Attosecond, High-Harmonic Optical Vortices with Tailored Spin and Orbital Angular Momentum

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CAMPUS DE EXCELENCIA INTERNACIONAL

ICFO The Institute of Photonic Sciences

Nonlinear Waves II (NW2A), NLO 2019

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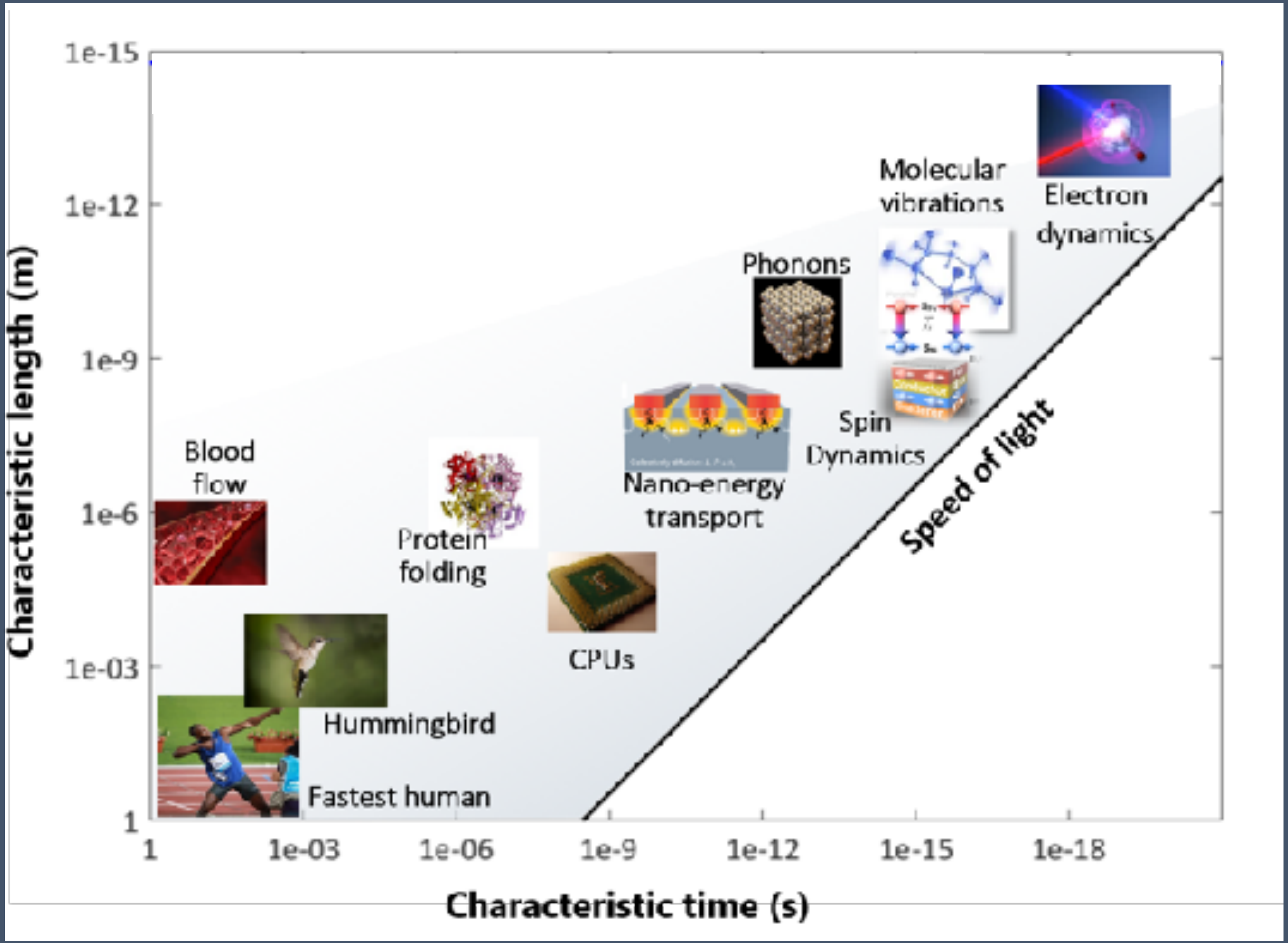
Life in the Fast Lane: The Nanoscale, Ultrafast Dynamics Underlying Emerging Technologies and Nature



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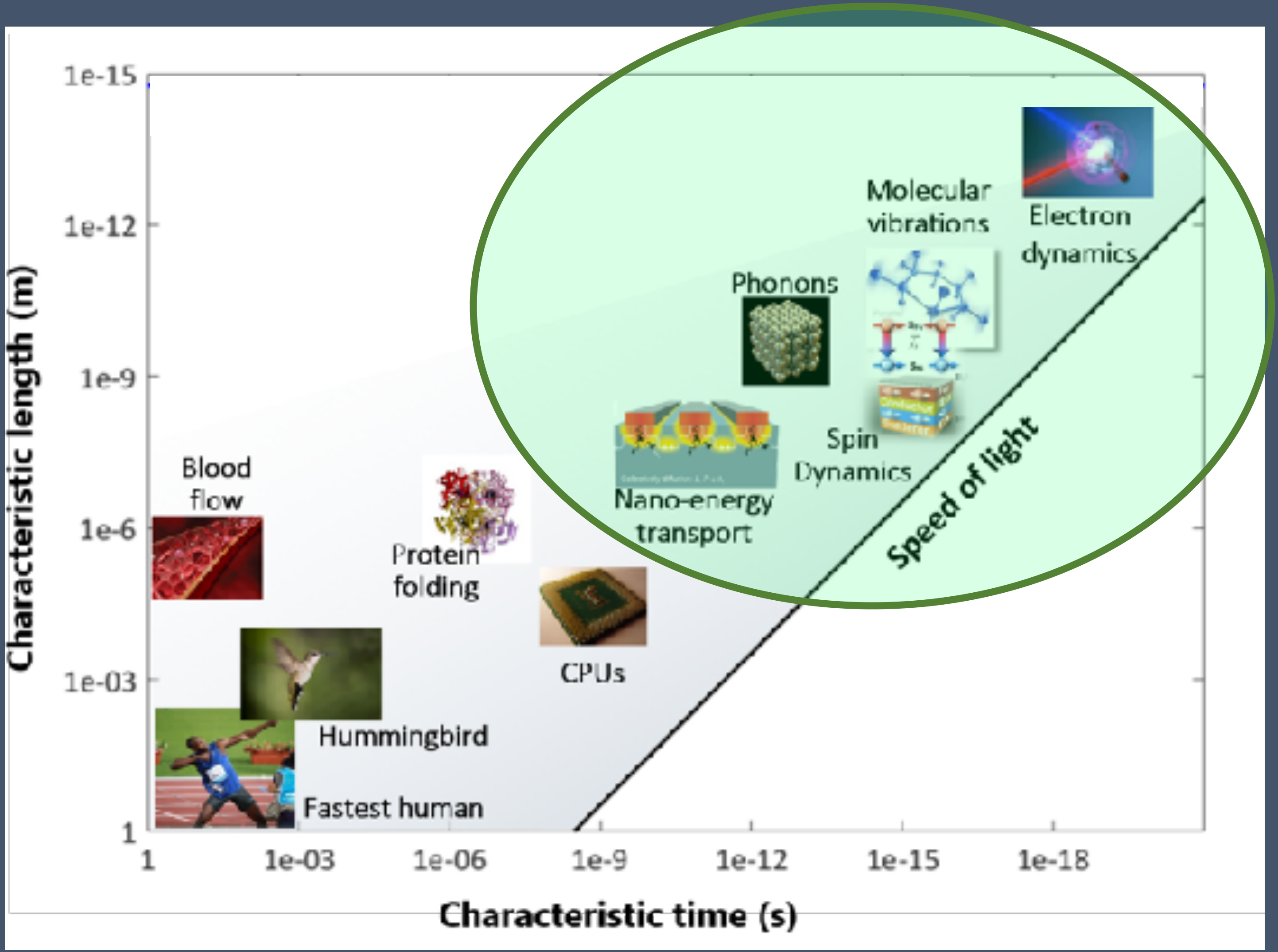

__Ultrafast, Short Wavelength Light is an Ideal Probe of the Nano-Quantum World__

- ✓ Elemental, chemical, spin specificity
- ✓ Short wavelength yields high-resolution 3D images of structure
- ✓ Ultrafast nature of x-rays captures dynamics relevant to function
- ✓ Nondestructive/non-invasive; “x-ray” vision

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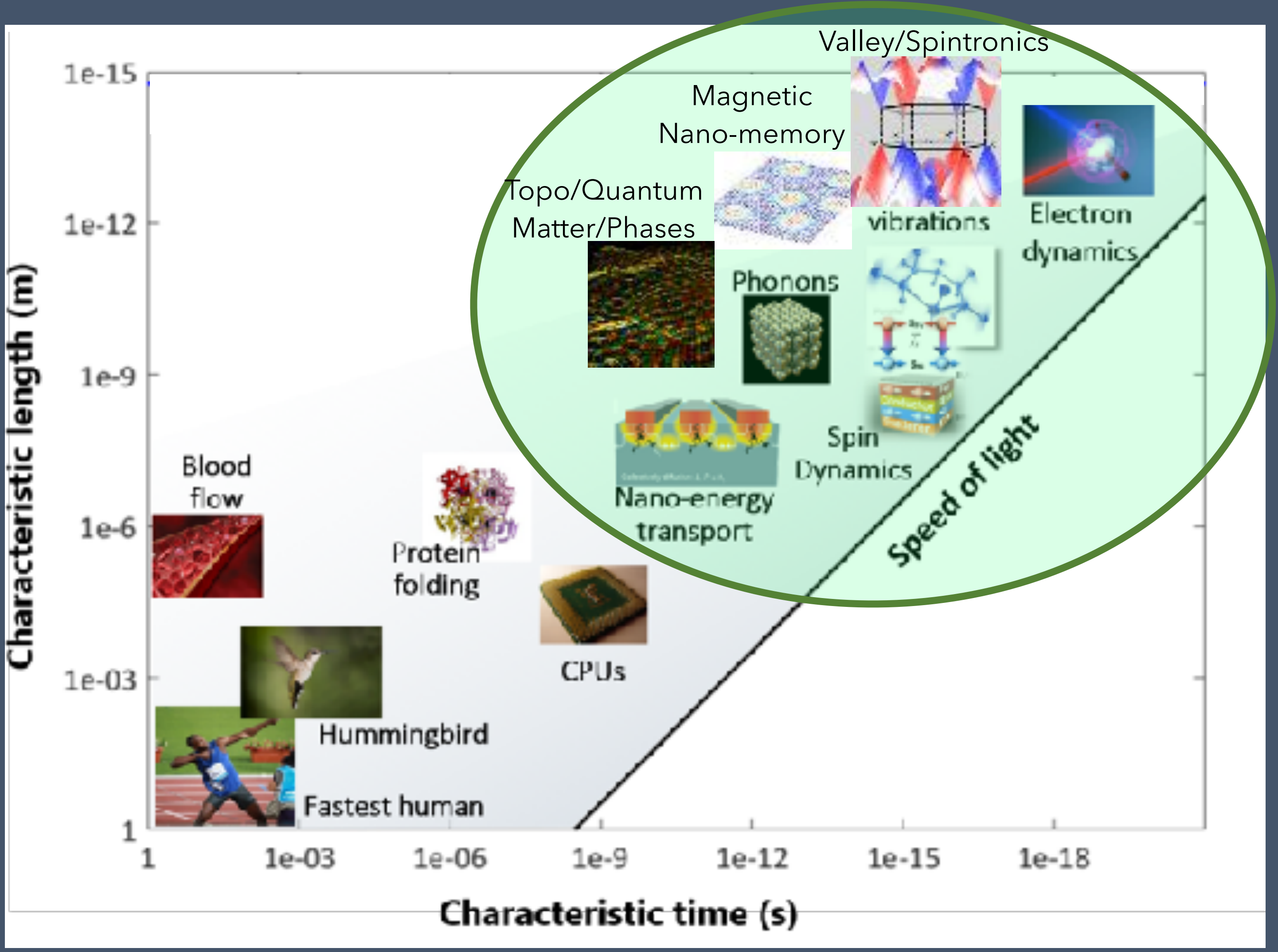

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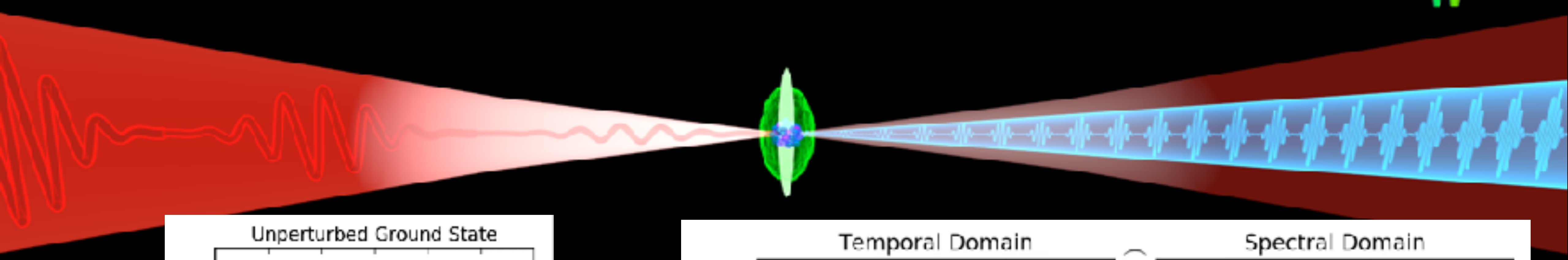
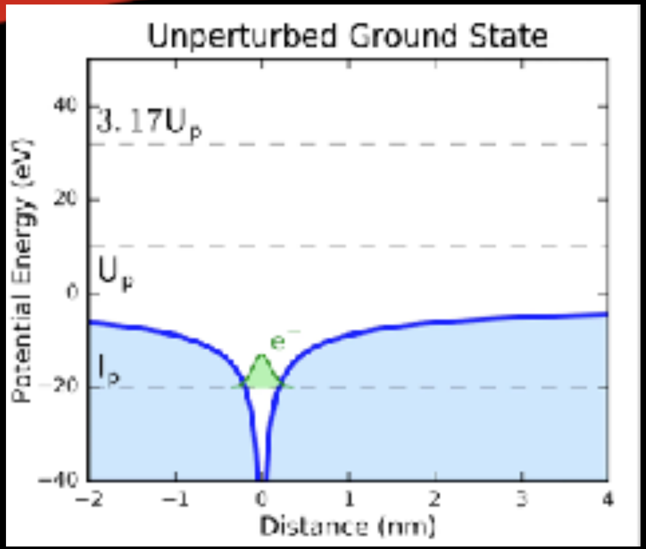
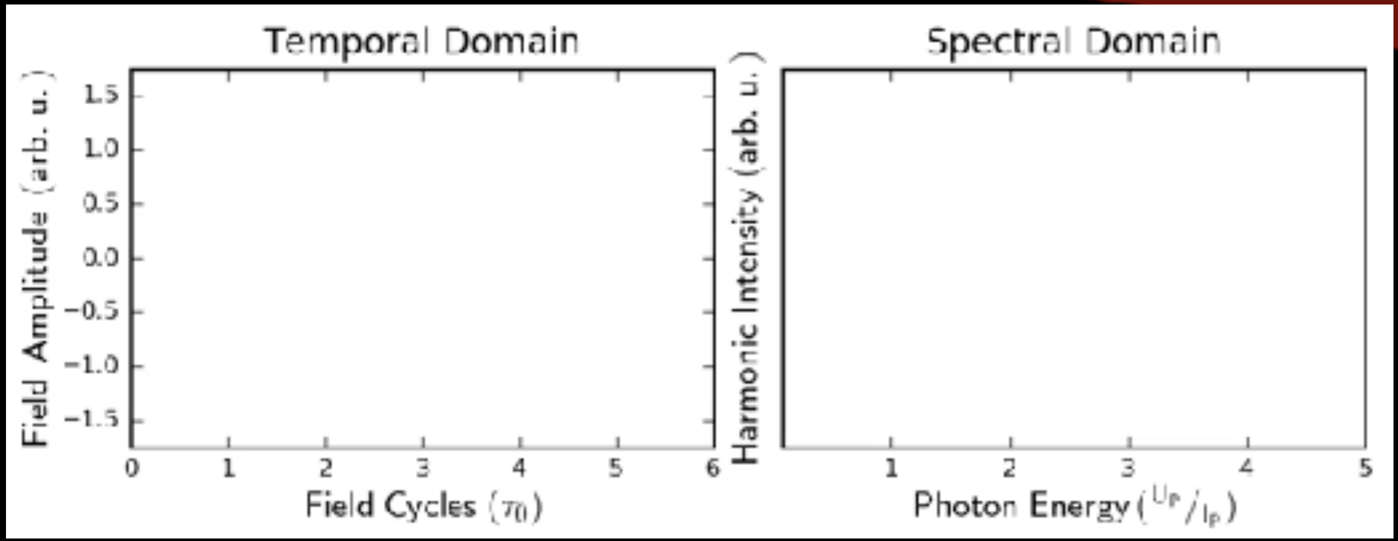
Future is Fast, Small, and Highly Structured!

- ➢ Many next-gen technologies are based on **chiral/topological materials.**
- ➢ Demands a need for ultrafast, ***structured/ chiral***, short-wavelength light!

High-Harmonic Generation (HHG): A Quantum Technology for Capturing the Fastest Dynamics in Nature







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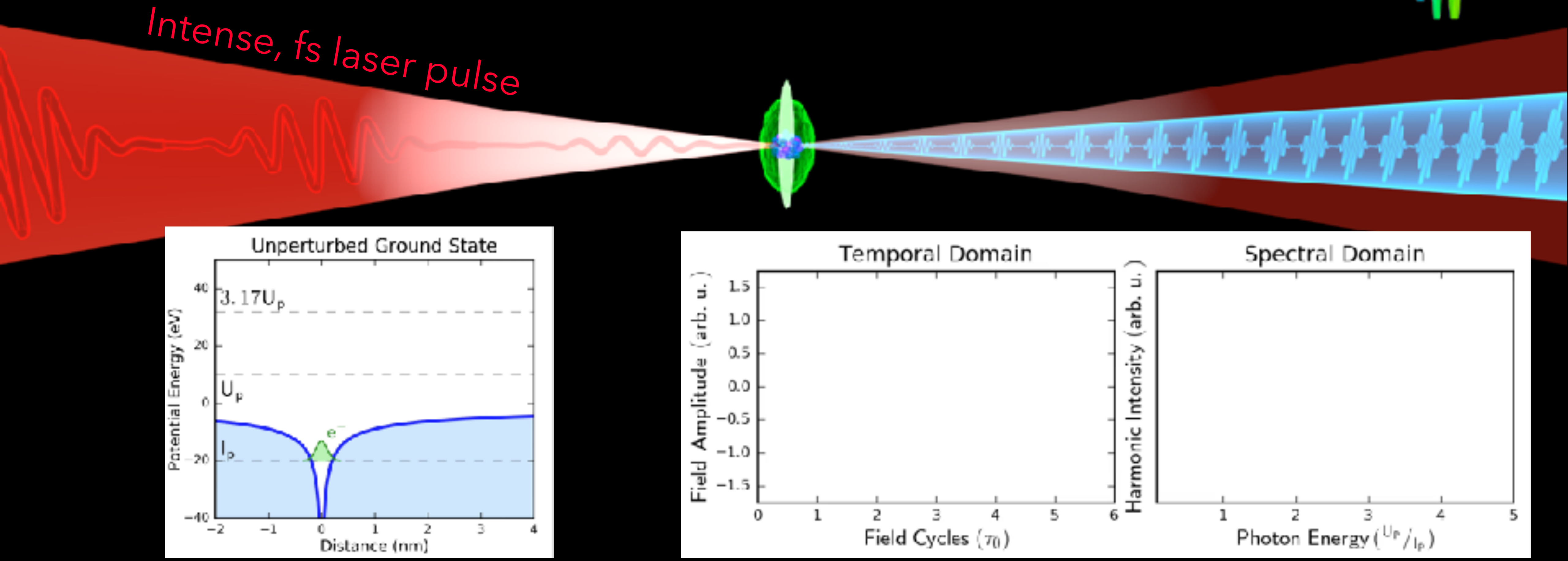

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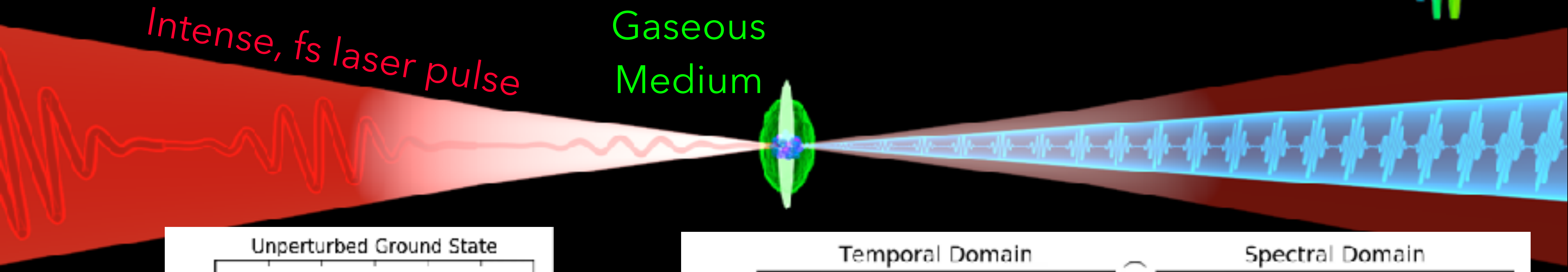

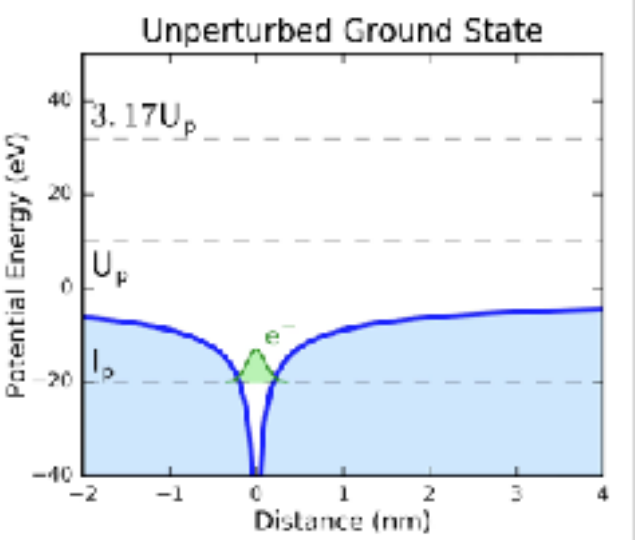

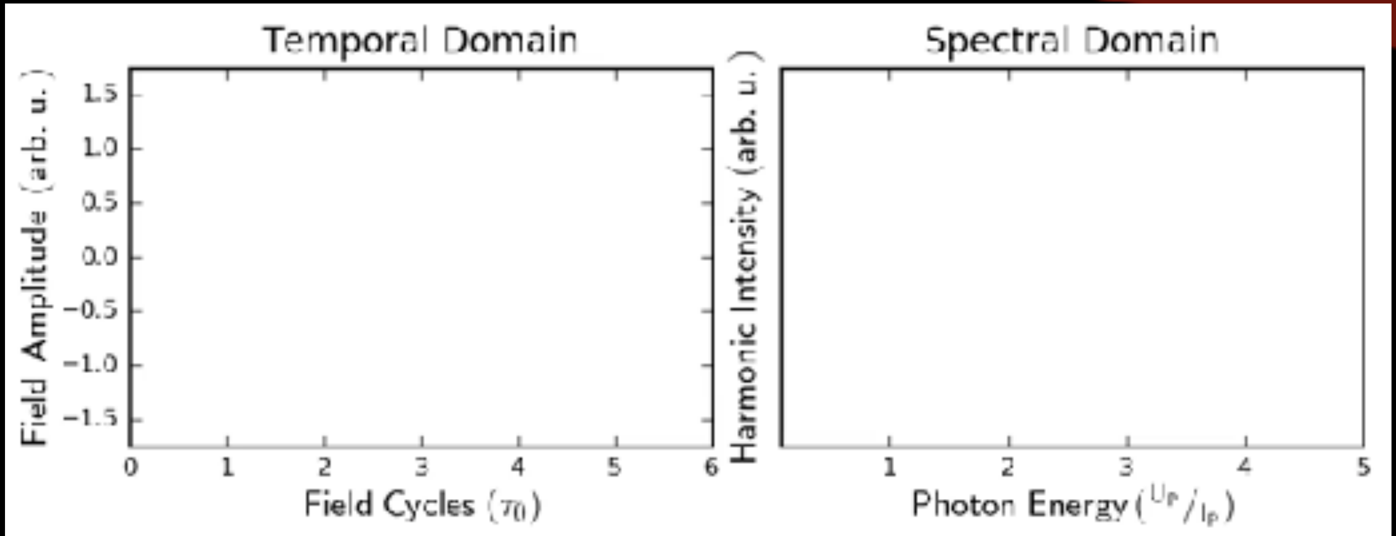

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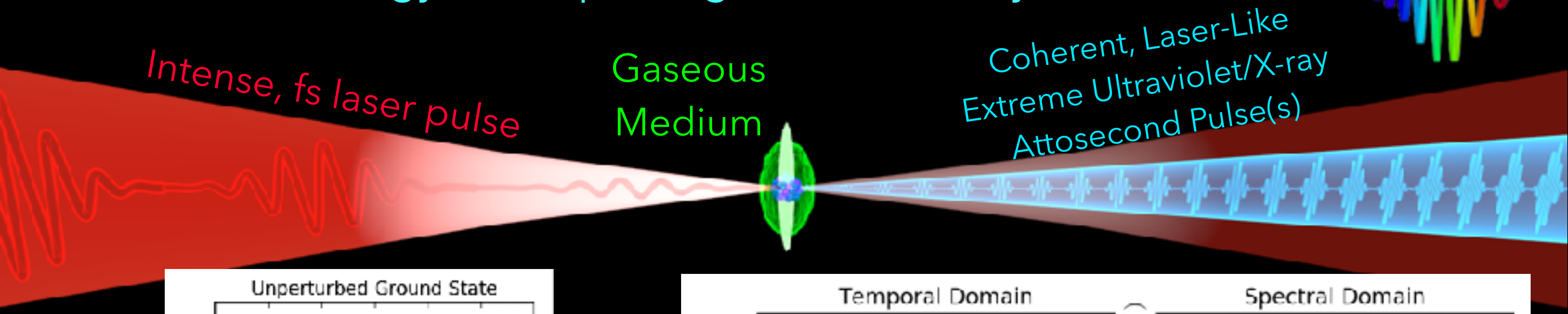

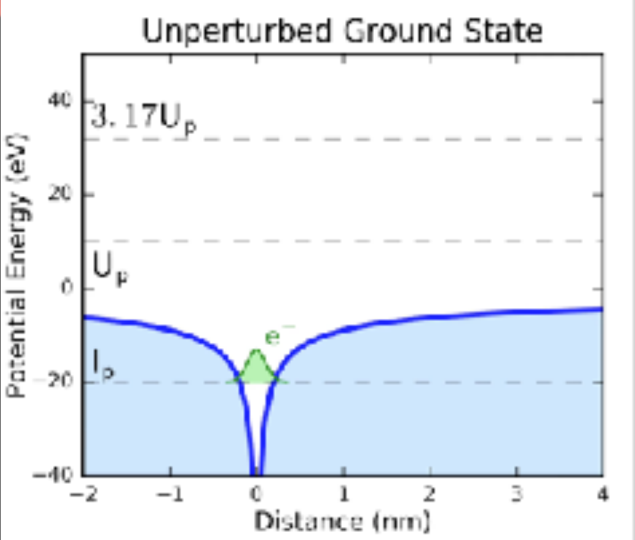

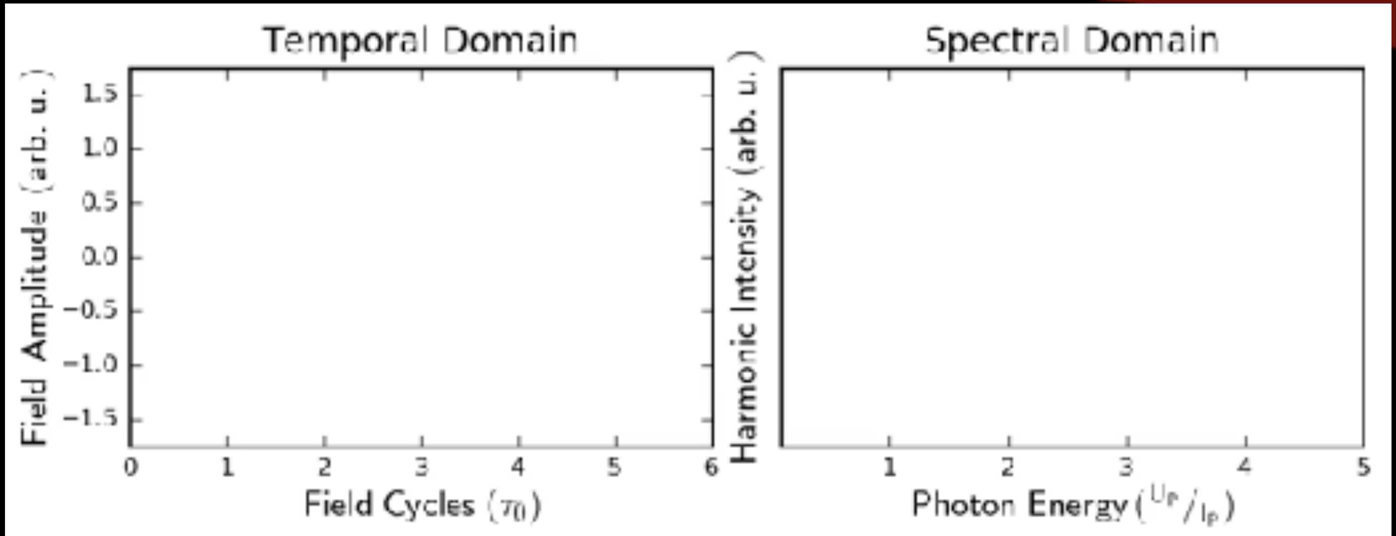

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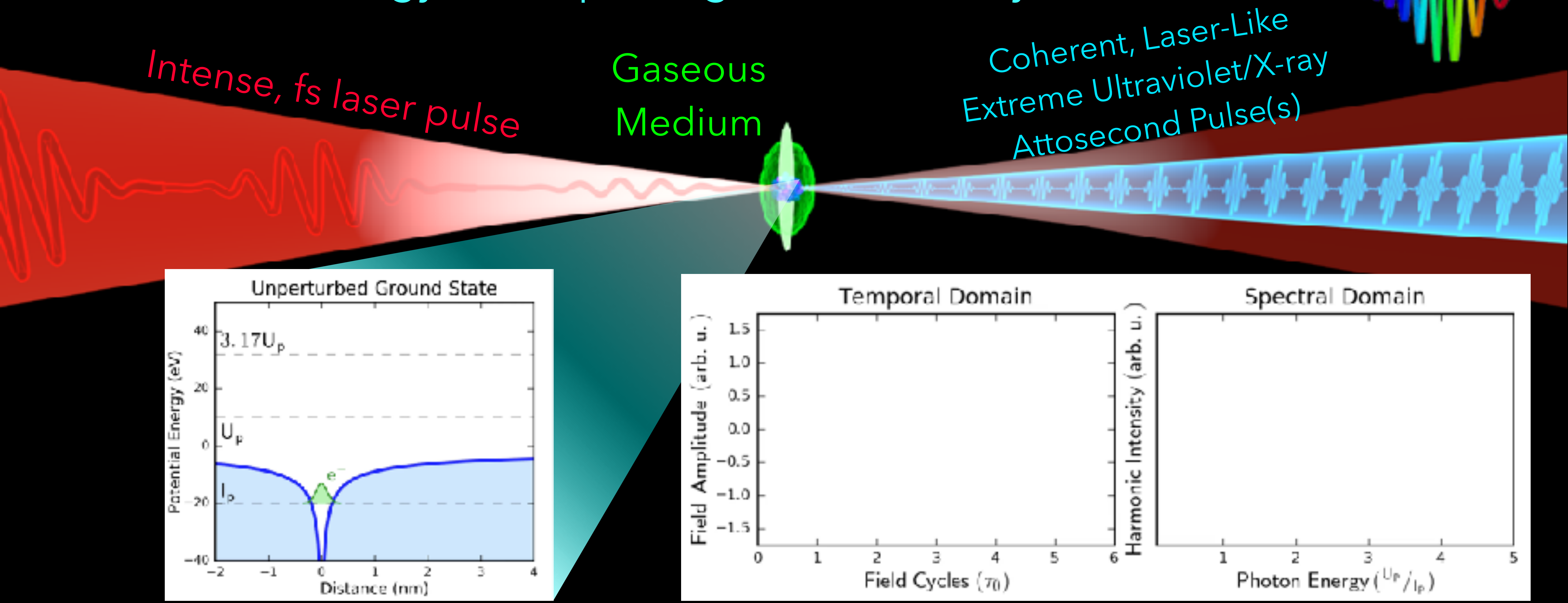

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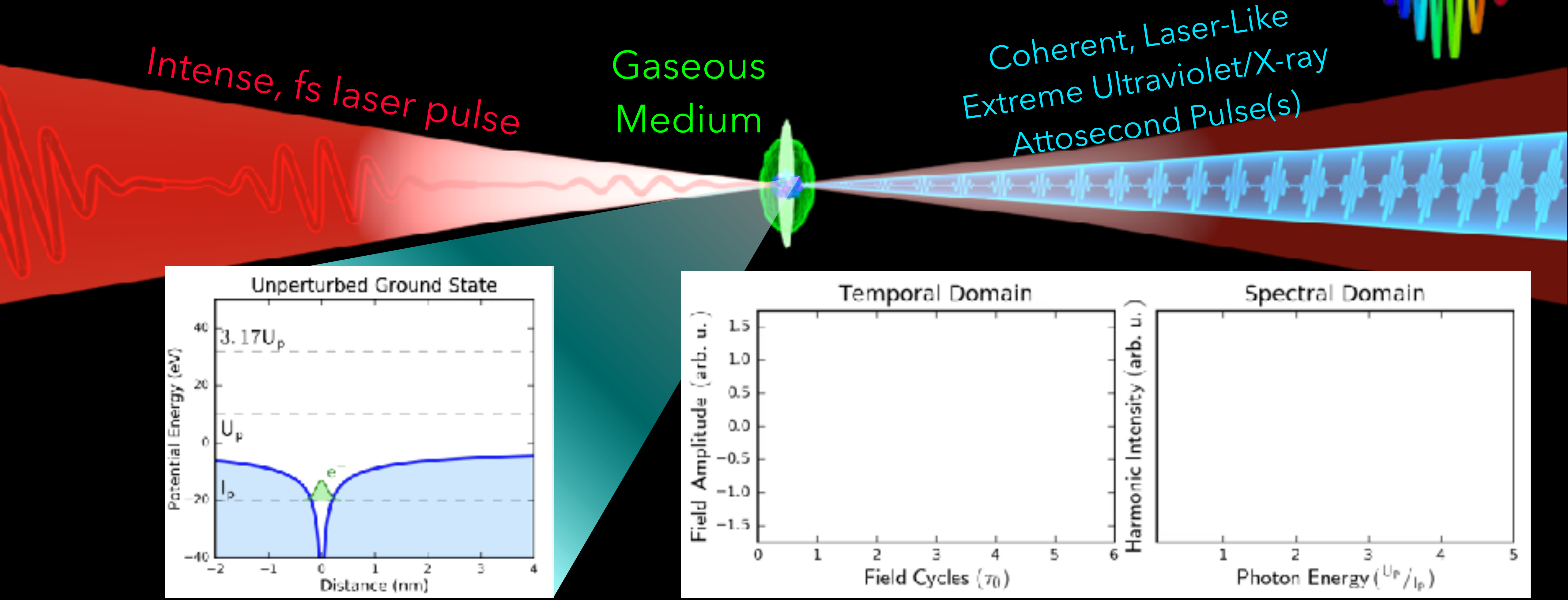

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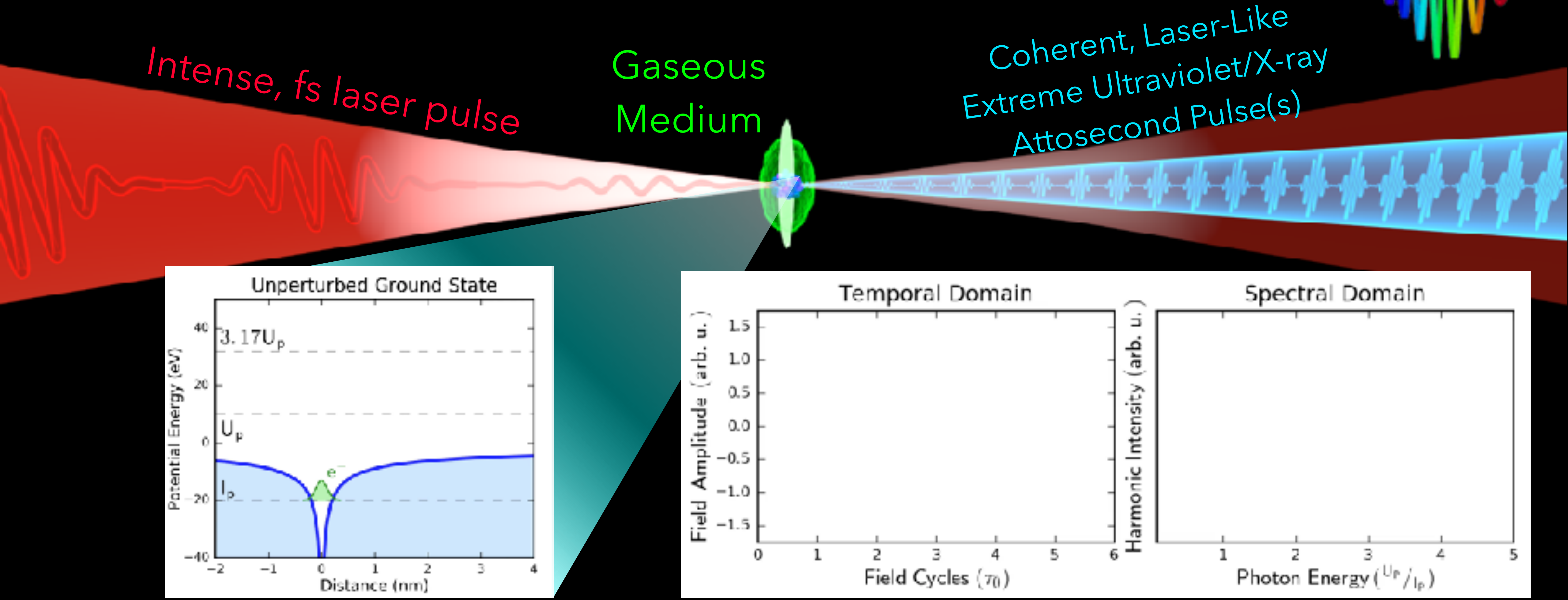

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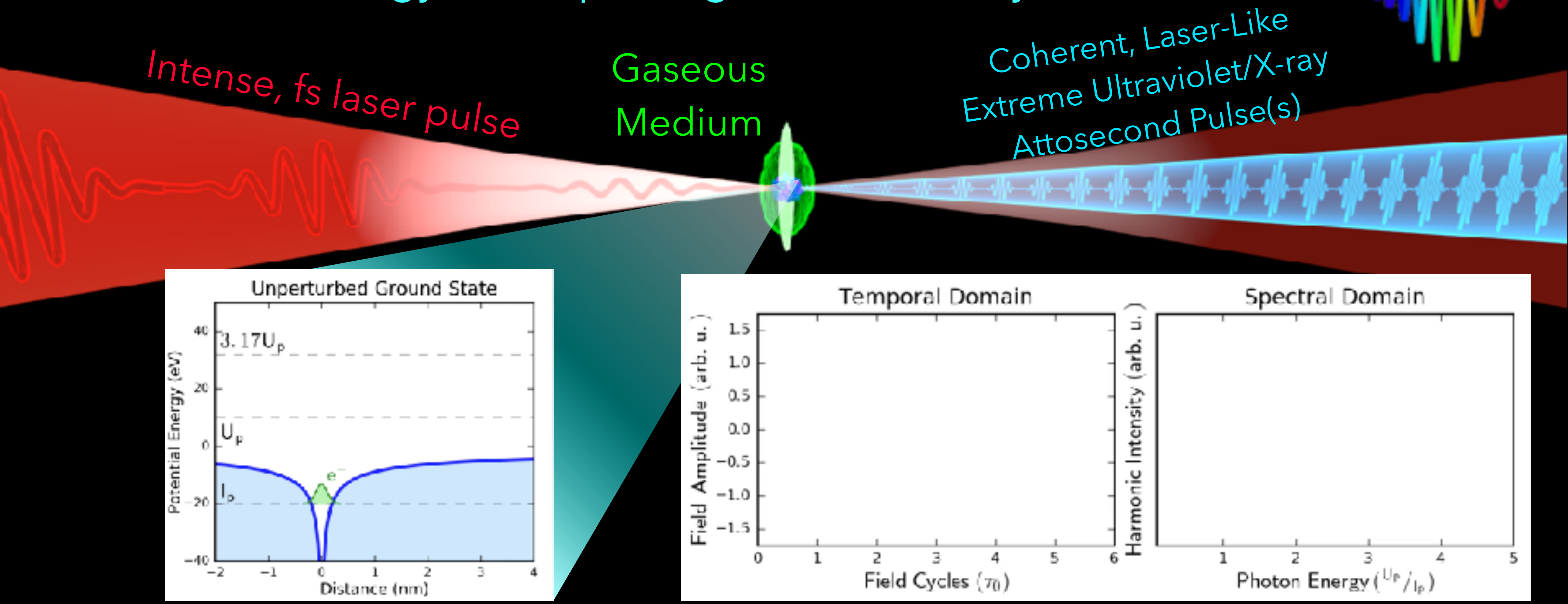

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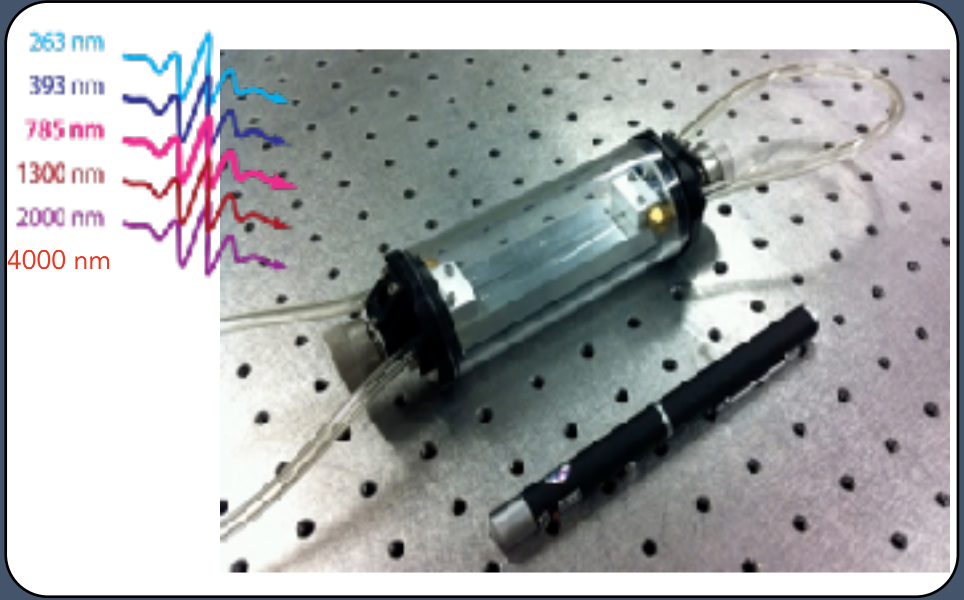
HHG in the Lab: Tailored EUV and Soft X-ray Beams with Laser-Like Spatiotemporal Coherence on a Tabletop



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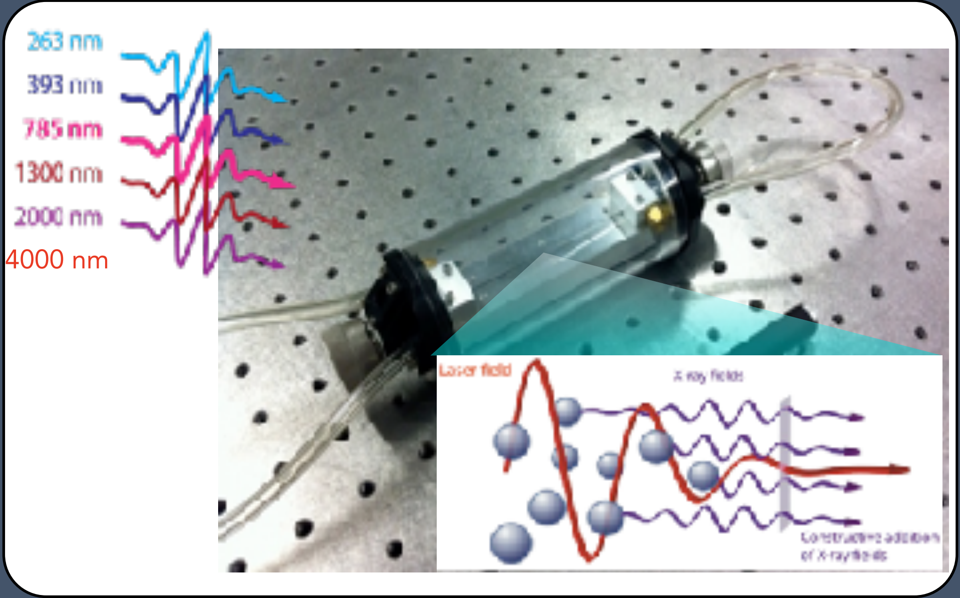

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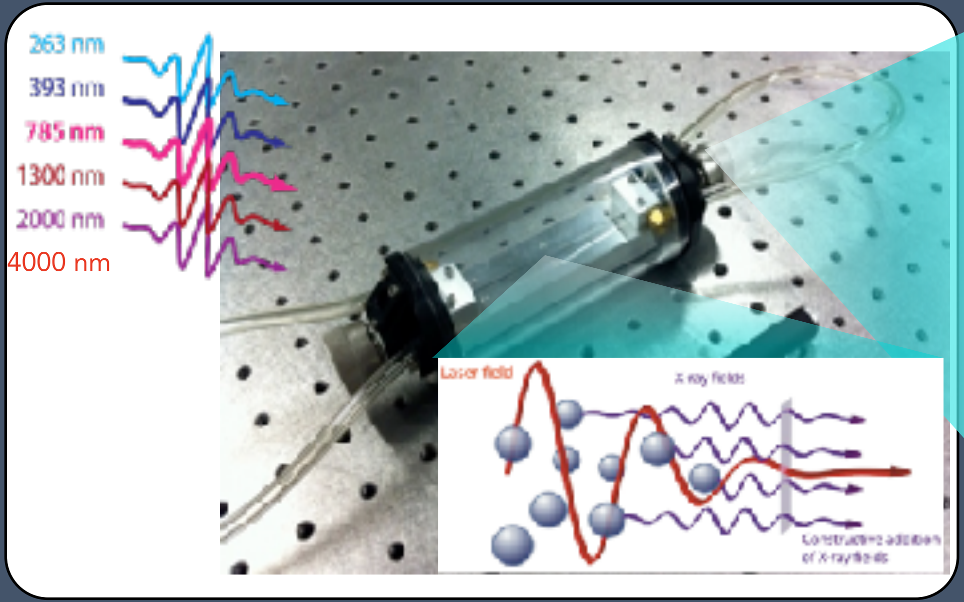

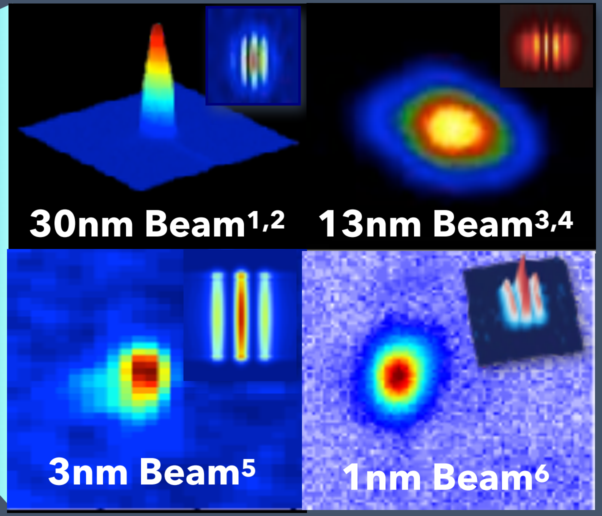

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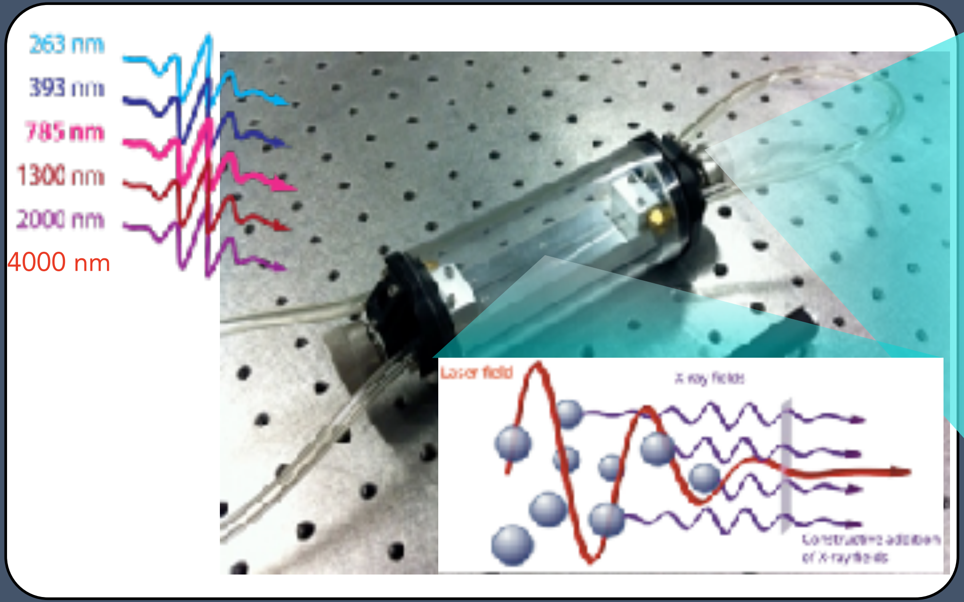

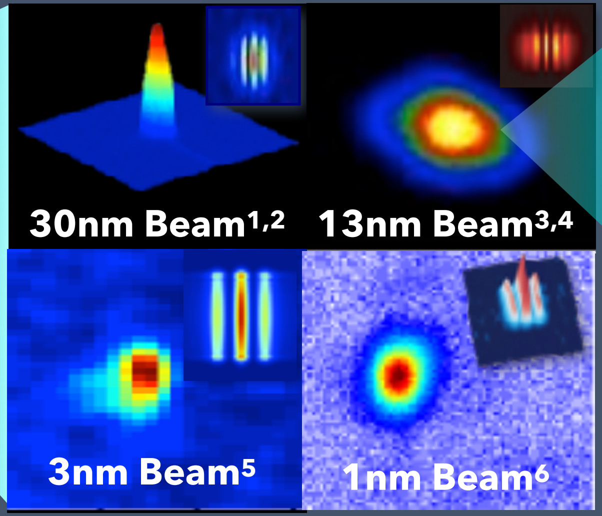

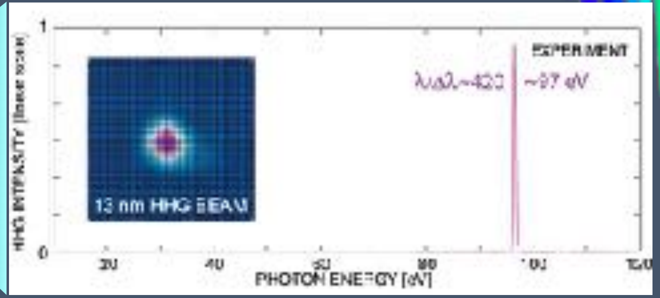

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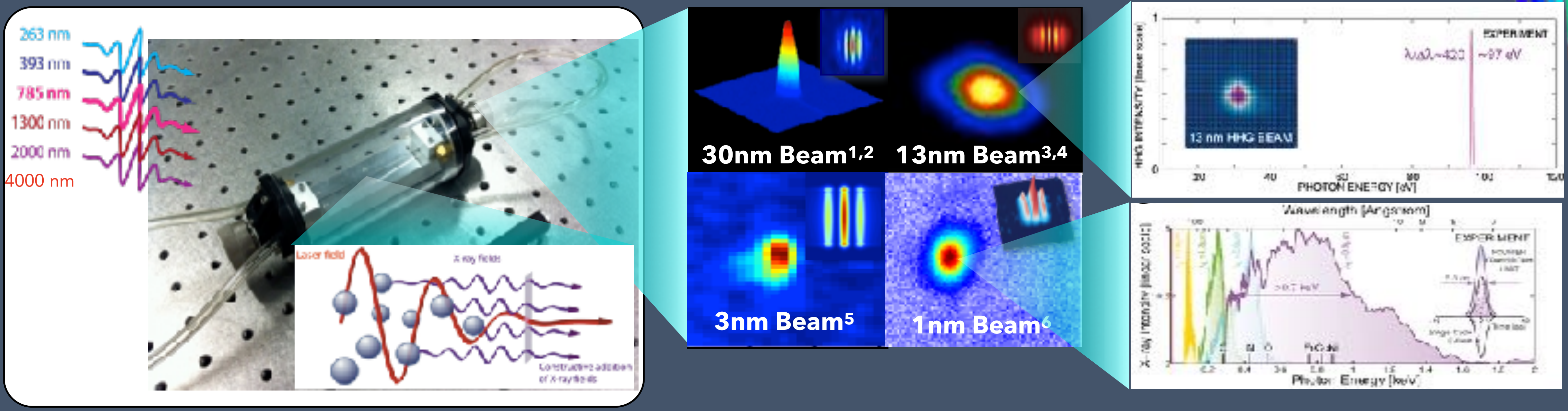

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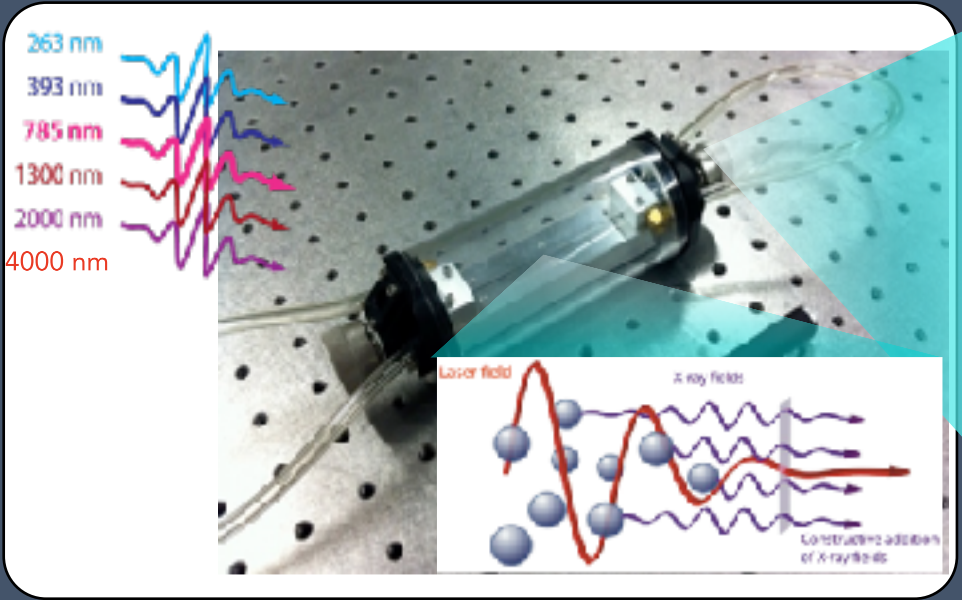

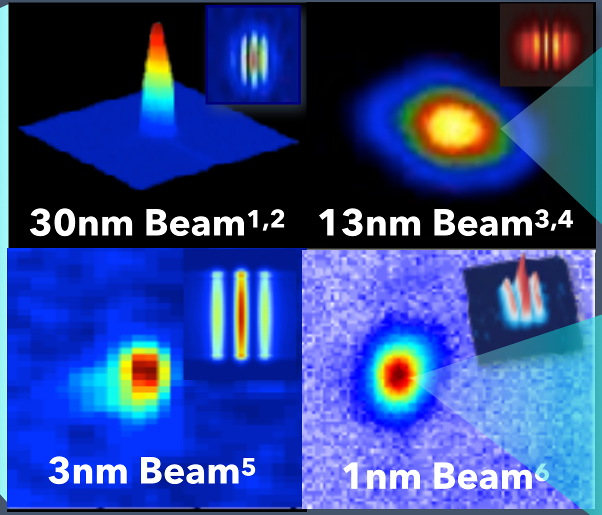

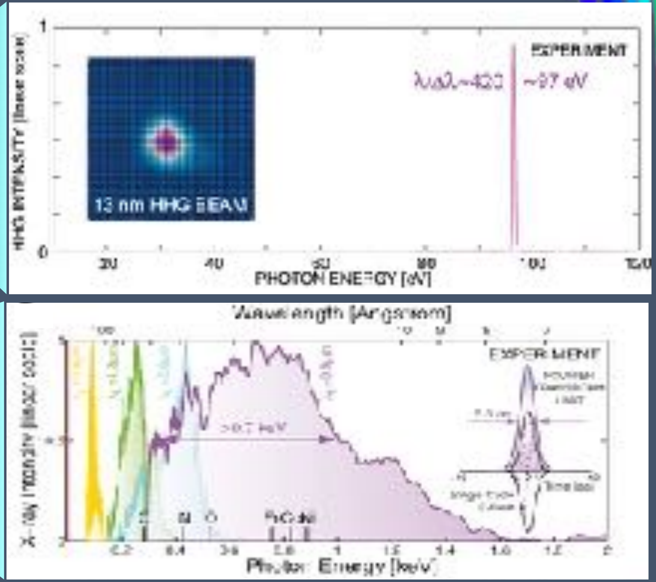

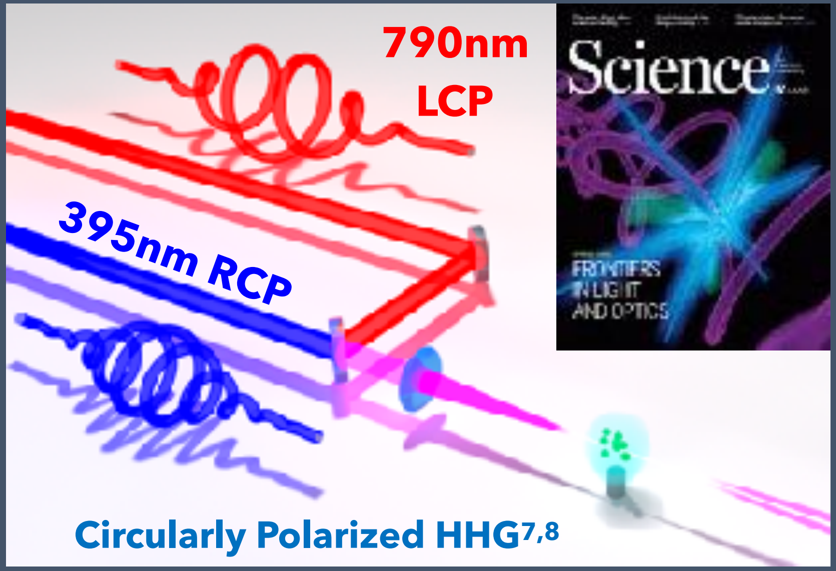

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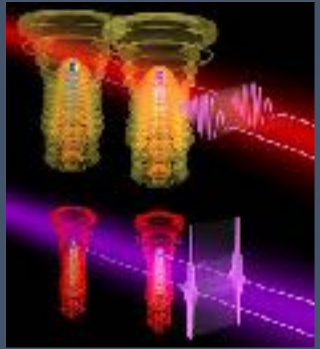
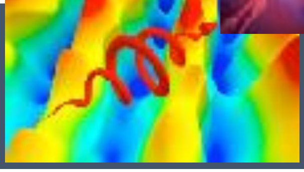
Light and Materials Science in the KM Group: AMO Dynamics at Extreme Spatial and Temporal Scales

New Paradigms in Attosecond Nonlinear Optics





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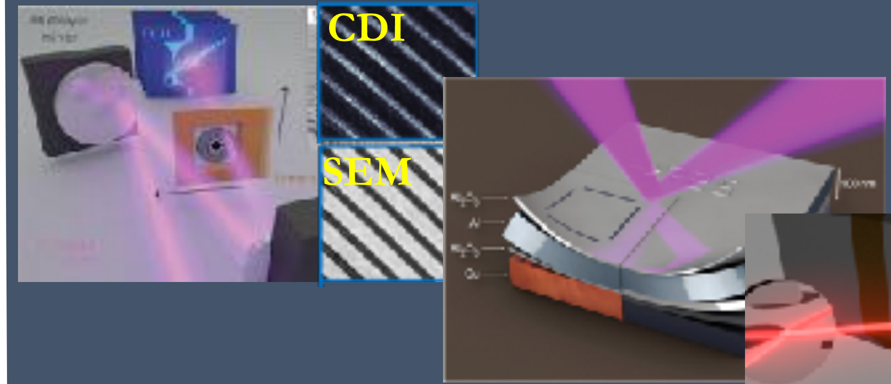
Ultrafast Coherent X-ray Imaging



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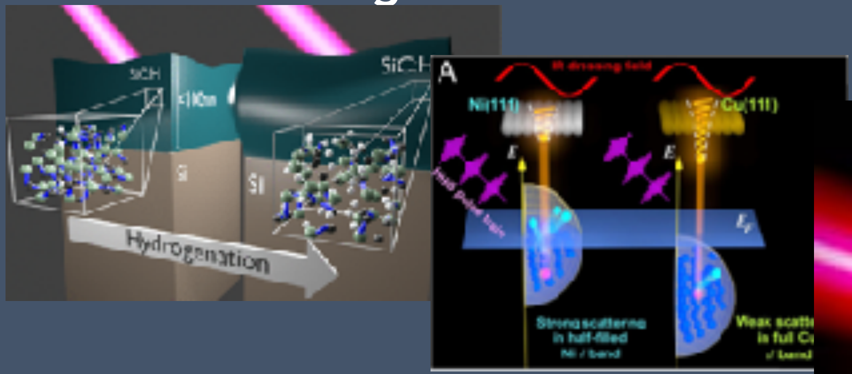
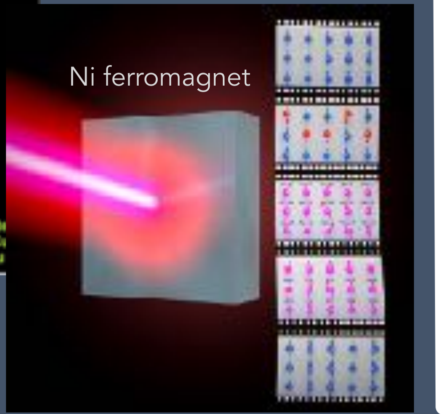
Uncovering New Ultrafast Materials Science





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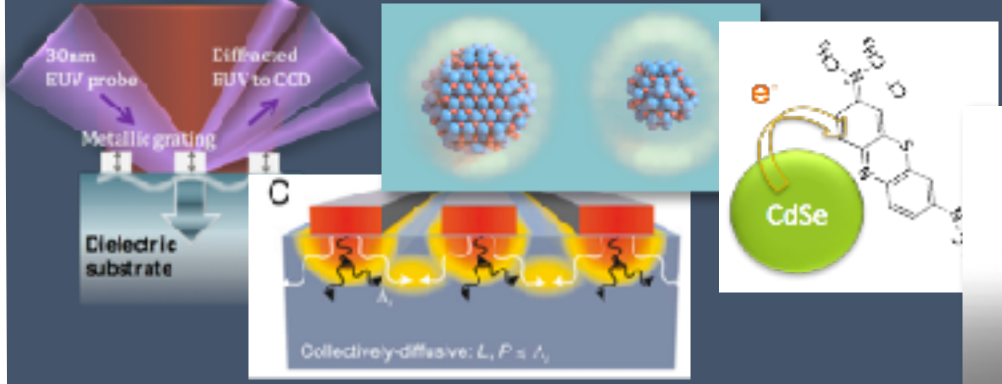
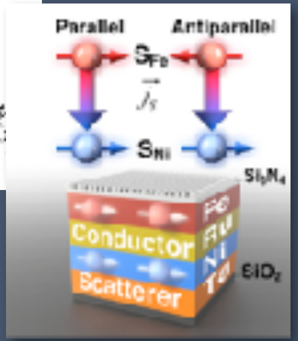
Nanoscale Charge, Spin, Energy Transport





Hoogeboom-Pot, et al. PNAS **112**, 2015.
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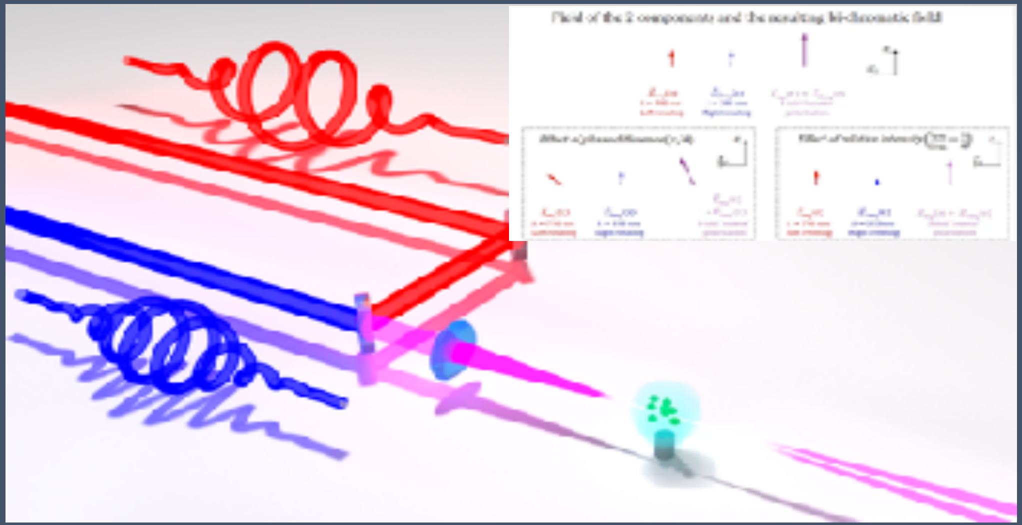
Spin Angular Momentum (SAM) in HHG



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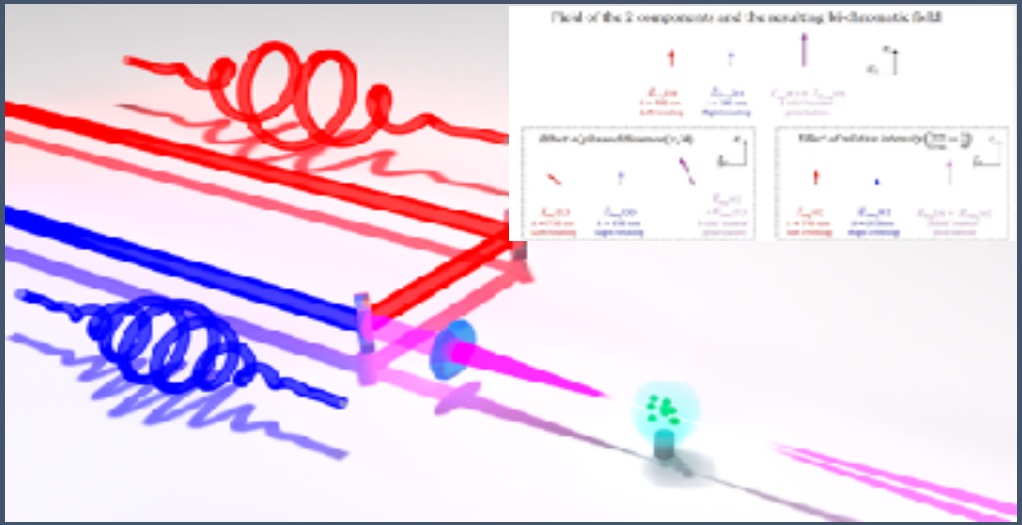

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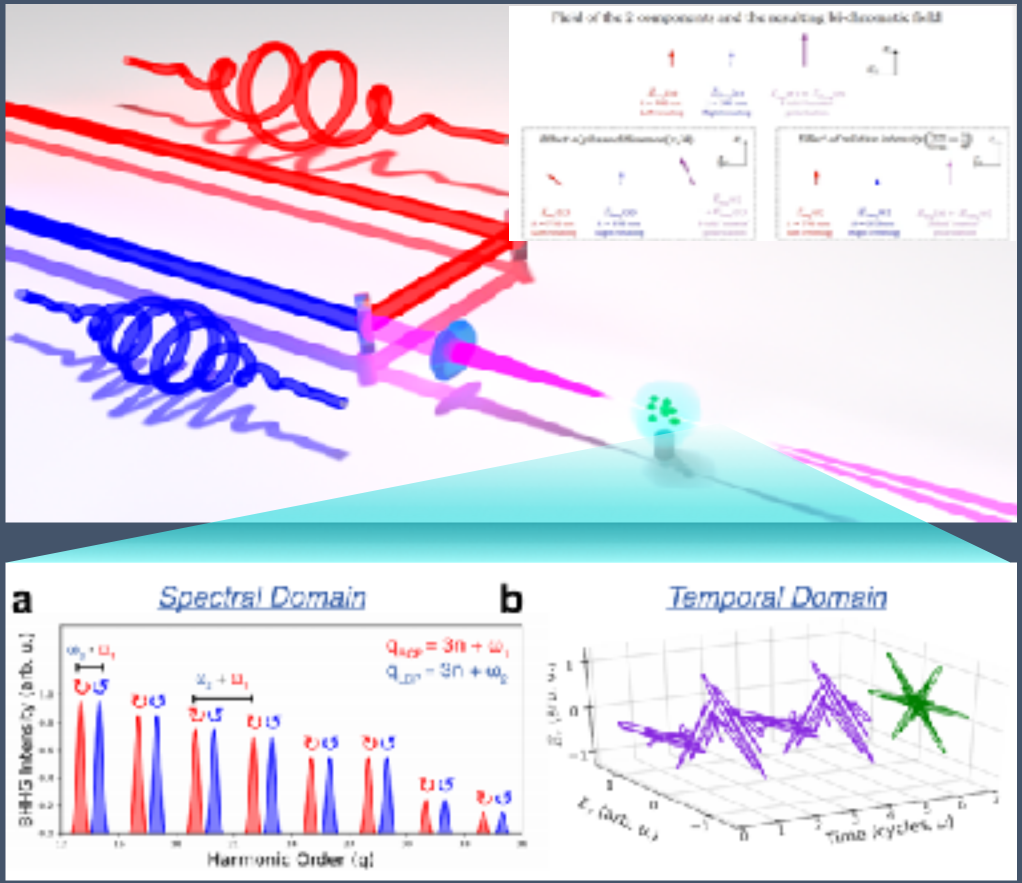

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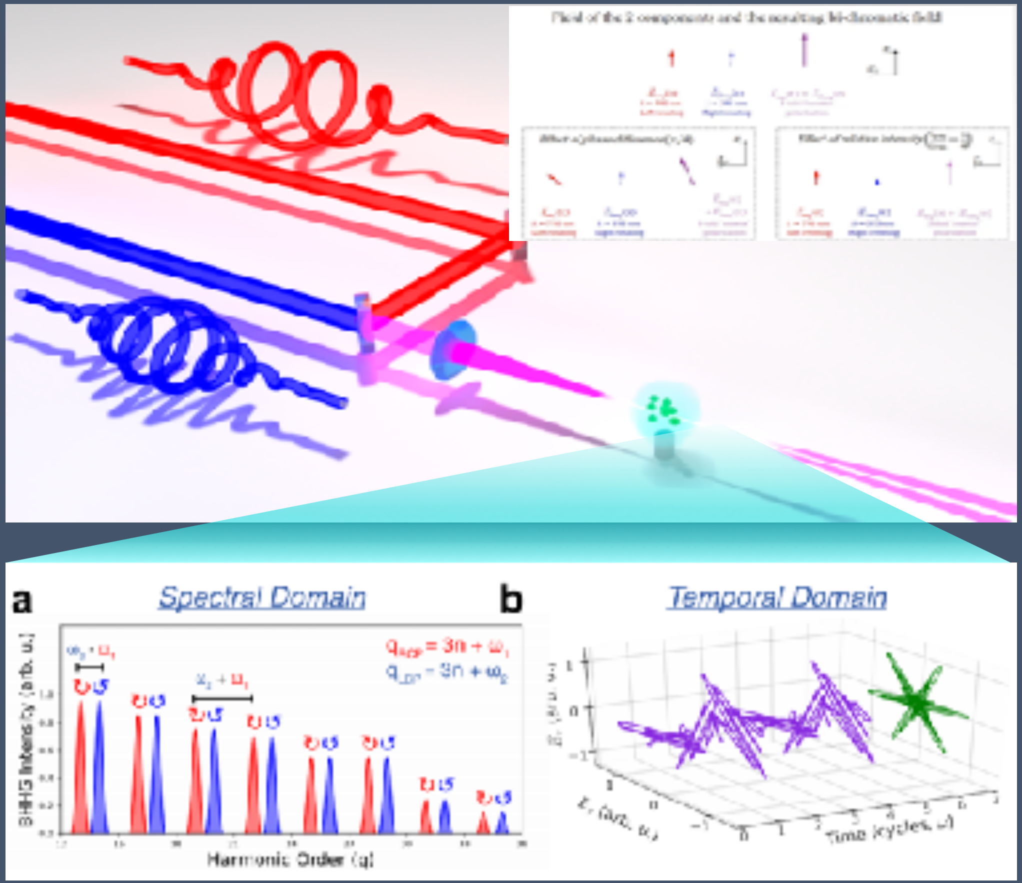

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Attosecond Helical Field Lines and Twisted EUV Photons: Spin and Orbital Angular Momentum in HHG

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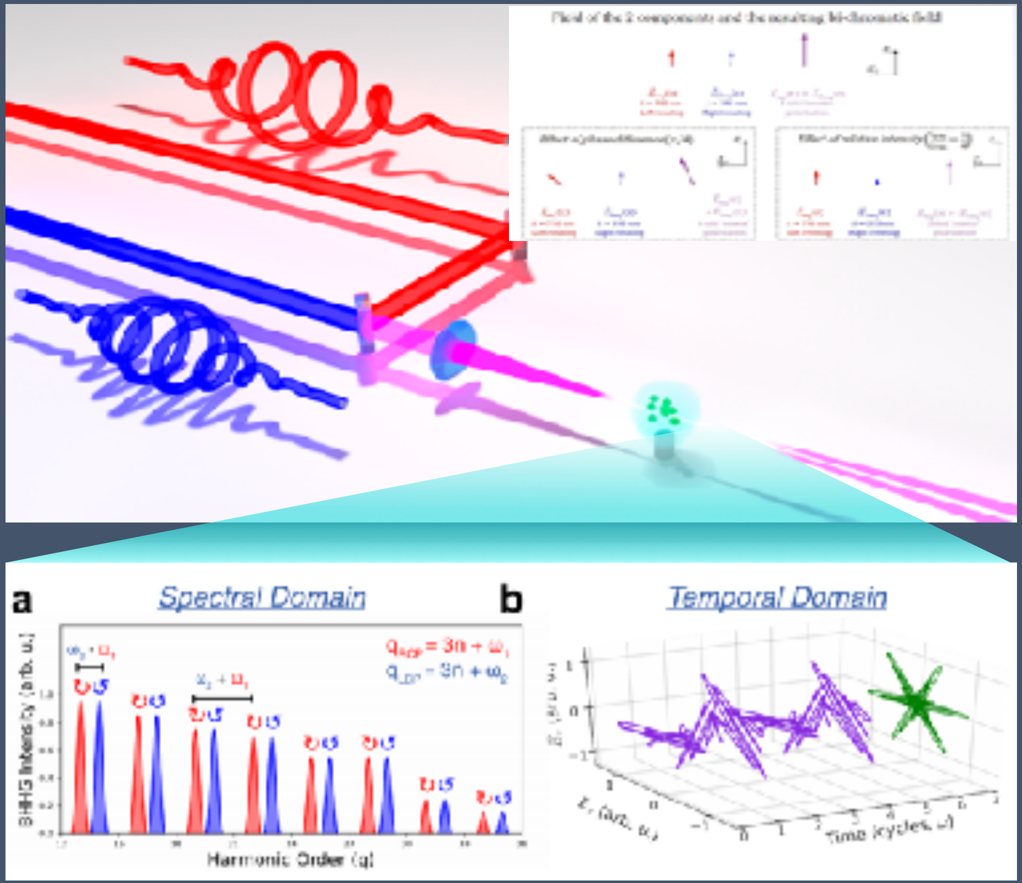

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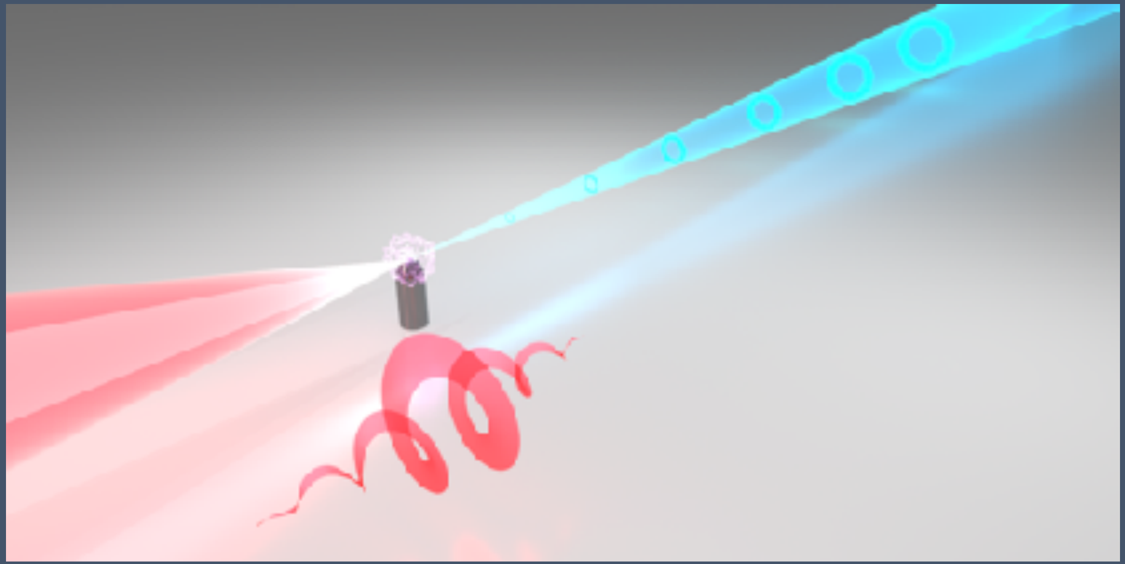

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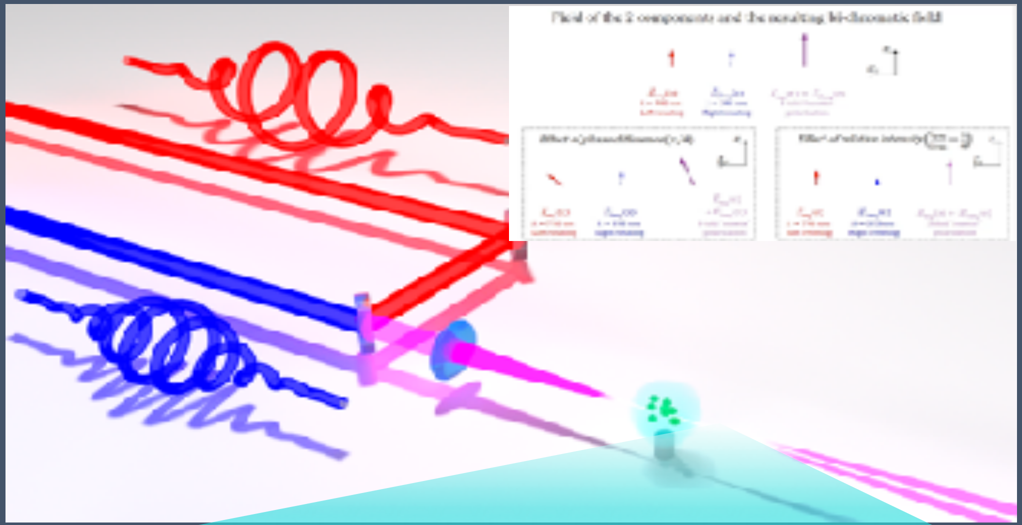

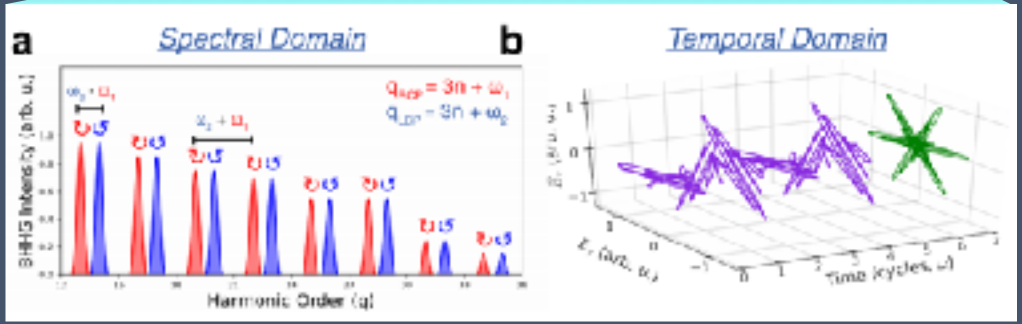

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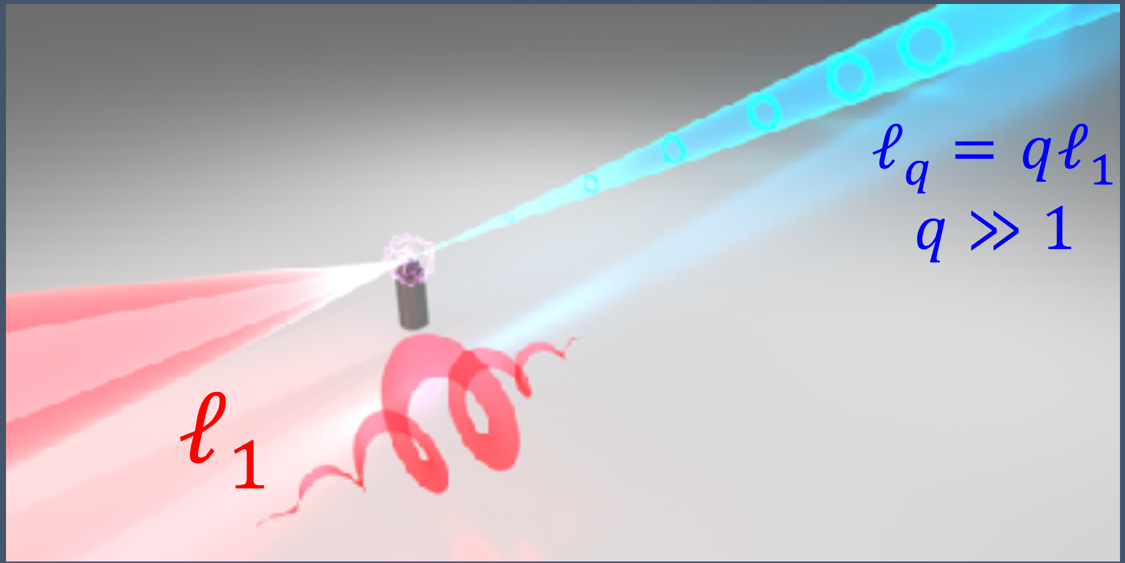

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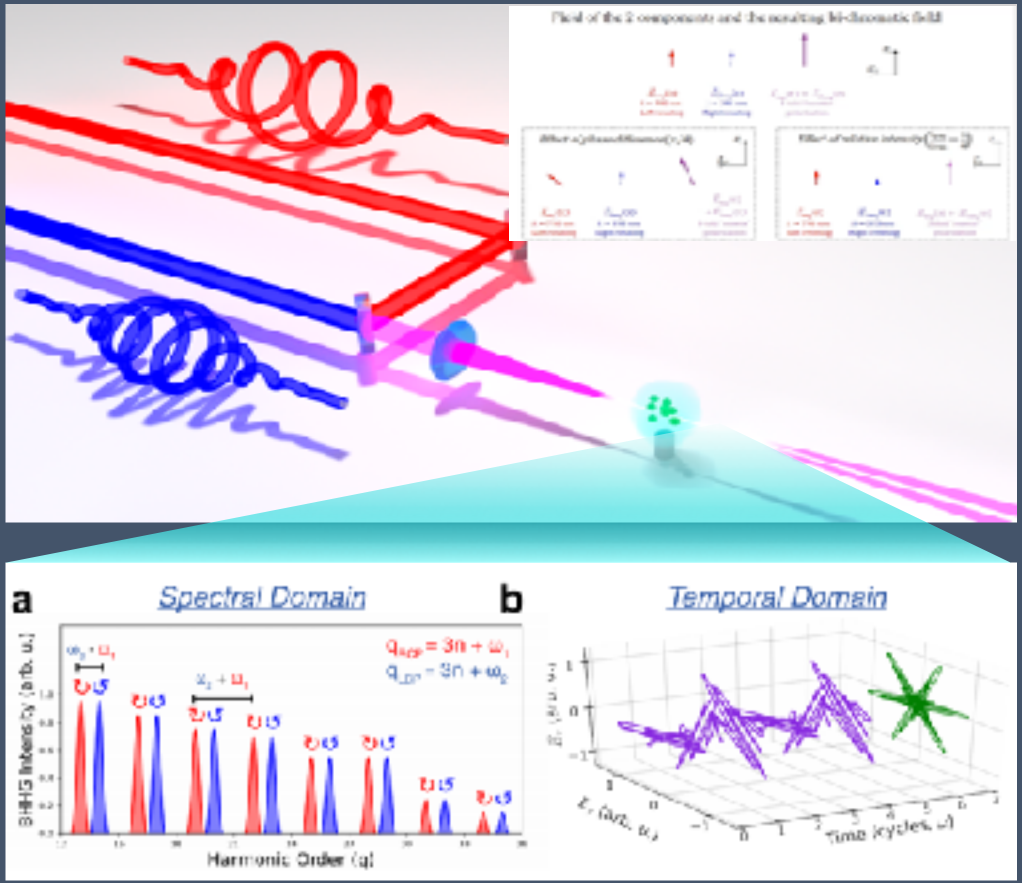

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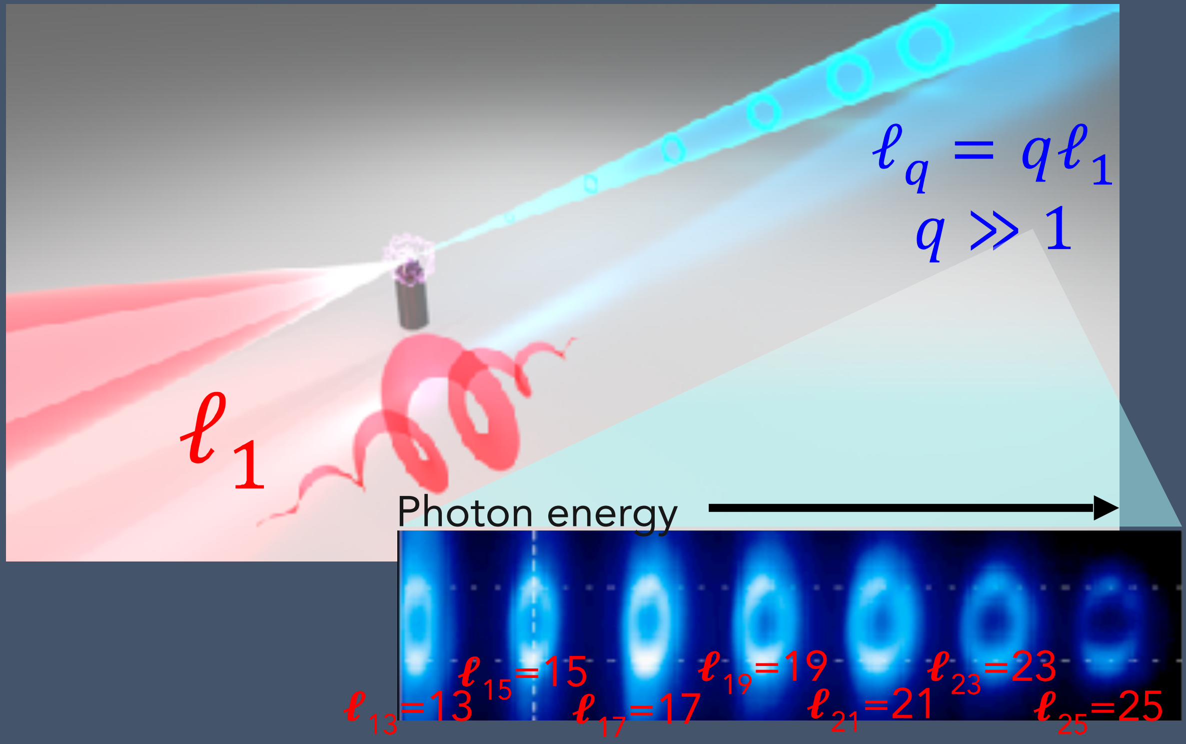

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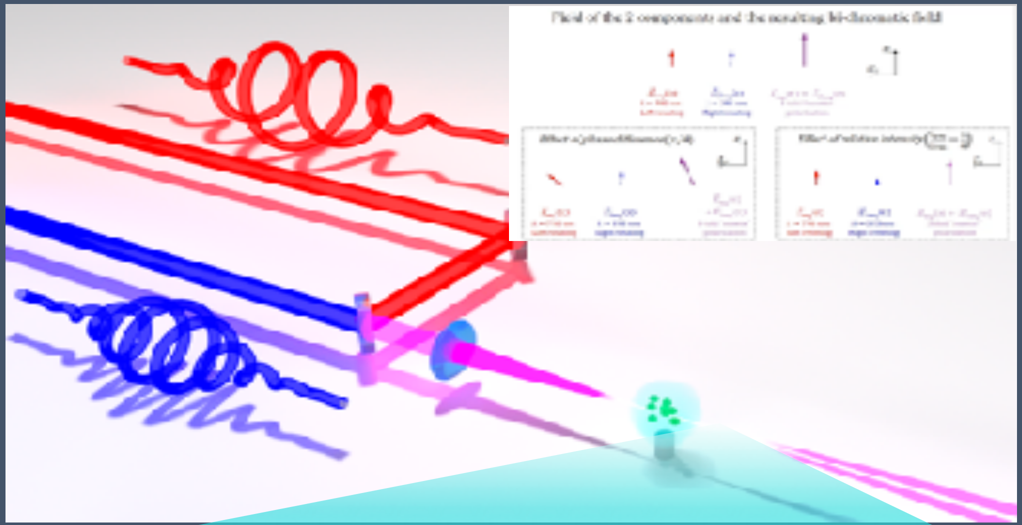

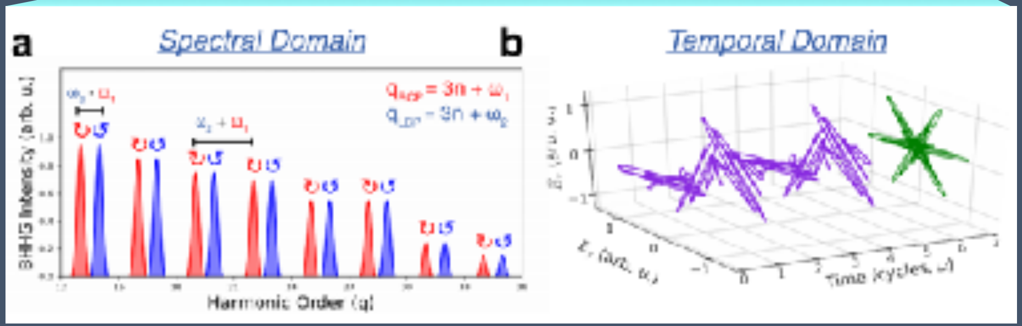

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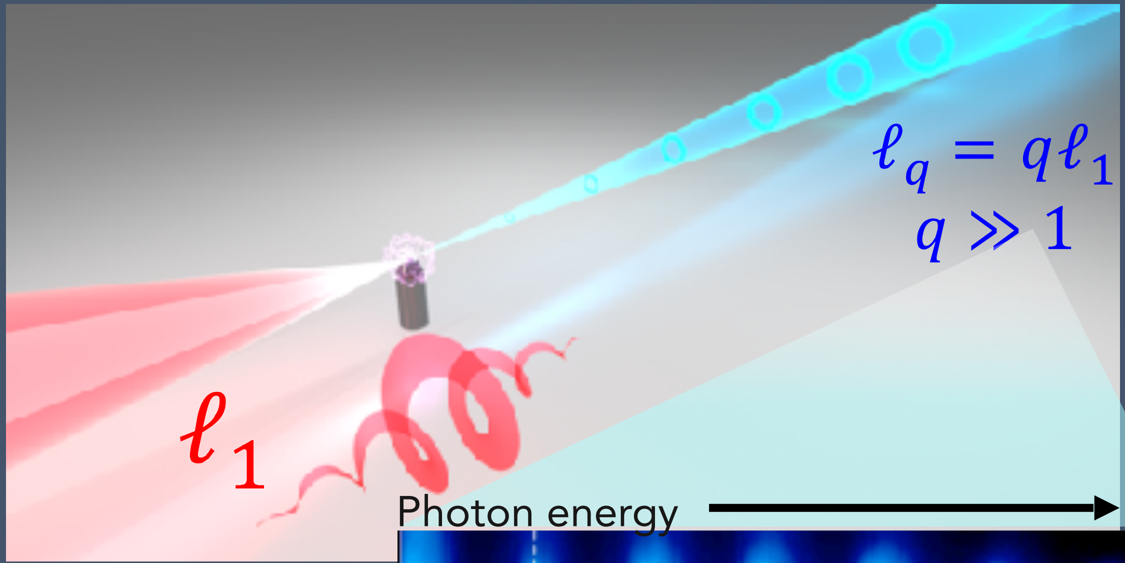

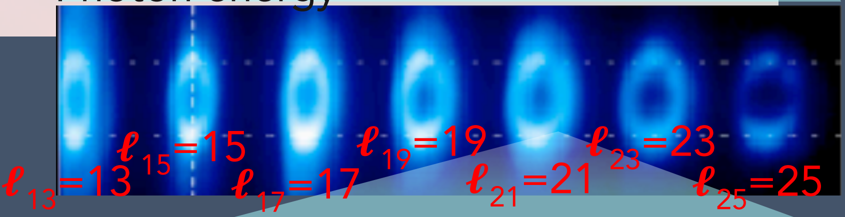

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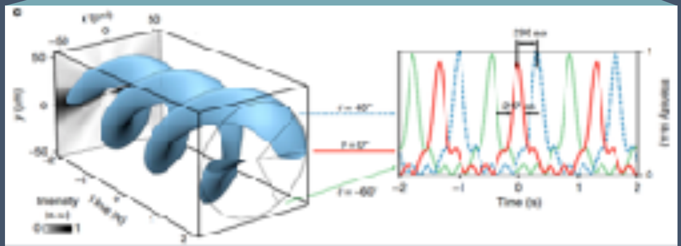

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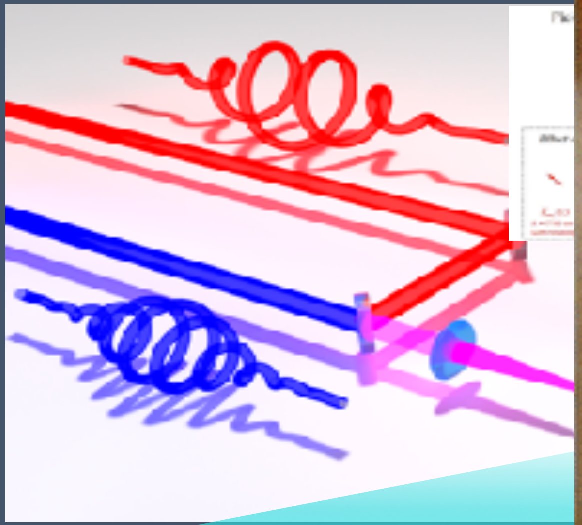

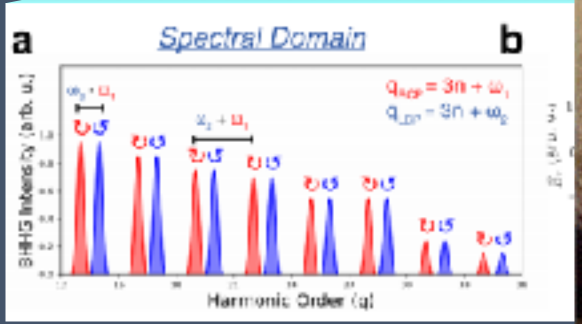

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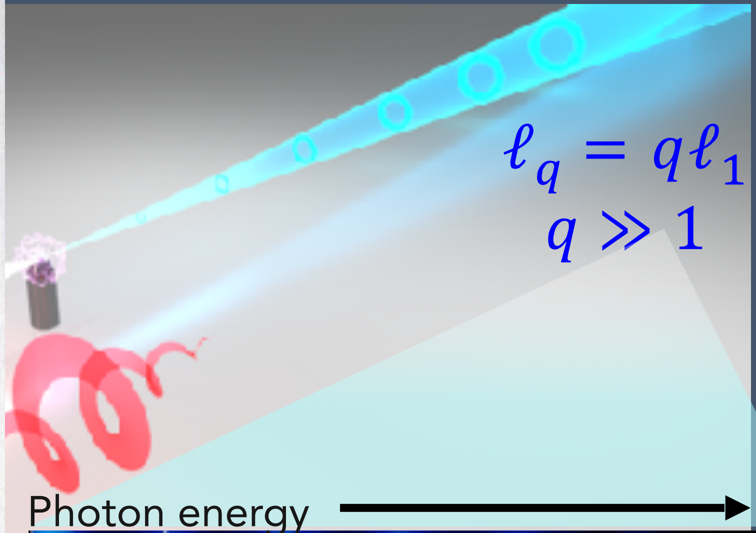

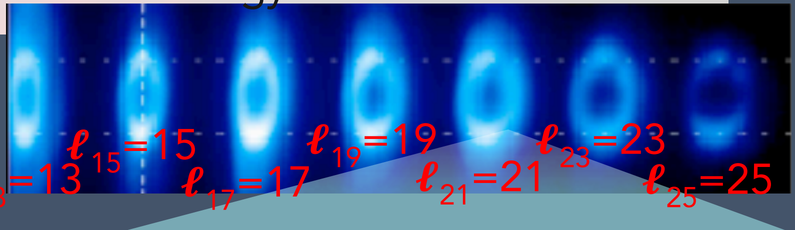

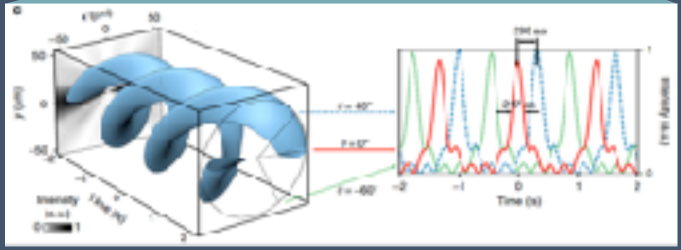

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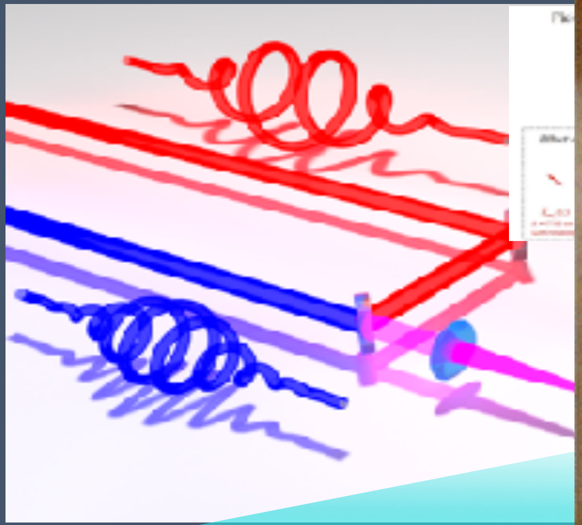

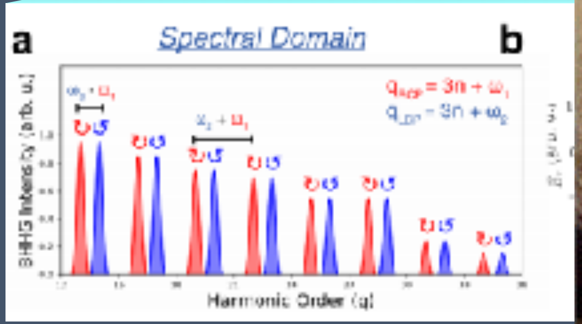

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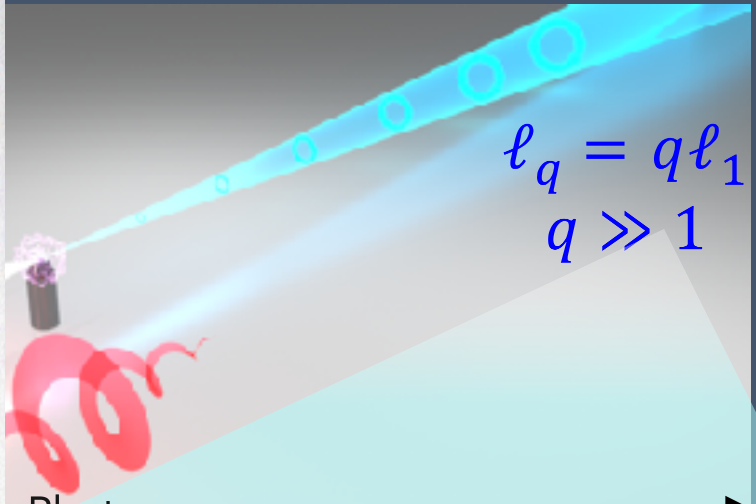
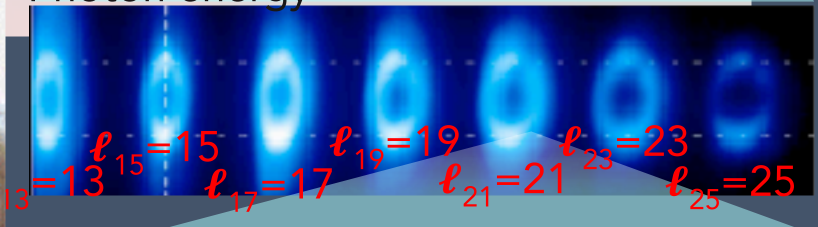
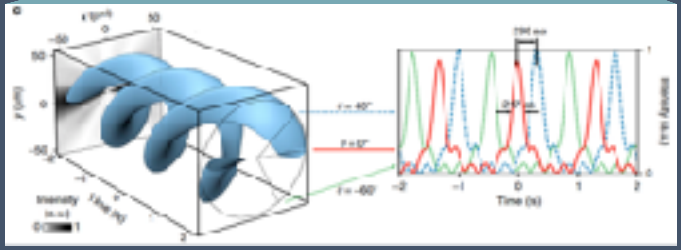


Photon energy





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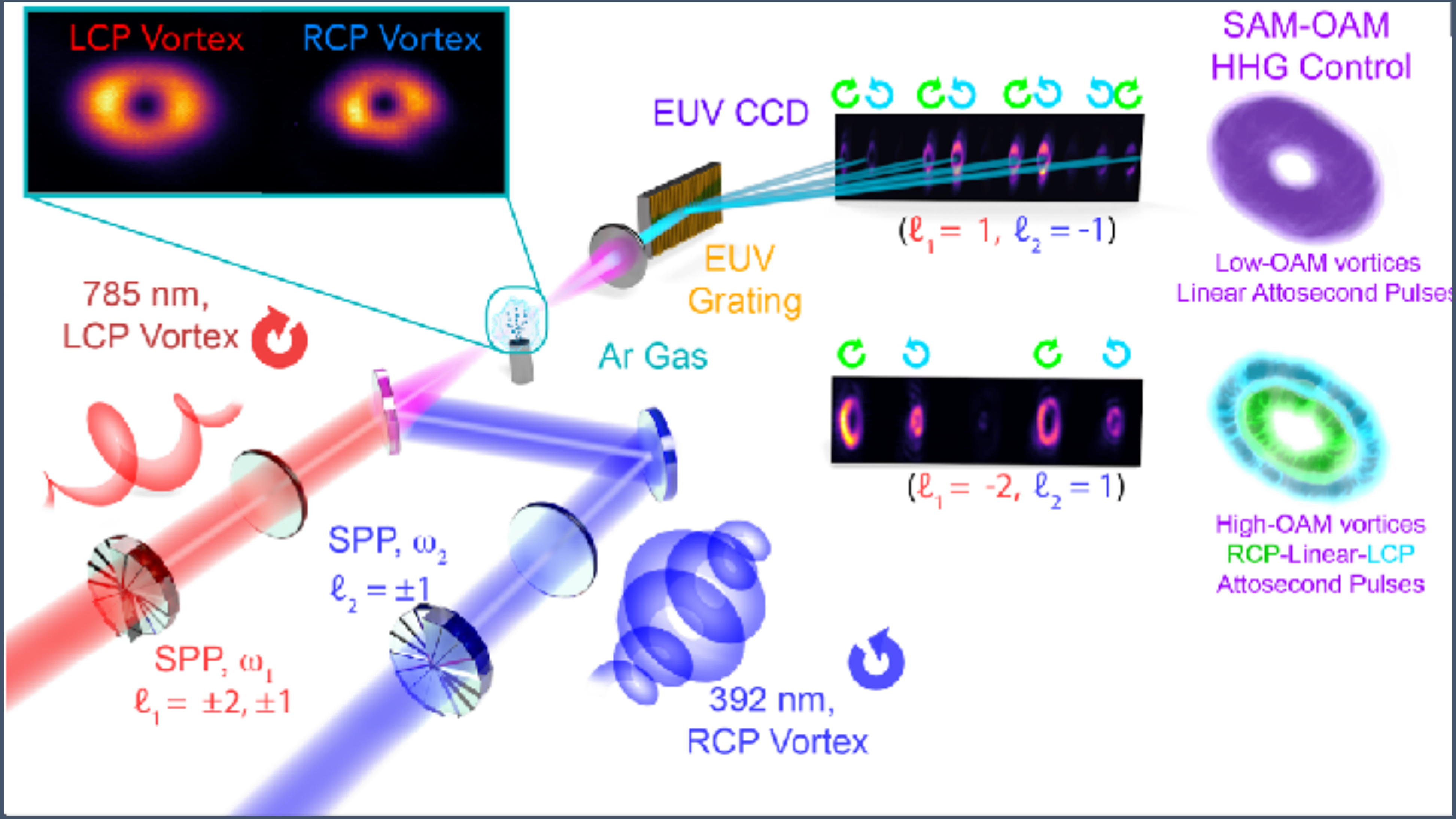
Two-Color HHG in the Presence of SAM and OAM: Exquisite Control of Attosecond, EUV Vortex Beams



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- High-harmonic generation is a parametric process, and thus most conserve energy and momentum (including SAM and OAM)

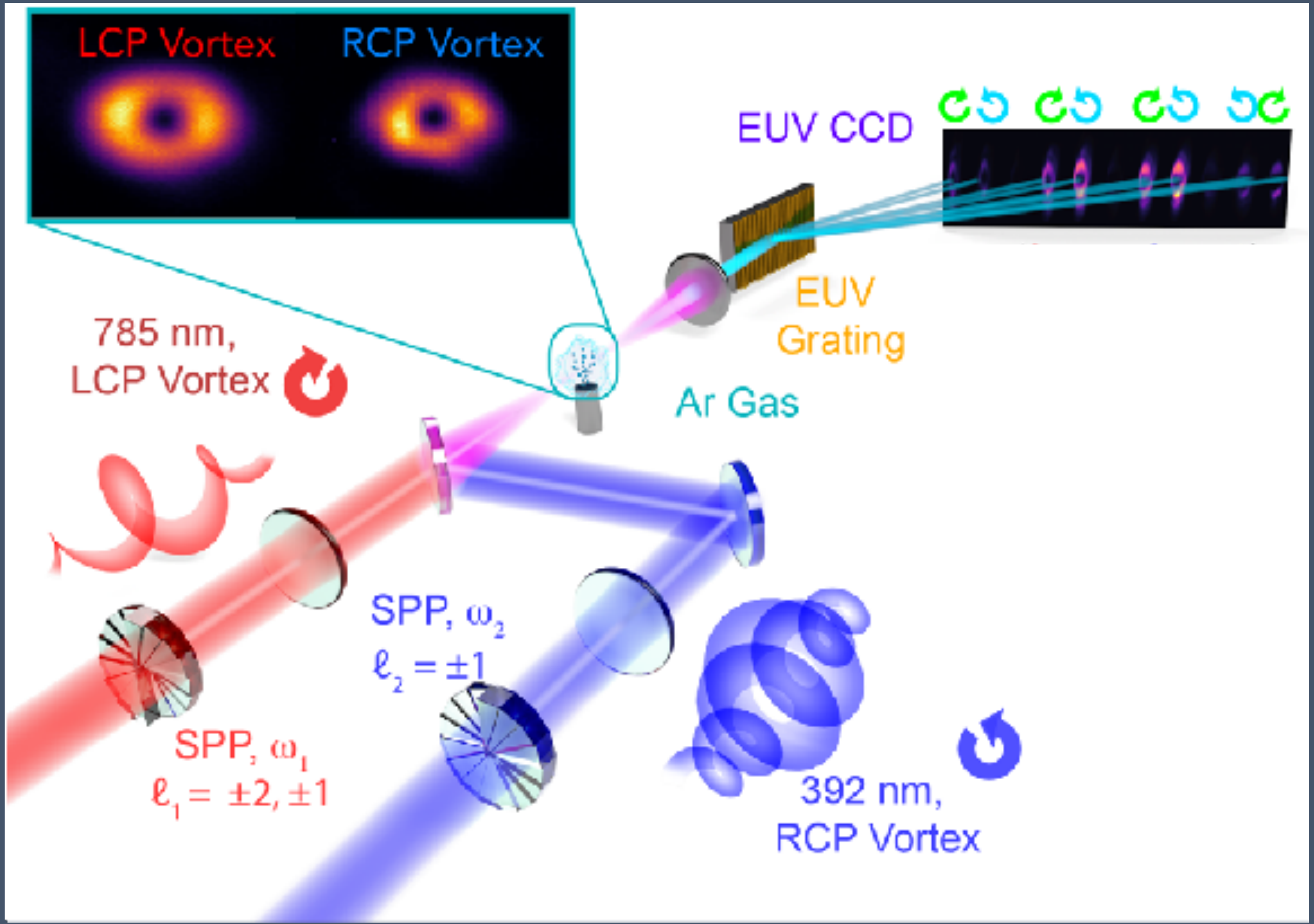
Constrain OAM via SAM!

$$\sigma_q = n_1\sigma_1 + n_2\sigma_2 \quad \textbf{(SAM)}$$

$$\omega_q = n_1\omega_1 + n_2\omega_2 \quad \textbf{(Lin. Momentum)}$$

$$n_2 = n_1 - \sigma_q\sigma_1 \quad \textbf{(Parity)}$$

$$\ell_{q,q+1} = \frac{q + 2\sigma_q\sigma_{1,2}}{3}(\ell_1 + \ell_2) - \sigma_q\sigma_{1,2}\ell_{2,1}$$



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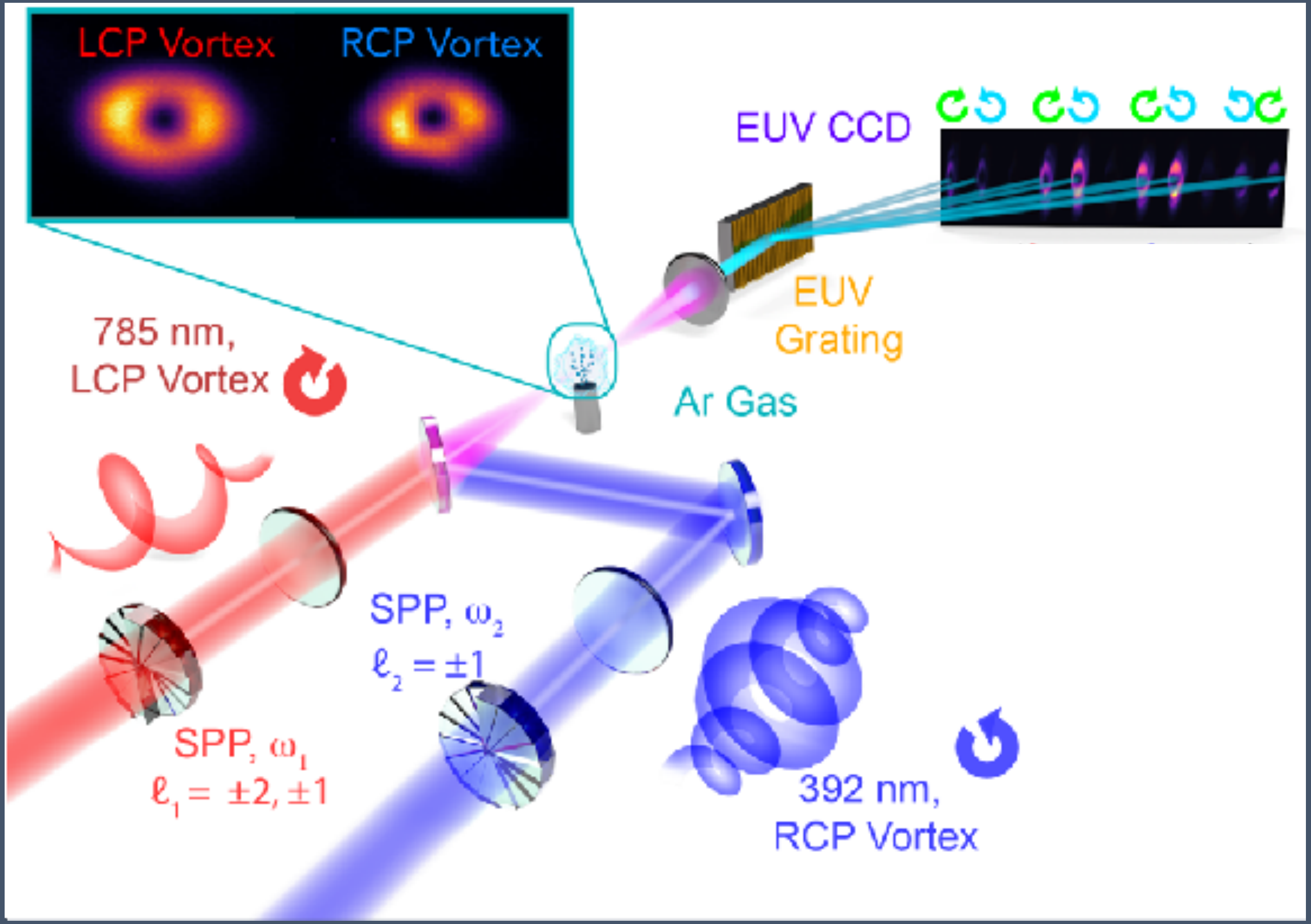
Torus-Knot Angular Momentum

$$J_\gamma = L + \gamma S = q\frac{\ell_1 + \ell_2}{3} \quad \therefore \quad \gamma = \frac{2\ell_1 - \ell_2}{3}$$



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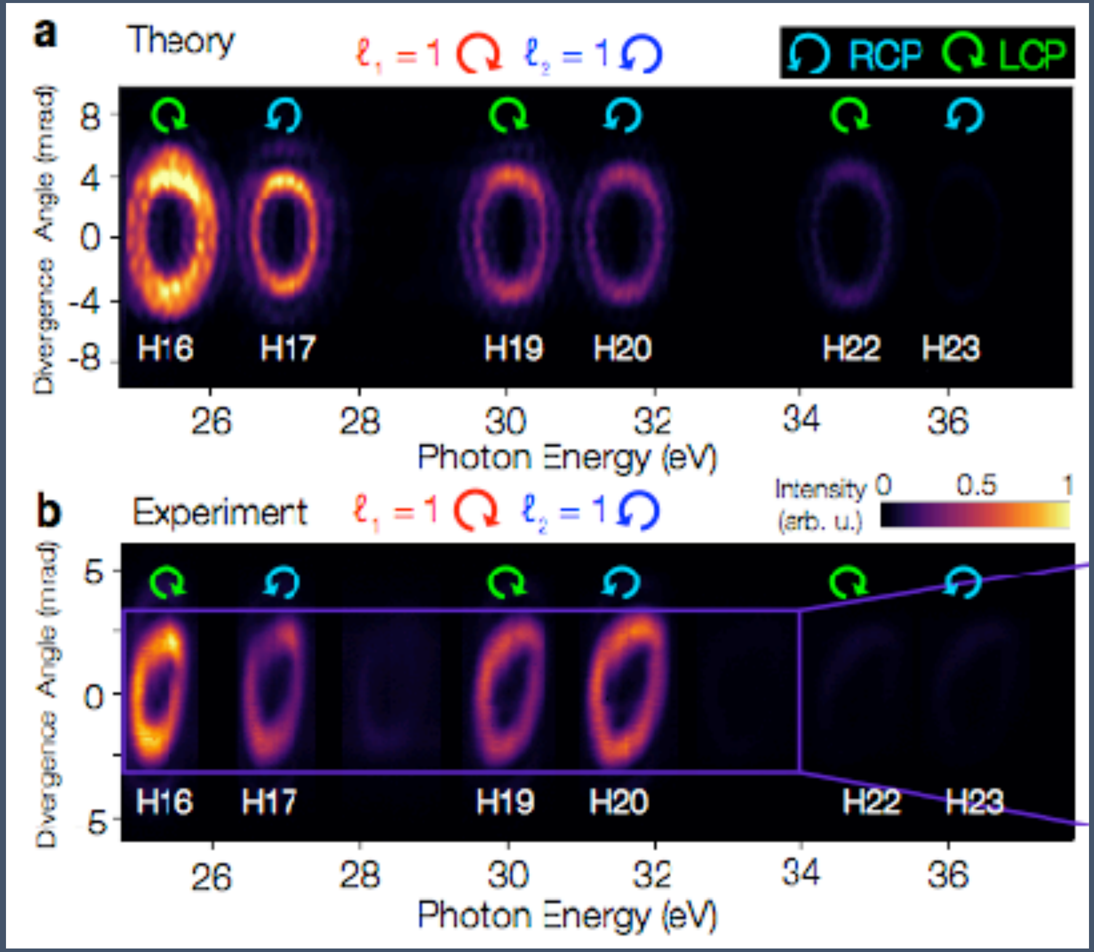
SAM-OAM HHG with Degenerate OAM Drivers: EUV Doughnuts with Same Twist, Opposite Helicity

➢ Driving the HHG process with a bicircular field with degenerate OAM yields pairs of EUV "doughnuts" with opposite helicity.



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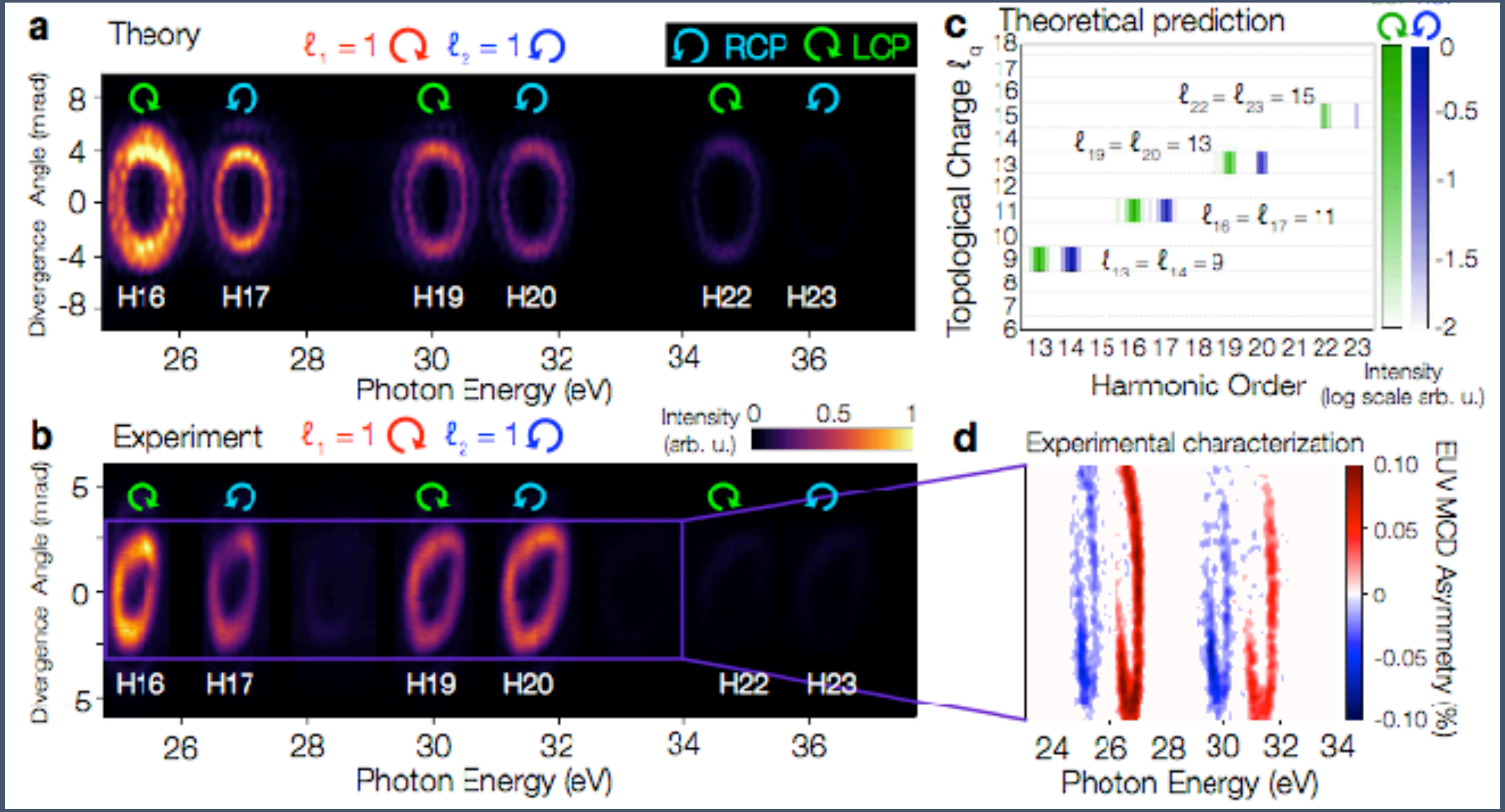

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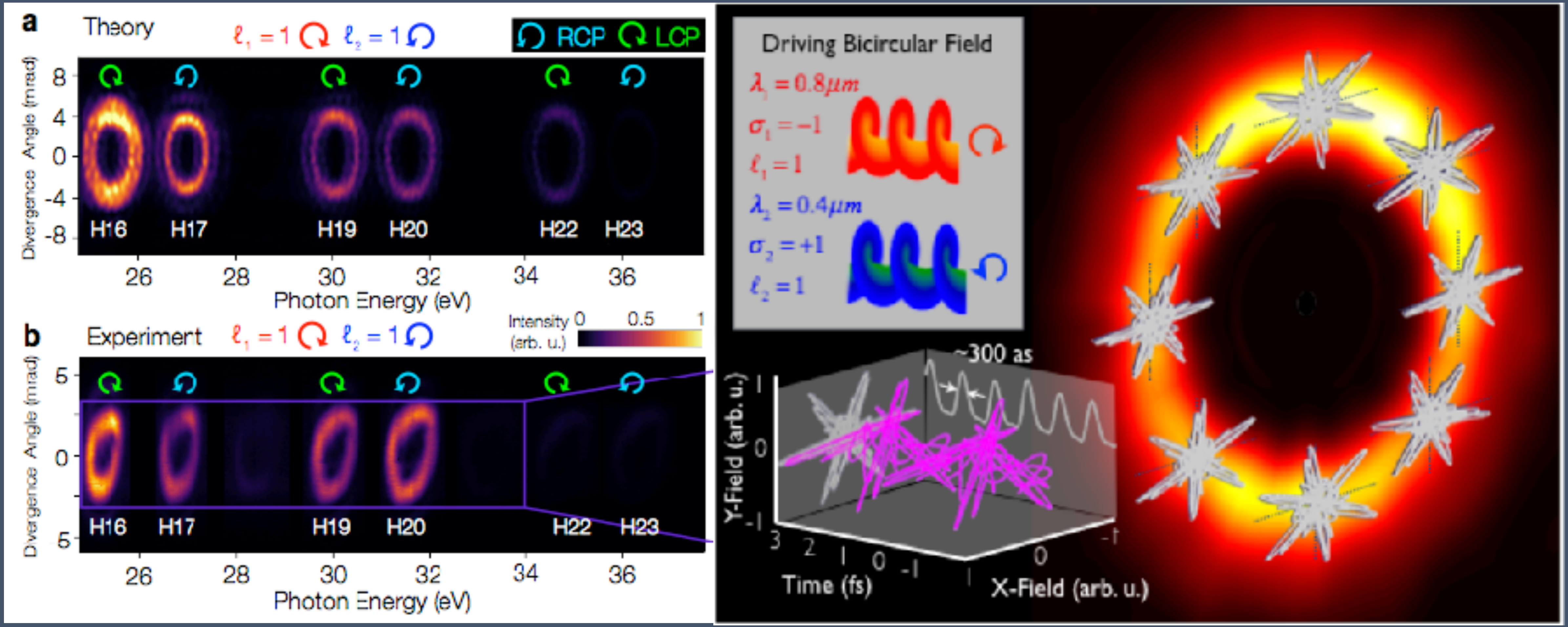

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➢ The presence of SAM constrains the allowed OAM values of the high-harmonics, and the OAM determines the divergence of the EUV vortices… Can we break the degeneracy?

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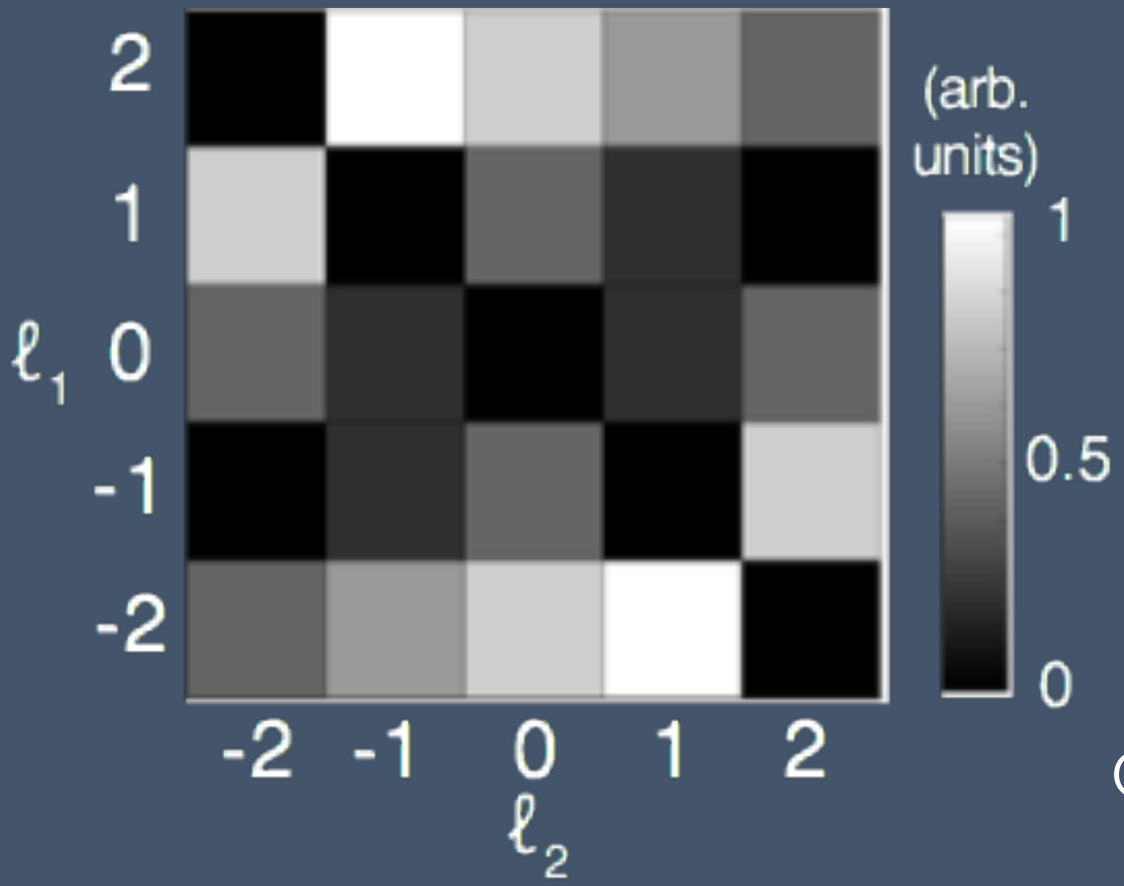

Isolated Vortices

Overlapped Vortices

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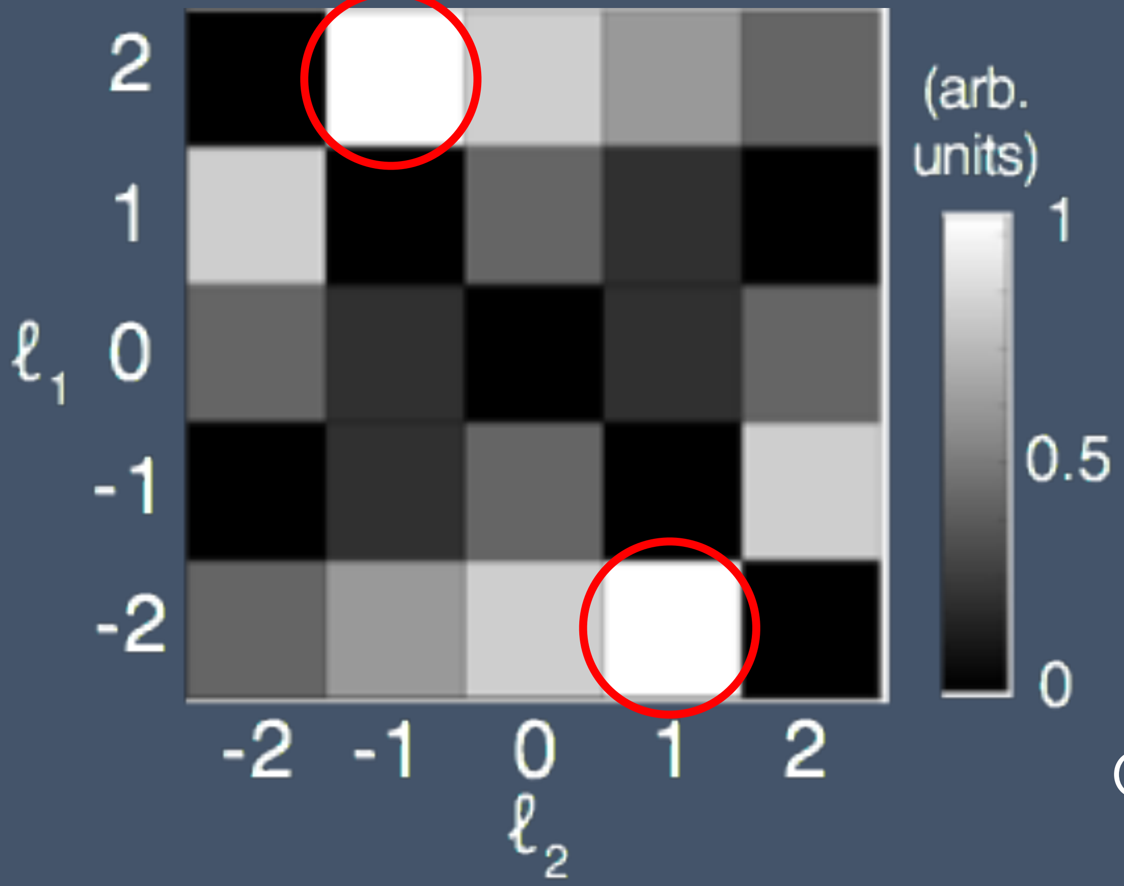

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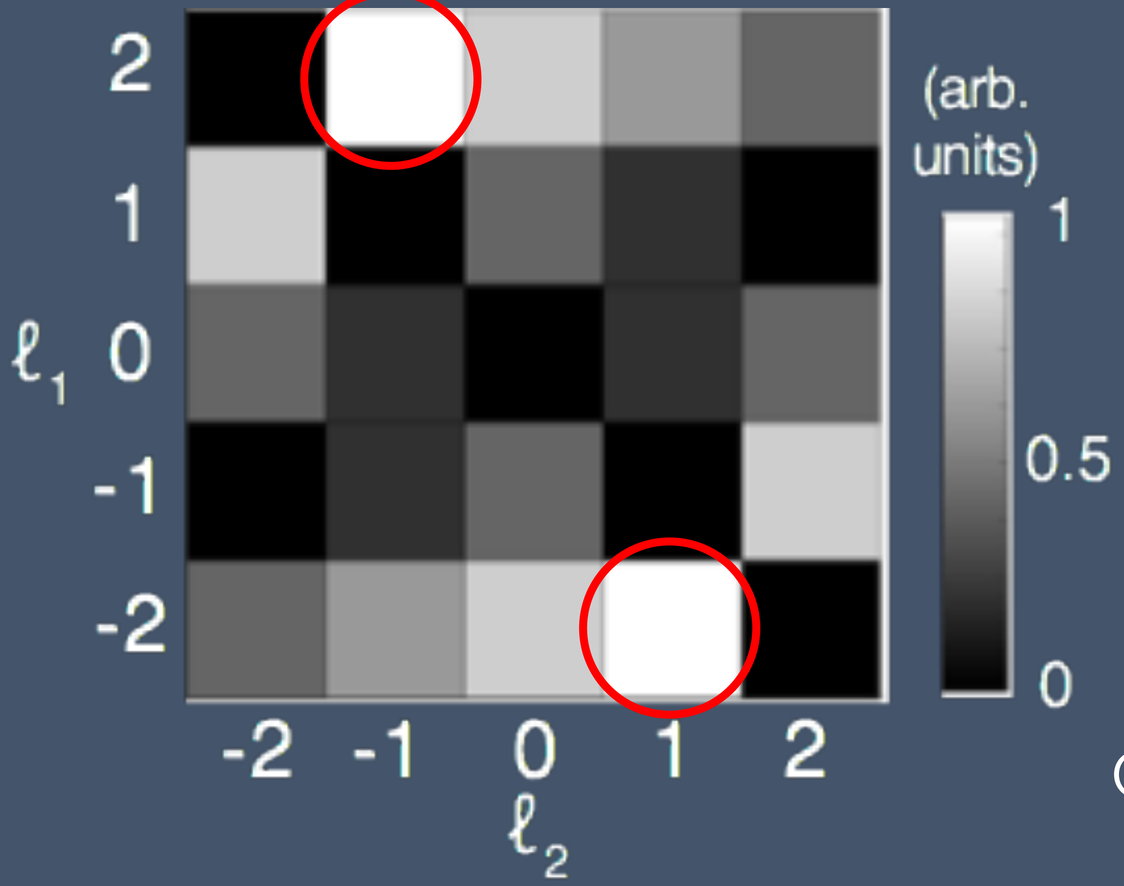
Divergence of HHG is maximized when:

1) OAM of drivers are opposite in sign
2) OAM of drivers differs by 1



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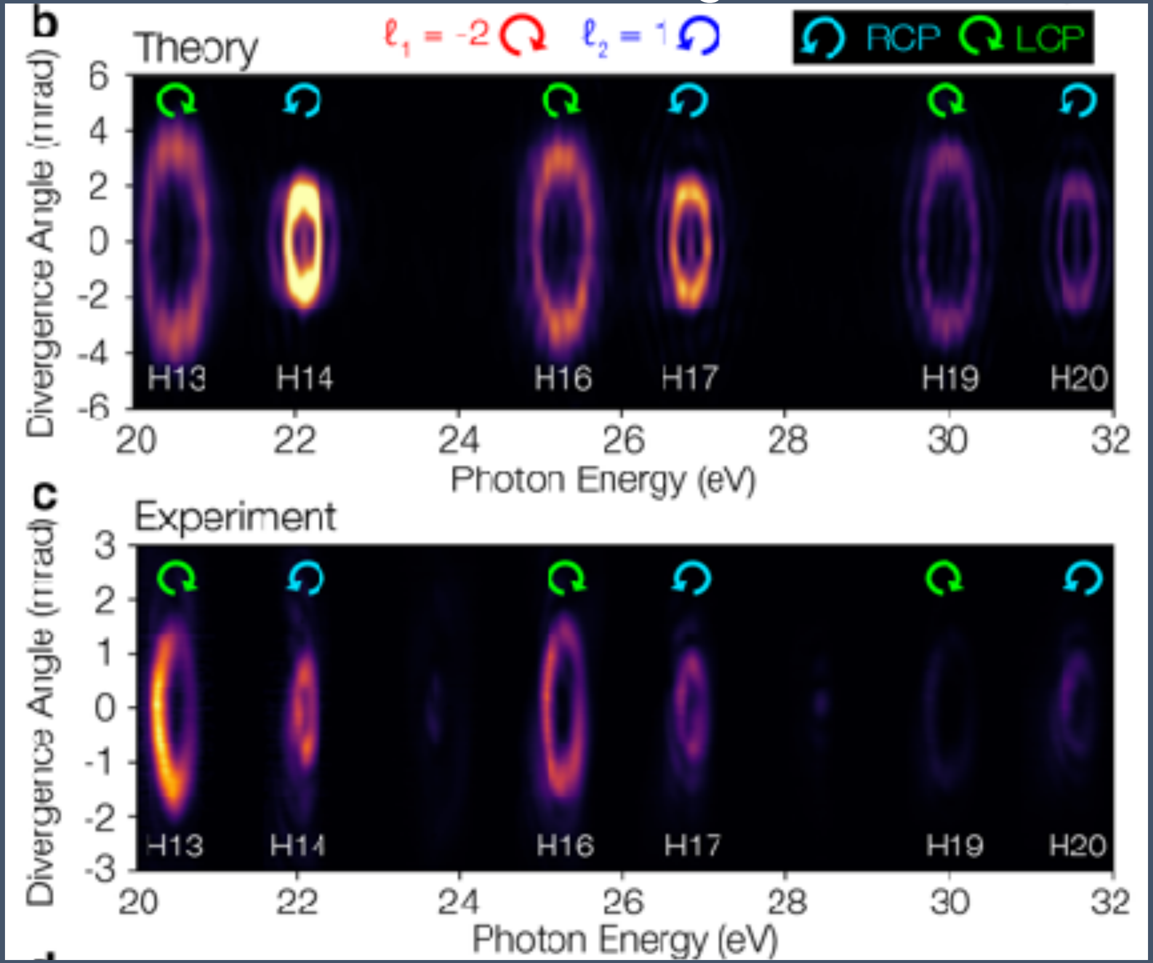

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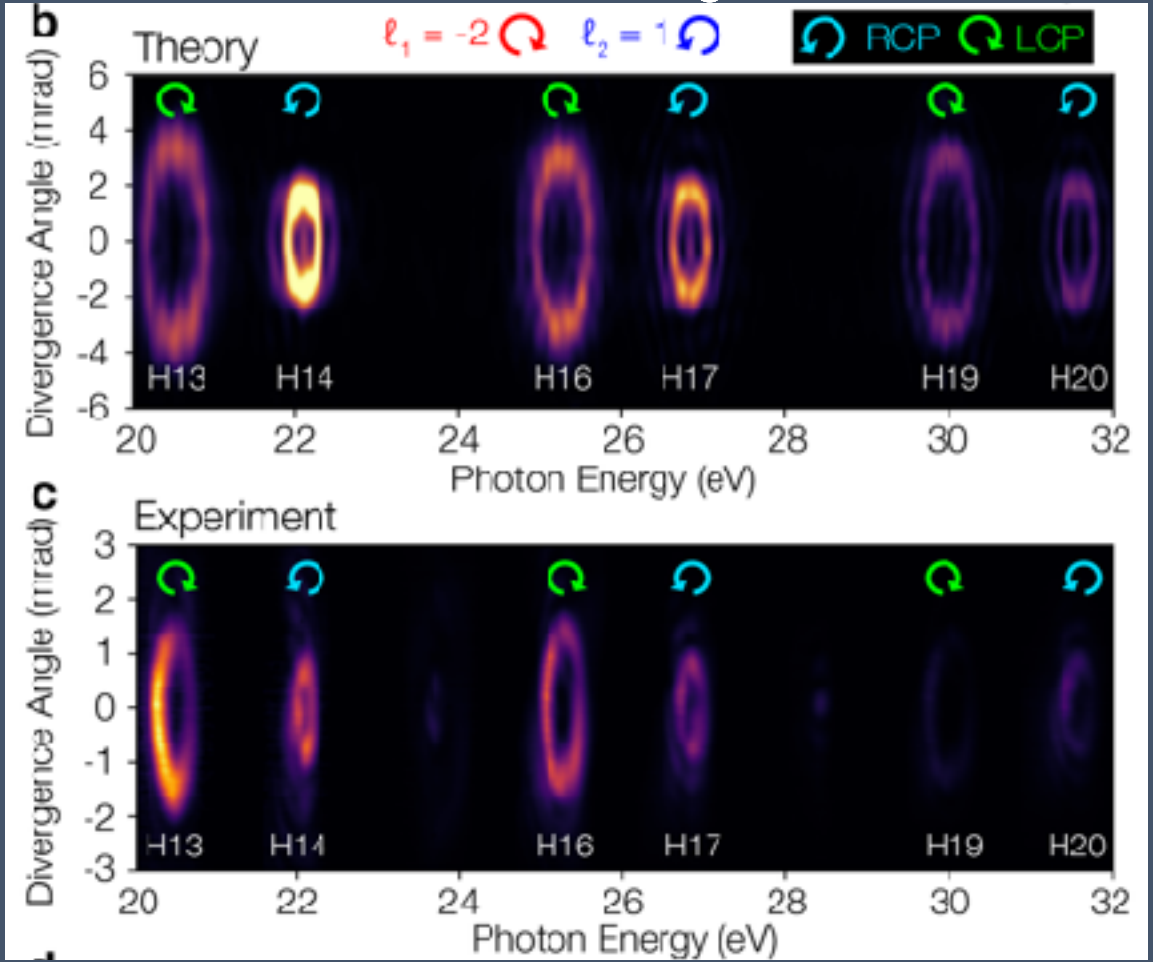

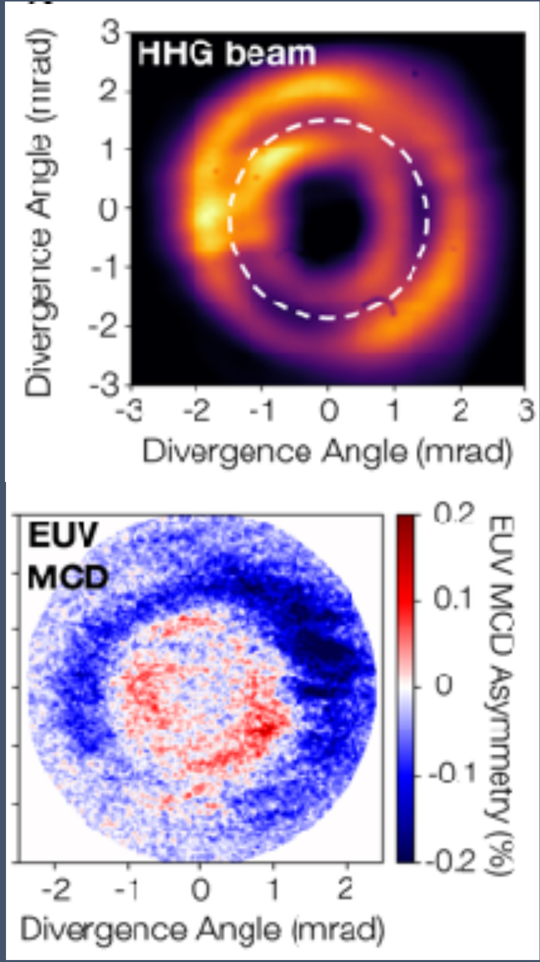

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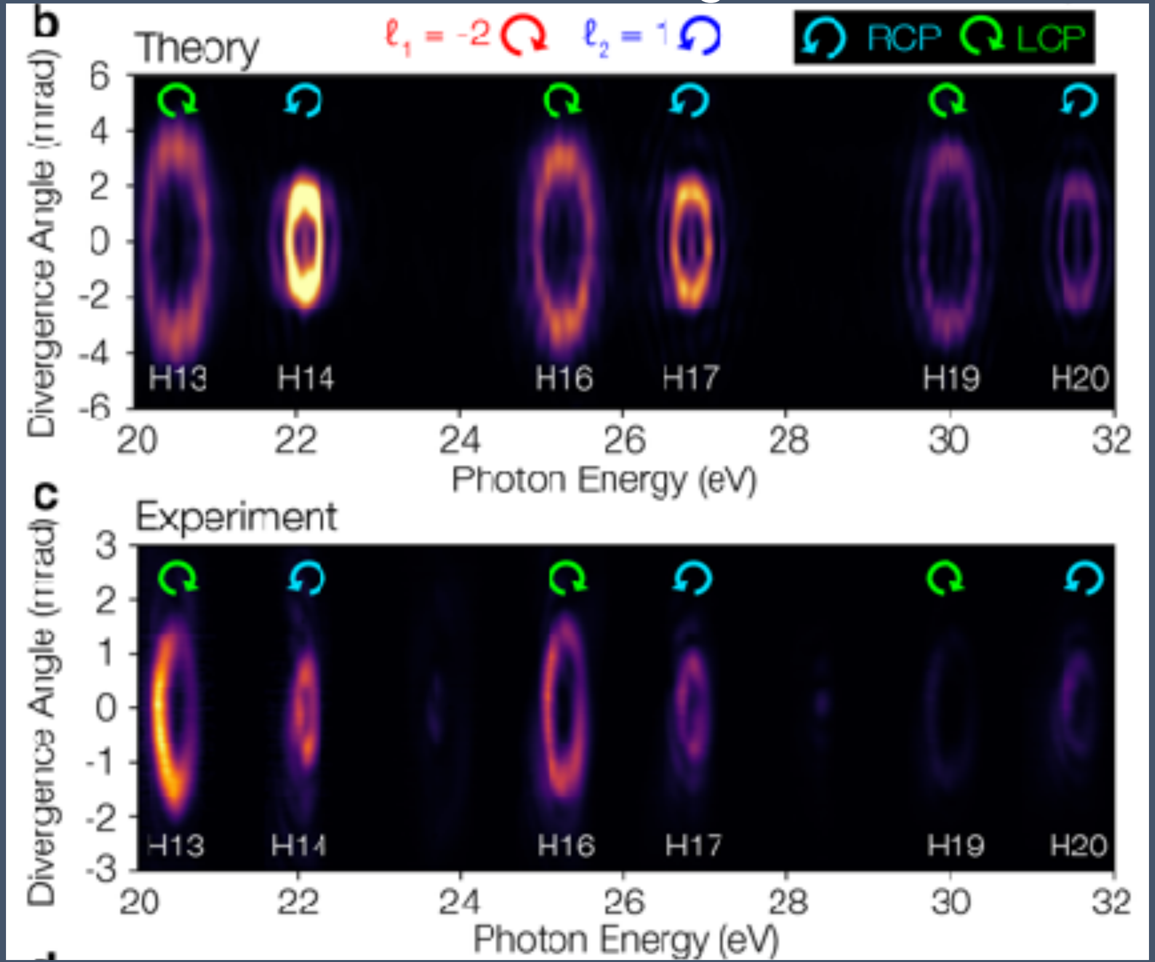

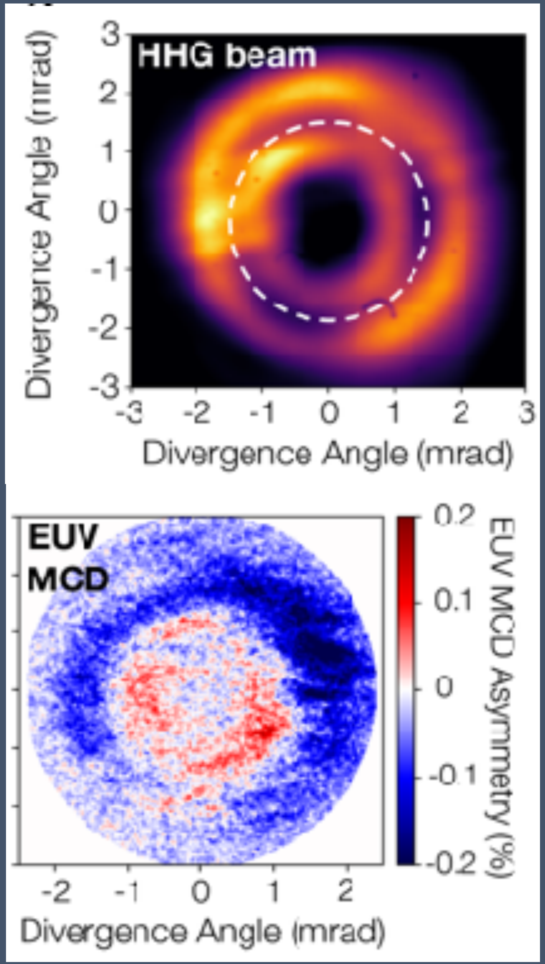

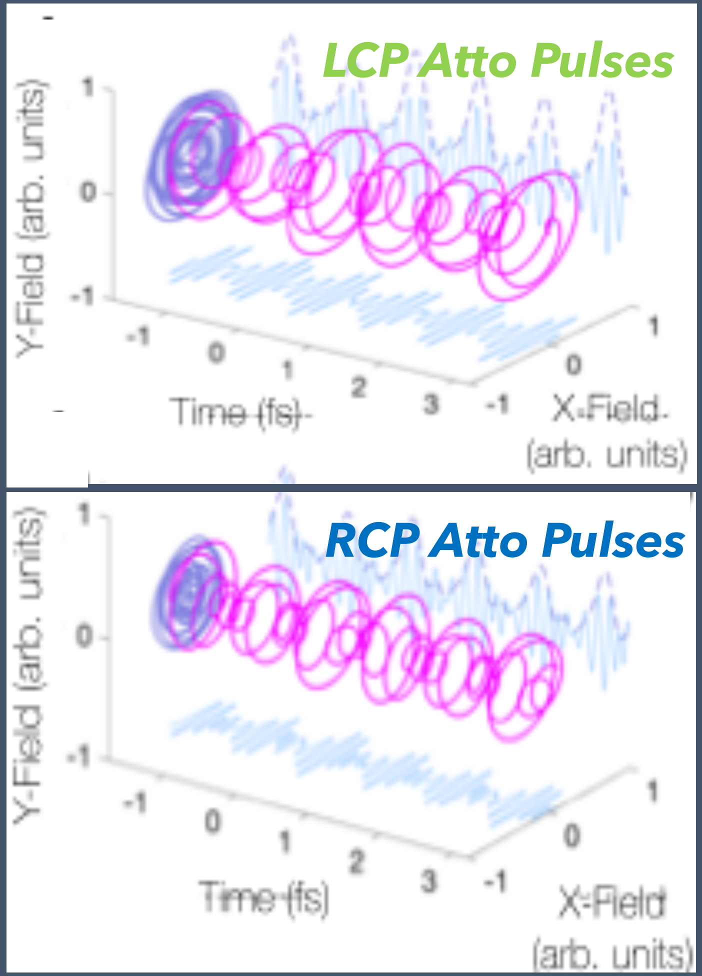

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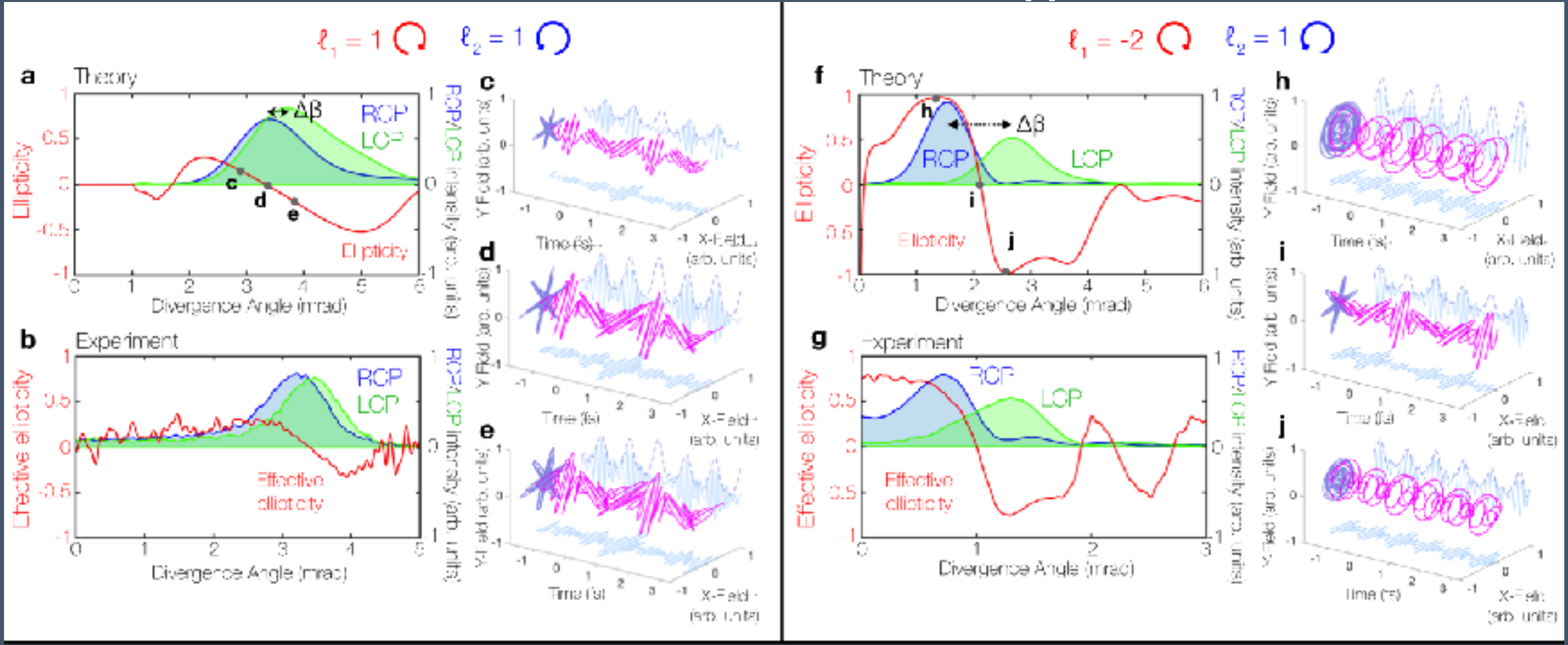
Entwined SAM-OAM Conservation in HHG: Attosecond Pulses from RCP to Linear to LCP

EUV Vortices with Same OAM, Opposite SAM (but overlapped)

EUV Vortices with Large OAM Difference, Opposite SAM



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Controlling the OAM in SAM-OAM HHG: High-Energy, Low-OAM Attosecond Vortices

➢ For most practical applications, we actually want ***low*** OAM high harmonics, but the physics of OAM HHG makes this difficult…

OAM Conservation w/ Single-Color Drivers

$$\ell_q = \ell_1 n_1$$

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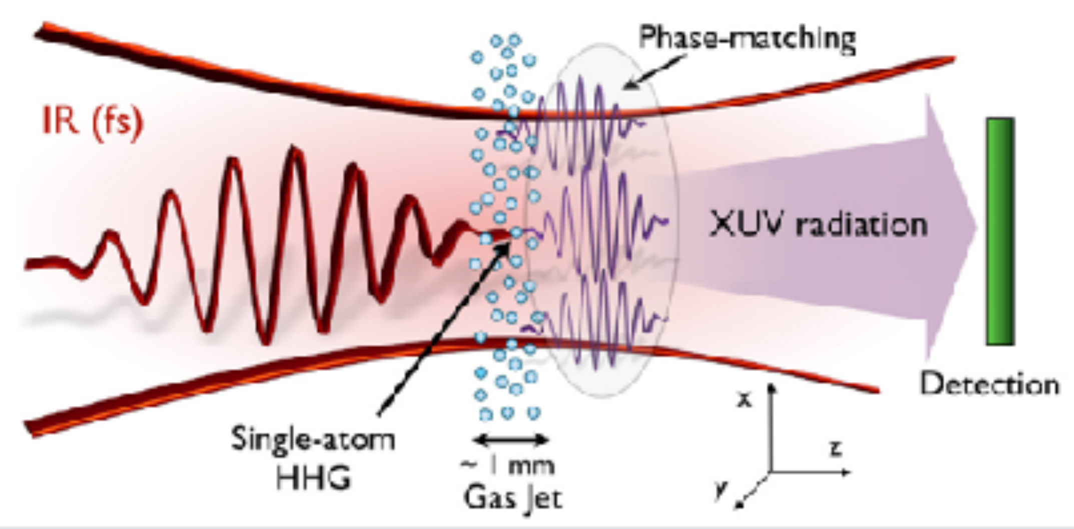

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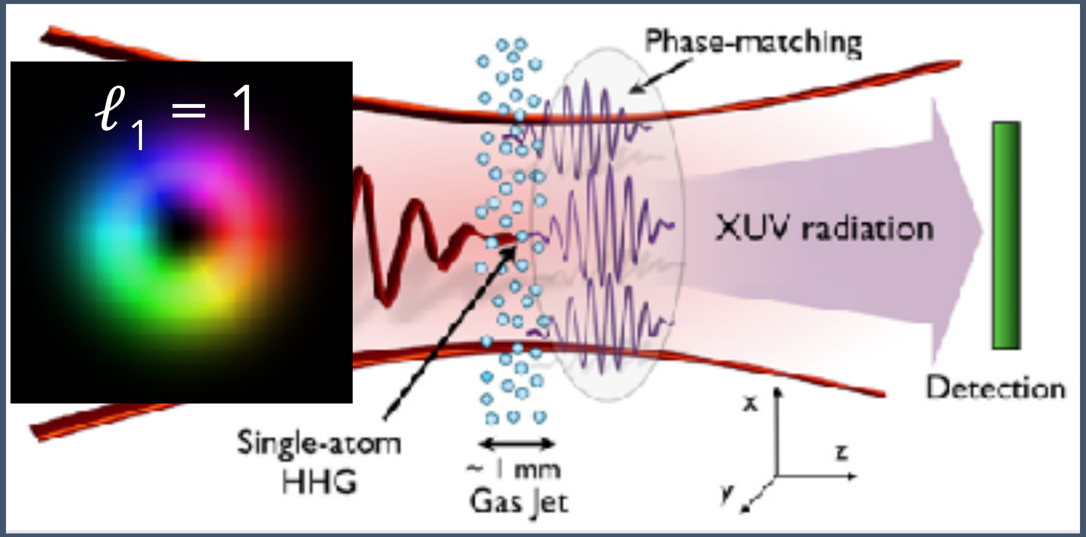

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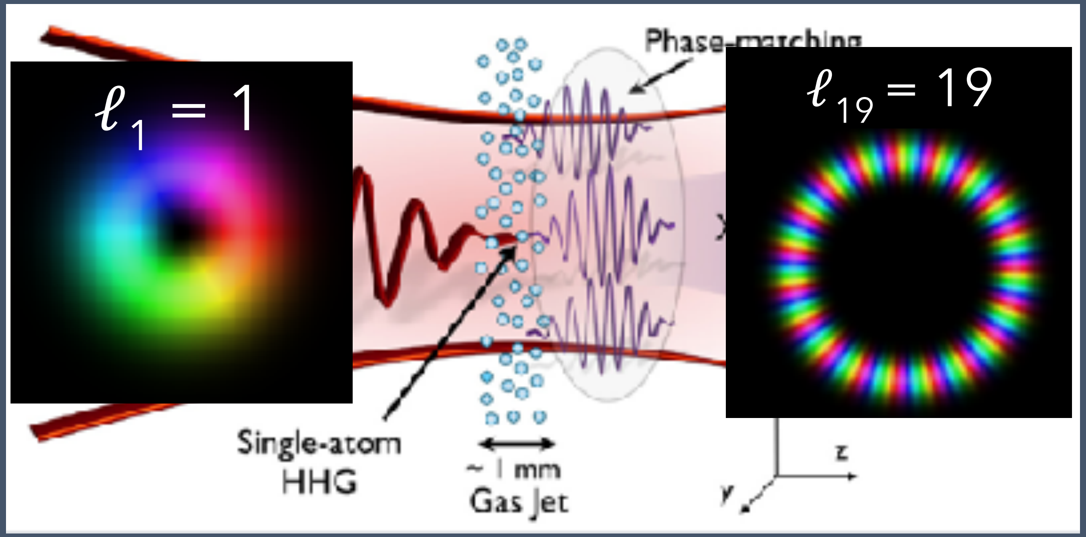
Pisanty, et al. *PRL* **122**, 2019

Controlling the OAM in SAM-OAM HHG: High-Energy, Low-OAM Attosecond Vortices

➢ For most practical applications, we actually want ***low*** OAM high harmonics, but the physics of OAM HHG makes this difficult…

OAM Conservation w/ Single-Color Drivers

$$\ell_q = \ell_1 n_1$$



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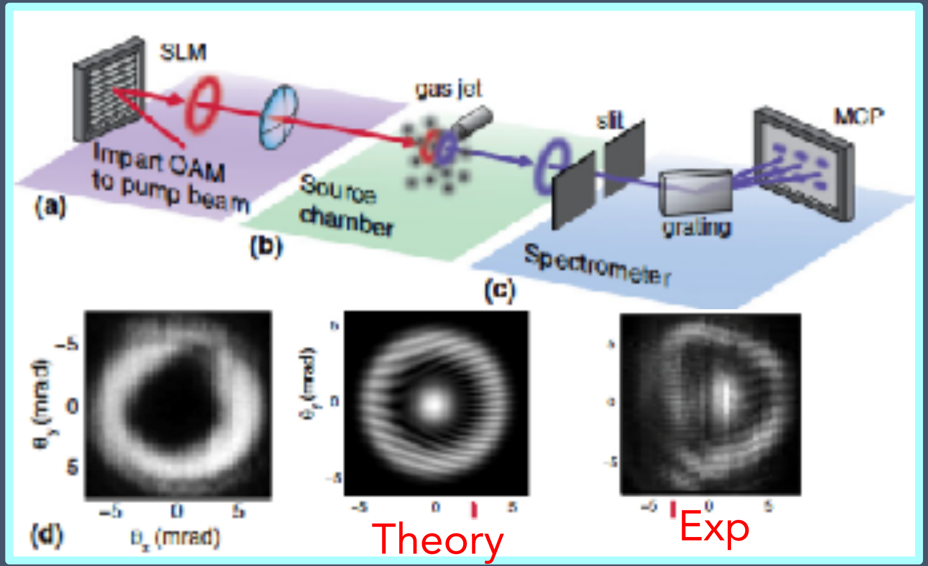

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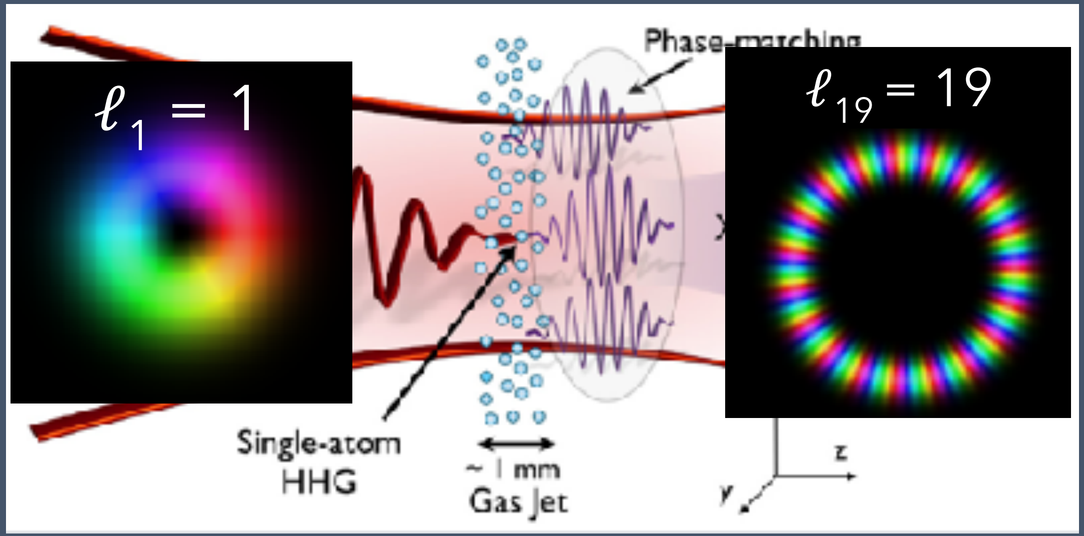

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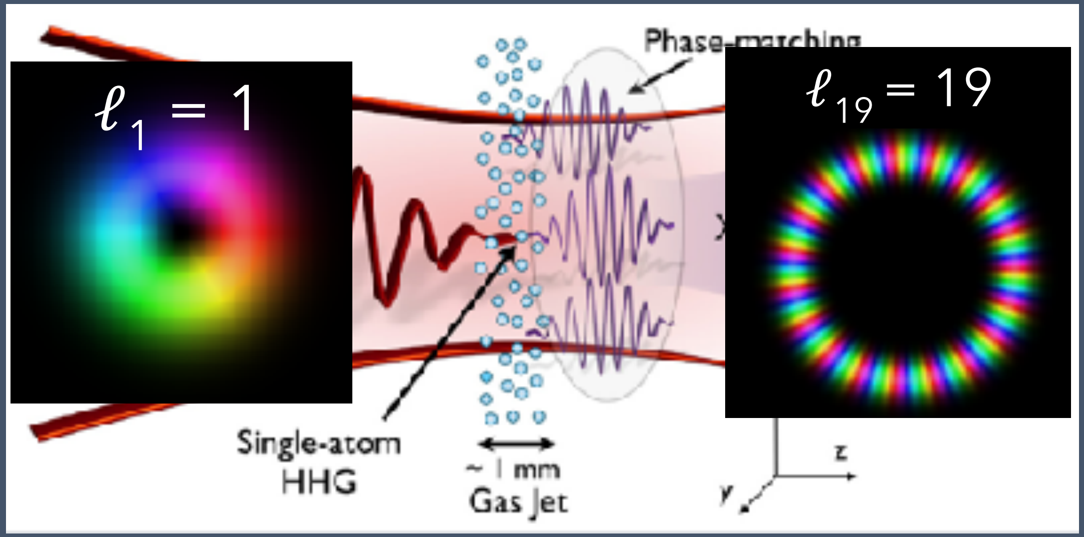

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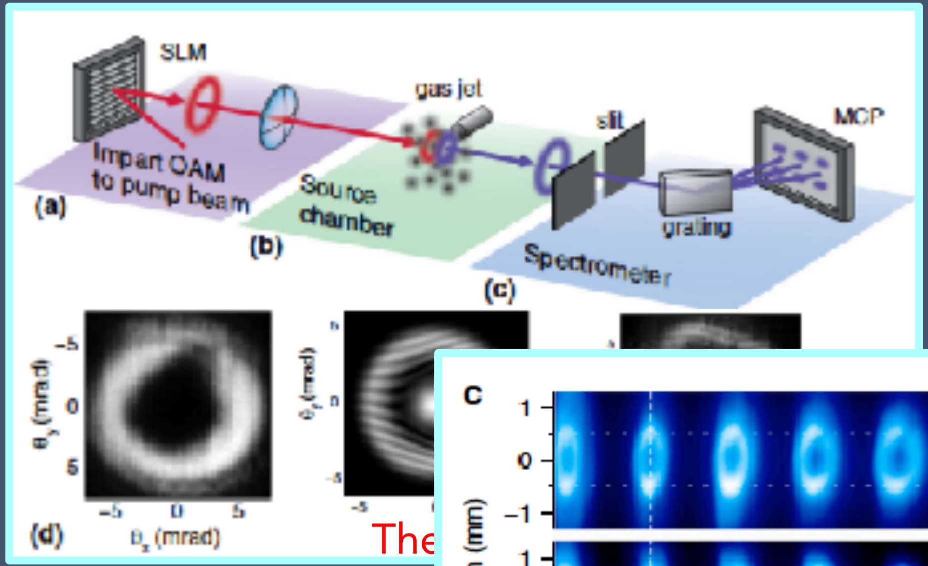
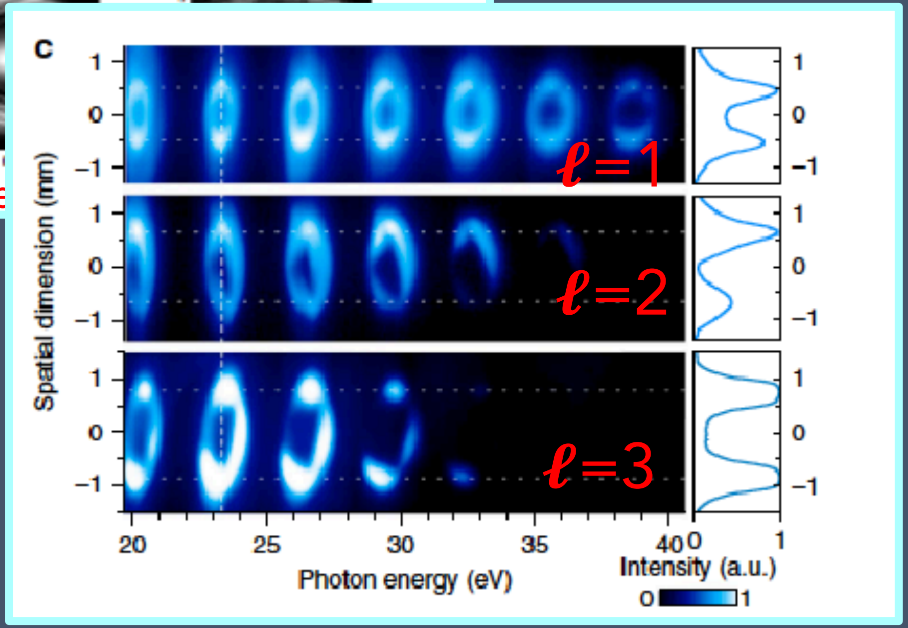


Géneaux, et al. Nat. Commun. 7, 2014



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OAM Conservation w/ Bicircular Driver

$$\ell_q = \frac{q + 2\sigma_q\sigma_1}{3}(\ell_1 + \ell_2) - \sigma_q\sigma_1\ell_2$$

$$\ell_1 = 1 \quad \ell_2 = -1$$

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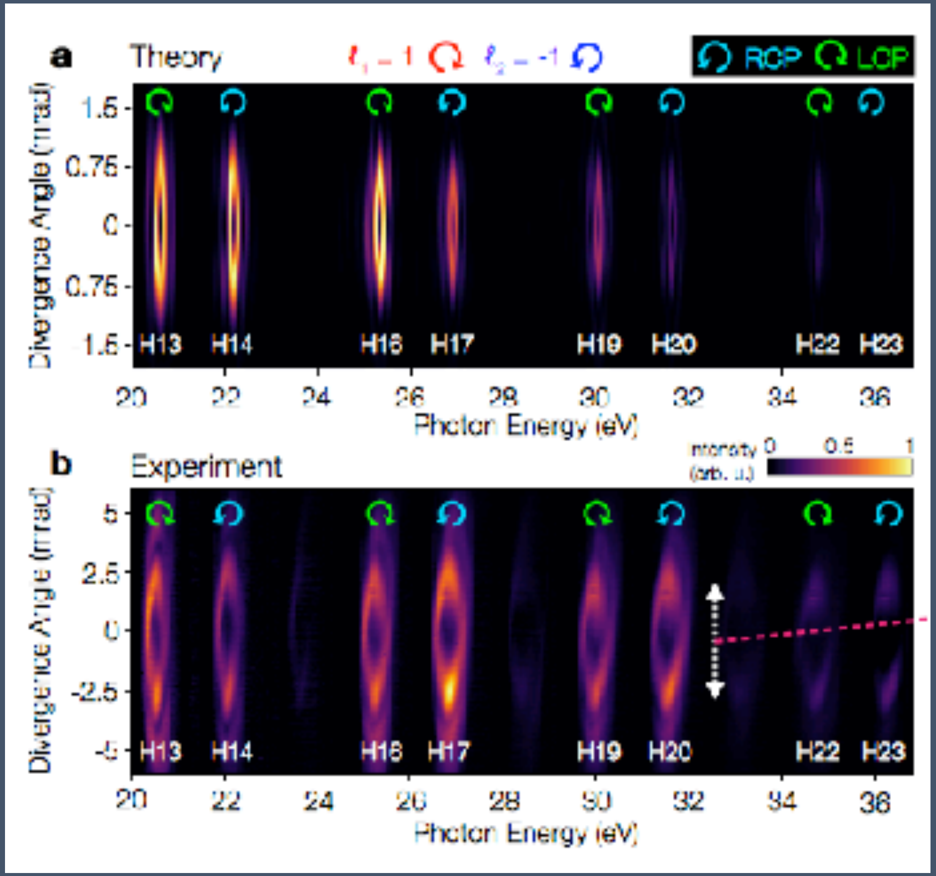

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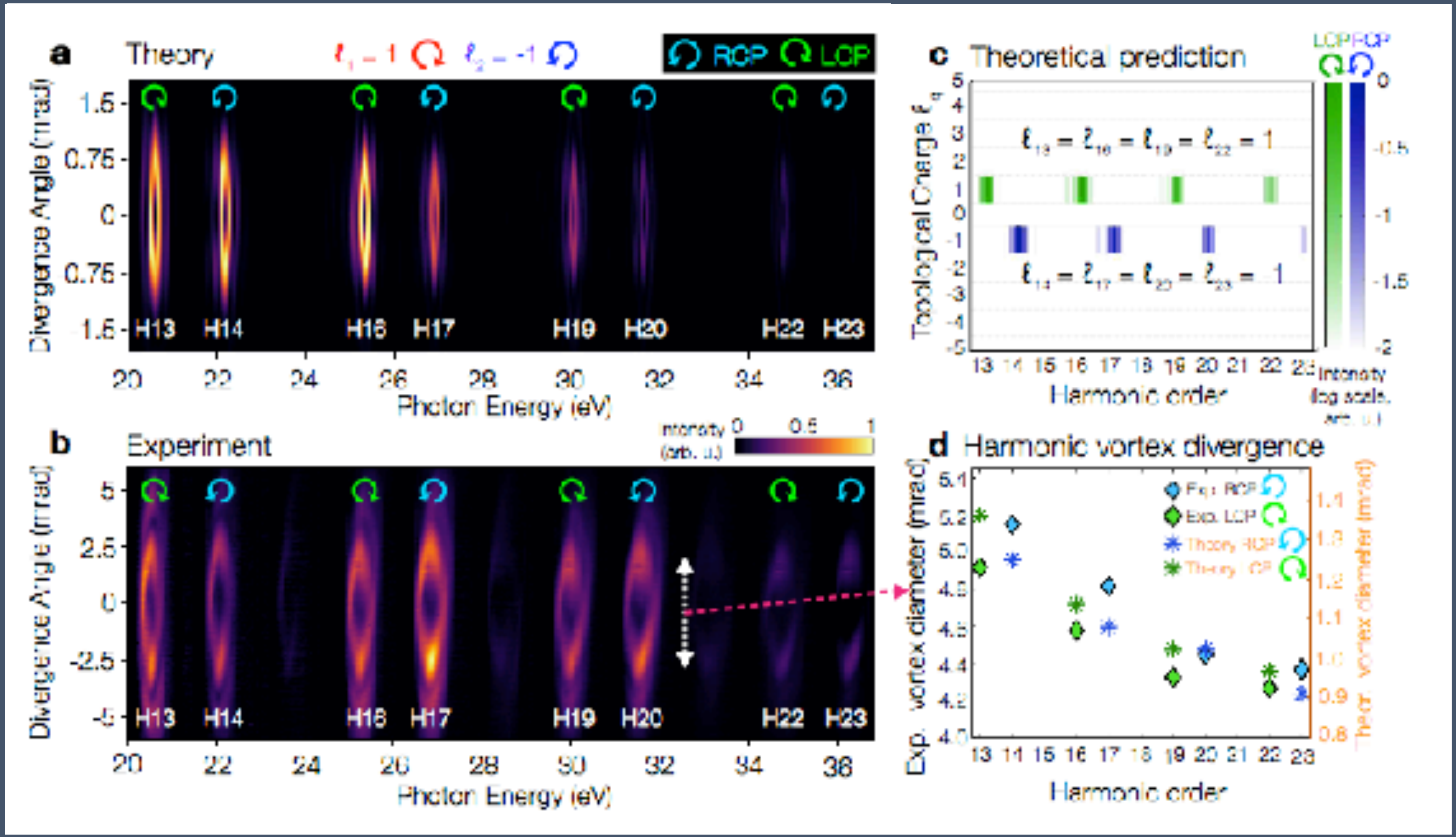

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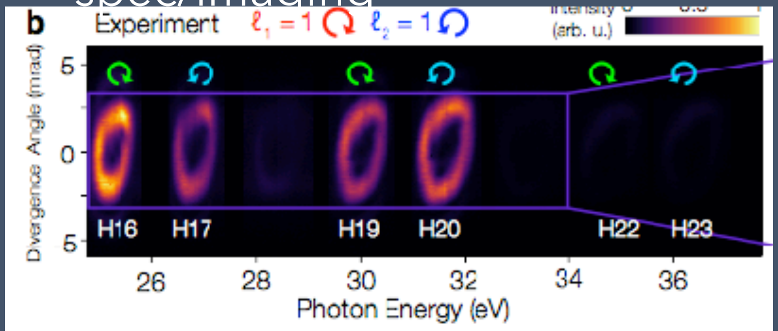
HHG with Simultaneous SAM-OAM Conservation:
Structured EUV Light with Designer SAM, OAM, Divergence

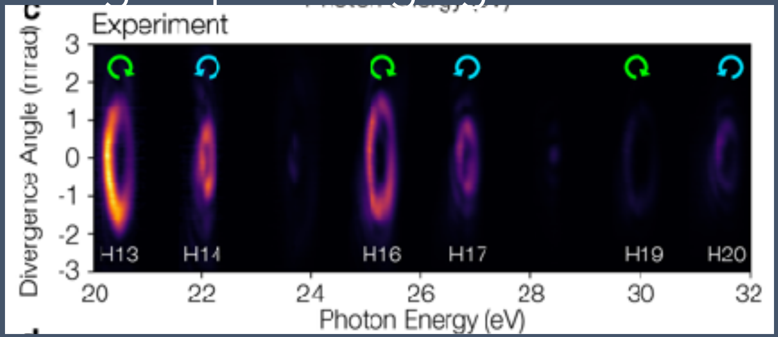
High OAM Vortices w/ Same OAM, Different SAM

- Linear atto pulses,
- OAM-mediated dichroic spec/imaging



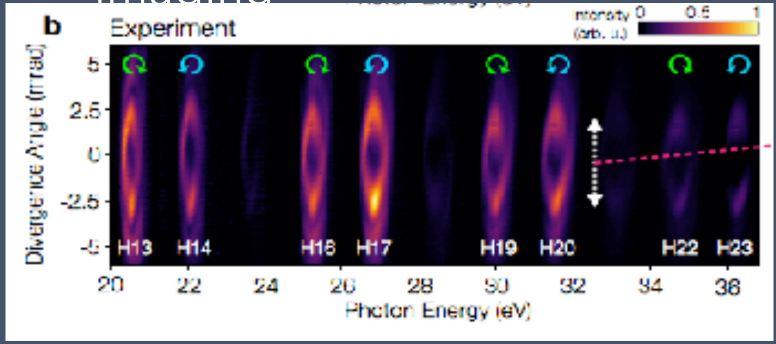
Spatially Isolated Vortices w/ Opposite SAM

- Circular atto pulses
- Spatially resolved, structured light spec/imaging



Low OAM Vortices w/ Opposite SAM

- Linear atto pulses
- Low OAM for controlled spec/imaging



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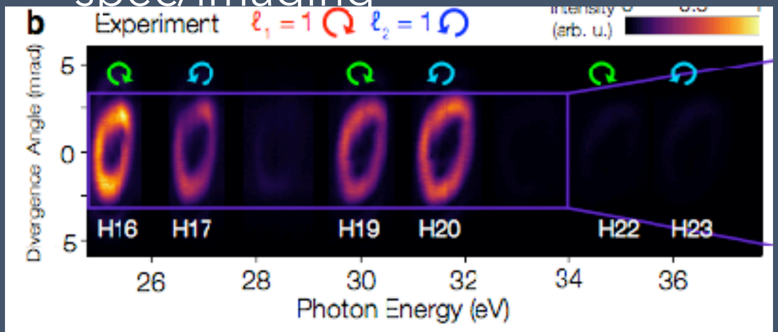

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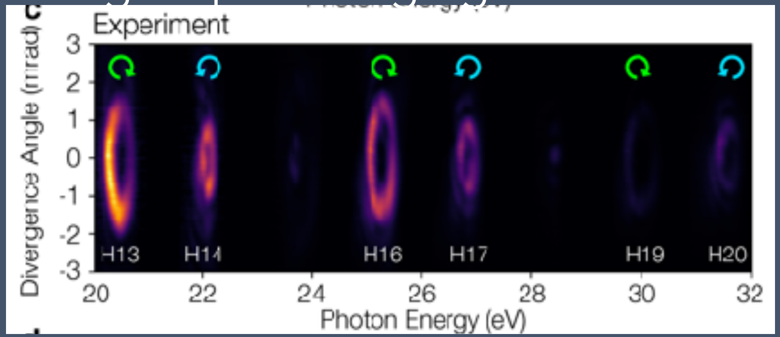

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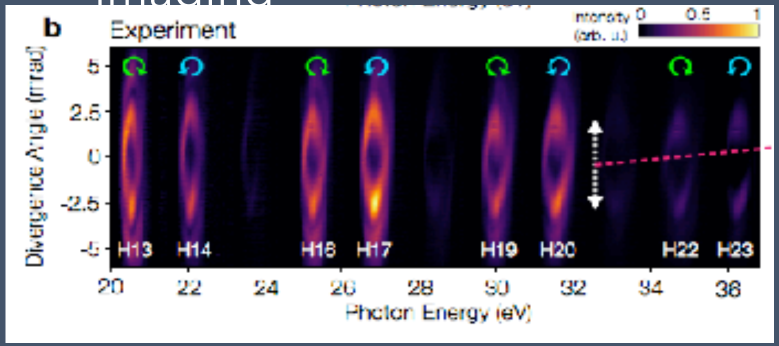
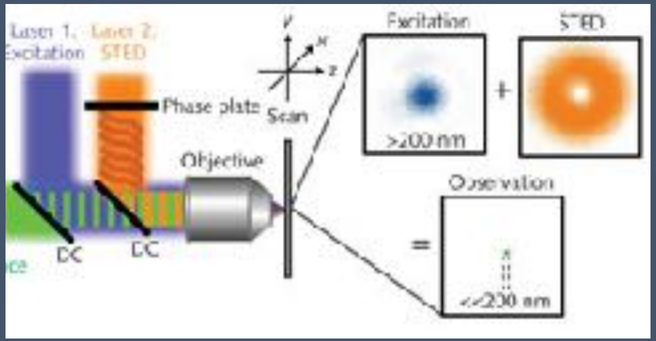
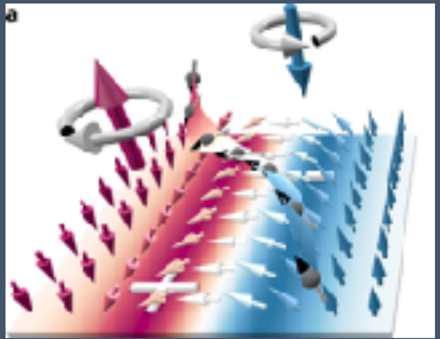


Mag Imaging/Control

EUV-based STED

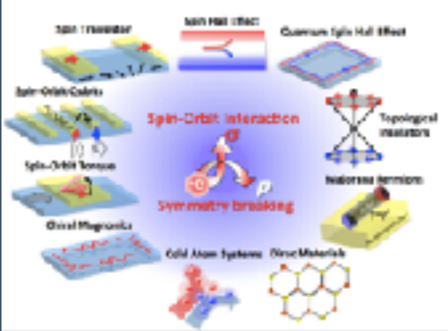


Orbital Magnetism



Optical Topologies

Spin/Orbit Interactions



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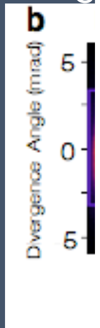
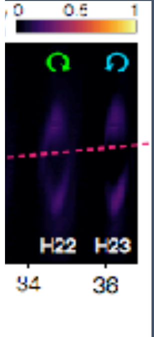
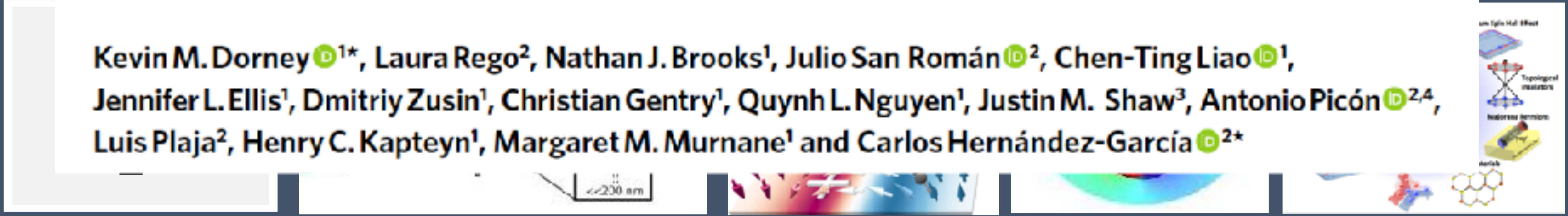
spec/





Mag

actions



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ARTICLES

https://doi.org/10.1038/s41566-018-0304-3

Controlling the polarization and vortex charge of attosecond high-harmonic beams via simultaneous spin–orbit momentum conservation

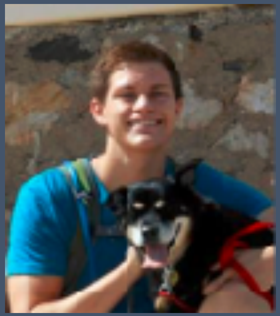
Kevin M. Dorney[1*], Laura Rego[2], Nathan J. Brooks[1], Julio San Román[2], Chen-Ting Liao[1], Jennifer L. Ellis[1], Dmitriy Zusin[1], Christian Gentry[1], Quynh L. Nguyen[1], Justin M. Shaw[3], Antonio Picón[2,4], Luis Plaja[2], Henry C. Kapteyn[1], Margaret M. Murnane[1] and Carlos Hernández-García[2*]

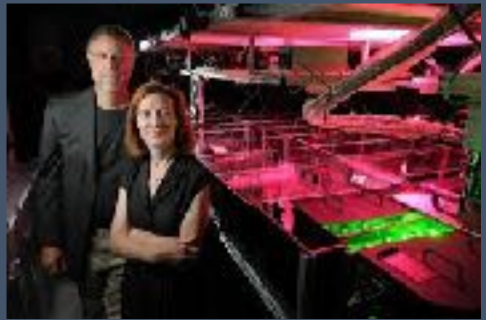
Excellent Group of Students, Collaborators and Advisors: Both at Home and Abroad!

JILA/NIST/CU Boulder (USA)

- Nathan Brooks
- Dr. Chen-Ting Liao
- Dr. Jennifer L. Ellis
- Dr. Dmitriy Zusin
- Christian Gentry
- Quynh L. Nguyen
- Justin M. Shaw (NIST)
- ***Prof. Henry Kapteyn***
- ***Prof. Margaret Murnane***



University of Salamanca (ESP)

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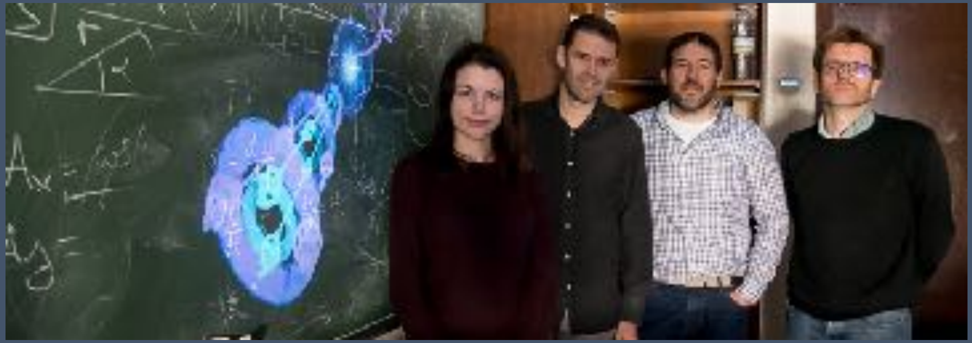


ICFO (ESP)

- Dr. Emilio Pisanty
- ***Prof. Maciej Lewenstein***


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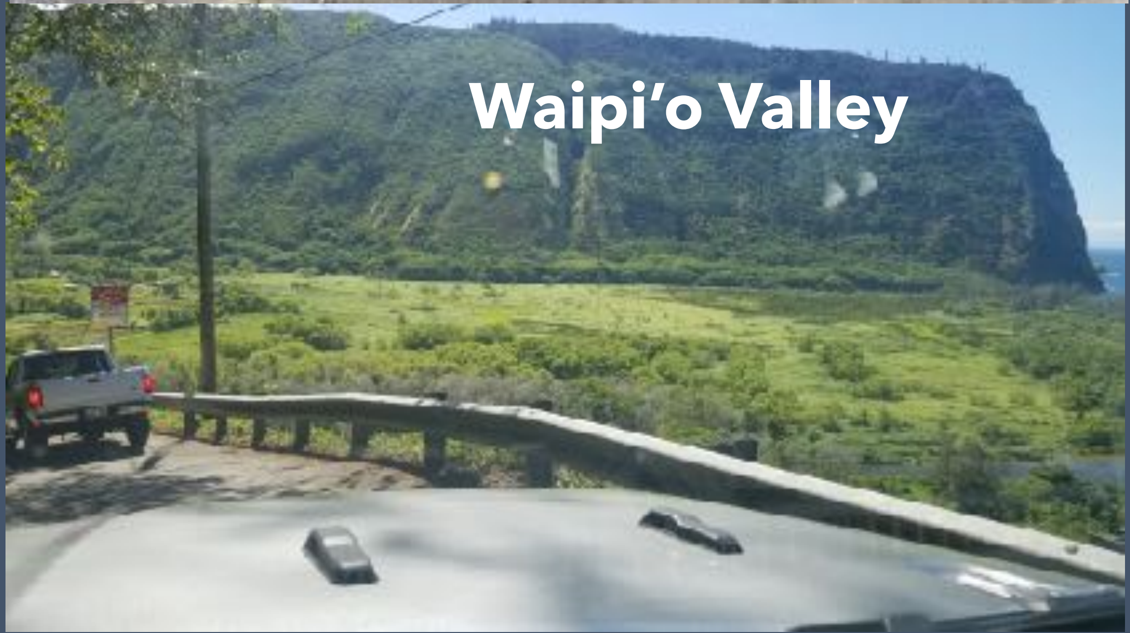
Thanks to Organizers, Support Staff, Advisors And… Of Course YOU!!!



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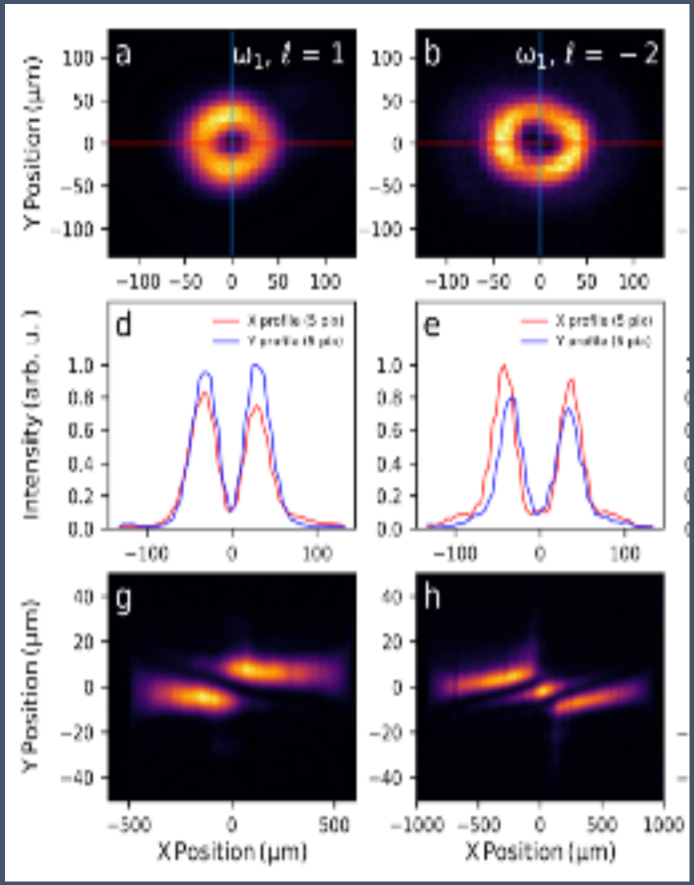
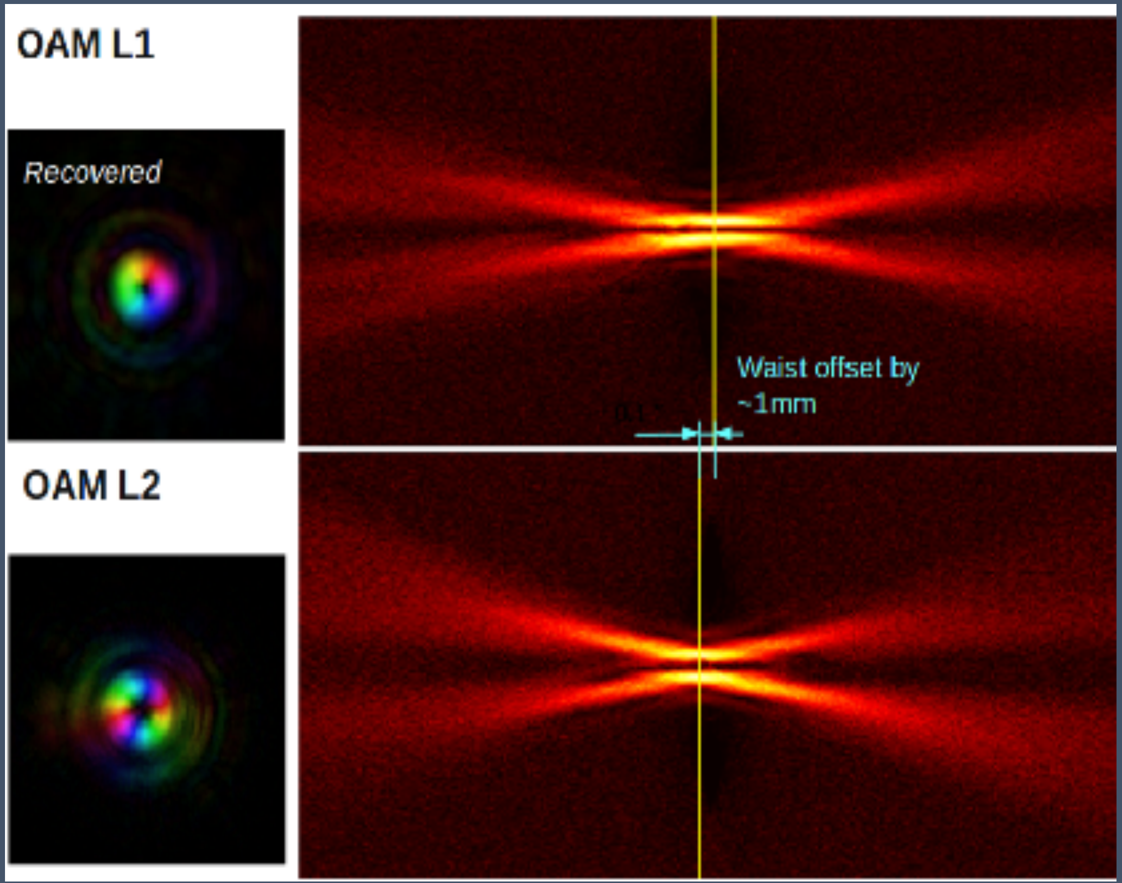
Generating and Quantifying High-Quality, Intense, Femtosecond Vortex Beams

Cylindrical Lens Analyzer[1]



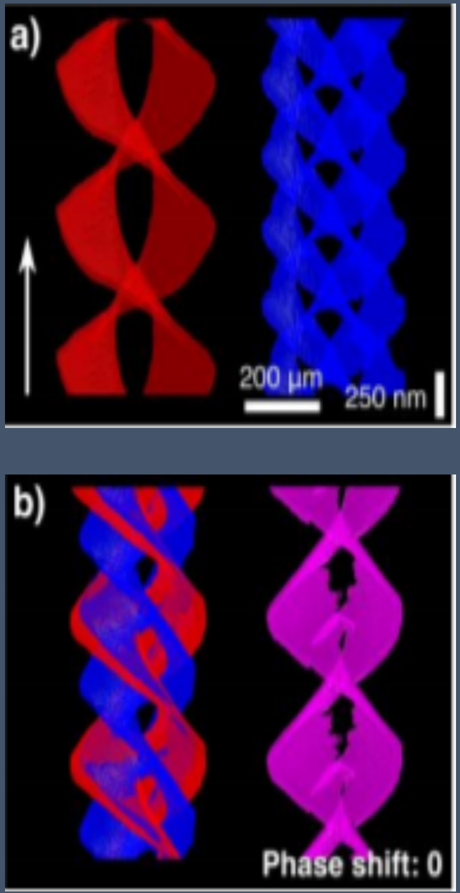
[1]Alperin, et al. *Opt. Lett.* **41**, 2016

Gerchberg-Saxton Phase Retrieval[2-4]



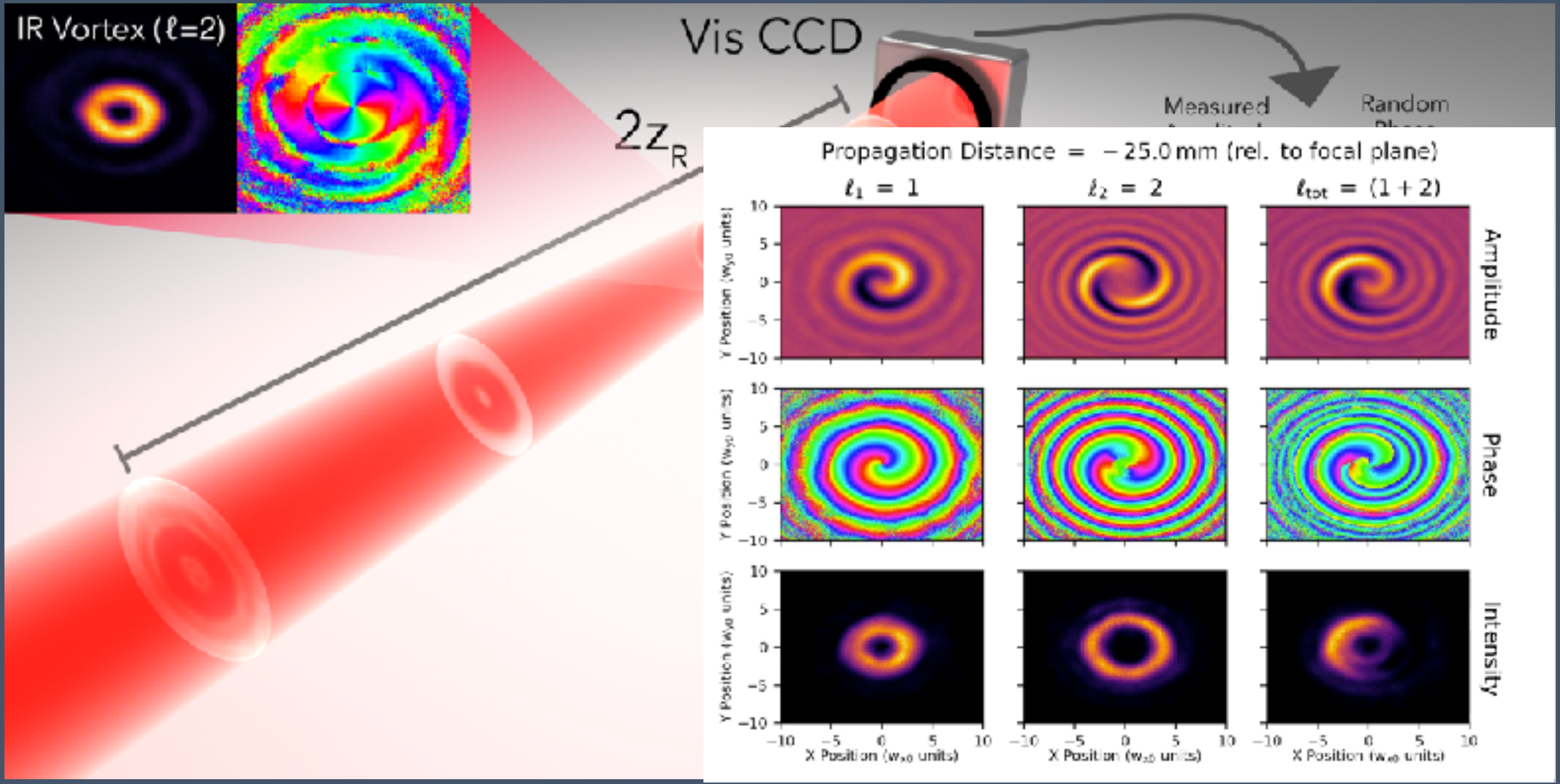
[2]Fu, et al. *Opt. Lett.* **41**, 2016
[3]Chang, et al. *Opt. Commun.* **405**, 2017
[4]Rego and **Dorney**, et al. Science, **364**, 2019

Ptychography[5,6]



[5]Saito, et al. *Jpn. J. Appl. Phys.* **56**, 2017
[6]Esashi, et al. *Opt. Exp.* **26**, 2018

Generating and Quantifying High-Quality, Intense, Mixed OAM Vortex Beams



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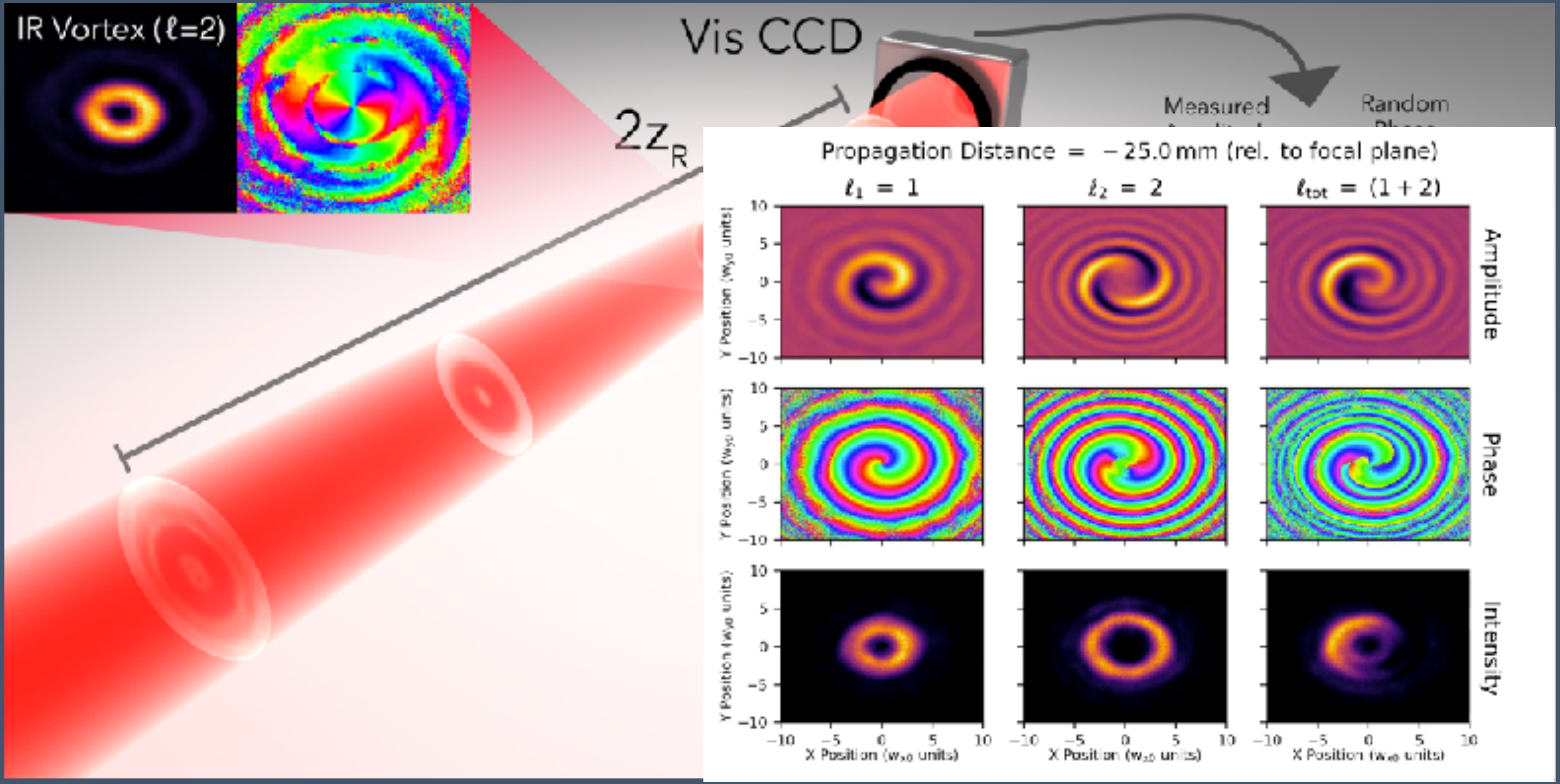

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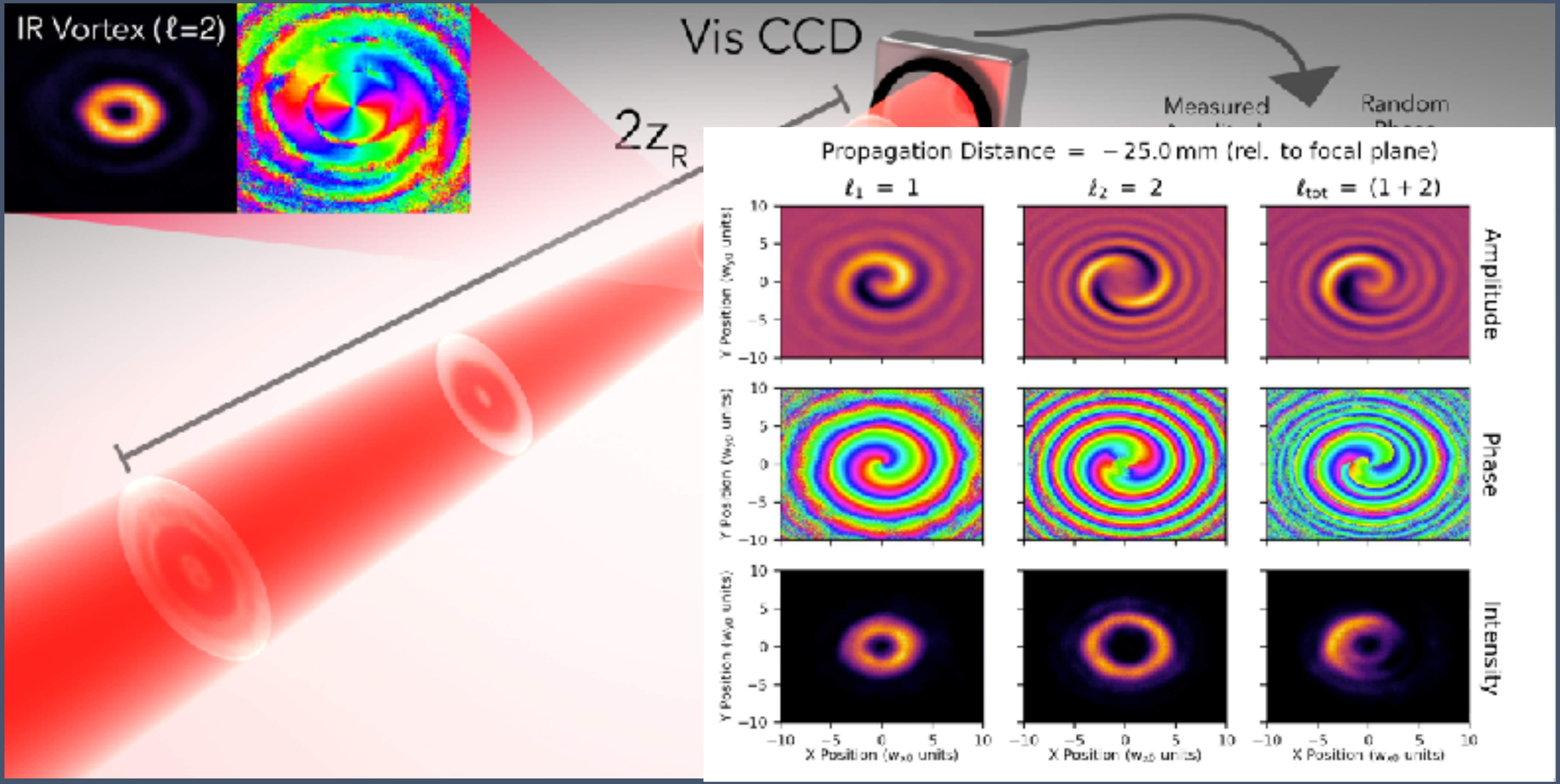

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