X-ray Free-Electron Lasers

Agostino Marinelli
SLAC National Accelerator Laboratory
and Stanford University

University of Hawaii
12/5/2024

Acknowledgements

XLEAP/XLEAP-II Collaboration:

SLAC

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UCLA

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Attosecond Campaign

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U.S. DEPARTMENT OF ENERGY | Office of Science | Basic Energy Sciences

Attosecond Core Group at LCLS

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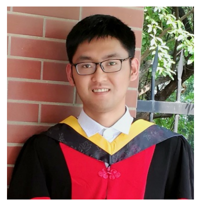
J. Cryan

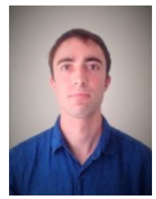
SLAC

PULSE

Stanford University

Current Team Members


Z. Zhang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N. Sudar


V. Guo

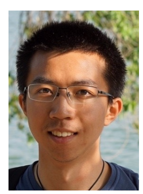

P. Franz


R. Robles


K. Larsen


E. Thierstein


T. Driver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Alumni


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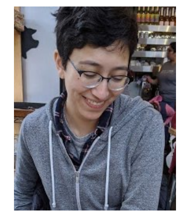
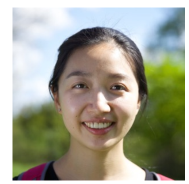
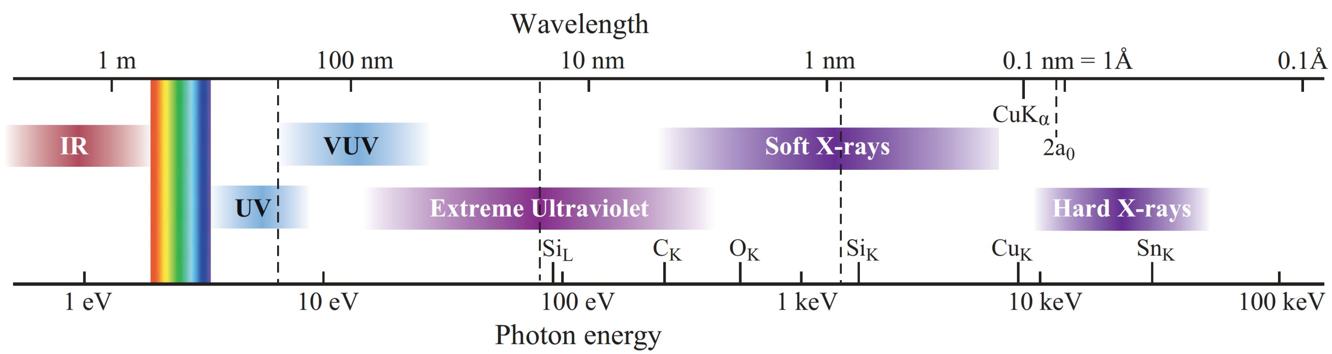

A. Wang


J. O'Neal

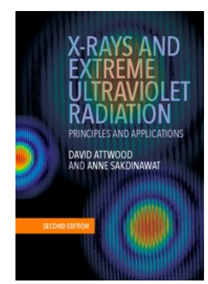

Siqi Li


J. Duris

X-Rays



D. Attwood, A. Sakdinawat



X-ray Vision


AS SUPERMAN CONCENTRATES HIS X-RAY VISION PIERCES THRU THE ROOM'S WALLS . .
50

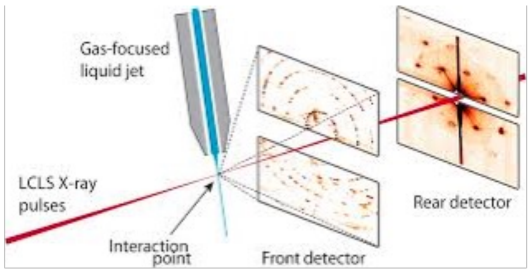

SUPERBOY!
Adventure COMICS
FEB. NO. 173
10¢
SUPERMAN DC NATIONAL COMICS
HOW DID THE BOY of STEEL LEARN TO CONTROL HIS POWERS? Read "SUPERBOY'S SCHOOL OF HARD KNOCKS!"
SUPERBOY! YOUR X-RAY VISION GAVE ME THE COMBINATION I FORGOT-- BUT IT'S BURNING UP MY MONEY!
BUT--BUT HOW DO I TURN IT OFF, DAD?

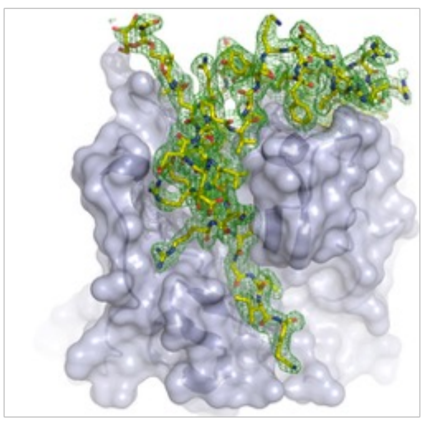

SUPERMAN DC NATIONAL COMICS
10¢
WORLD'S FINEST COMICS
FEB. NO. 115
APPROVED BY THE COMICS CODE AUTHORITY
"The CURSE THAT DOOMED SUPERMAN!"
SUPERMAN'S GONE HAYWIRE! HE'S FOCUSING HIS X-RAY VISION ON THE WATER--AND CHURNING IT UP INTO STEAM!
YES, BATMAN, HE MUST BE IN THE GRIP OF THE SWAMI!

What is a Good Use of X-Rays?

X-Ray Diffraction Imaging

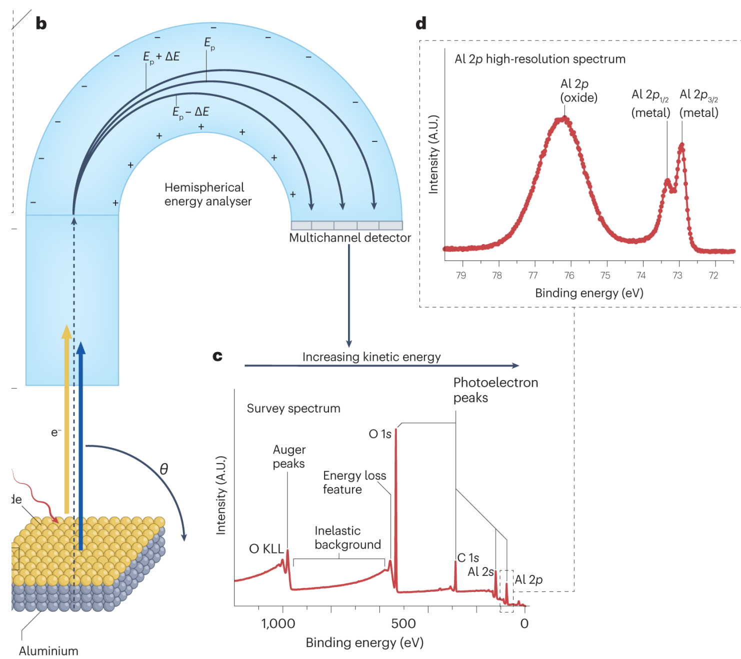
Resolution ~ Angstrom





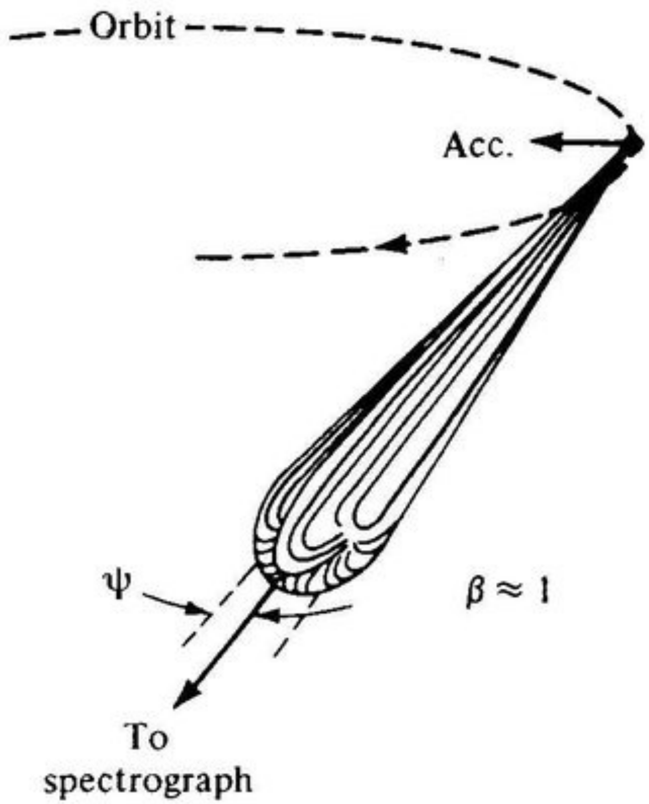
21 February 2013, SPIE Newsroom. DOI: 10.1117/2.1201302.004713

X-Ray Spectroscopy



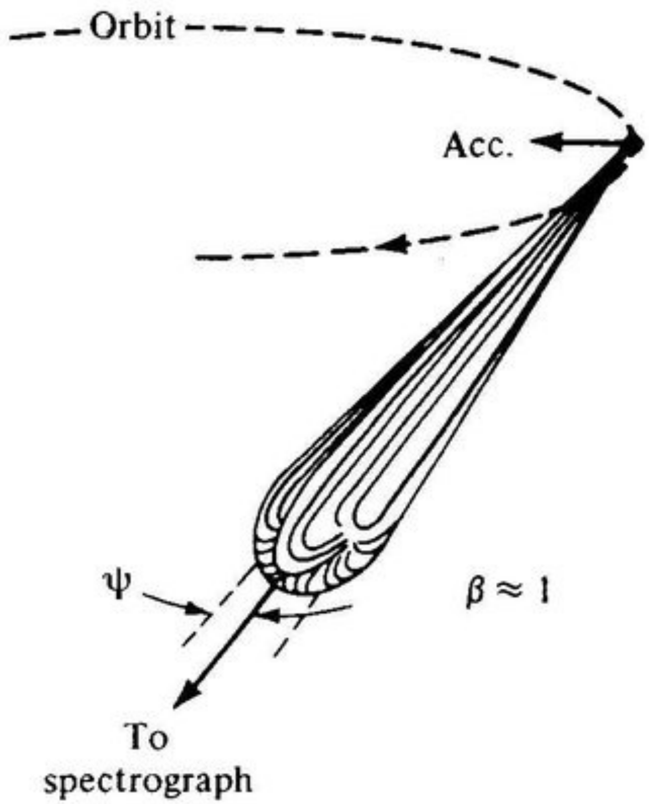
Nat Rev Methods Primers **3**, 40 (2023)

Why Relativistic Electrons?



$$\omega_r \propto \gamma^2$$

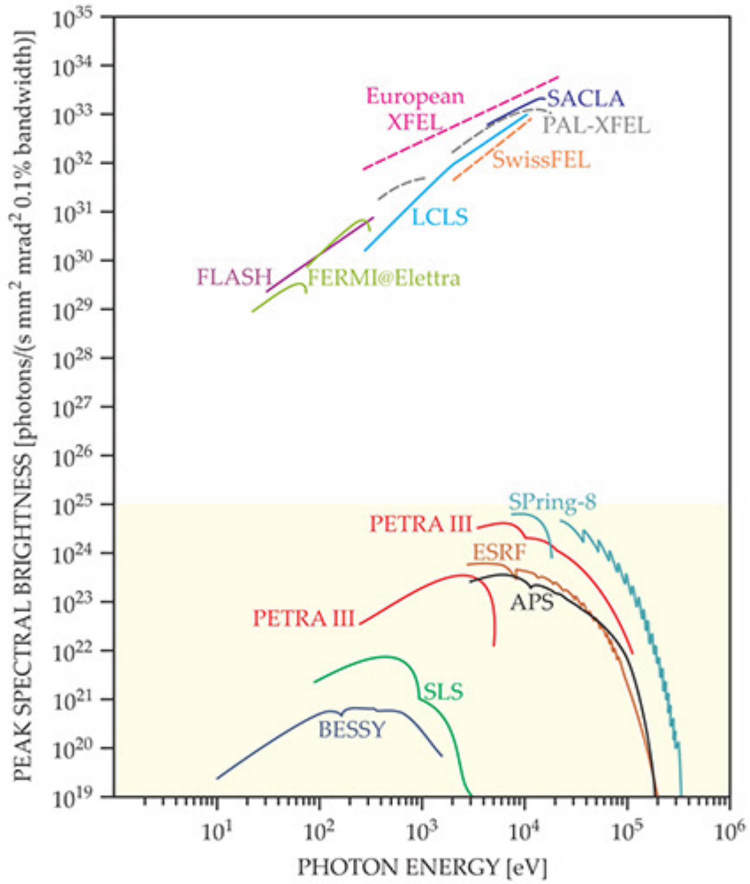
Why Relativistic Electrons?



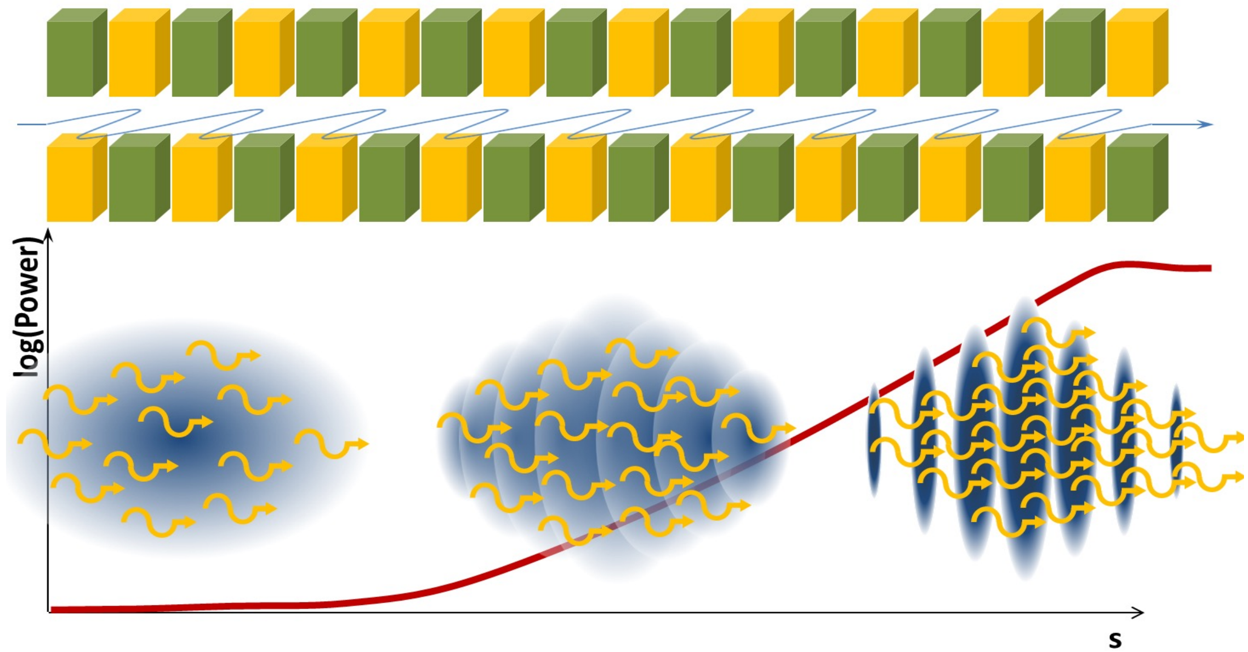
$$\omega_r \propto \gamma^2$$

$$\frac{dU}{dt} \propto \gamma^2$$

X-ray Free-Electron Lasers



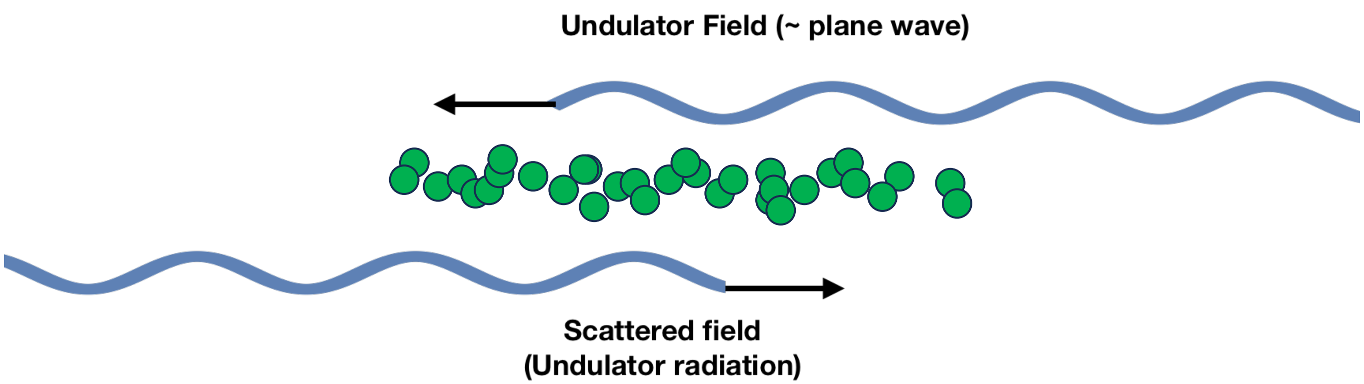
Free-Electron Laser

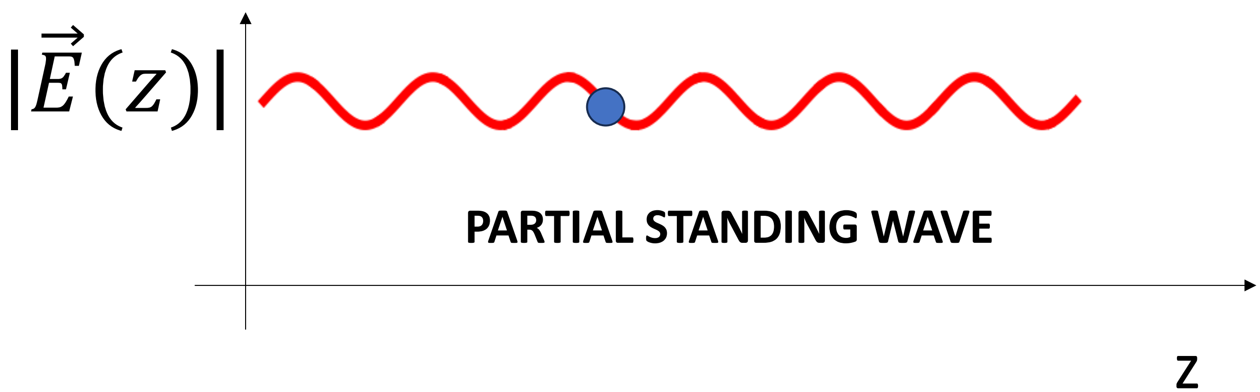


$$\lambda_r = \lambda_u(\frac{1}{\beta_z} - 1)$$

Source: https://www.helmholtz-berlin.de

FEL IN THE REST FRAME

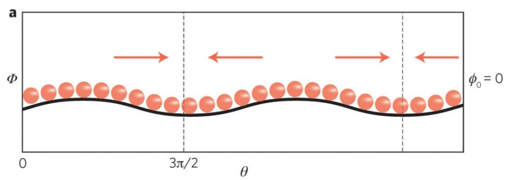




The Ponderomotive Force

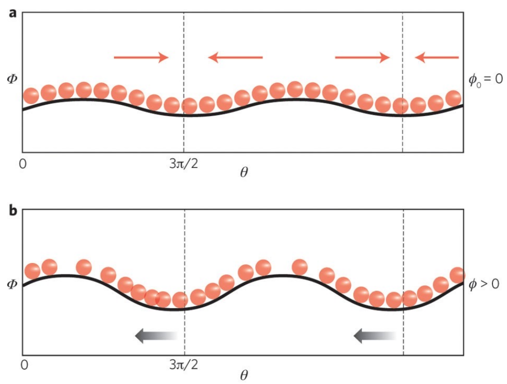
https://www.youtube.com/watch?v=XTJznUkAmIY&list=PPSV
Harvard Natural Sciences Lecture Demonstrations

Why?



McNeil, Thompson *Nature Photon* **4**, 814–821 (2010).

Why?



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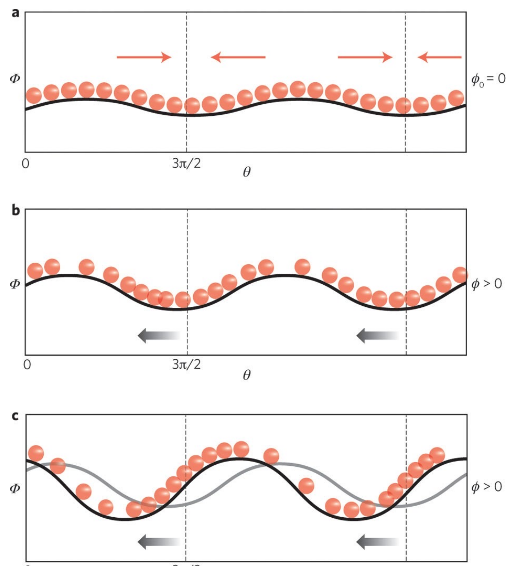
Why?



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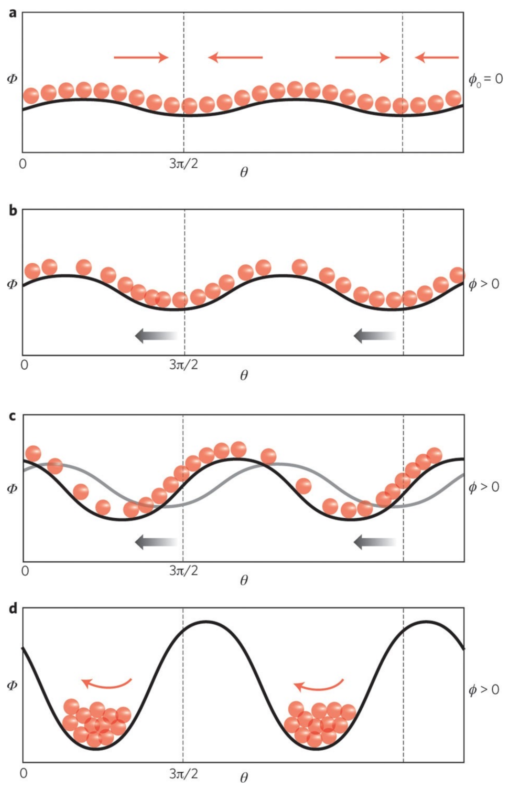

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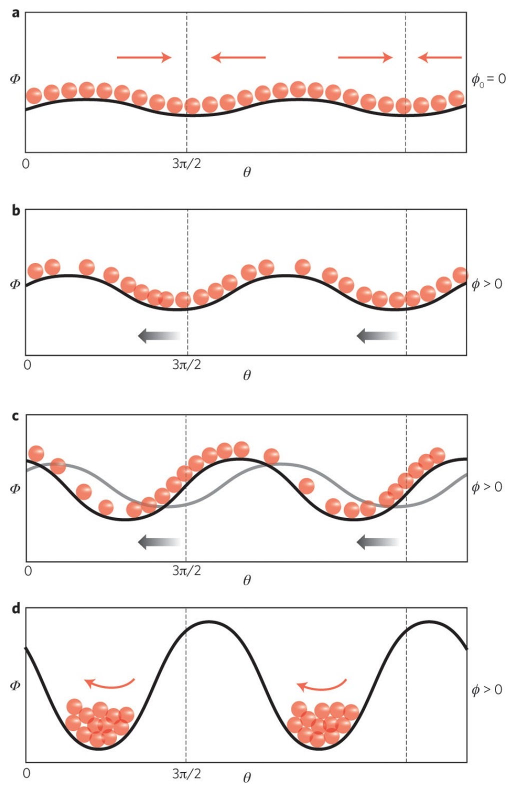

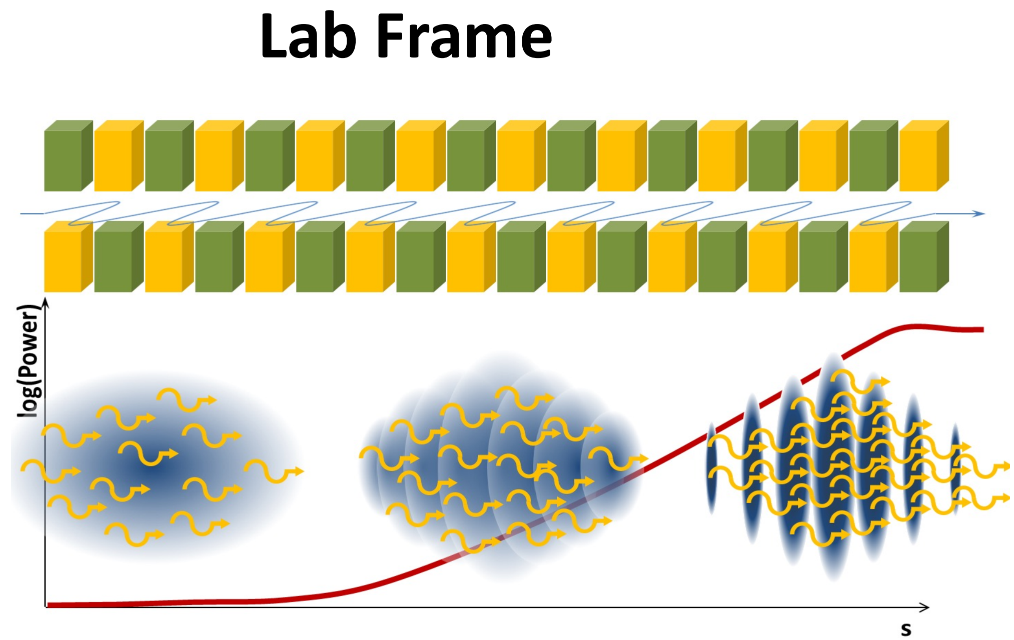

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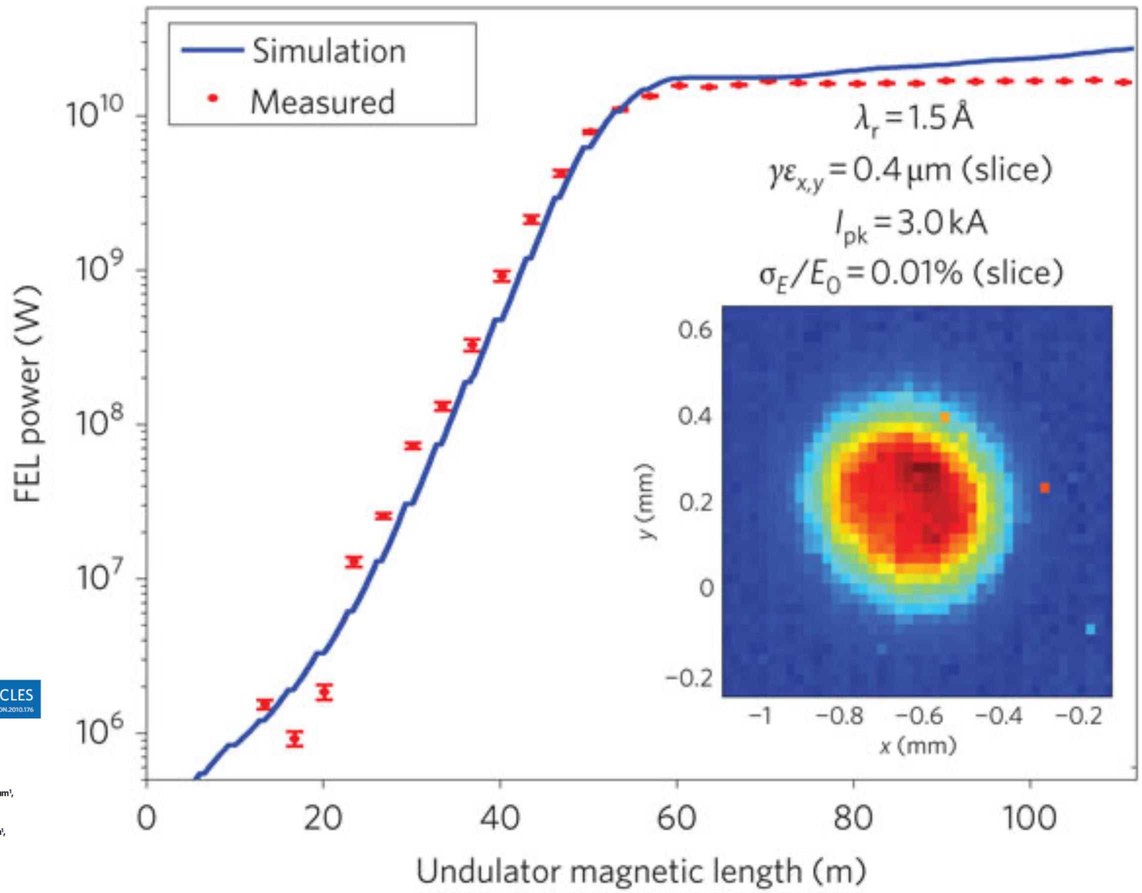
The X-ray Free-Electron Laser

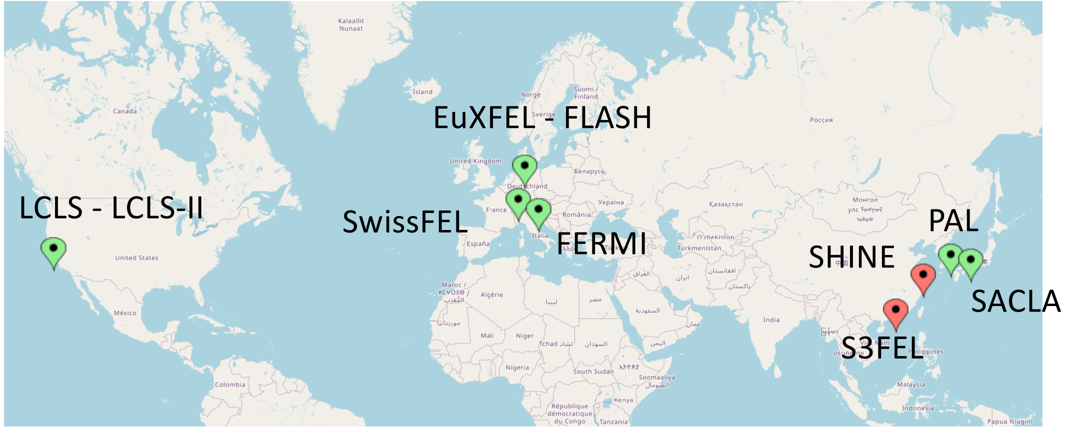


nature photonics ARTICLES
PUBLISHED ONLINE: 1 AUGUST 2010 | DOI: 10.1038/NPHOTON.2010.176

First lasing and operation of an ångstrom-wavelength free-electron laser

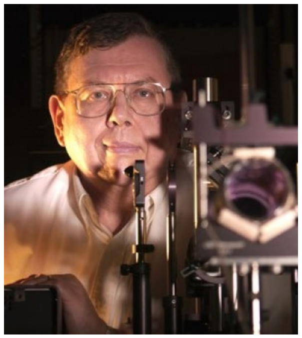
P. Emma[1*], R. Akre[1], J. Arthur[1], R. Bionta[2], C. Bostedt[1], J. Bozek[1], A. Brachmann[1], P. Bucksbaum[1], R. Coffee[1], F.-J. Decker[1], Y. Ding[1], D. Dowell[1], S. Edstrom[1], A. Fisher[1], J. Frisch[1], S. Gilevich[1], J. Hastings[1], G. Hays[1], Ph. Hering[1], Z. Huang[1], R. Iverson[1], H. Loos[1], M. Messerschmidt[1], A. Miahnahri[1], S. Moeller[1], H.-D. Nuhn[1], G. Pile[3], D. Ratner[1], J. Rzepiela[1], D. Schultz[1], T. Smith[1], P. Stefan[1], H. Tompkins[1], J. Turner[1], J. Welch[1], W. White[1], J. Wu[1], G. Yocky[1] and J. Galayda[1]

X-ray Free-Electron Lasers



First proposal: Pellegrini, C. A 4 to 0.1nm FEL based on the SLAC linac. Proc. of the Workshop on 4th Generation Light Sources (1992)

A Little Bit of History



Invention of FEL
Madey, John MJ. "Stimulated emission of bremsstrahlung in a periodic magnetic field." *Journal of Applied Physics* 42.5 (**1971**): 1906-1913.

FEL Instability:
Saldin (1980)
Bonifacio and Pellegrini (1984)

First proposal of an XFEL: Pellegrini, C. A 4 to 0.1nm FEL based on the SLAC linac. Proc. of the Workshop on 4th Generation Light Sources (1992)

10 um
1998 UCLA

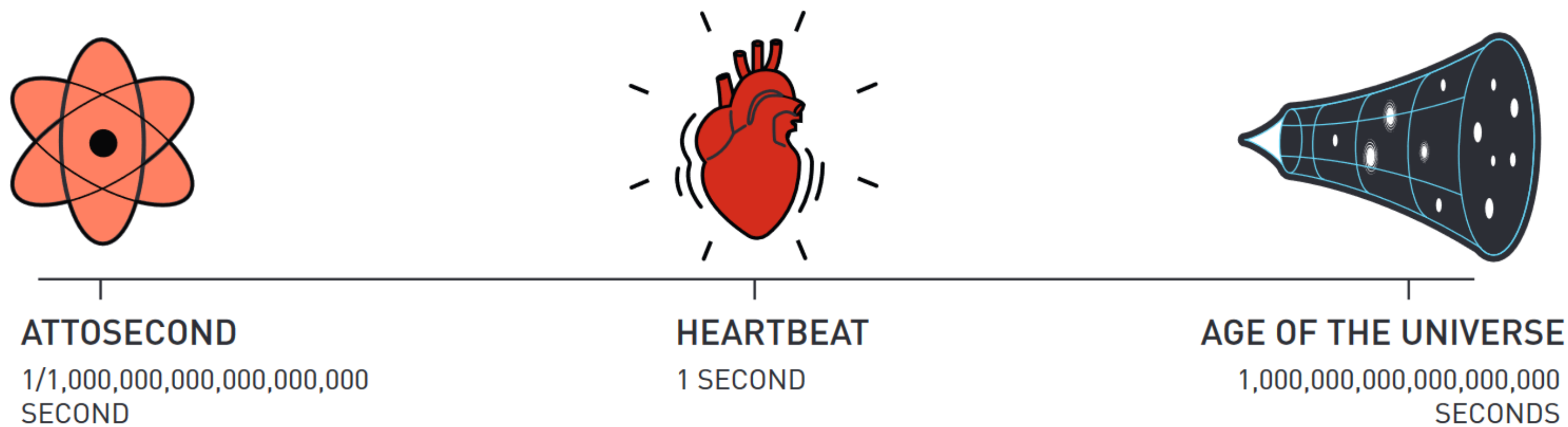
385 nm
2001 Argonne

13.7 nm
2007 DESY

0.15 nm
2010 SLAC

10 um | **1 um** | **100 nm** | **10 nm** | **1 nm fs** | **0.1 nm**

Attosecond Science



Electrons' movements in atoms and molecules are so rapid that they are measured in attoseconds. An attosecond is to one second as one second is to the age of the universe.

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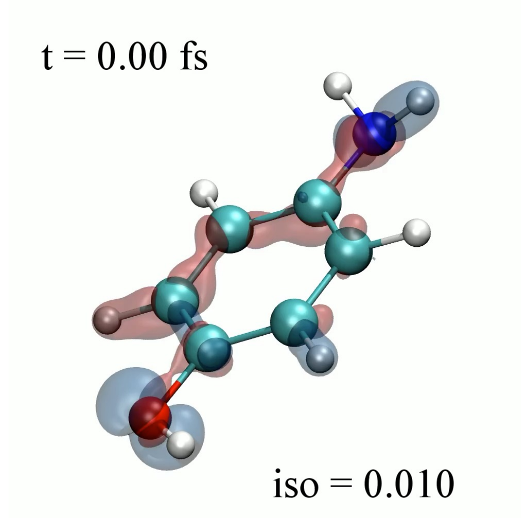
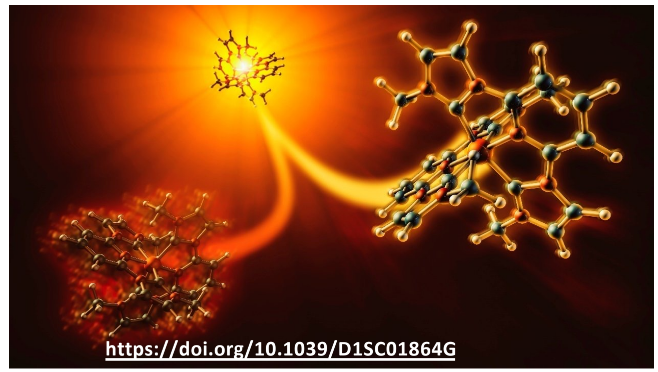
Attosecond Electron Dynamics

Attosecond science =
Study of electron dynamics



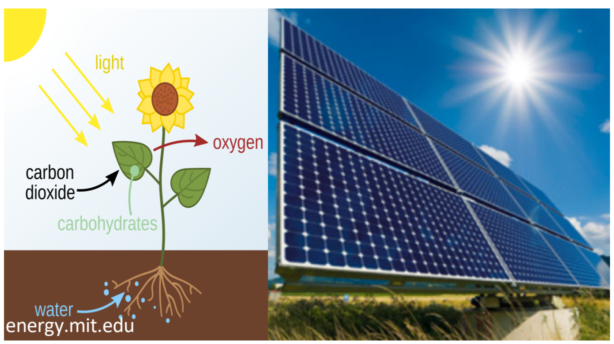
Attosecond Electron Dynamics

First step in chemistry

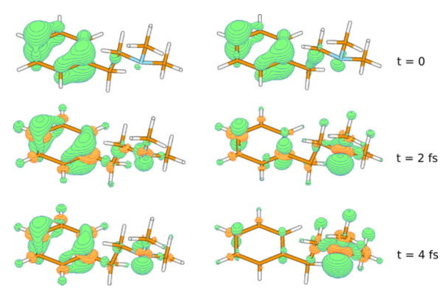


Attosecond science =
Study of electron dynamics

Radiation-matter interaction



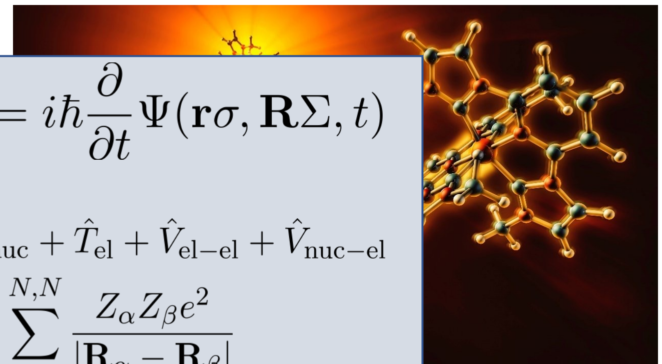
Multi-body quantum mechanics



J. Chem Phys. 8 129(10):104305 (2008)

Attosecond Electron Dynamics

First step in chemistry



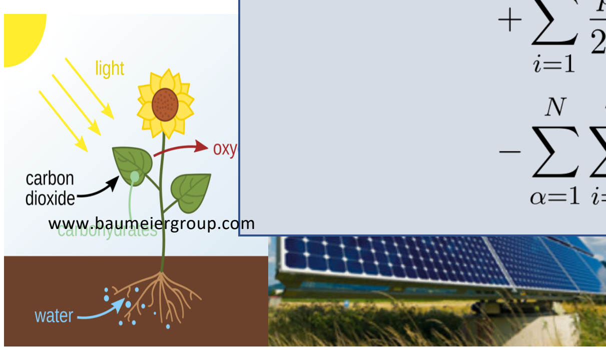
Attosec

Study of e

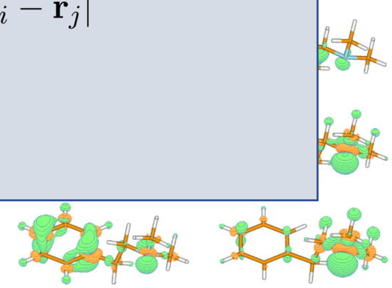
$$\hat{H}_{\mathrm{mol}}\Psi(\mathbf{r}\sigma,\mathbf{R}\Sigma,t) = i\hbar\frac{\partial}{\partial t}\Psi(\mathbf{r}\sigma,\mathbf{R}\Sigma,t)$$

$$\begin{aligned}
\hat{H}_{\mathrm{mol}} &= \hat{T}_{\mathrm{nuc}} + \hat{V}_{\mathrm{nuc-nuc}} + \hat{T}_{\mathrm{el}} + \hat{V}_{\mathrm{el-el}} + \hat{V}_{\mathrm{nuc-el}} \\
&= \sum_{\alpha=1}^{N}\frac{\hat{P}_\alpha^2}{2M_\alpha} + \frac{1}{2}\sum_{\alpha,\beta}^{N,N}\frac{Z_\alpha Z_\beta e^2}{|\mathbf{R}_\alpha - \mathbf{R}_\beta|} \\
&\quad + \sum_{i=1}^{n}\frac{\hat{p}_i^2}{2m} + \frac{1}{2}\sum_{i,j}^{n,n}\frac{e^2}{|\mathbf{r}_i - \mathbf{r}_j|} \\
&\quad - \sum_{\alpha=1}^{N}\sum_{i=1}^{n}\frac{Z_\alpha e^2}{|\mathbf{r}_i - \mathbf{R}_\alpha|}
\end{aligned}$$

Radiation-



mechanics



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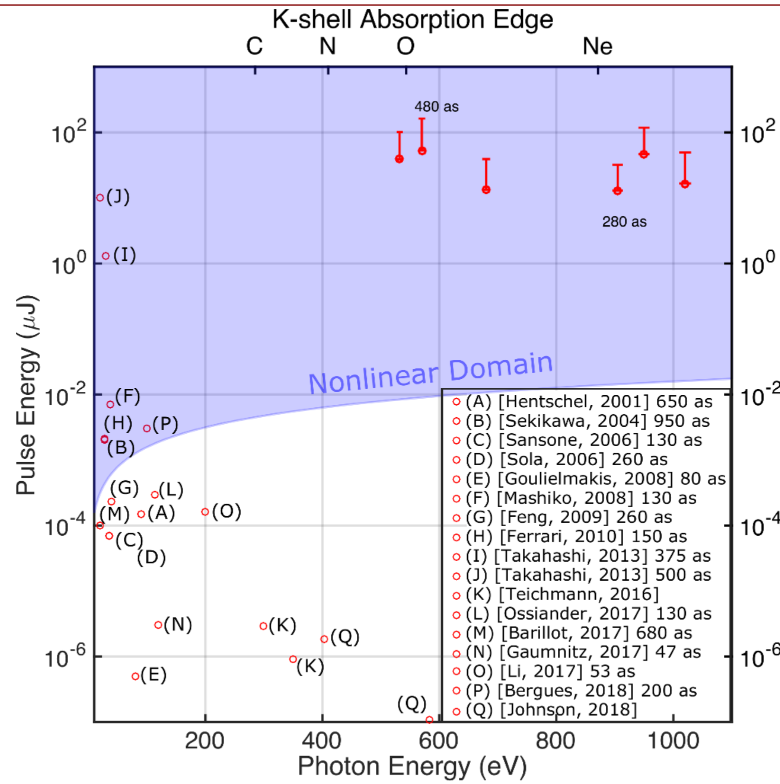
Why Attosecond X-ray FELs?



Advances In Atomic, Molecular, and Optical Physics 71, 1-64

J. Duris, S. Li et al. *Nature Photonics* 14.1 (2020): 30-36.

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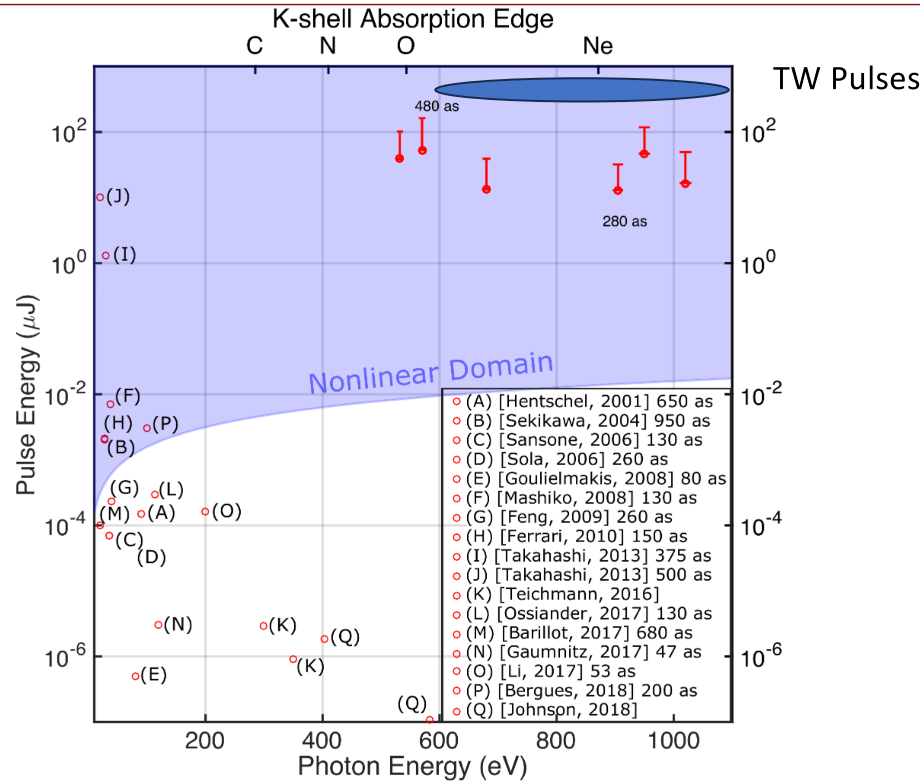

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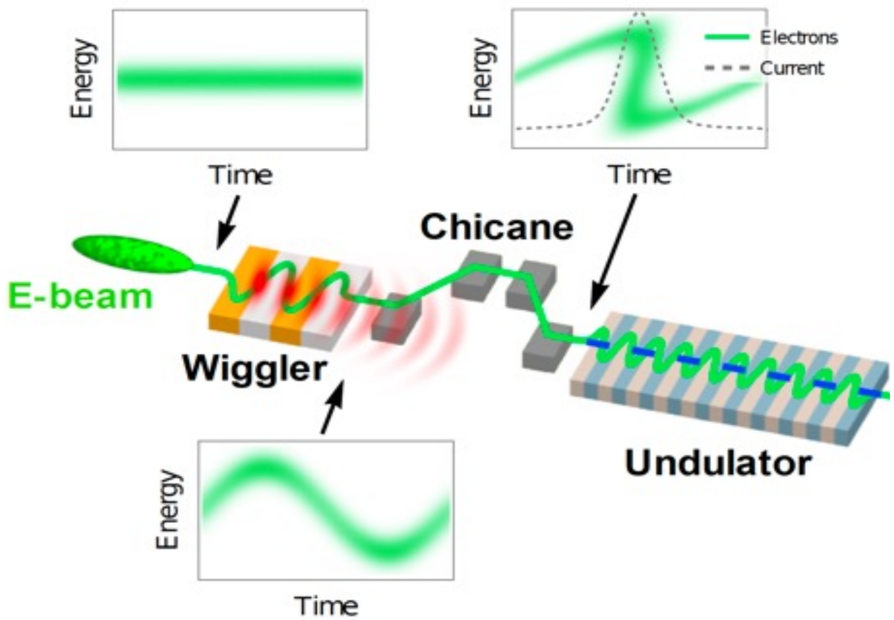
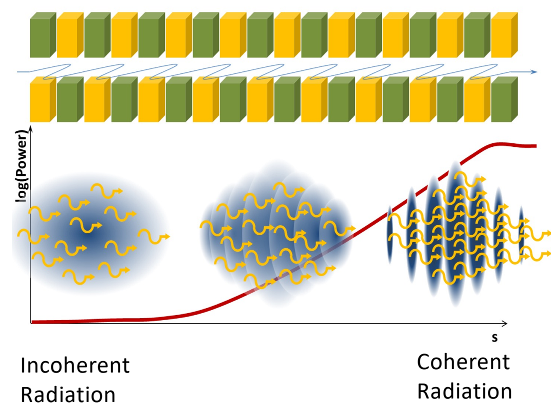
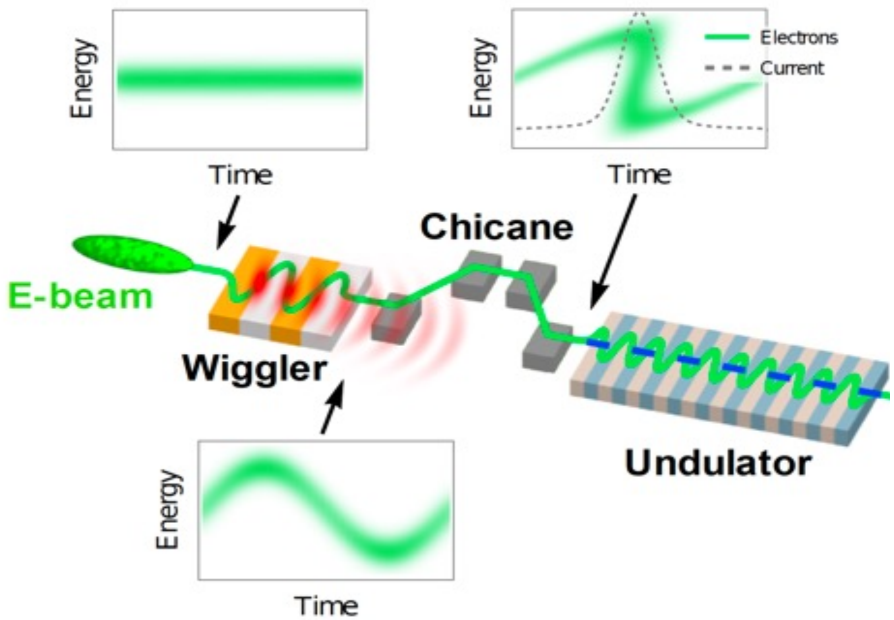
E-Beam Shaping





J. Duris, S. Li et al. *Nat. Photonics* 14.1 (2020): 30-36.
J. MacArthur., et al. Phys. Rev. Lett 123.21 (2019): 214801

E-Beam Shaping



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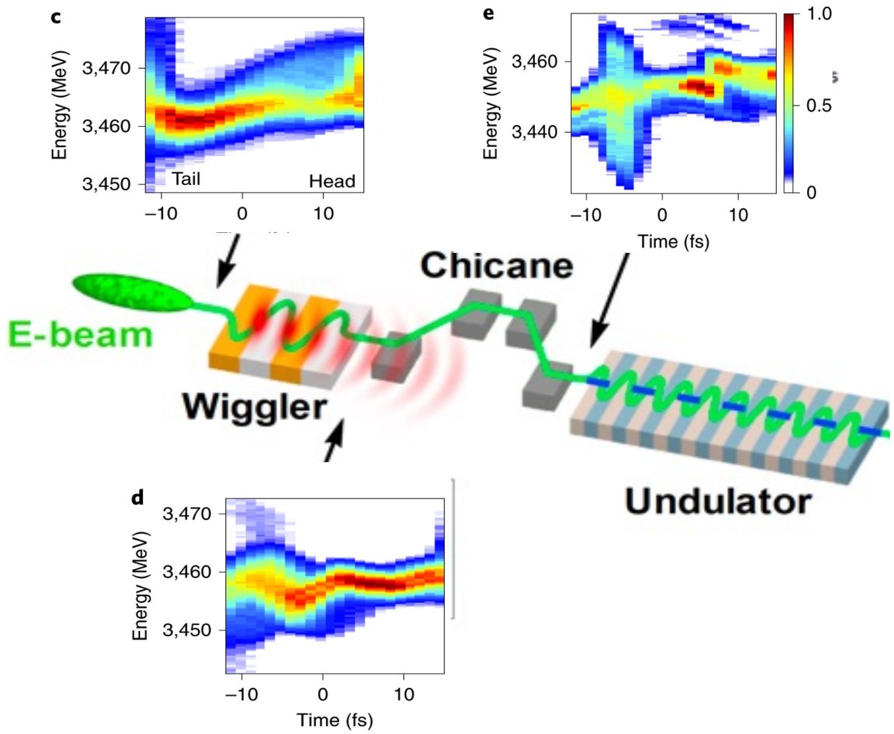

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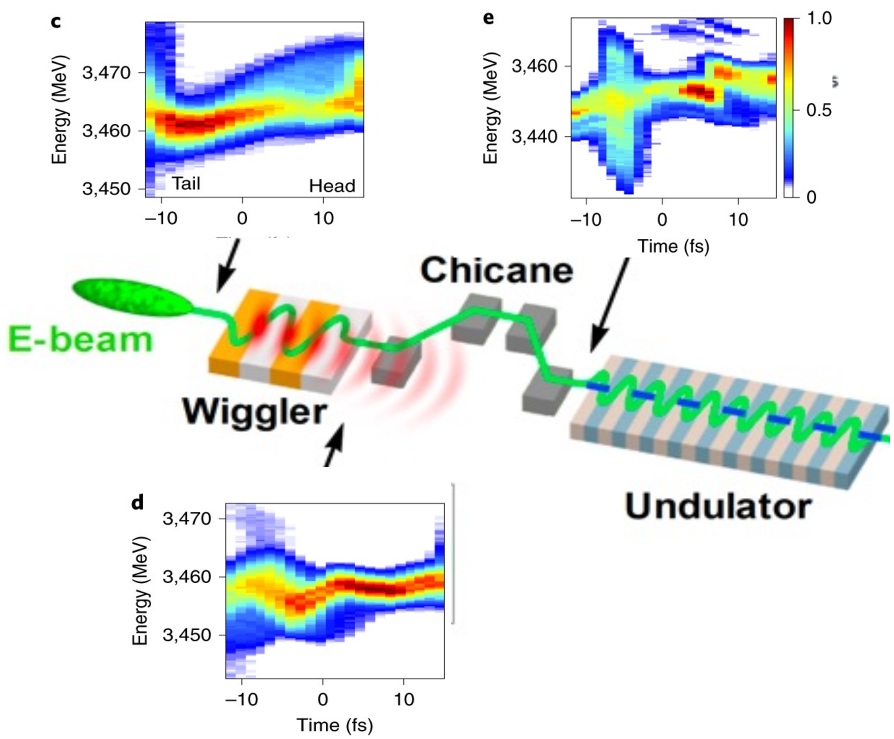

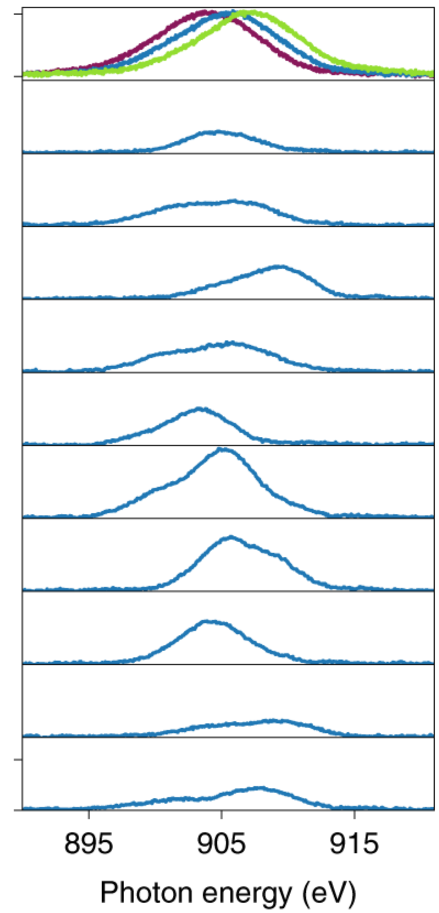

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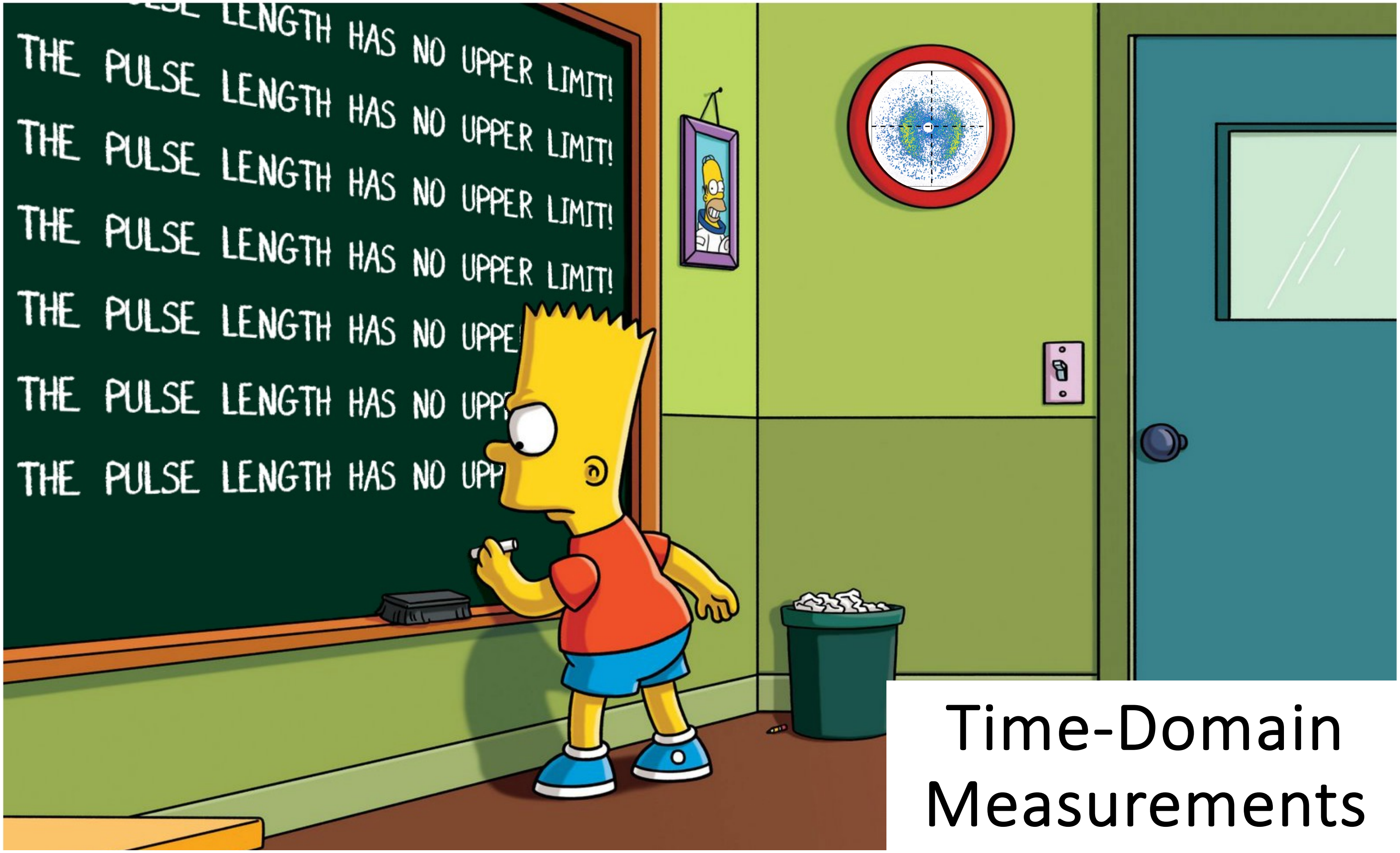
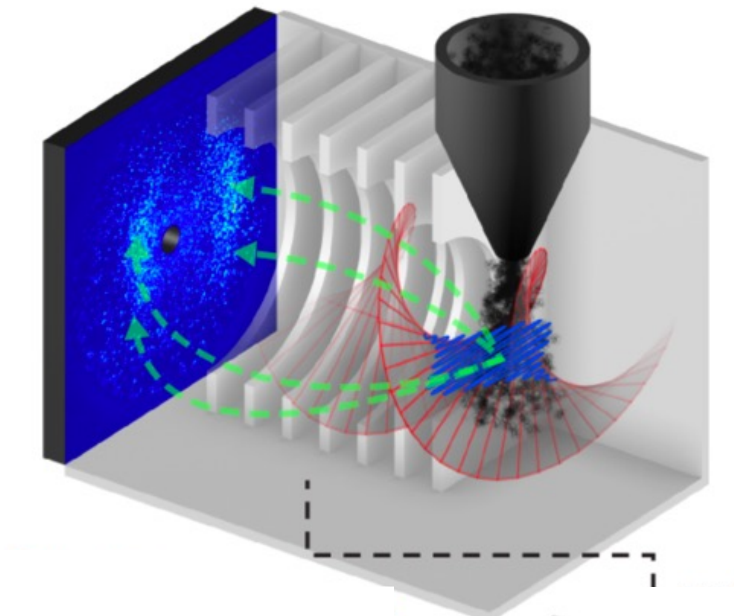
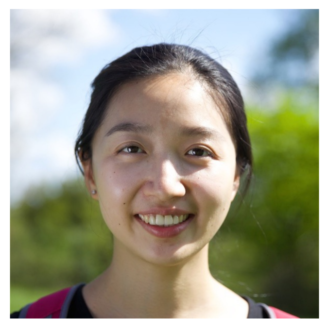


Time-Domain Measurements

Time-Domain Measurements

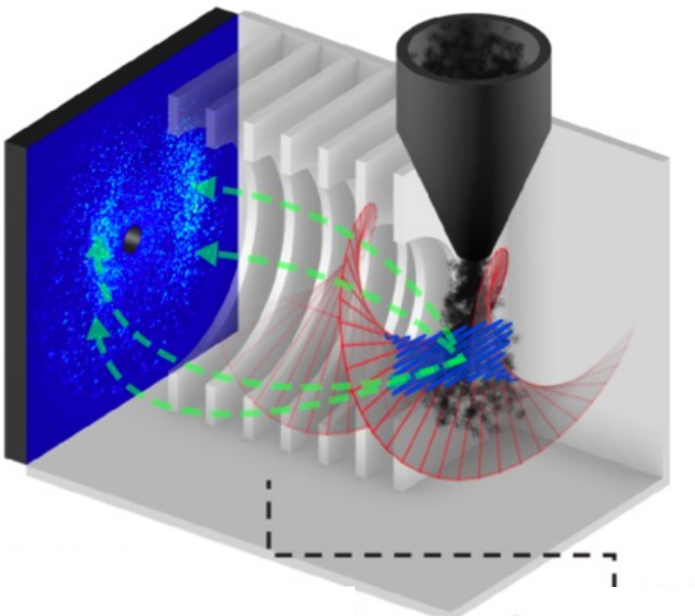


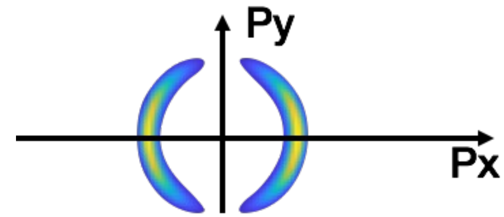
S. Li *et al.* Optics Express 26 4531 (2018)
S. Li *et al.* AIP Advances 8 115308 (2018)
J. Duris, **S. Li** et al. *Nat. Photonics* 14.1 (2020): 30-36.
S. Li *et al*. *Science* 375.6578 (2022): 285-290.



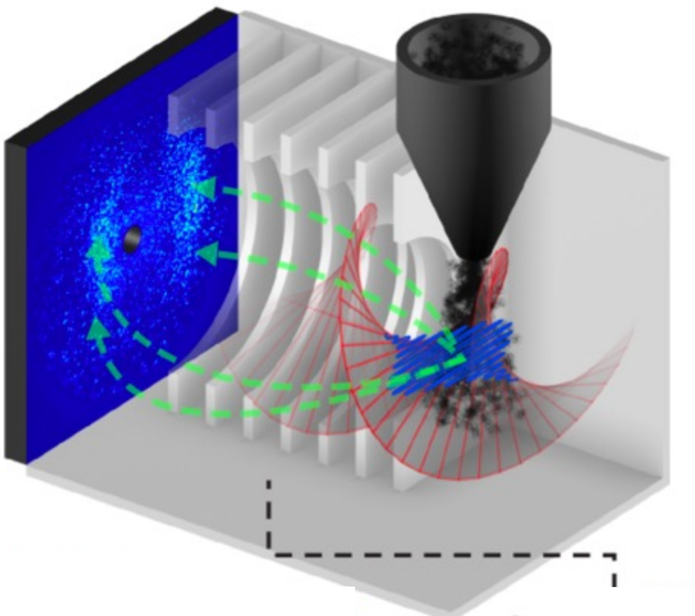
Siqi Li

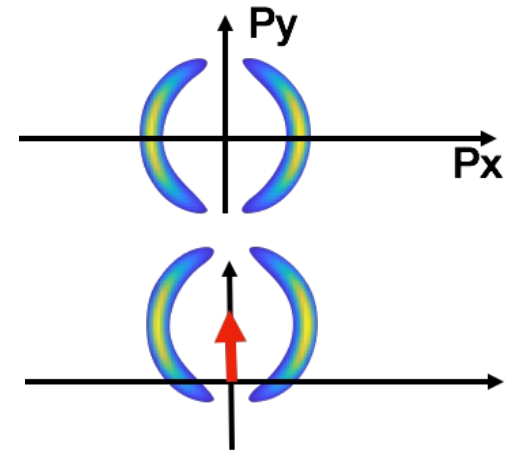
Time-Domain Measurements



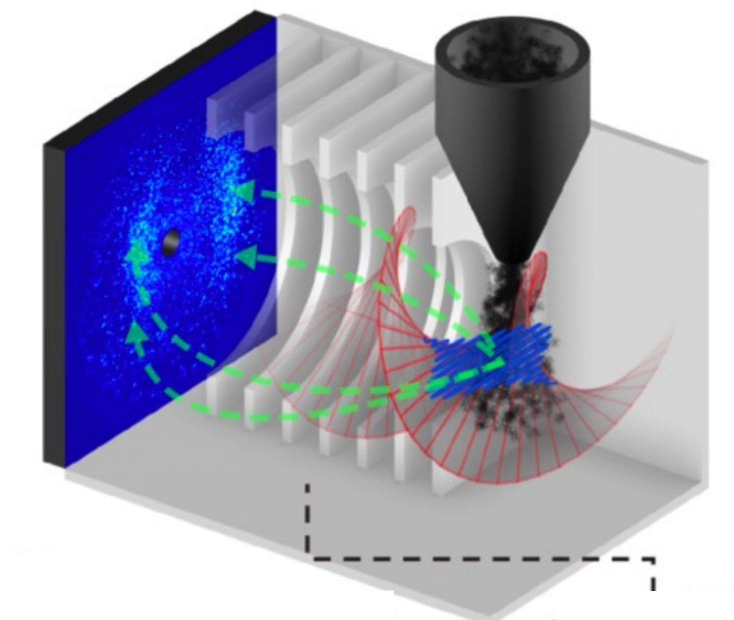


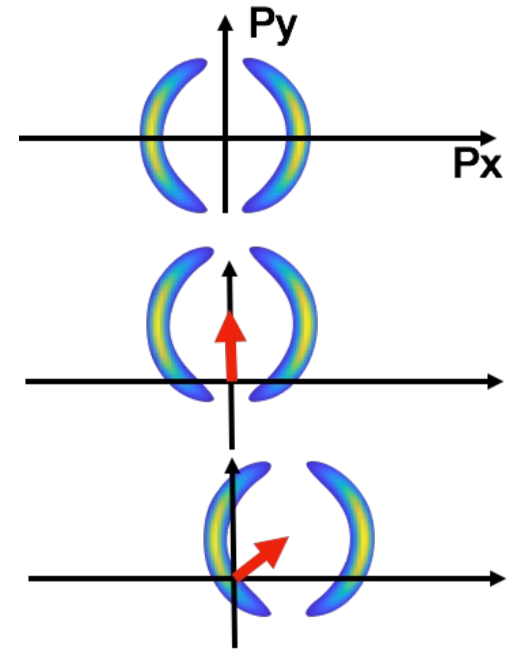
Time-Domain Measurements



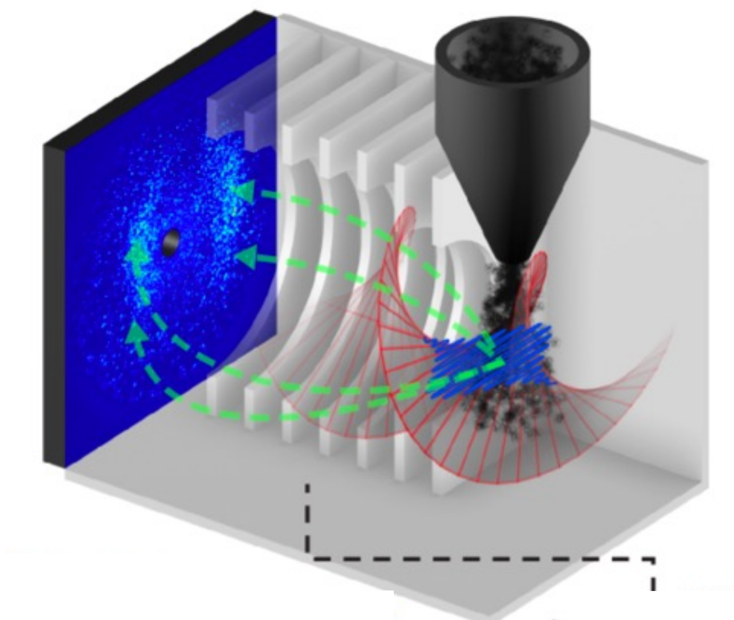


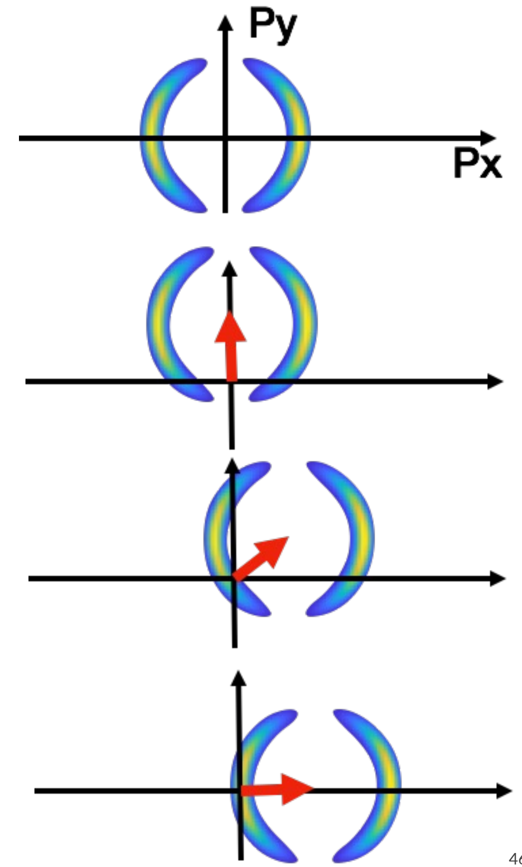
Time-Domain Measurements



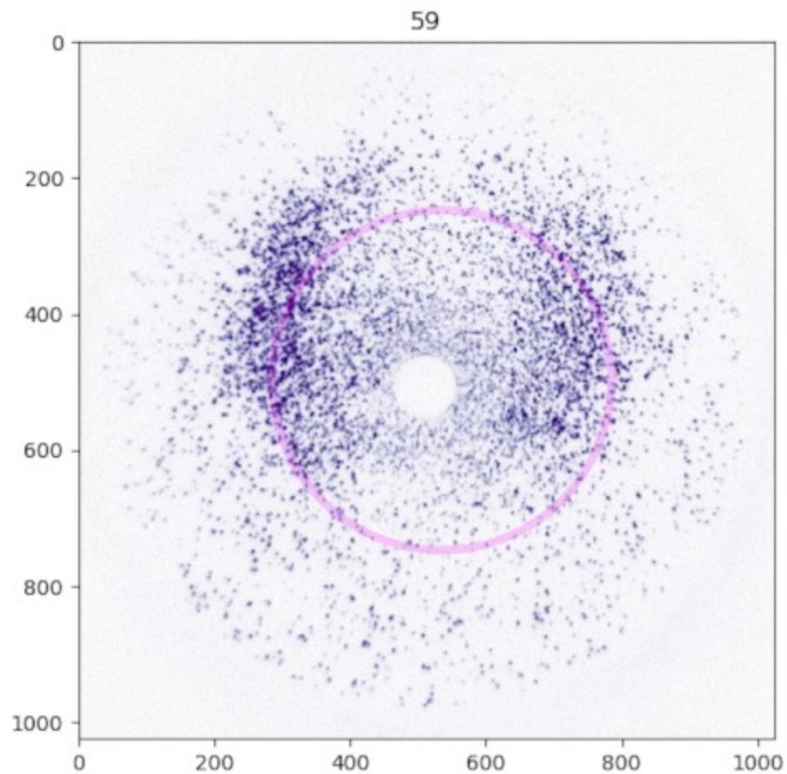


Time-Domain Measurements

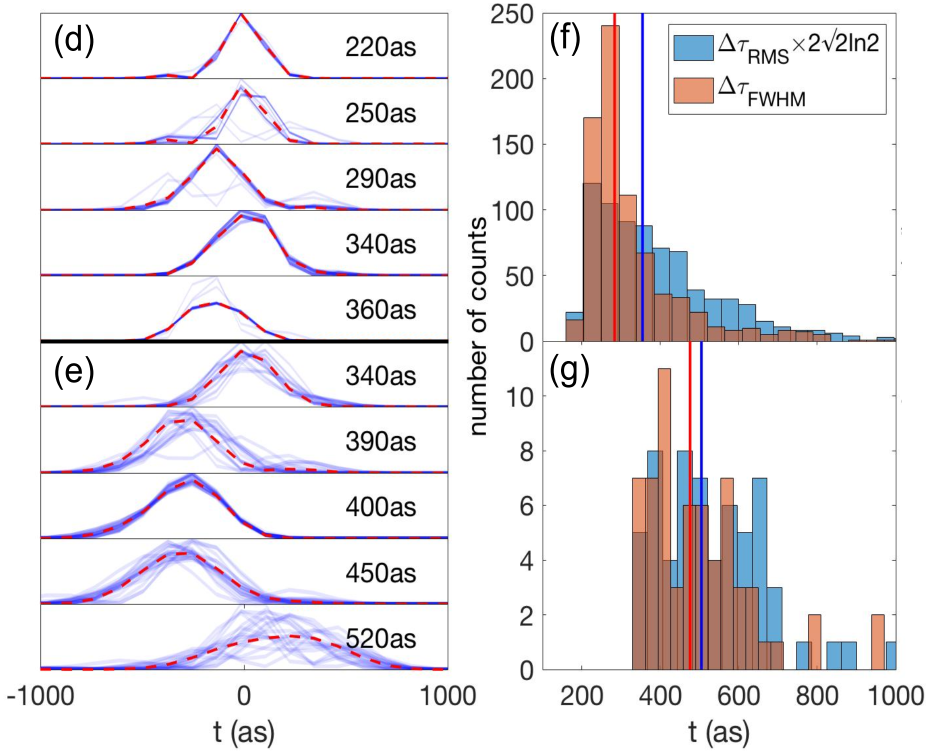




Time-Domain Measurements



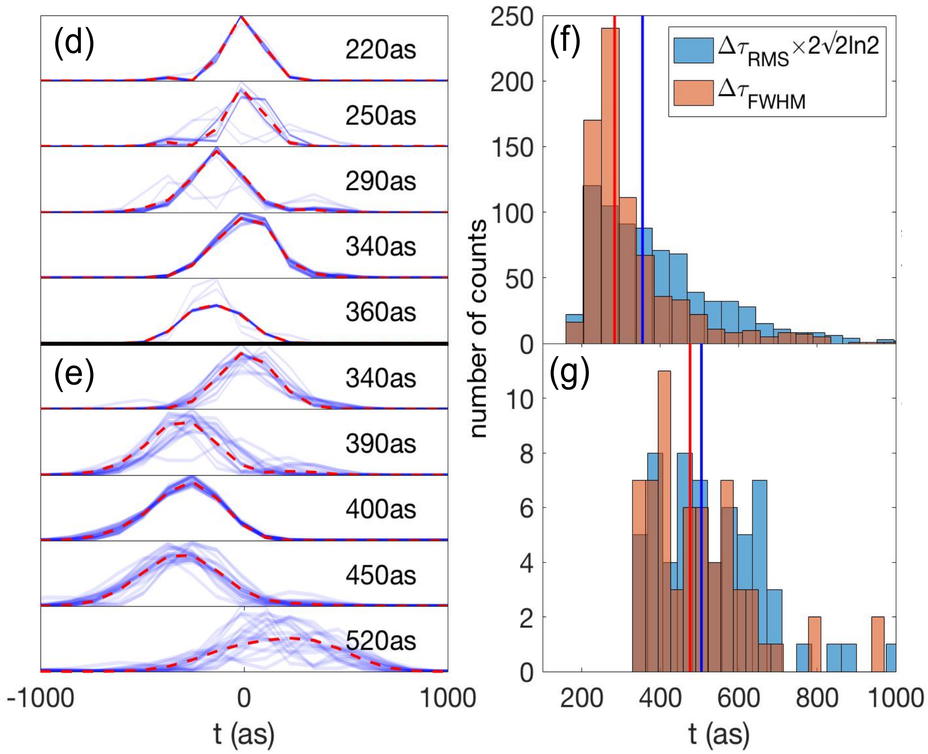
Results



J. Duris, S. Li et al. *Nature Photonics* 14.1 (2020): 30-36.

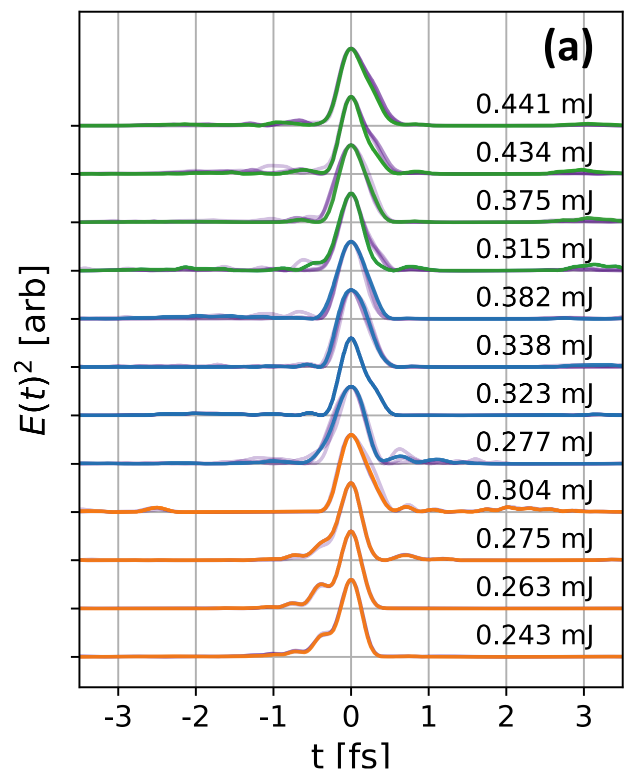
S. Li et al. Optics Express Vol. 26, [Issue 4](), pp. 4531-4547 (2018)

Results



J. Duris, S. Li et al. *Nature Photonics* 14.1 (2020): 30-36.

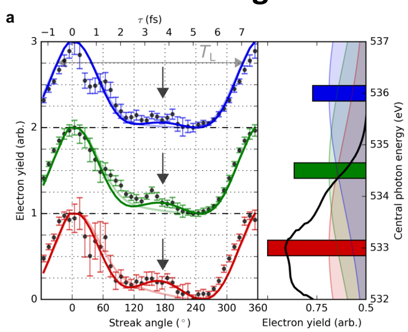
S. Li et al. Optics Express Vol. 26, [Issue 4](), pp. 4531-4547 (2018)



P. Franz et al. *Nat. Photon.* (2024): 1-6

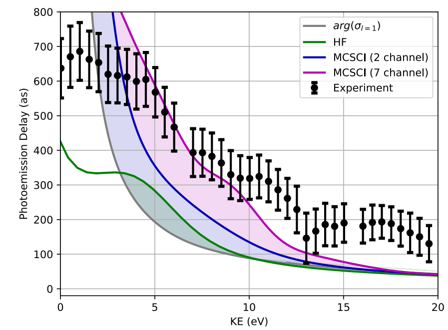
Attosecond Science at LCLS

Electronic Coherence in Auger-Meitner Decay



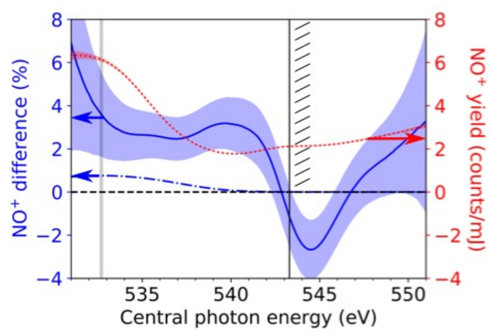
S. Li, T. Driver et al. *Science* 375.6578 (2022): 285-290.

Photoemission delays



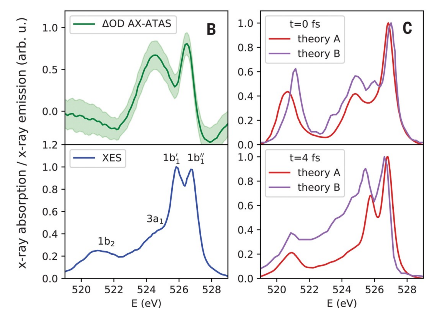
T. Driver et al. Nature 632 (8026), 762-767

Non-linear methods



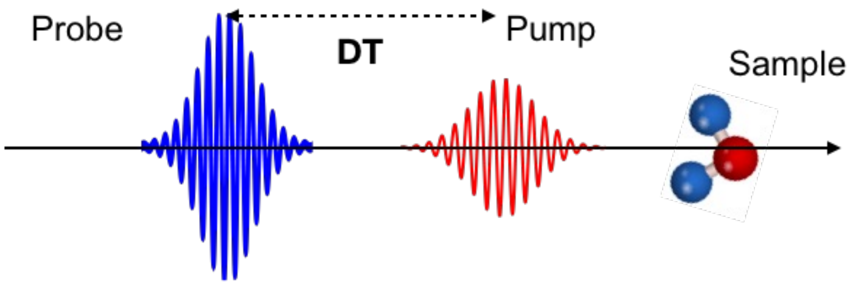
J. O'Neal *Physical review letters* 125.7 (2020): 073203

Pump/Probe Experiments

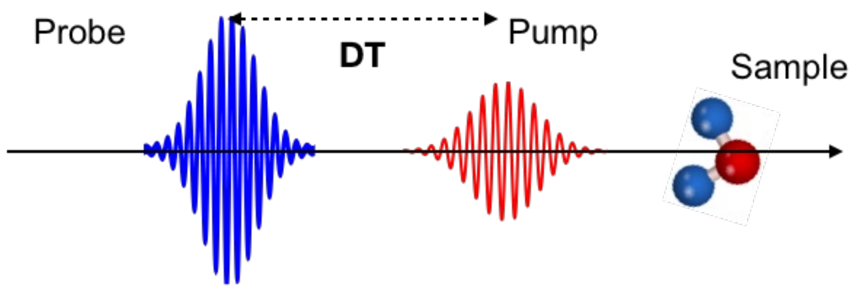


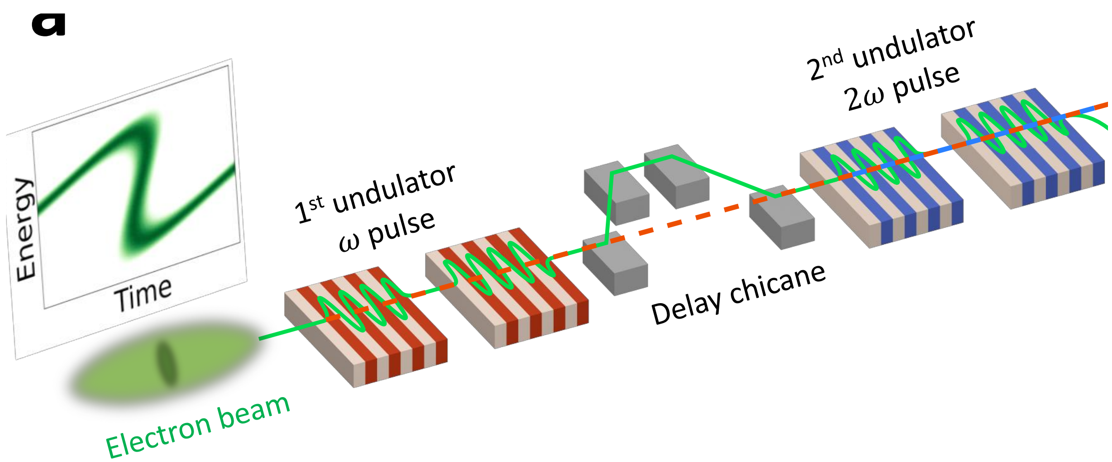
Li, Shuai, et al. *Science* (2024): eadn6059.

Attosecond Pump/Probe Setup

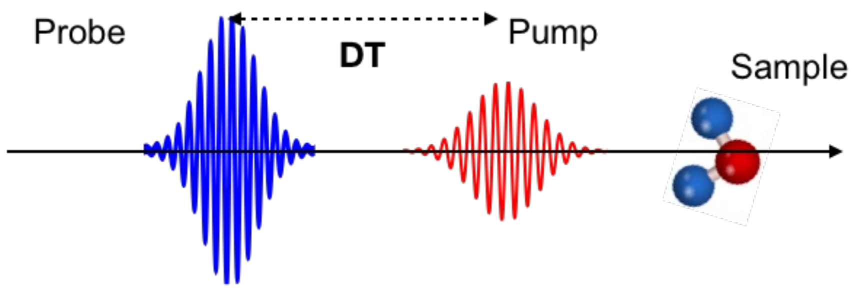


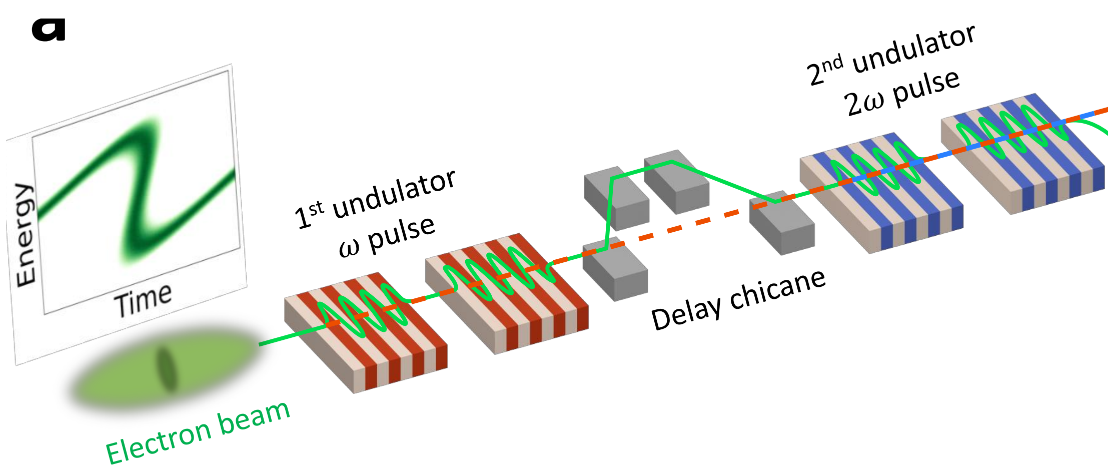
Attosecond Pump/Probe Setup



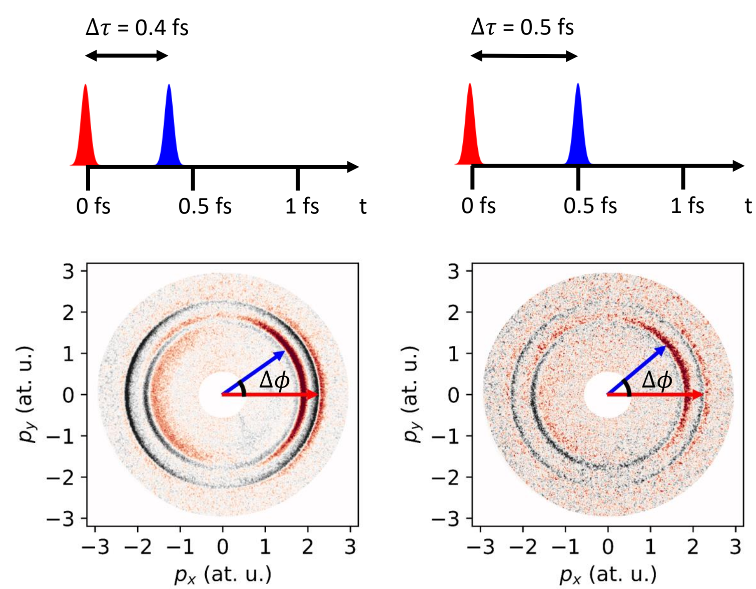


Attosecond Pump/Probe Setup

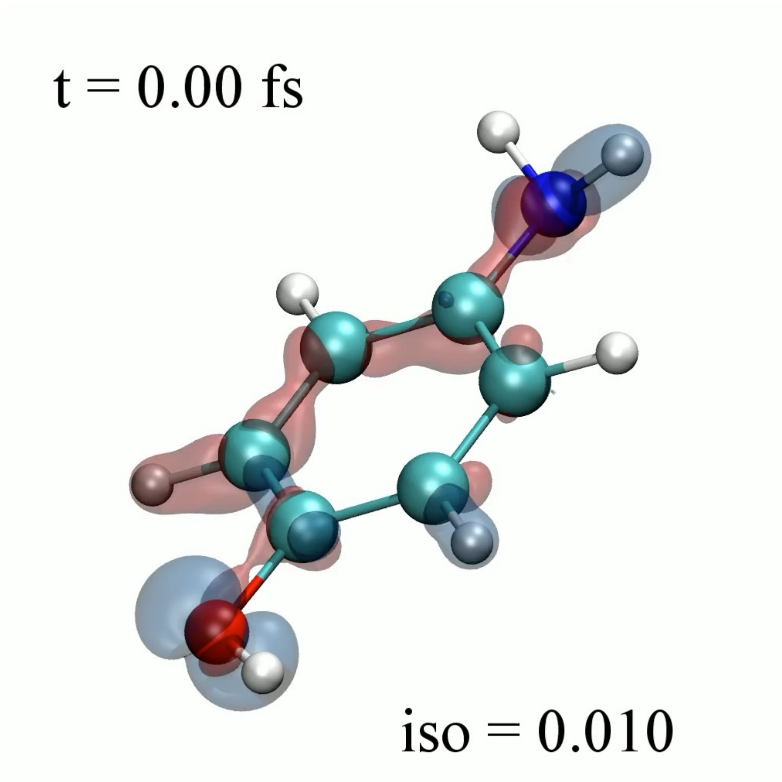




Z. Guo, et al. *Nature Photonics* (2024): 1-7.



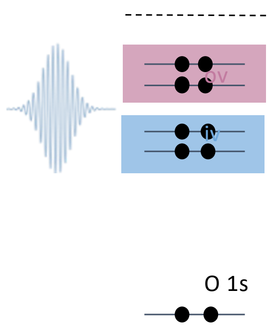
Pump/Probe Demonstration

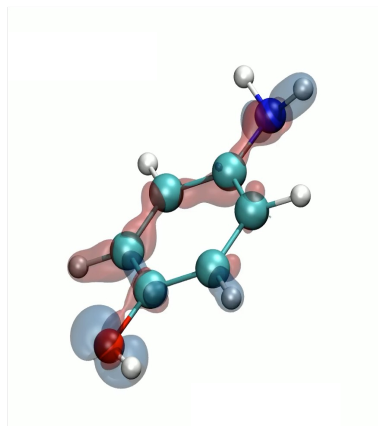


Simulation: G. Grell, F. Martin et al.

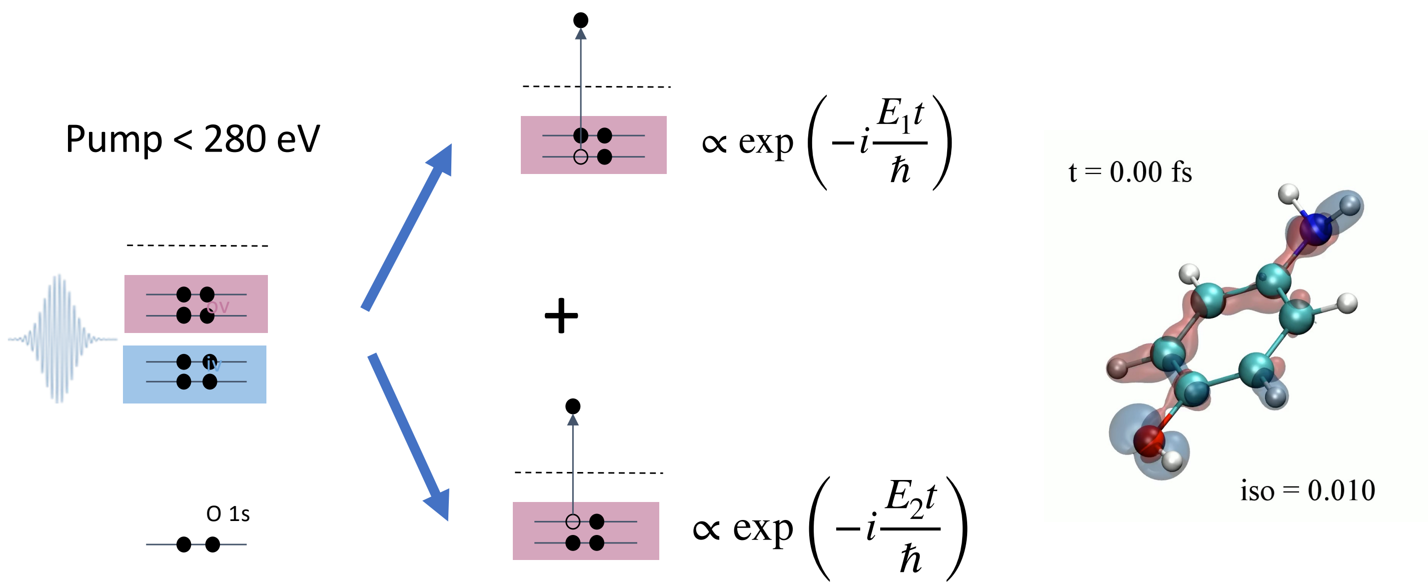
Pump-Probe Scheme

Pump < 280 eV

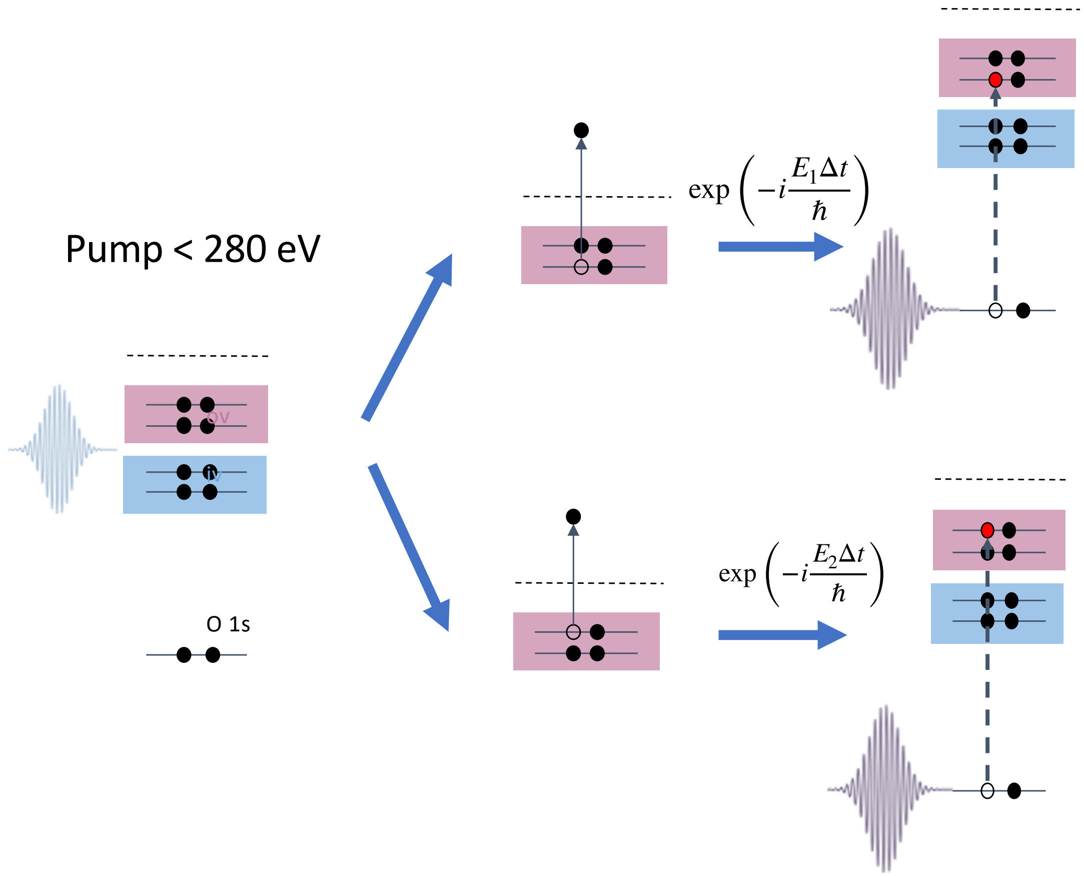




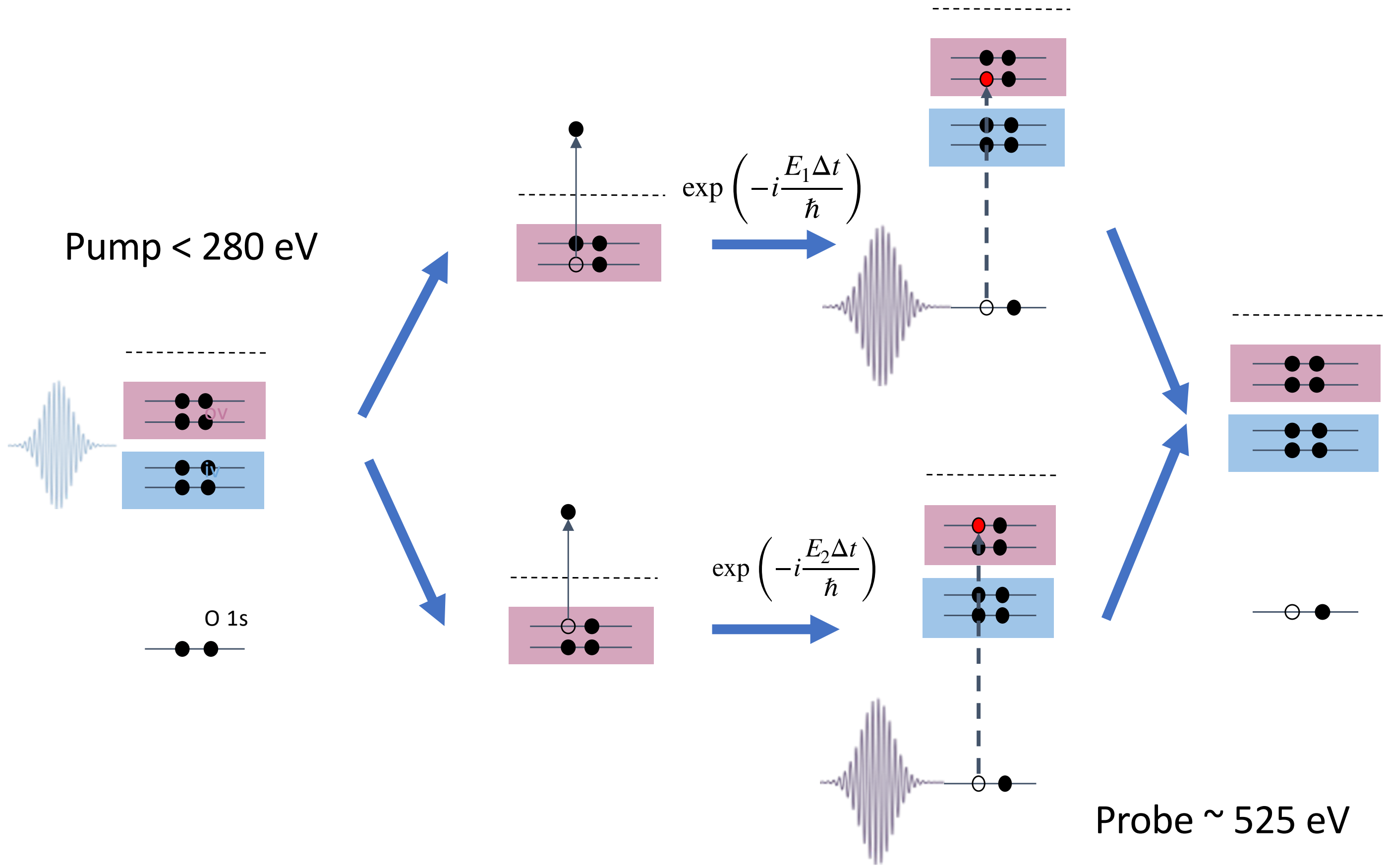
Pump-Probe Scheme



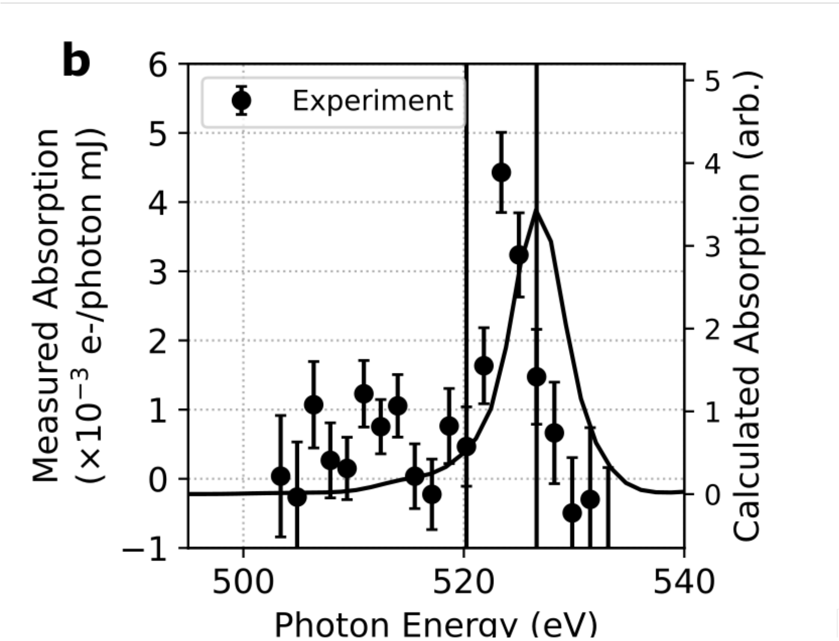
Pump-Probe Scheme

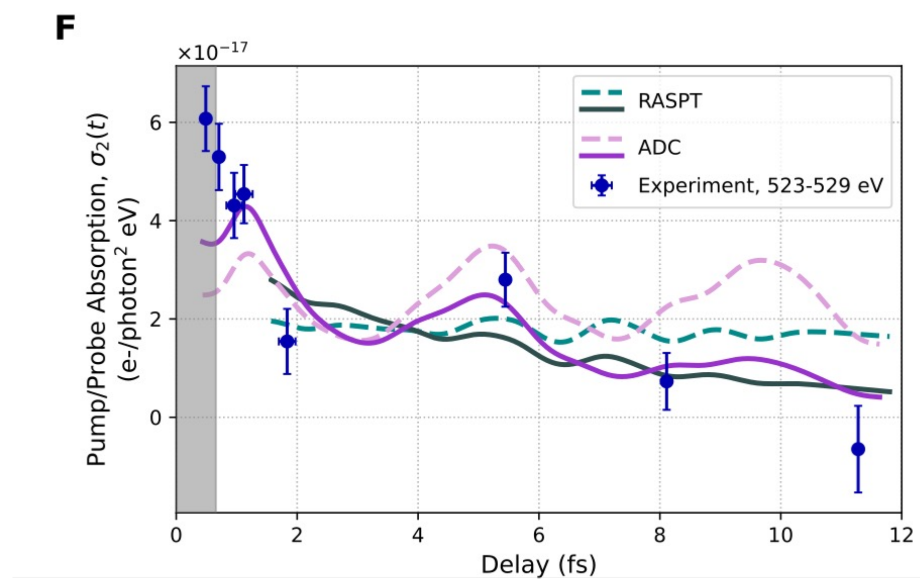


Pump-Probe Scheme



Pump/Probe Demonstration

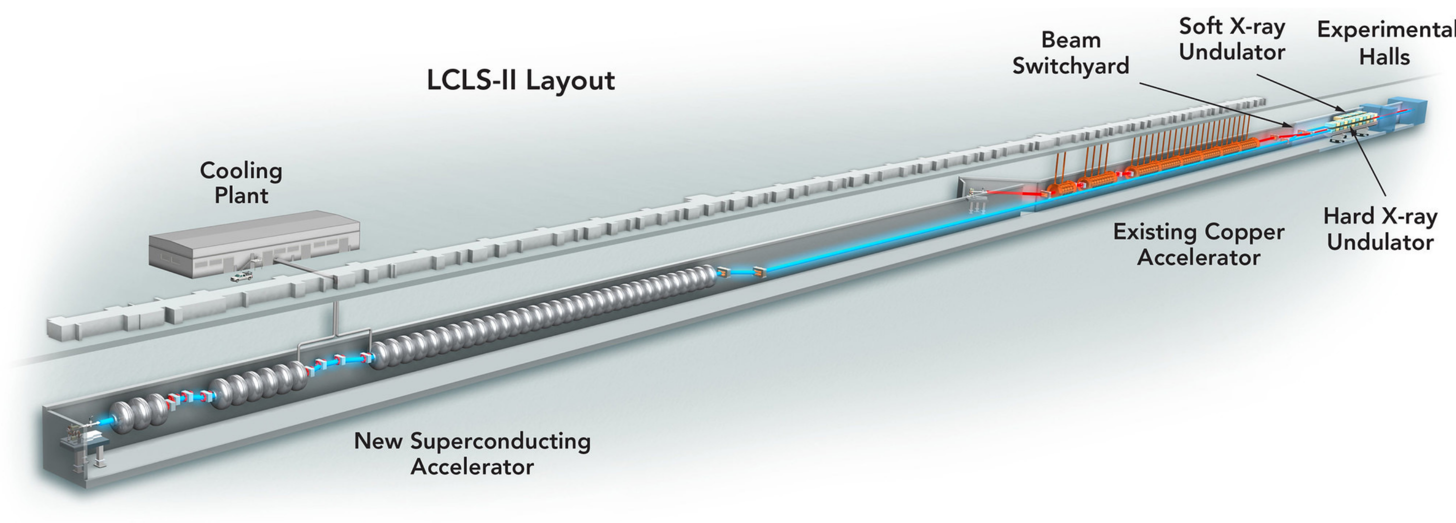




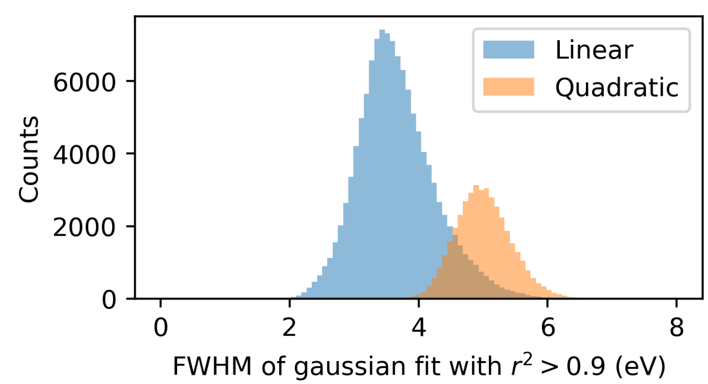
Analysis:
T. Driver, Z. Guo E. Isele
(SLAC/Stanford)
D. Tuthill (OSU)

Simulations:
M. Ruberti and
V. Averbukh (Imperial College)

The LCLS-II



Currently at 8 kHz
Up to 1 MHz in the future
Demonstrated attosecond pulses at high rep rate!



Wavelength

10 um
1998 UCLA

385 nm
2001 Argonne

13.7 nm
2007 DESY

0.15 nm
2010 SLAC

10 um **1 um** **100 nm** **10 nm** **1 nm fs** **0.1 nm**

Time Resolution

Early Days
2010

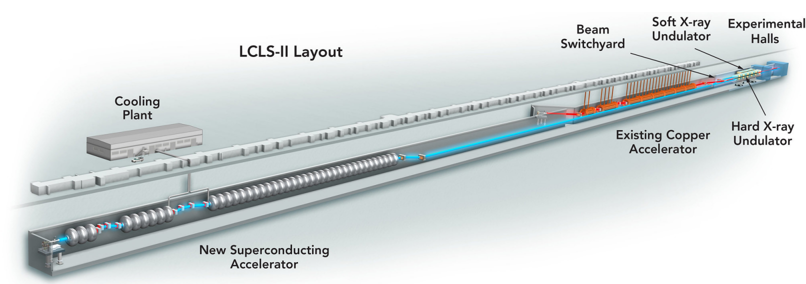
Time sorting
2013-14

2-Color FELs
2013-16

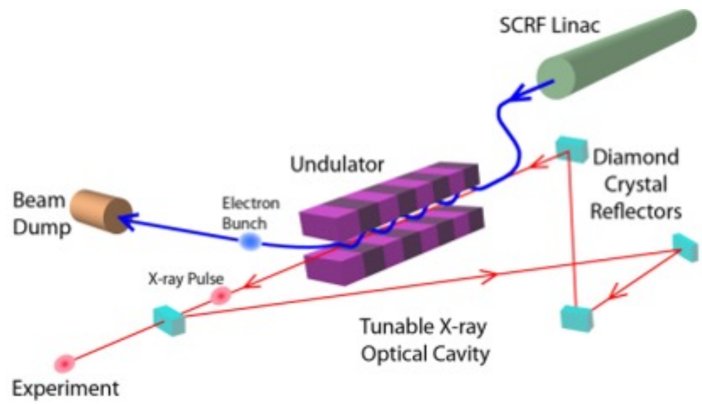
Attosecond FELs
2020-ongoing

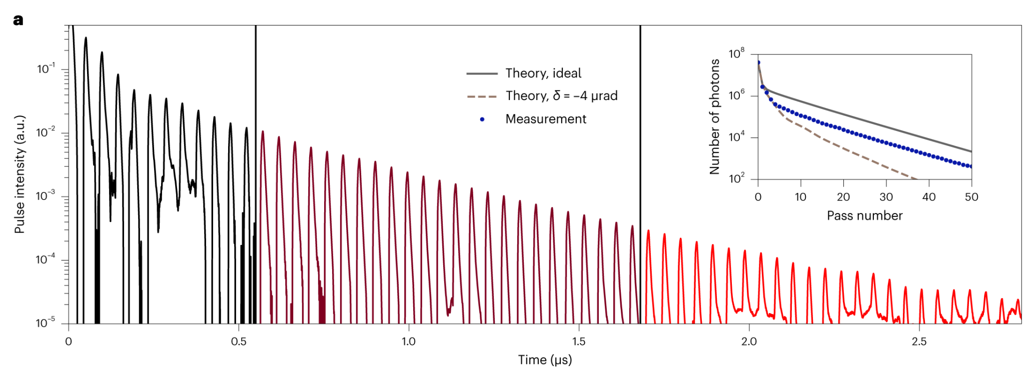
1 ps **100 fs** **10 fs** **1 fs** **0.1 fs**

Average power x 10^4



What’s Next?

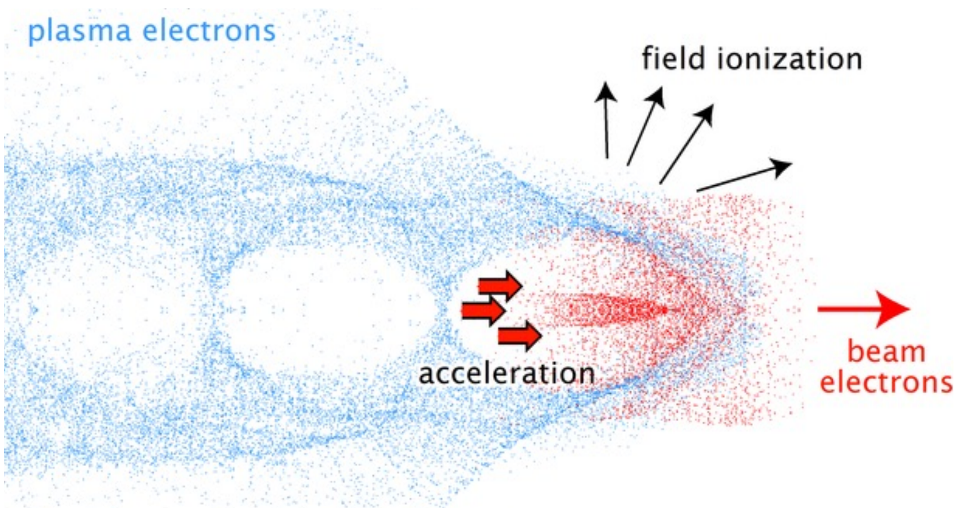




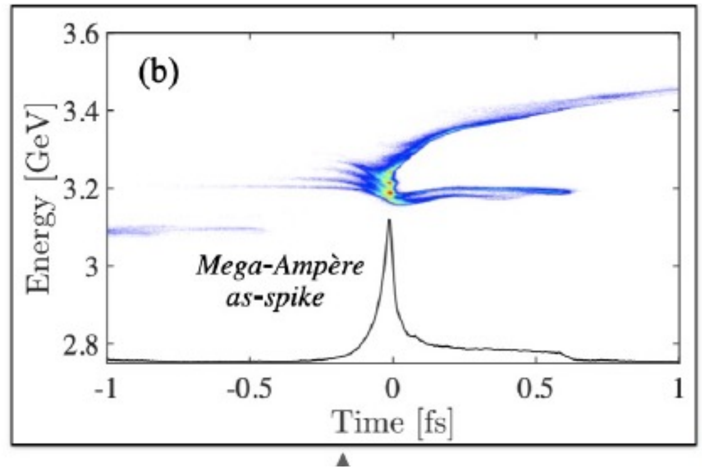
Up to 2 orders of magnitude higher brightness than SASE

Margraf, Rachel, et al.
Nature Photonics 17.10 (2023): 878-882.

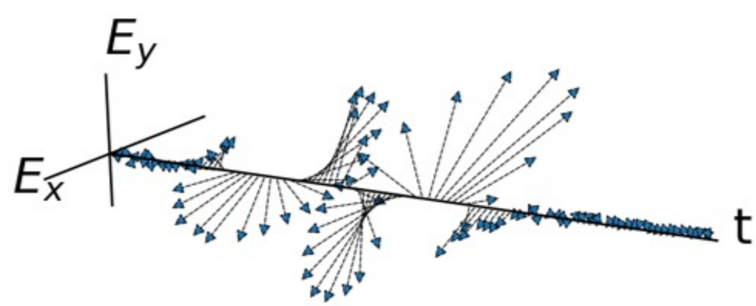
What's Next?



By Rasmus Ischebeck at English Wikipedia, CC BY 2.5,
https://commons.wikimedia.org/w/index.php?curid=15117906



C. Emma et al. APL Photonics 6 (7), 076107



You can't make attosecond pulses without breaking a few eggs…

You can’t make attosecond pulses without breaking a few eggs…

You can't make attosecond pulses without breaking a few eggs...

You can’t make attosecond pulses without breaking a few eggs…

You can't make attosecond pulses without breaking a few eggs…

Questions?

ChatGPT can you create an image of an egg getting hit by an attosecond x-ray laser pulse and exploding?