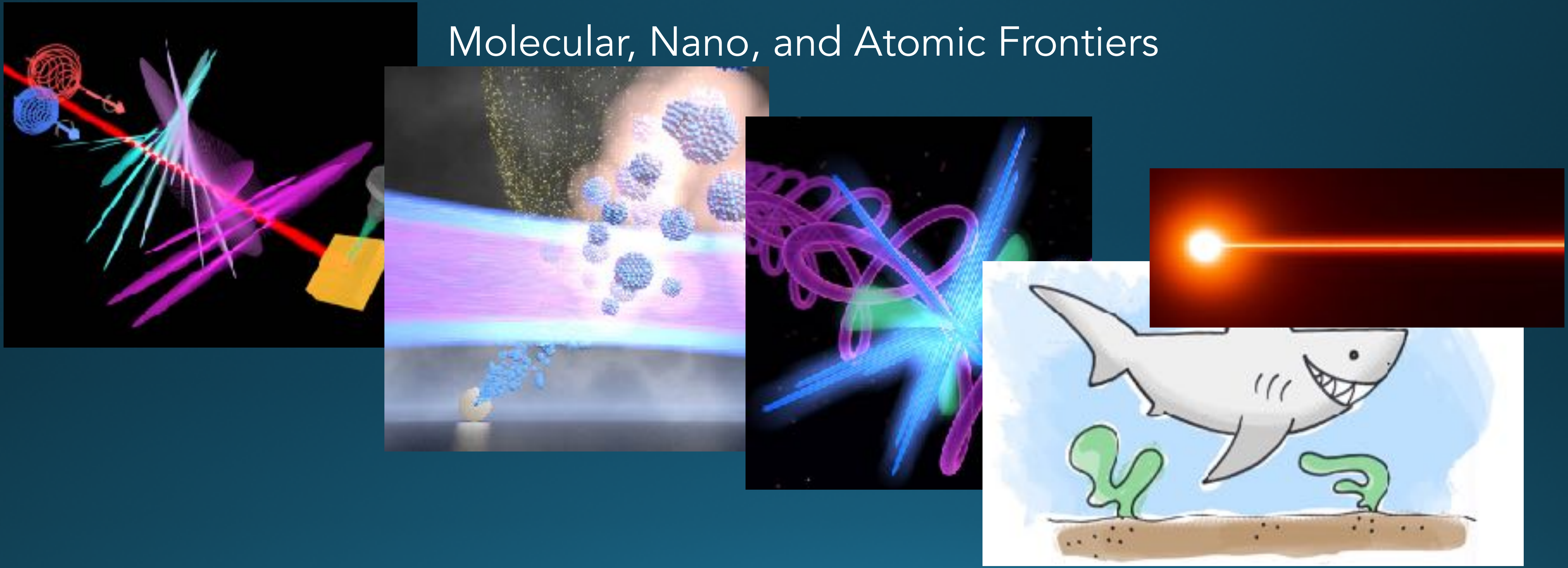
How to Create and Control Nature’s Most Exotic Light Source:

X-ray and Attosecond Light Science at the Molecular, Nano, and Atomic Frontiers



Kevin M. Dorney

Kapteyn-Murnane Group, JILA and University of Colorado Boulder

KM Group and JILA:
Excellent students, collaborators, and **advisors**

KM Group Spring 2017

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JILA NIST CU

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KM Group Spring 2017

Collaborators

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Berkeley
UNIVERSITY OF CALIFORNIA

COLORADO SCHOOL OF MINES

TU WIEN
TECHNISCHE UNIVERSITÄT WIEN
Vienna University of Technology

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LaserLaB AMSTERDAM
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KMLABS
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$$$$

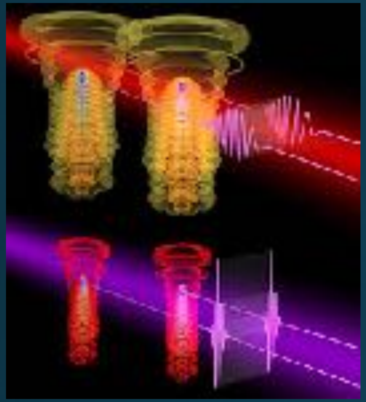
intel

DARPA

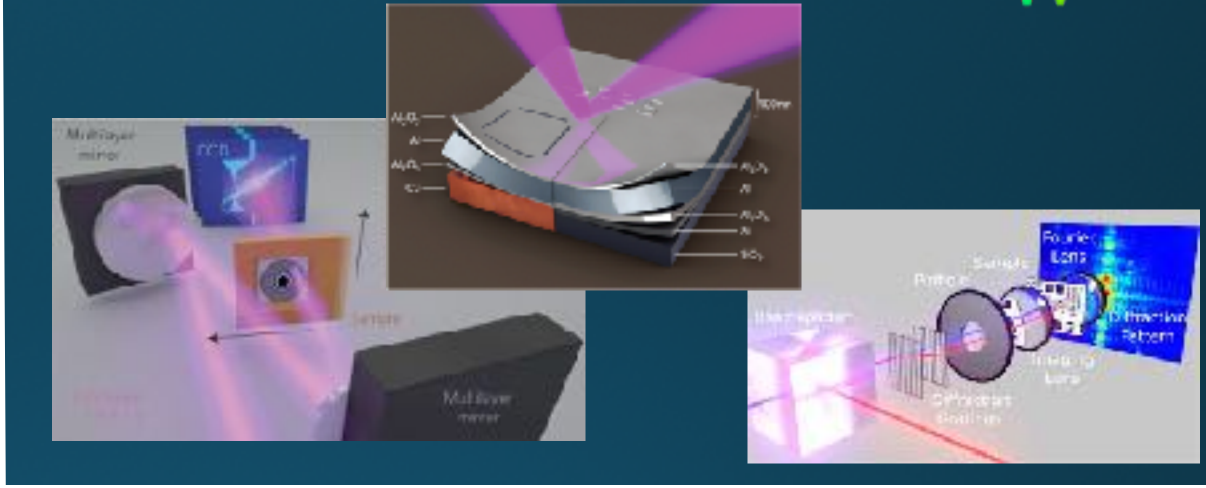
NSF

Light and Materials Science in the KM Group:
AMO Dynamics at Extreme Spatial and Temporal Scales

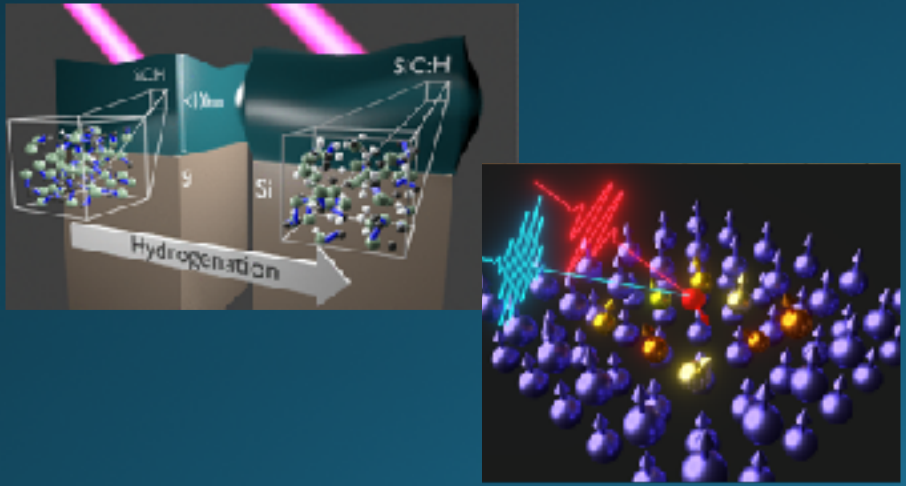
Attosecond Extreme Nonlinear Optics

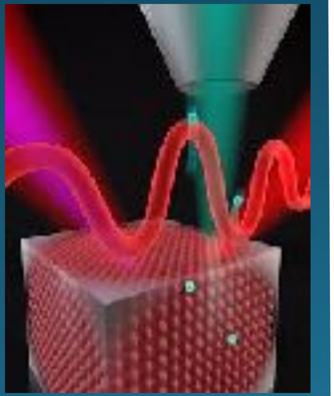


Coherent x-ray Imaging

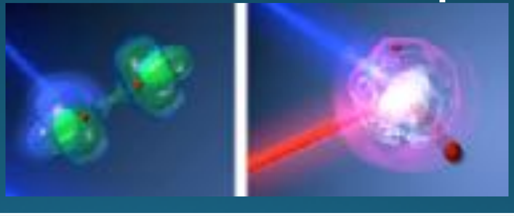


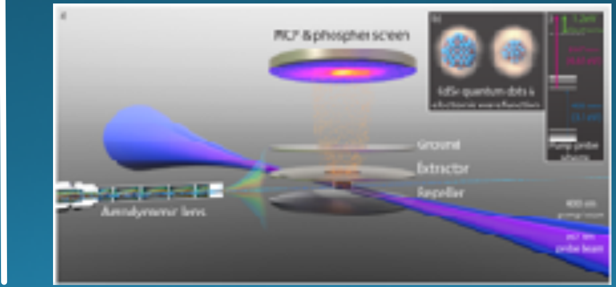
Ultrafast Materials Science

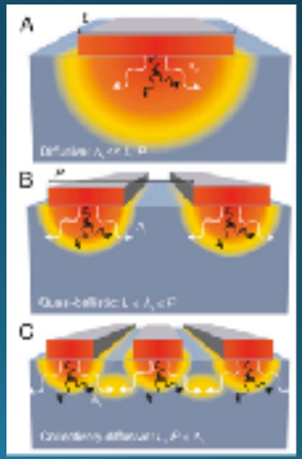


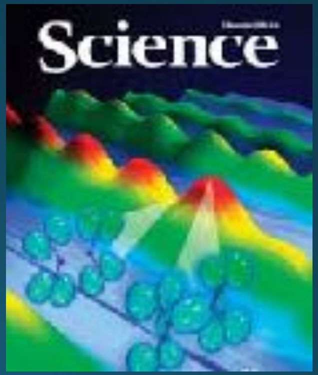


Nano-Molecular Spectroscopy and Dynamics









Fundamental Science Research… Who Cares?

"Oh, you do scientific research? Neat! What exactly are you working on???"

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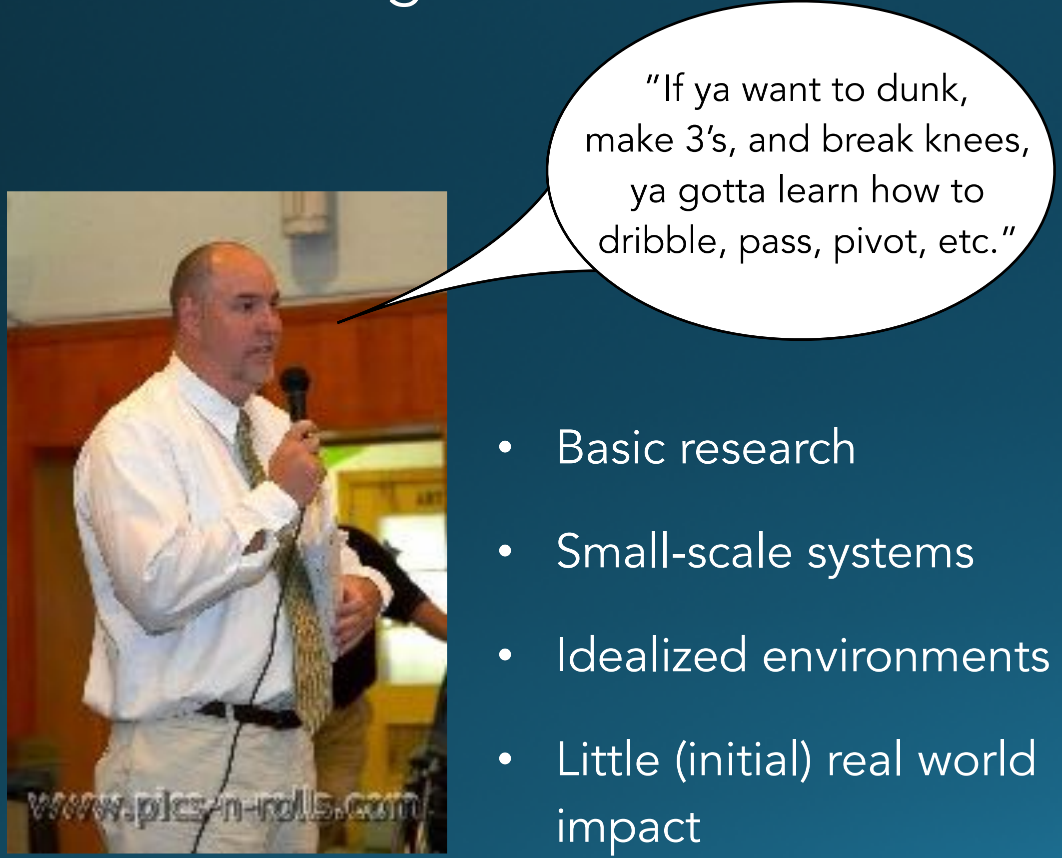

- Basic research
- Small-scale systems
- Idealized environments
- Little (initial) real world impact

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Mastering Fundamentals → Understanding and Manipulating Nature!

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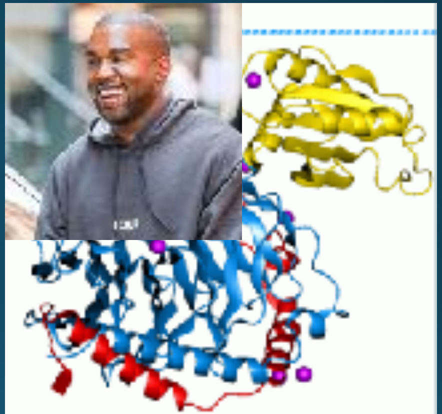
Blue LEDs (2014)

G Proteins (2012)



CCDs Detectors (2009)

Laser (1964)

Green Fluorescent Protein (2008)

Fundamental Light Science in the KM Group: Where Lasers Meet X-Rays!

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Visible/Invisible Laser Benefits Society

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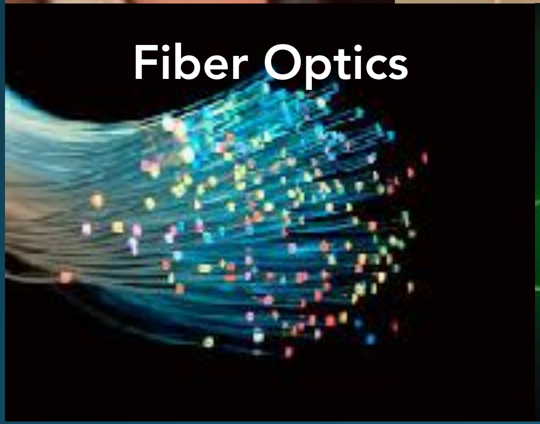
Laser Eye Surgery

Laser Machining



Fiber Optics

Protecting Fine Art!

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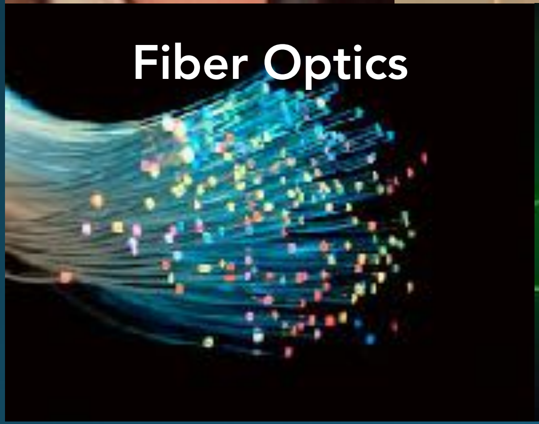
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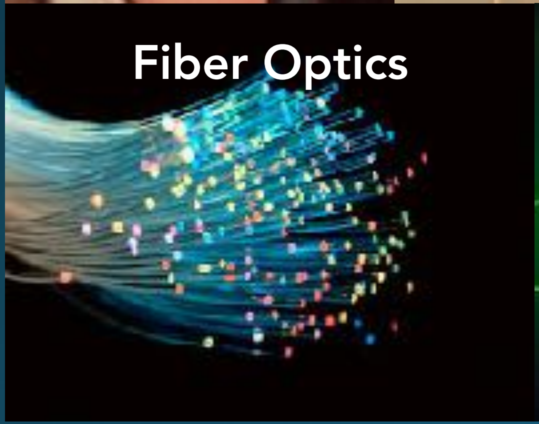
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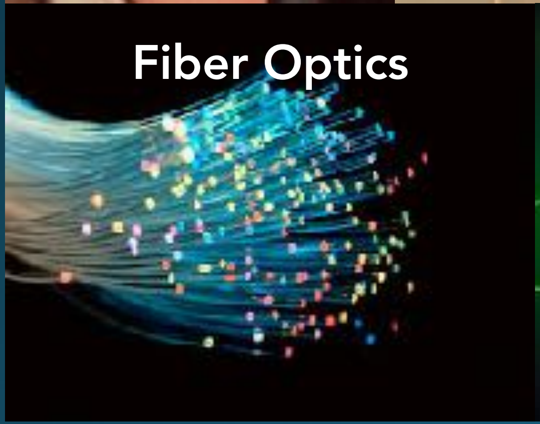
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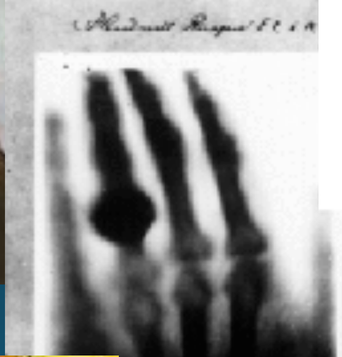

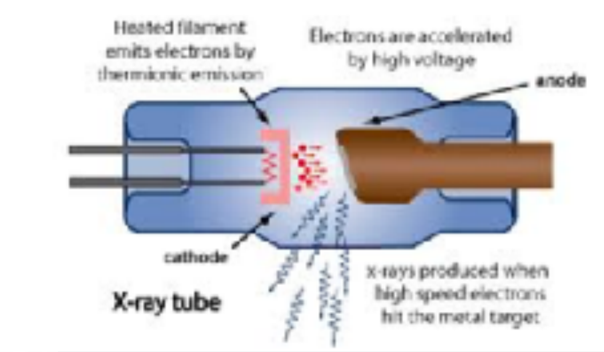

Fundamental Light Science in the KM Group: Do We Really Need X-ray Lasers?

The White Whale of the Physical Sciences

- Direct observation of atomic and molecular scale transformations at their natural **time** and **length scales**.

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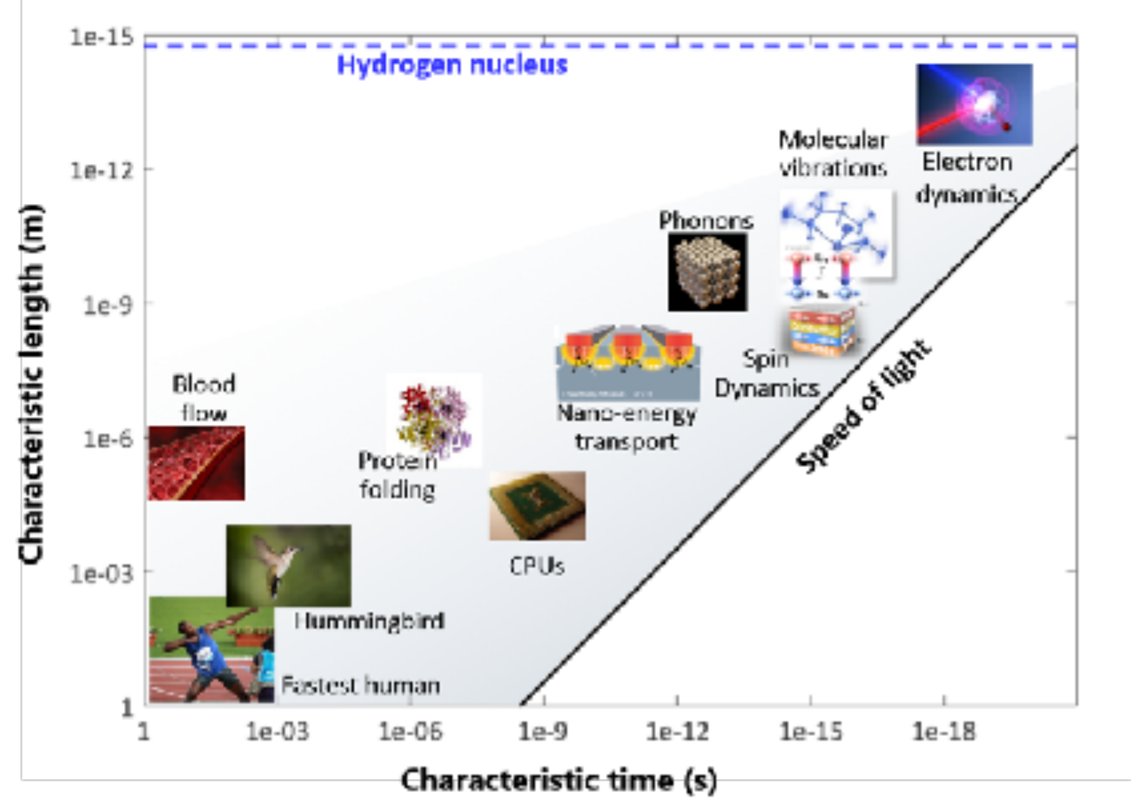

Courtesy: Nico Hernandez Chupak, KM Group

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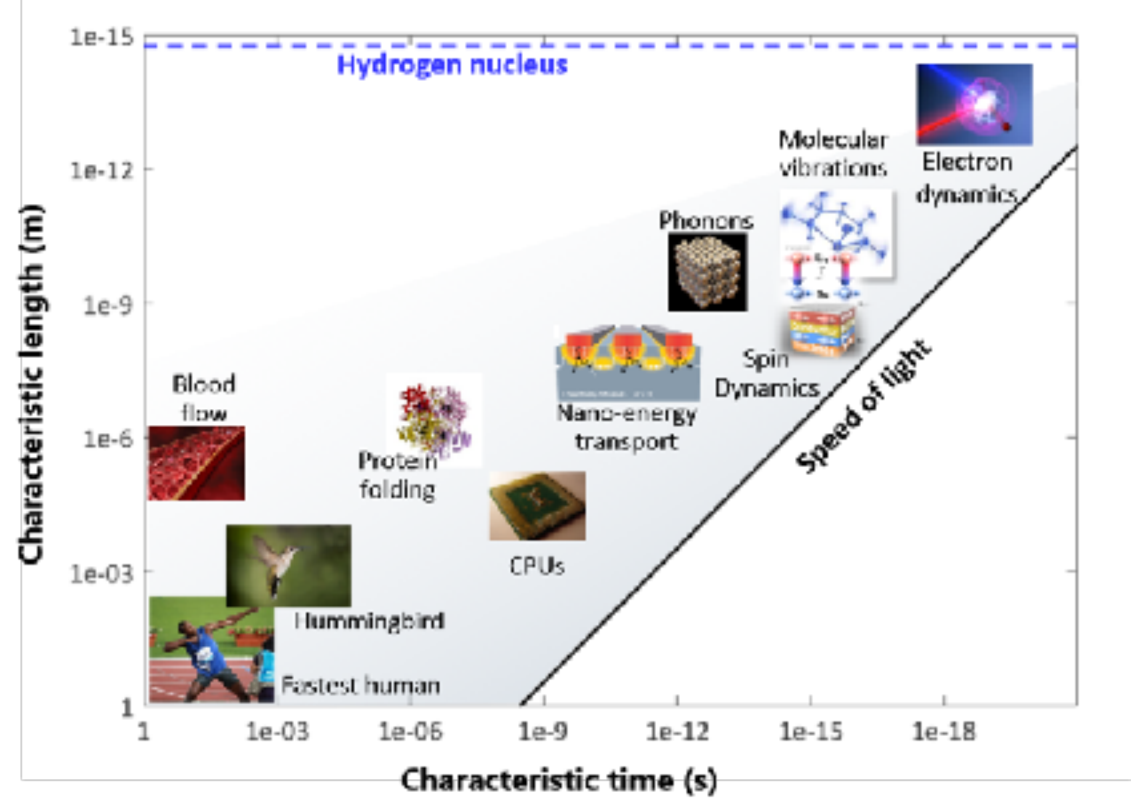

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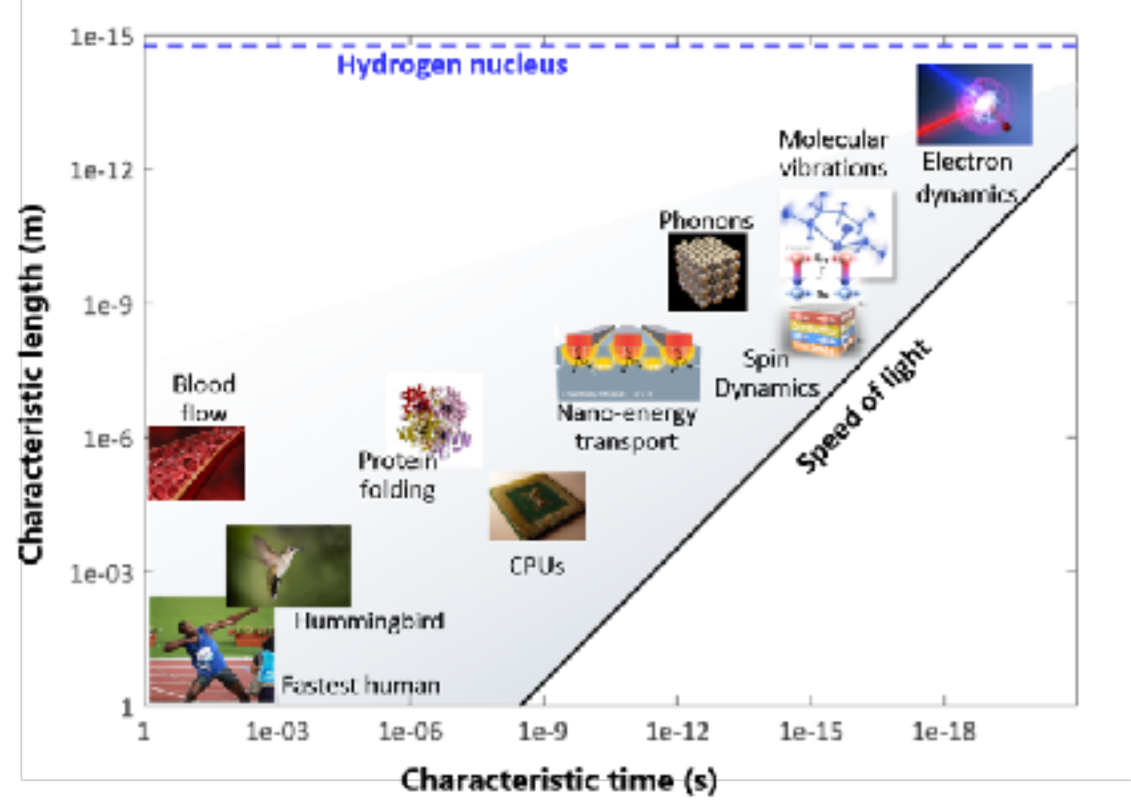

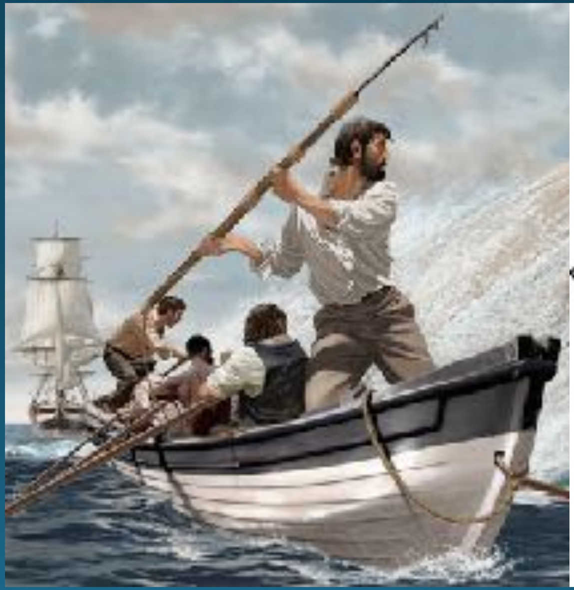

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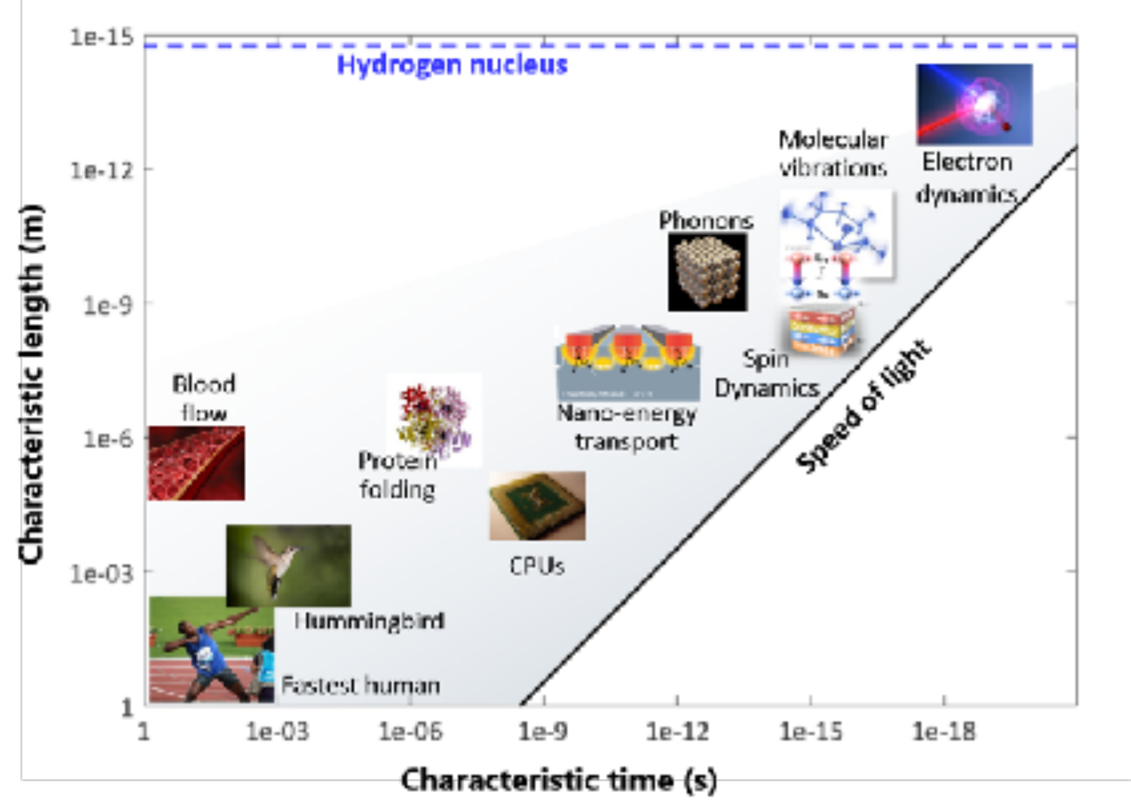

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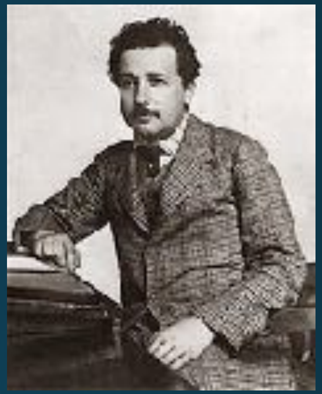

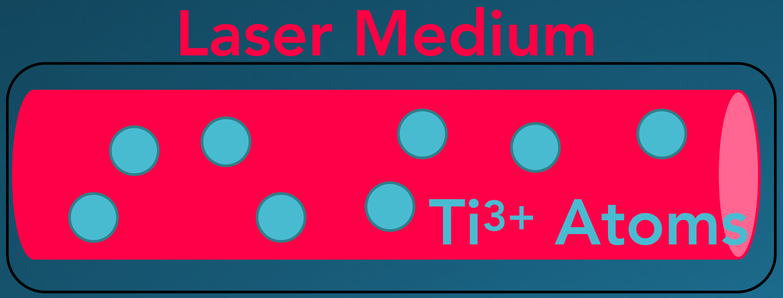

Laser Medium

Ti^{3+} Atoms

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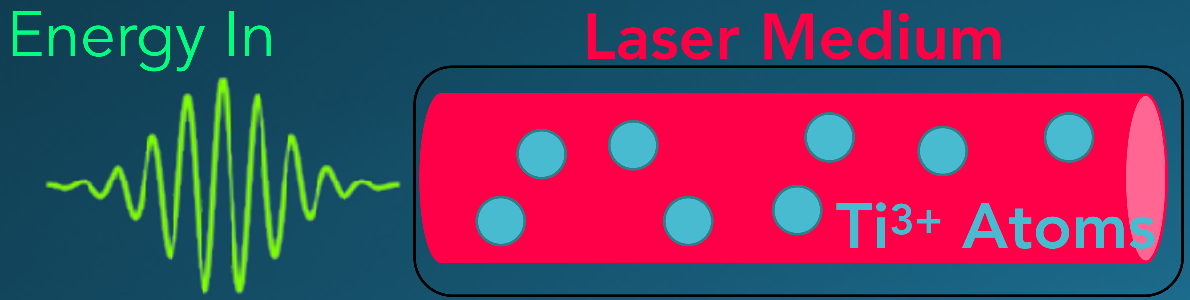

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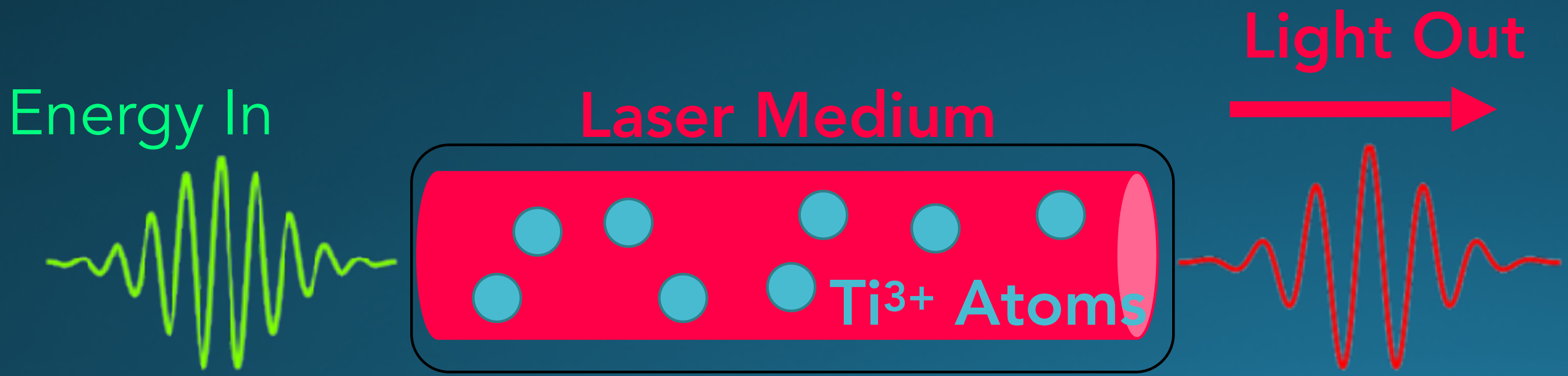

Energy In

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Light Out

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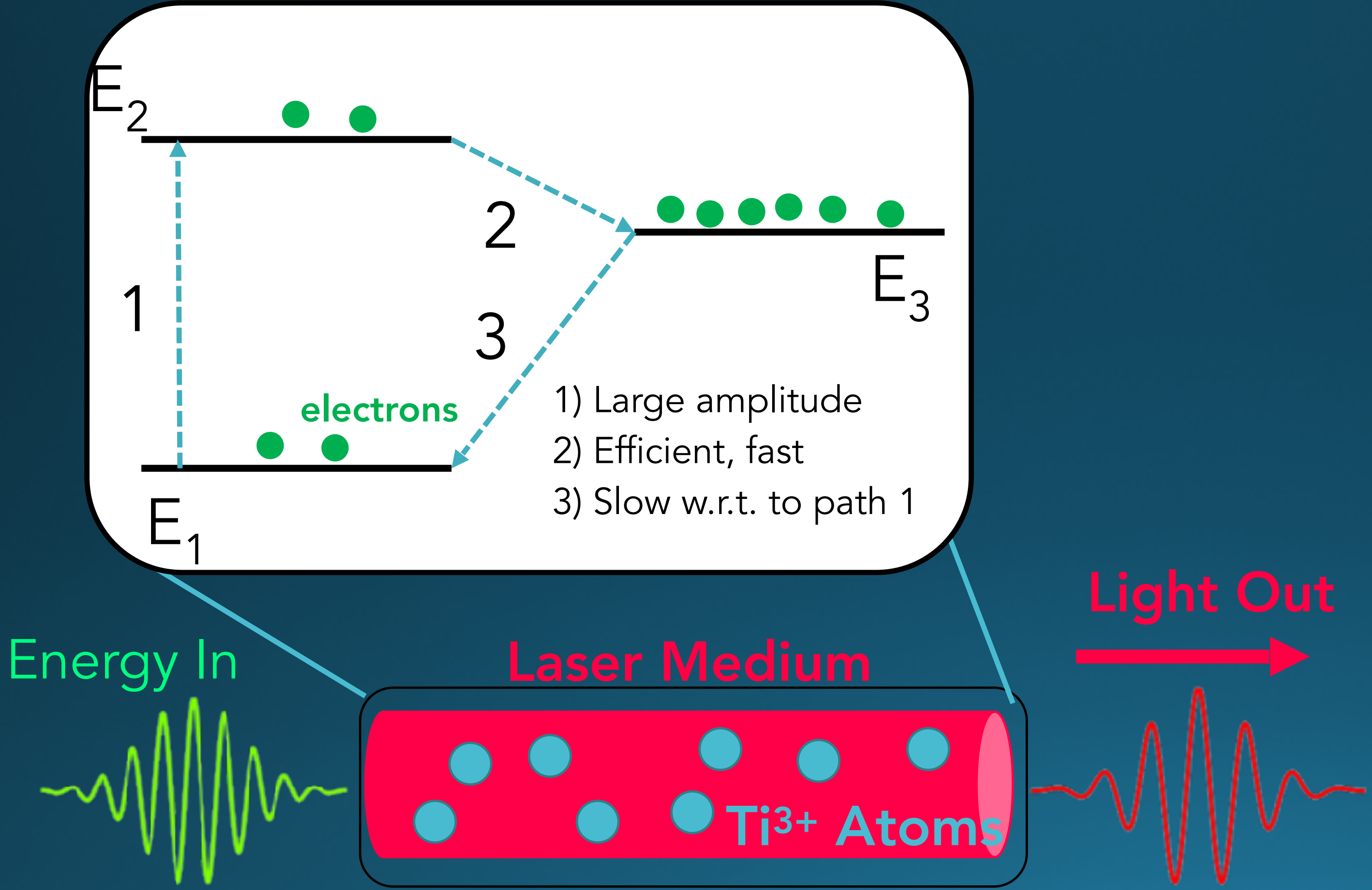

1) Large amplitude
2) Efficient, fast
3) Slow w.r.t. to path 1

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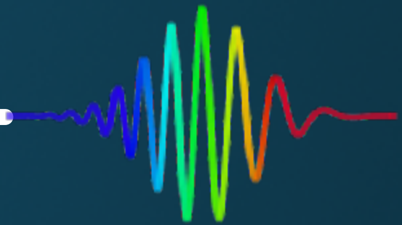

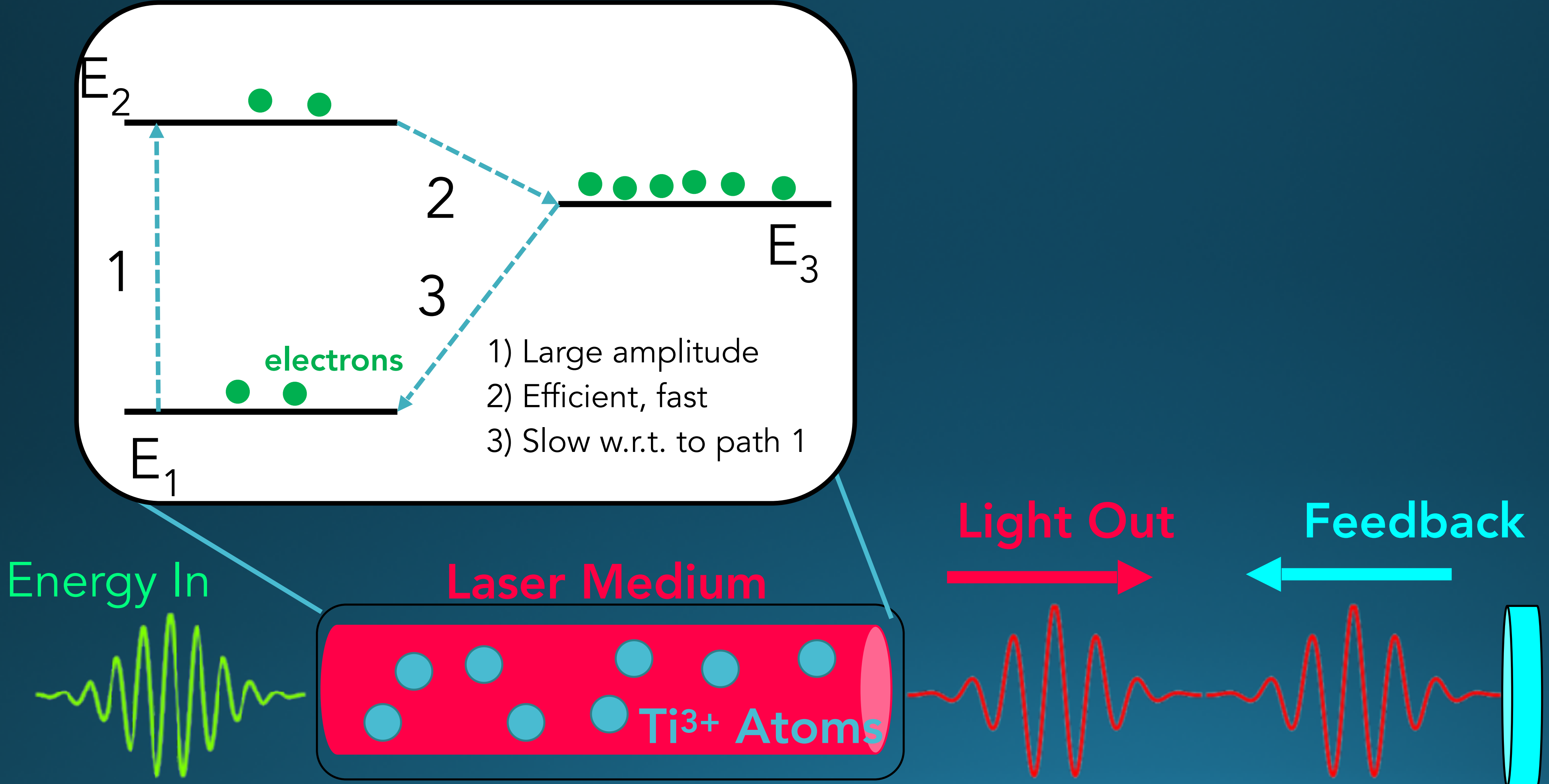

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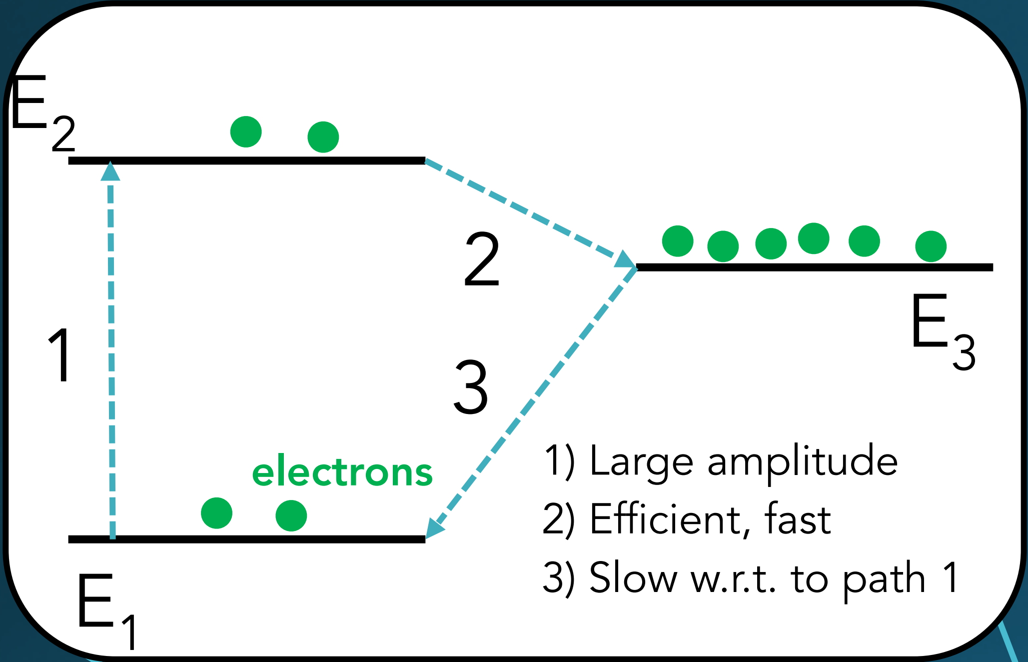

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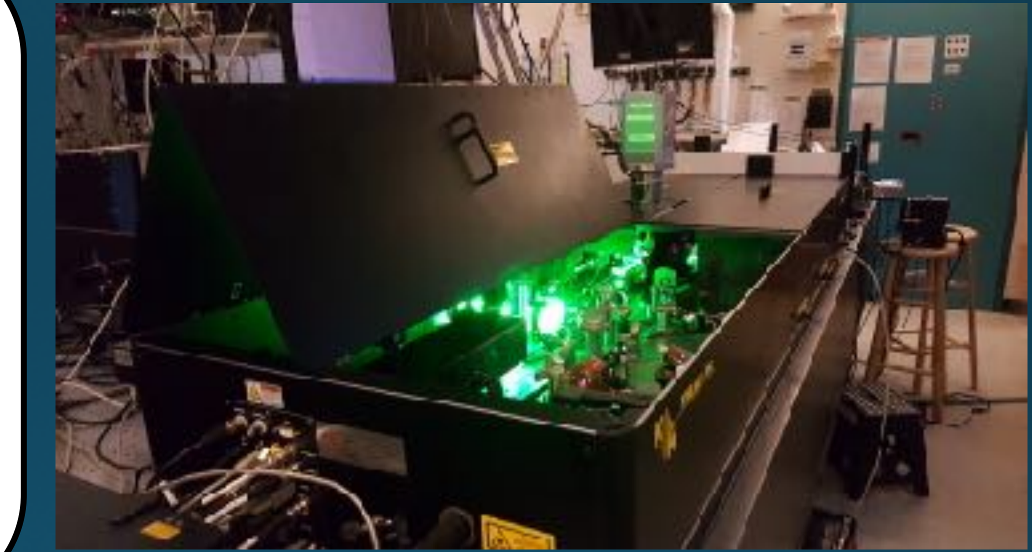

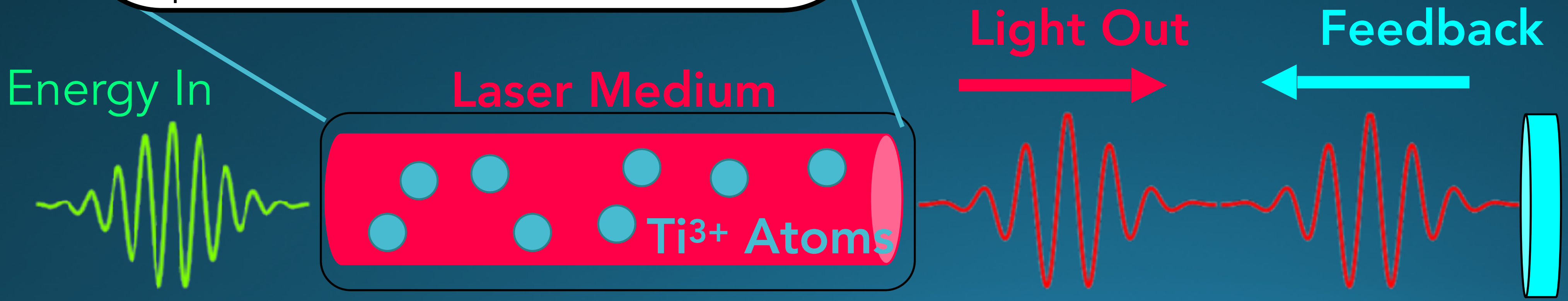

Fundamental Light Science in the KM Group: Ultrafast Lasers, Nature’s Fastest Pancakes

- Most lasers we see in day-to-day life are **continuous wave** lasers.

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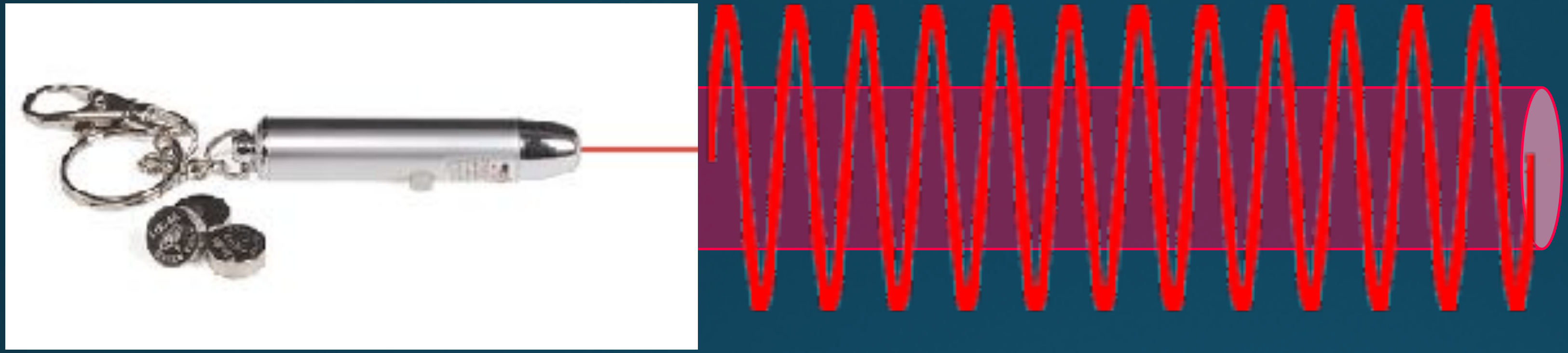

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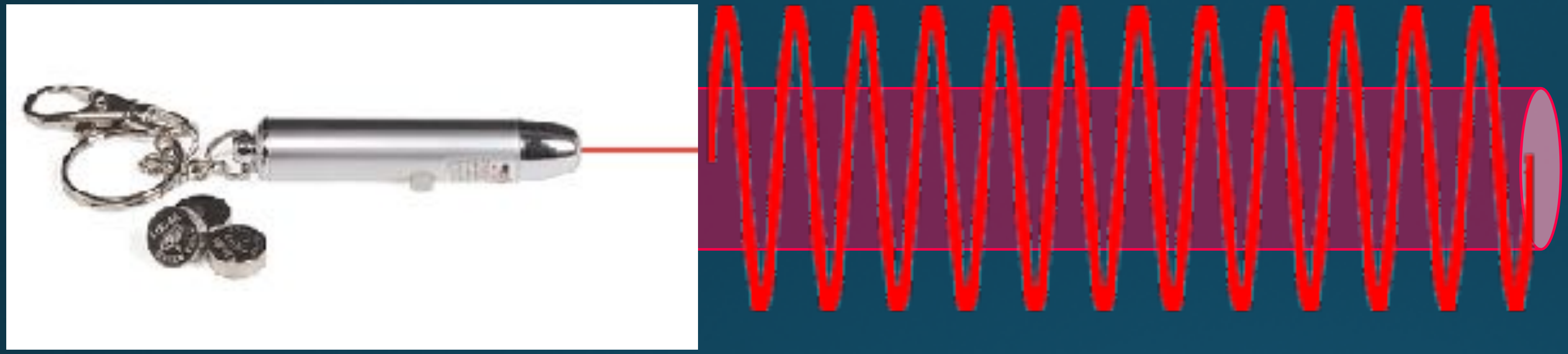

CW Laser Light

Precise frequency/wavelength
High Average Power
Very Long Term Stability
Easily Engineered/Designed

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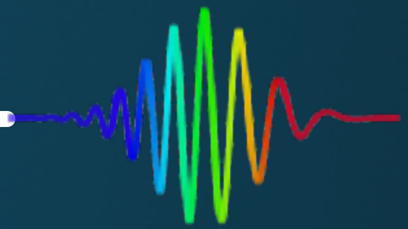

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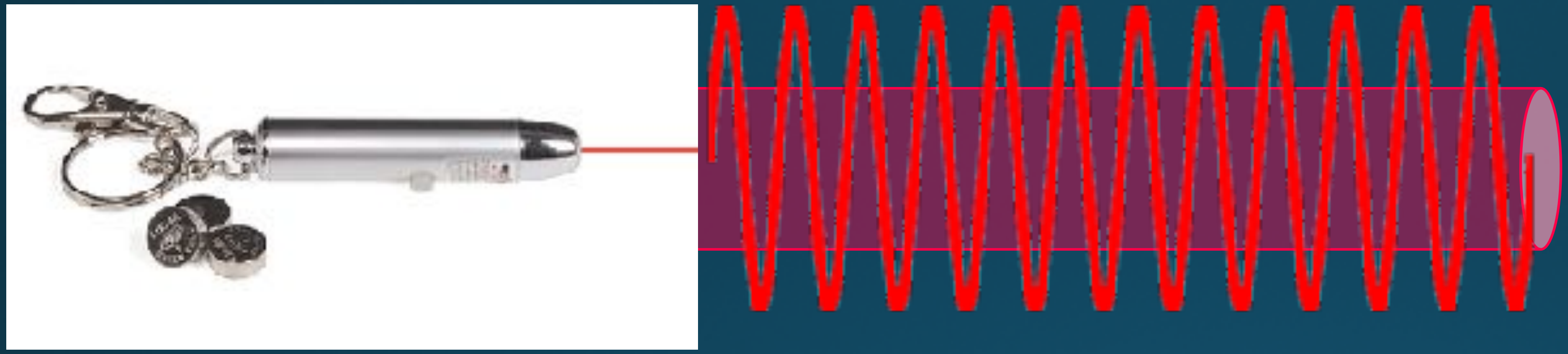

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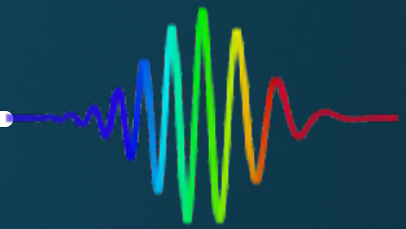

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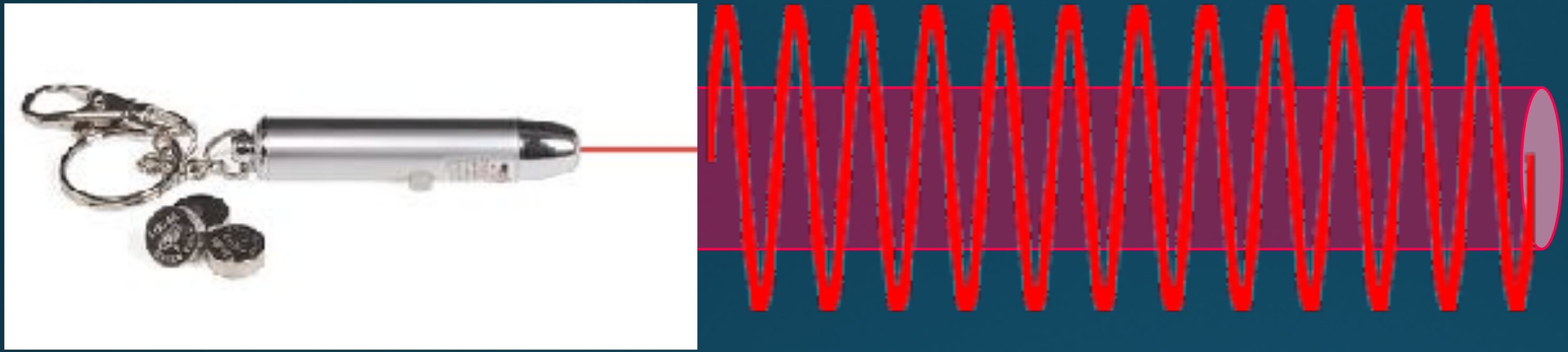

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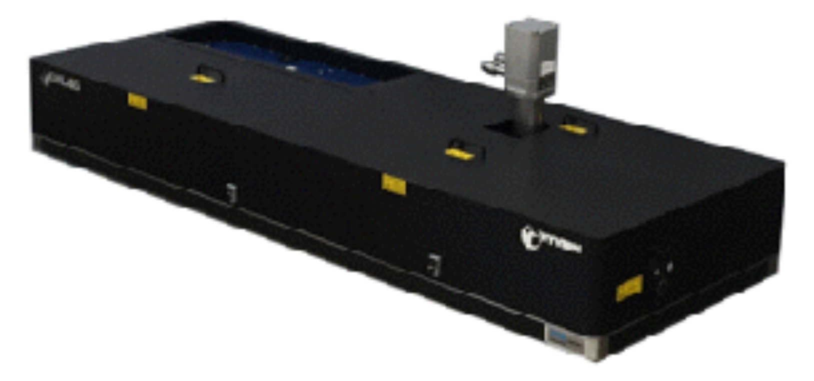

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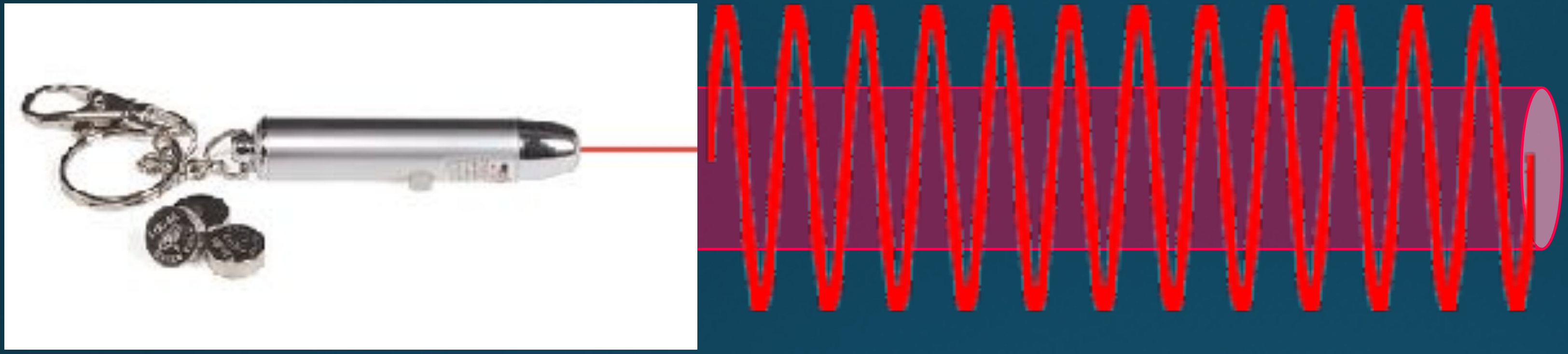

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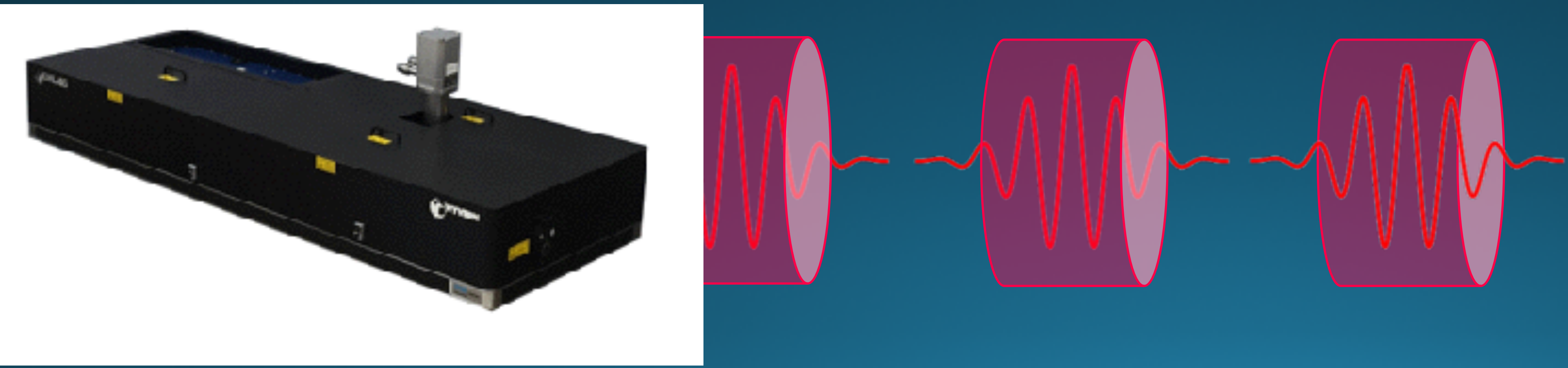

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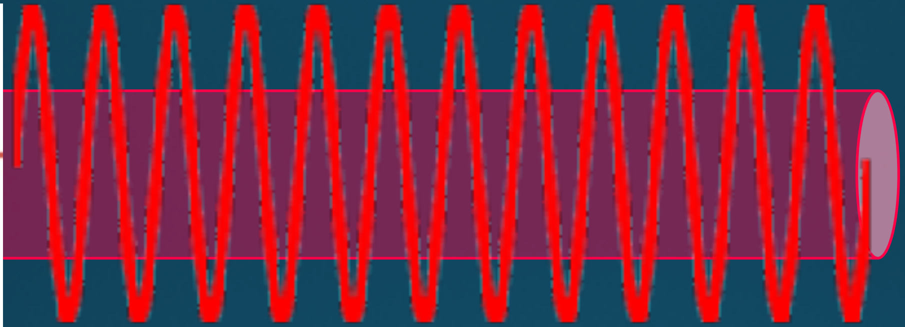

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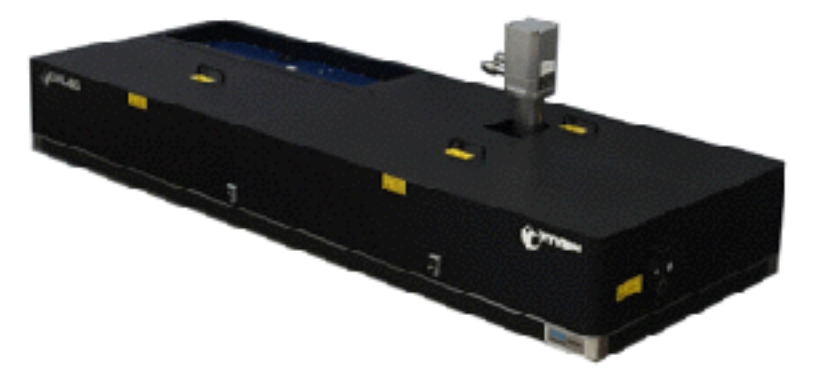

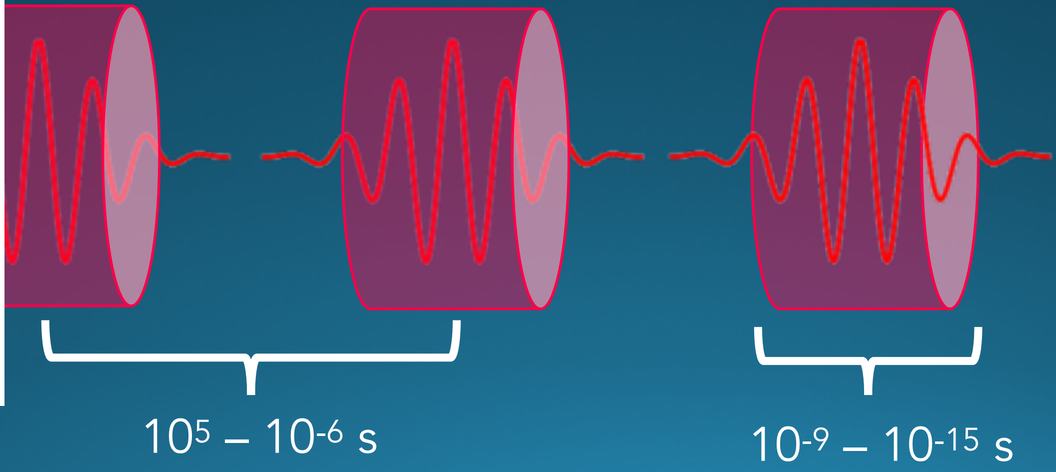

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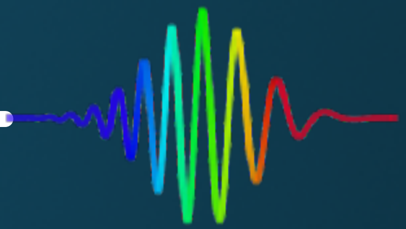

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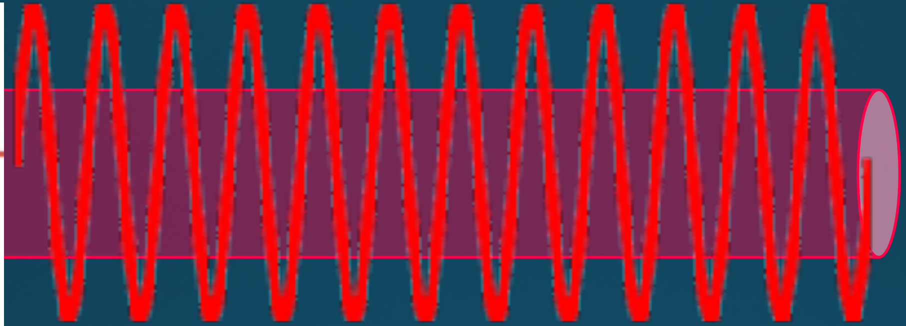

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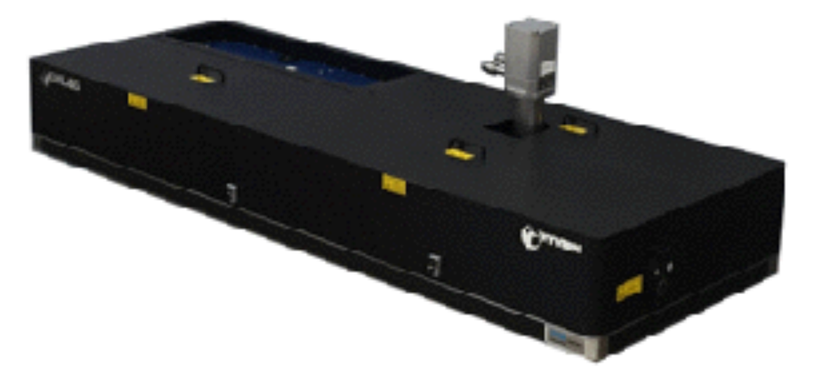

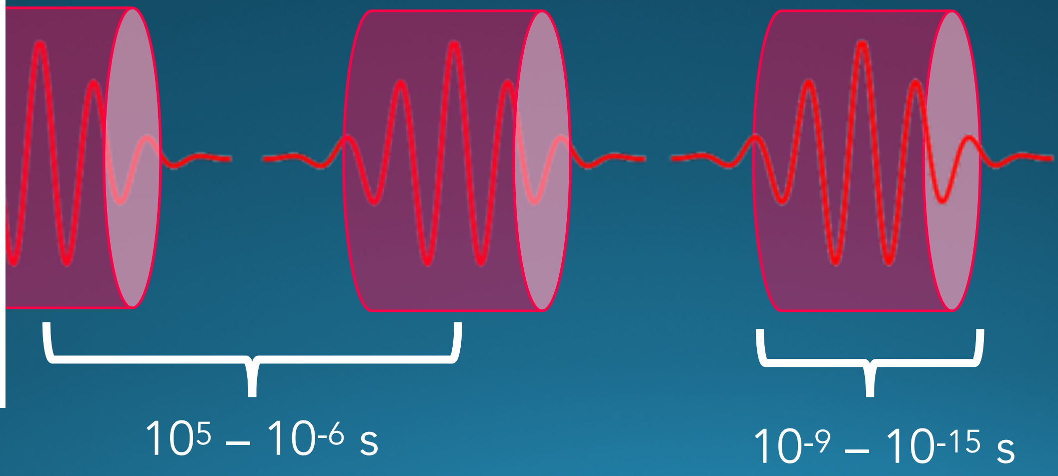

UF Laser Light

Many Frequencies/Wavelengths
Very High Intensity
Flashes "on" for $10^{-9} – 10^{-15}$ s
More Complicated to Design

Ultrafast Laser Amplifiers in the KM Group:
Complicated Beasts!

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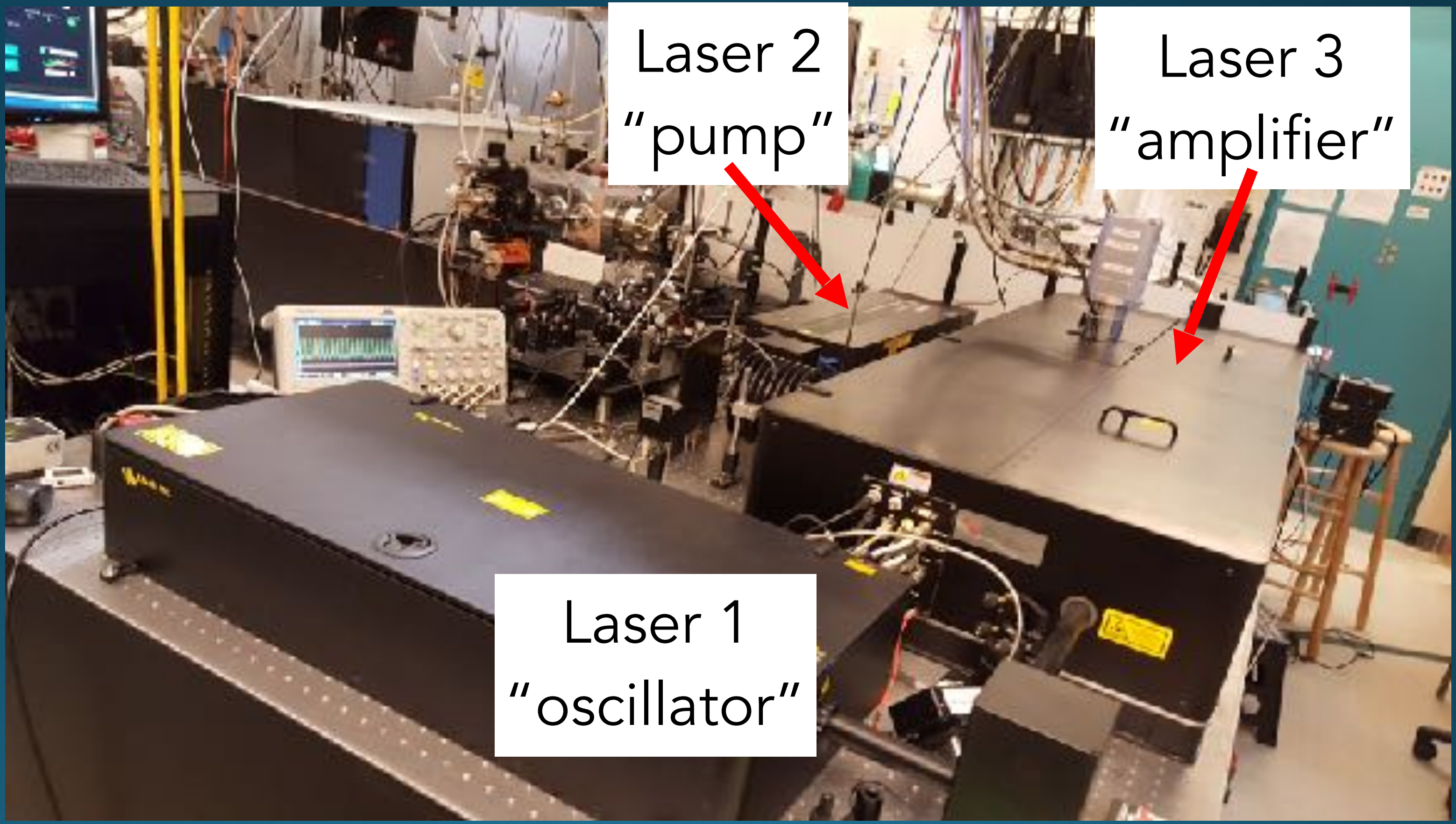

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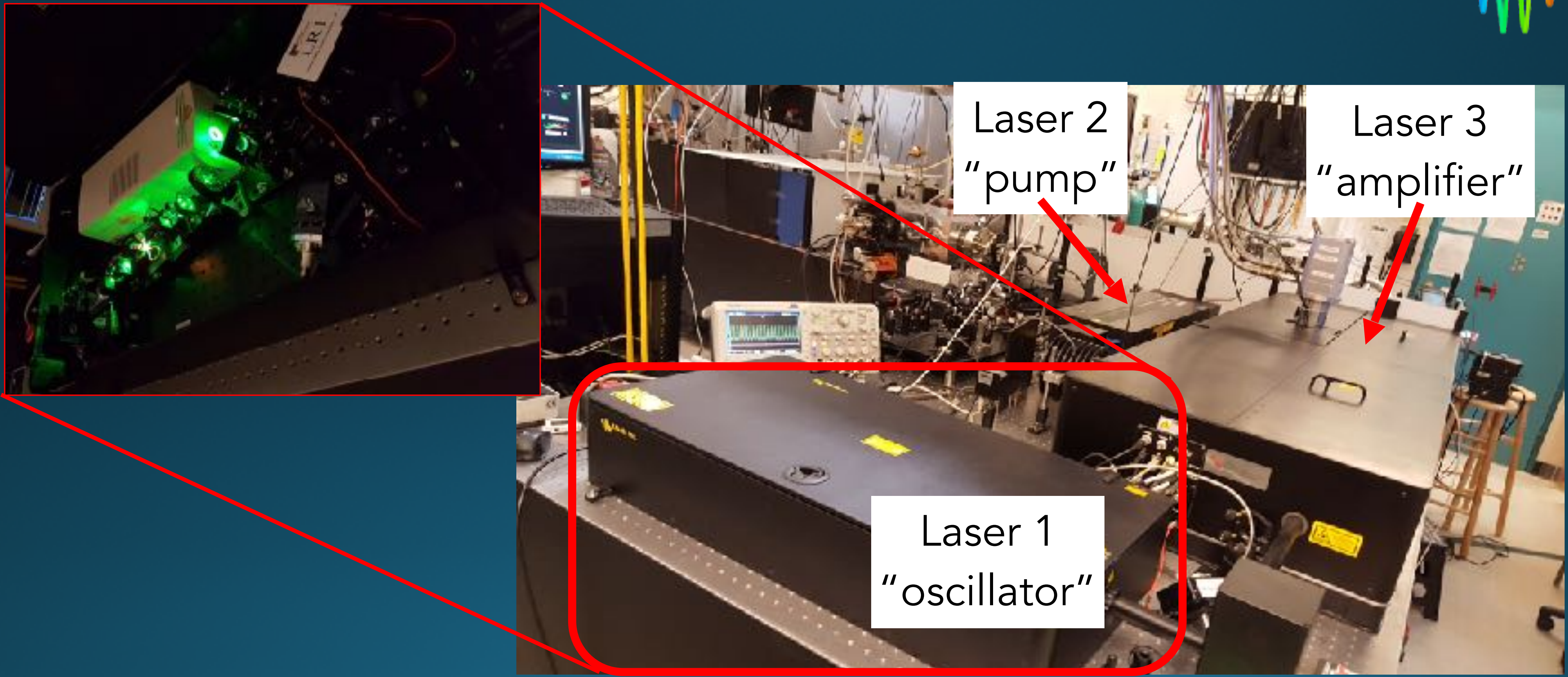


Laser 2
"pump"

Laser 3
"amplifier"

Laser 1
"oscillator"

Ultrafast Laser Amplifiers in the KM Group: **Really Big Freakin' Lasers!**

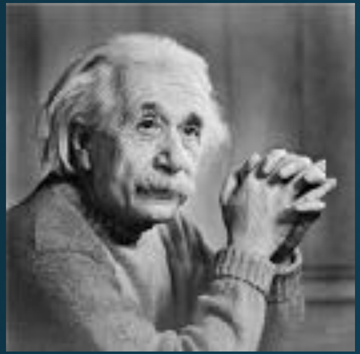
Ultrafast Laser Amplifiers in the KM Group:

Really Big Freakin' Lasers!

Ultrafast Laser Amplifiers in the KM Group:
Really Big Freakin' Lasers!

Fundamental Light Science in the KM Group: How Do We Make an X-ray Laser?

- So… We already have lasers and x-rays… Is it really that hard to combine them?



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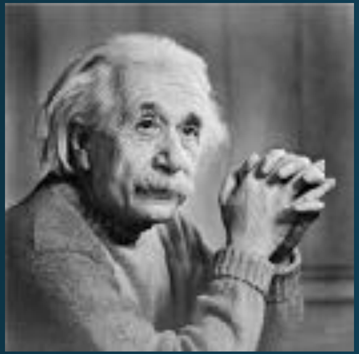

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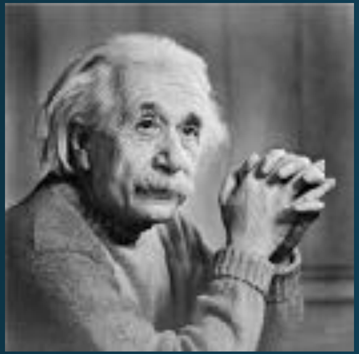

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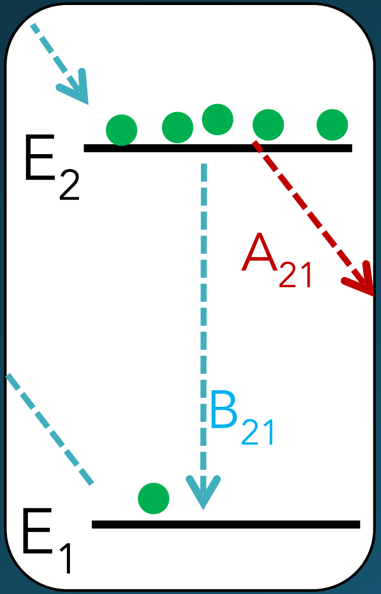

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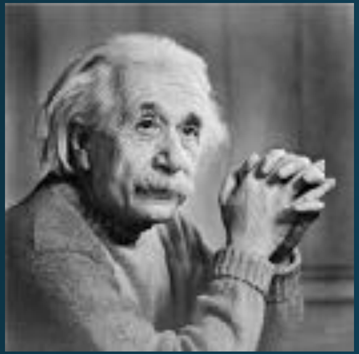

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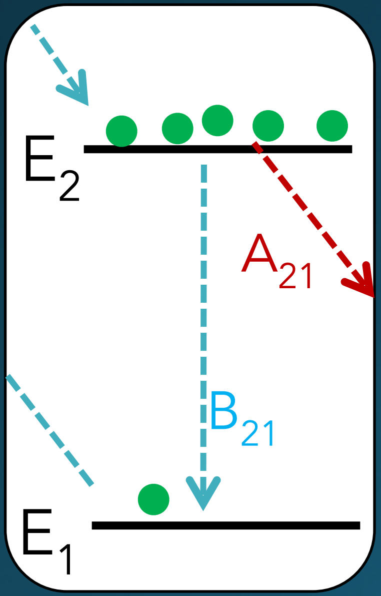

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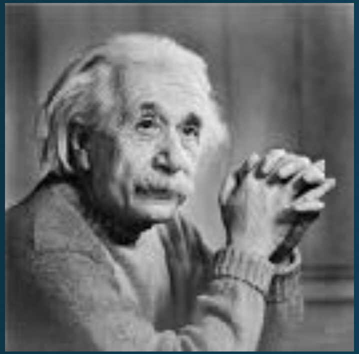

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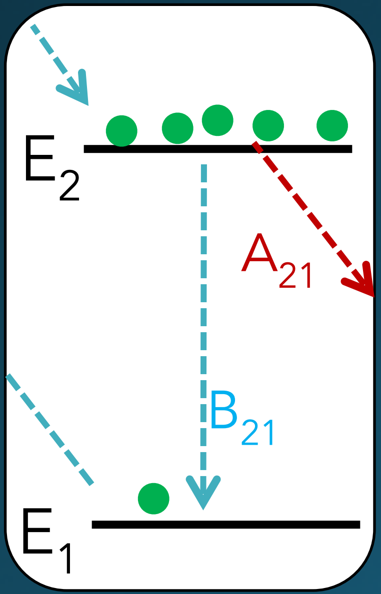

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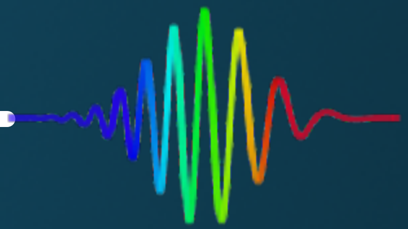

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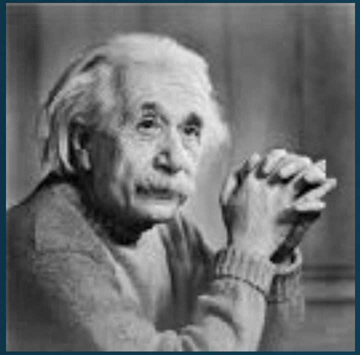

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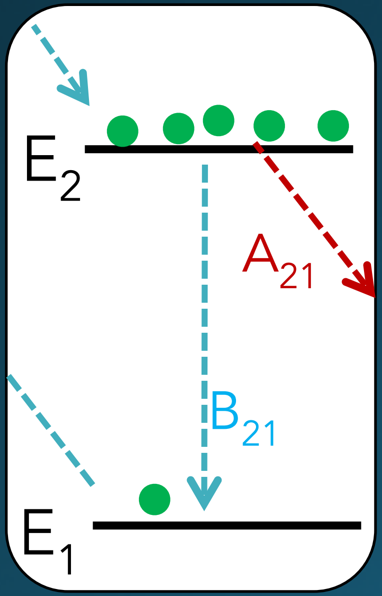

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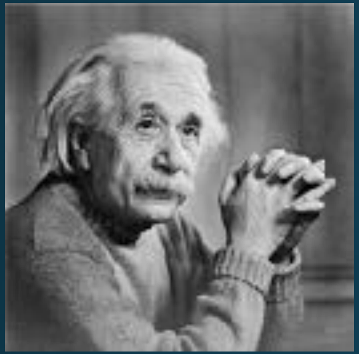

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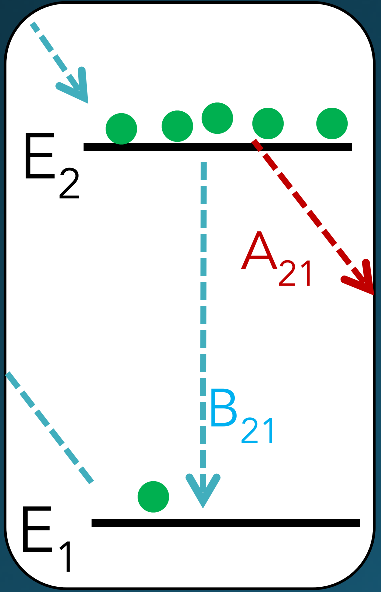

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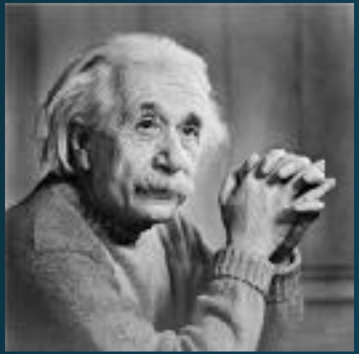

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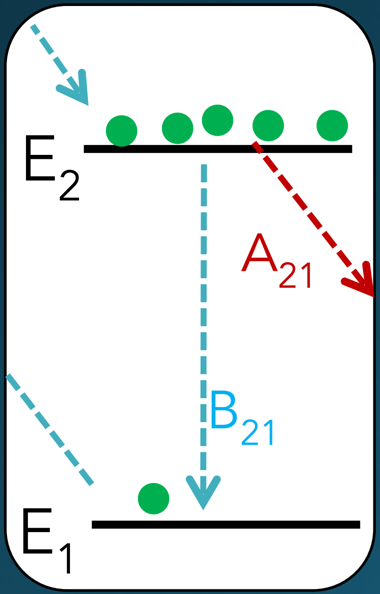

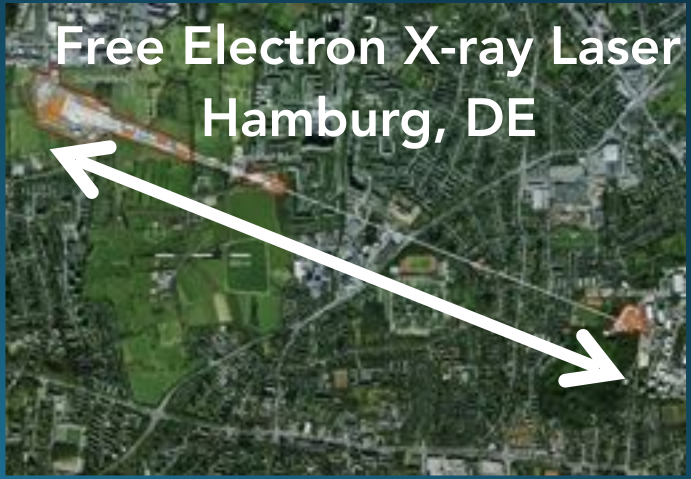

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High-Harmonic Generation (HHG)!

- Instead of building an X-ray laser directly, we upconvert visible laser light.

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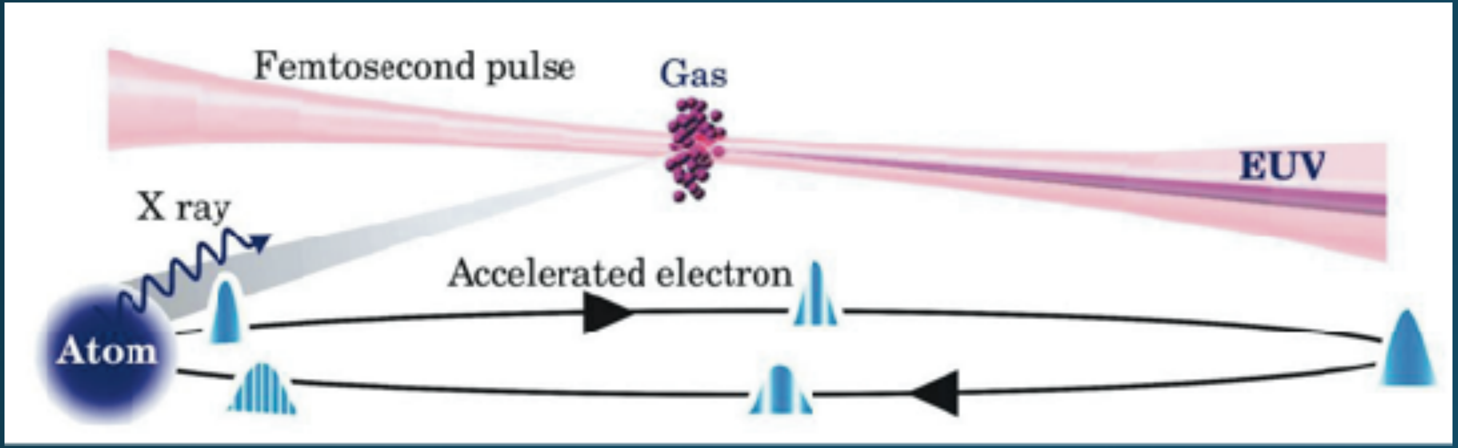

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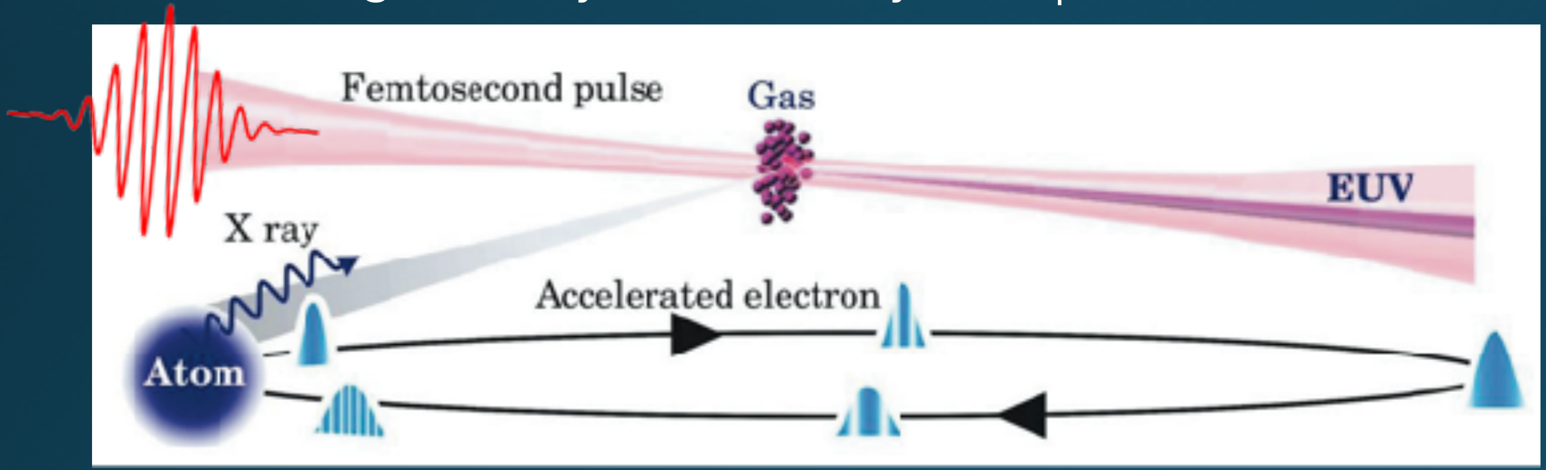

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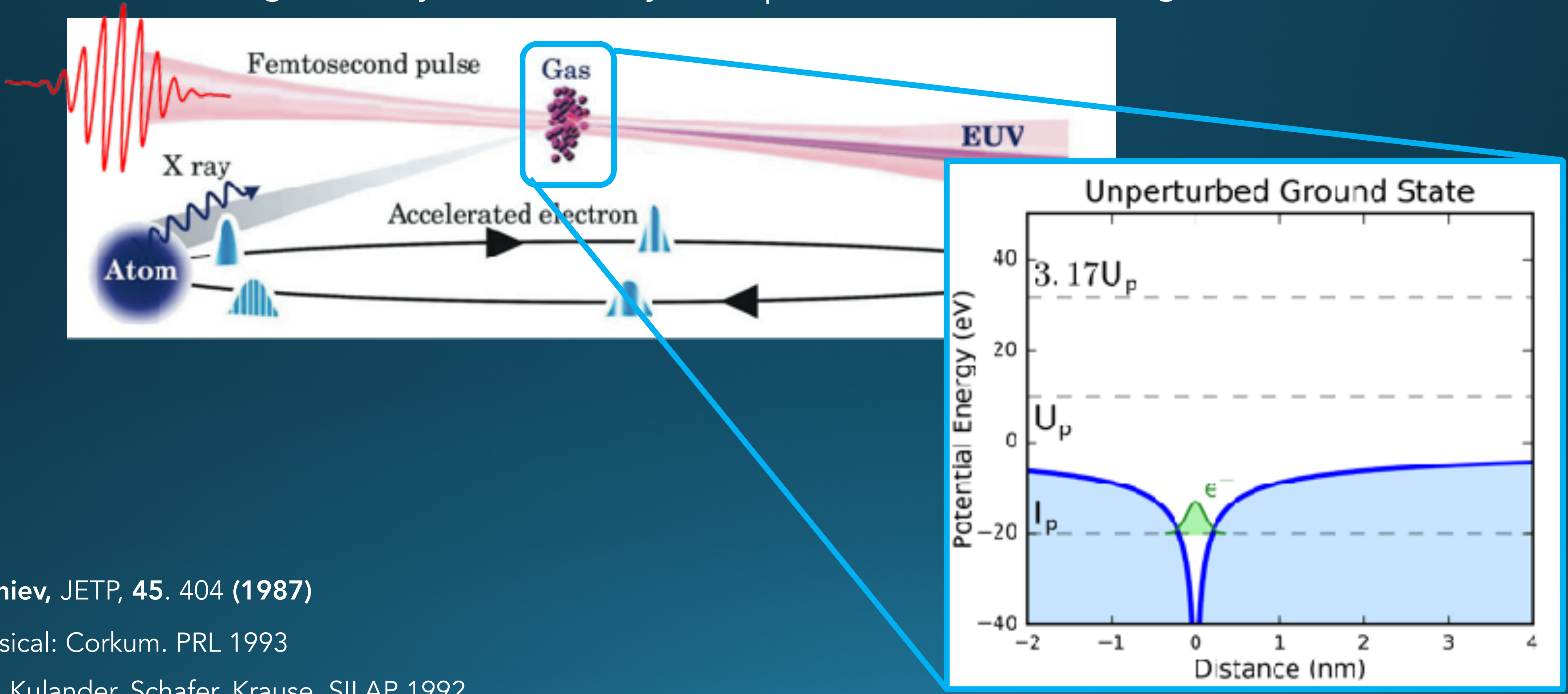

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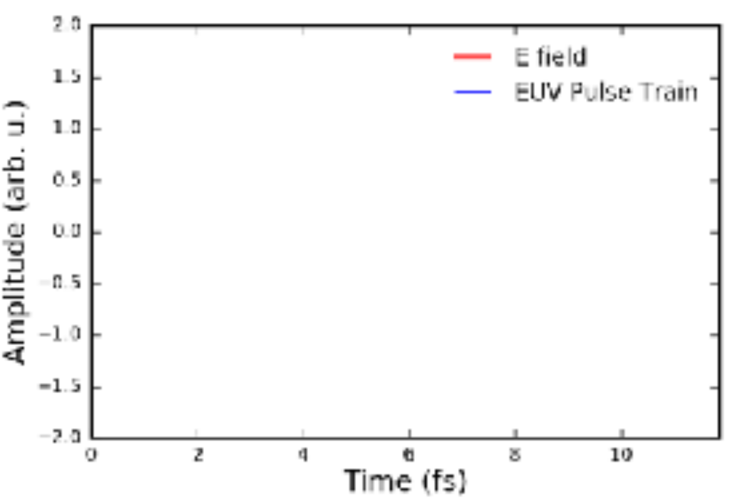
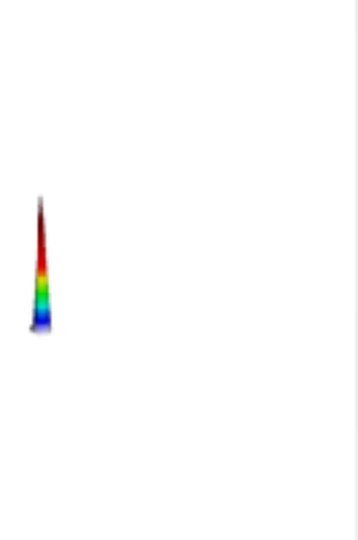
Using HHG to Generate Bright X-rays: Spectrotemporal Properties and Structure

- The entire HHG process occurs during a single pulse of the driving laser.
- Microscopically
  - Field-driven electrons recombine over a distribution of times (e.g., energies), generating harmonics at some multiple of the laser frequency.
  - Emitted light is coherent, high energy, and sub-femtosecond (10^{-15} s)!





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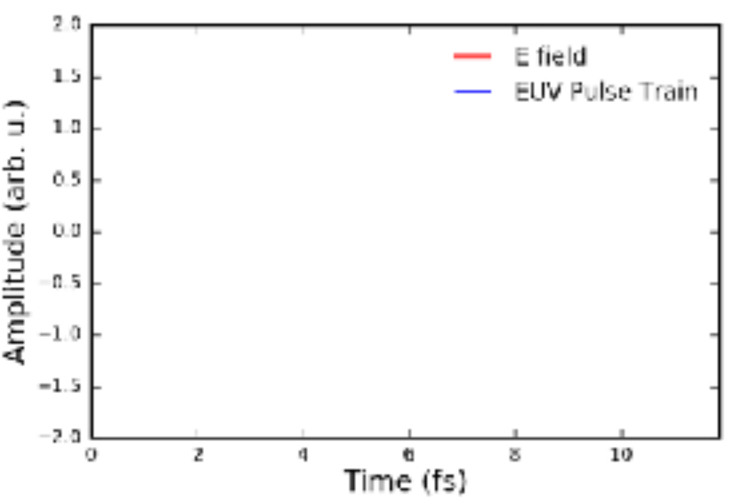

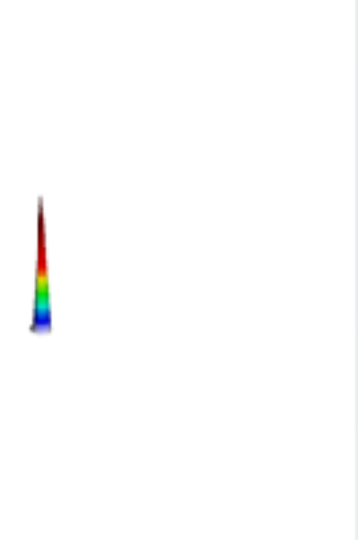

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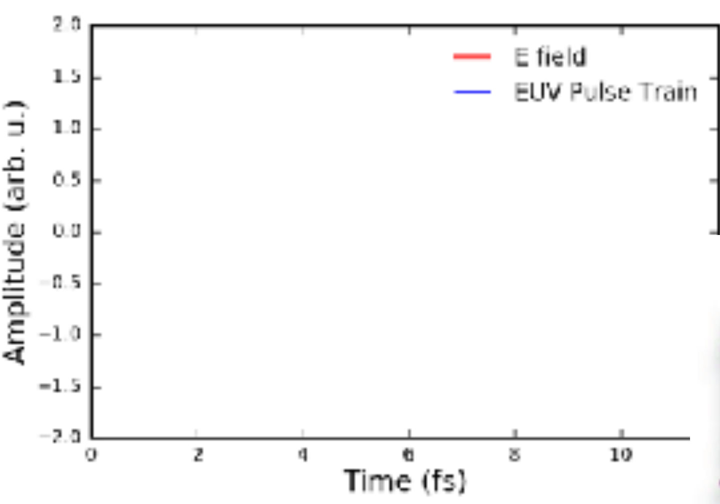

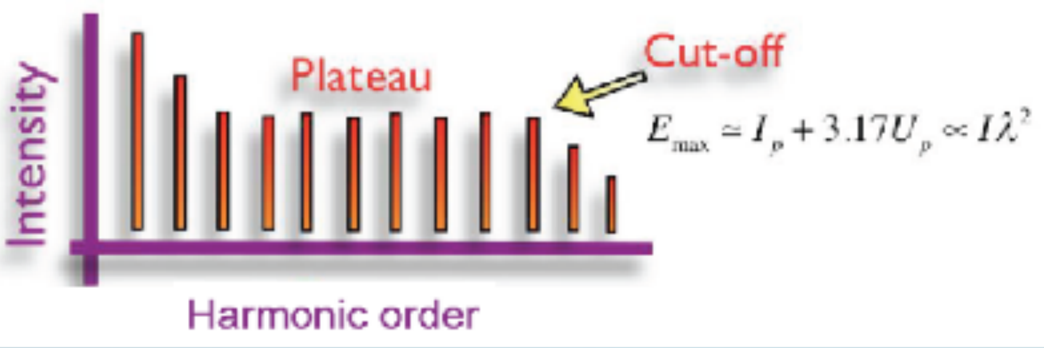

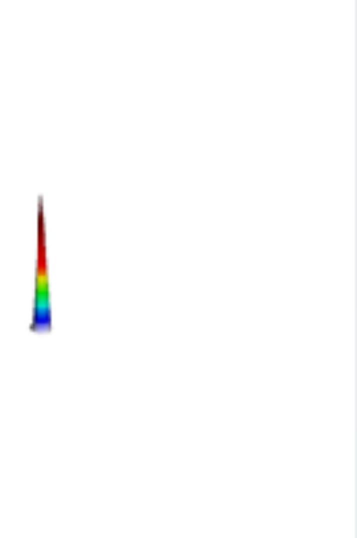

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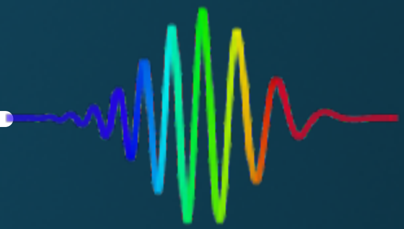

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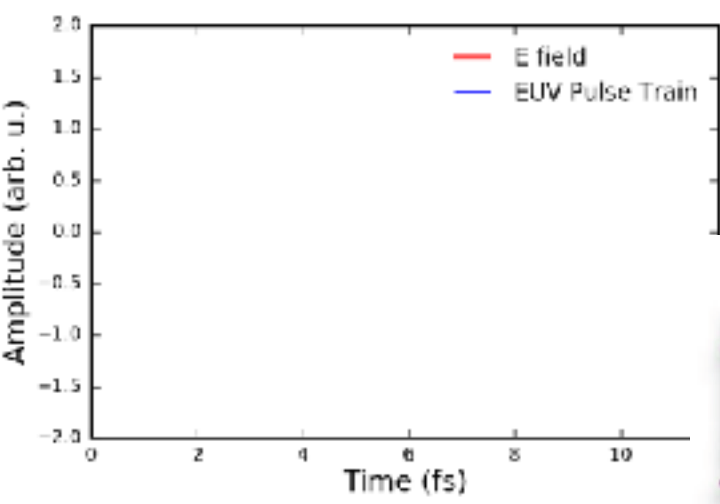

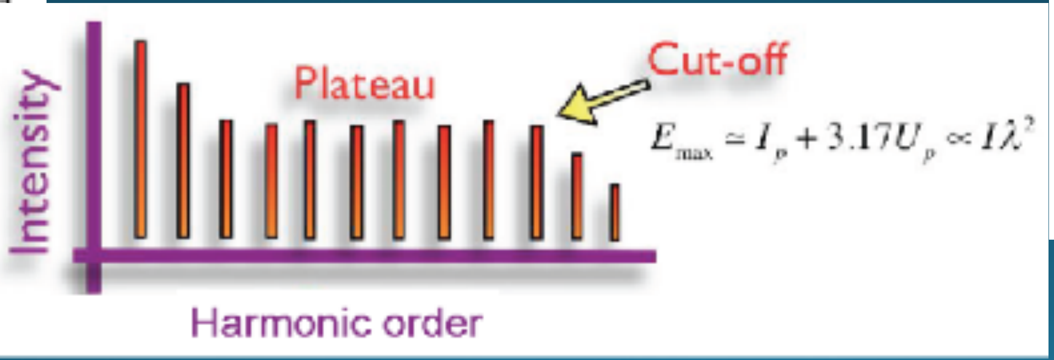

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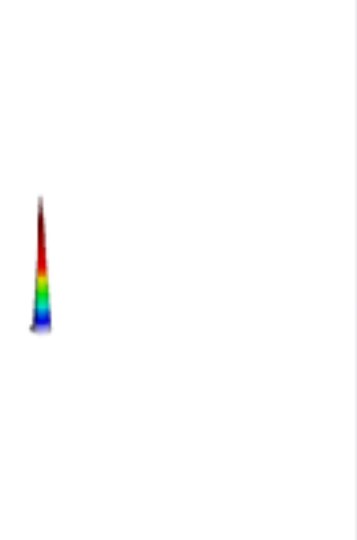

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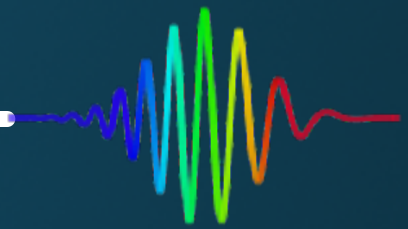

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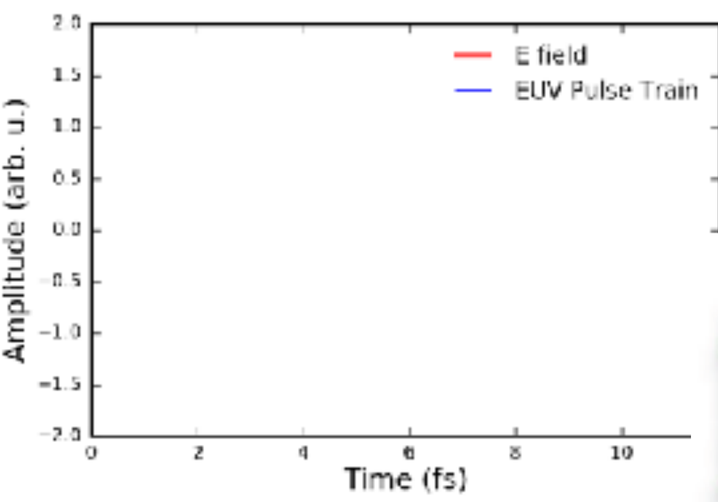

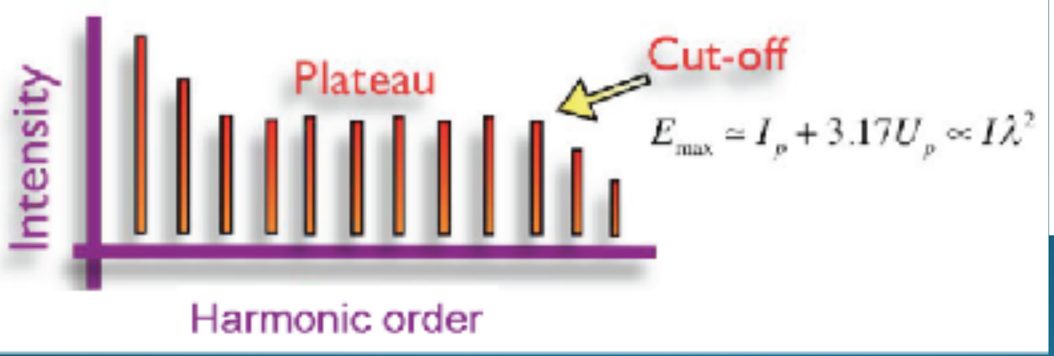

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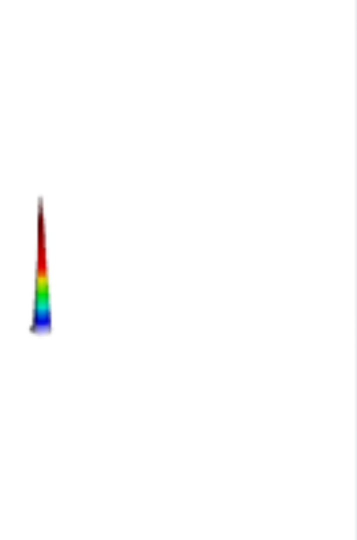

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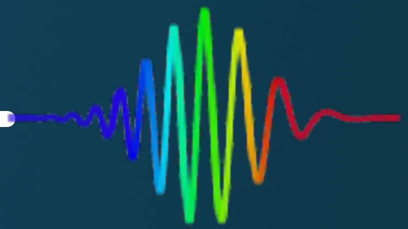

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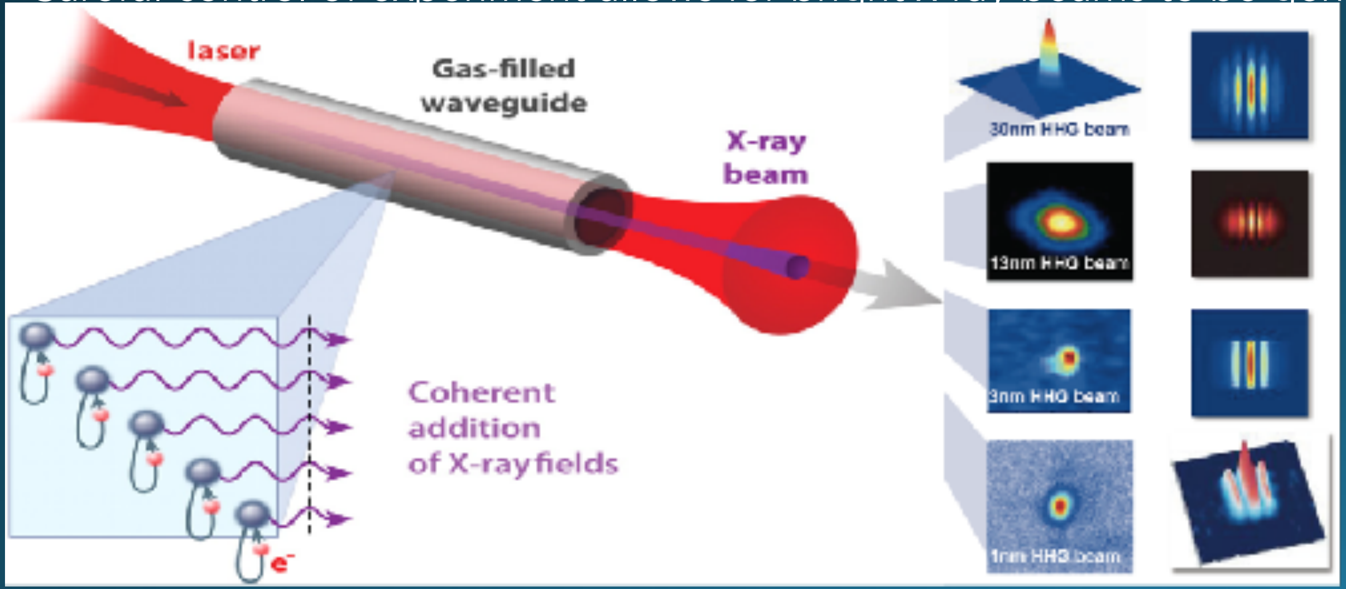

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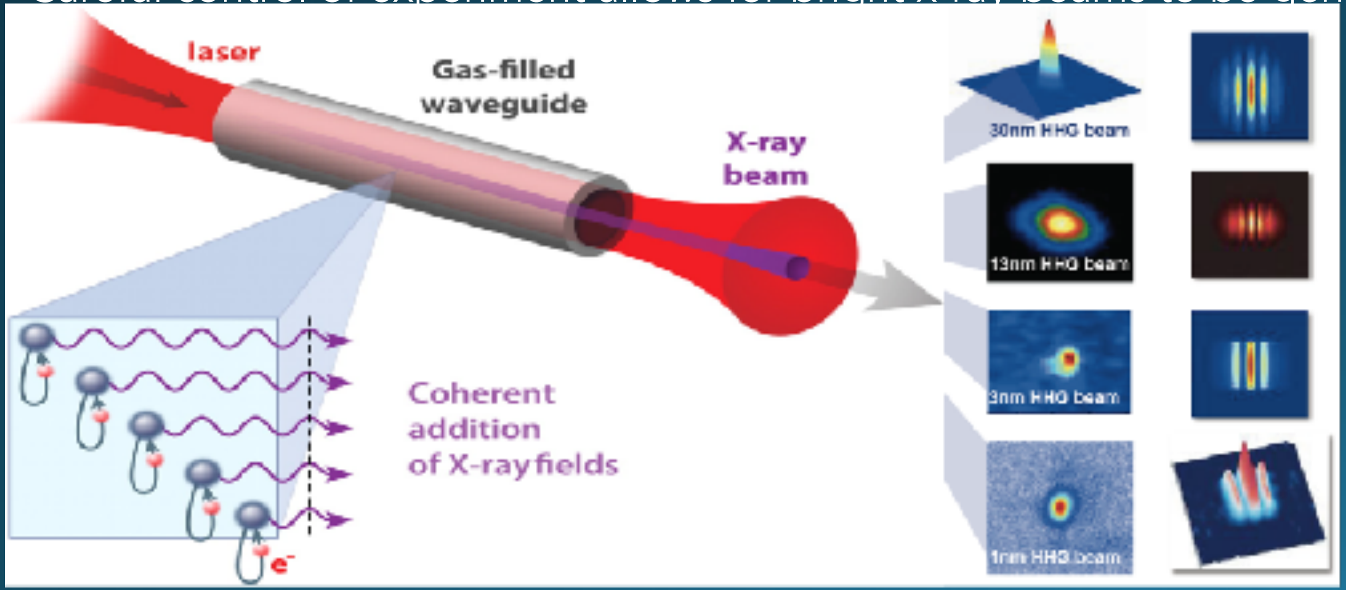

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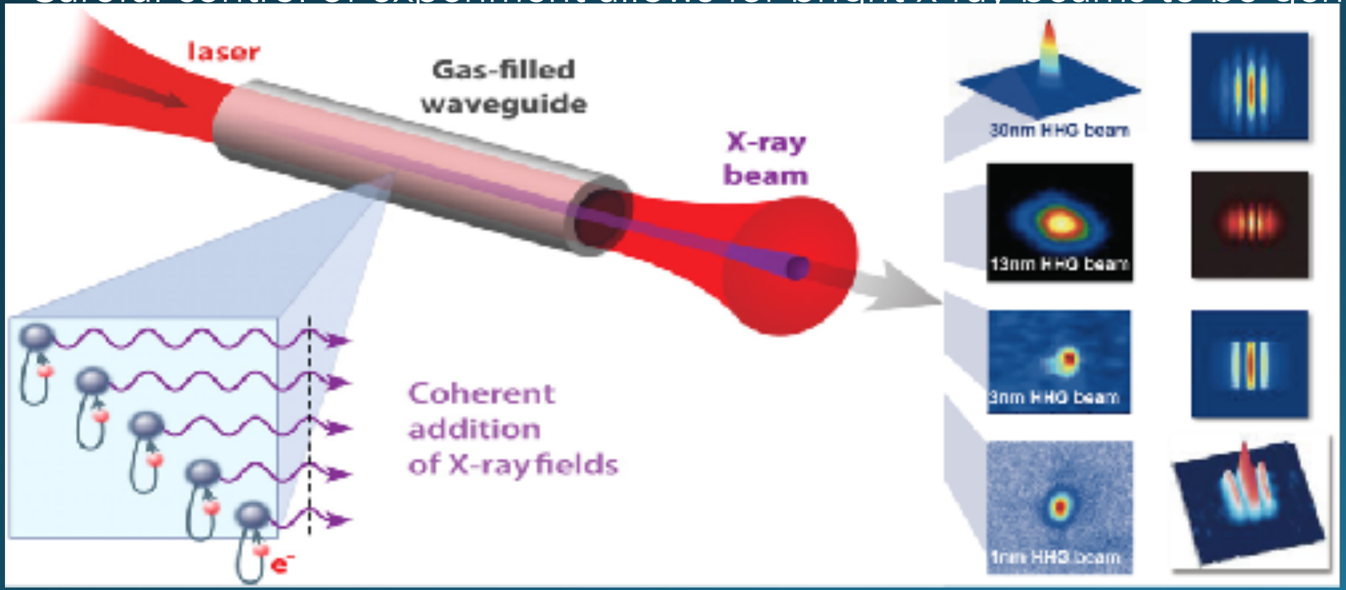

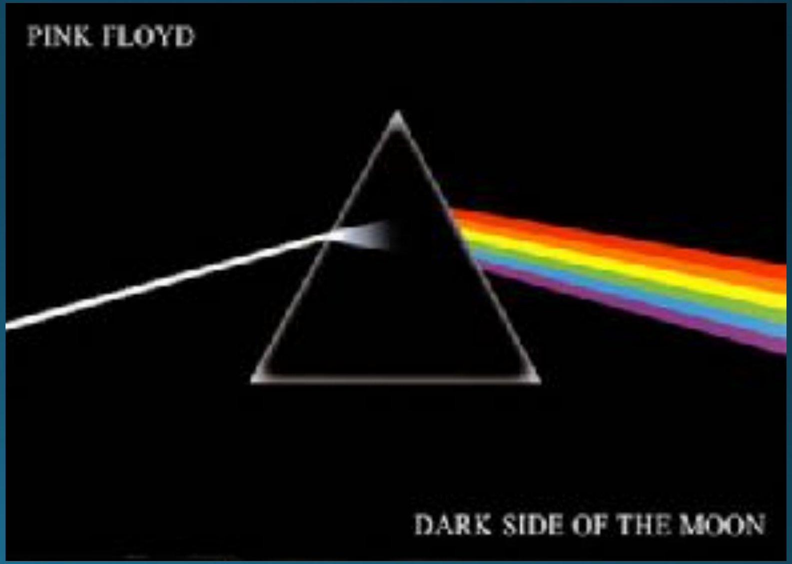

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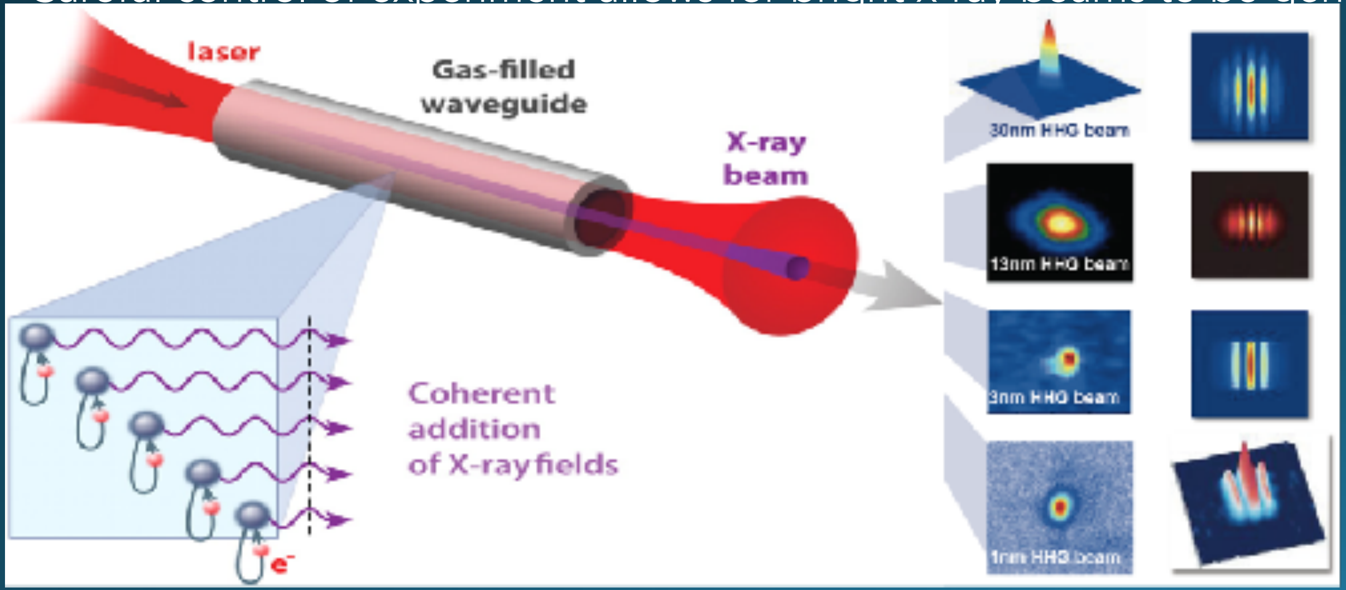

Custom Tailored EUV and X-ray Light From a Table-Top: Exquisite Control Over the Entire Up-Conversion Process

Chen, PNAS, 111, 2014
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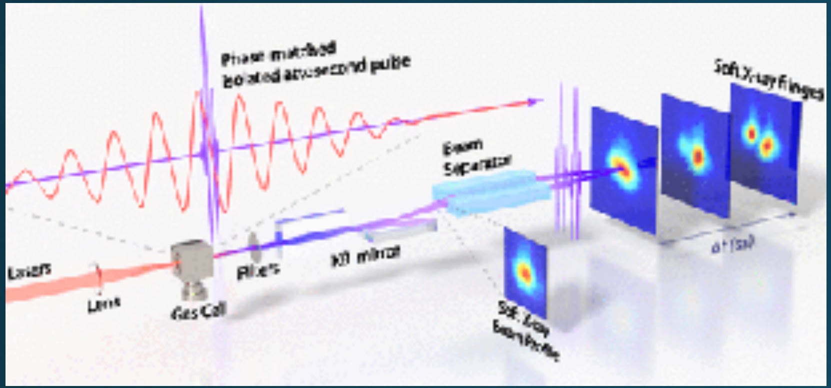

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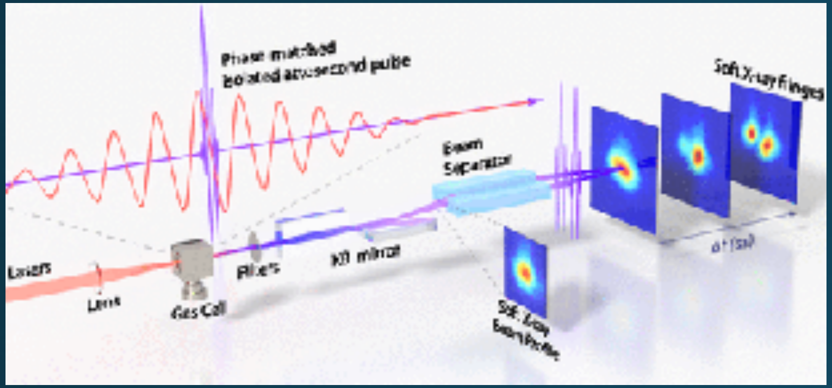
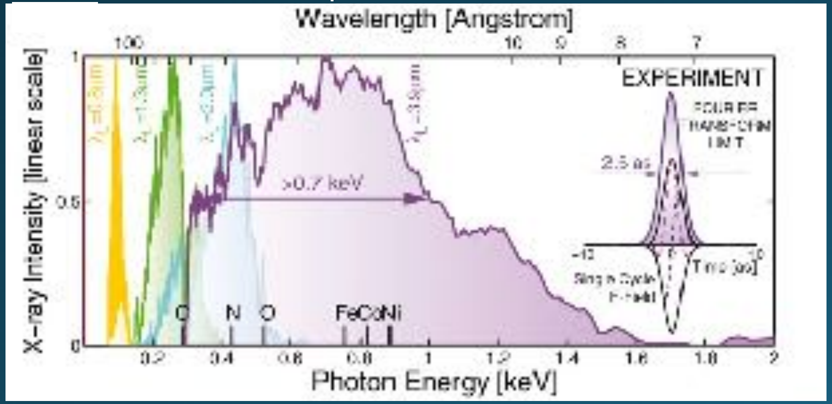


Coherent, Zeptosecond, keV X-rays



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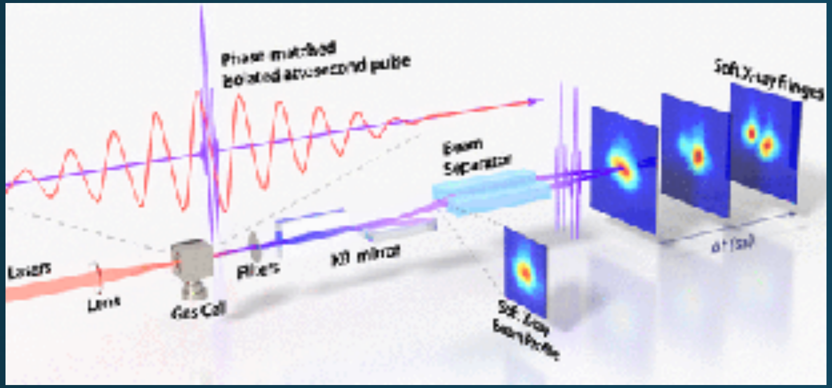

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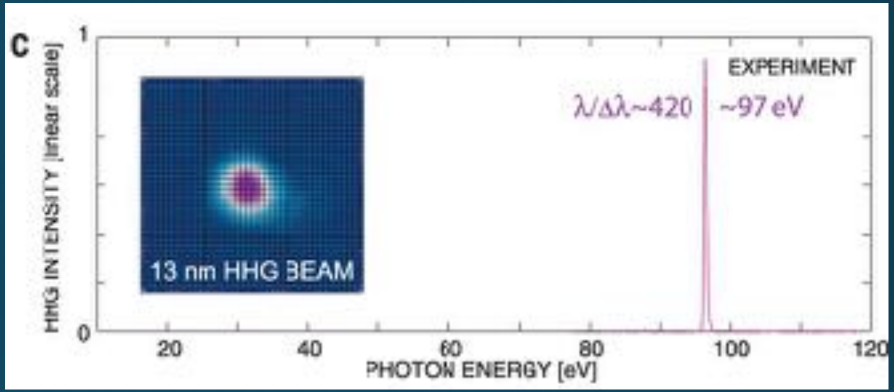

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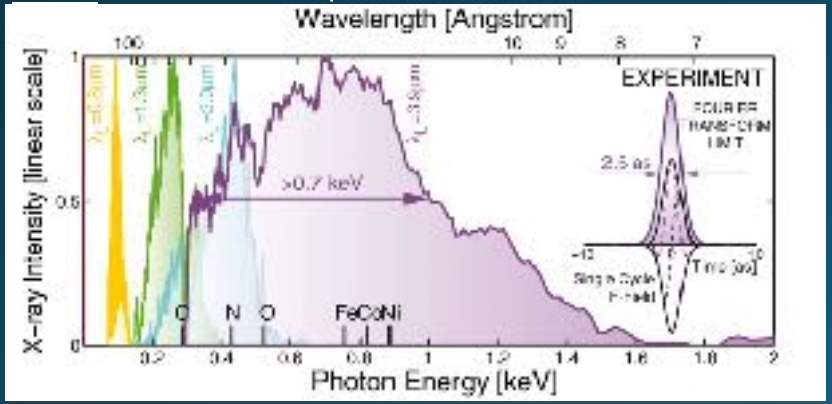

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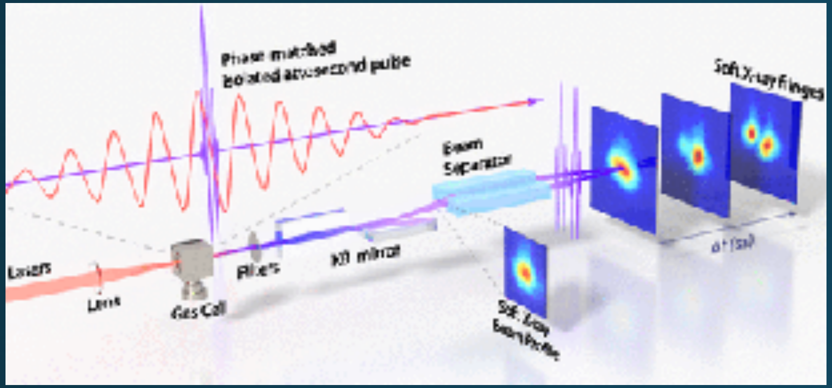

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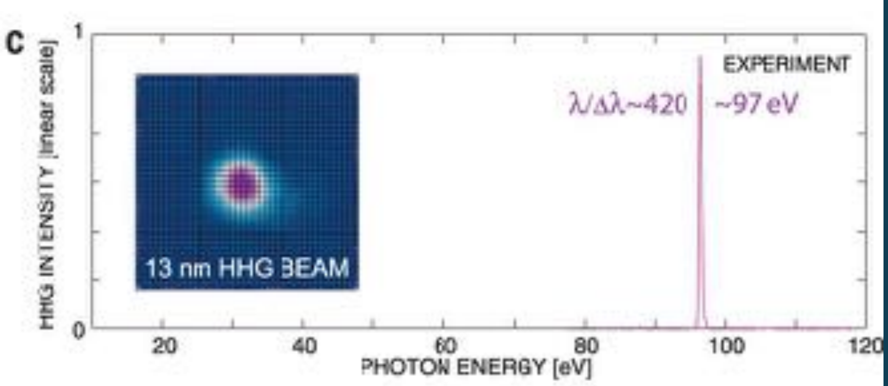

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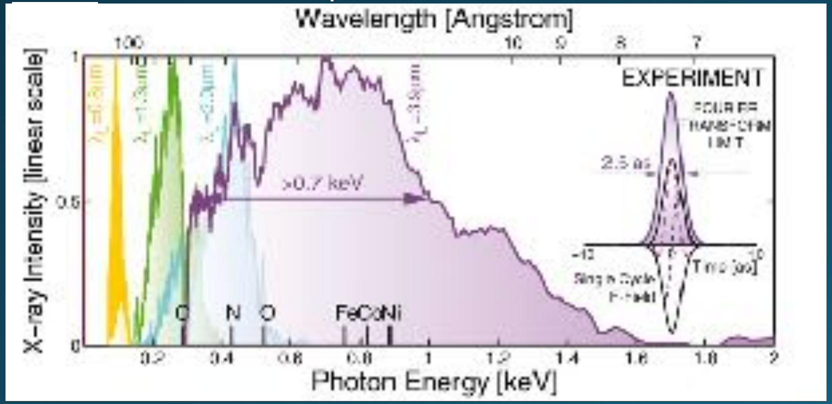
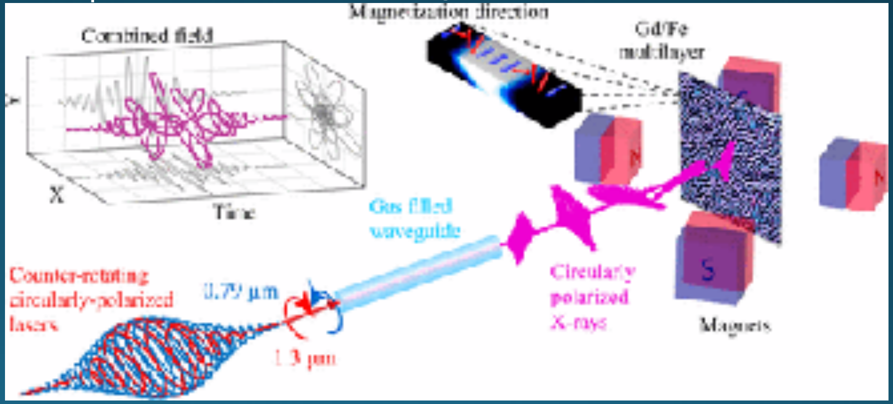
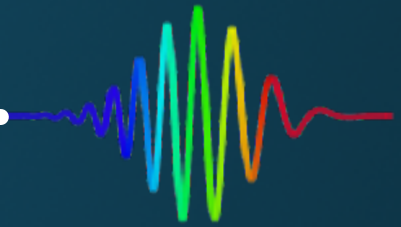


Elliptical and Circularly Polarized Harmonics

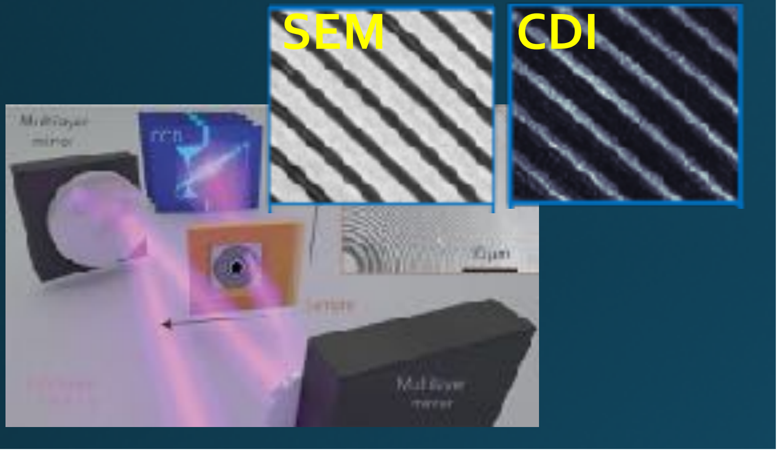


Chen, PNAS, 111, 2014
Popmintchev, Science, 6086, 2012
Popmintchev, Science, 6265, 2015
Fan, PNAS, 2015

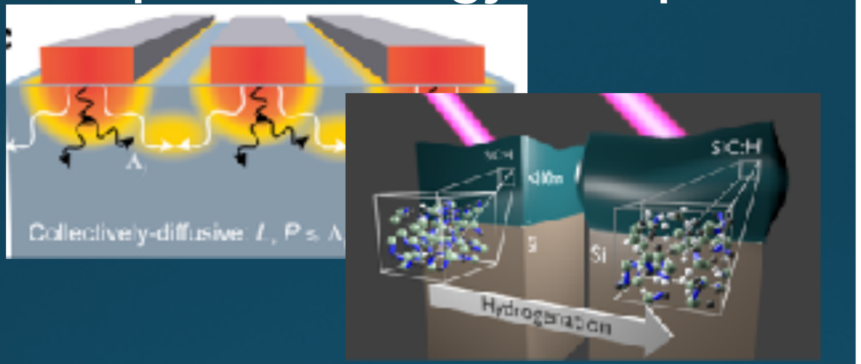
Tailored HHG Waveforms:
Ideal Probes for the Nano and Atto Worlds



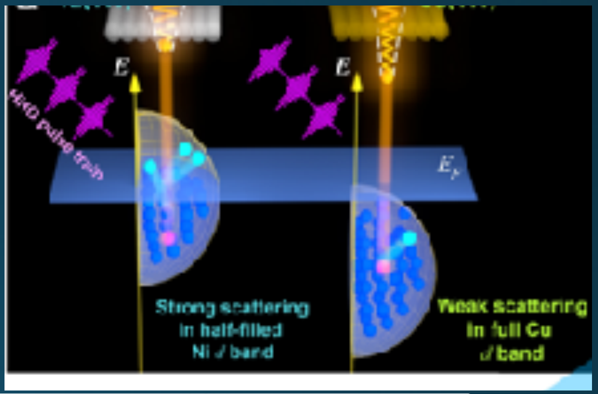
Nanoscale Imaging/Dynamics

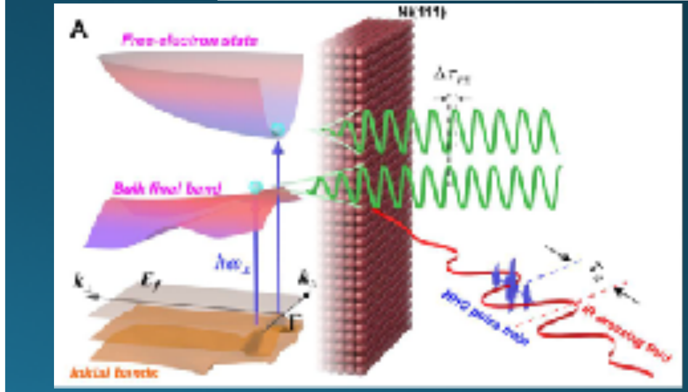


Nanoscale Mechanical Properties, Energy Transport

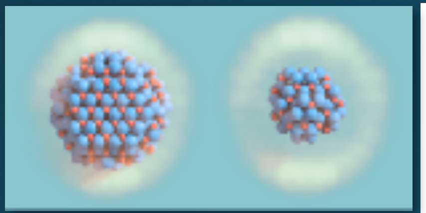


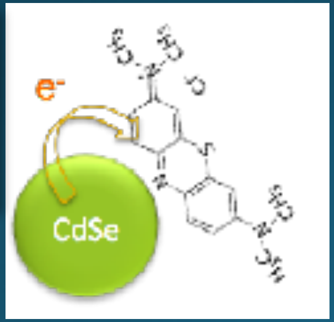
Unraveling Coupled Dynamics in Condensed Materials





Charge/Energy Flow in Molecular/Nano Systems





Spin Transport in Magnetic
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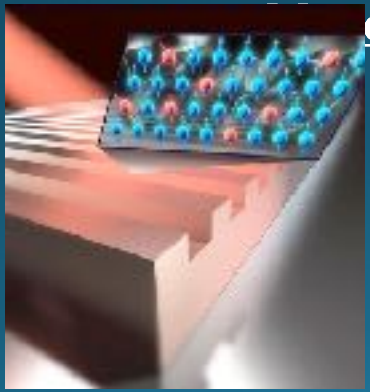

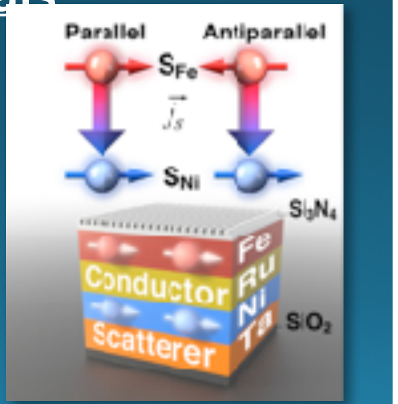

Nano X-Ray Vision:
Directly Visualizing the Nano Landscape

- The nanotechnology sector (e.g., computer chips, cameras, etc.) is quickly outpacing its own characterization methods.
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  - Shorter wavelengths = smaller features!

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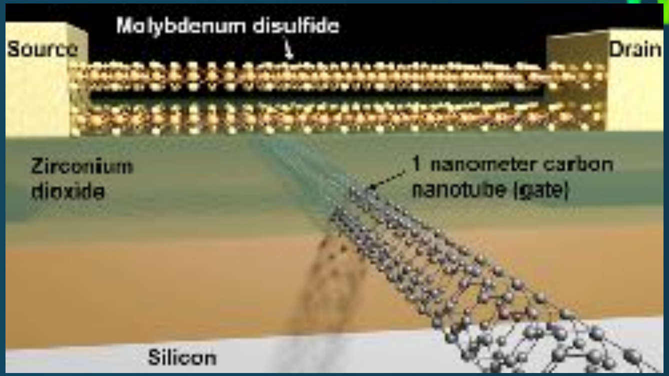

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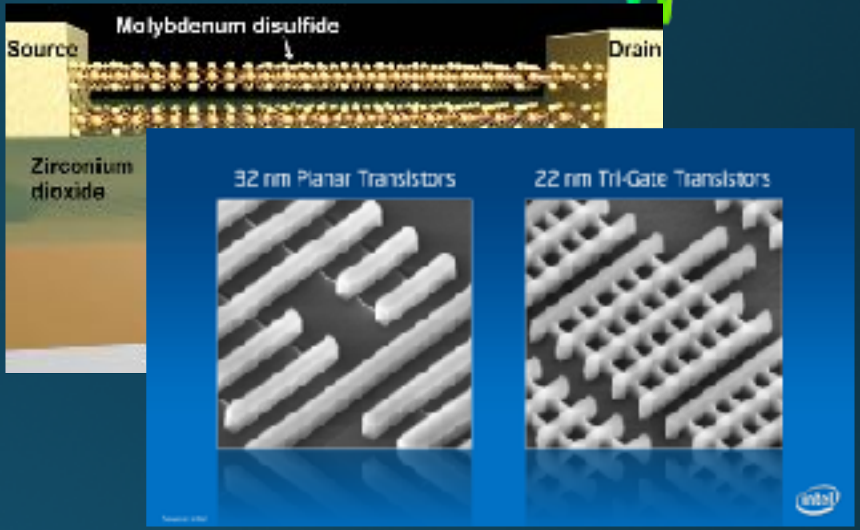

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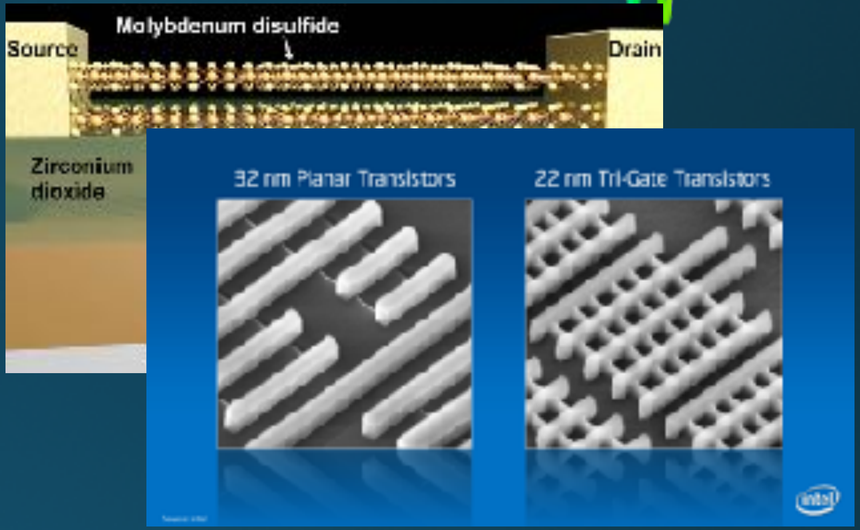

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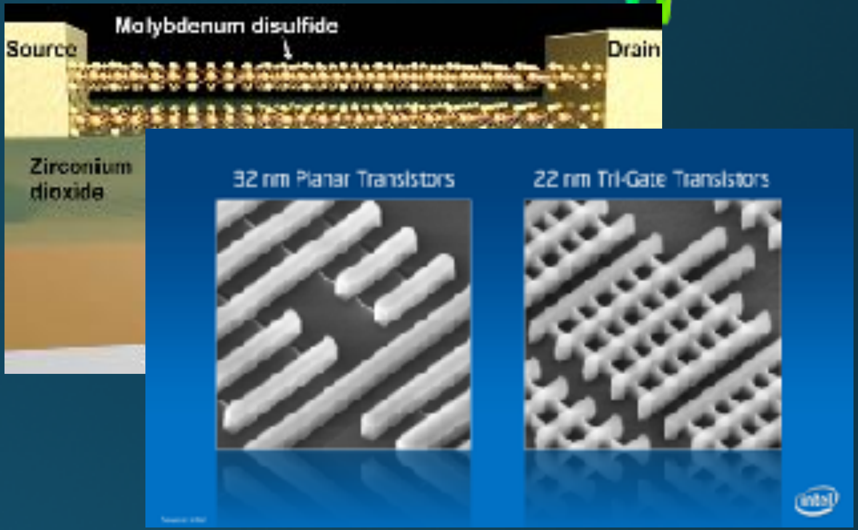

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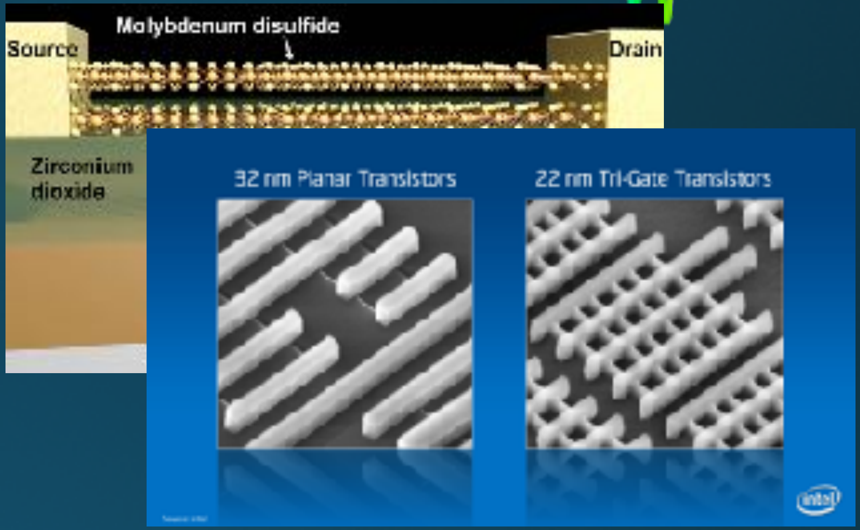

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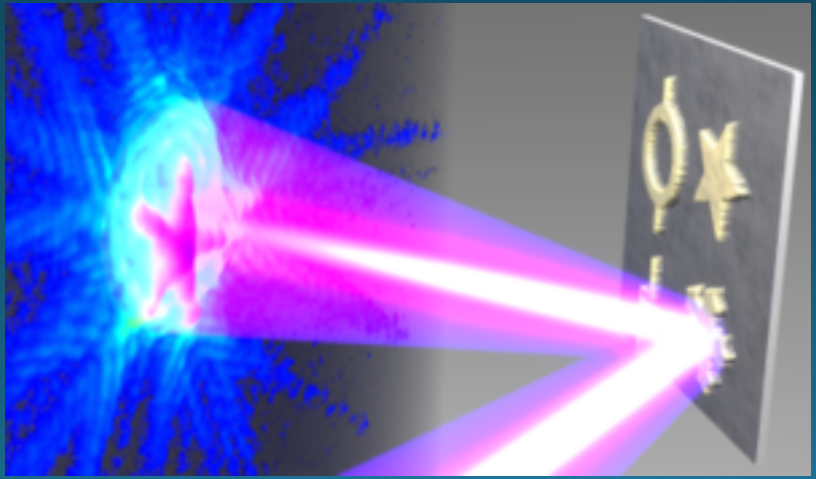

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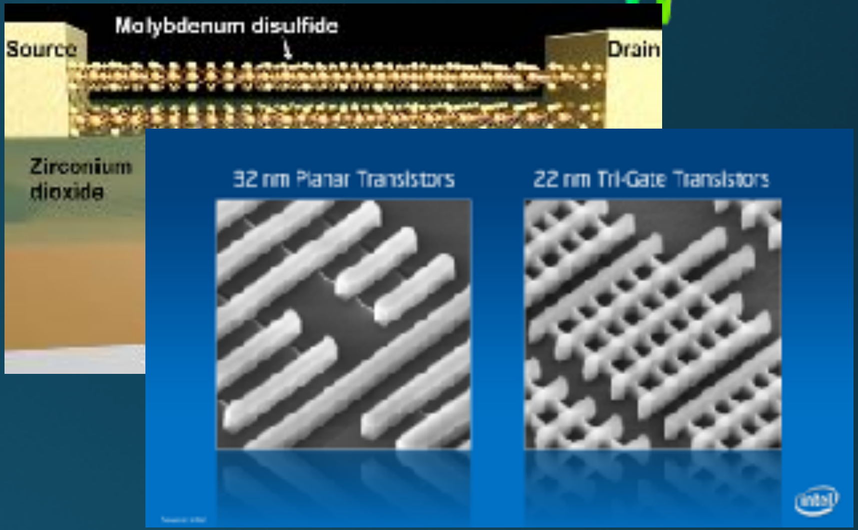

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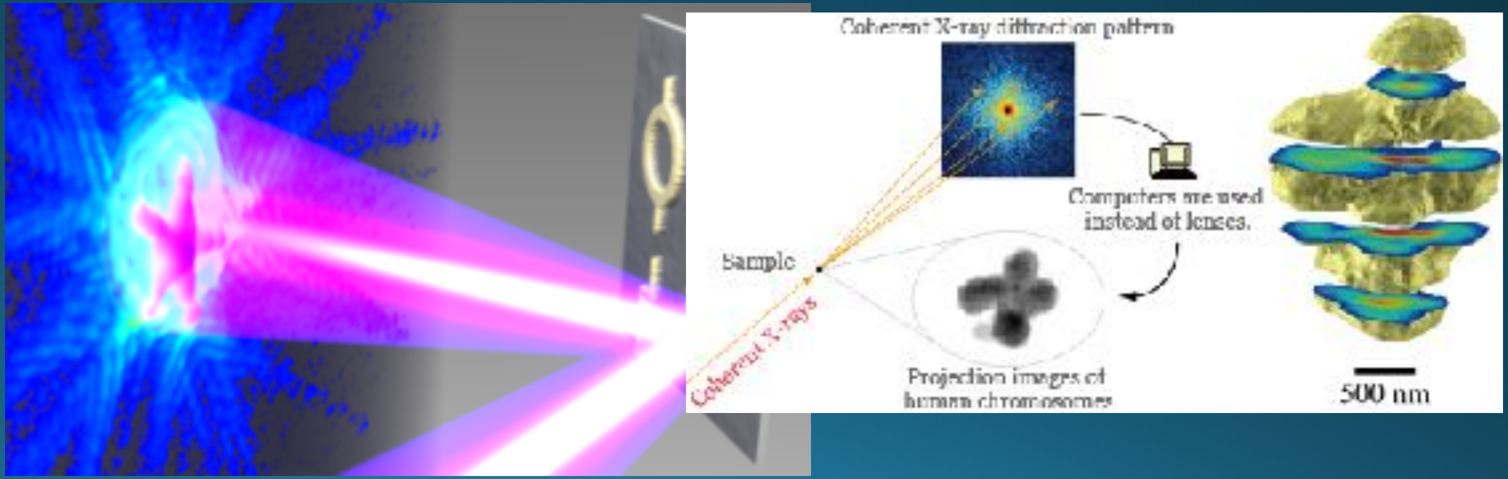
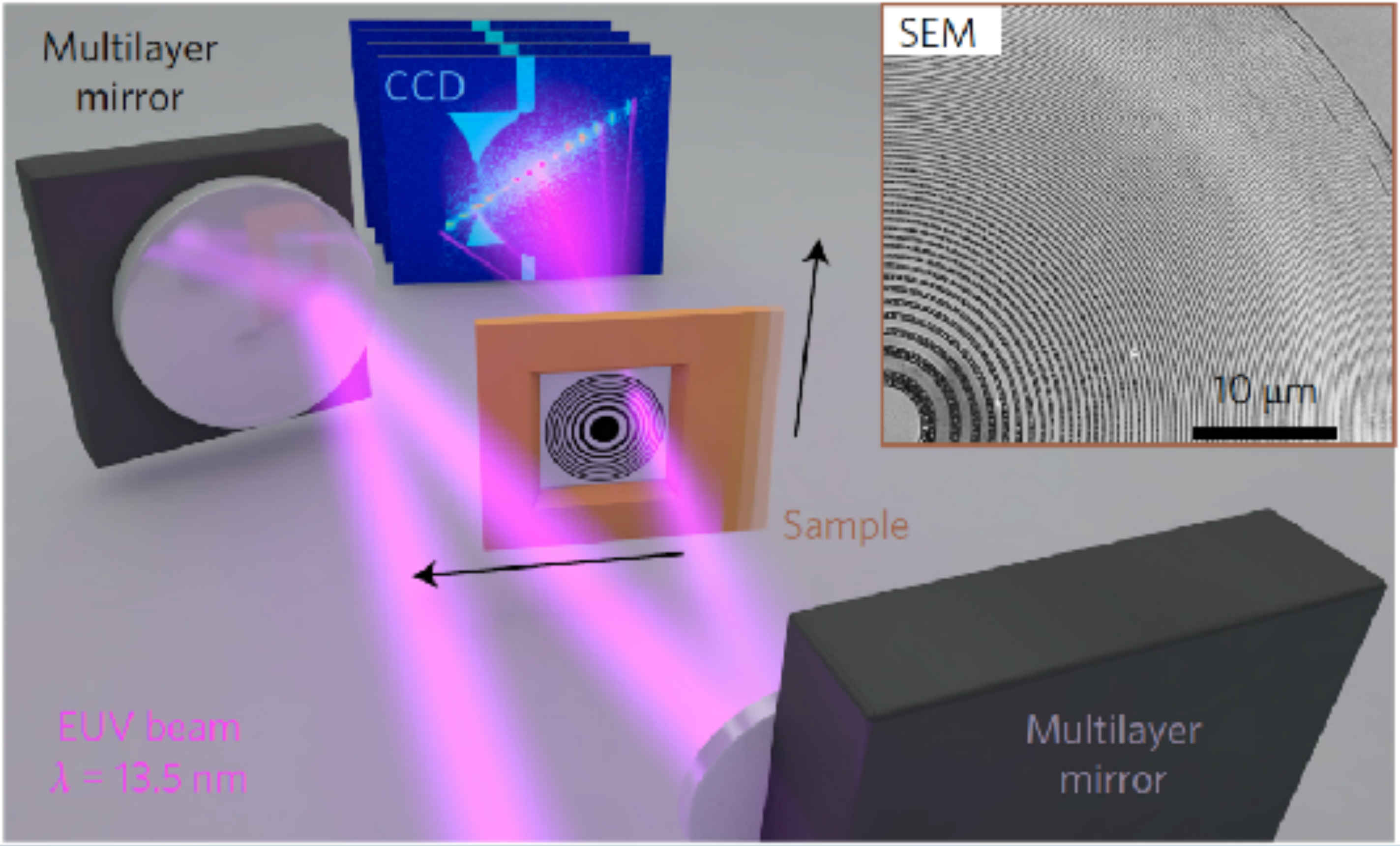


Pushing the Resolution of HHG-based Imaging: First Sub-Wavelength Images!



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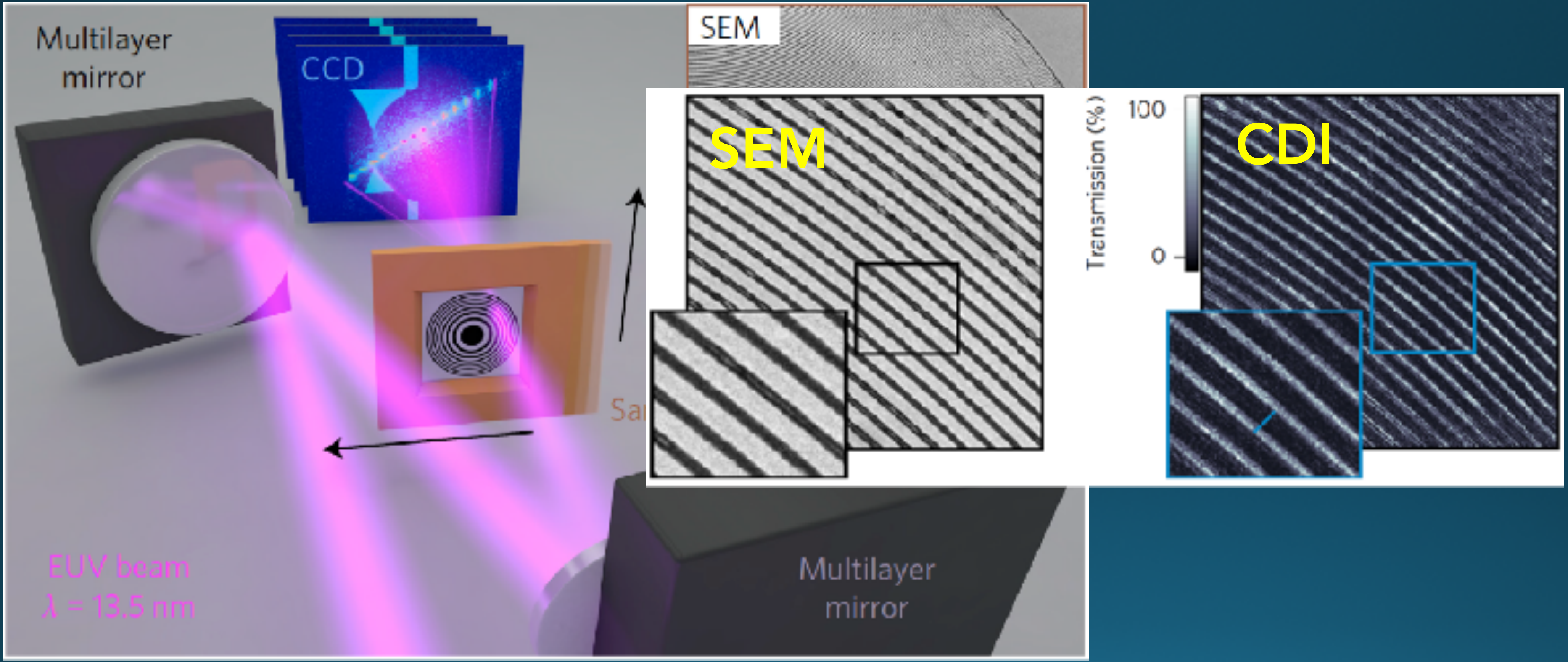

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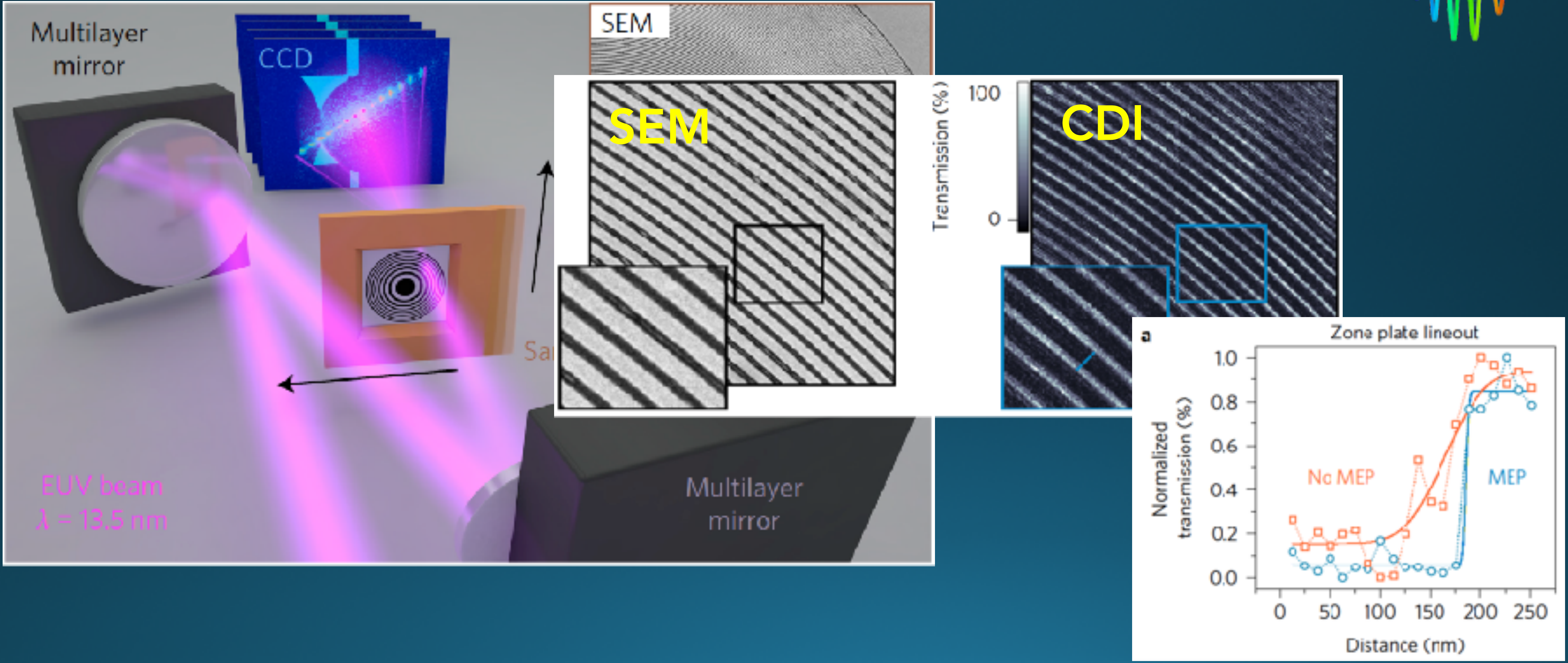

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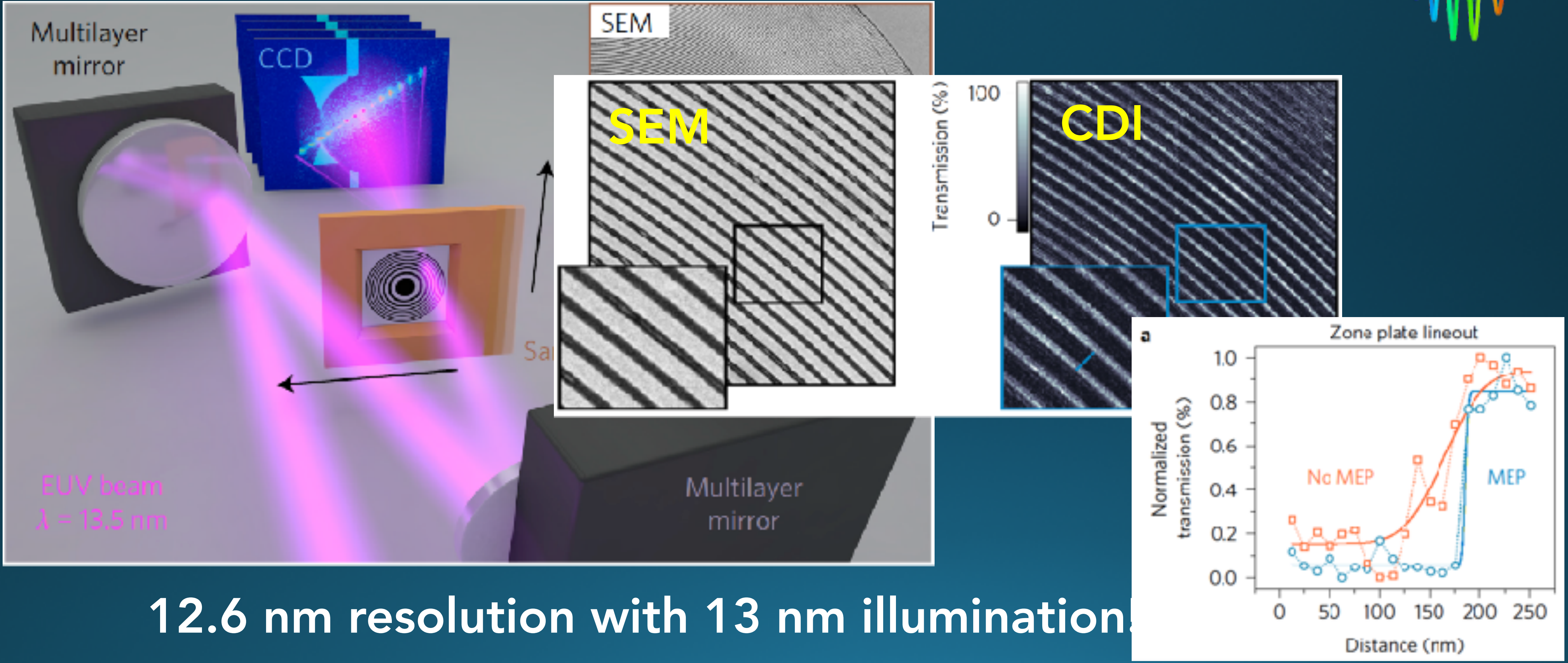
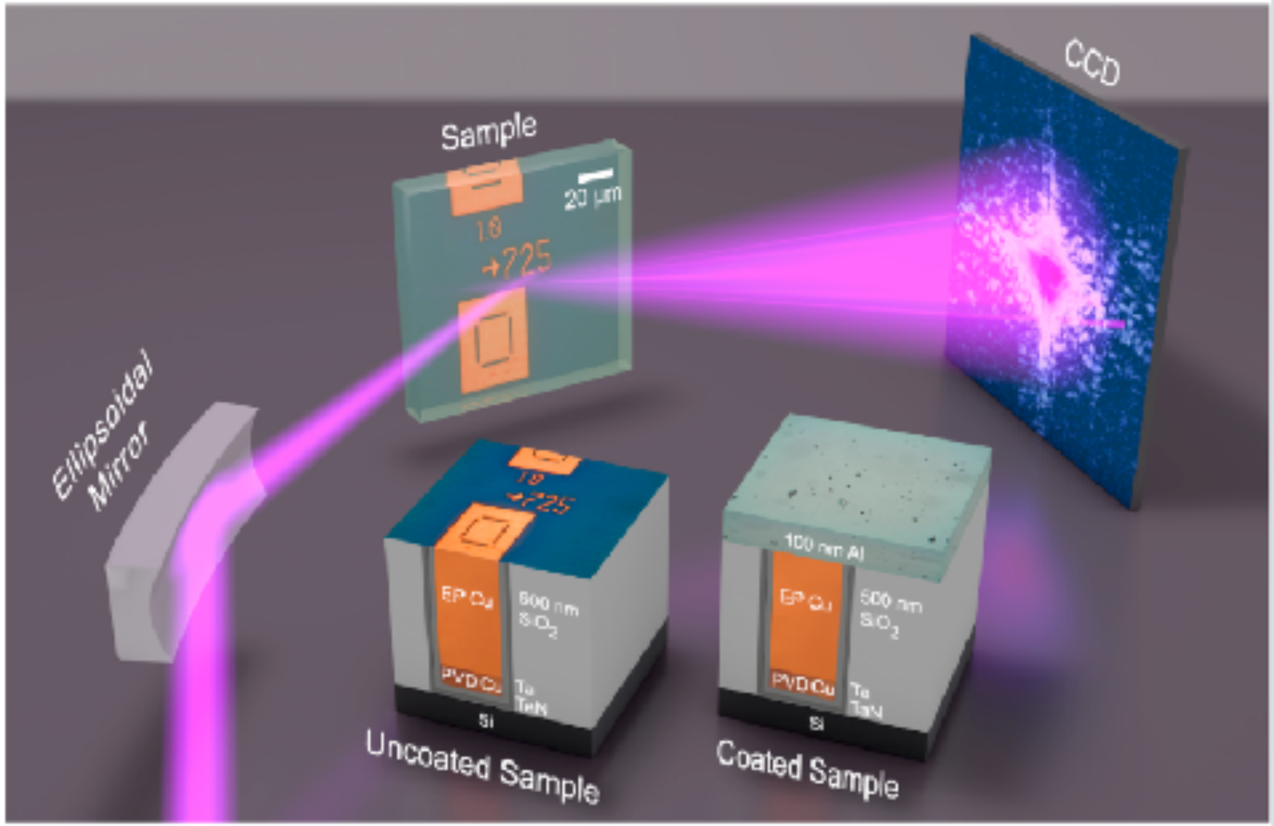


12.6 nm resolution with 13 nm illumination!

Real (No Really) X-Ray Vision: Peering Through Diffusion Layers in Materials



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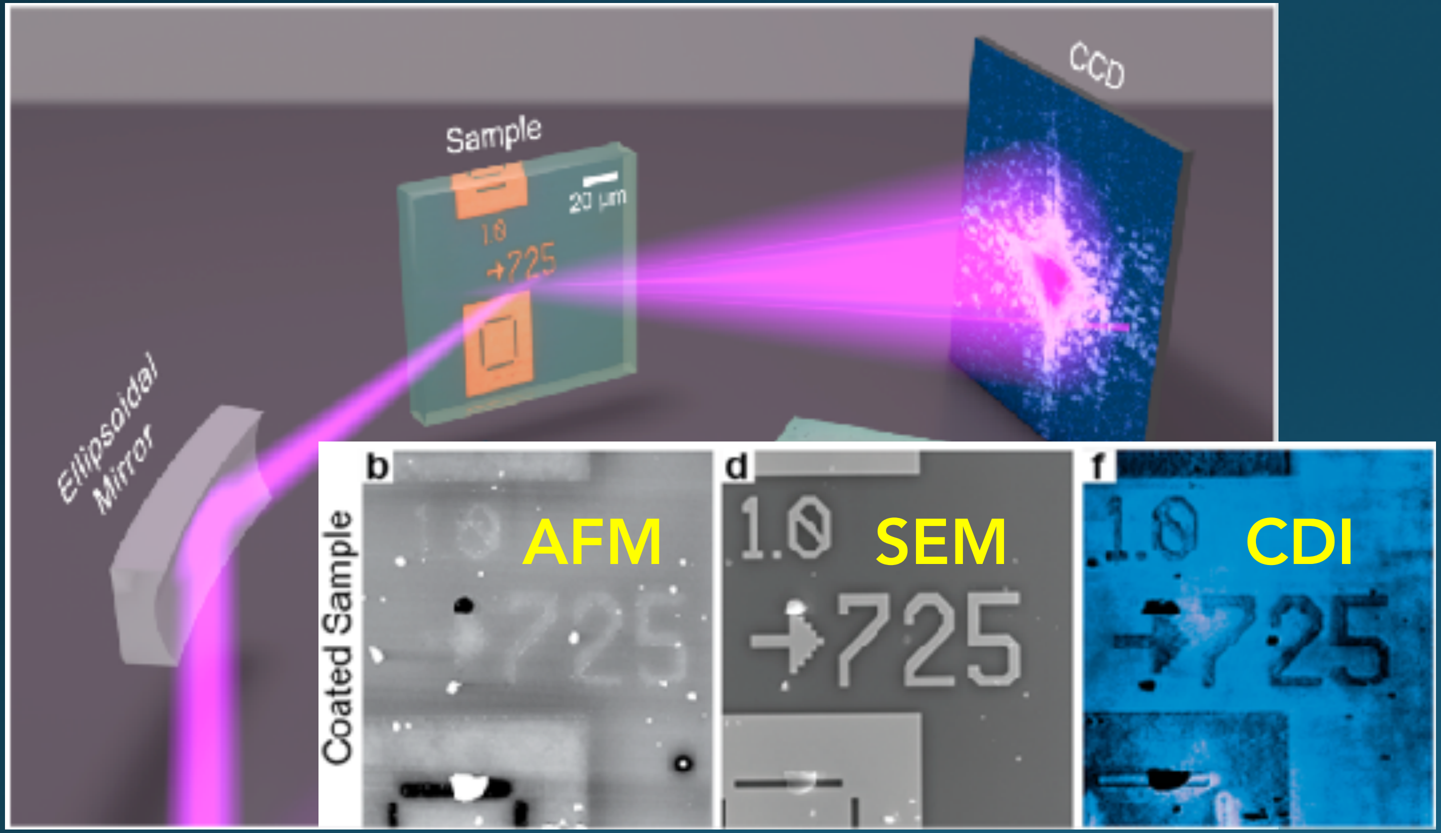

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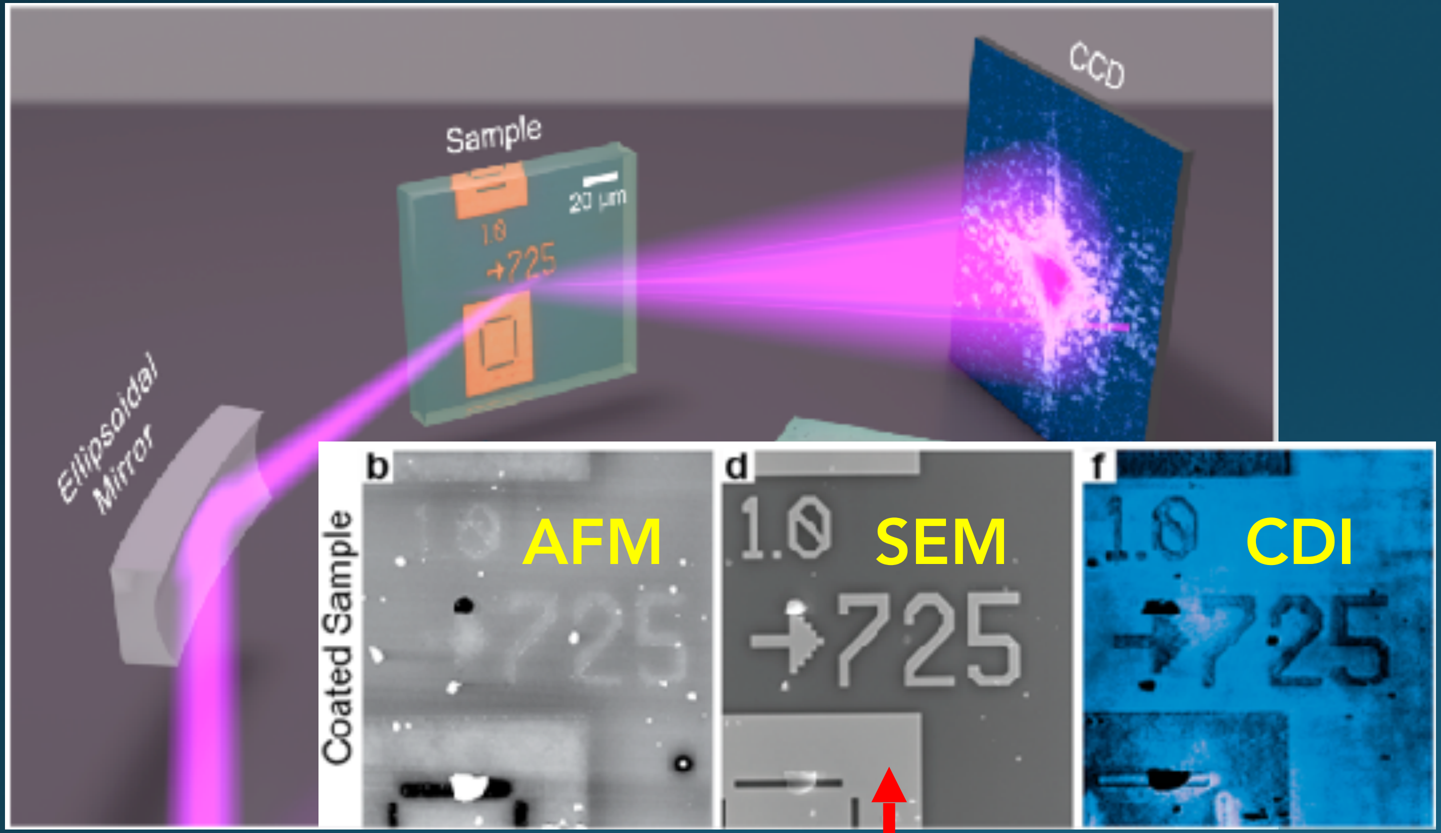

Destrcutive

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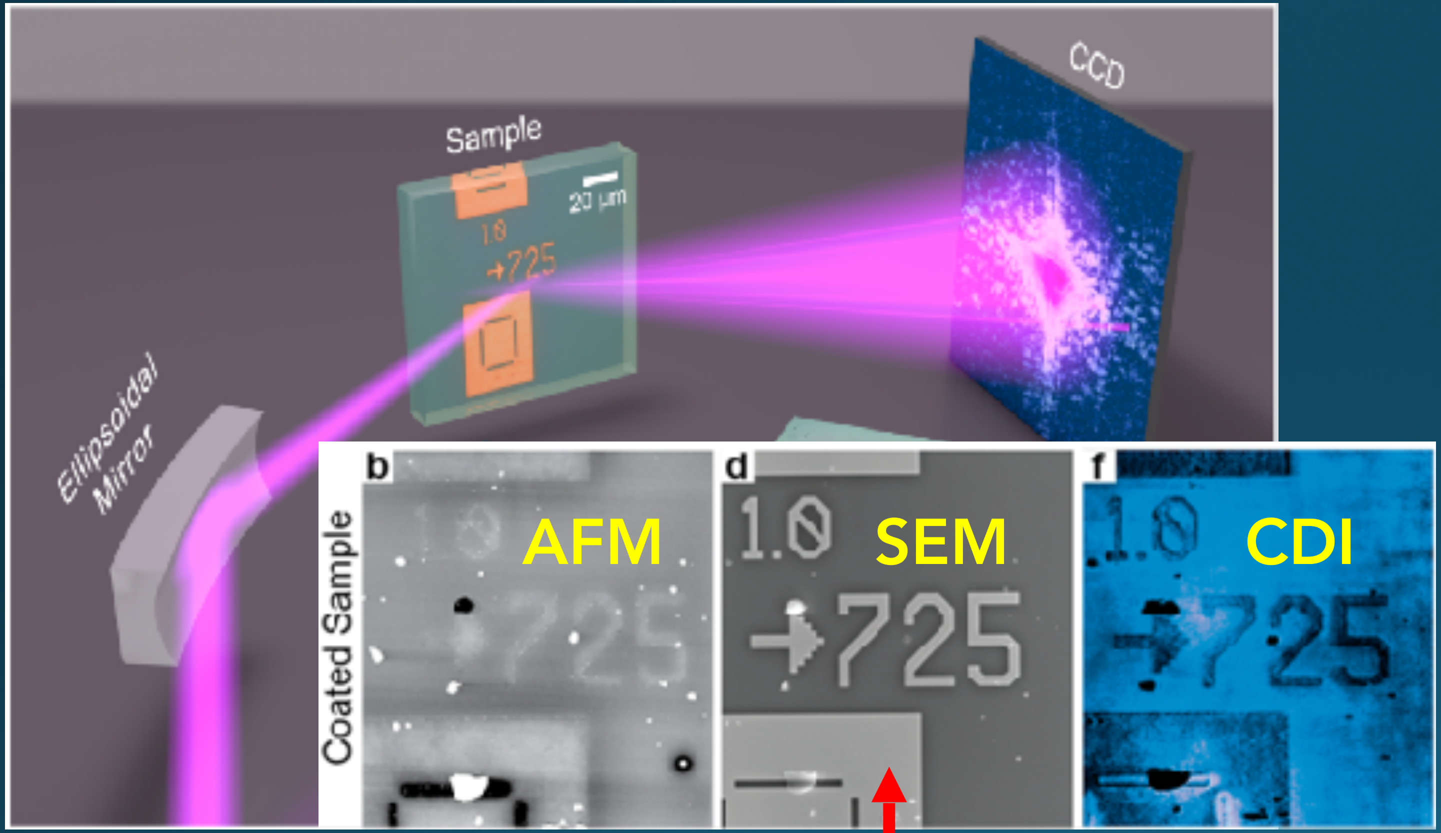

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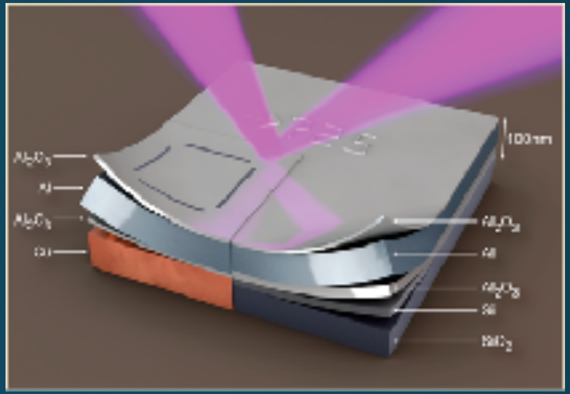

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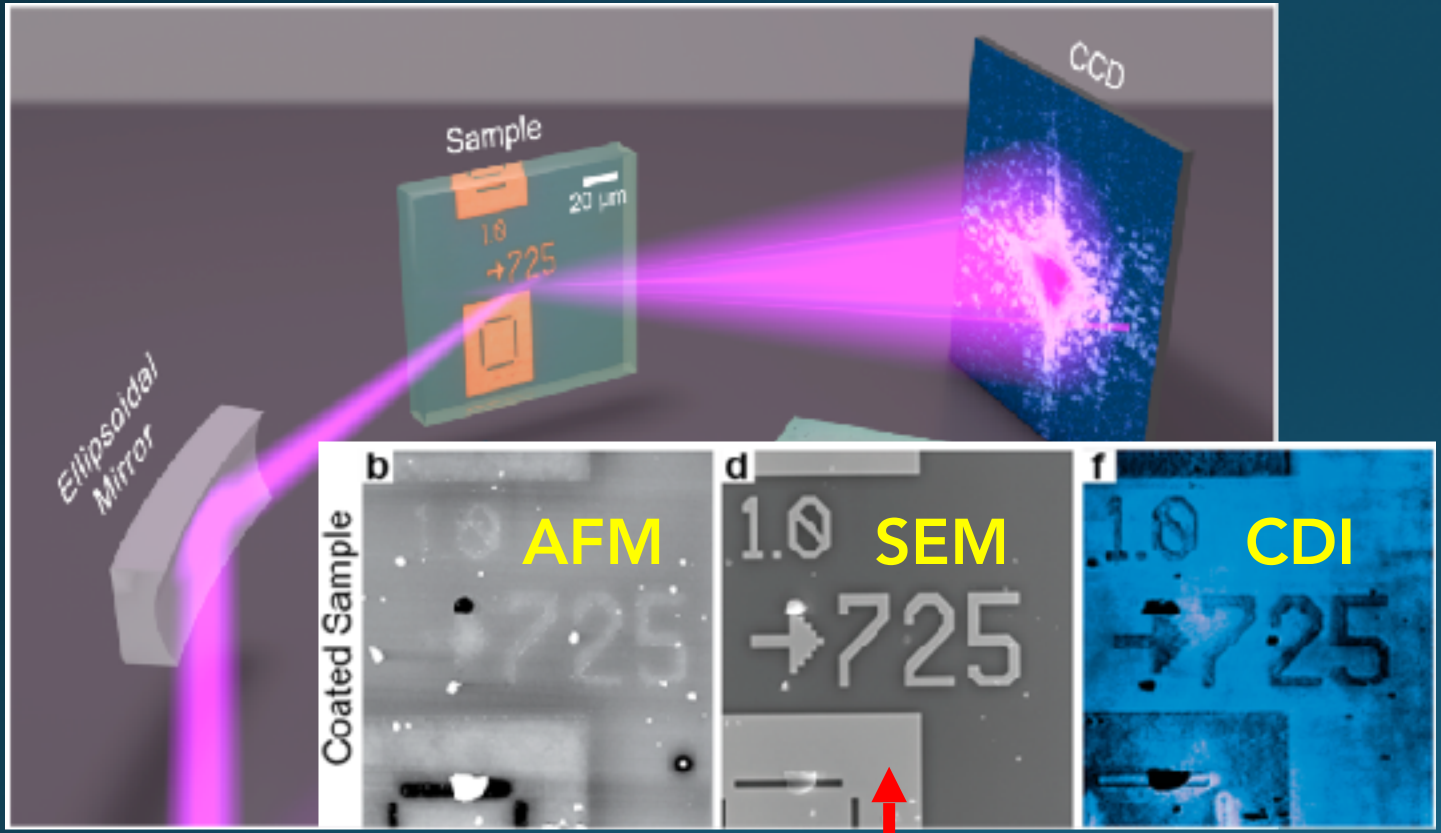

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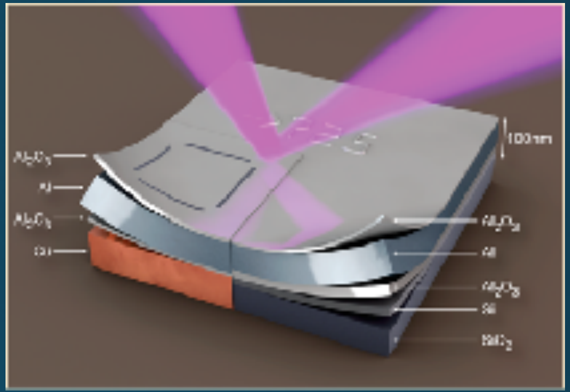

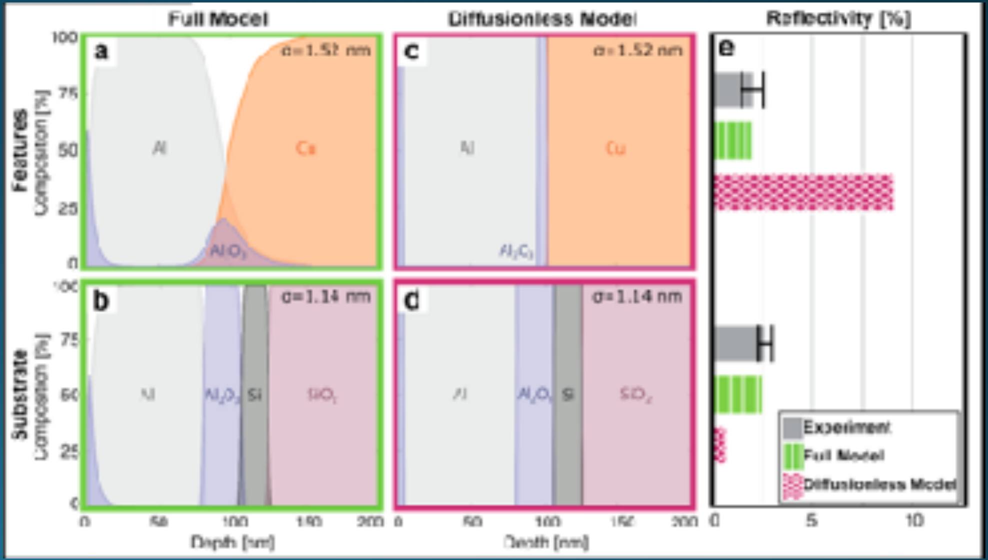

X-Ray Movies:
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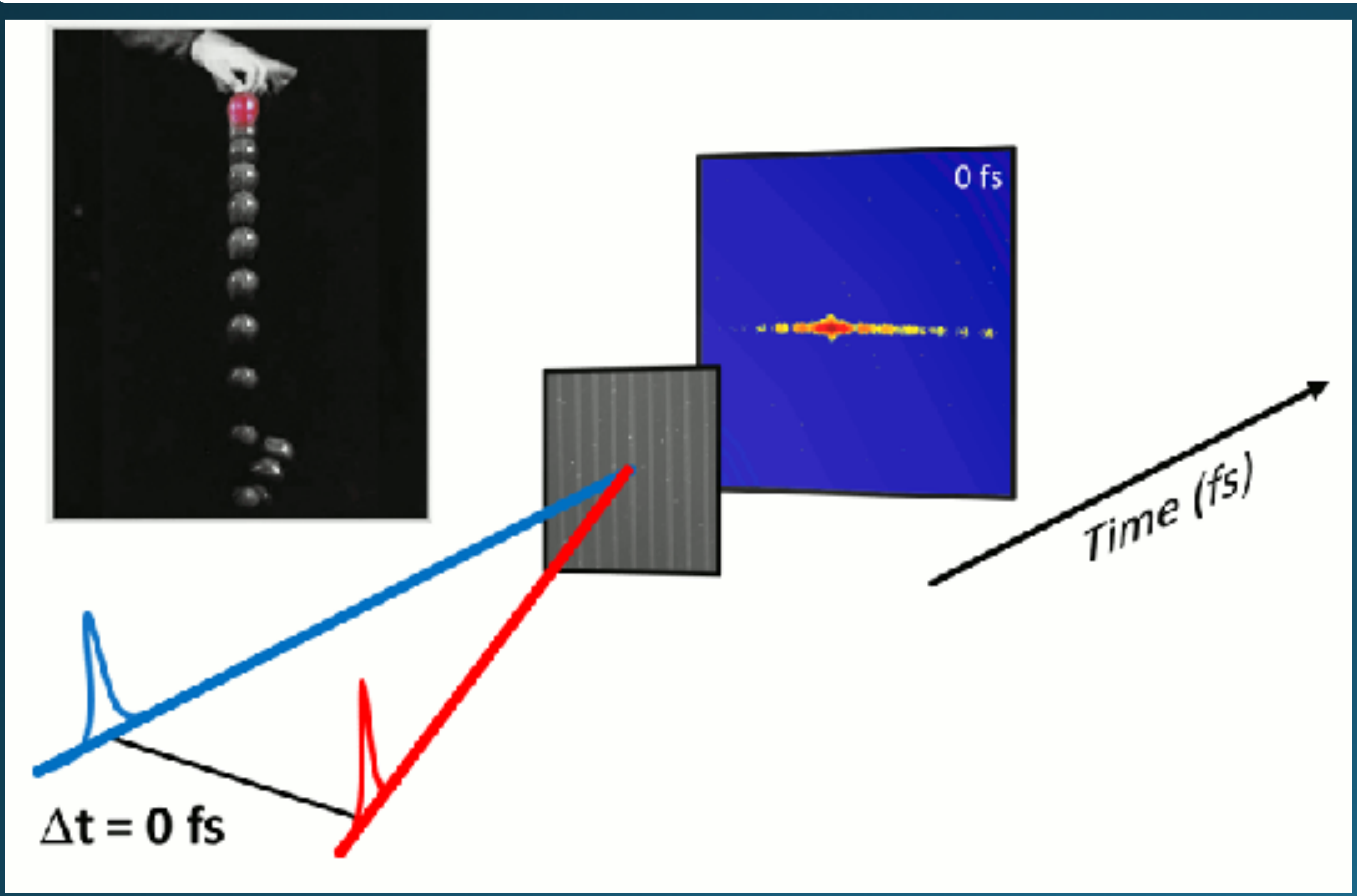

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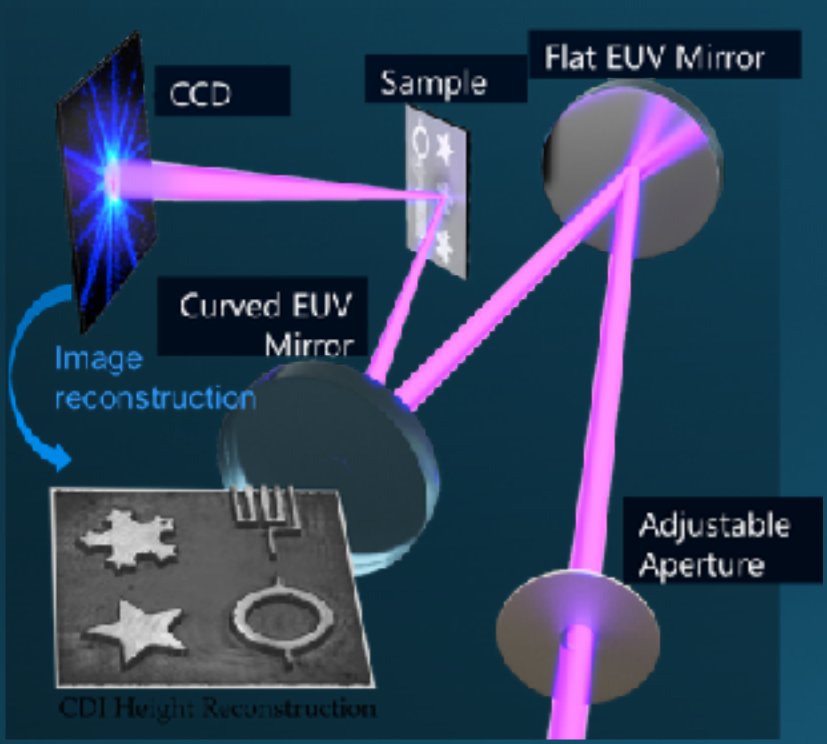

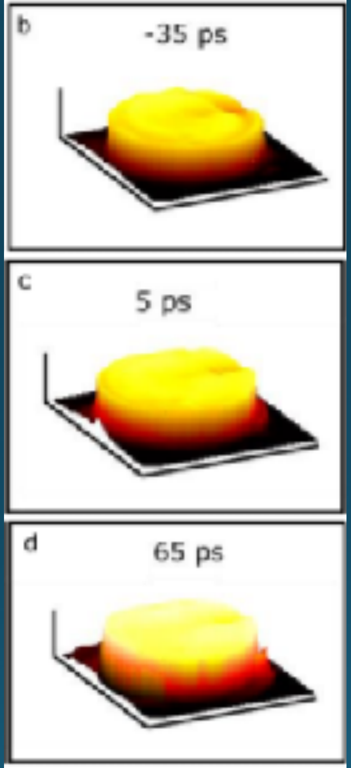

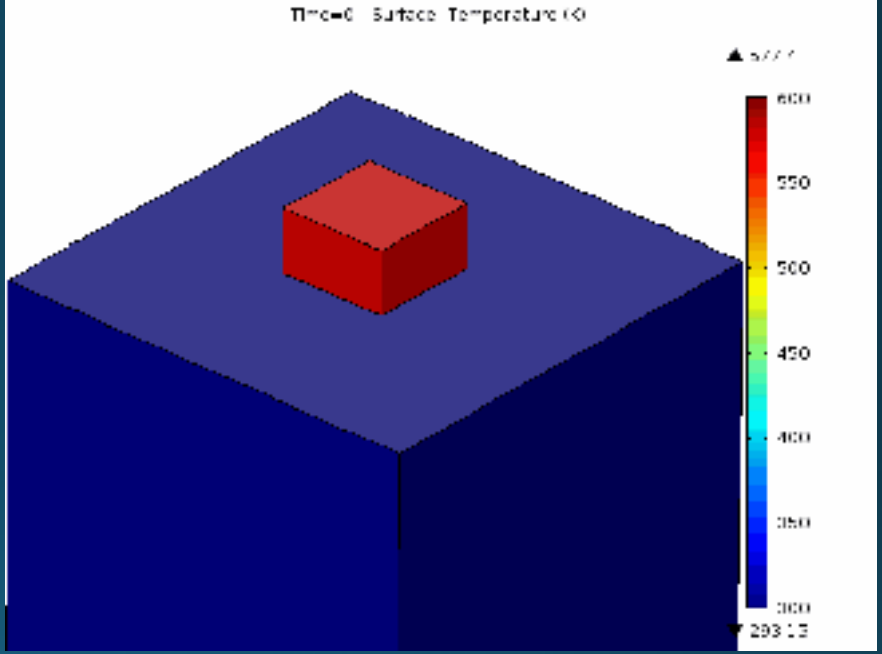

R. M. Karl, et al. Proc. CLEO, Post deadline, JTh5C.8. (2017)

Quantifying New, Nanoscale Materials Properties: Catching Up With the Rest of Nanotechnology

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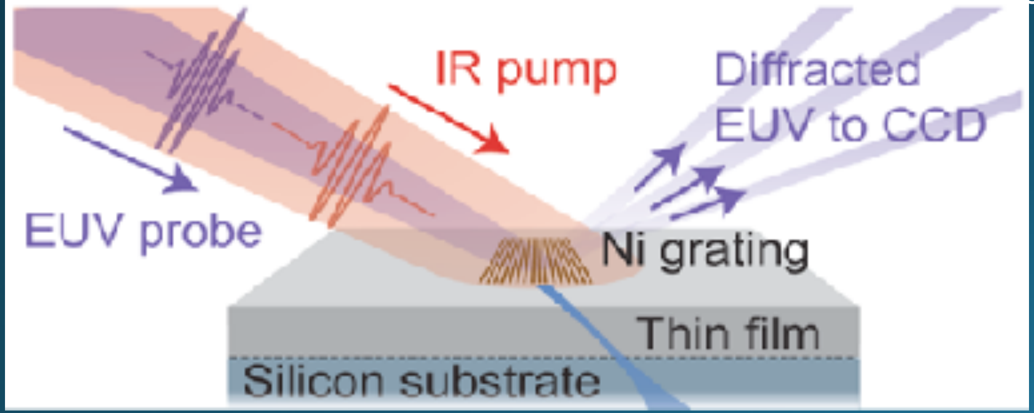

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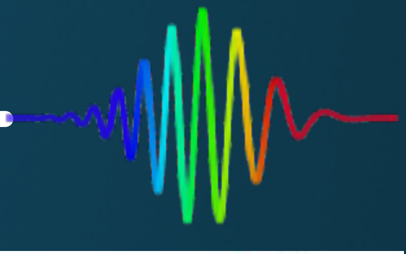

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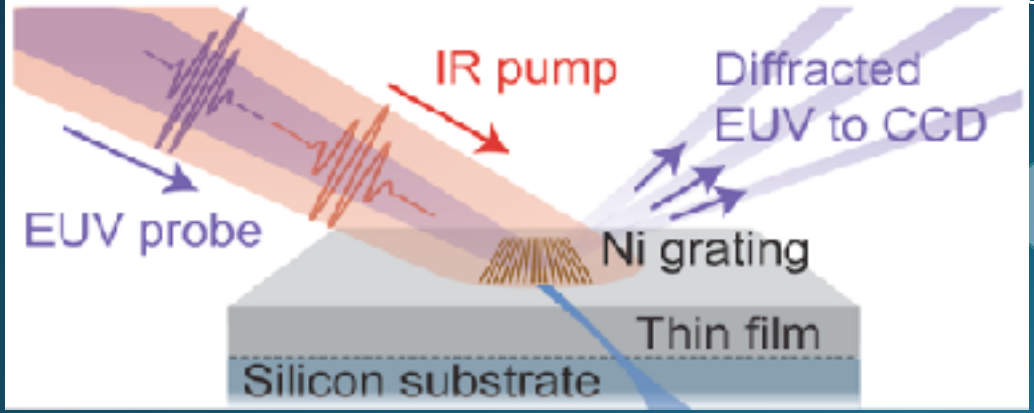

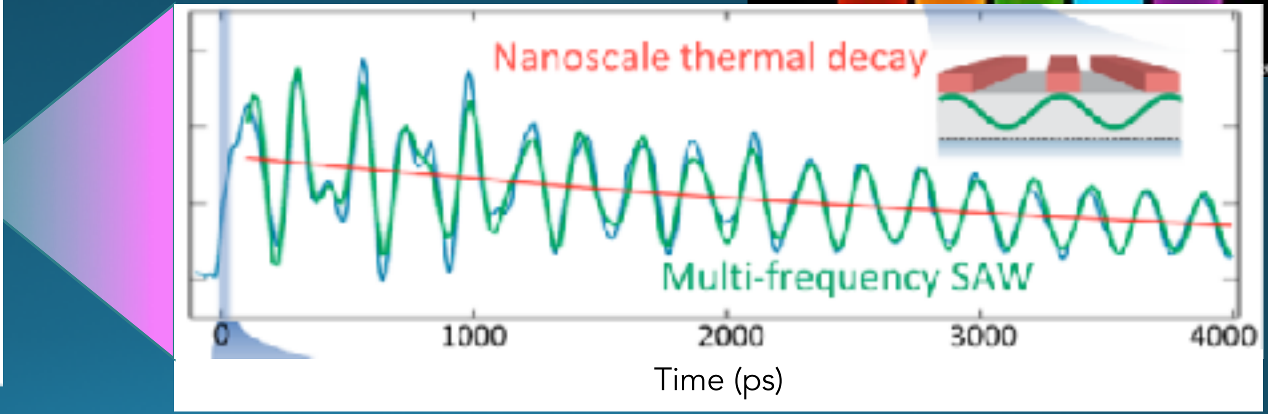

HHG Illuminates Emergent Material Properties and Novel Electron Transport Pathways

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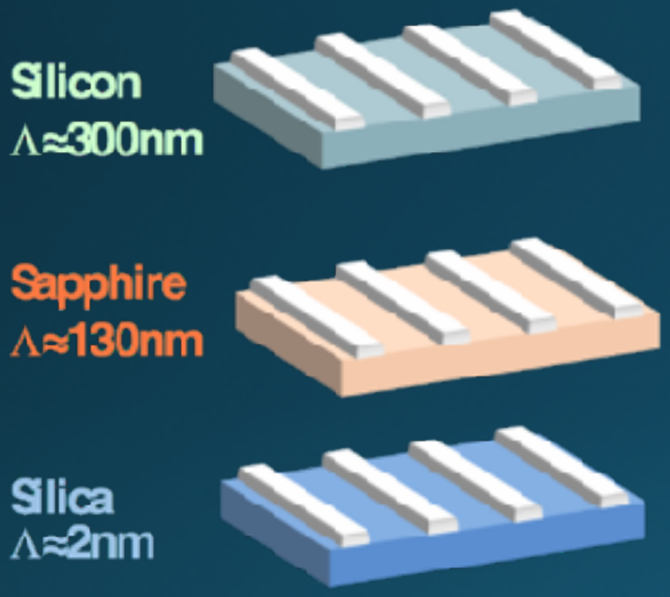

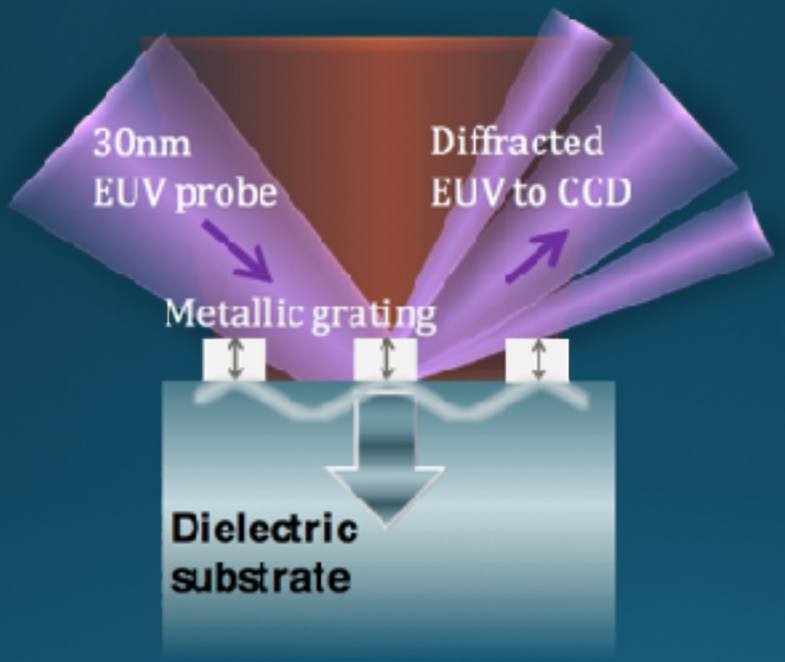

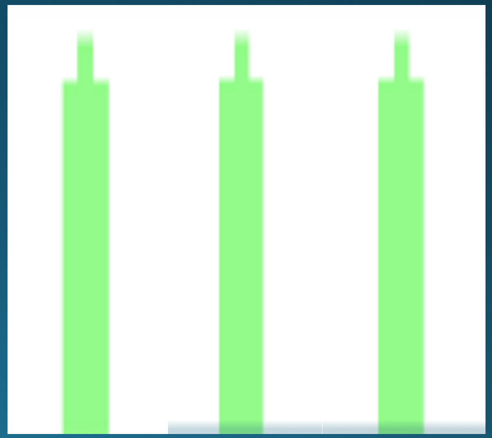

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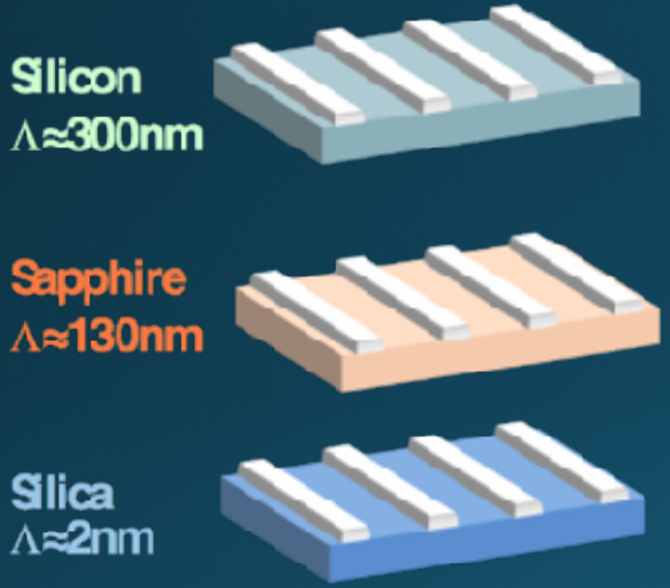

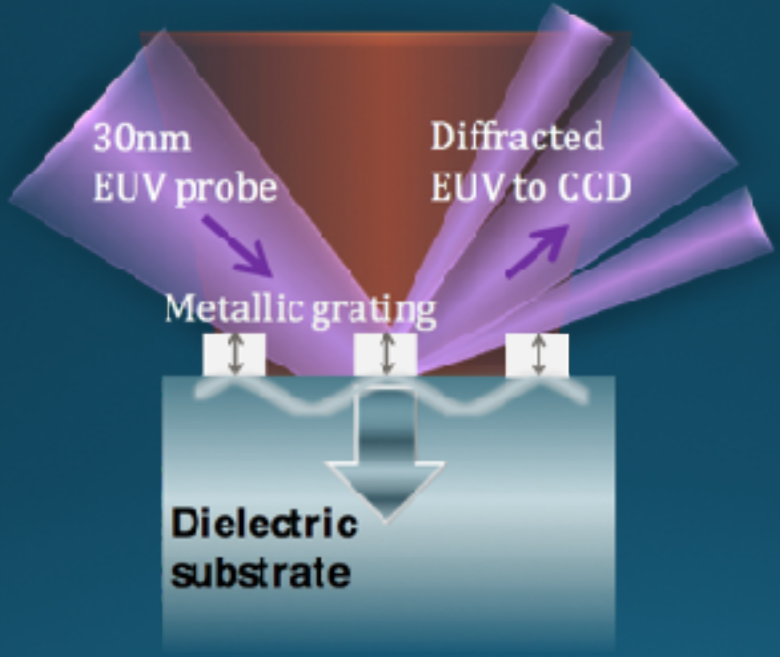

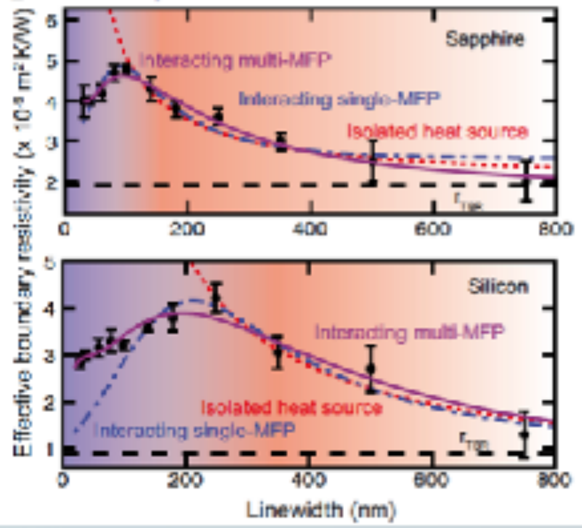

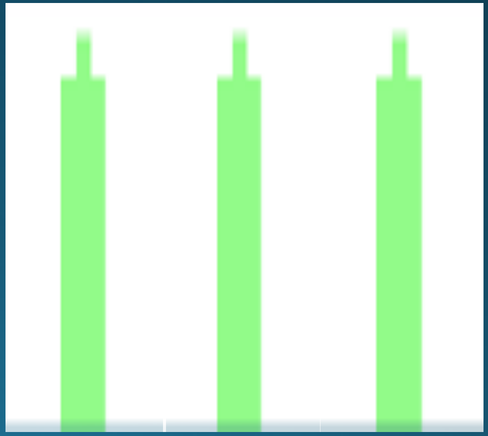

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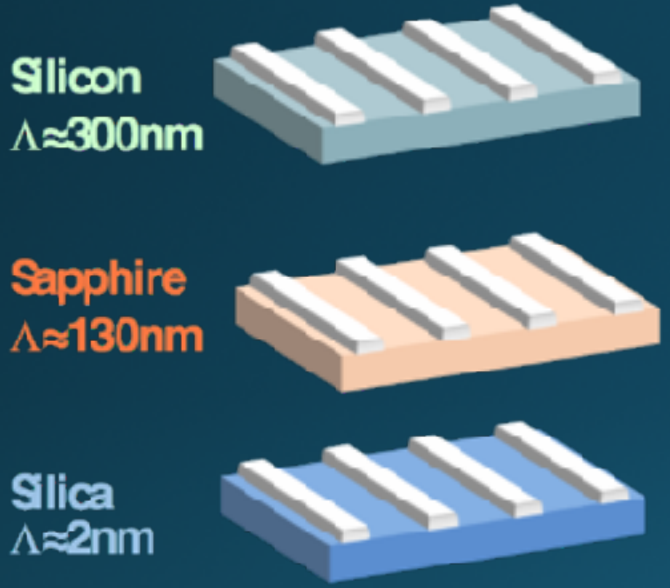

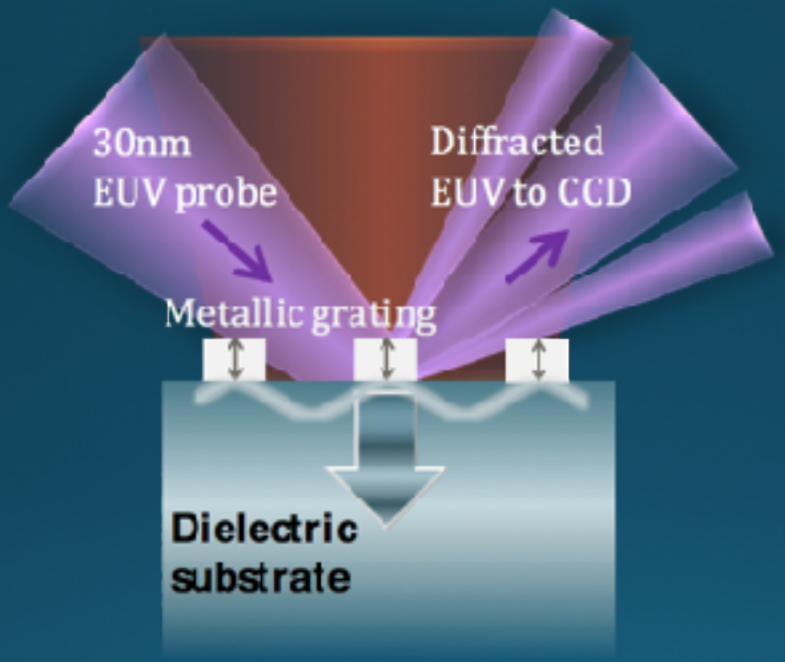

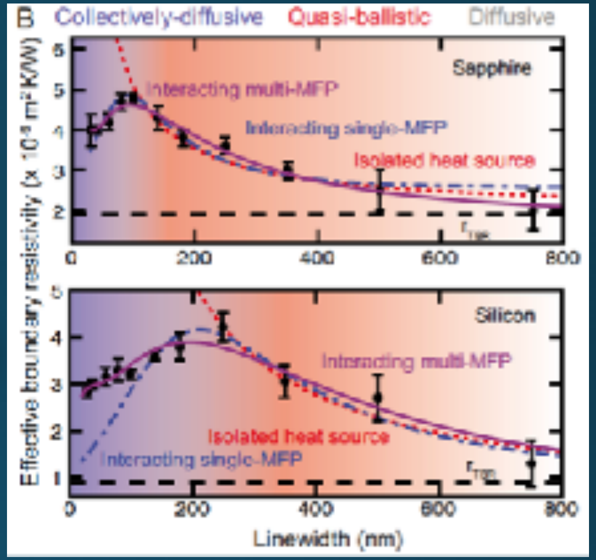

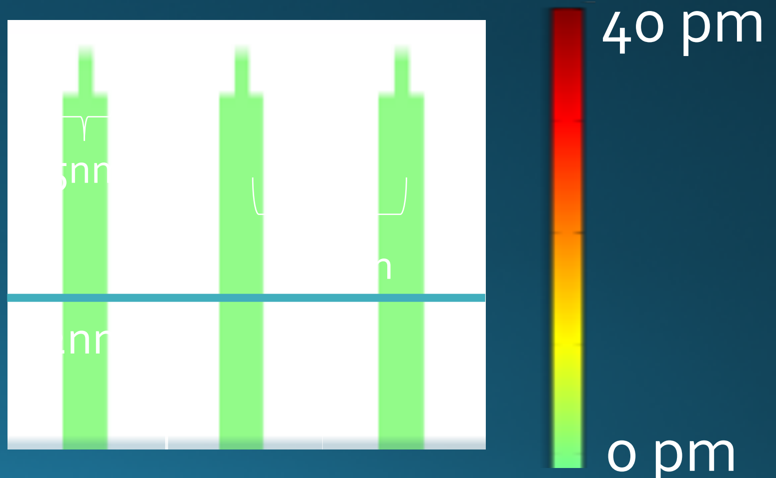

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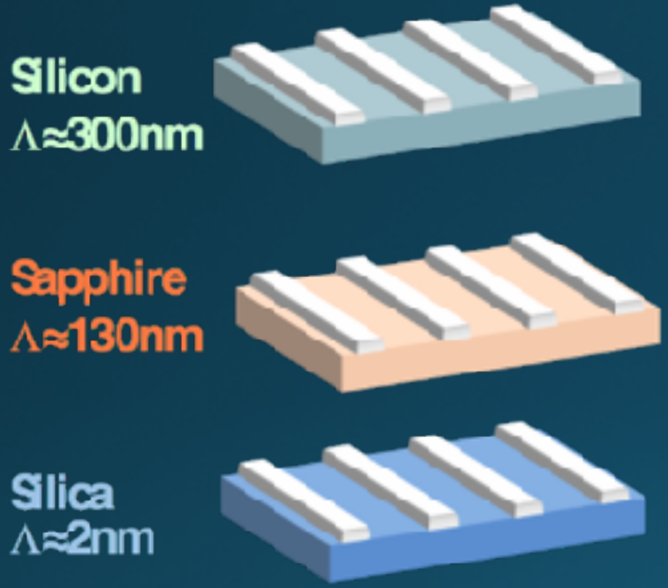

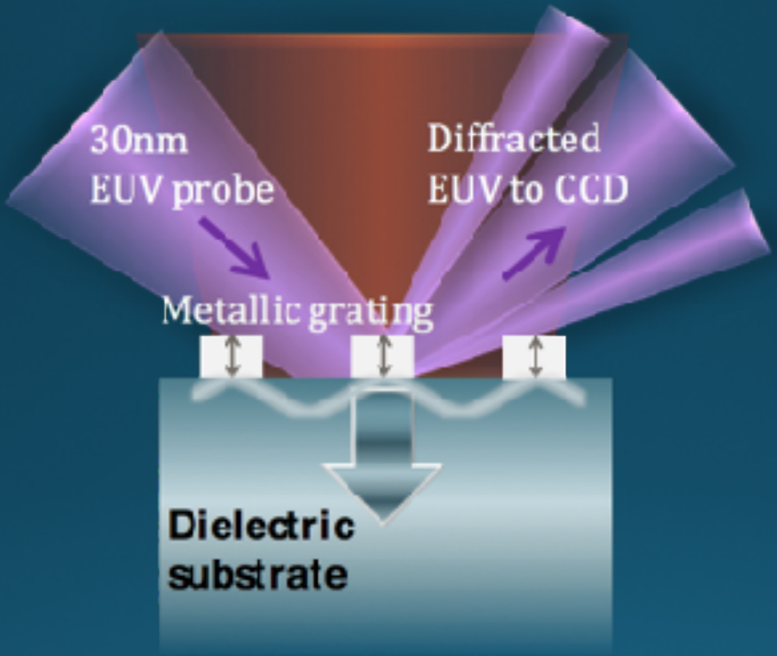

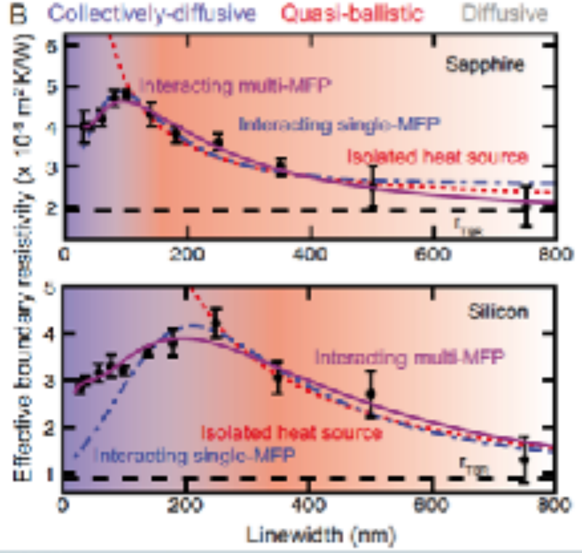

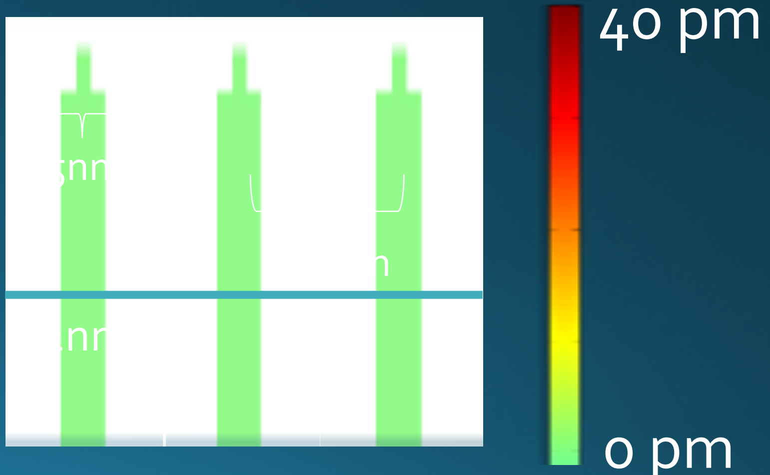

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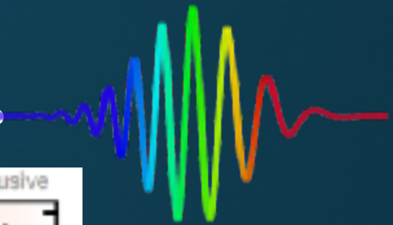

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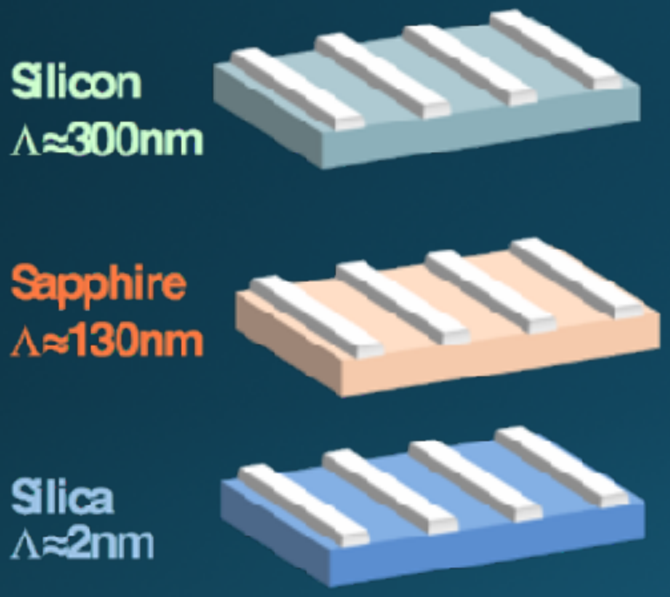

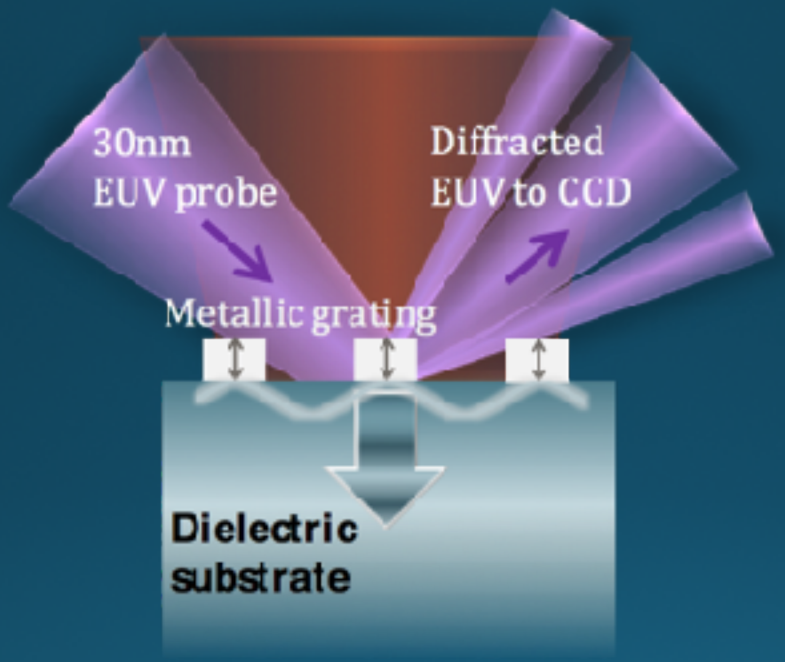

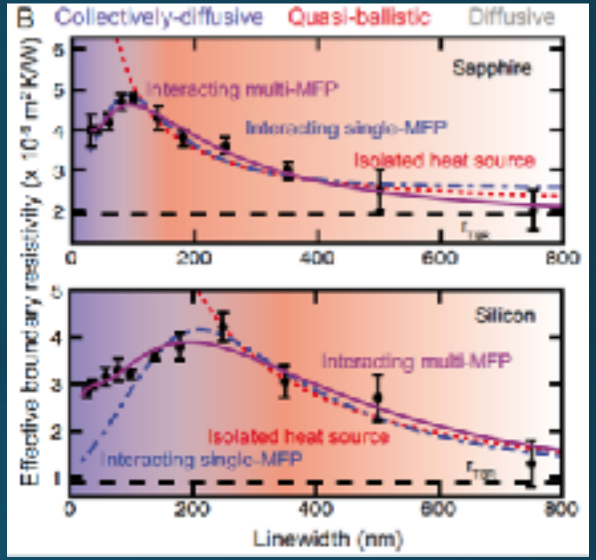

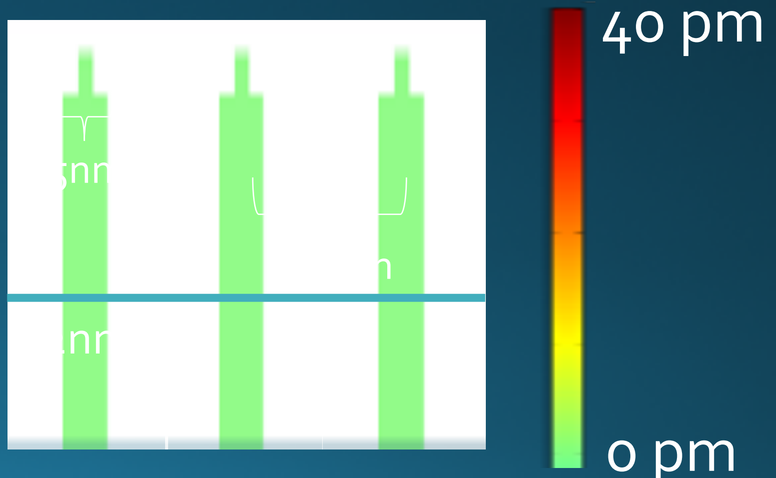

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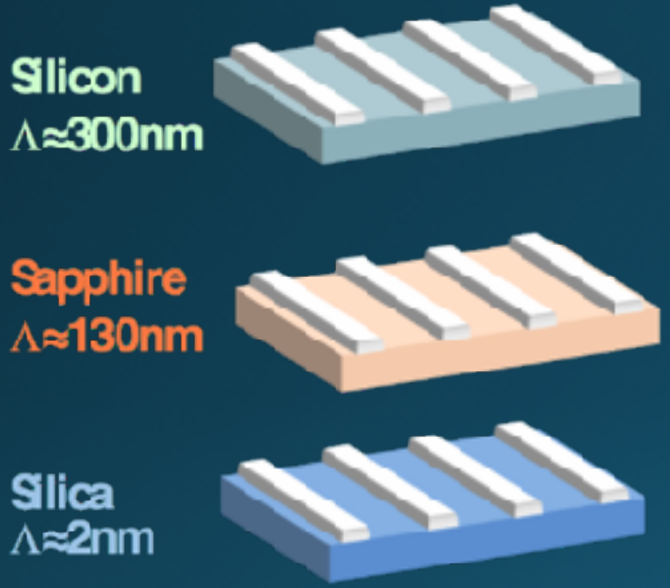

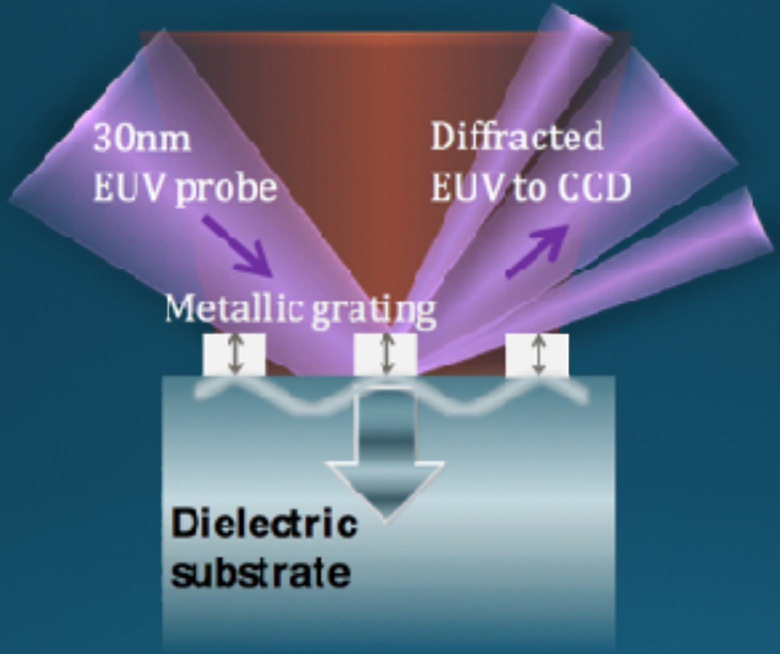

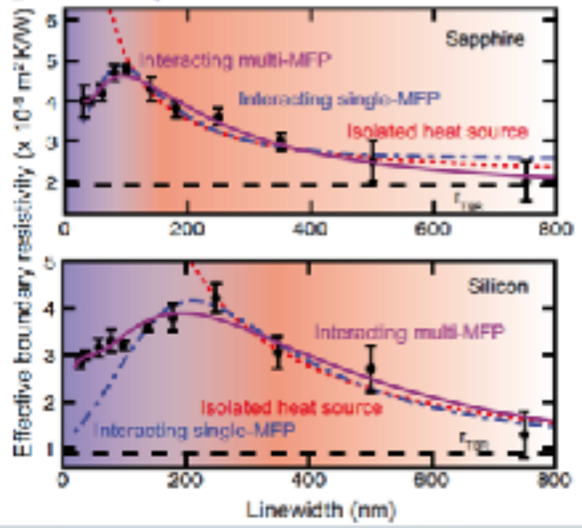

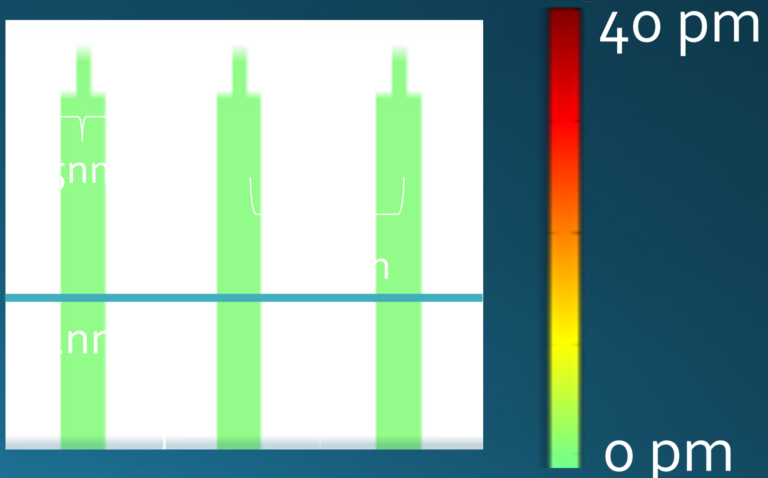

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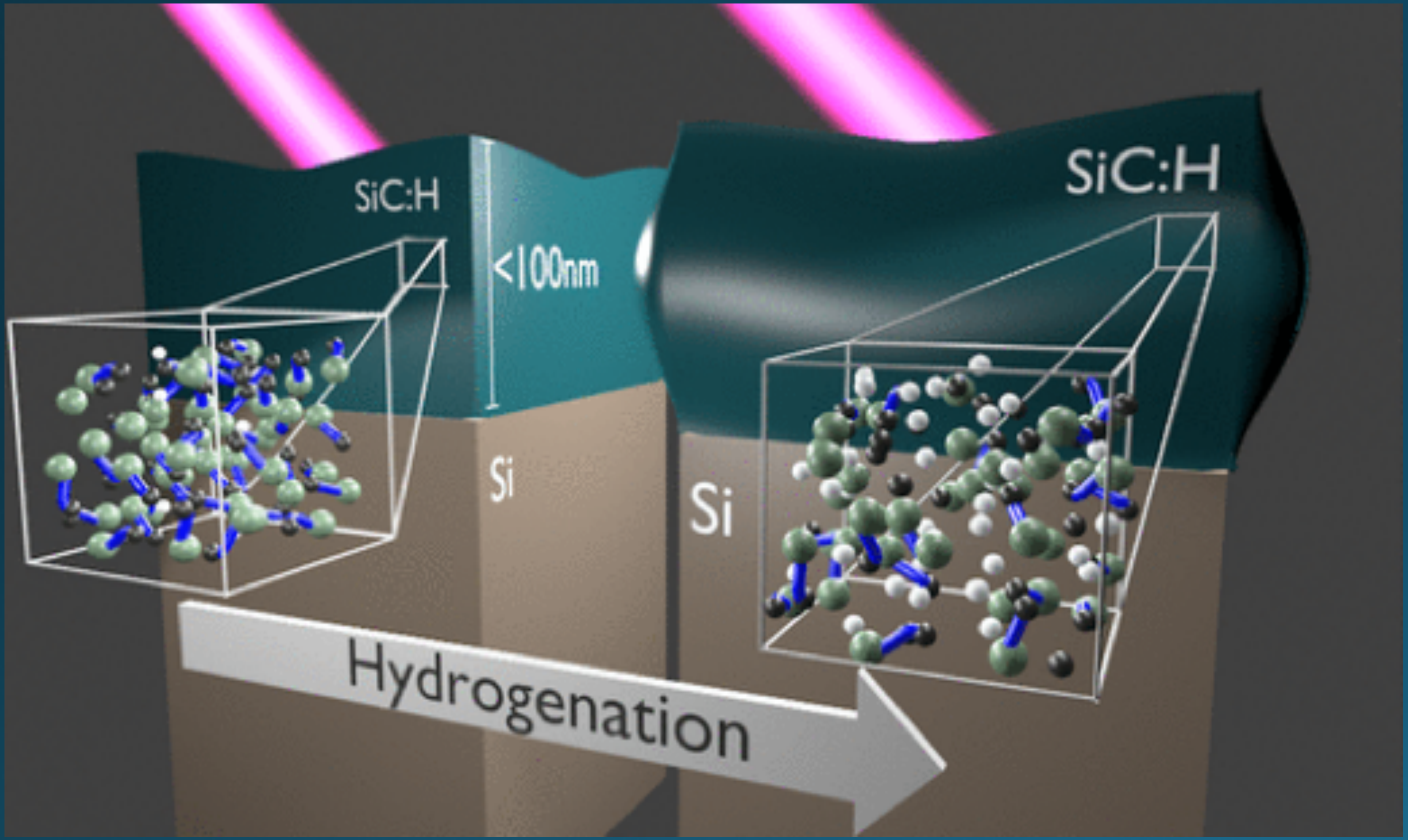

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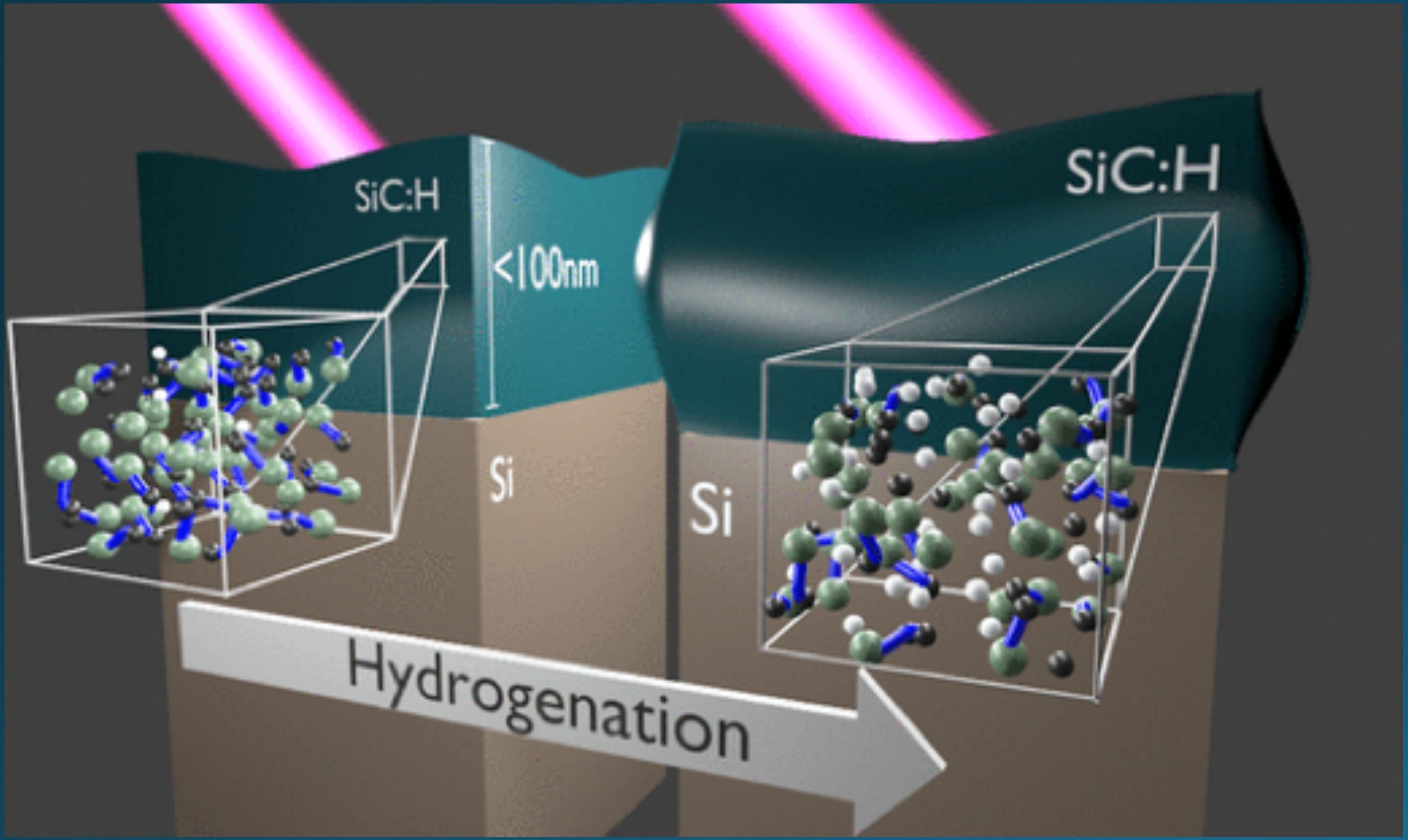

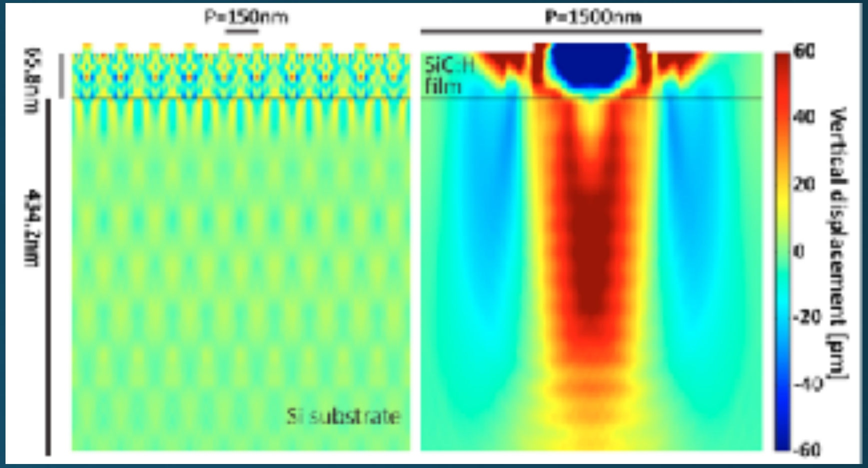

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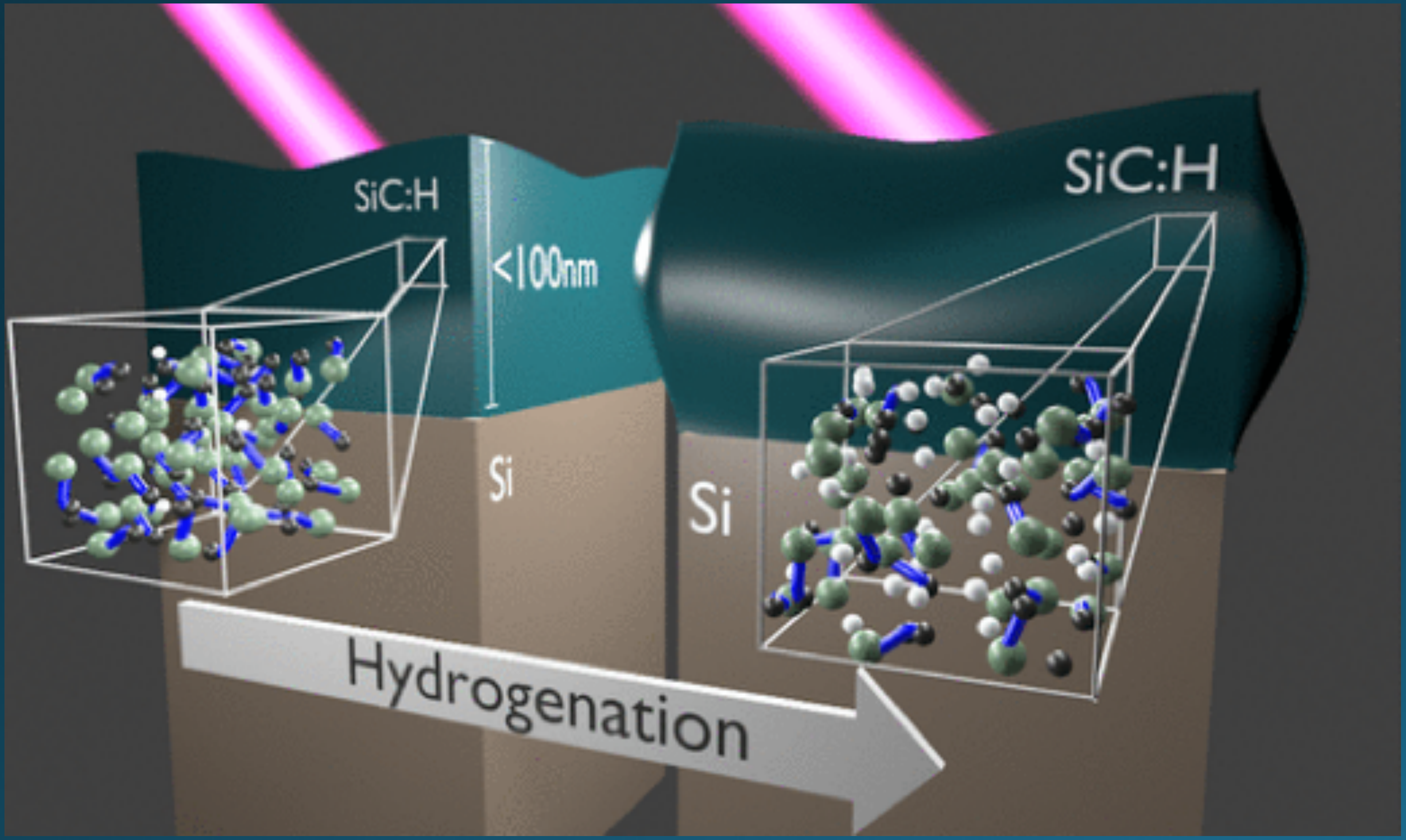

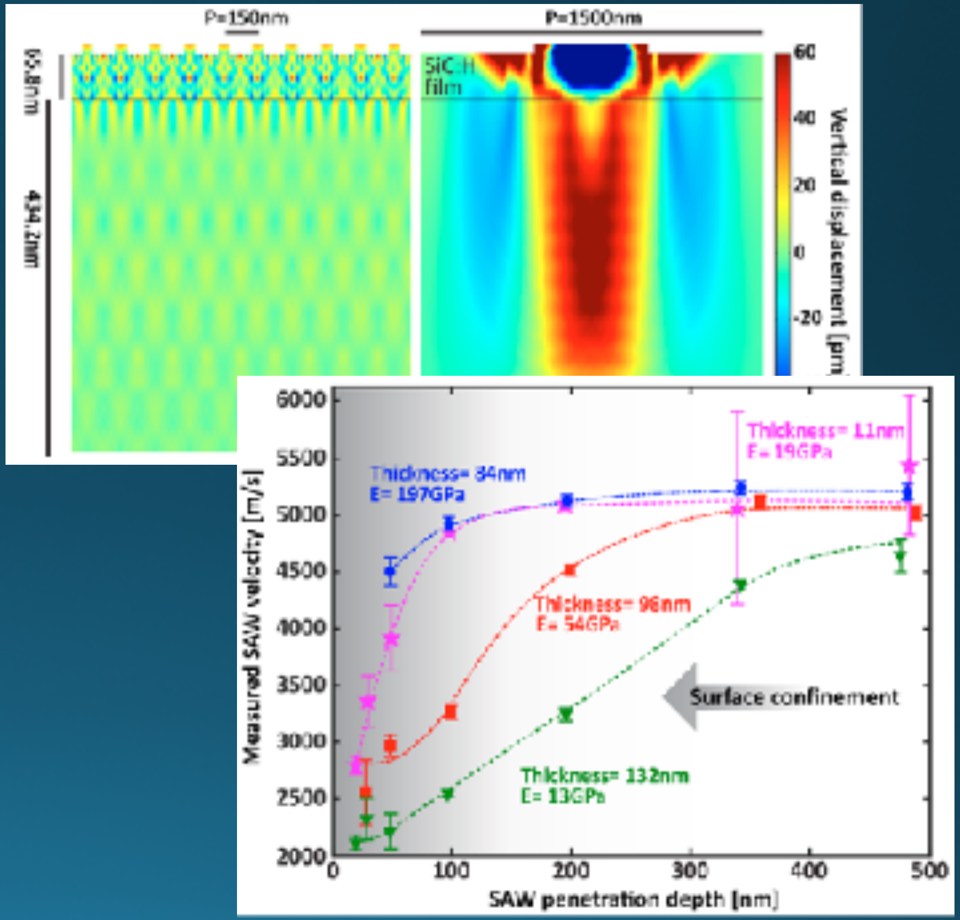

Resolving Molecular Dynamics in Real Time: Molecular Movies of Chemical Transformation

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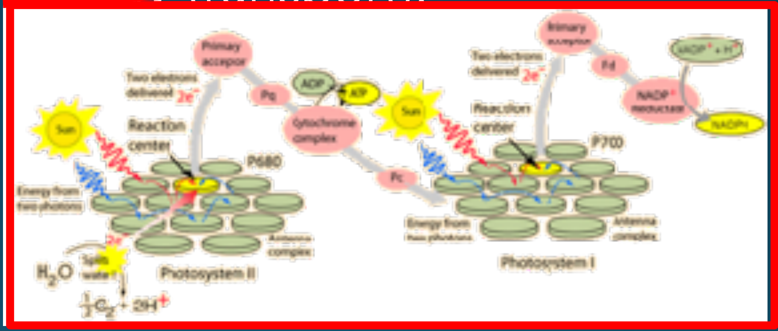

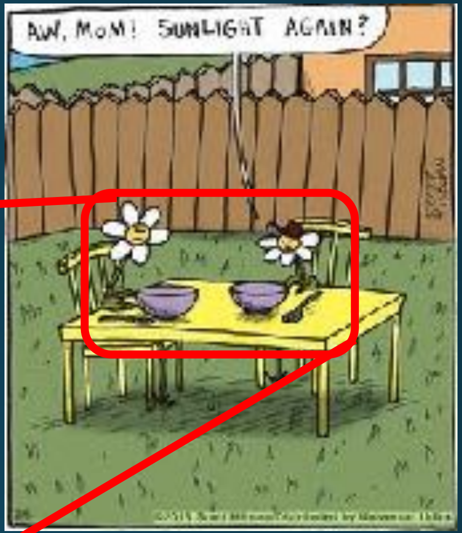

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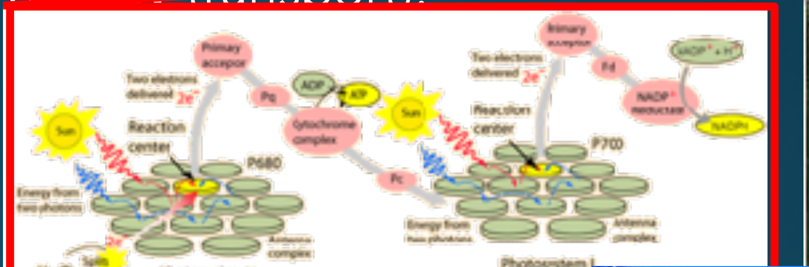

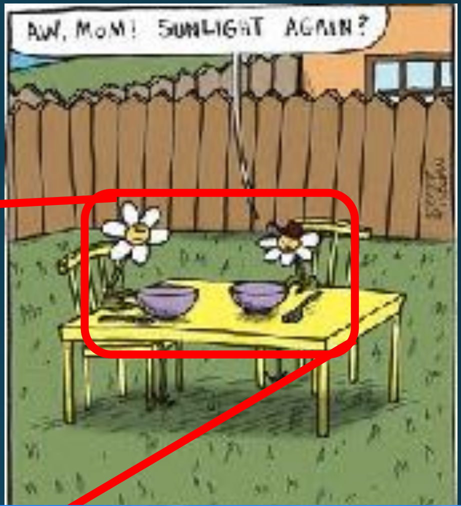

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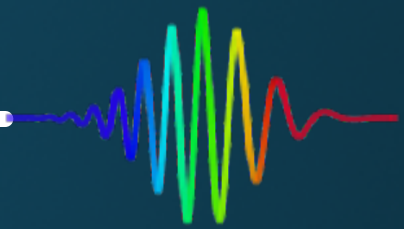

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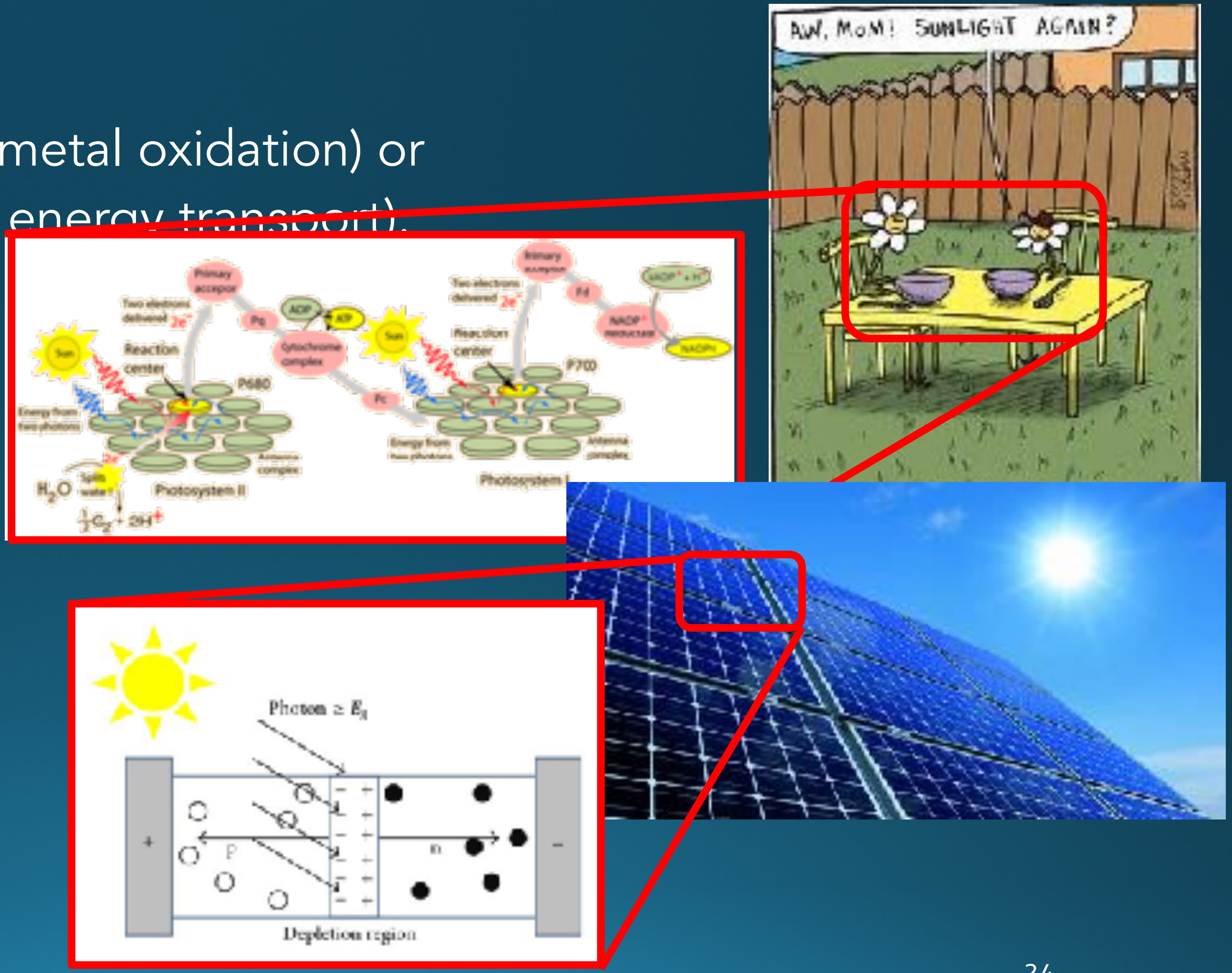

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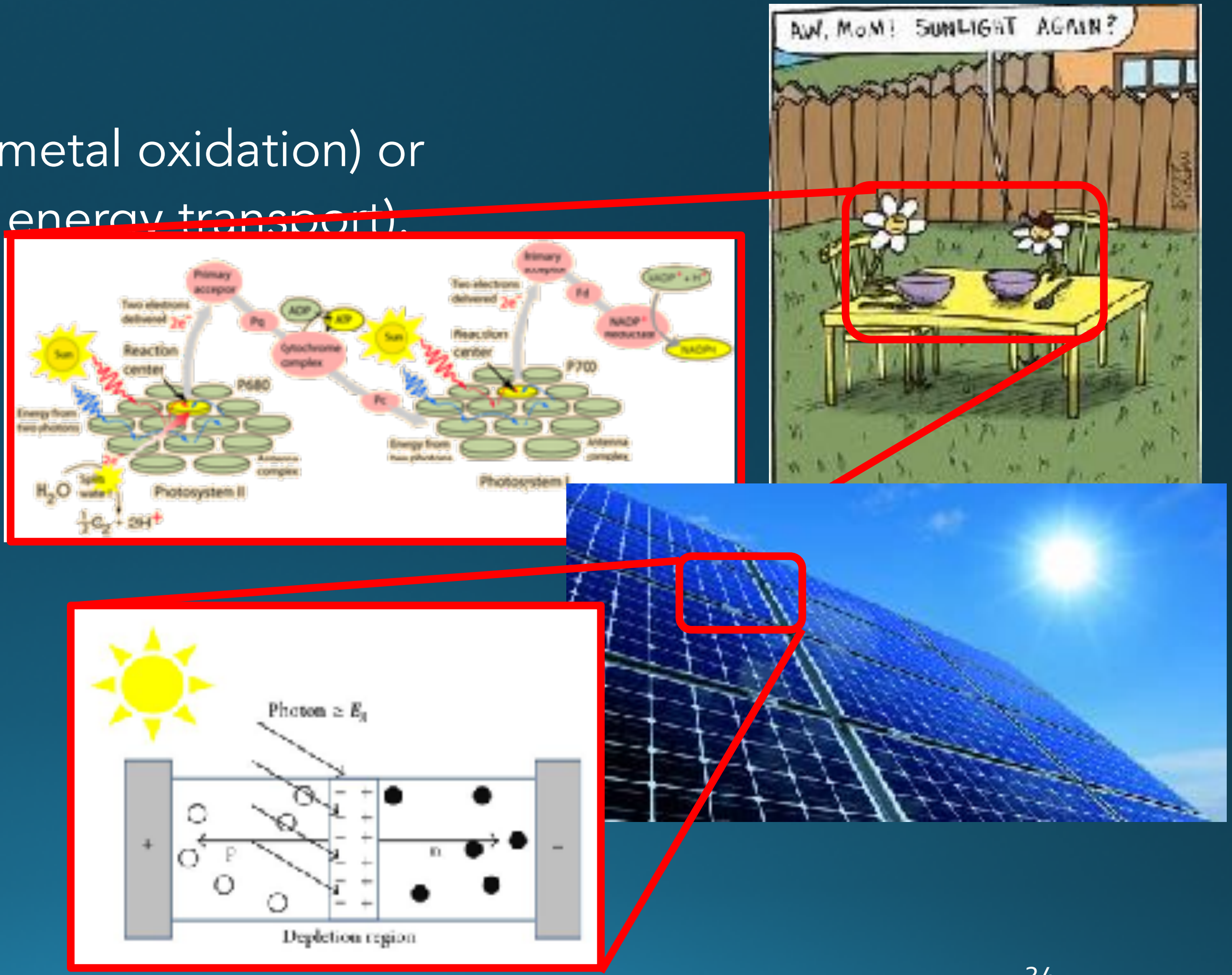

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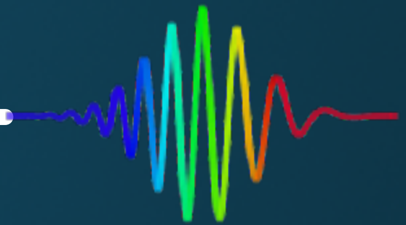

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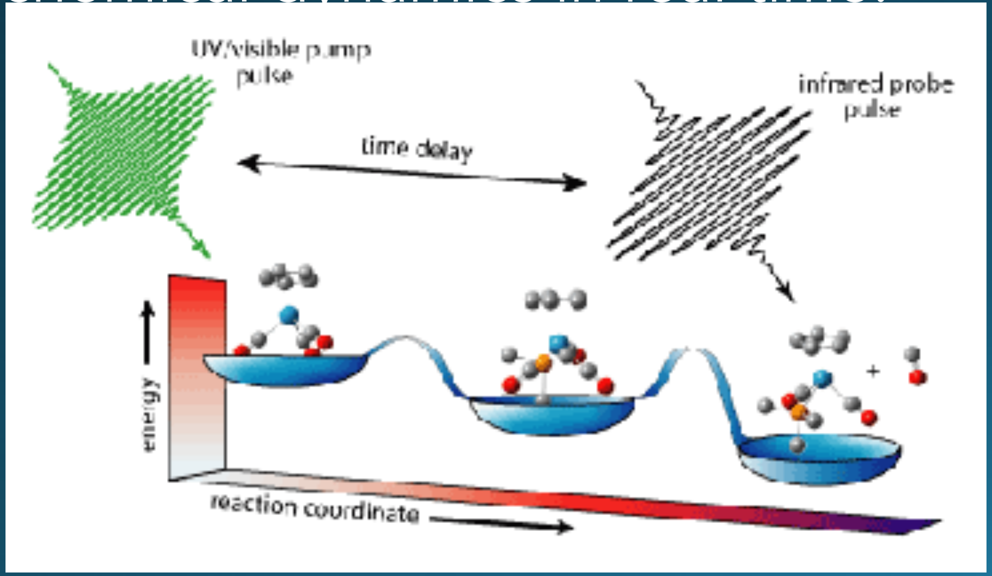

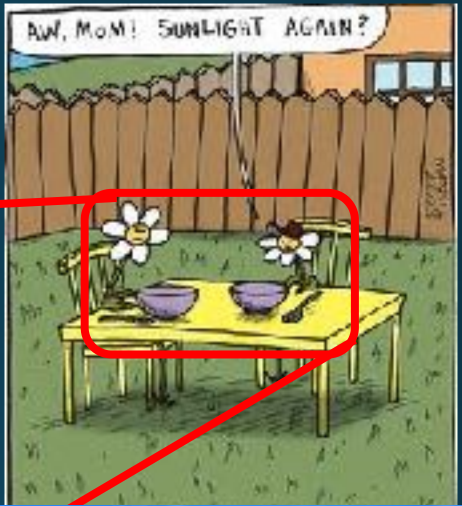

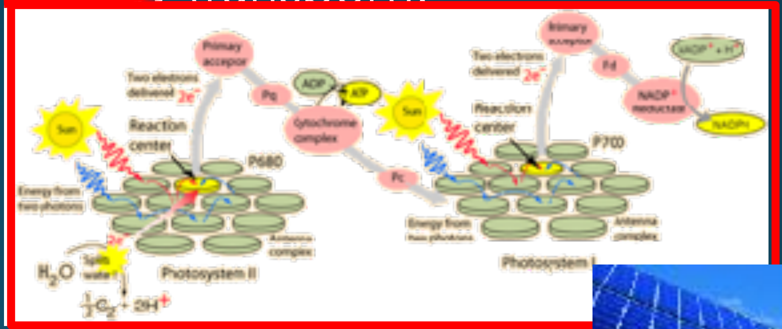

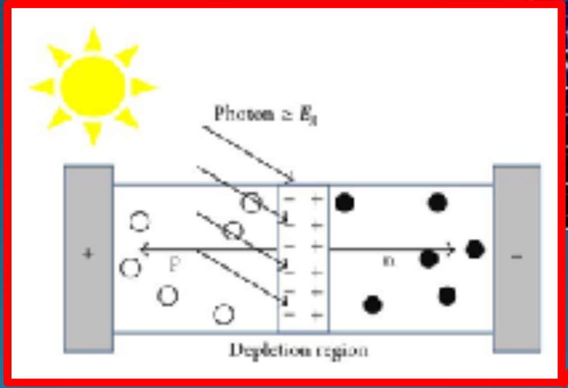

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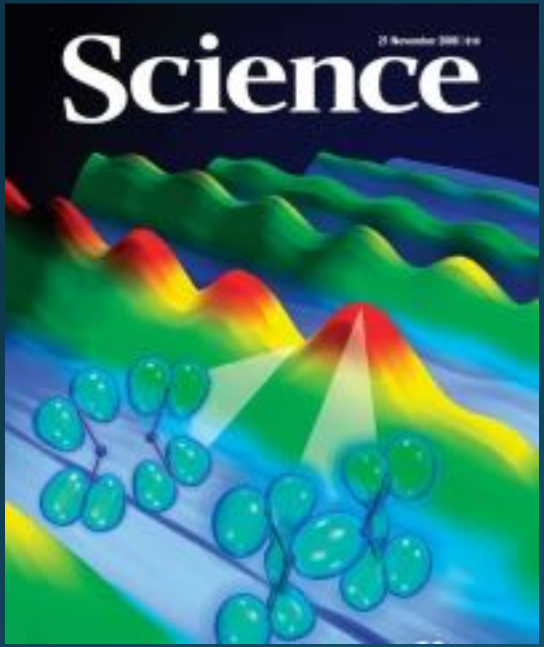

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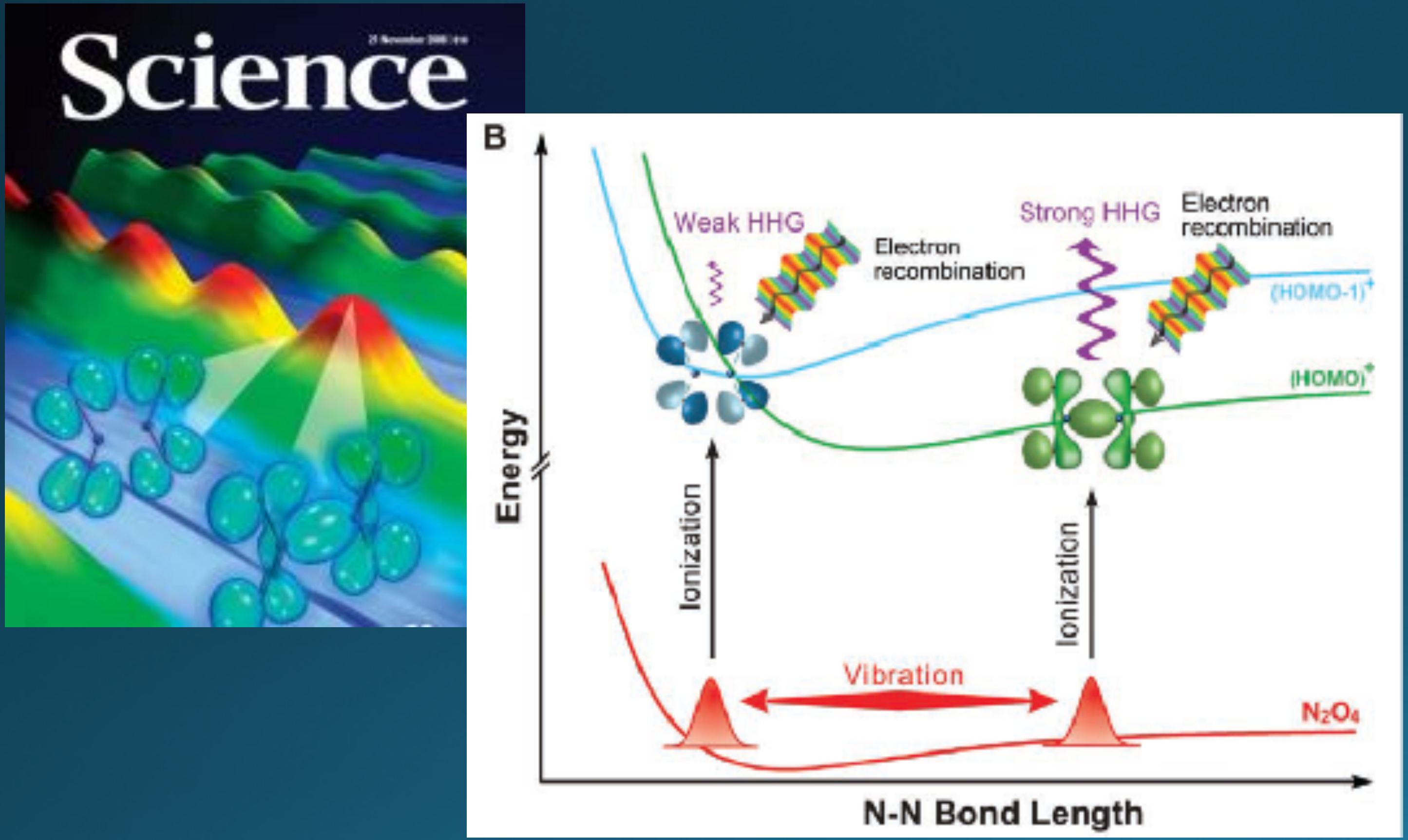

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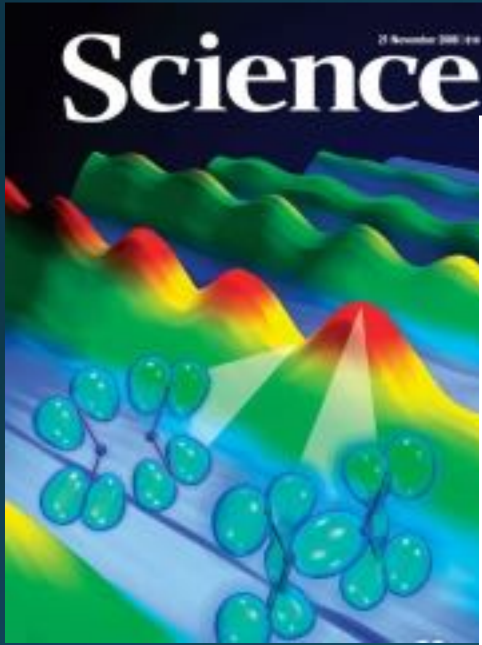

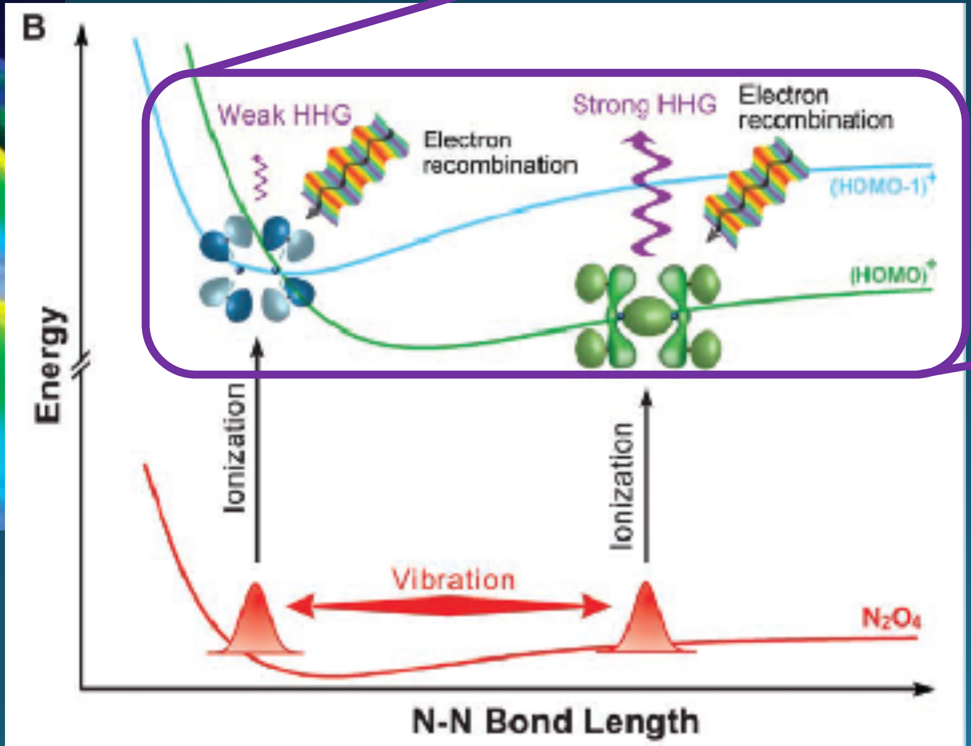

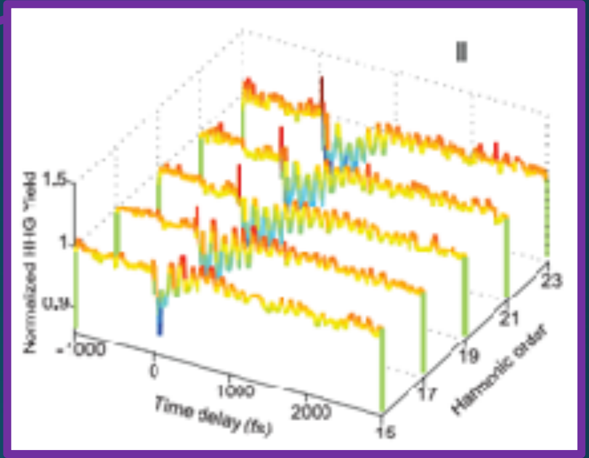

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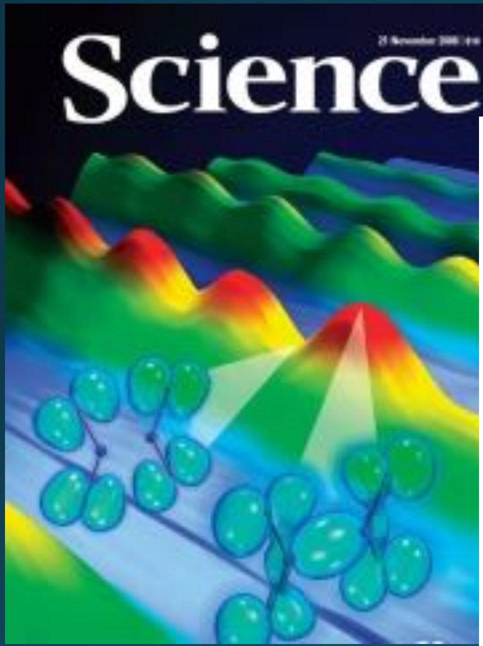

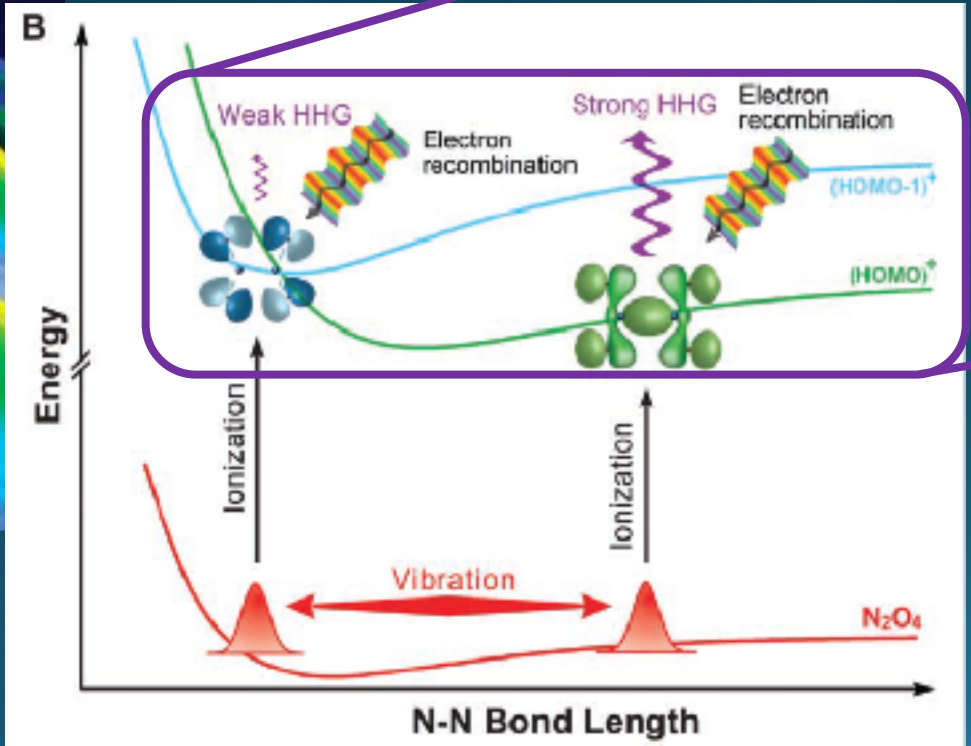

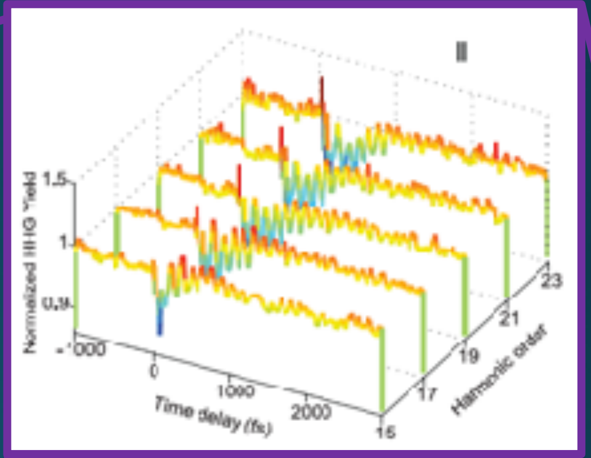

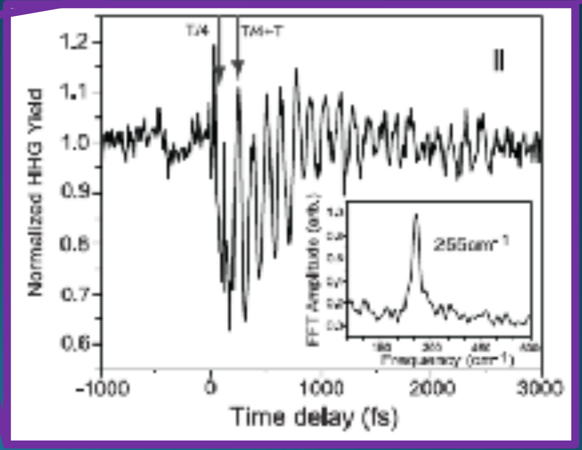

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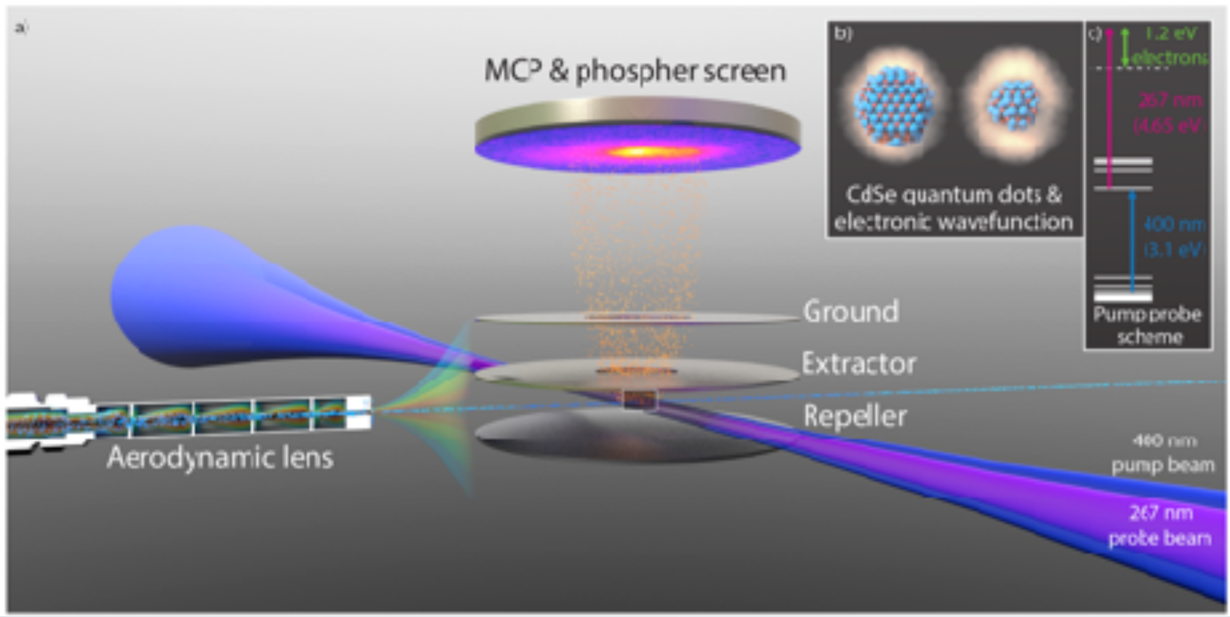

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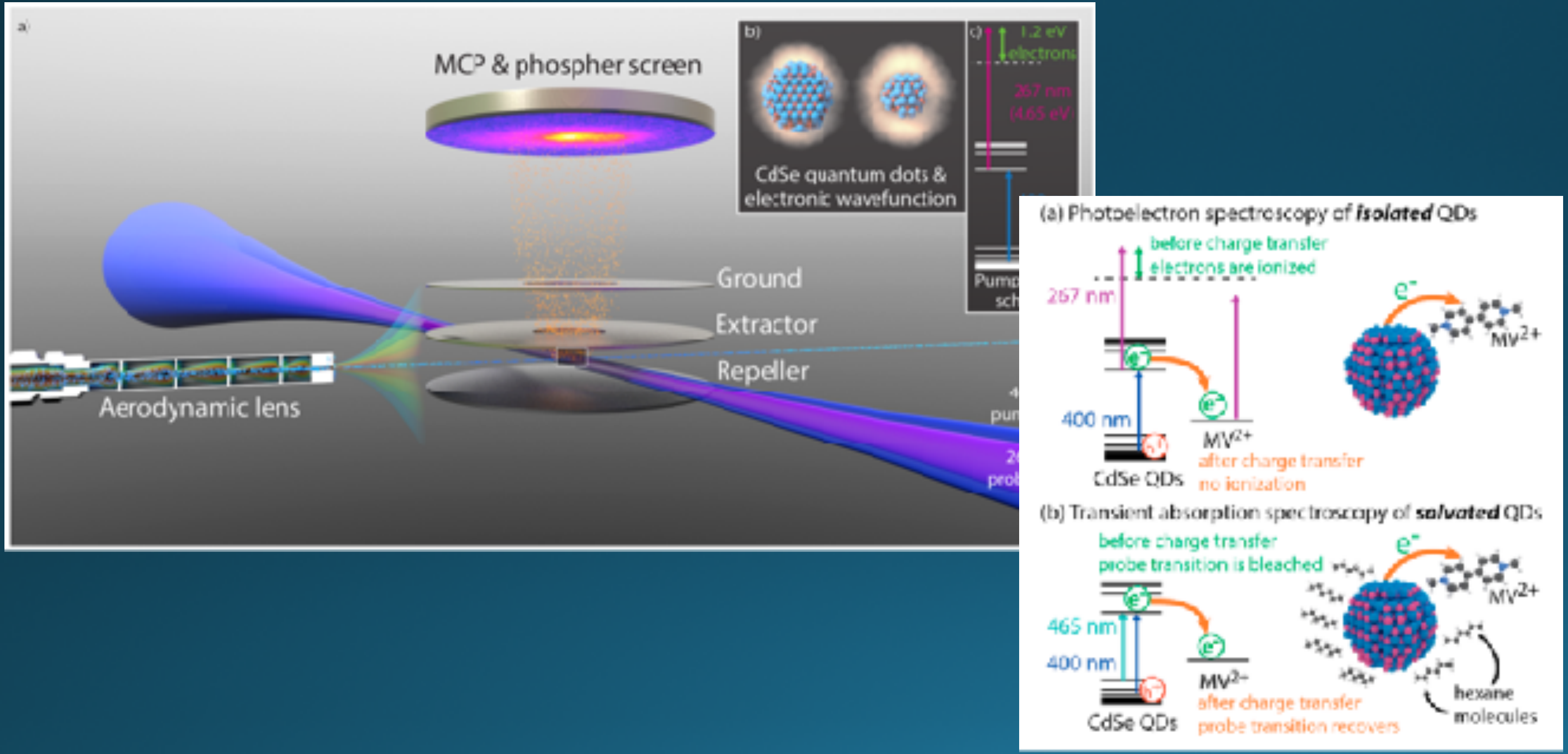

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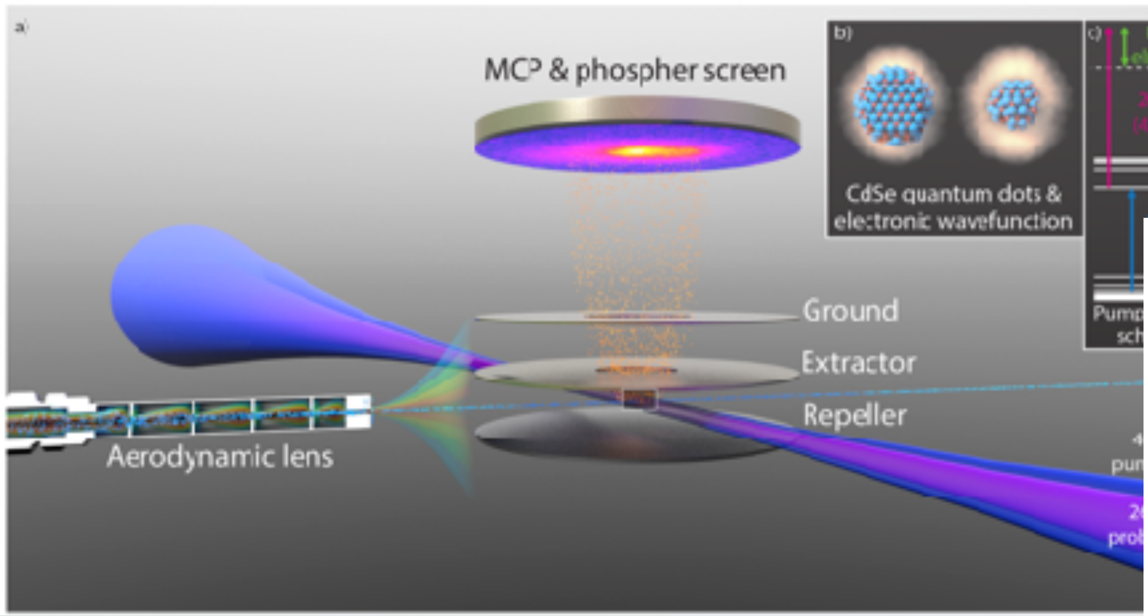

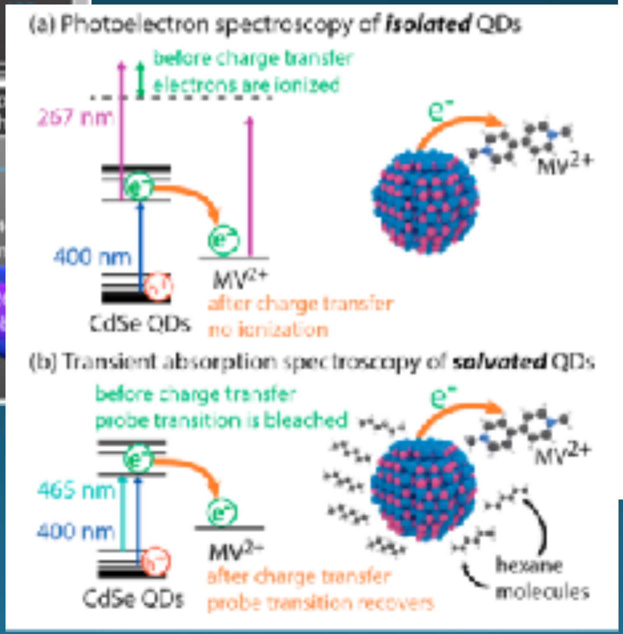

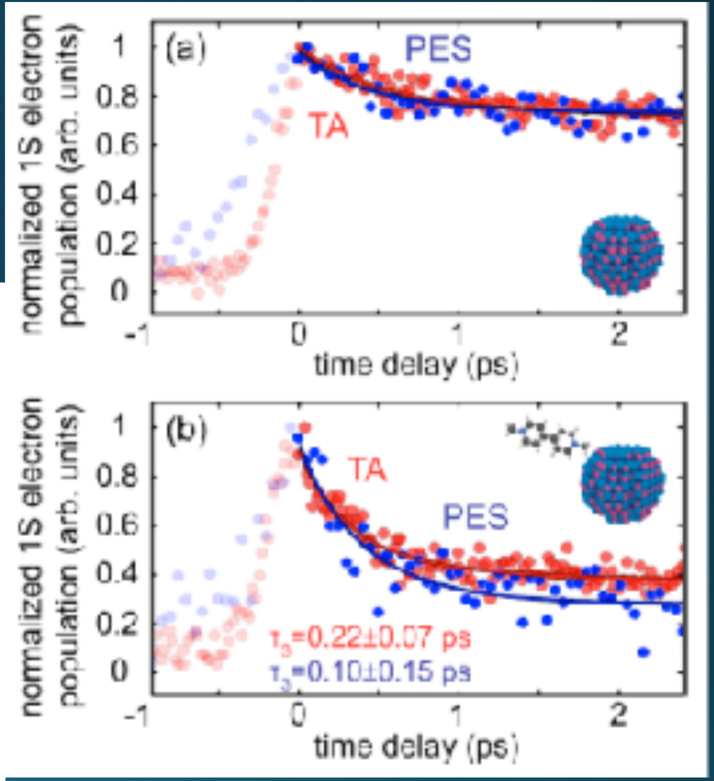

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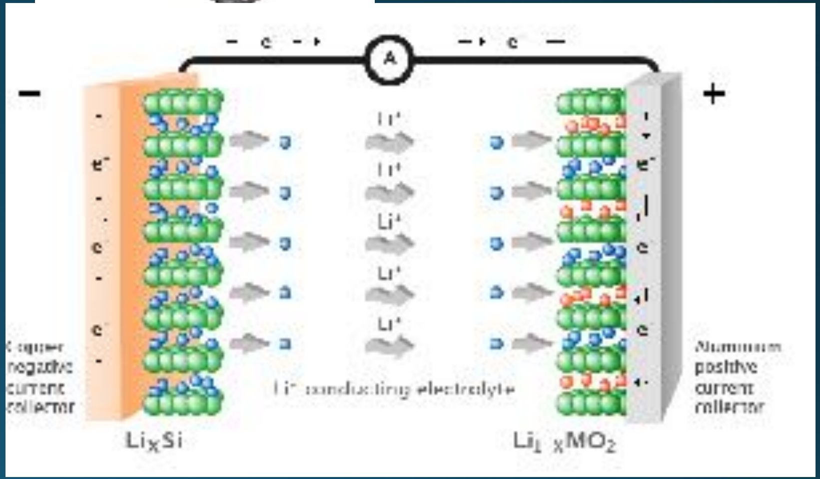

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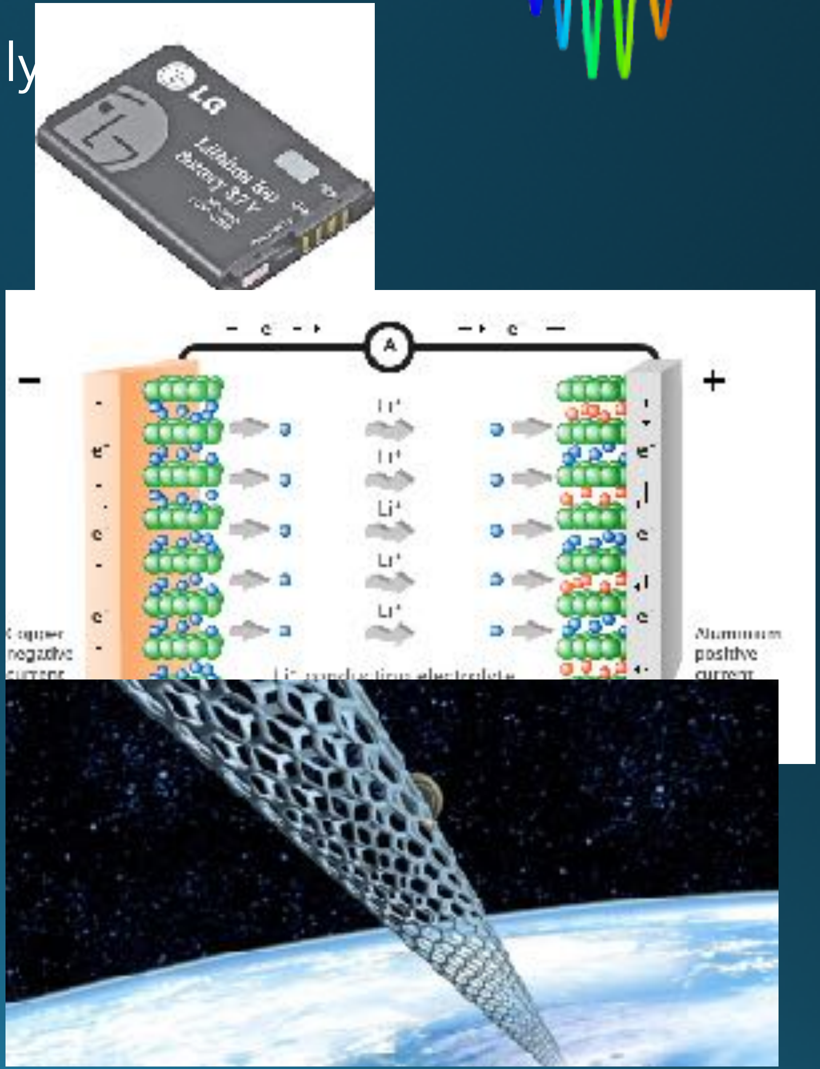

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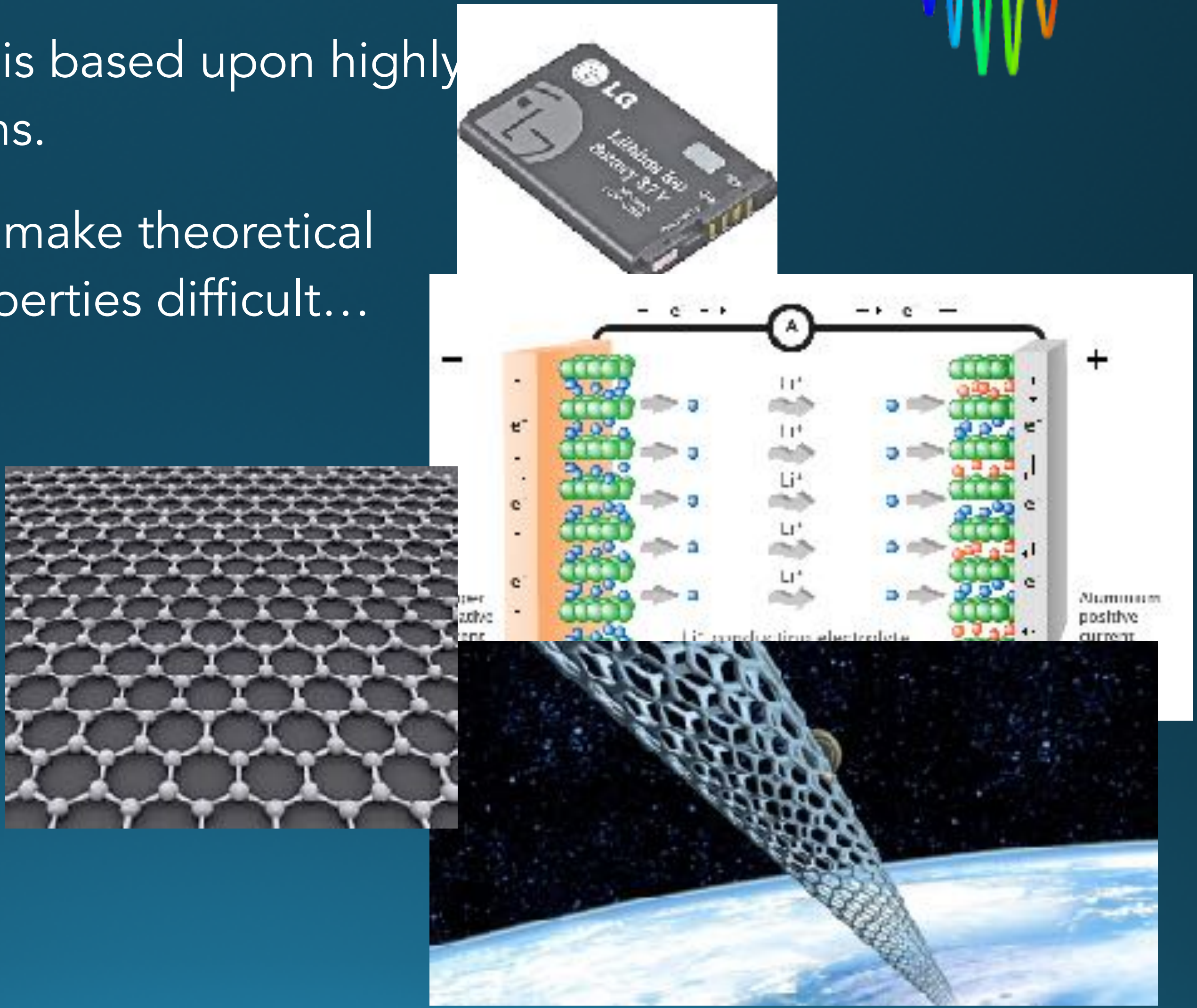

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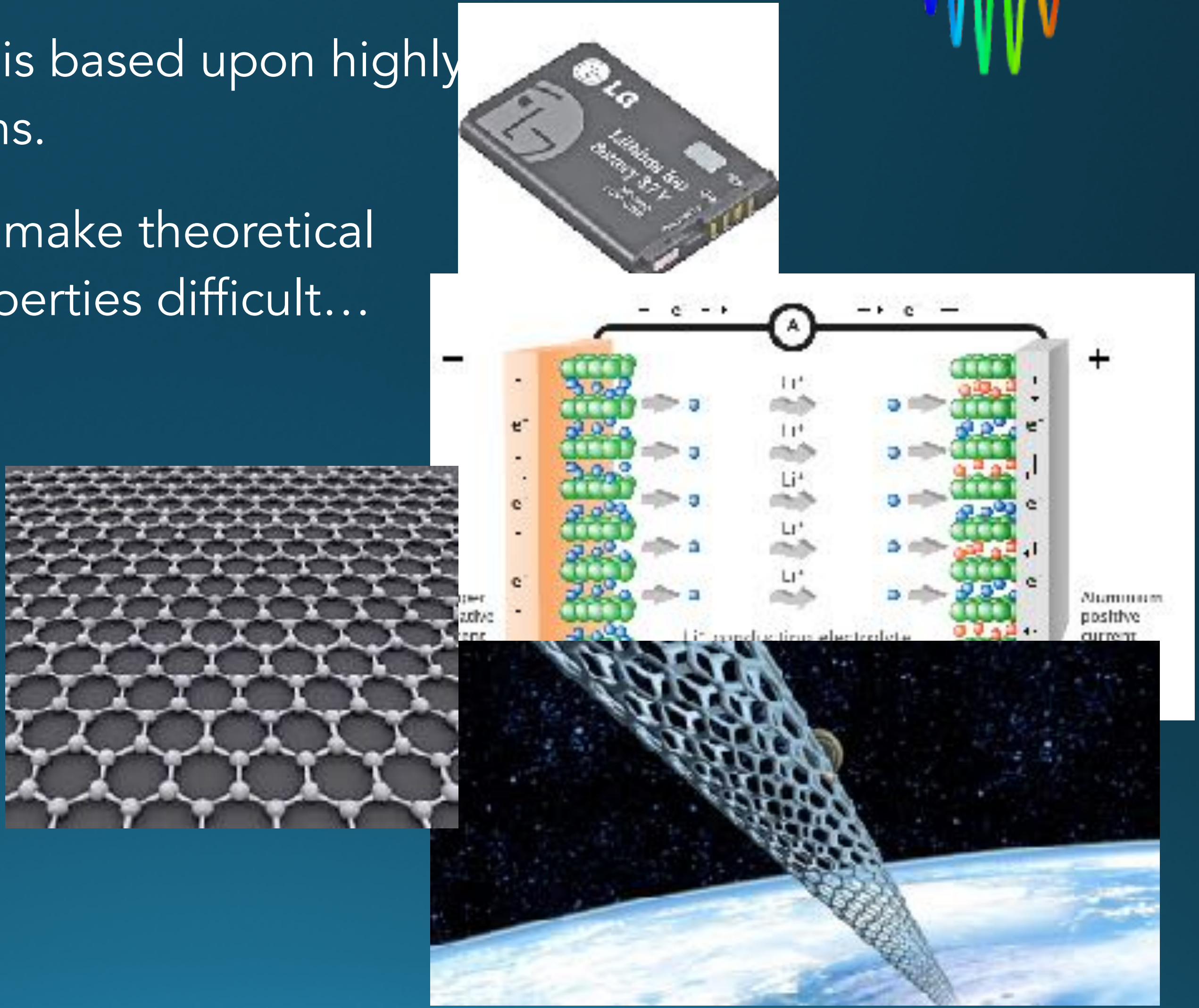

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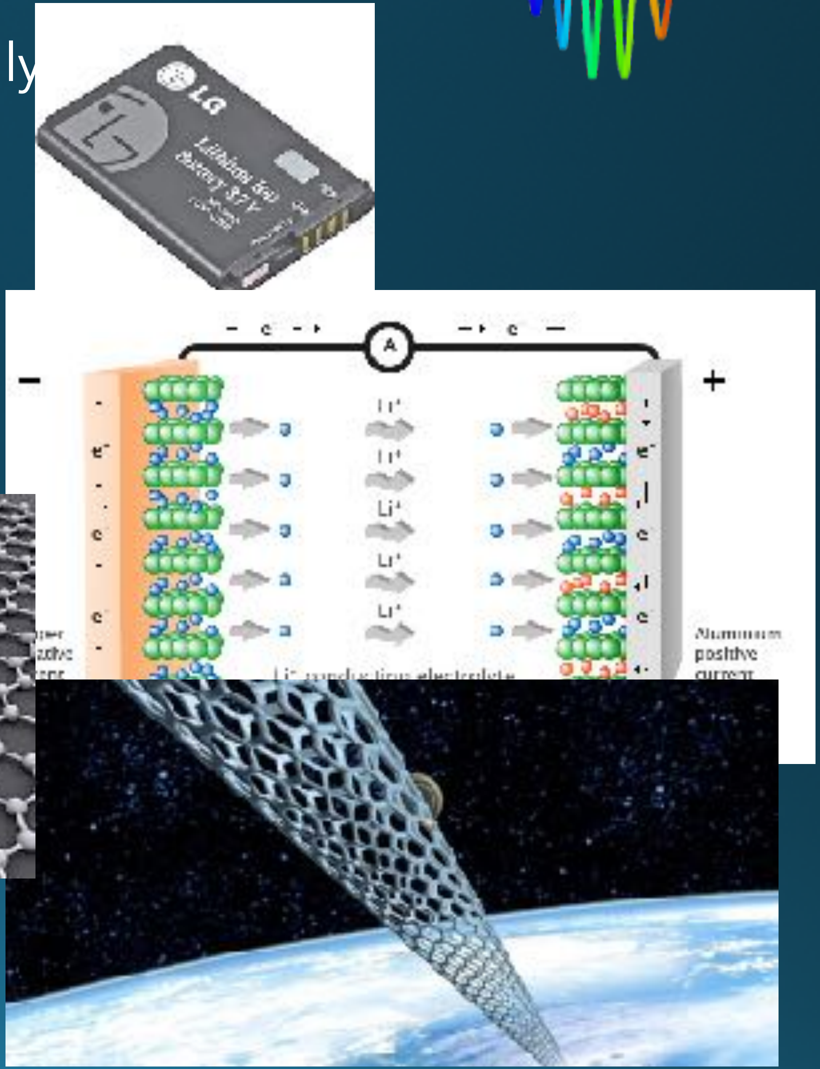
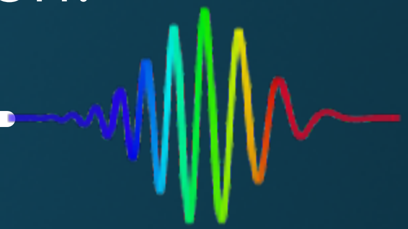


Resolving Attosecond Time Delays in Photoionization: The Photoelectric Effect Takes It’s Time



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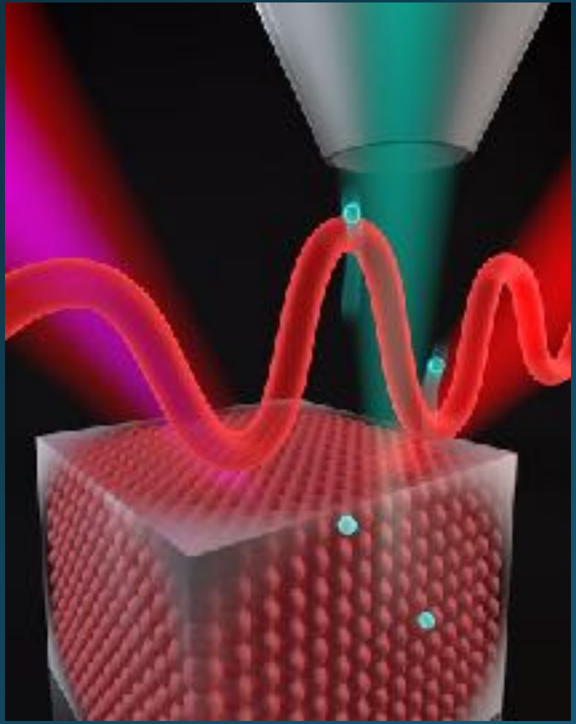

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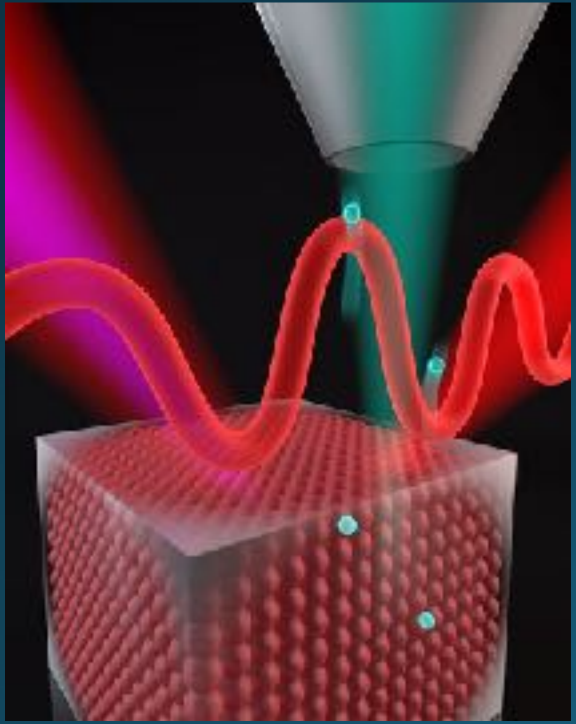

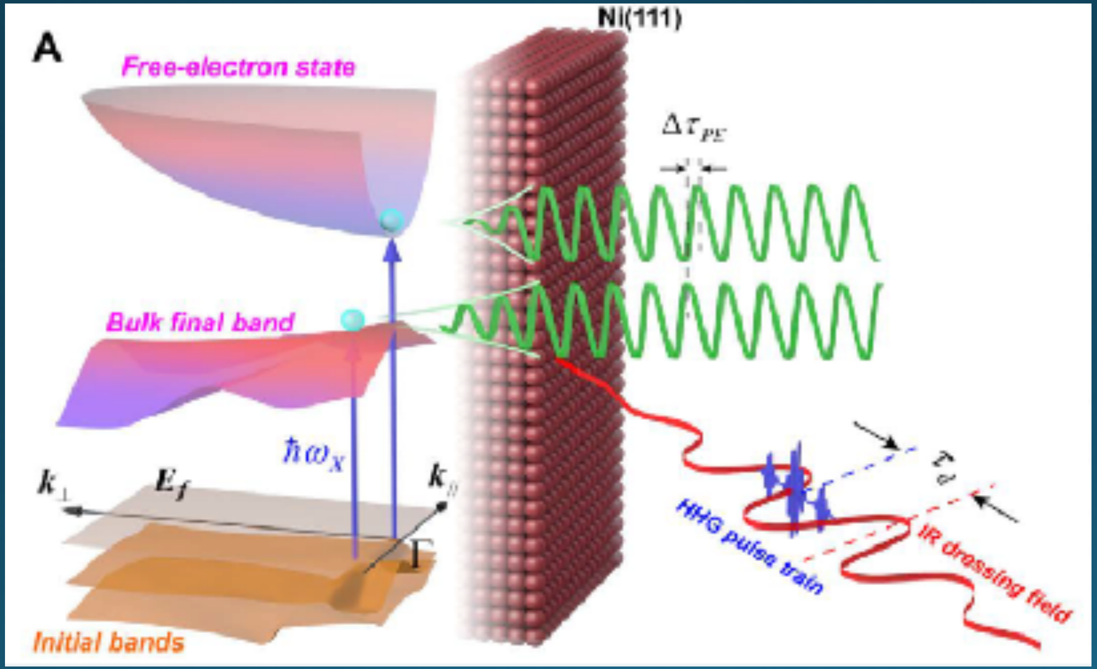

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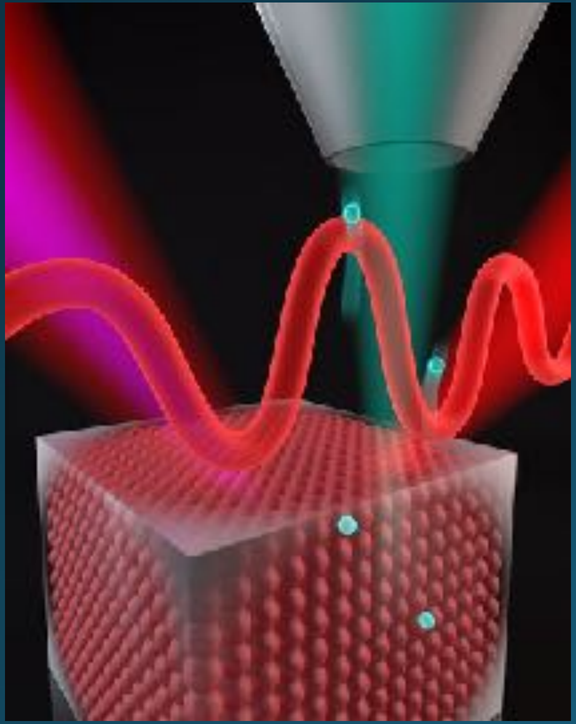

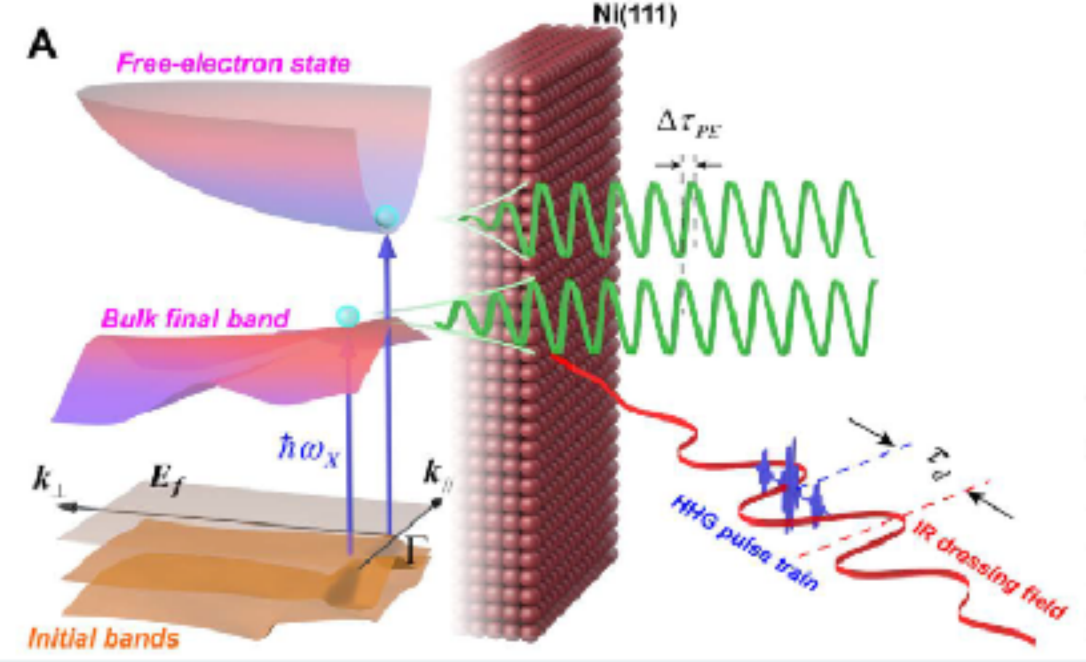

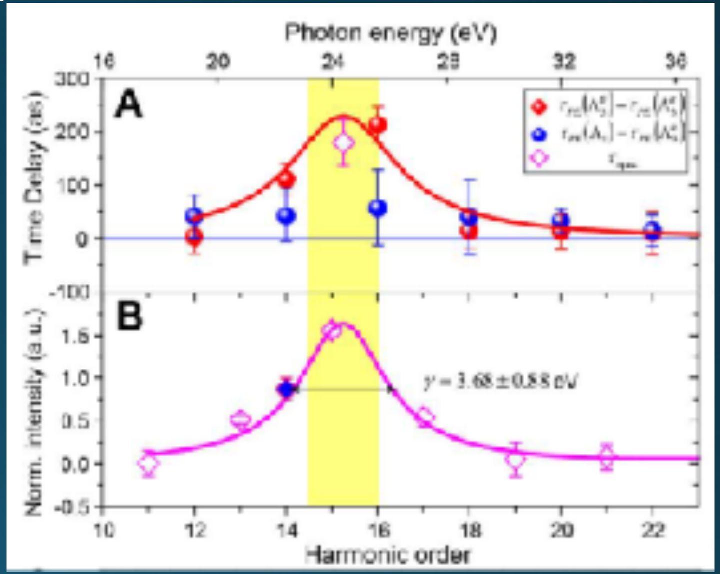

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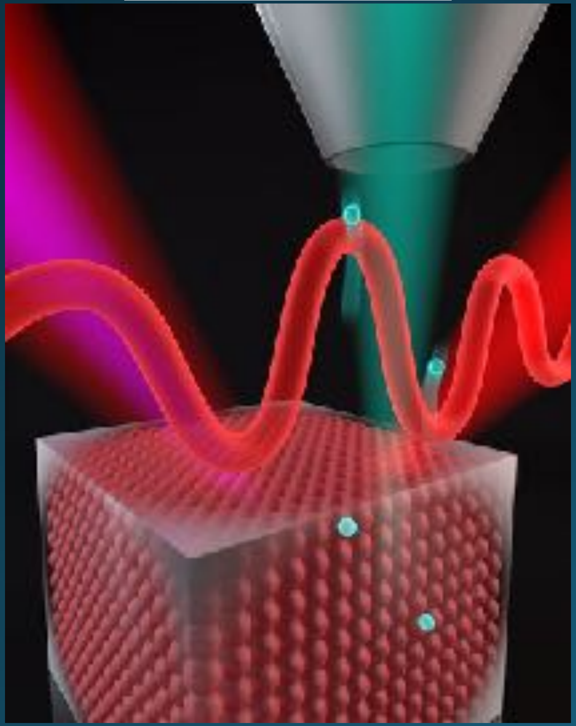

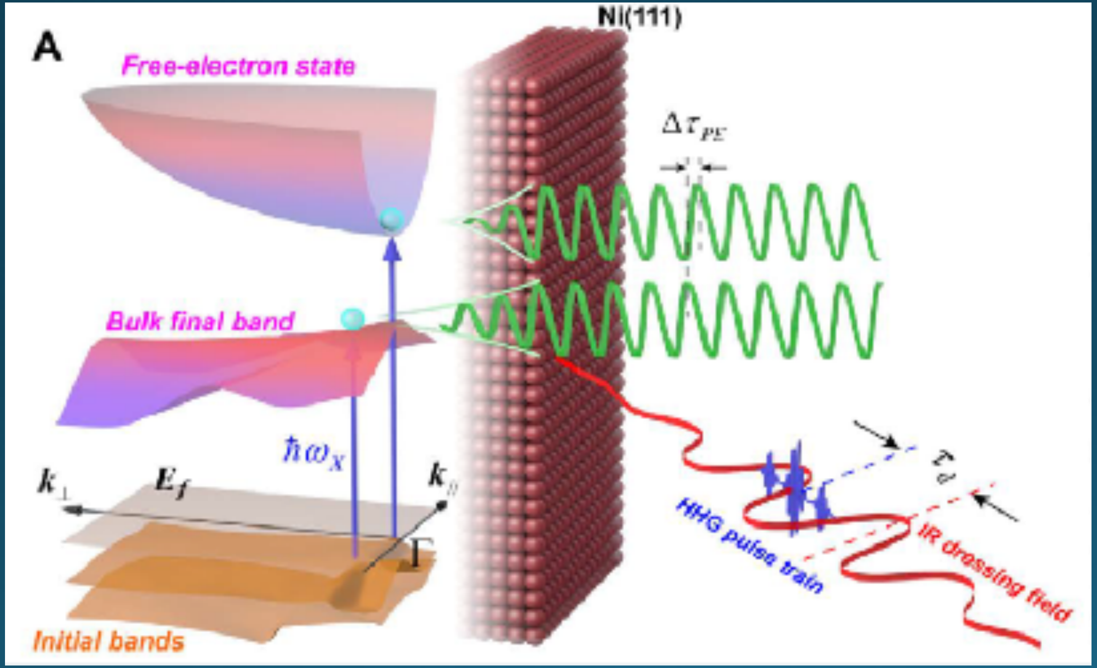

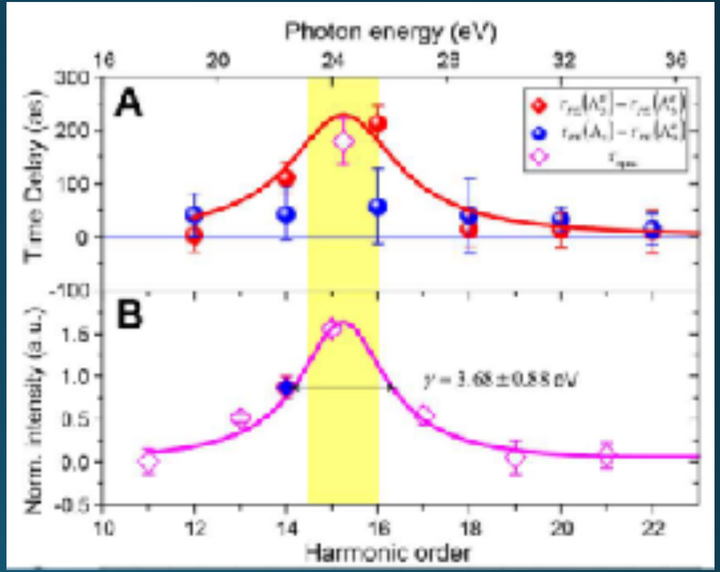

Shortest state-resolved lifetime measured… ~ 200 attoseconds!

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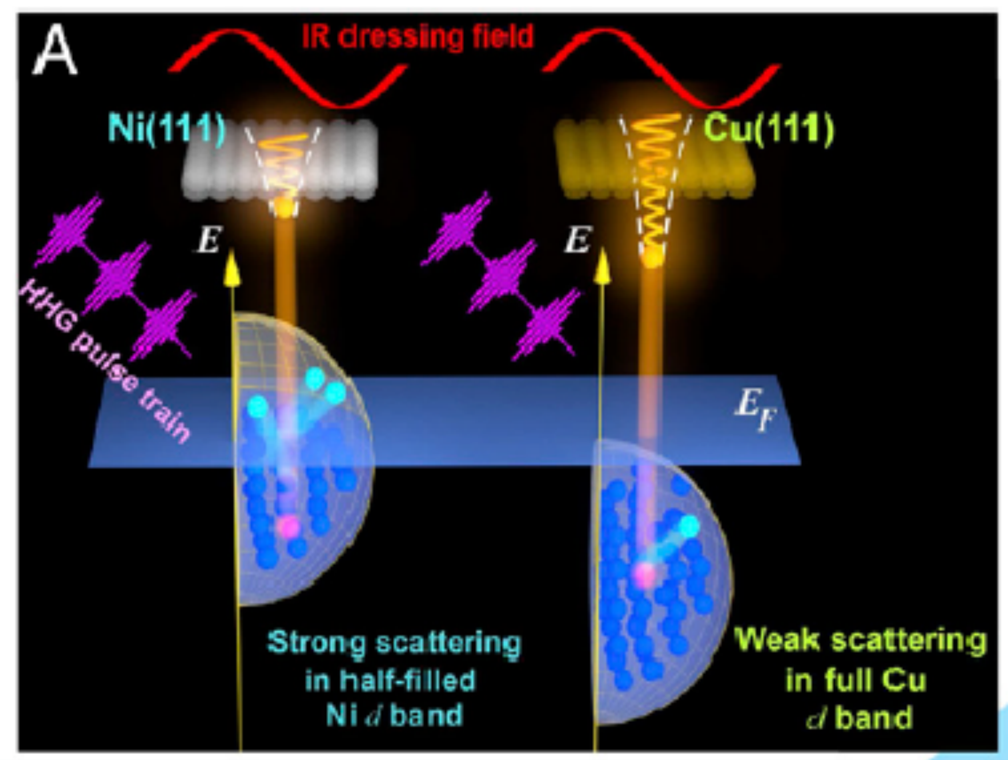

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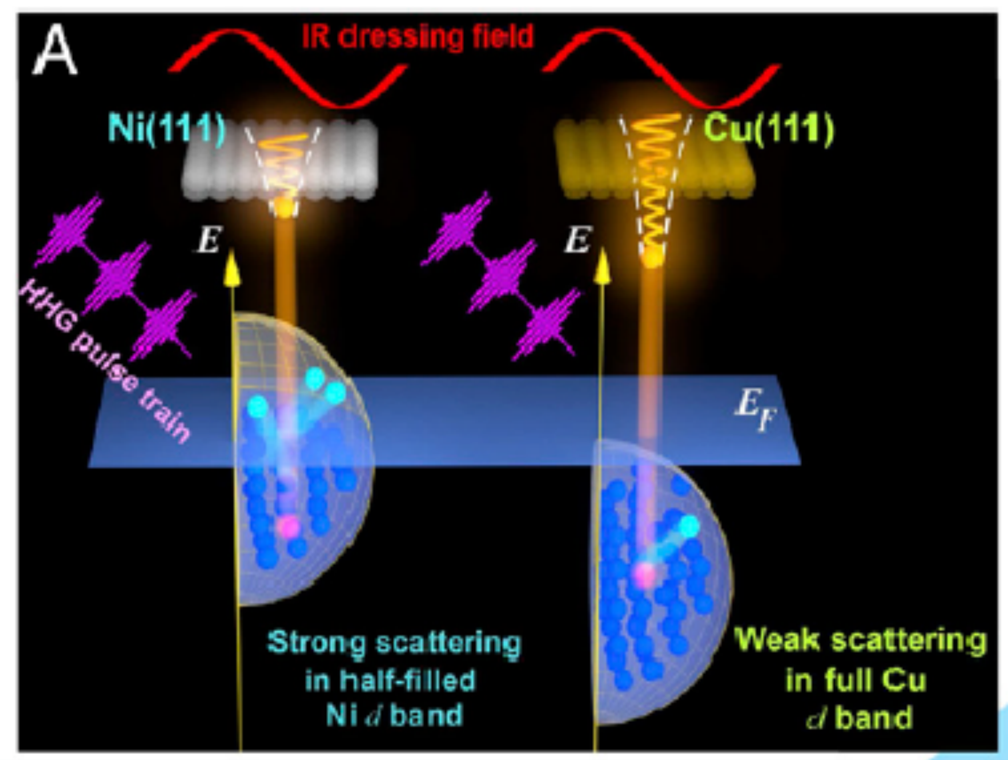

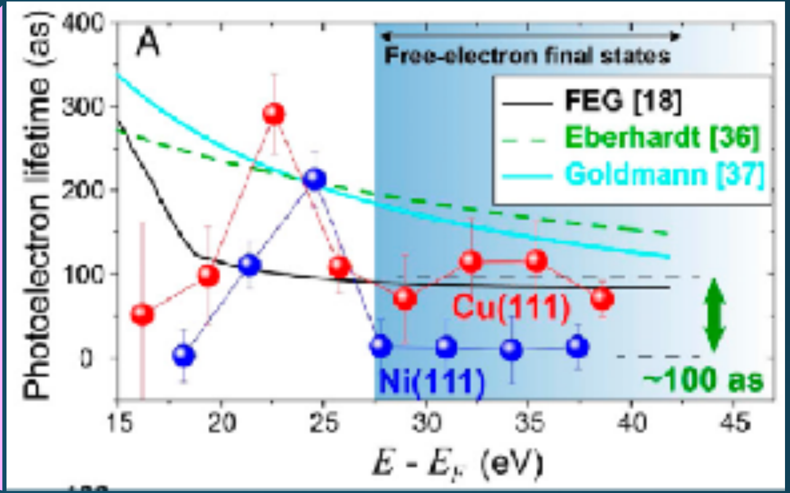

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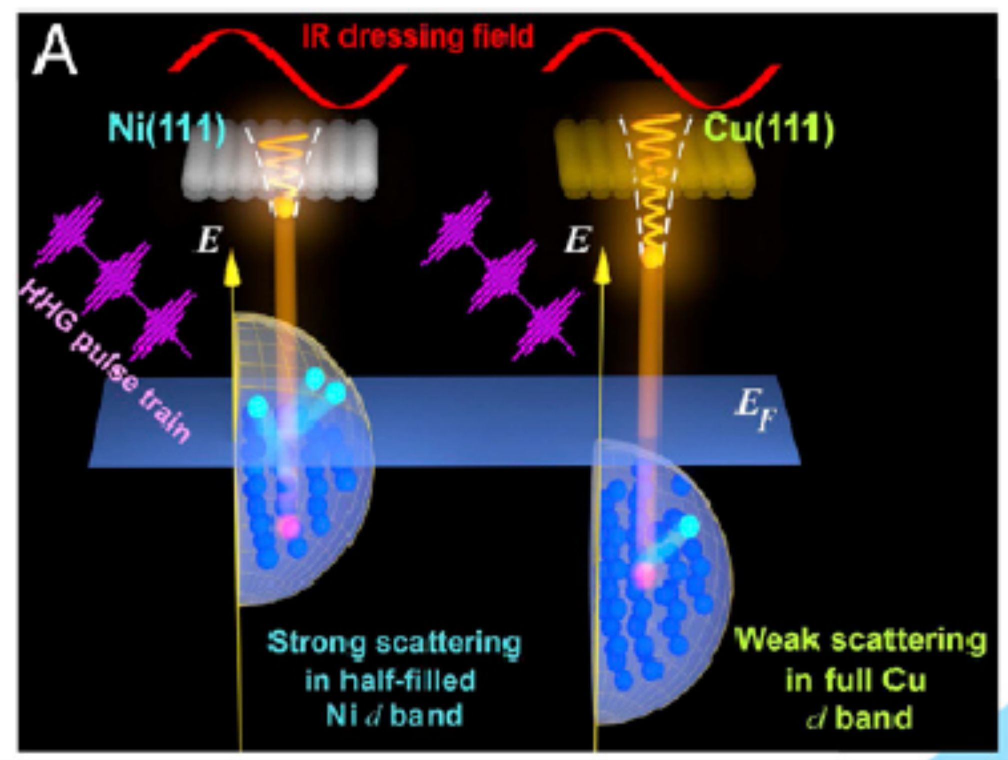

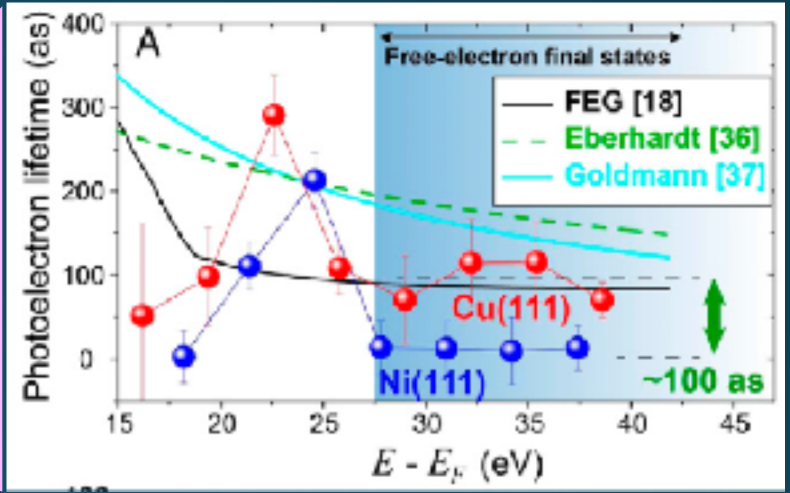

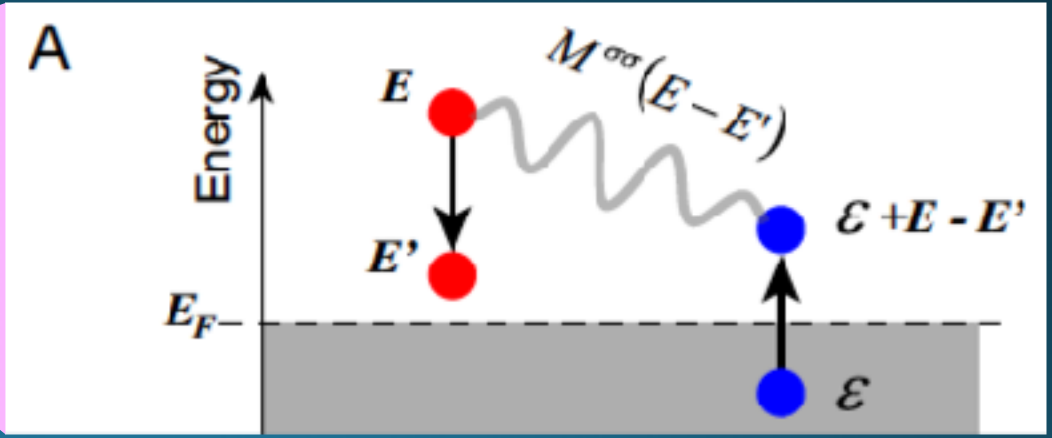

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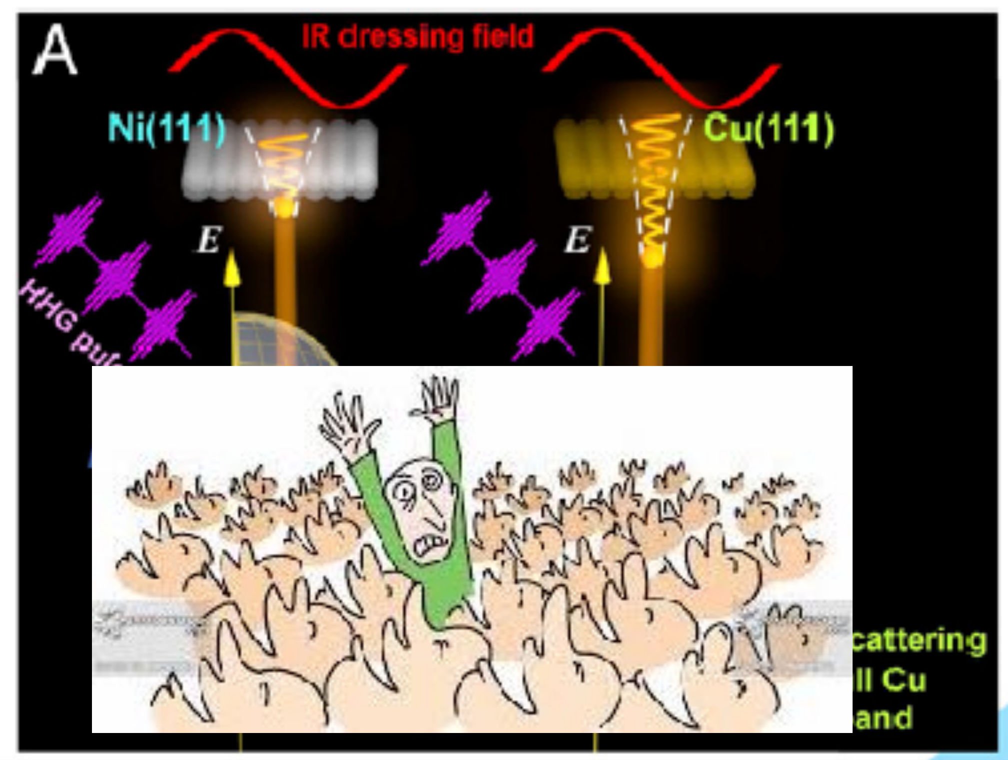

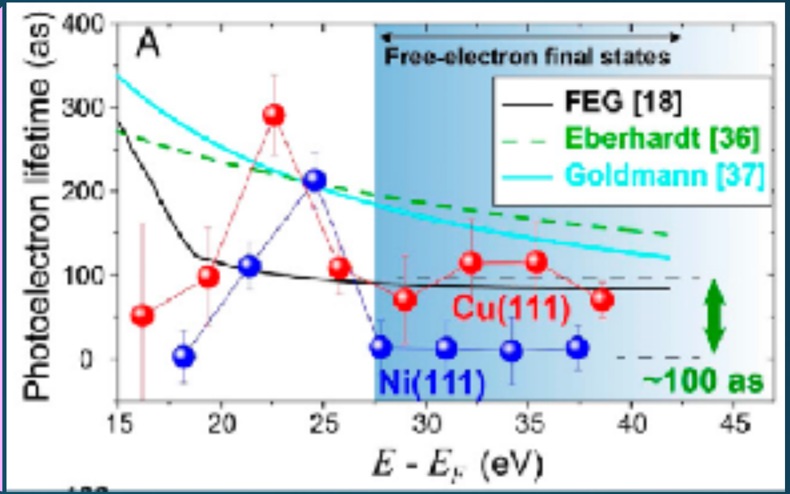

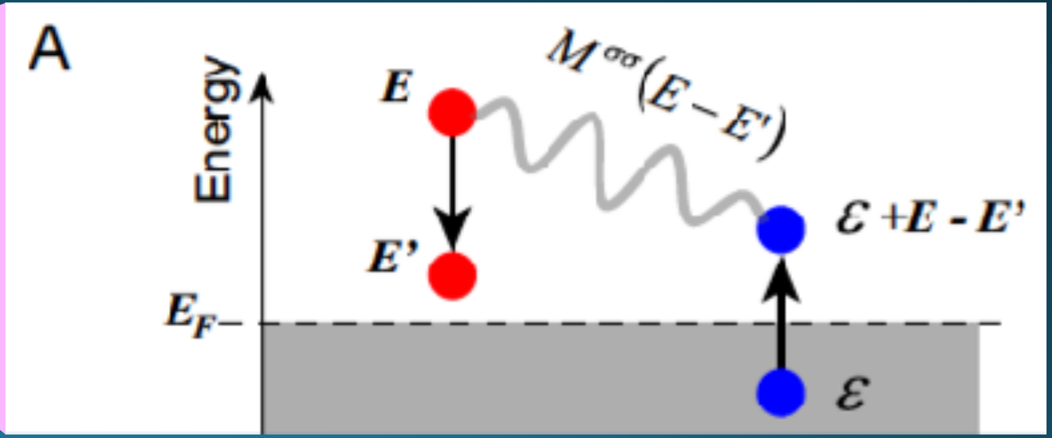

Quantifying the Ultrafast Laser-Induced Demagnetization of Magnetic Films

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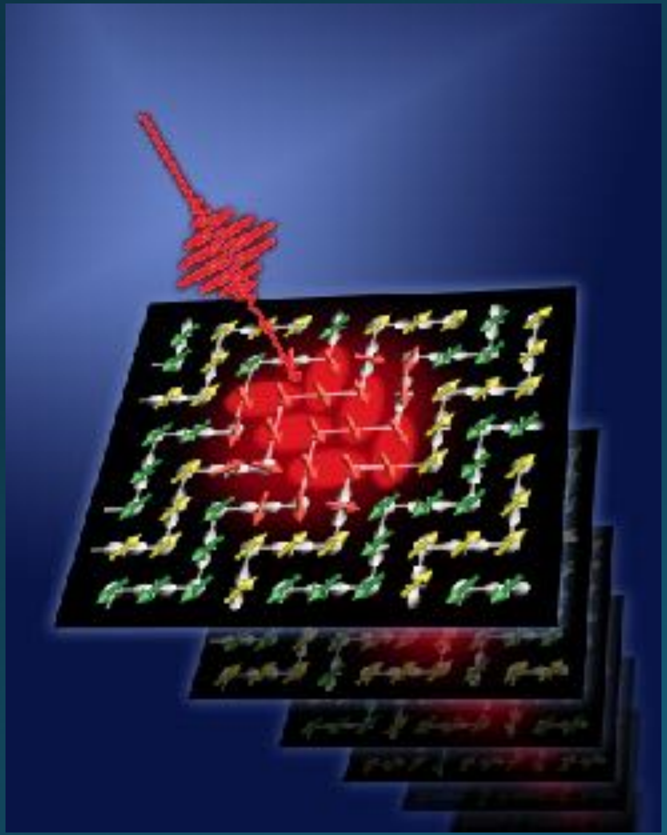

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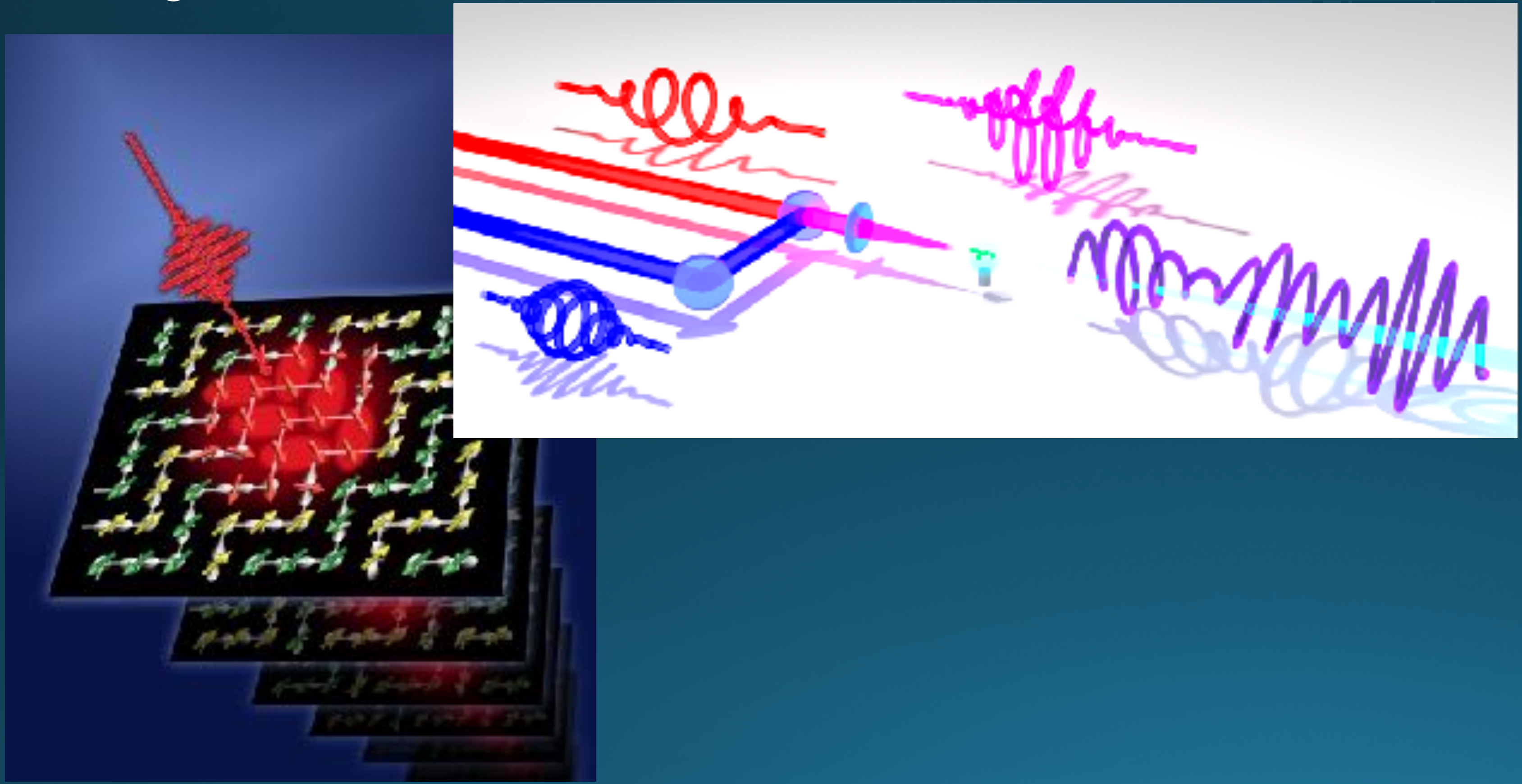

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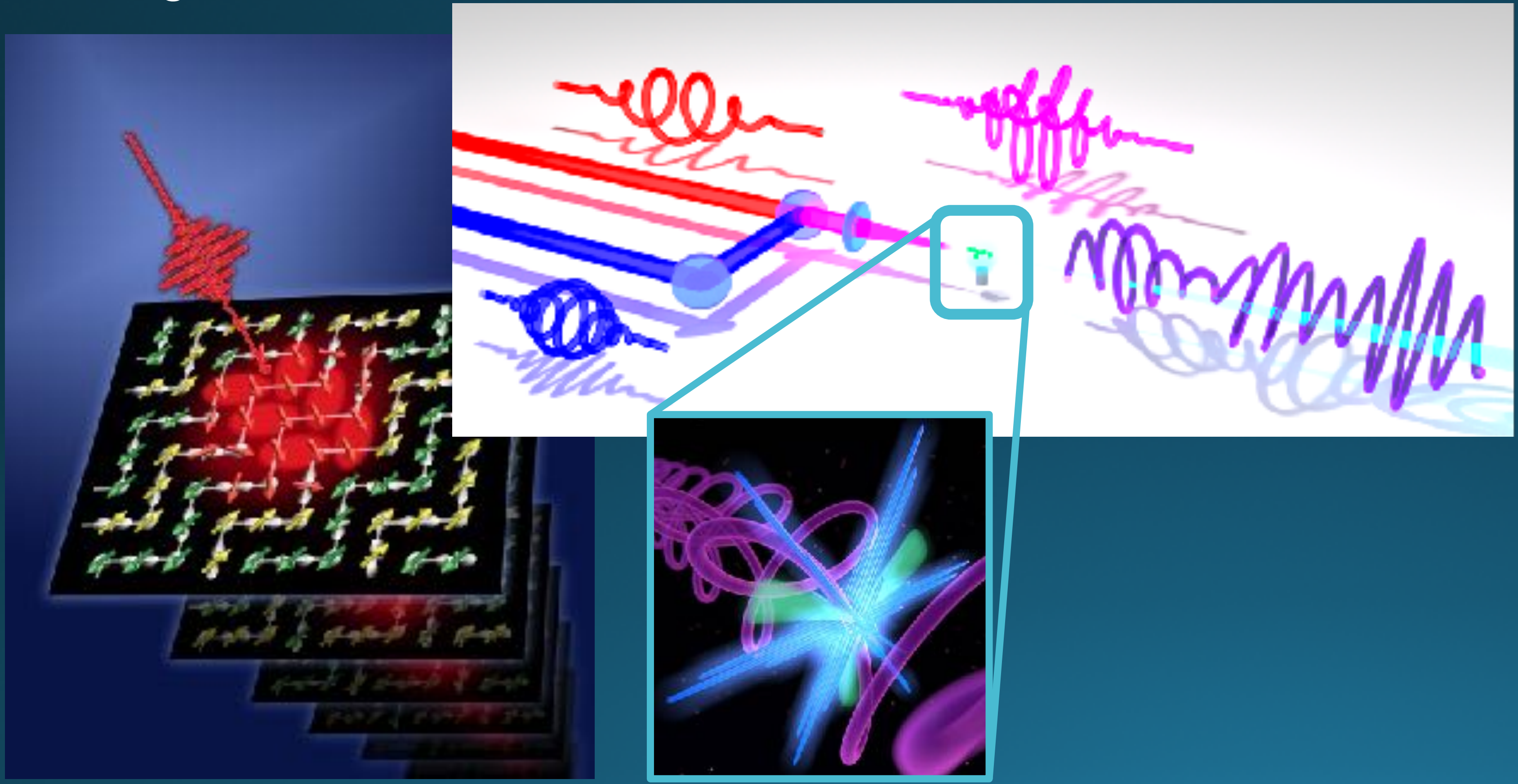

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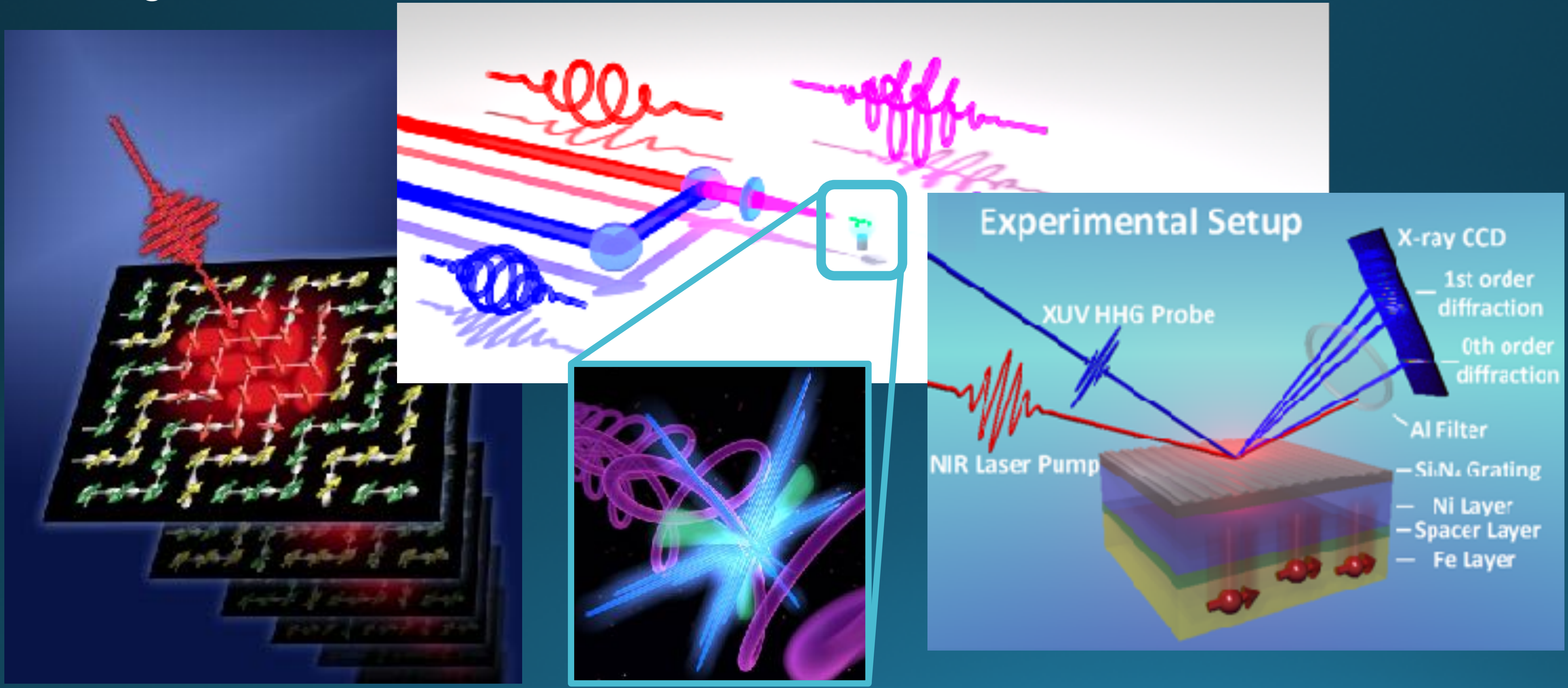

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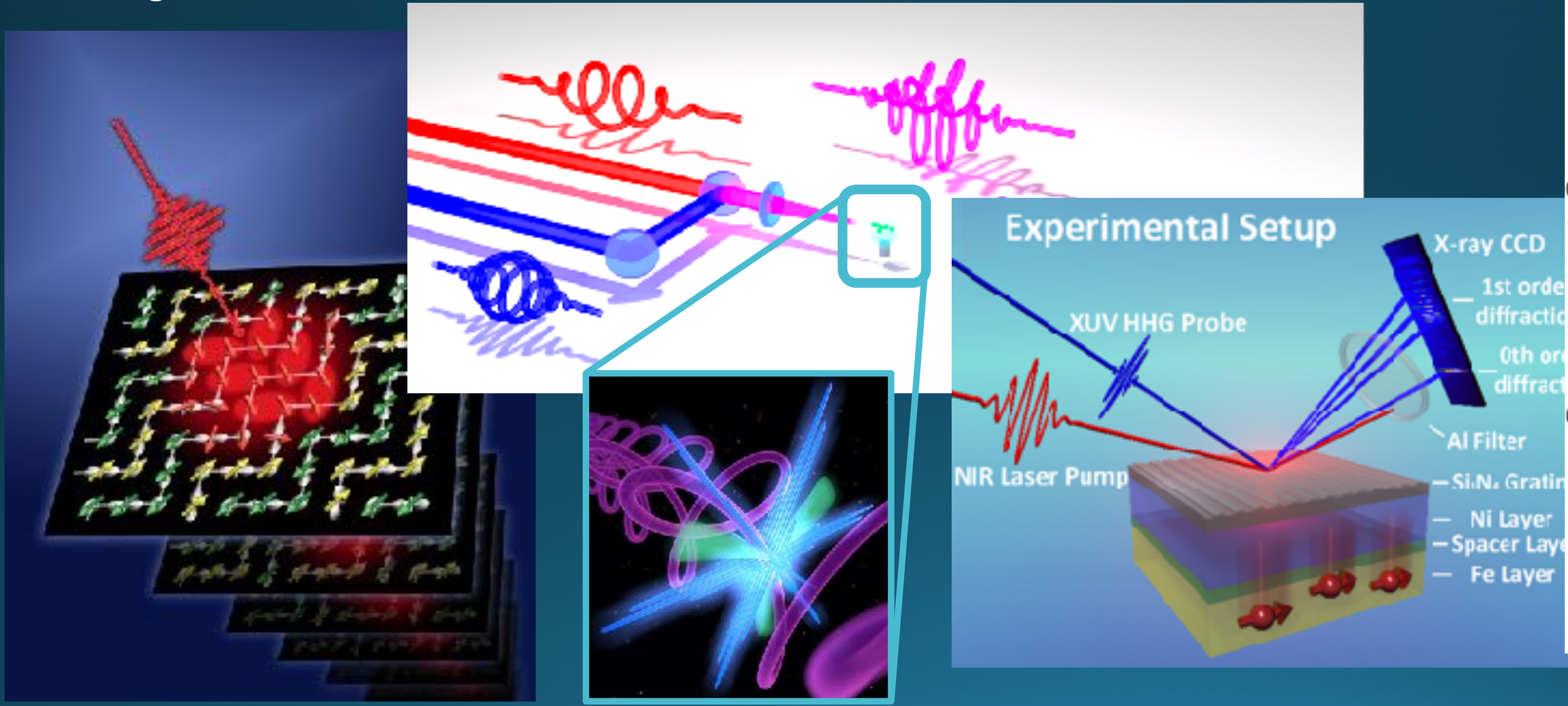

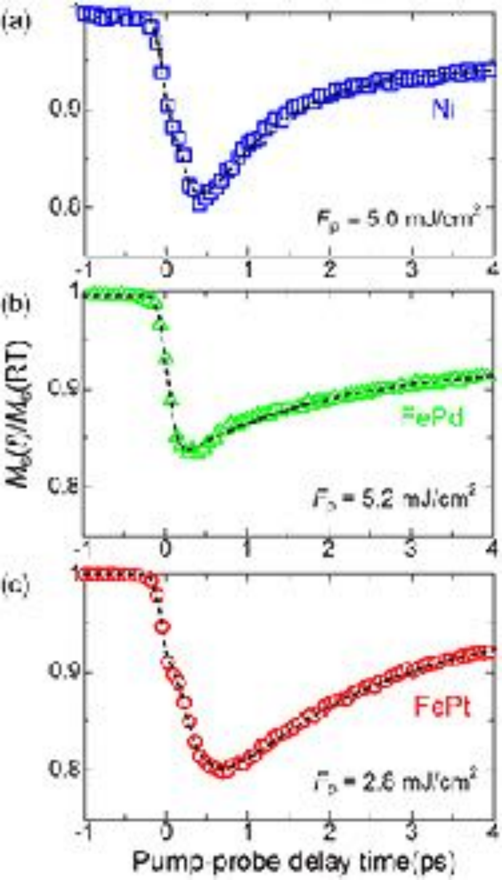

Creating a New Class of X-Ray Lasers: Pushing the Limits of Attosecond Science

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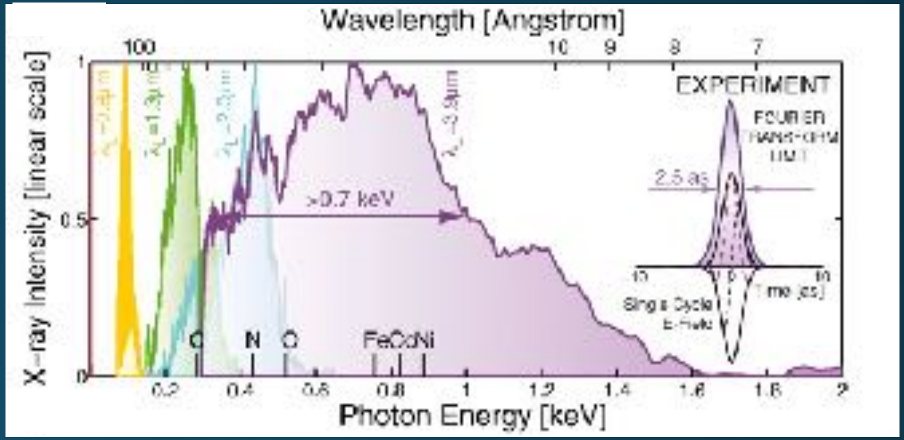

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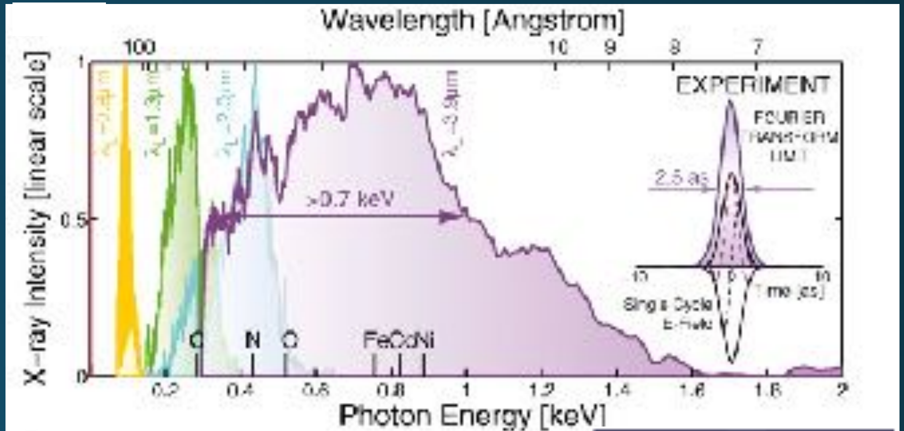

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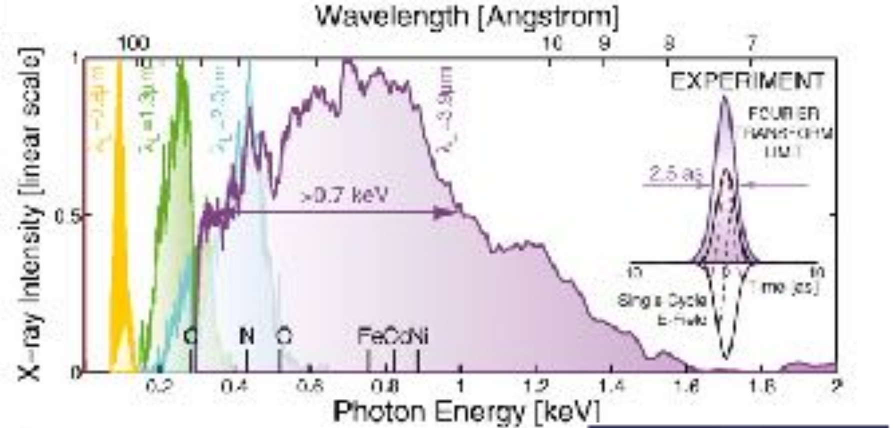

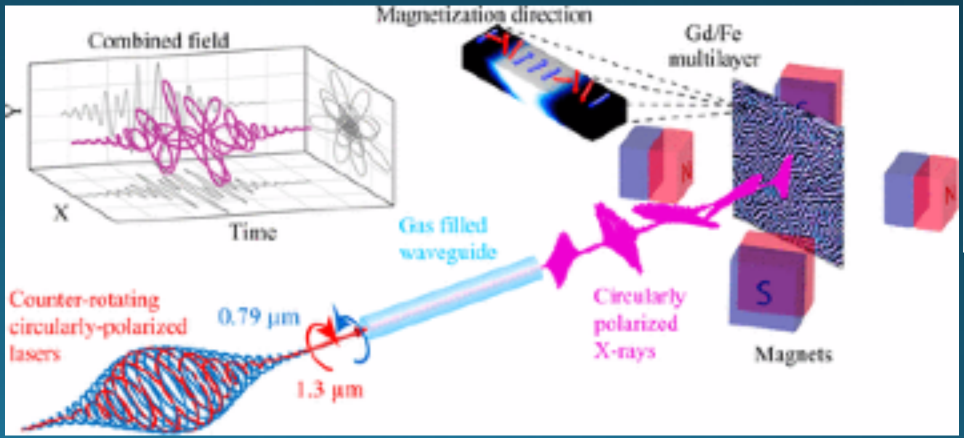

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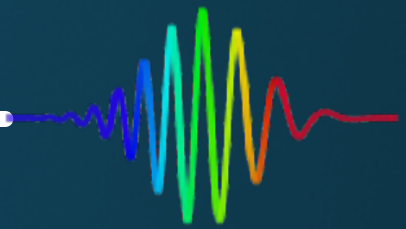

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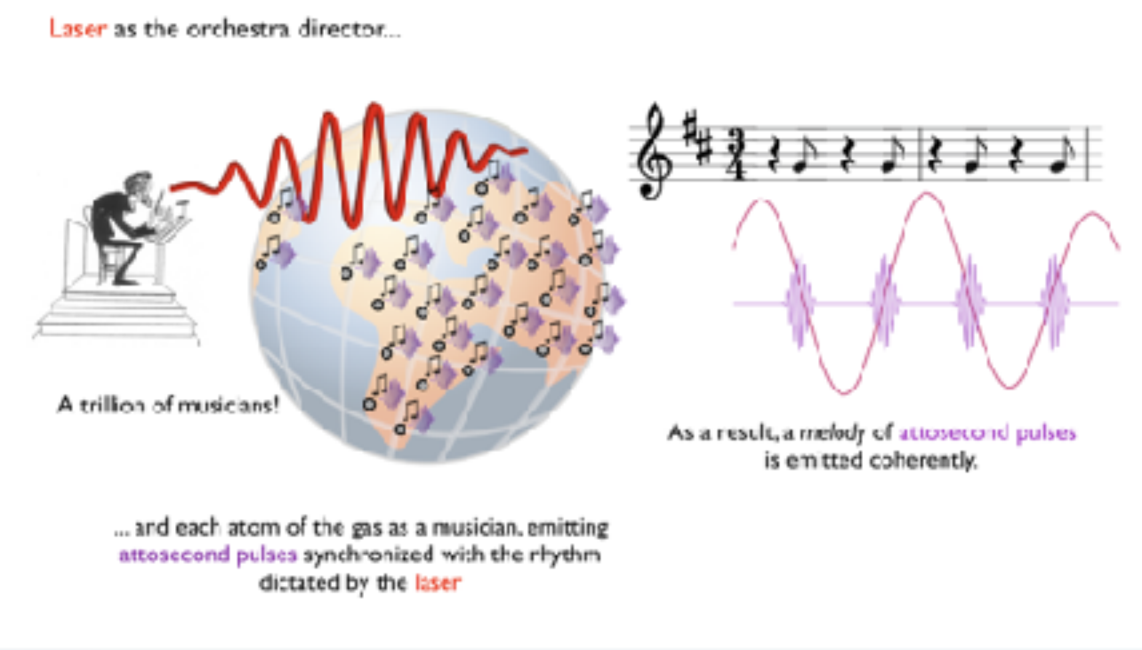

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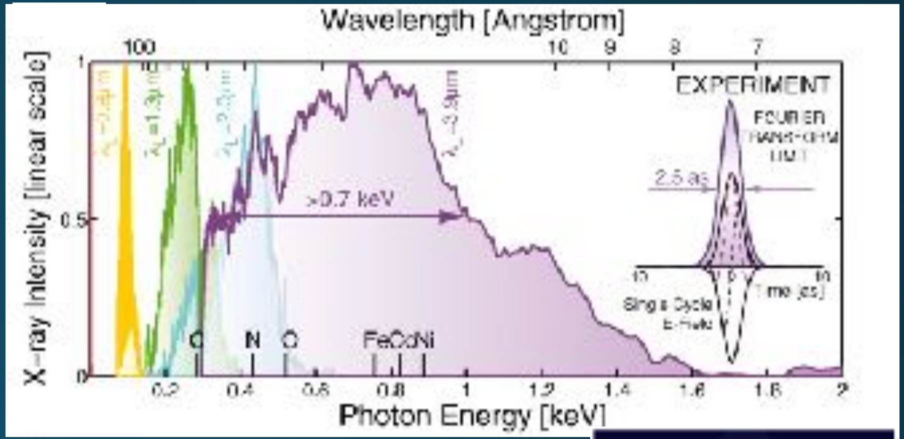

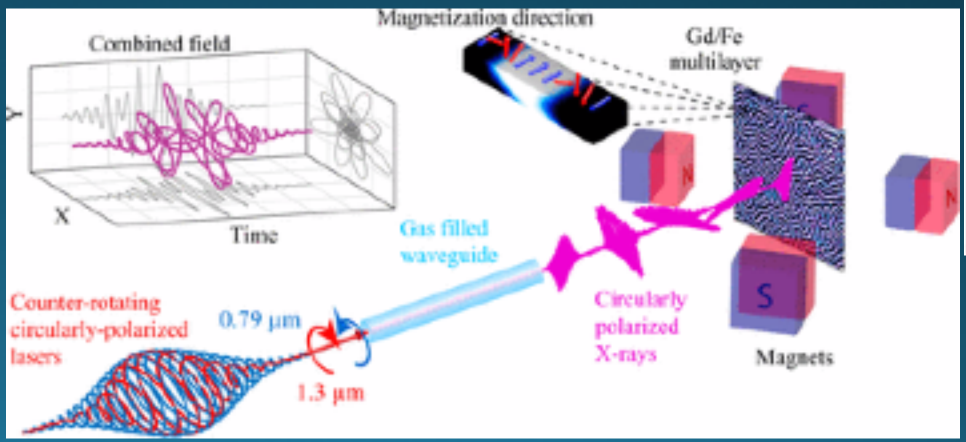

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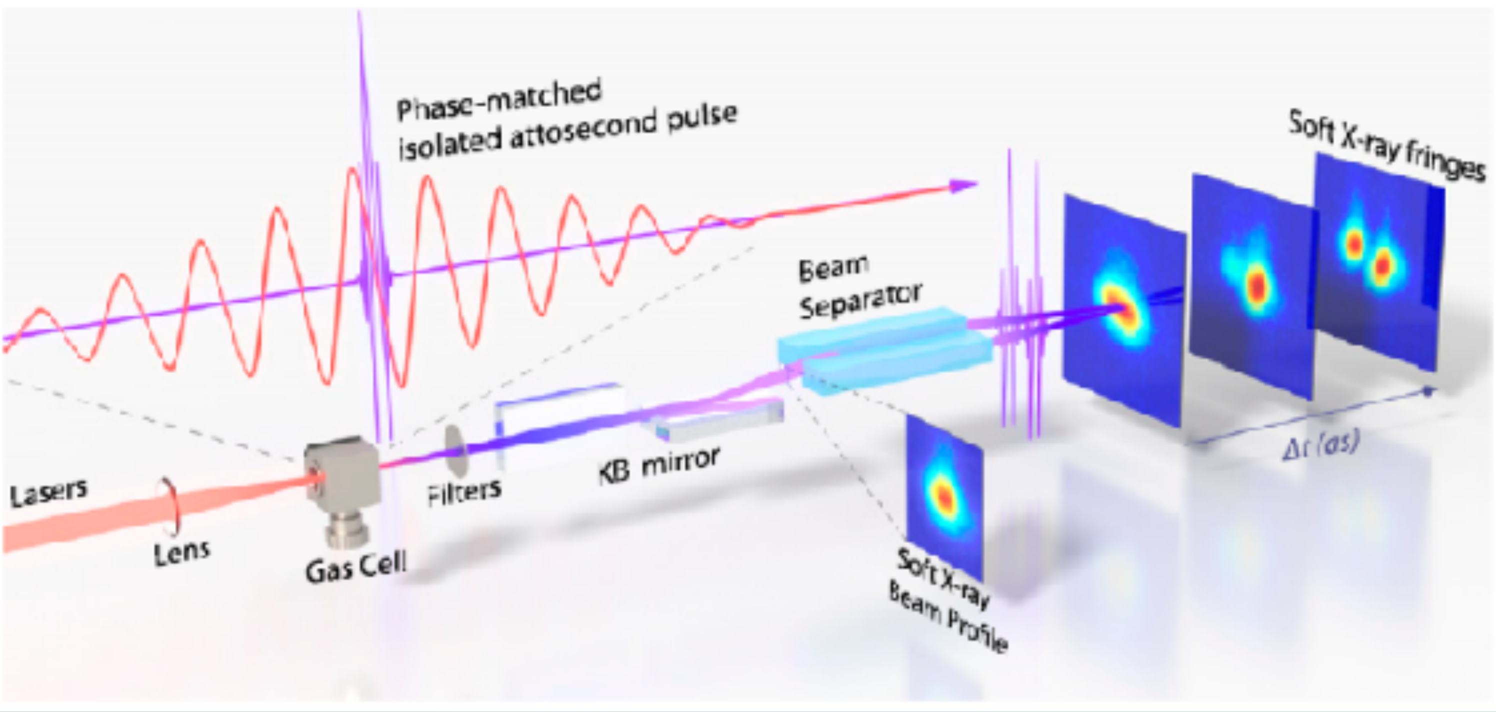

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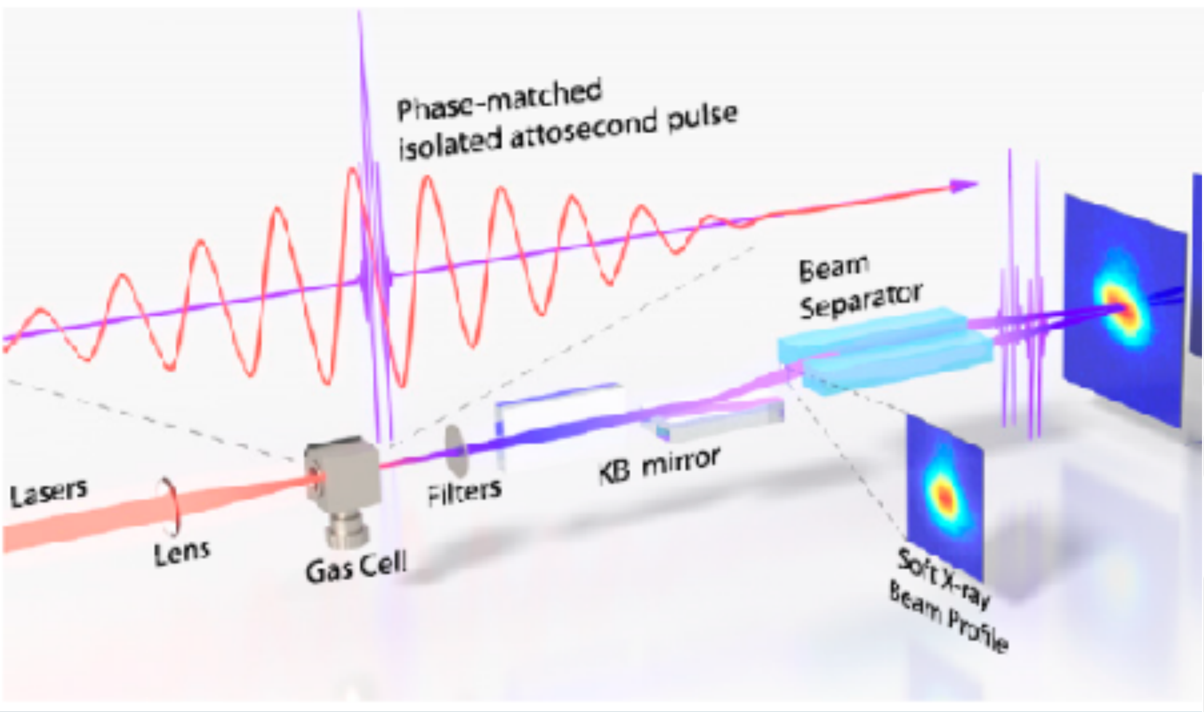

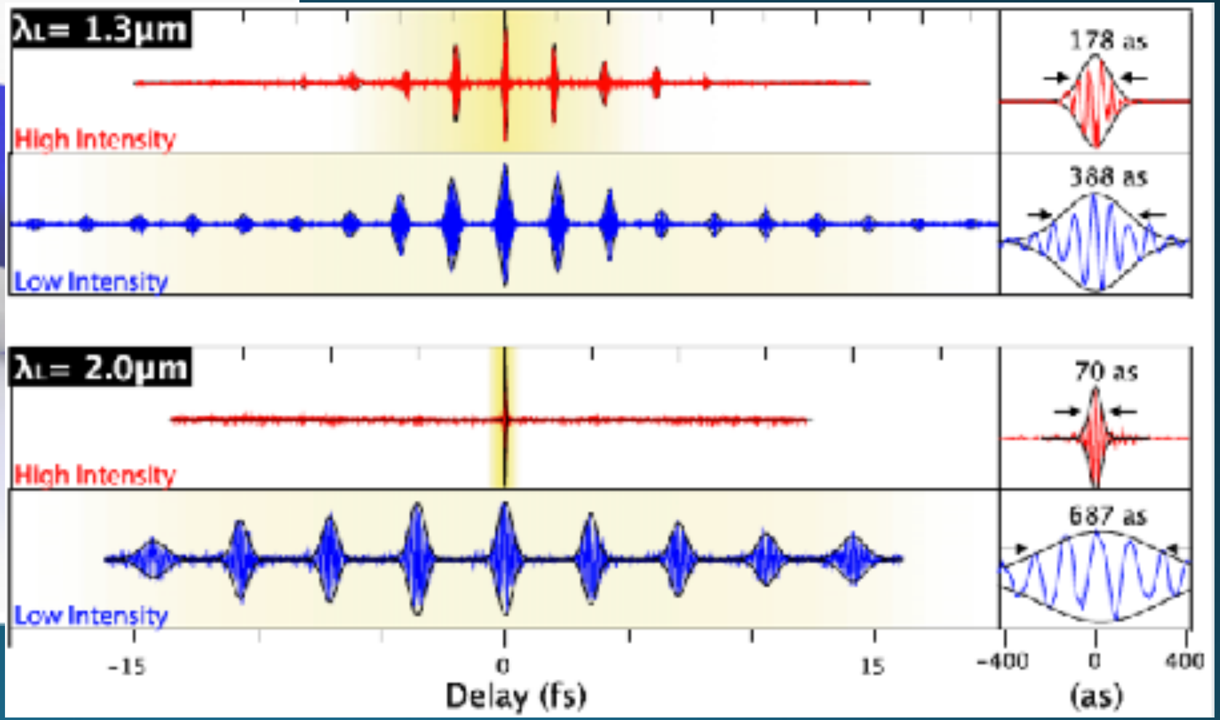

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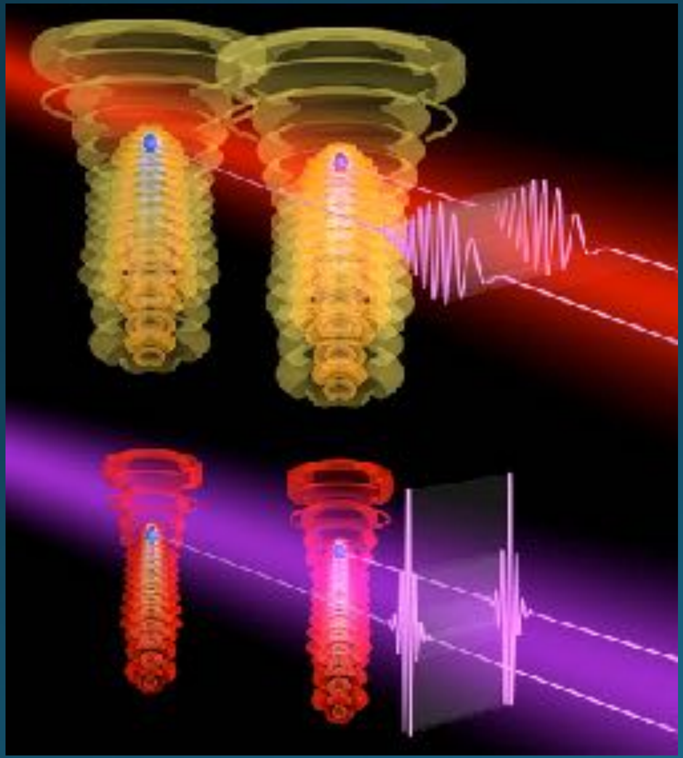

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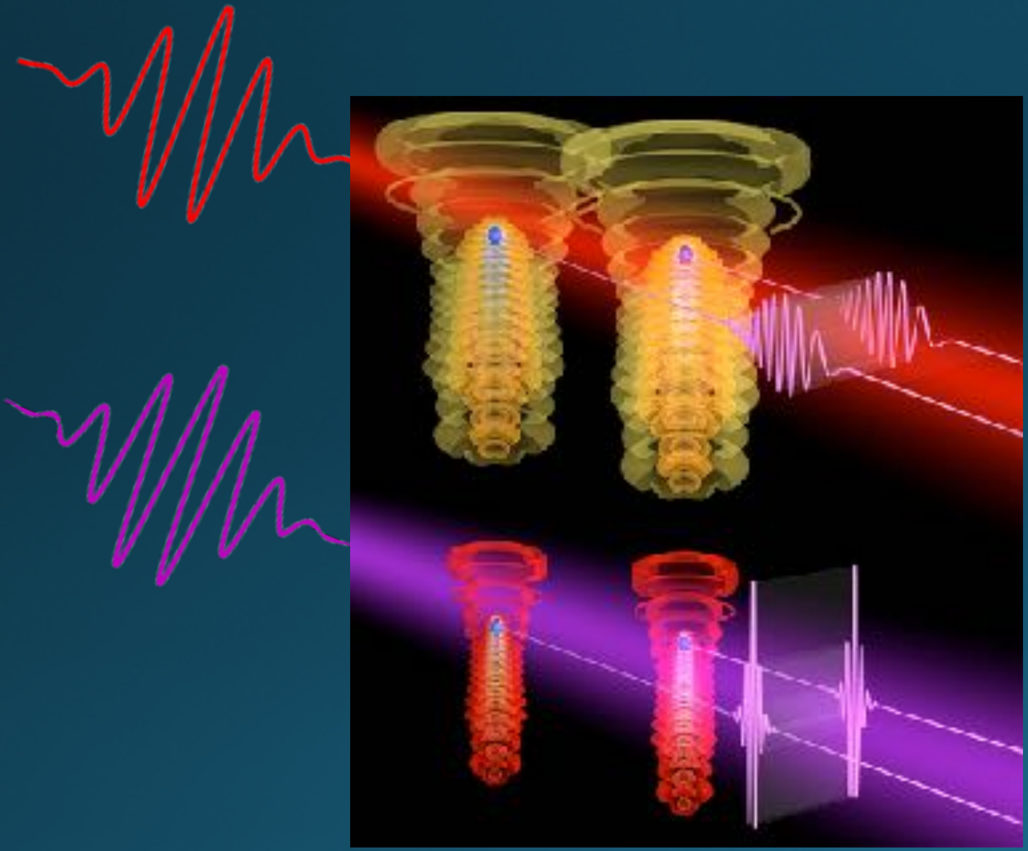

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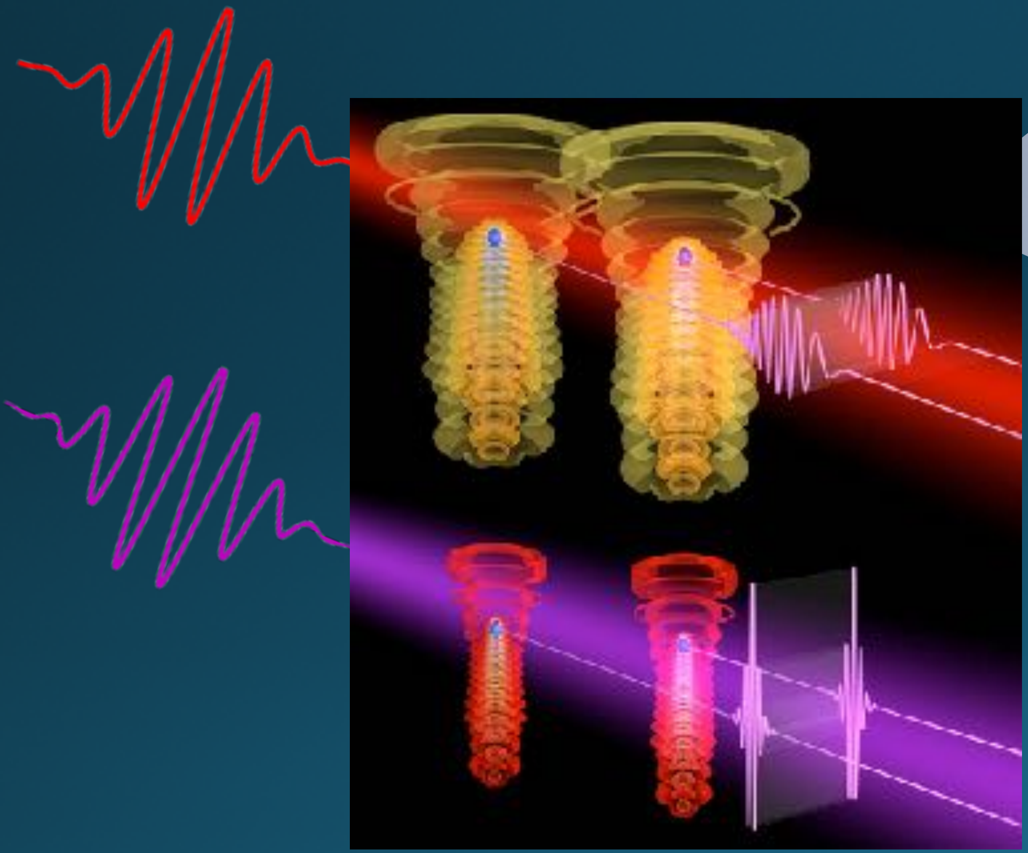

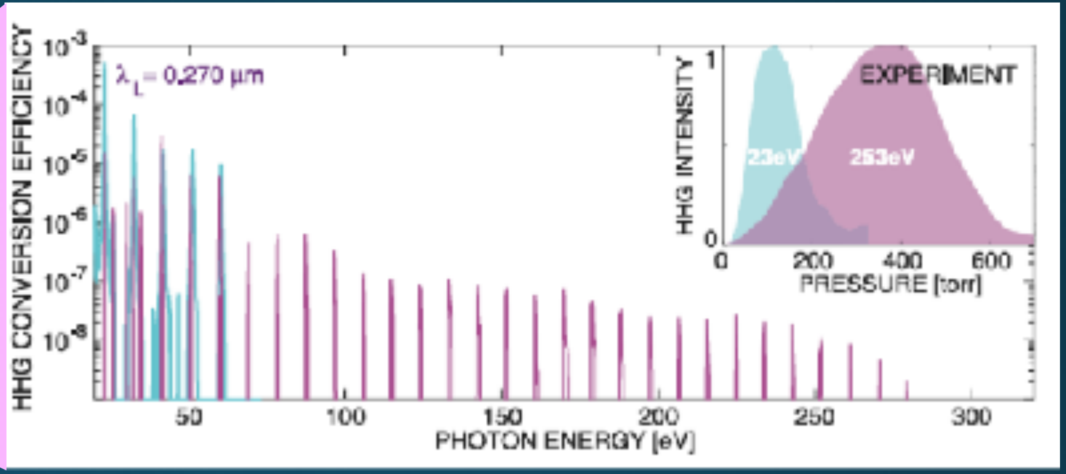

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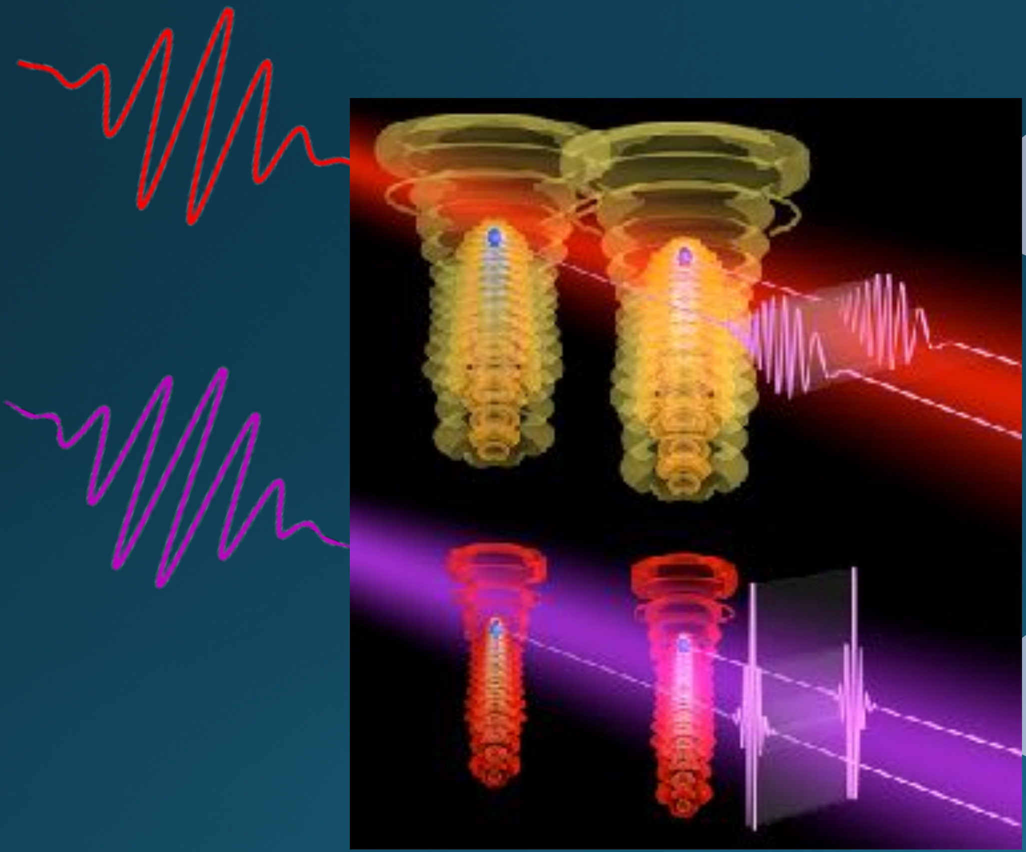
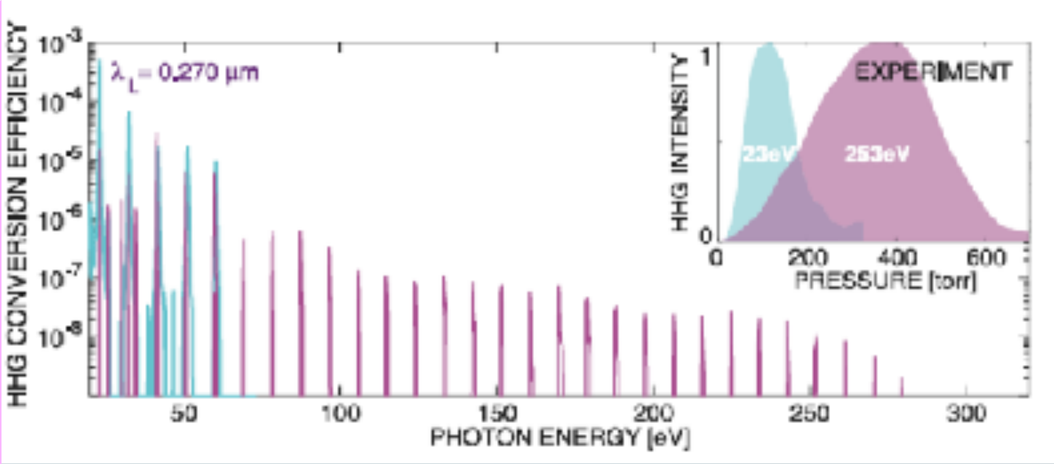
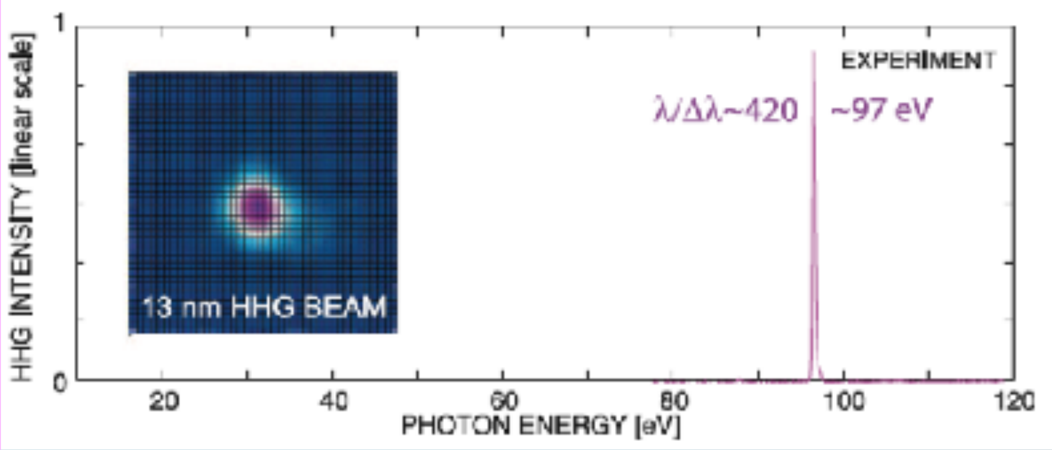


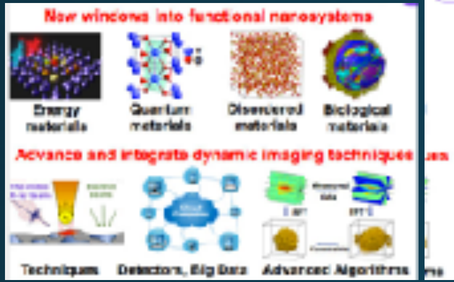




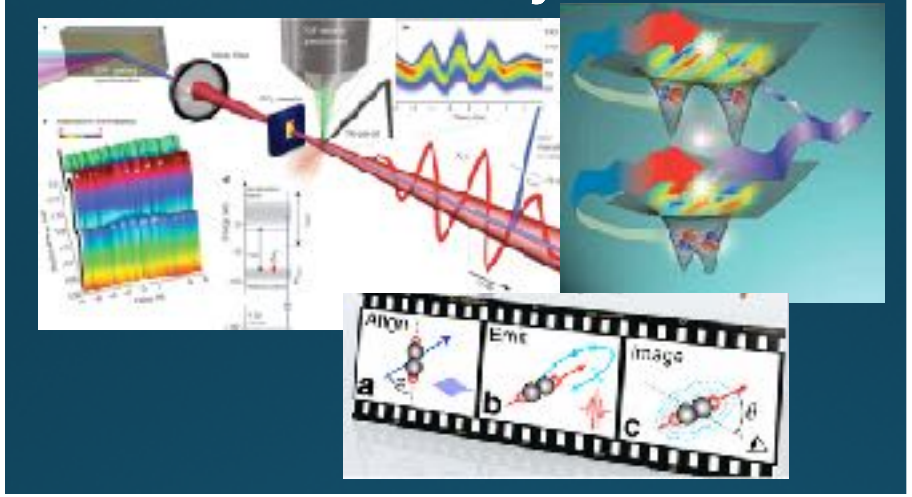
Future of Ultrafast Light and Materials Science: Probing Nature at Its Fundamental Limits

Real Time Functional Imaging

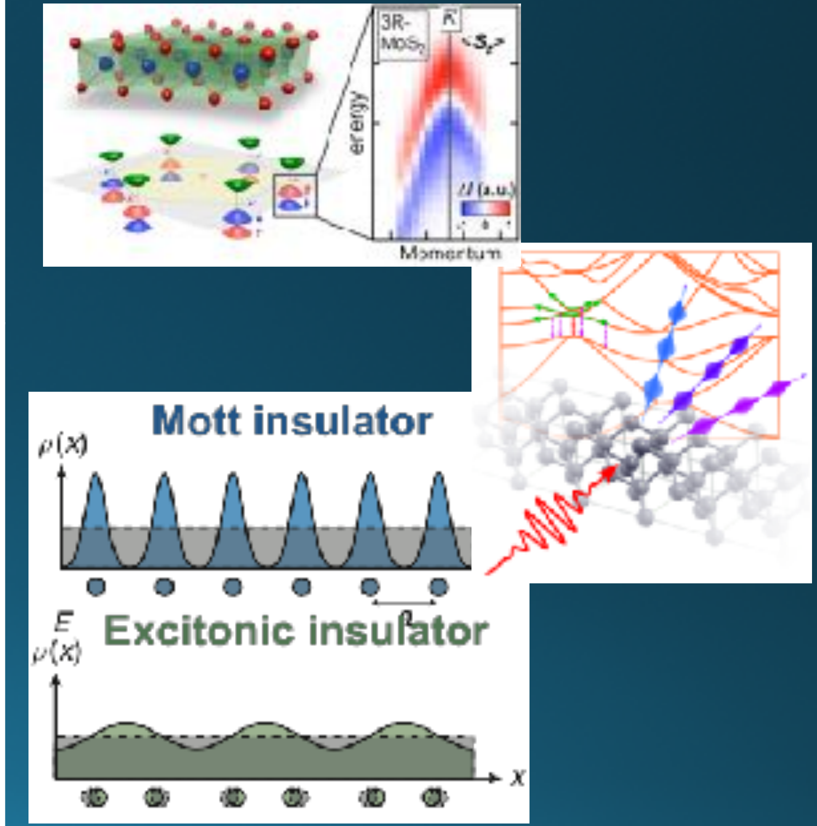
STROBE
NSF SCIENCE AND TECHNOLOGY CENTER



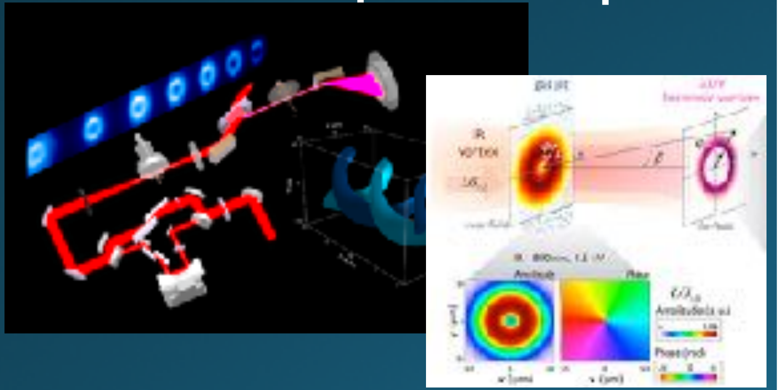
Attosecond Dynamics



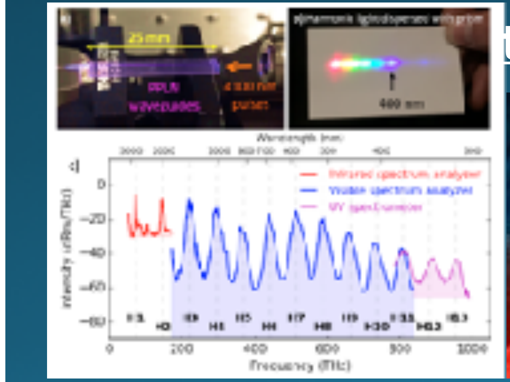
Tracking the Ultrafast Migration of Charge in Correlated Materials



Structured Light Beams for Advanced Spectroscopies



New Sources of Ultrafast Laser



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