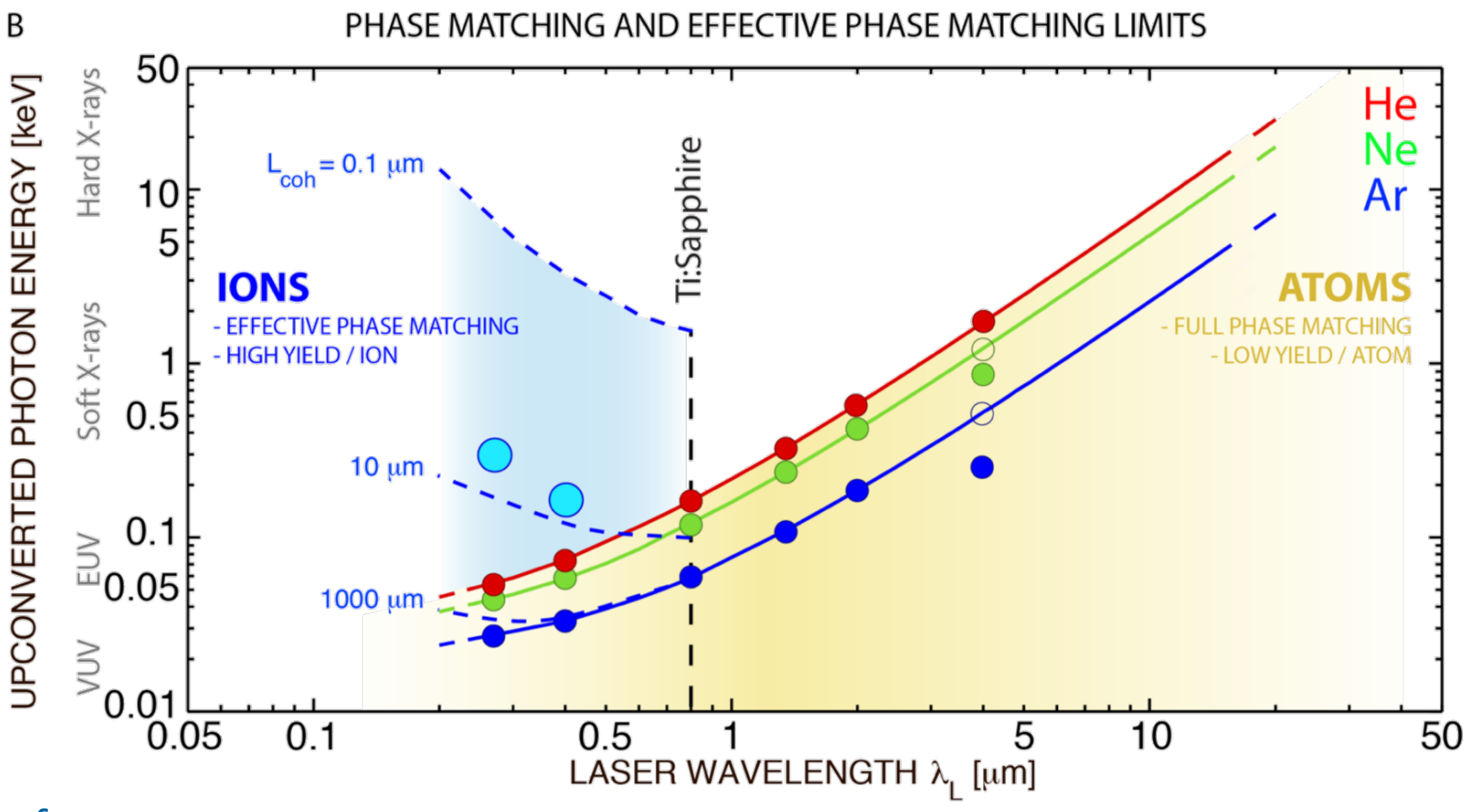
Full range of wavelength scaling



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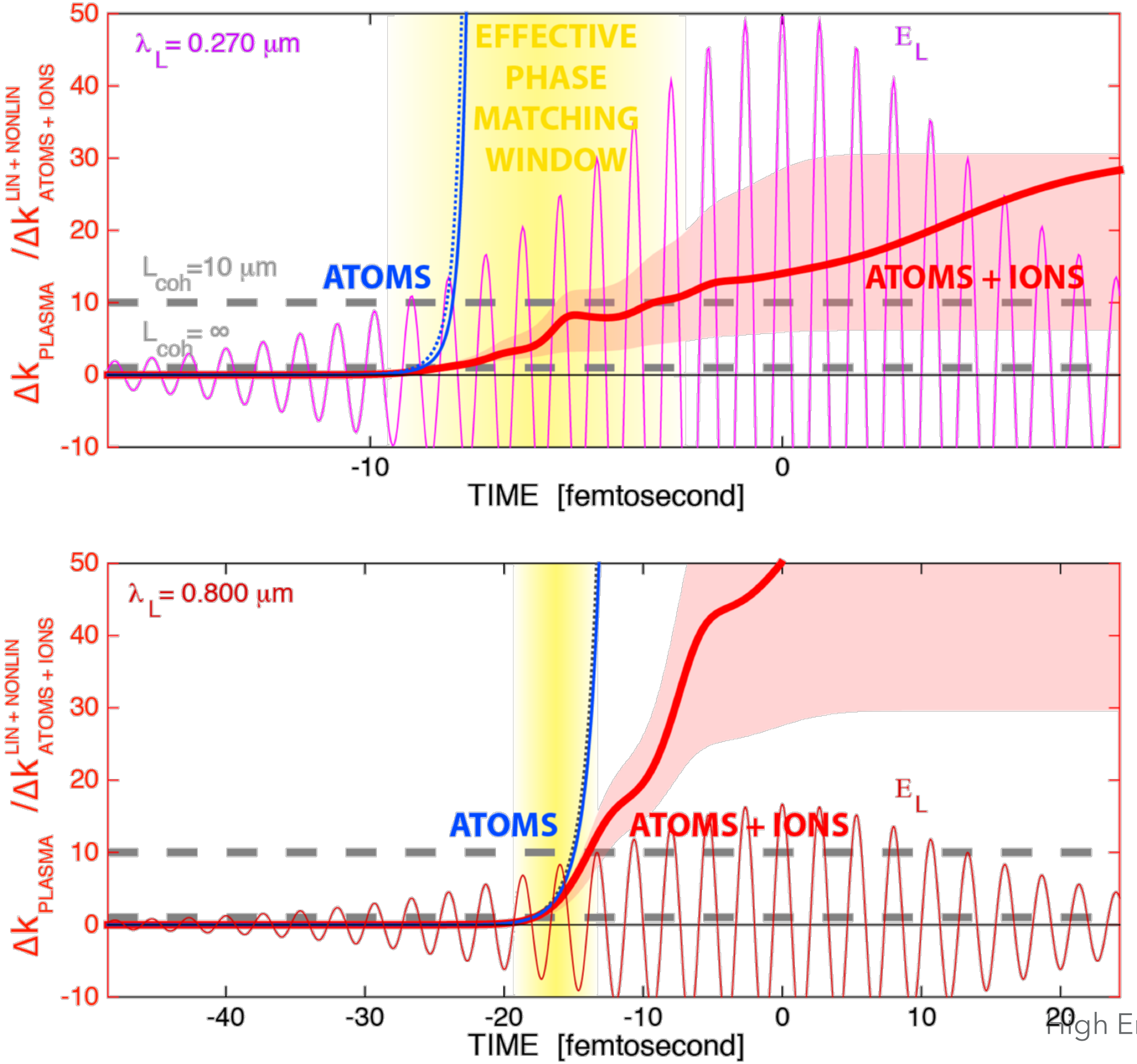
Larger phase matching window



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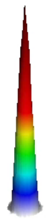
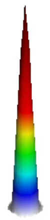
Electron wavefunctions

Linear polarization 

Circular polarization 





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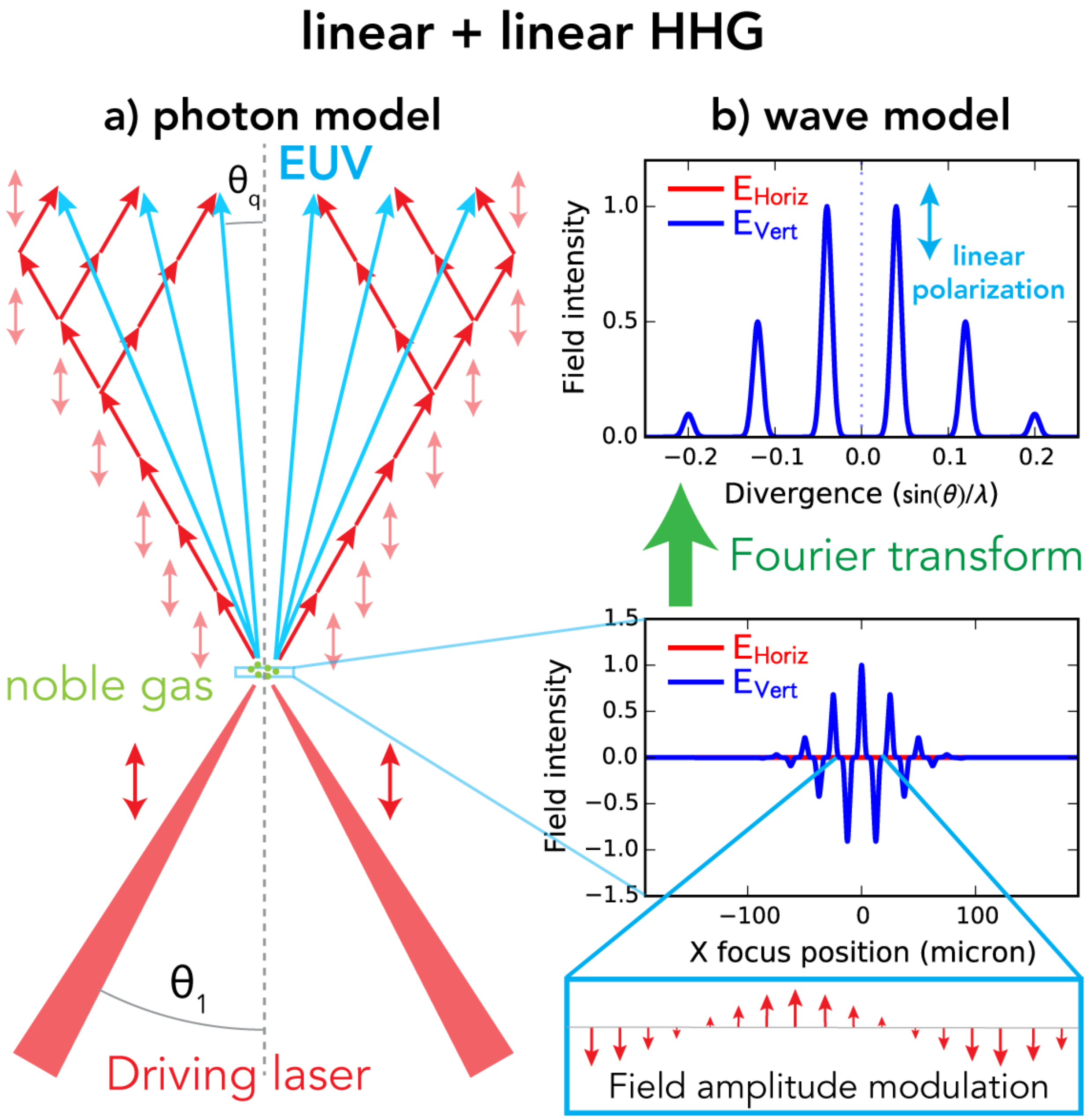
Non-collinear HHG

- Conservation of momentum
- Conservation of energy
- Conservation of parity



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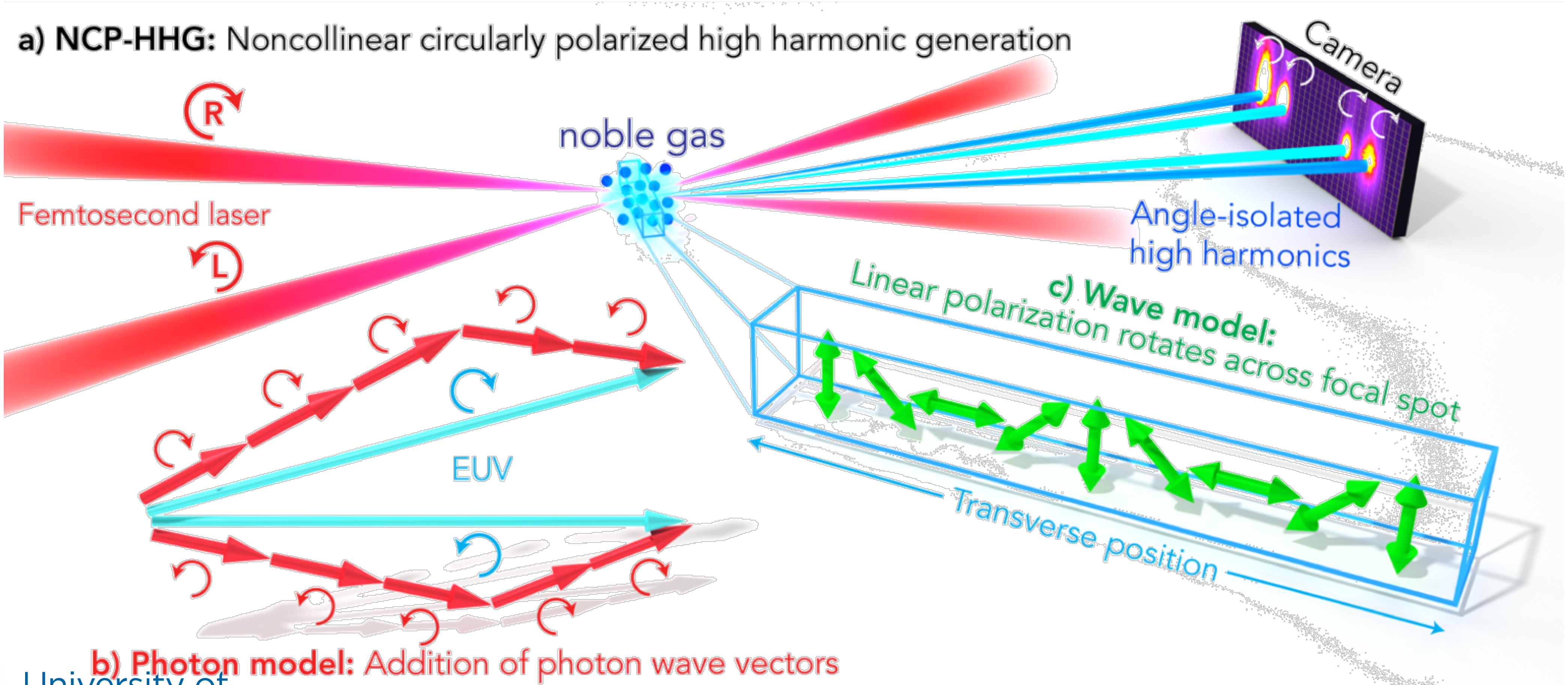
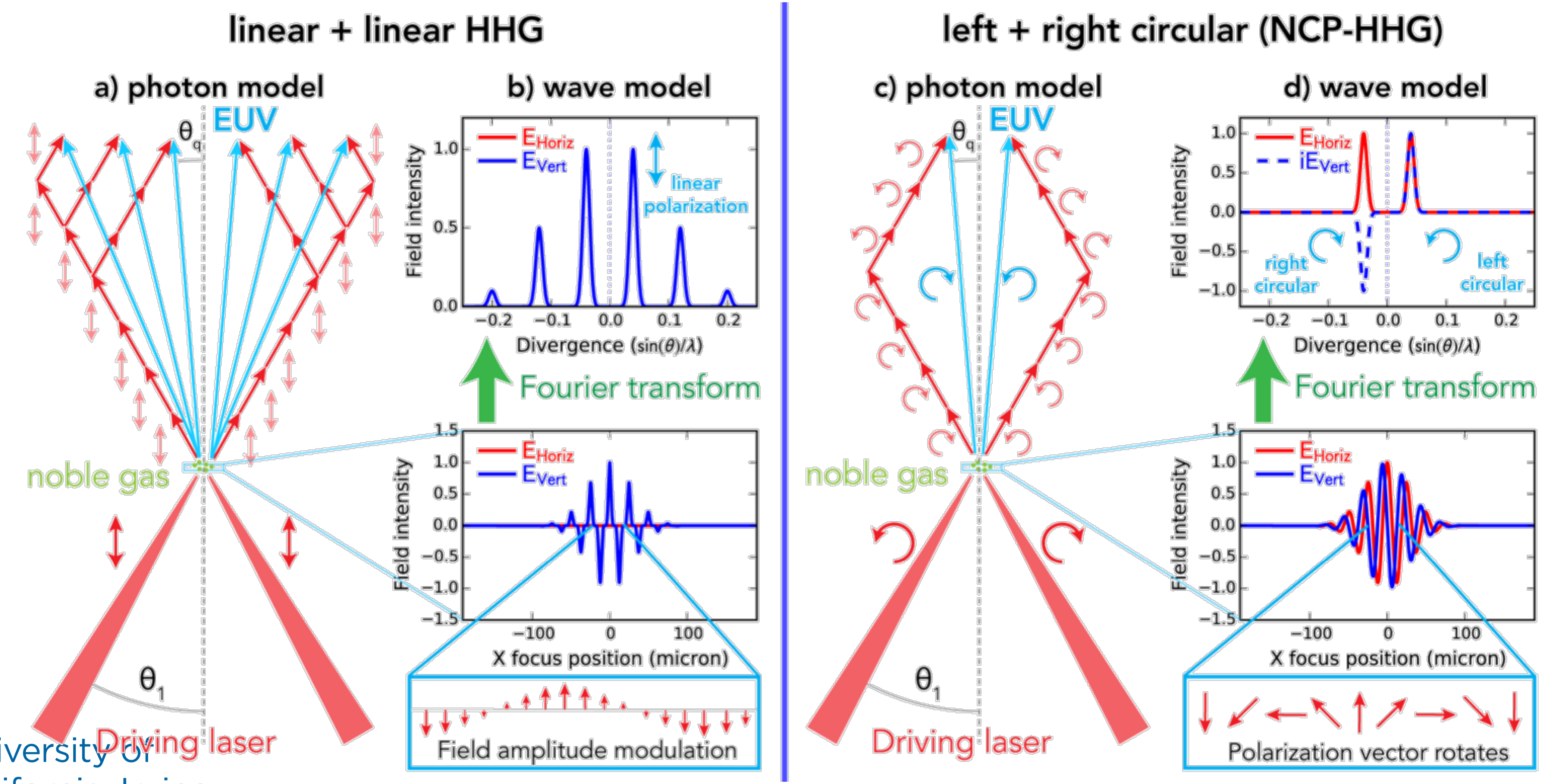
Noncolinear HHG



[D. Hickstein, et al., Nat. Phot. (2015)]

Conservation of spin angular momentum



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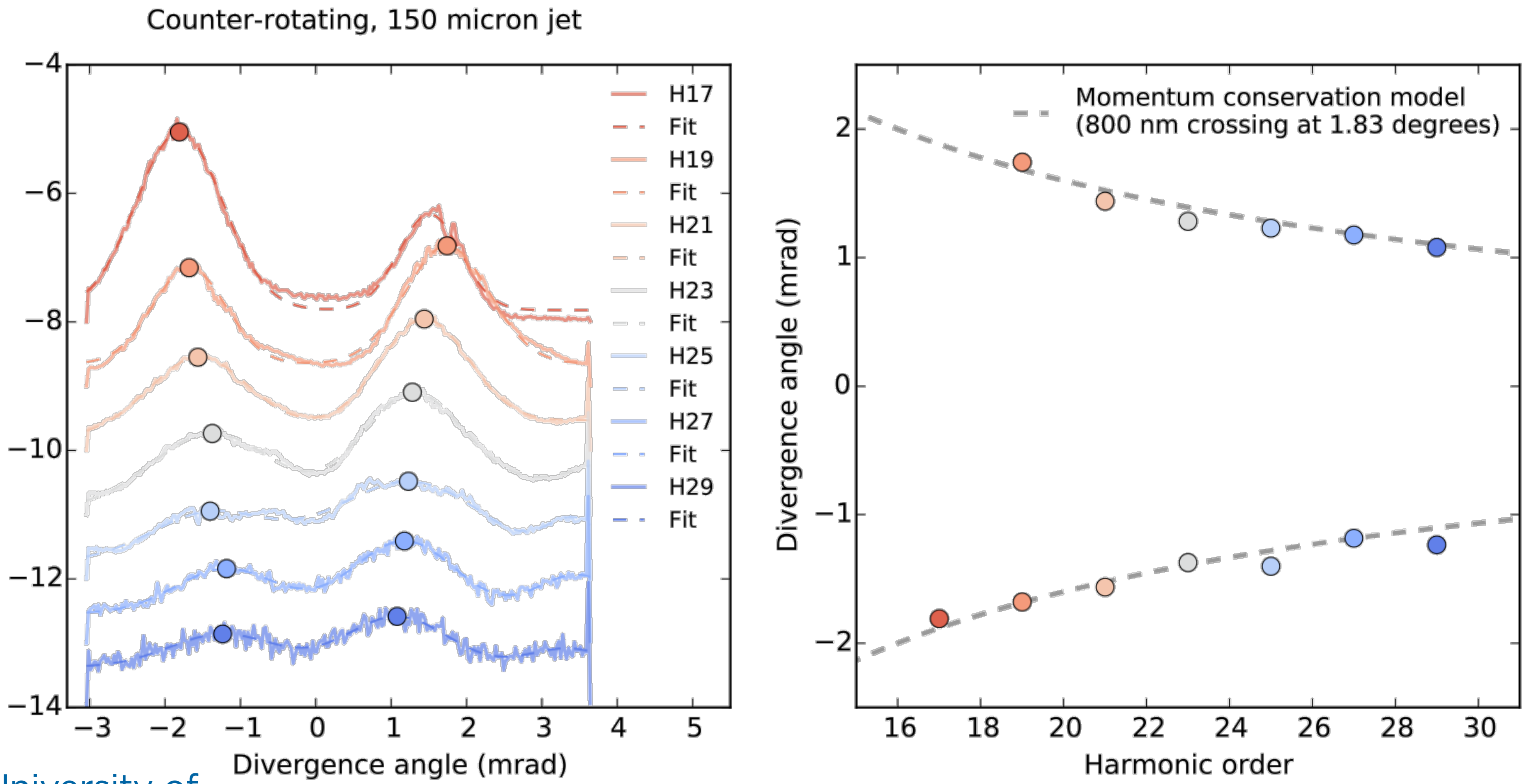
Converging harmonics



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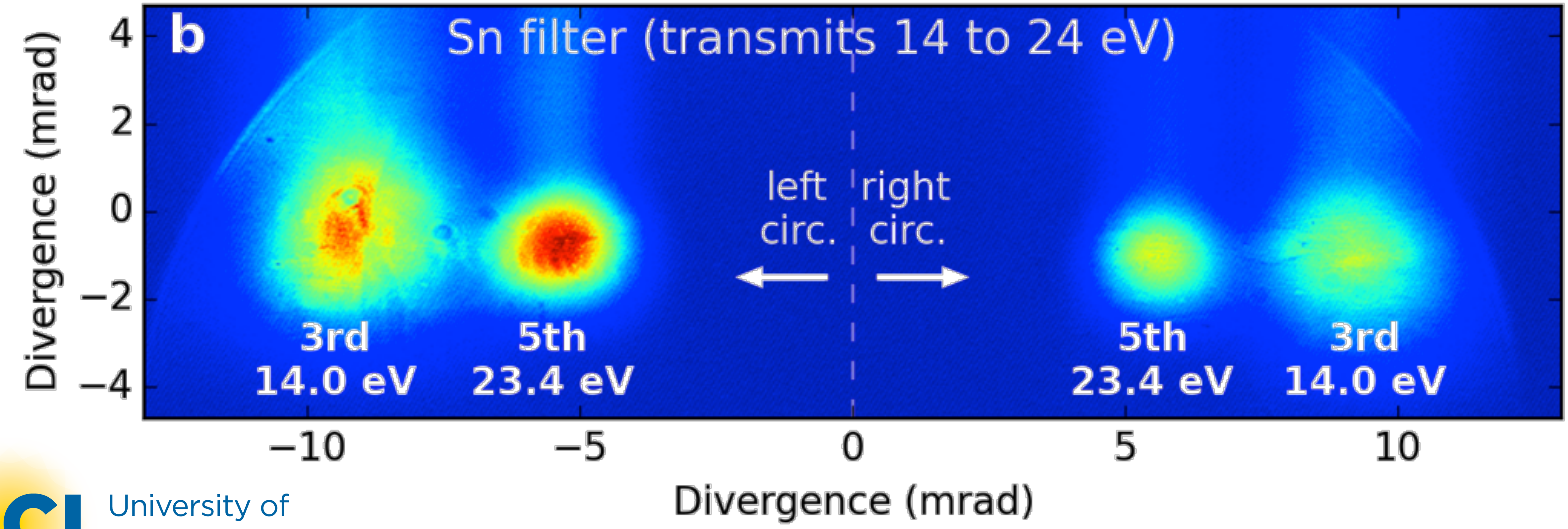
Spatially separated harmonics

- Argon harmonics with 267 nm drivers



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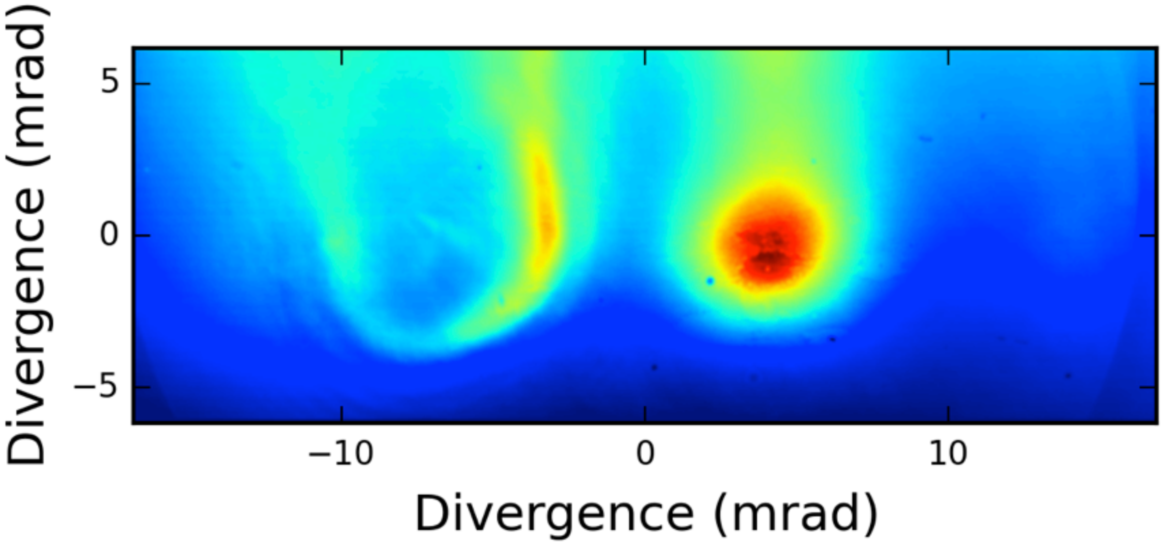
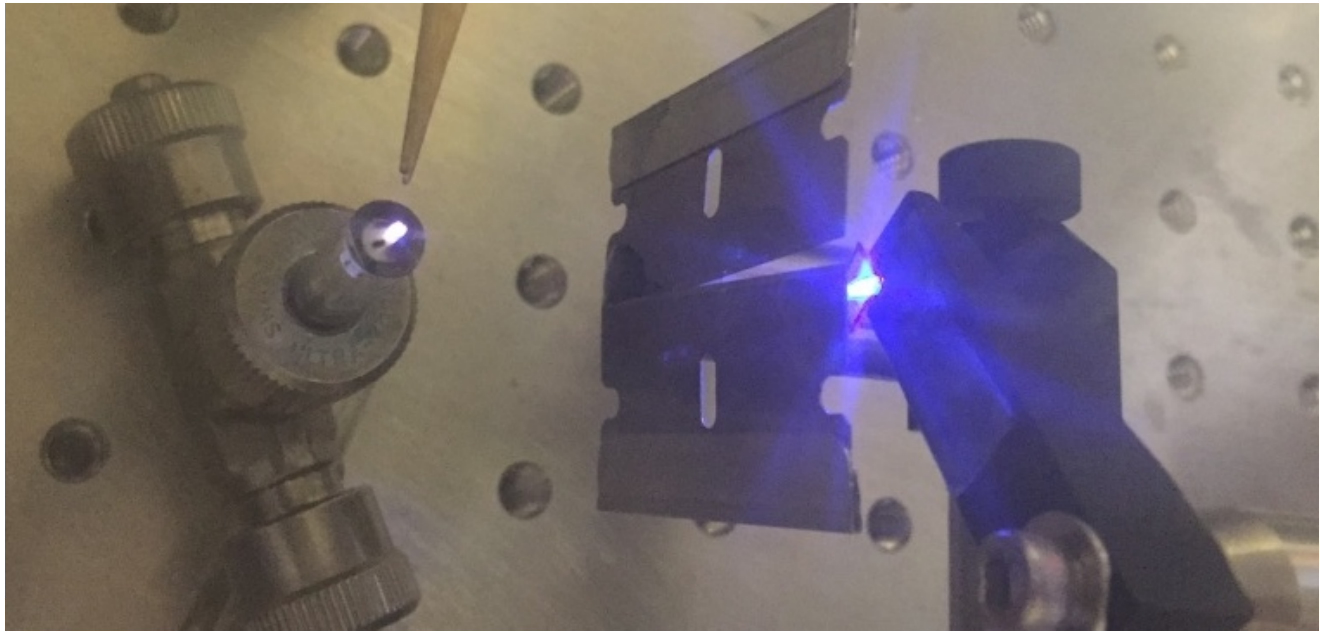
Spatially separated harmonics

- Human hair obstructing harmonic beam but not fundamental





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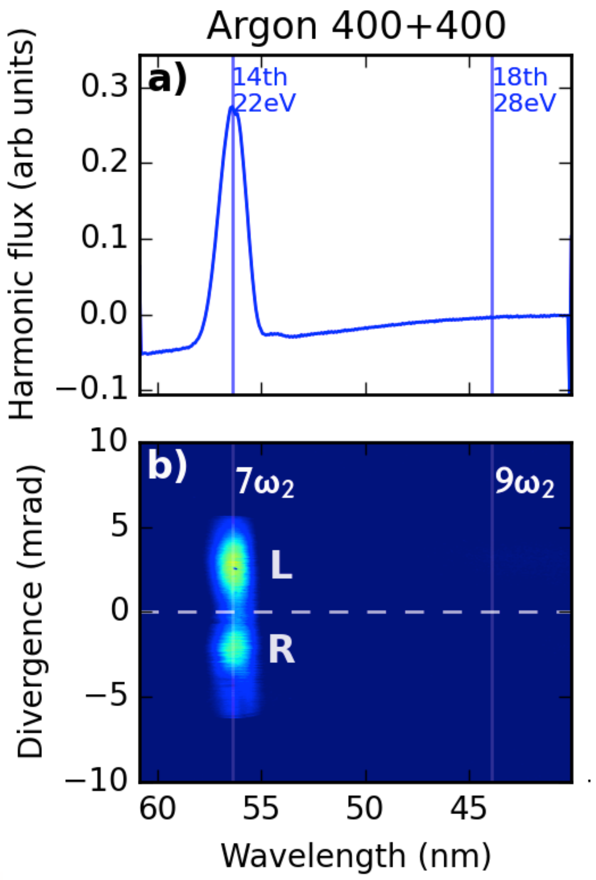
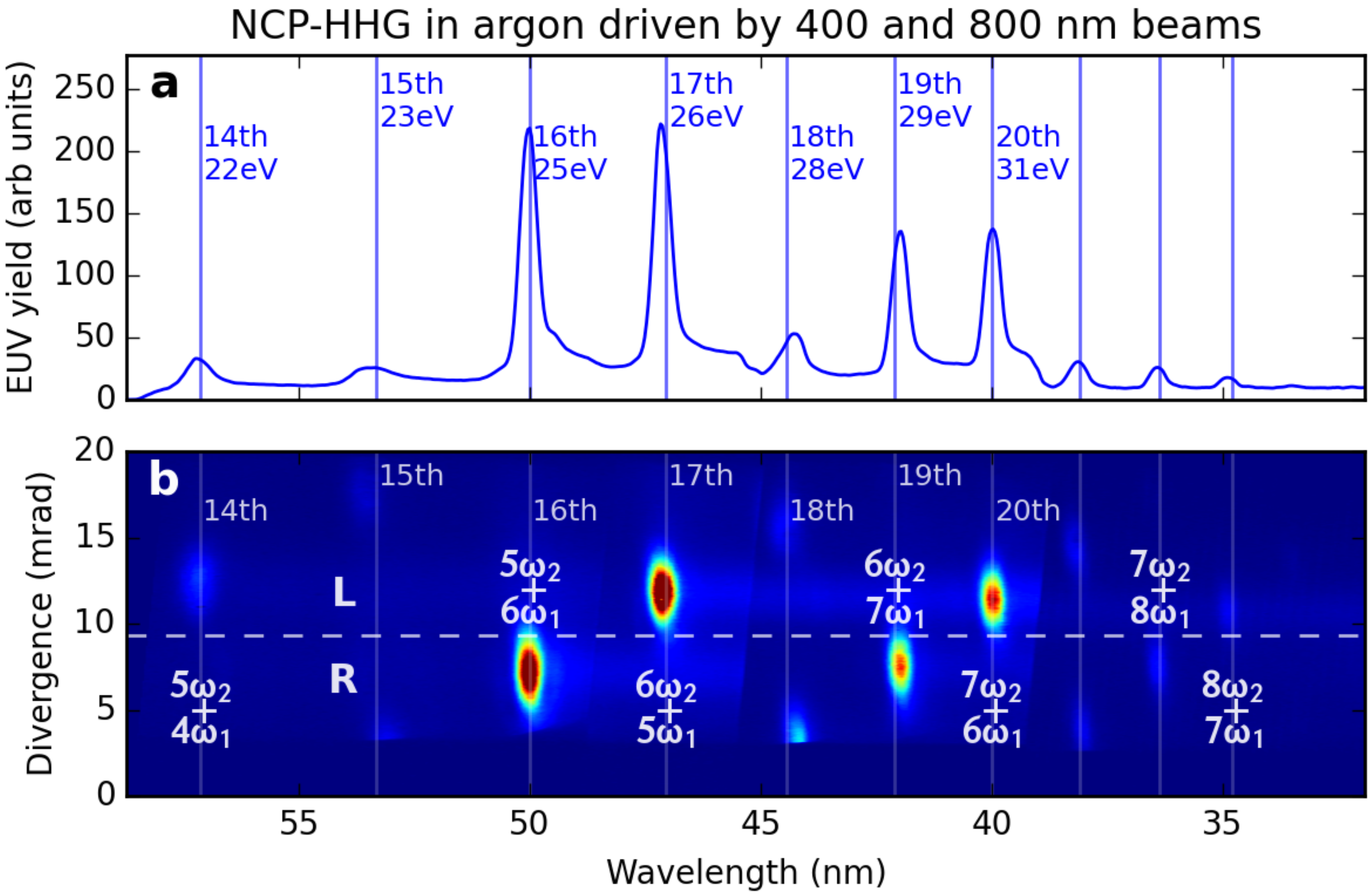
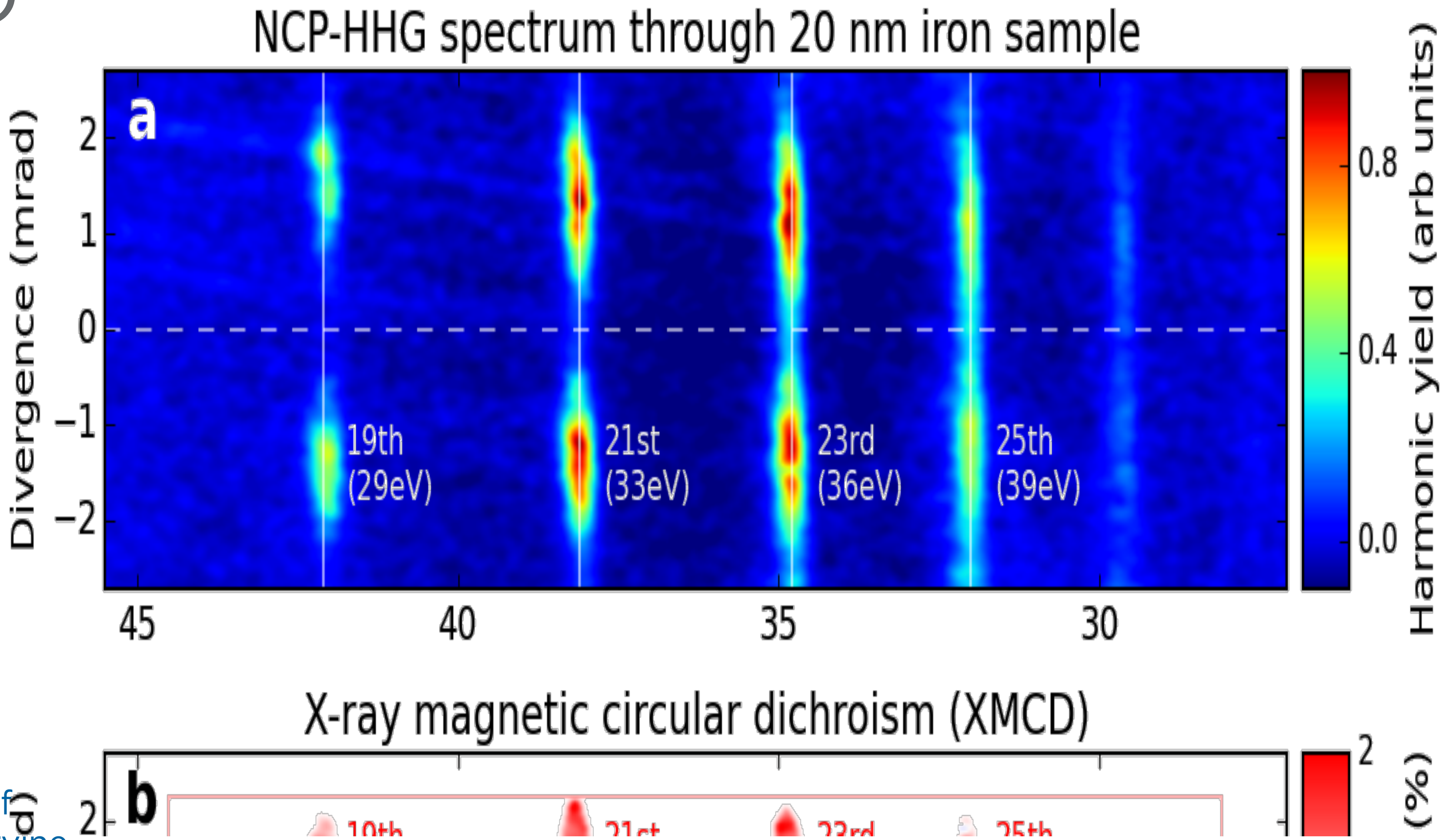
Varying wavelengths





XMCD



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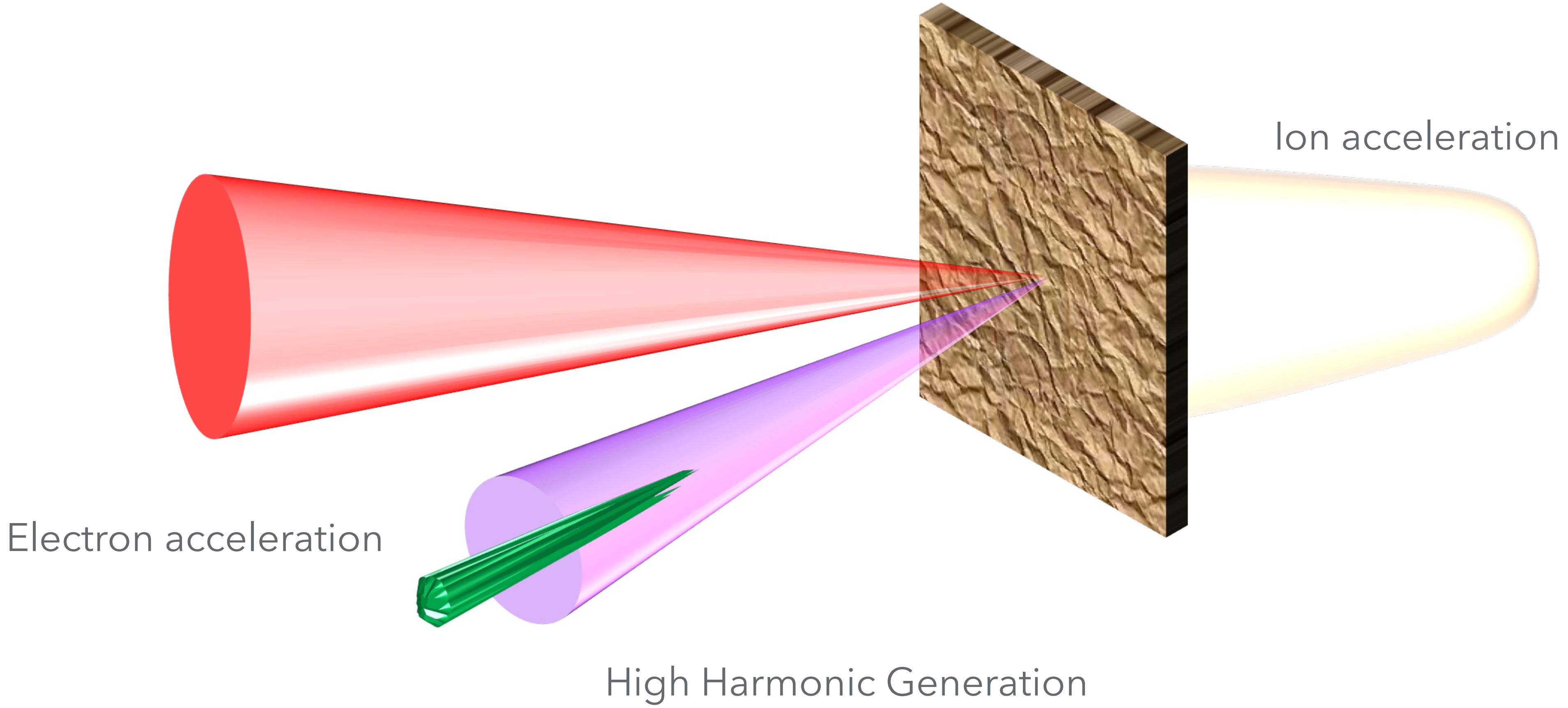
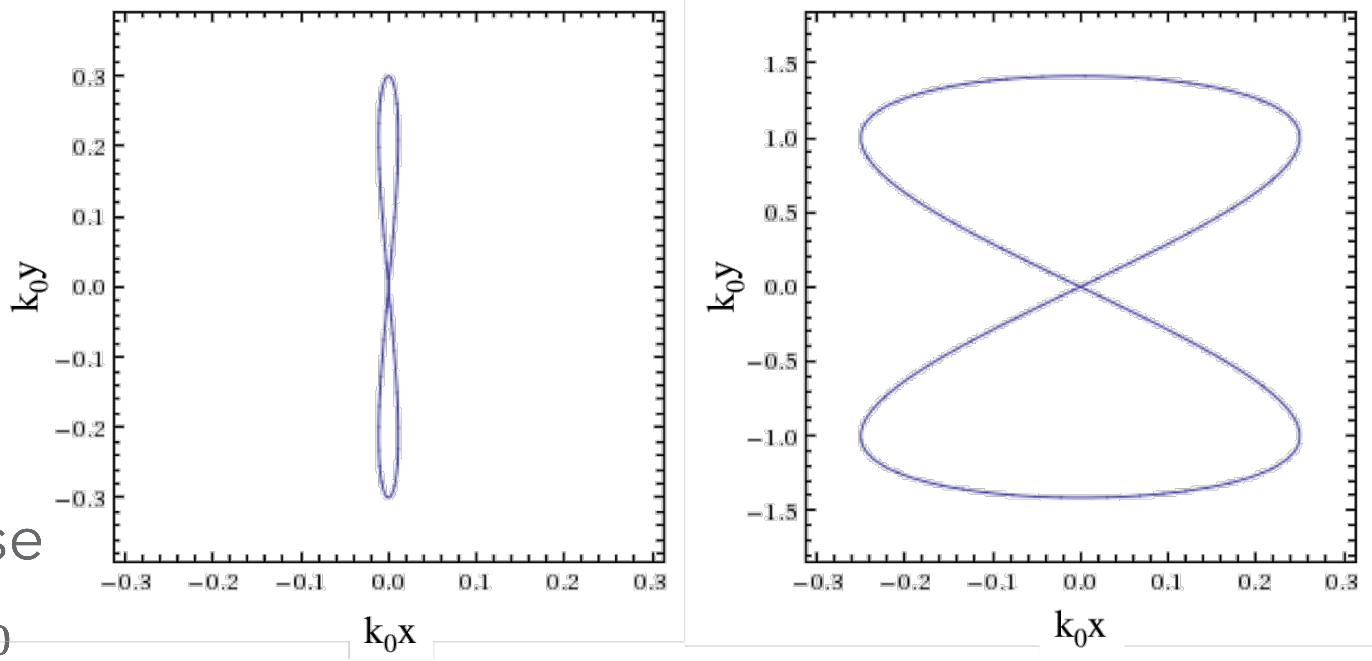
Interactions of lasers and solids



Scaling relationship

- Electron motion described with normalized vector potential
  - Ponderomotive force $\propto \langle a_0 \rangle^2$
  - Lorentz force motion $\propto a_0^2$ in longitudinal, $\propto a_0$ in transverse
  - Relativistic Lorentz factor $\propto a_0$

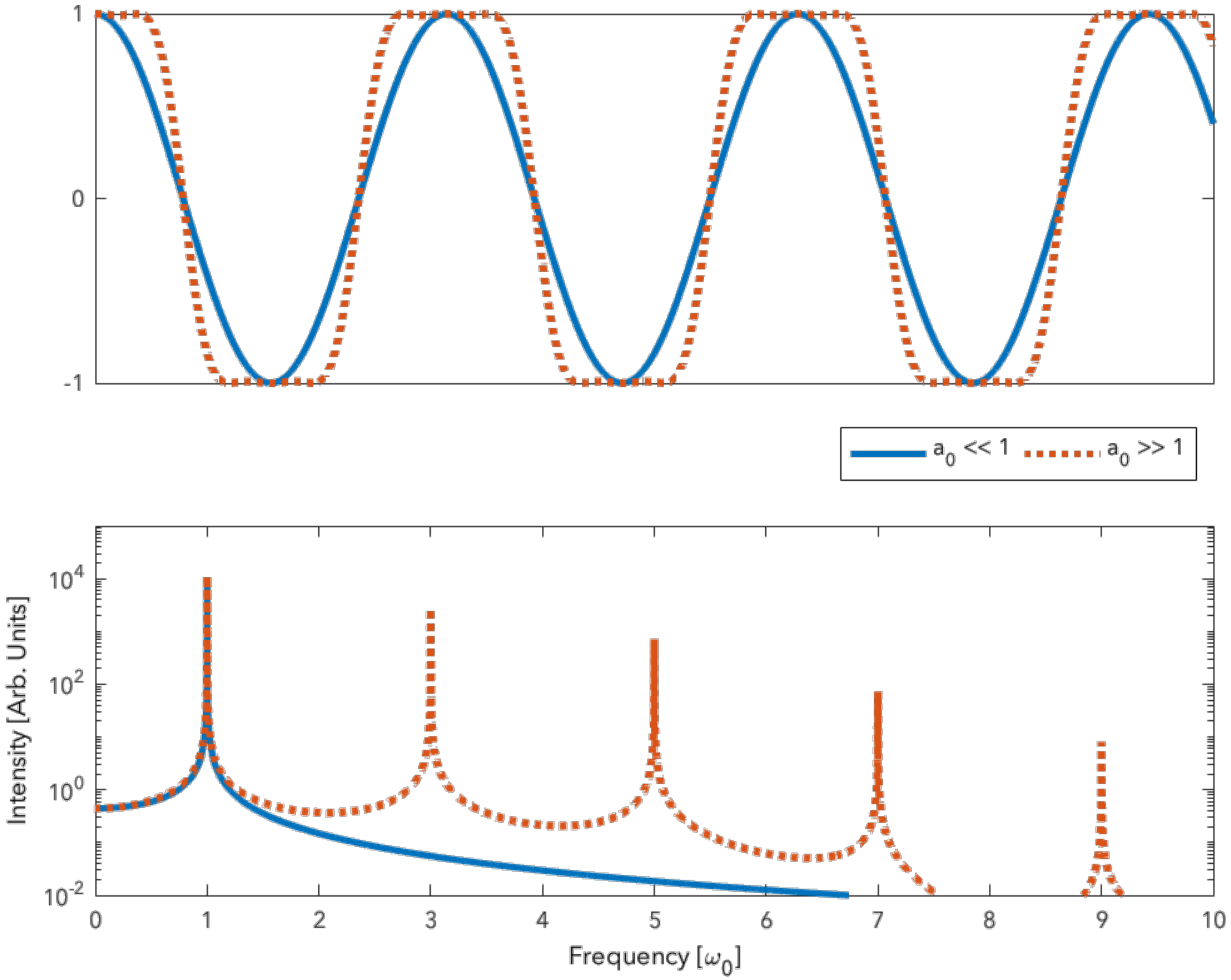


$$a_0 = \frac{p_0}{m_e c} = -\frac{e_c A_0}{m_e c} = -\frac{e_c E_0}{m_e c \omega_0}$$

$$a_0 = 0.85 \times 10^{-9} \lambda \sqrt{I}$$

Energy transfer

- Relativistic HHG from aharmonic motion
- HHG from solids is a bulk phenomena
- Relativistic oscillating mirror model



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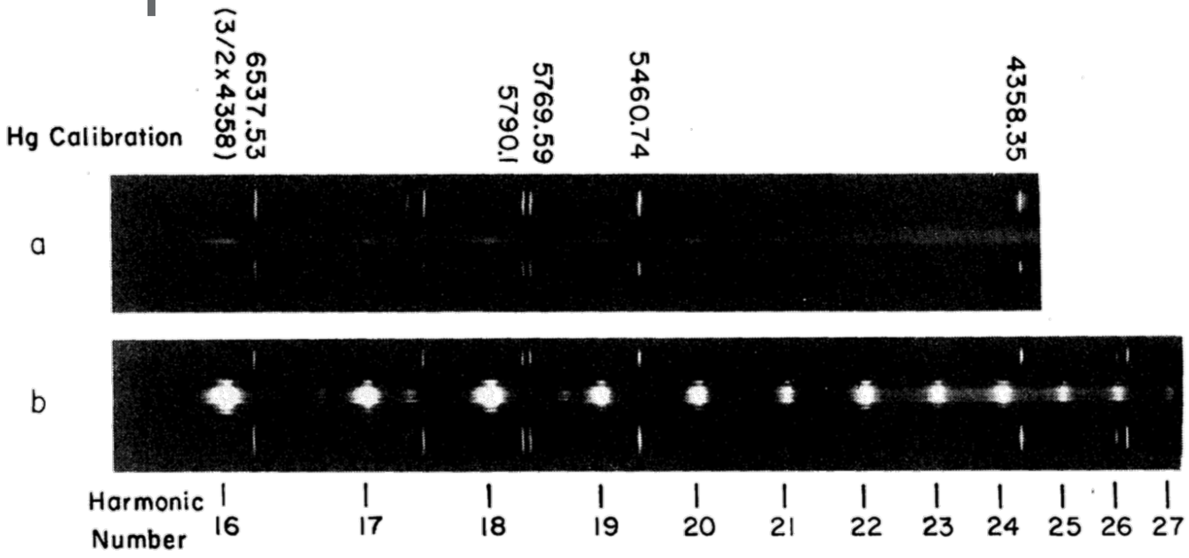
Early relativistic HHG experiments

- 1981 CO_2 laser experiment
  - 10^{16} Wcm^{-2} on target
  - 8 beams ~1 kJ
  - 0.6 ns FWHM envelope
- Since CPA all experiments at NIR
- Evidence of $I\lambda^2$ scaling

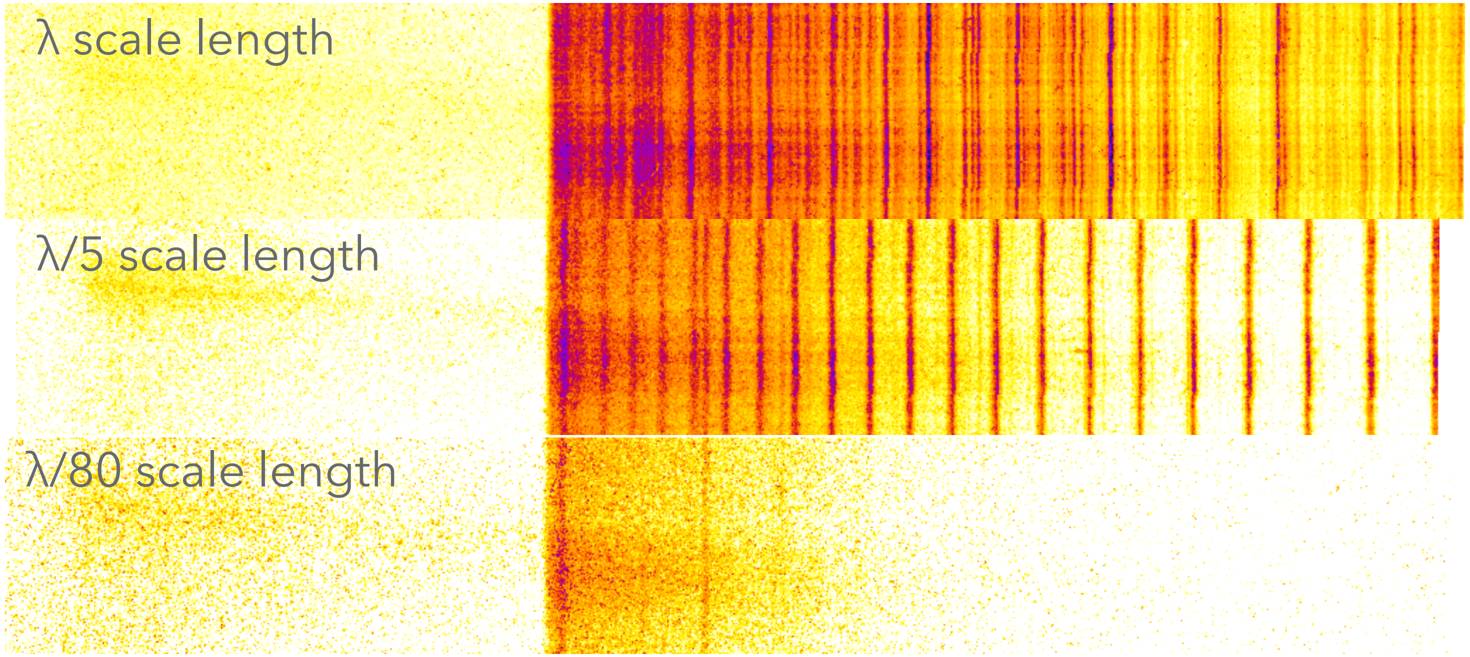


H. L. Carman, D. W. Forslund, and J. M. Kindel, PRL **46**, 29 (1981)

Scale length influence on HHG

- 800 nm experiments
- 10^{17} – 10^{21} Wcm^{-2}

- Preplasma controlled with heating beam



F. Dollar, et al., PRL **110**, 175002 (2013)

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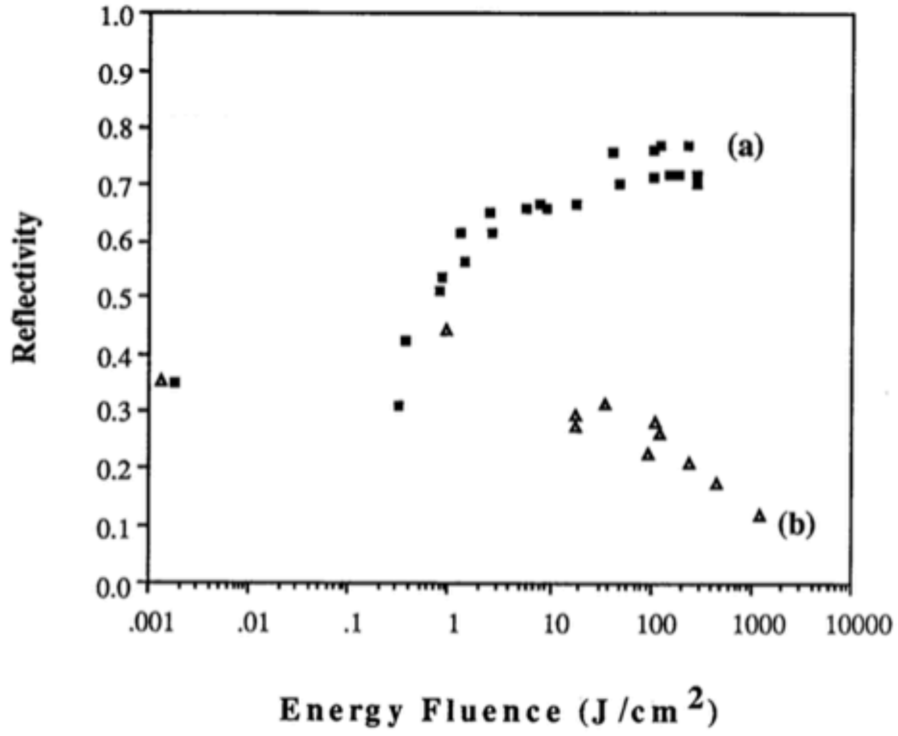
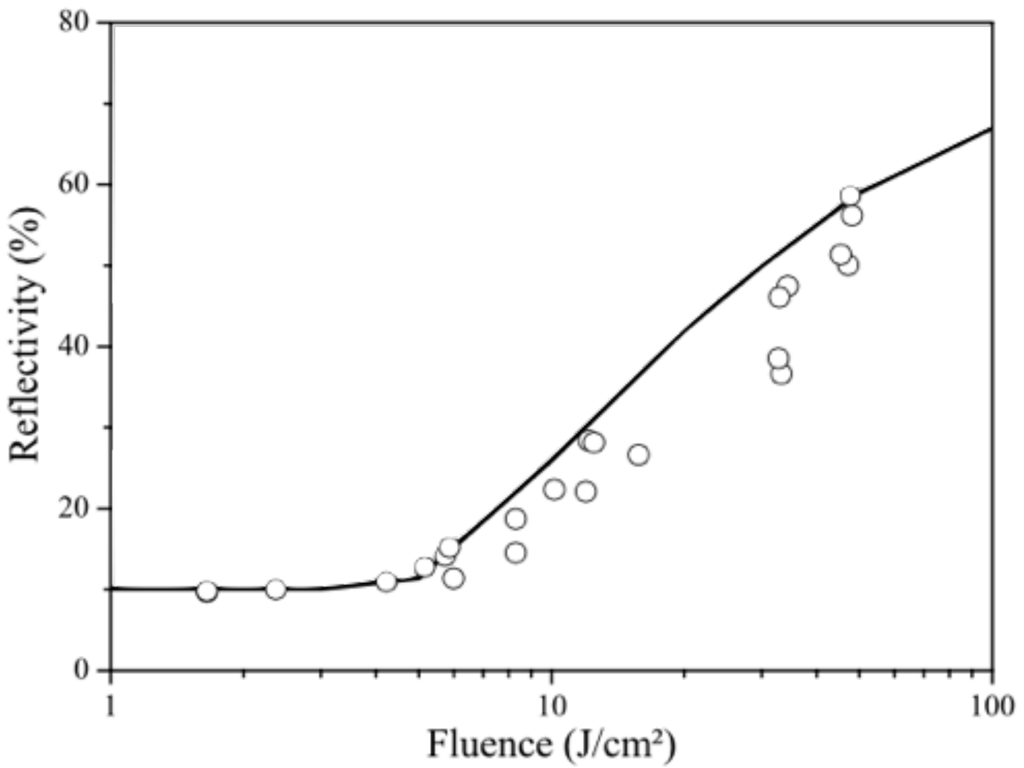
Laser absorption into solids



M. Murnane, Thesis, 1989



G. Doumy, et al., Phys. Rev. E **69** 1 (2004)

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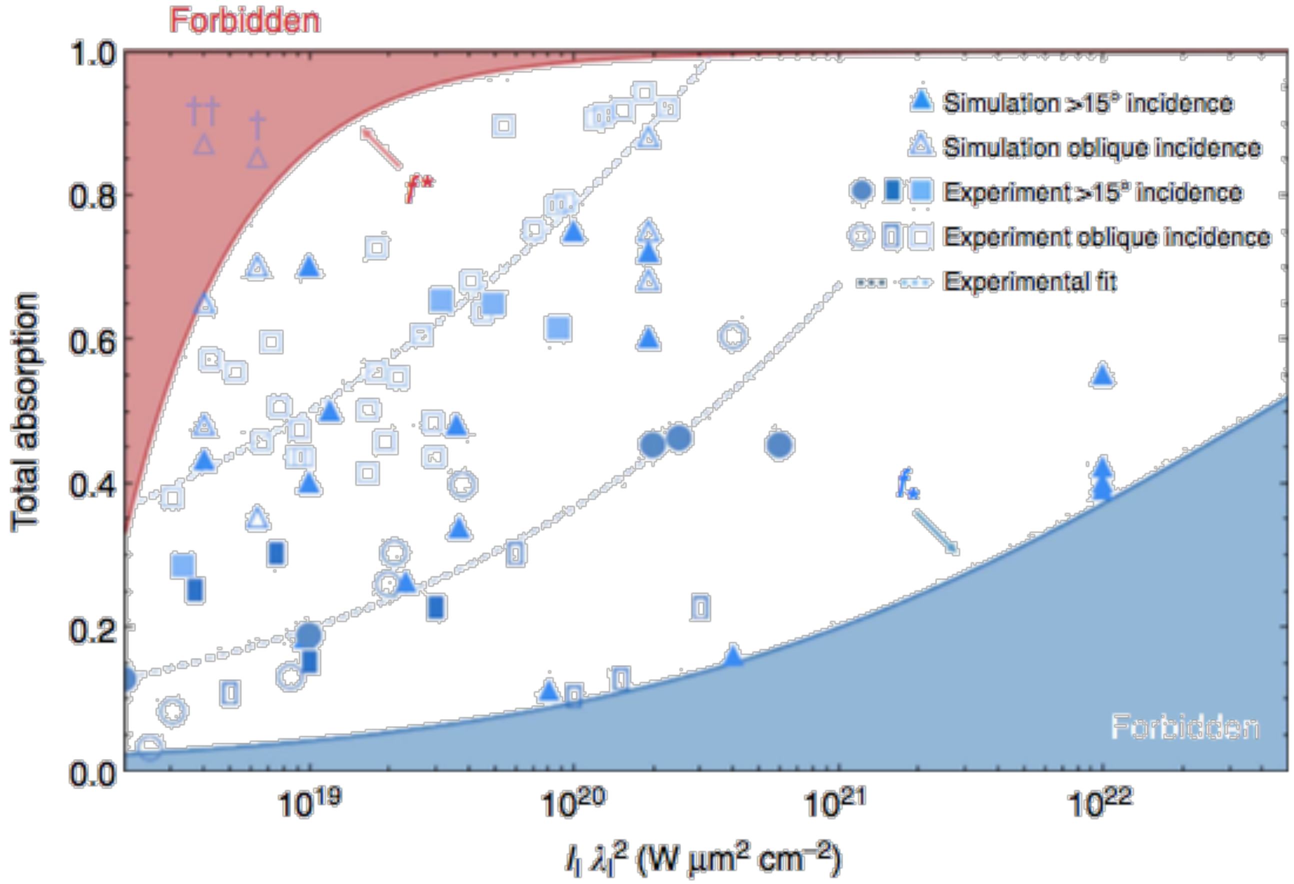
Absorption understanding

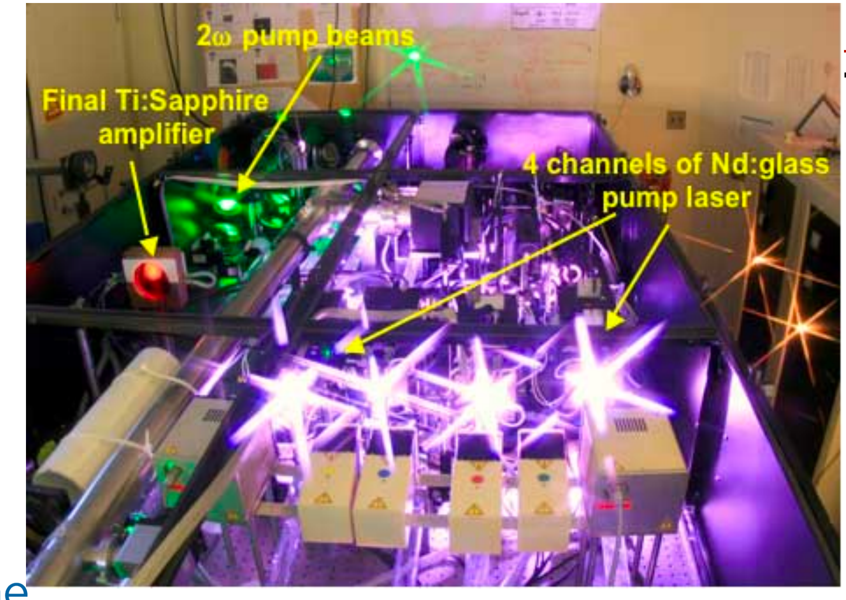
- Experiment and simulation shows large variation in absorption measurement
- Variables include:
  - Pulse duration
  - Polarization
  - Plasma density profile
  - Focal conditions

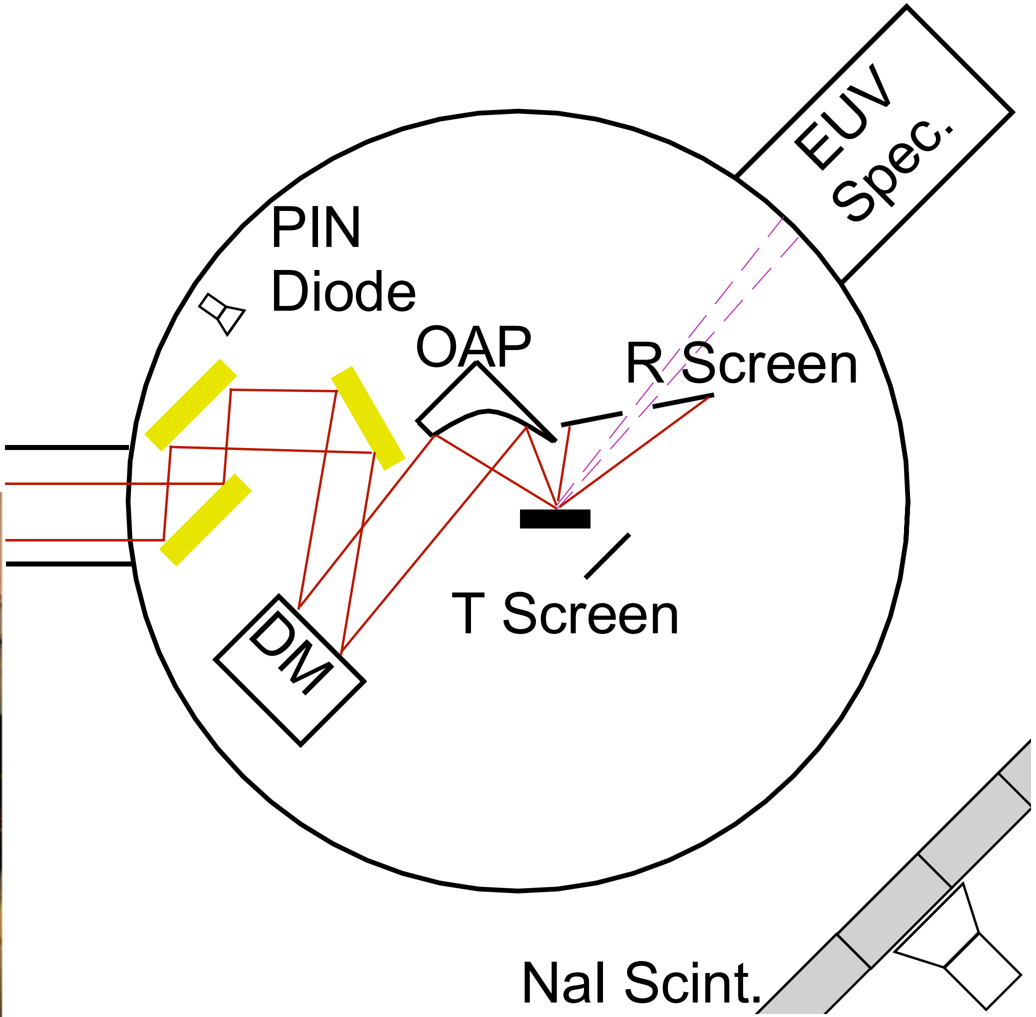


M. C. Levy, et al., Nat. Comm. 5, 4149 (2014)

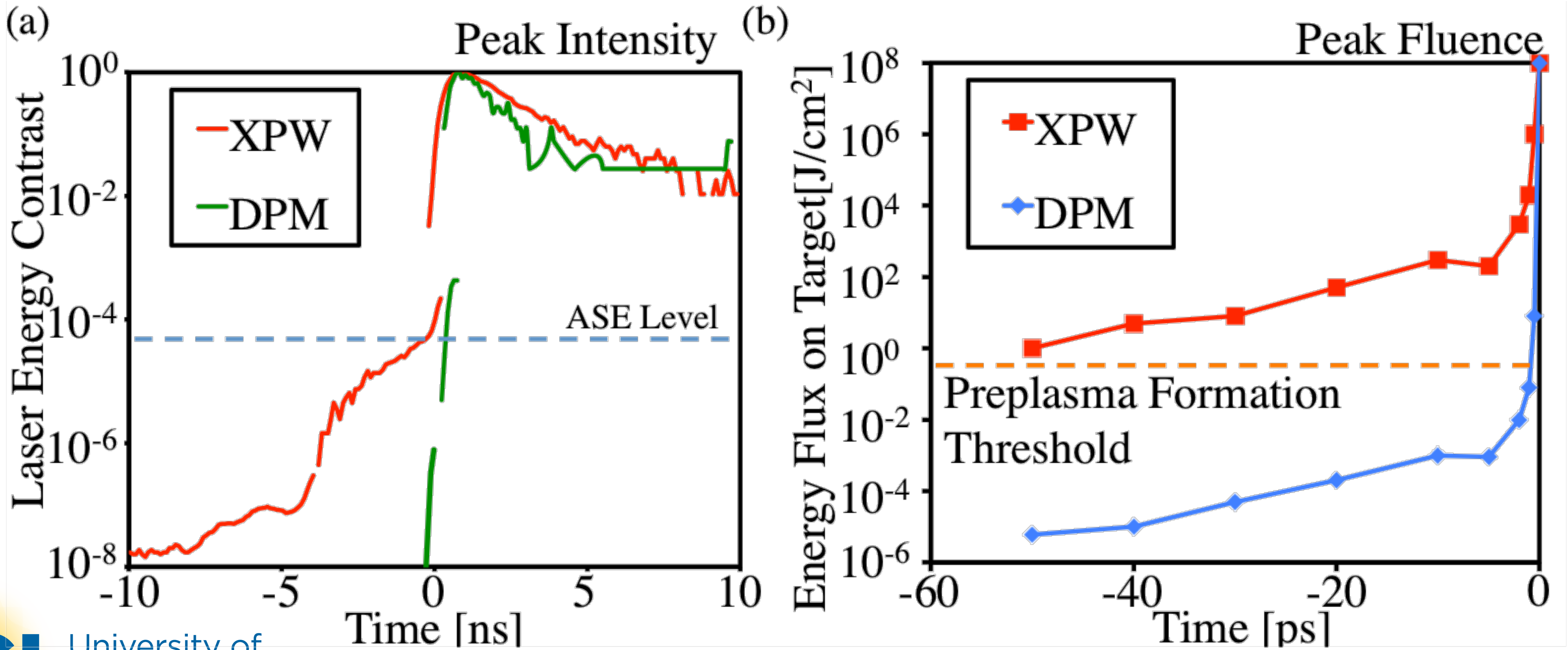
Experimental setup

- HERCULES
  - 800 nm, 0.1 Hz
  - 30 fs
  - 1.5 J



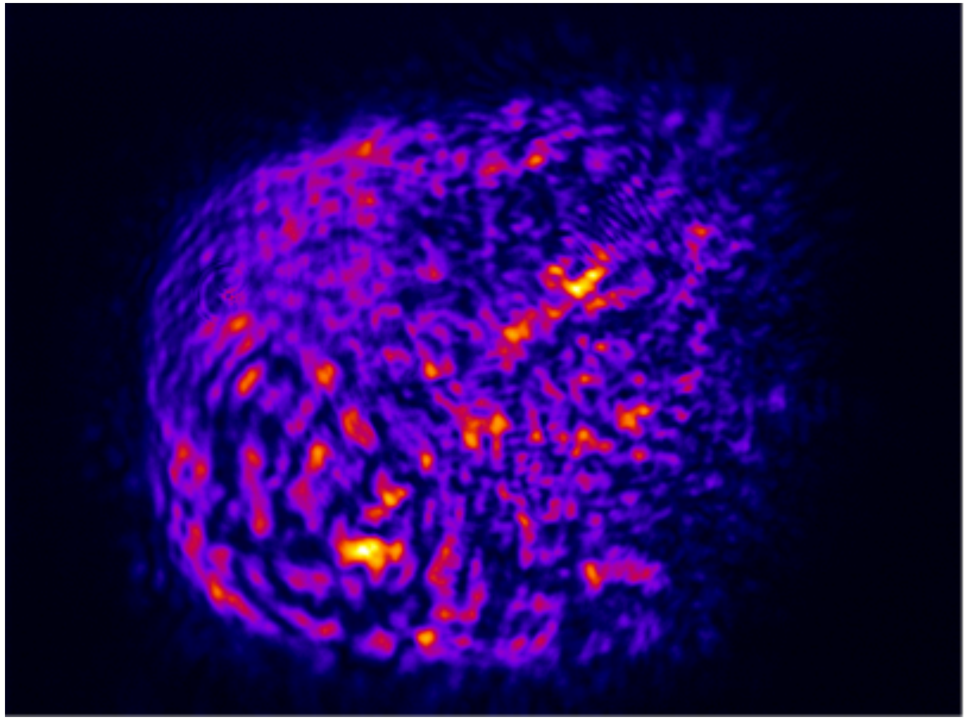


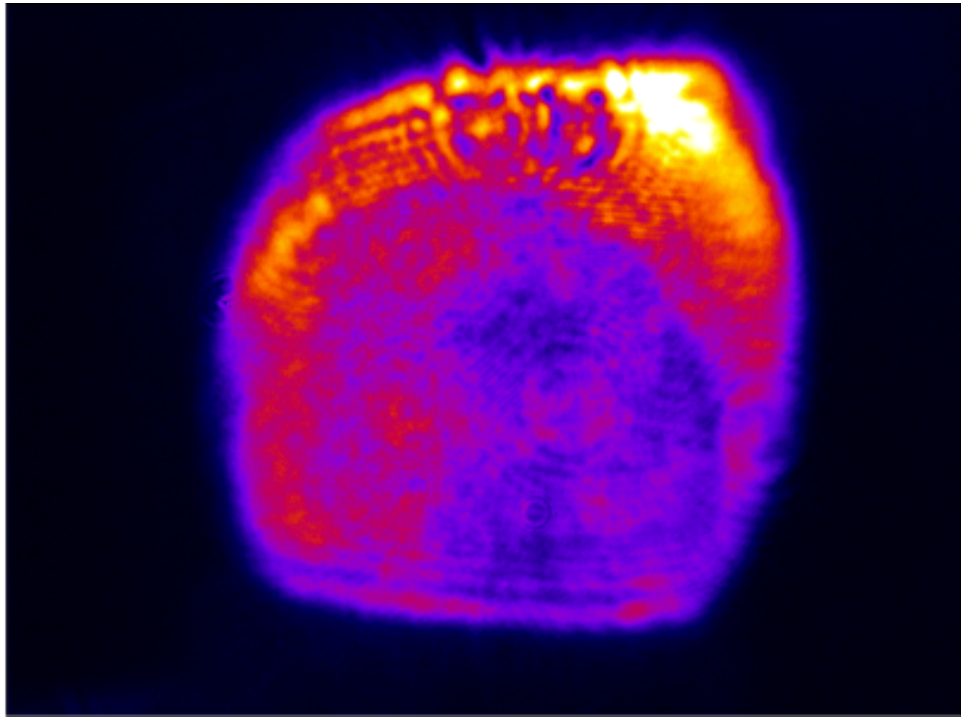
Pulse cleaning



Contrast issues

- XPW comparison between 10^{16} and 10^{15} plasma mirror





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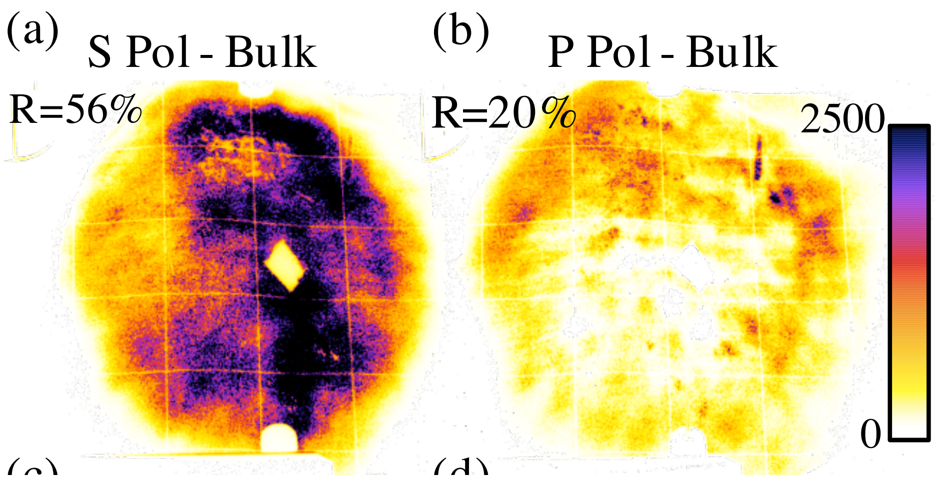
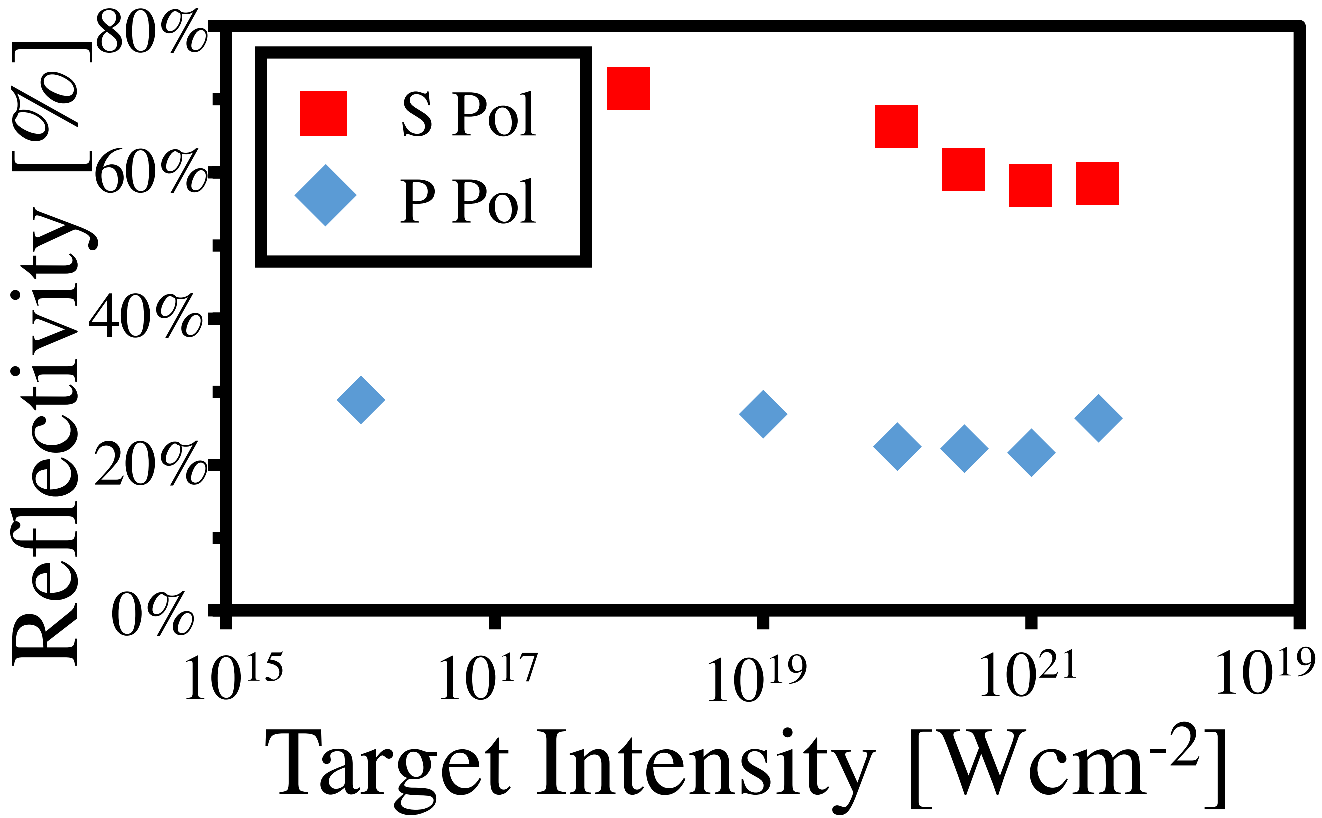
Polarization dependence





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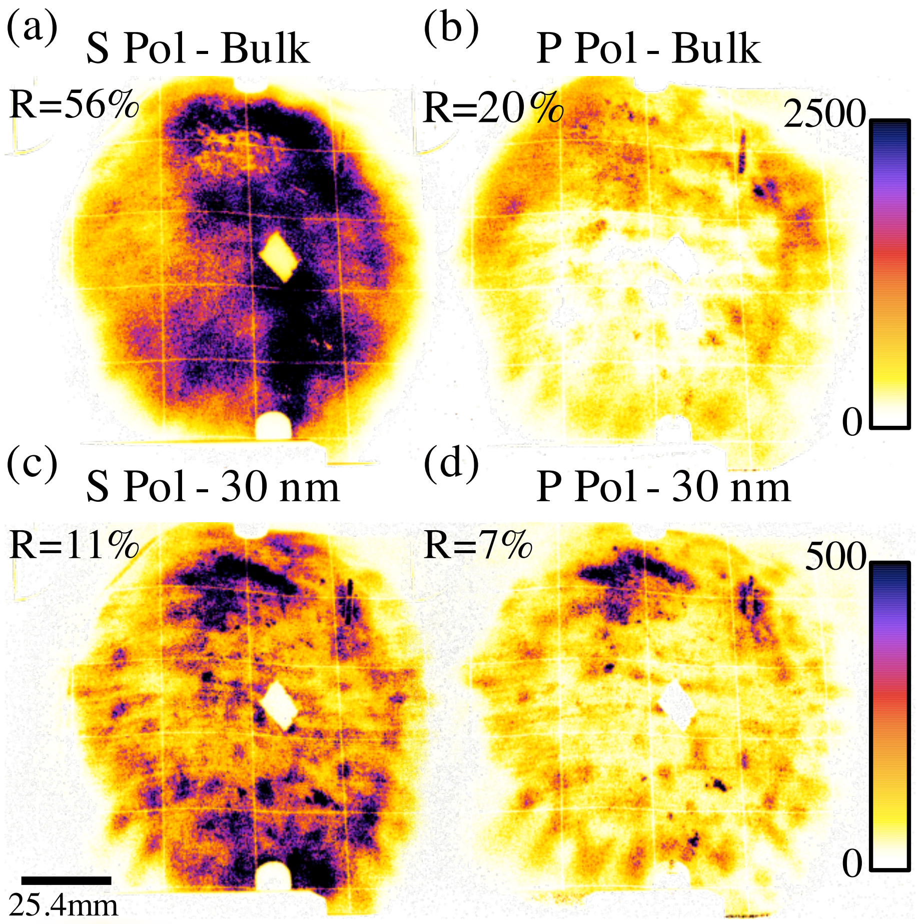
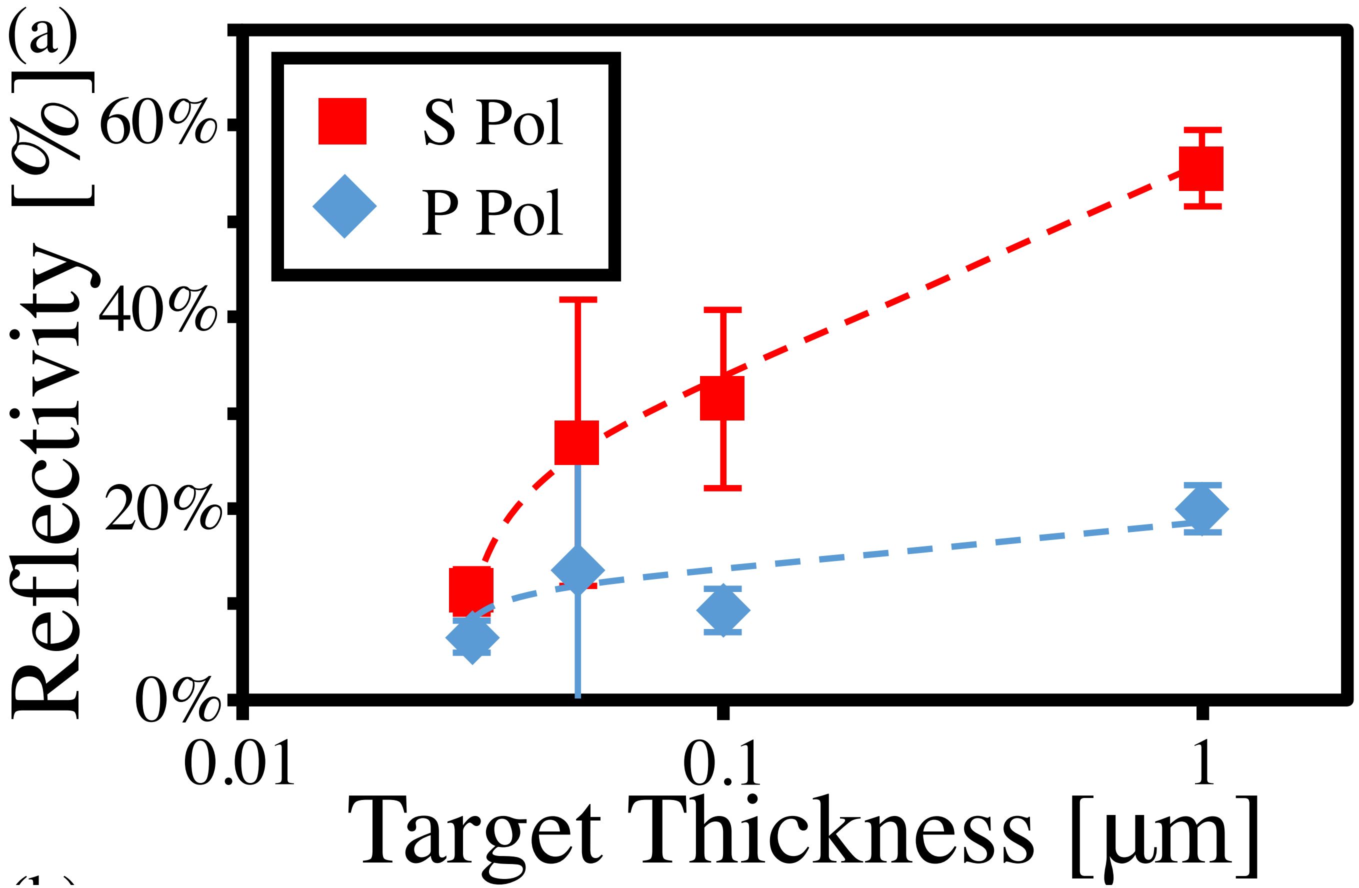
F. Dollar, et al., New J. Phys. **19** 063014(2017)

Polarization dependence





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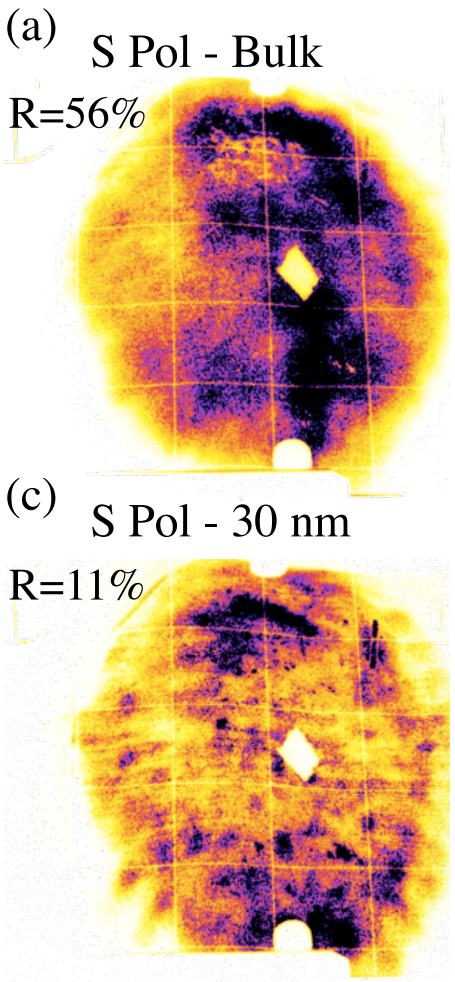
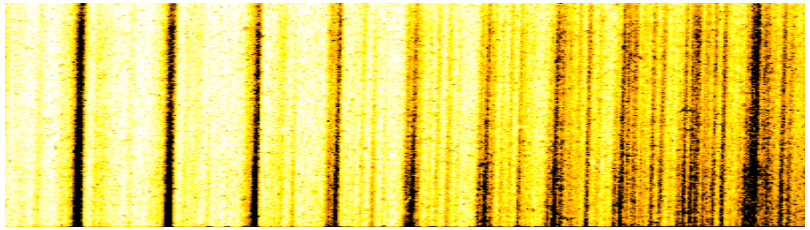
HHG with ion motion

- Harmonics were lost for thinner targets with modulated beam profiles

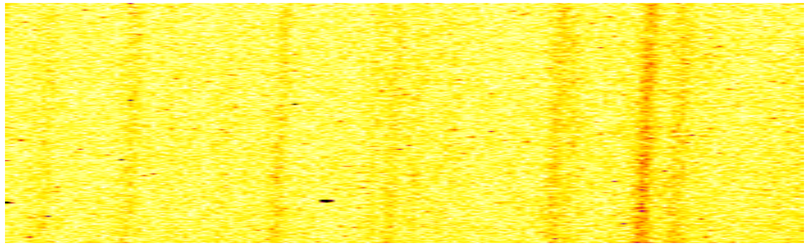
- Modulation at plasma surface prevents coherent buildup of x-rays



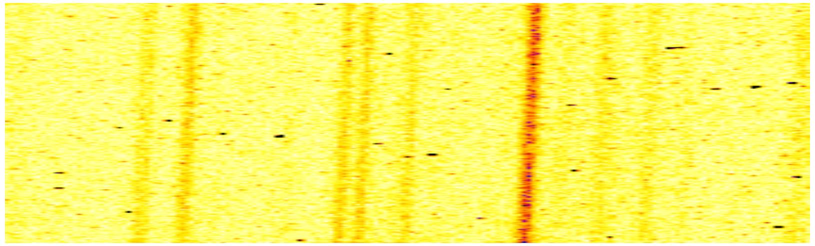
Bulk x-ray emission



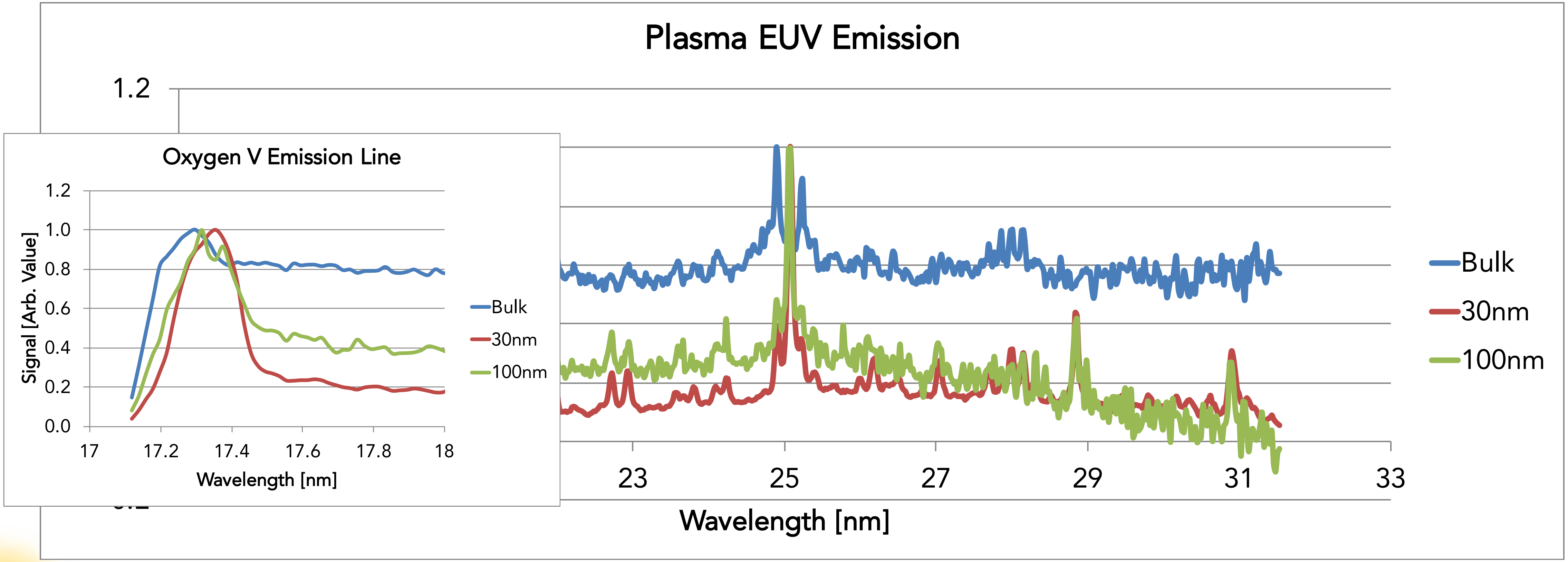
1000 nm x-ray emission



30 nm x-ray emission



Redshifting Oxygen Lines



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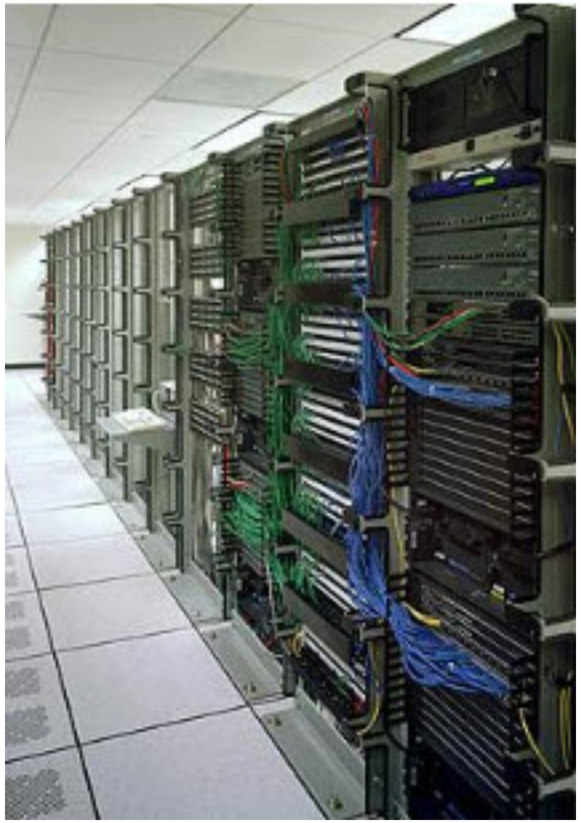
PIC Simulation capabilities

- GreenPlanet computing cluster @UCI
- 592 Intel Xeon E5 cores
- 6 GB/core

- Collaboration with PICKSC for simulation codes
  - OSIRIS 4.0 particle-in-cell
  - OSHUN VFP



We acknowledge the OSIRIS Consortium (UCLA/IST Portugal) for use of OSIRIS.

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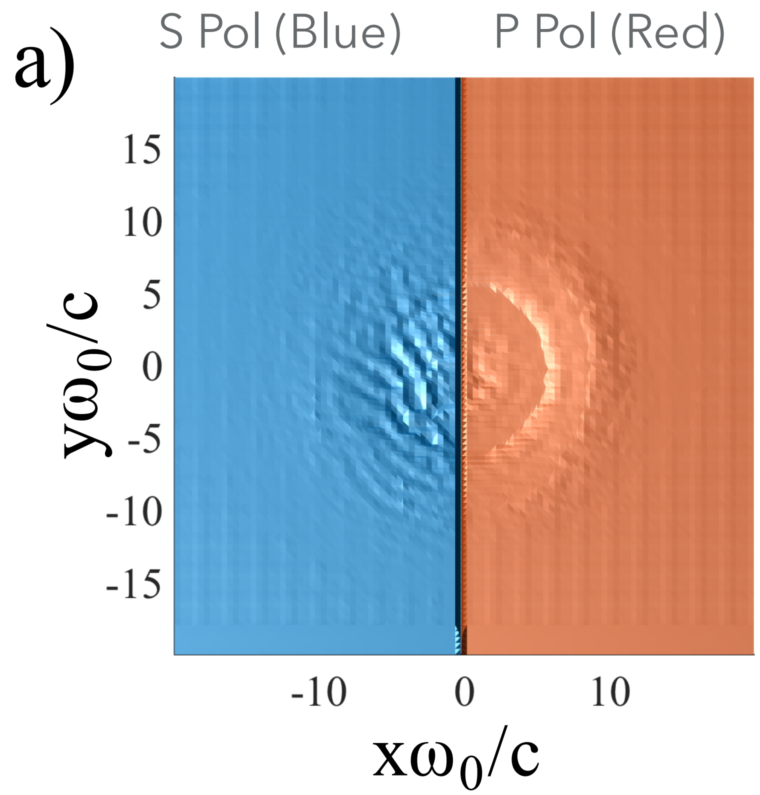
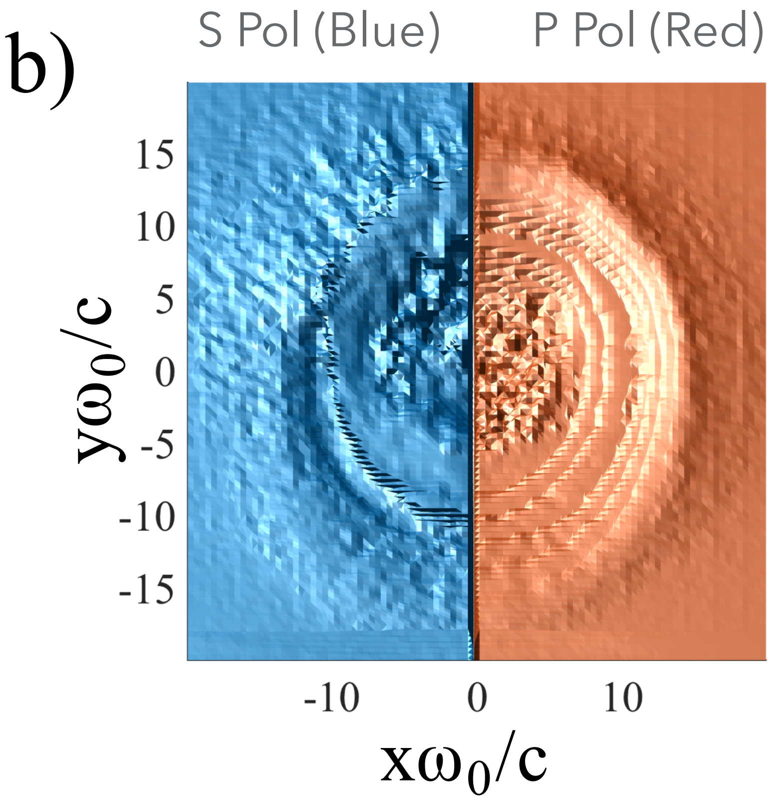
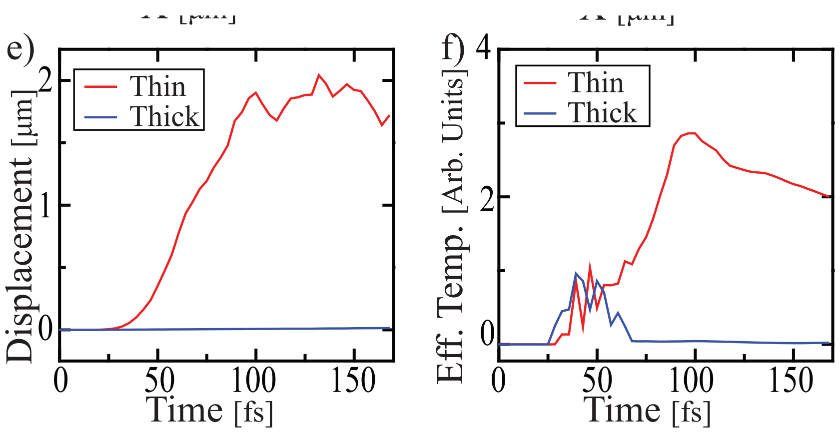
3D Simulations

F. Dollar, et al., New J. Phys. **19** 063014(2017)
F. Dollar, et al., PRL **108**, 175005 (2012)





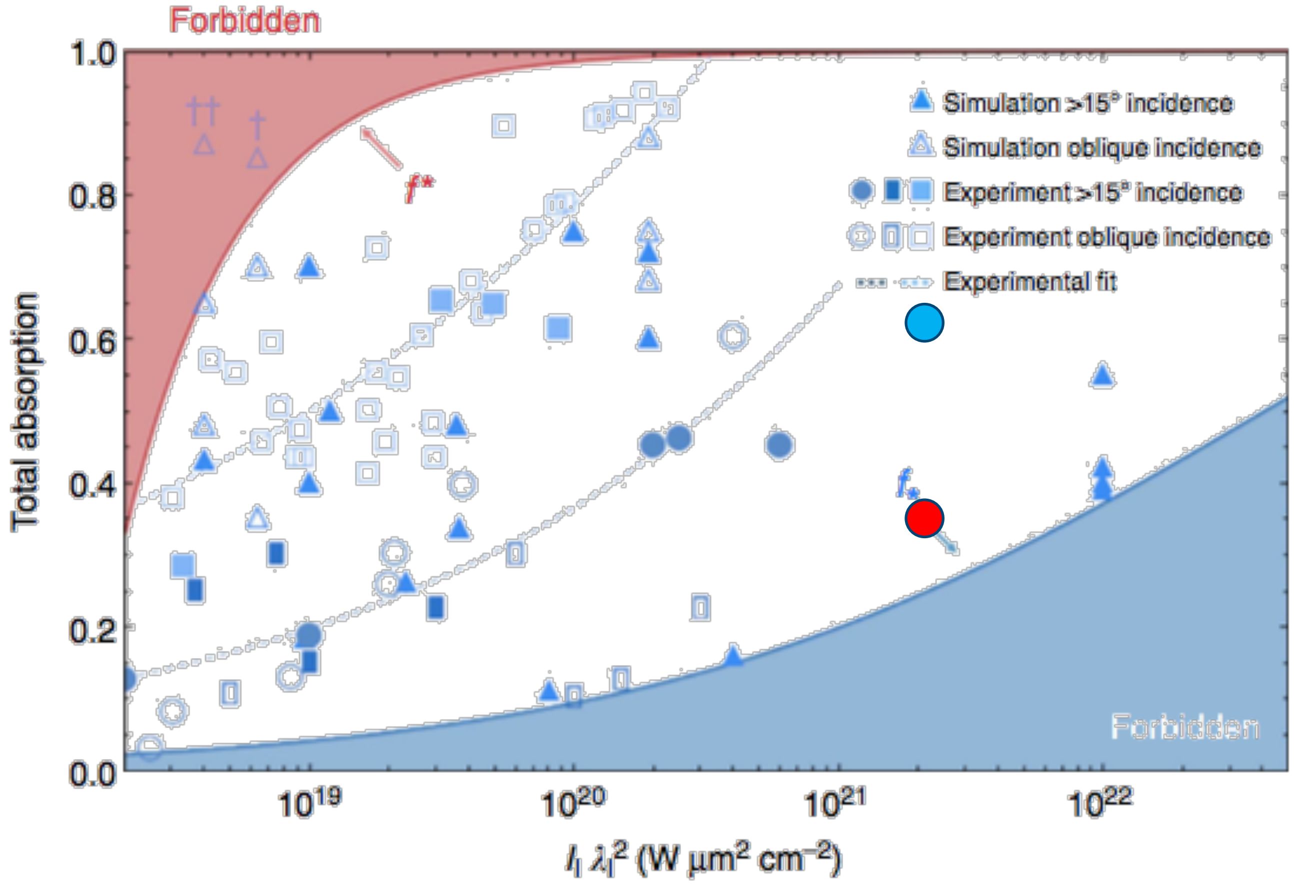


Low intensity

High intensity

Absorption understanding

- High contrast experiments
- Much lower absorption observed than general trends



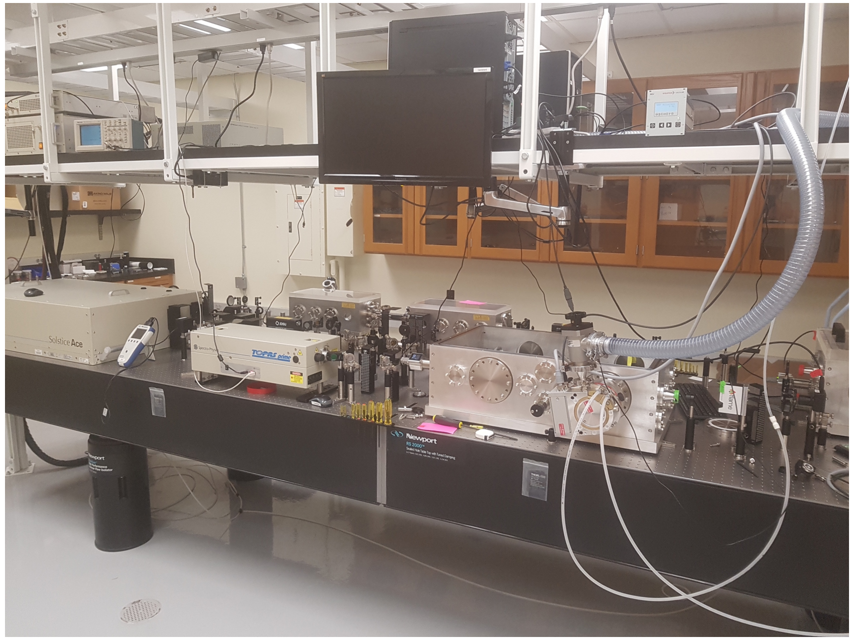
M. C. Levy, et al., Nat. Comm. 5, 4149 (2014)

Relativistic HHG

- Fundamental questions remain
  - What is the relation between hot electron generation and HHG?
  - How do plasma conditions affect surface plasma waves?
  - Do single atom scalings hold for collective effects?

- Mid infrared provides unique experimental opportunities
  - Visible harmonics
  - Overdense targets
  - Higher a_0 for a given intensity

Experimental setup at UCI



M squared <1.1

Solstice ACE

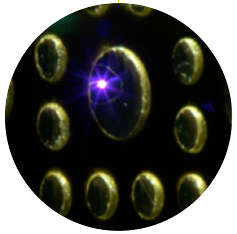
800 nm

1 kHz, 7 mJ, 35 fs

Mid-Infrared Beam

1300-2100 nm

1 kHz, 1.3/0.7 mJ, 40 fs



Probe Beams

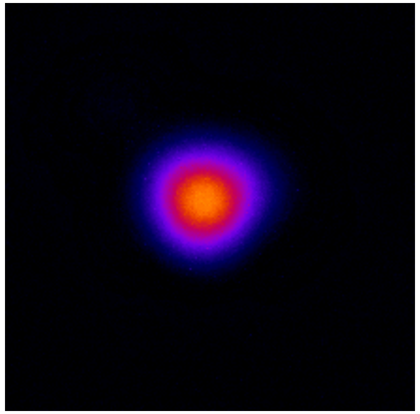
2 x 800 nm

1 kHz, 1 mJ, 35 fs

Femtokit

267-400 nm

1 kHz, 2 mJ, 35 fs



4.17 μm measured
4.07 μm diffraction limit

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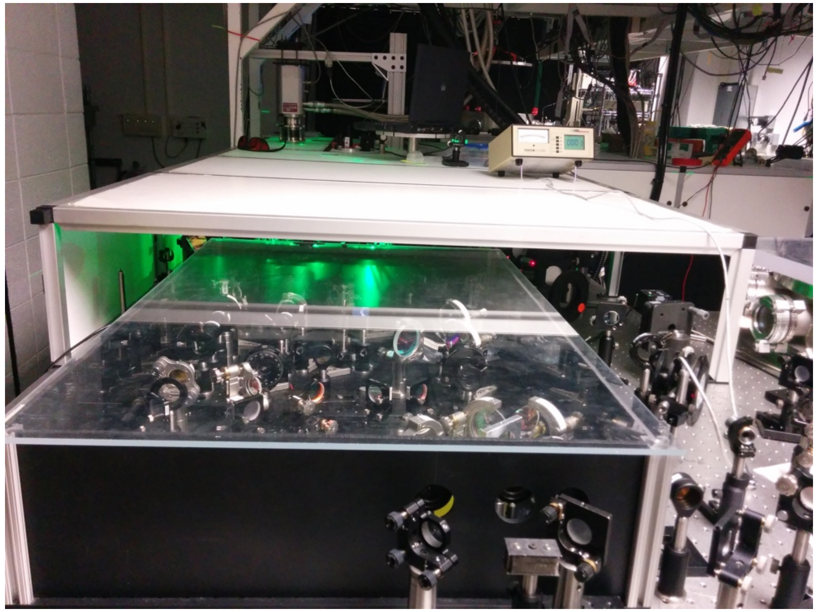
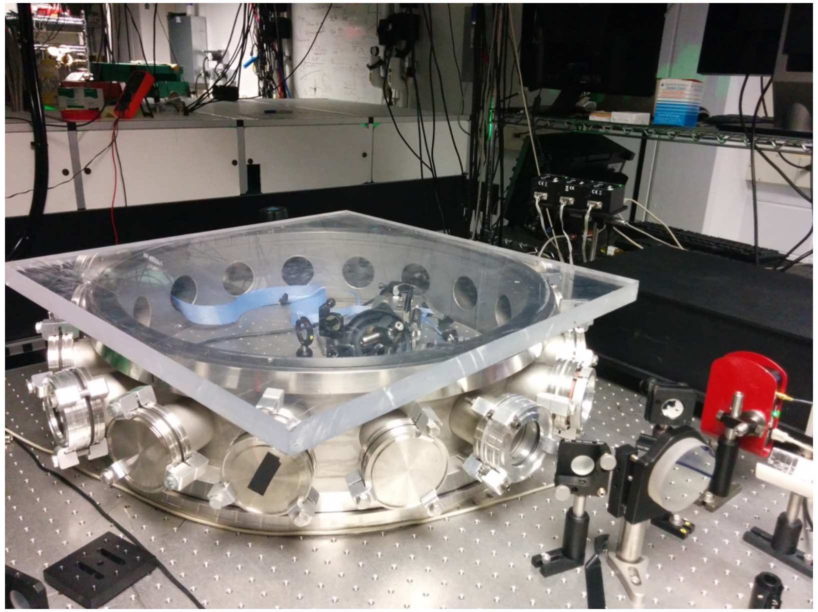
Experimental setup at Michigan

- Lambda Cubed
  - 800 nm, 0.5 kHz
  - 30 fs
  - 20 mJ
- 2 micron OPA
  - 35 fs
  - 2 mJ





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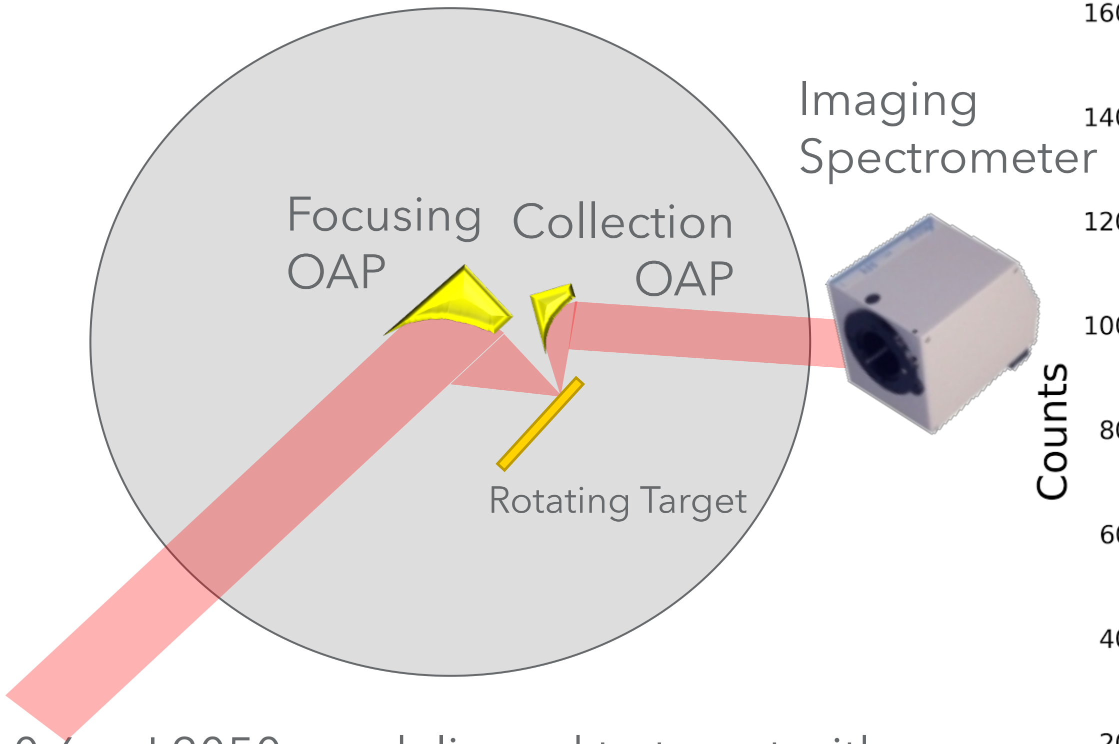
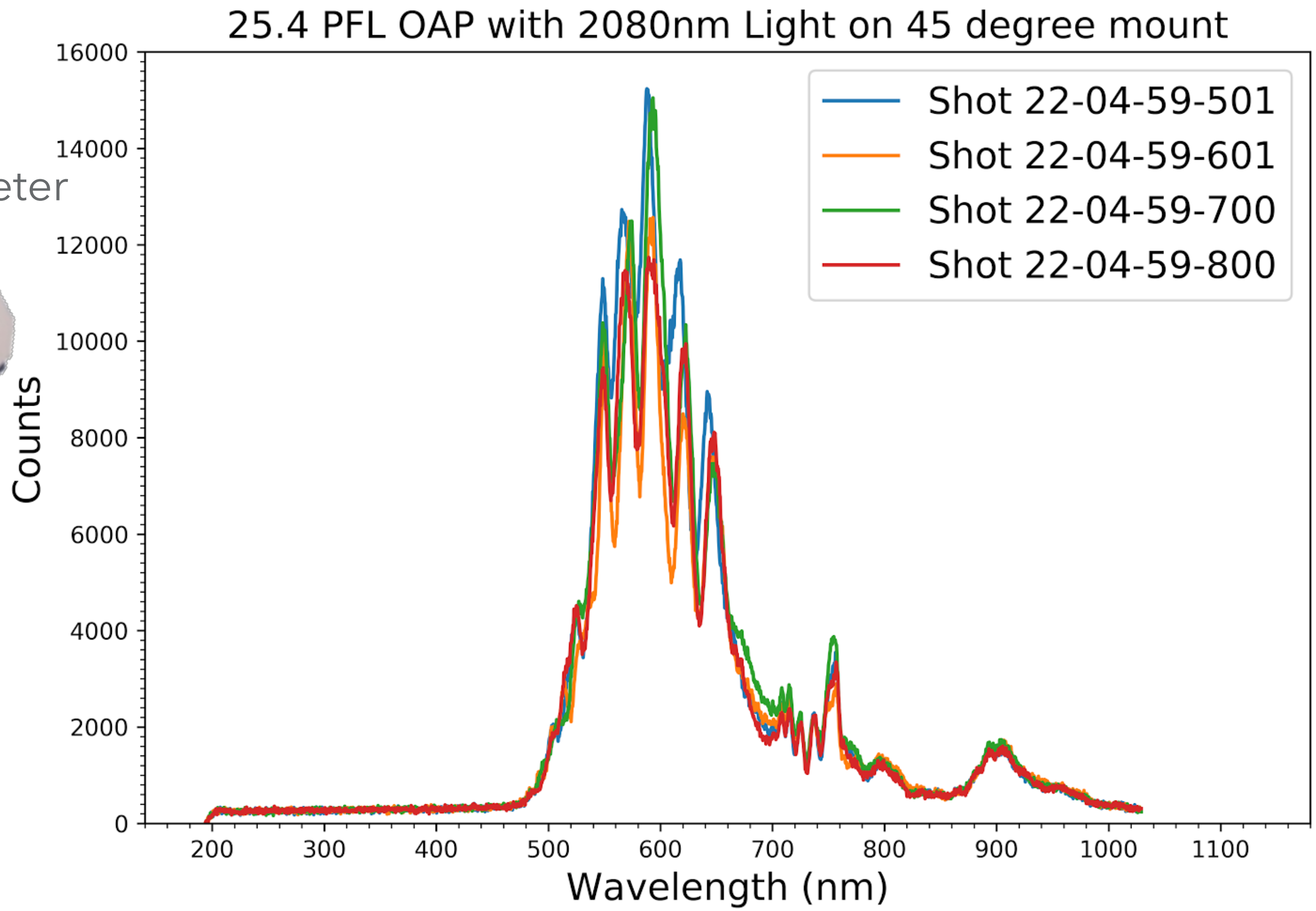
Low order harmonic emission



0.6 mJ 2050 nm delivered to target with $>10^{16}$ Wcm^{-2}



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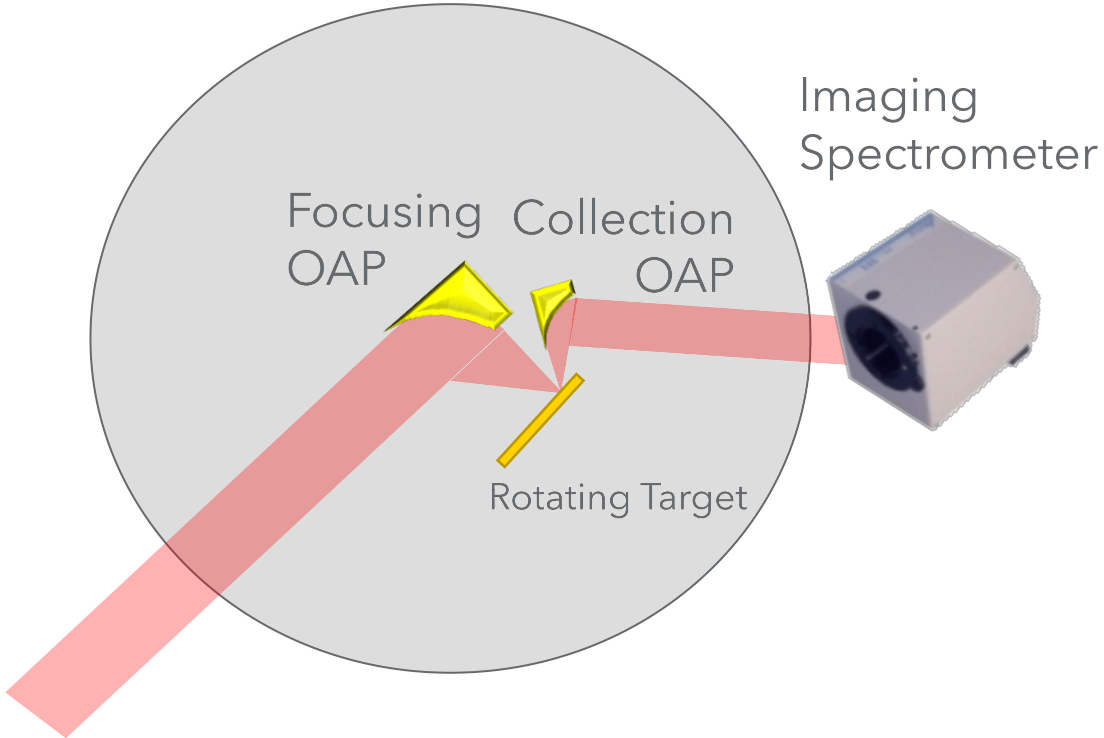
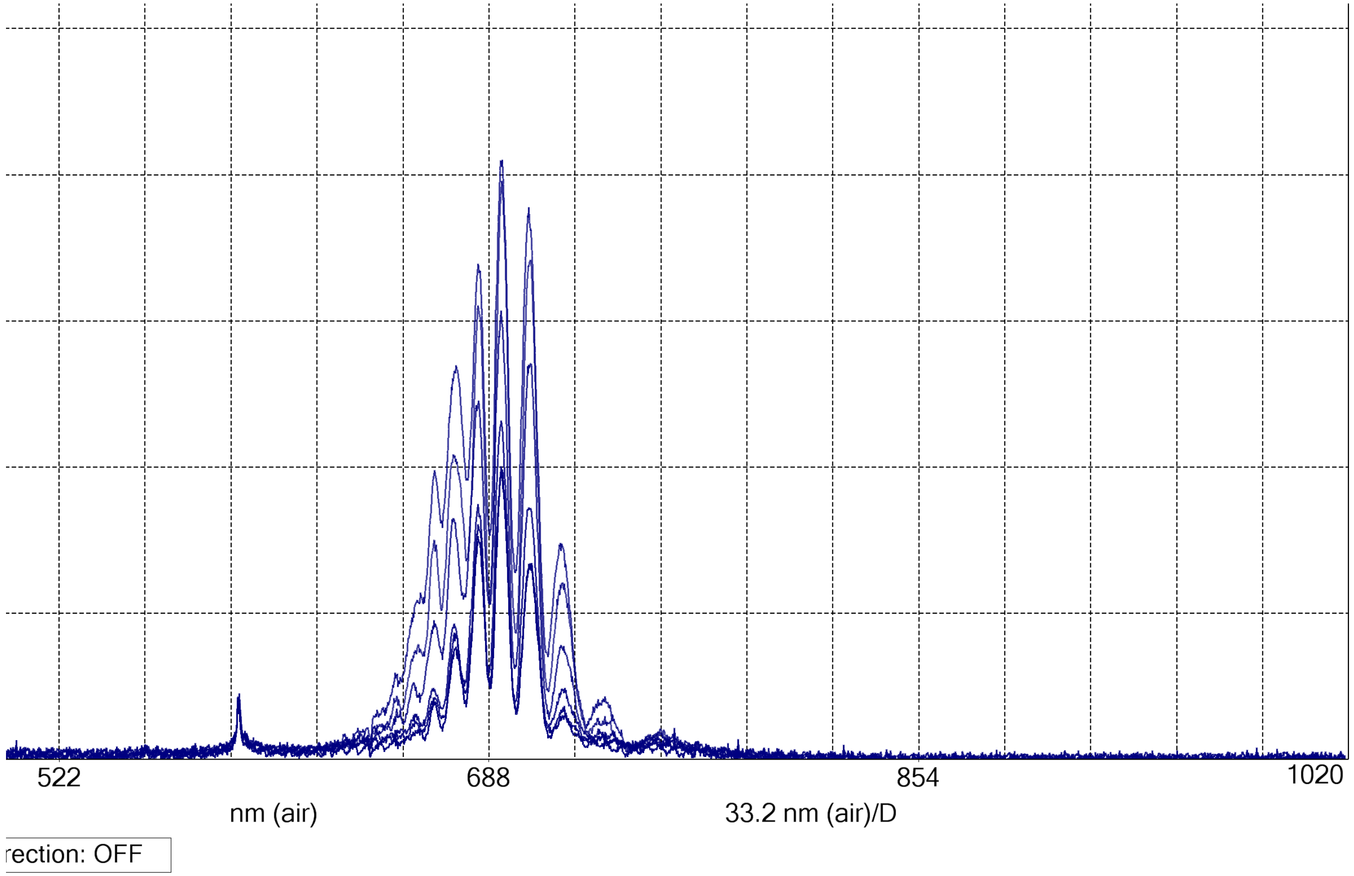
Low order harmonic





1.6 mJ 1950 nm delivered to target with $>10^{16}$ Wcm^{-2}

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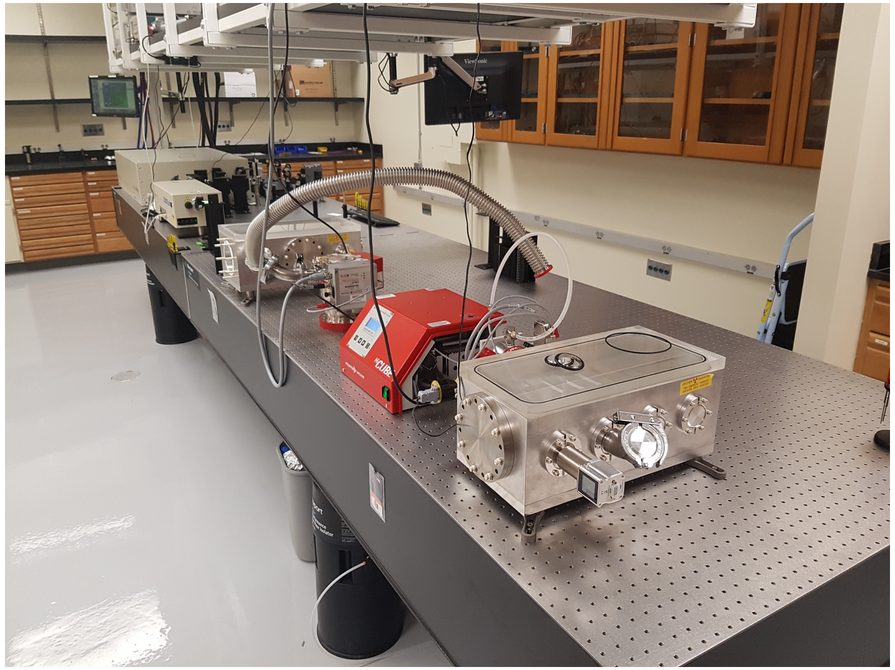
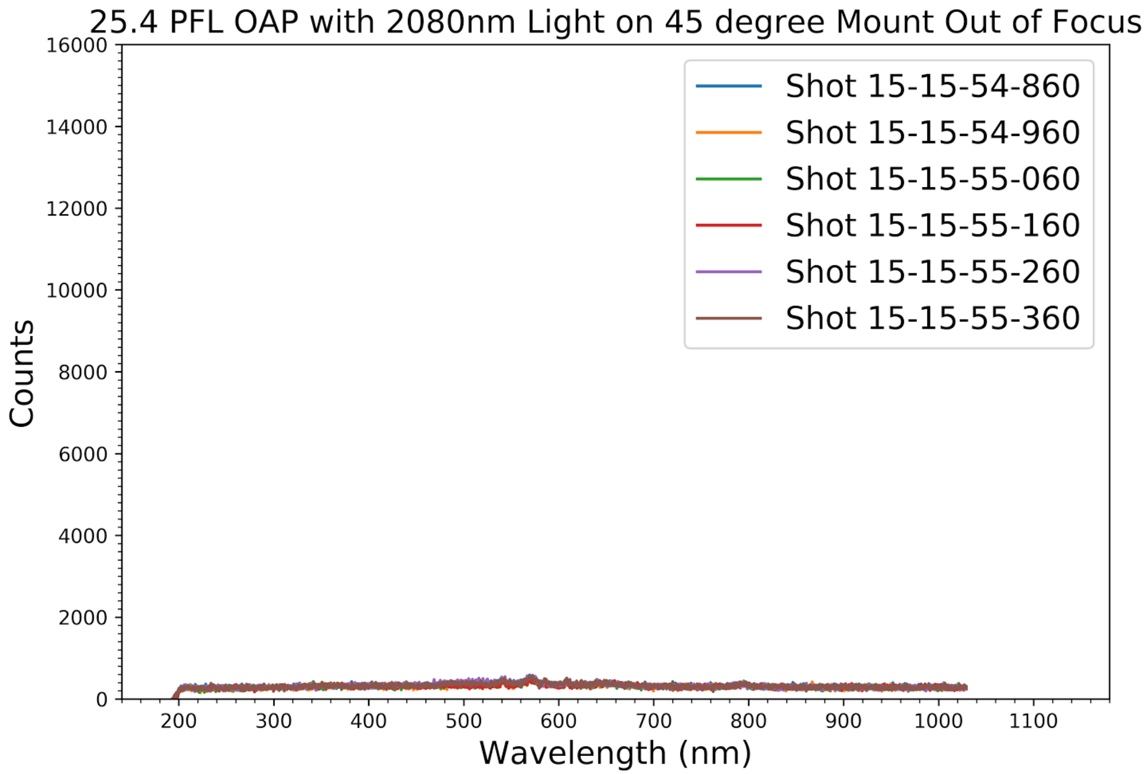
Low order harmonic emission





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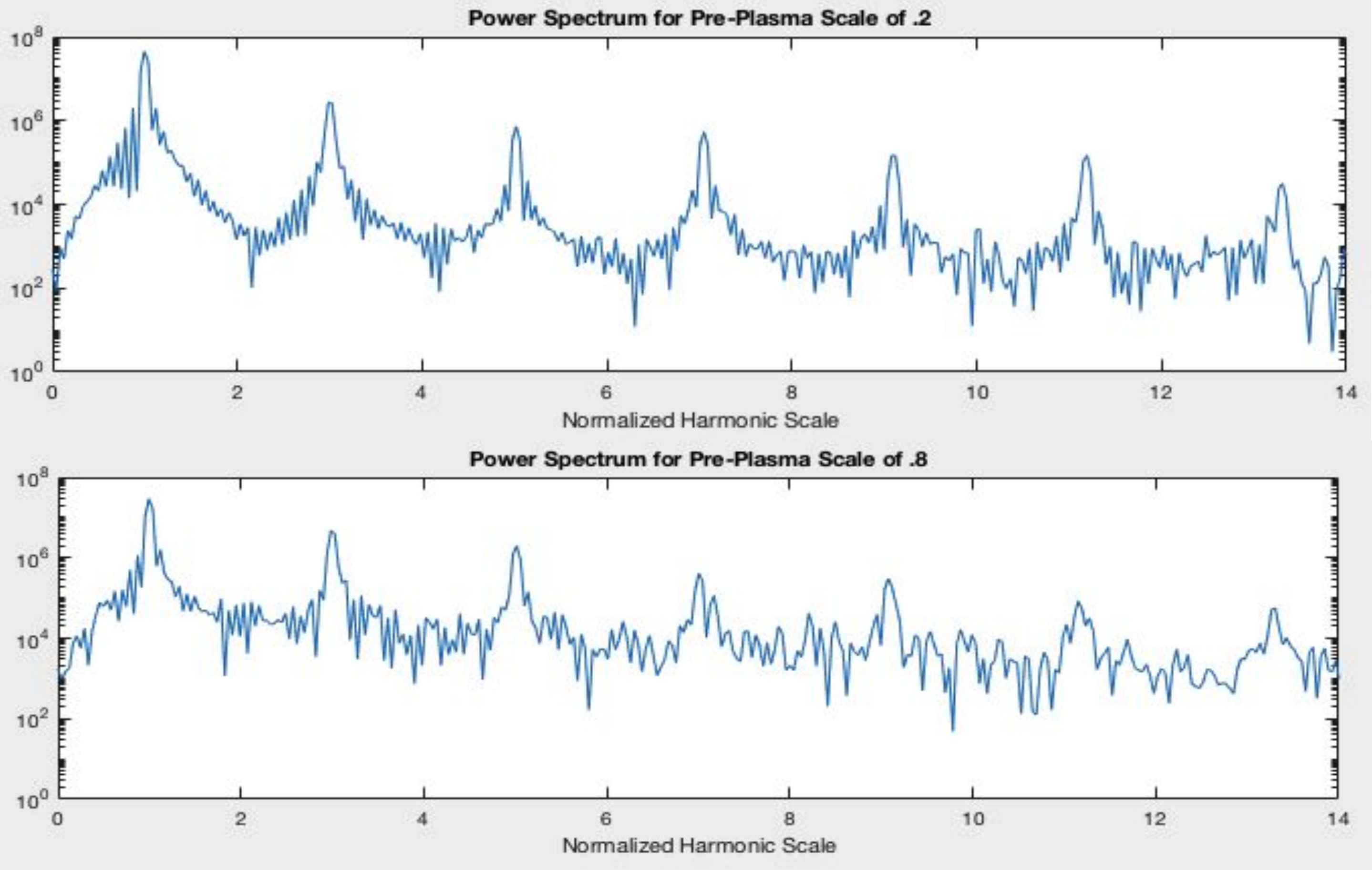
OSIRIS Simulation results

- OSIRIS 3D3V PIC Simulations
  - Reflected beam profiles
  - Incident beam a_0=15
  - Target density $60n_{crit}$



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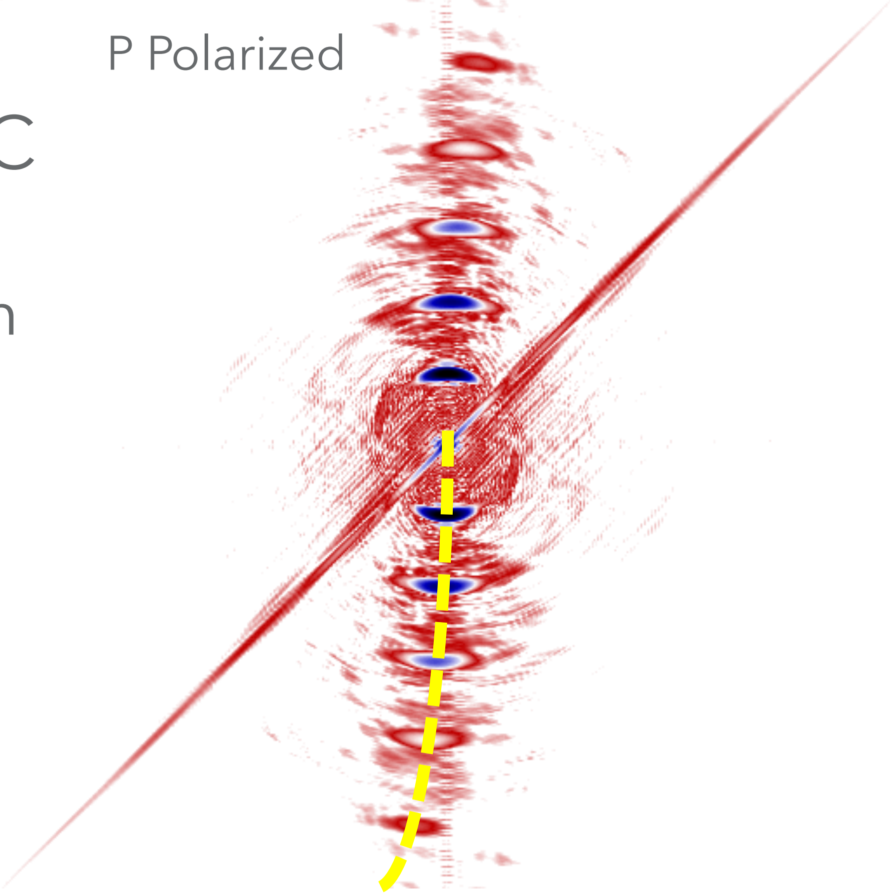
OSIRIS Simulation results

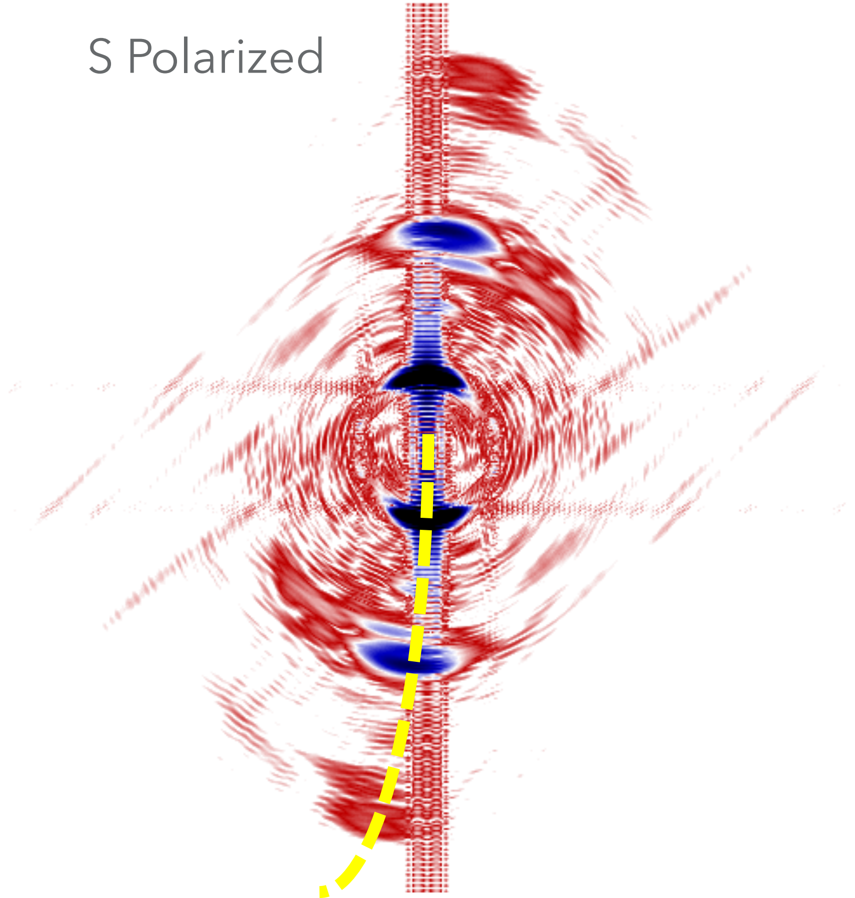
- OSIRIS 3D3V PIC Simulations
  - Reflected beam profiles
  - Incident beam a_0=1
  - Target density 500n_{crit}

P Polarized



Fourier transform of
Electric field x-direction

S Polarized



Fourier transform of
Electric field z-direction

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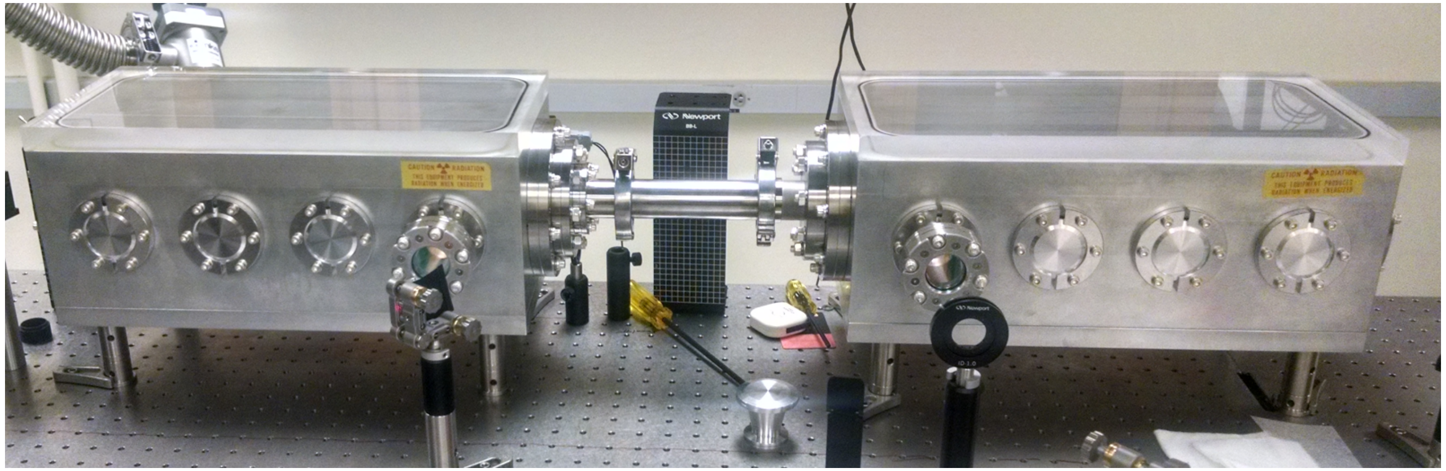
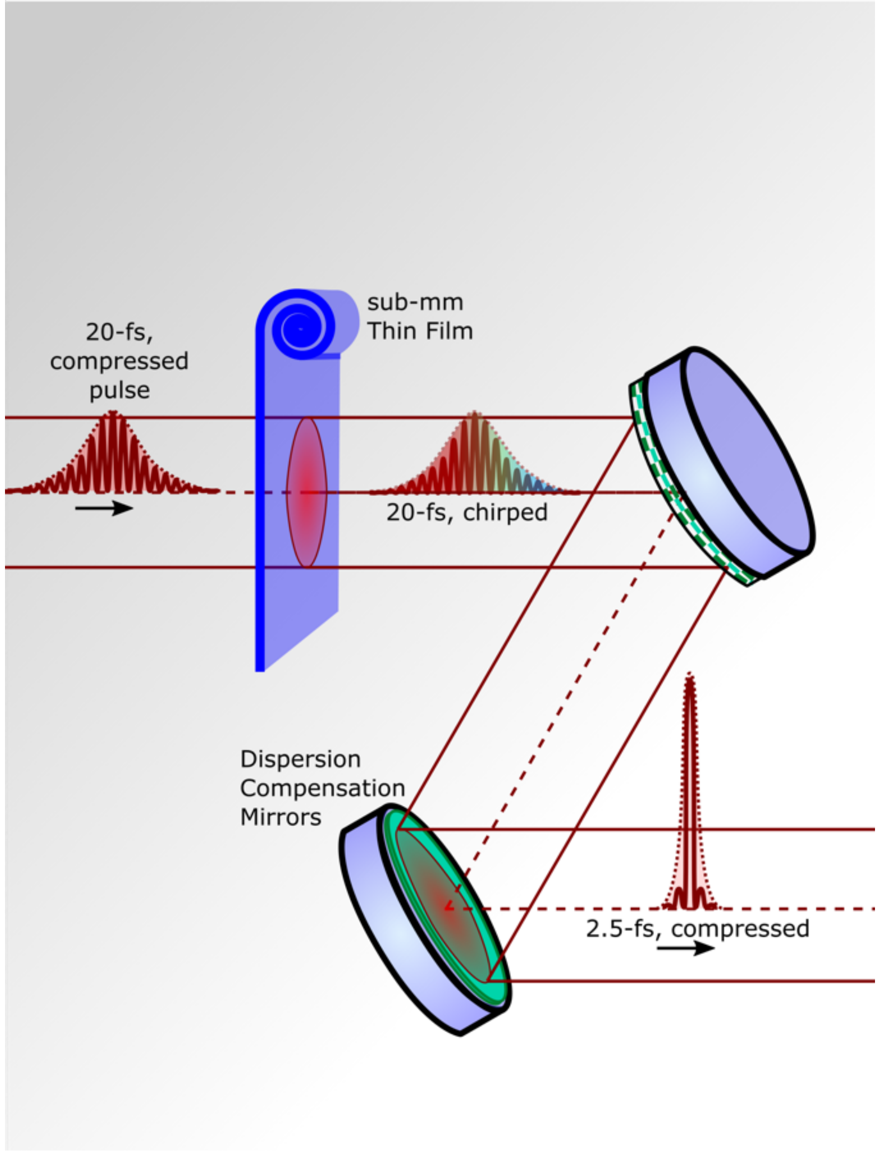
Thin film compression





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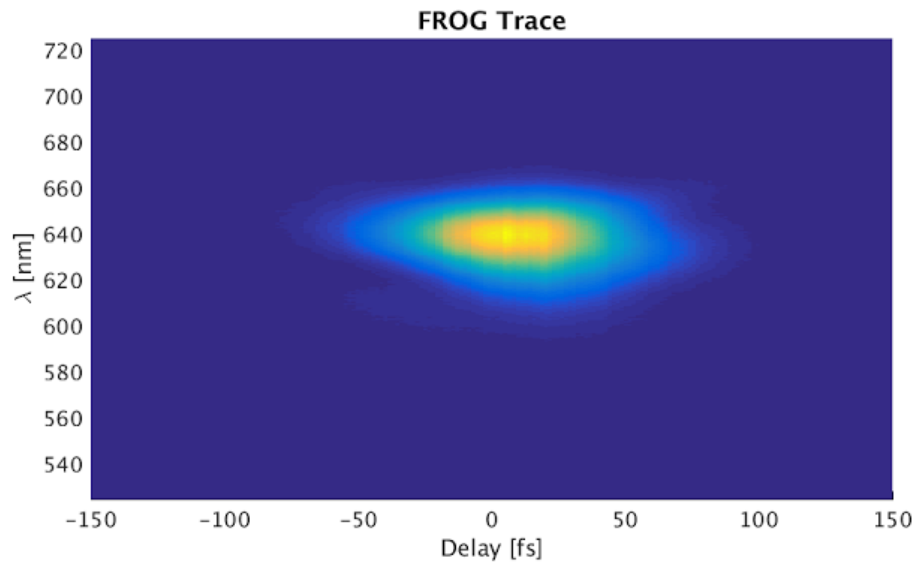
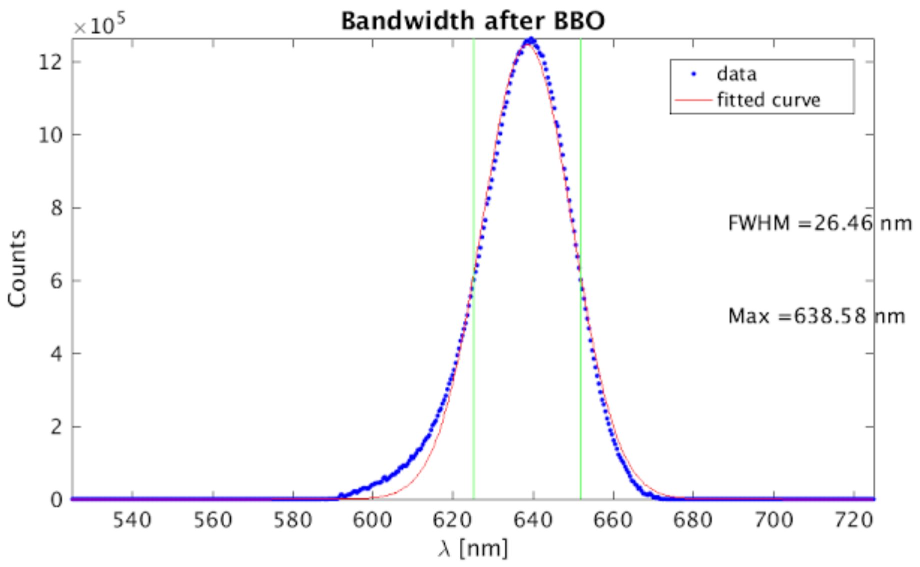
G. Mourou, et.al., European Physical Journal-Special Topics, 223(6): p. 1181-1188 (2014).

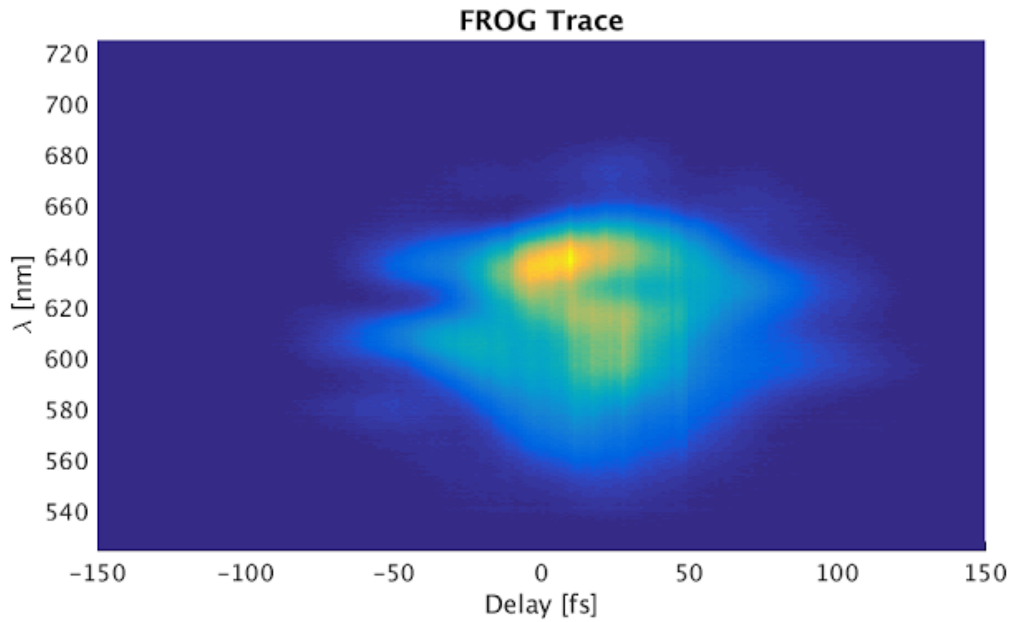
FROG trace



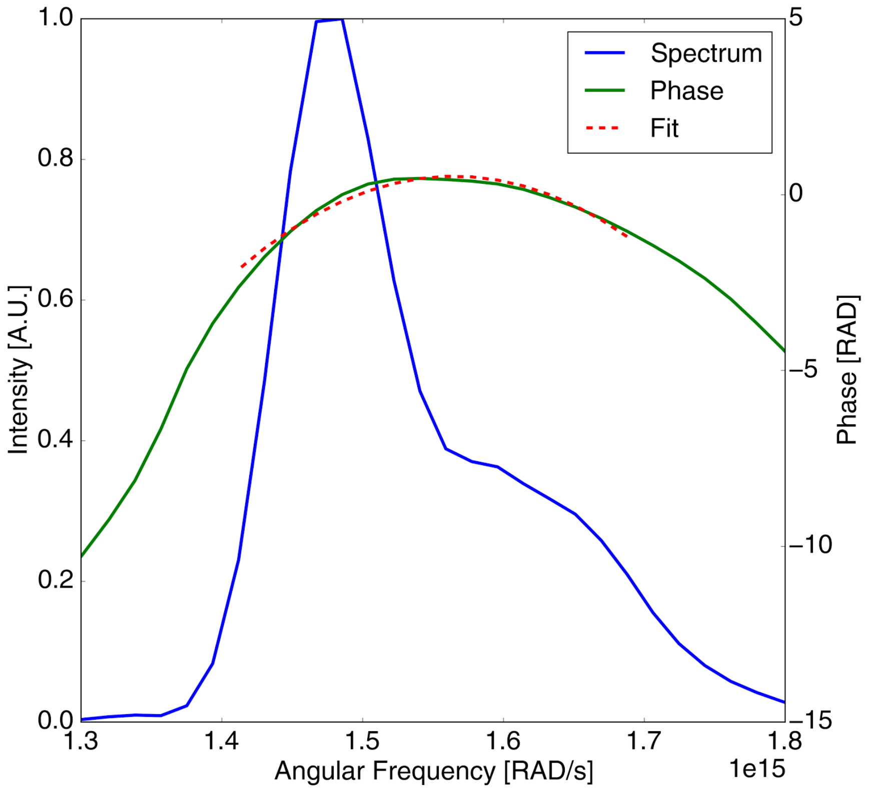


"standard" uncompressed beam

Compression at 1260



Reconstructed phase



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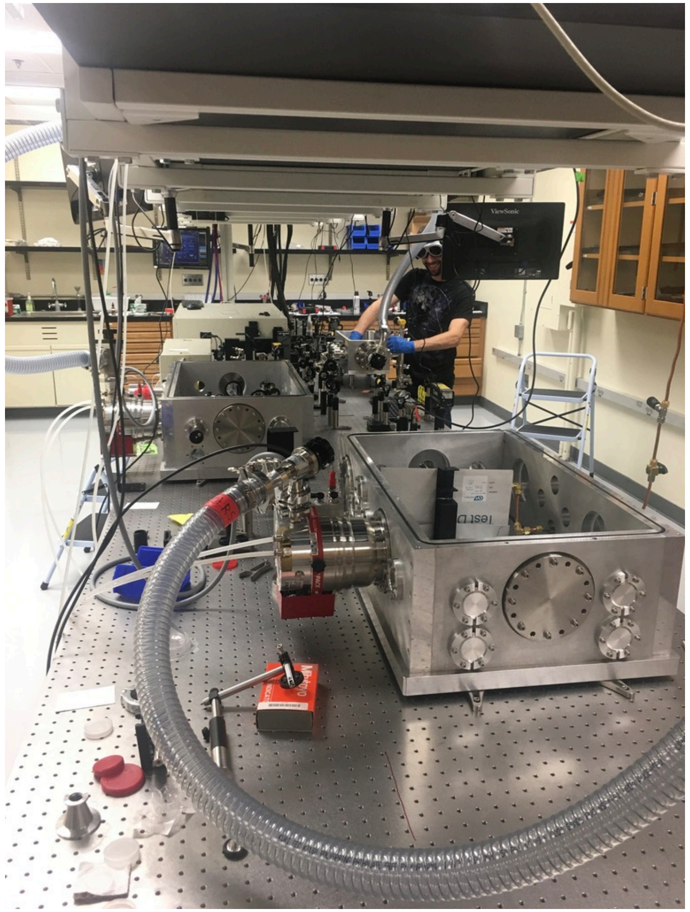
Conclusions

- Laser driven, coherent X-ray probes offer a large number of opportunities
  - Supercontinuum for dynamic XAFS
  - High flux narrow lines for Thomson scattering
  - Circular polarization for dichrosim
- High field harmonics offer additional advantages
  - Higher energy cutoffs and scalings
  - Information about laser solid interactions
- Ion motion increasingly complicates absorption



Acknowledgements

Thank you to Paul and Casi and to you for listening!

UCI
Tam Nguyen
Deano Farinella
Sahel Hakima
Hunter Allison
Matt Stanfield
Nick Beier
Cheyenne Nelson
Edgar Ibarra
Toshi Tajima

UCI University of California, Irvine

UCI School of Physical Sciences

Alfred P. Sloan FOUNDATION

Michigan group
(Karl Krushelnick &
Alec Thomas)

JILA group
(Margaret Murnane &
Henry Kapteyn)

STROBE NSF SCIENCE AND TECHNOLOGY CENTER