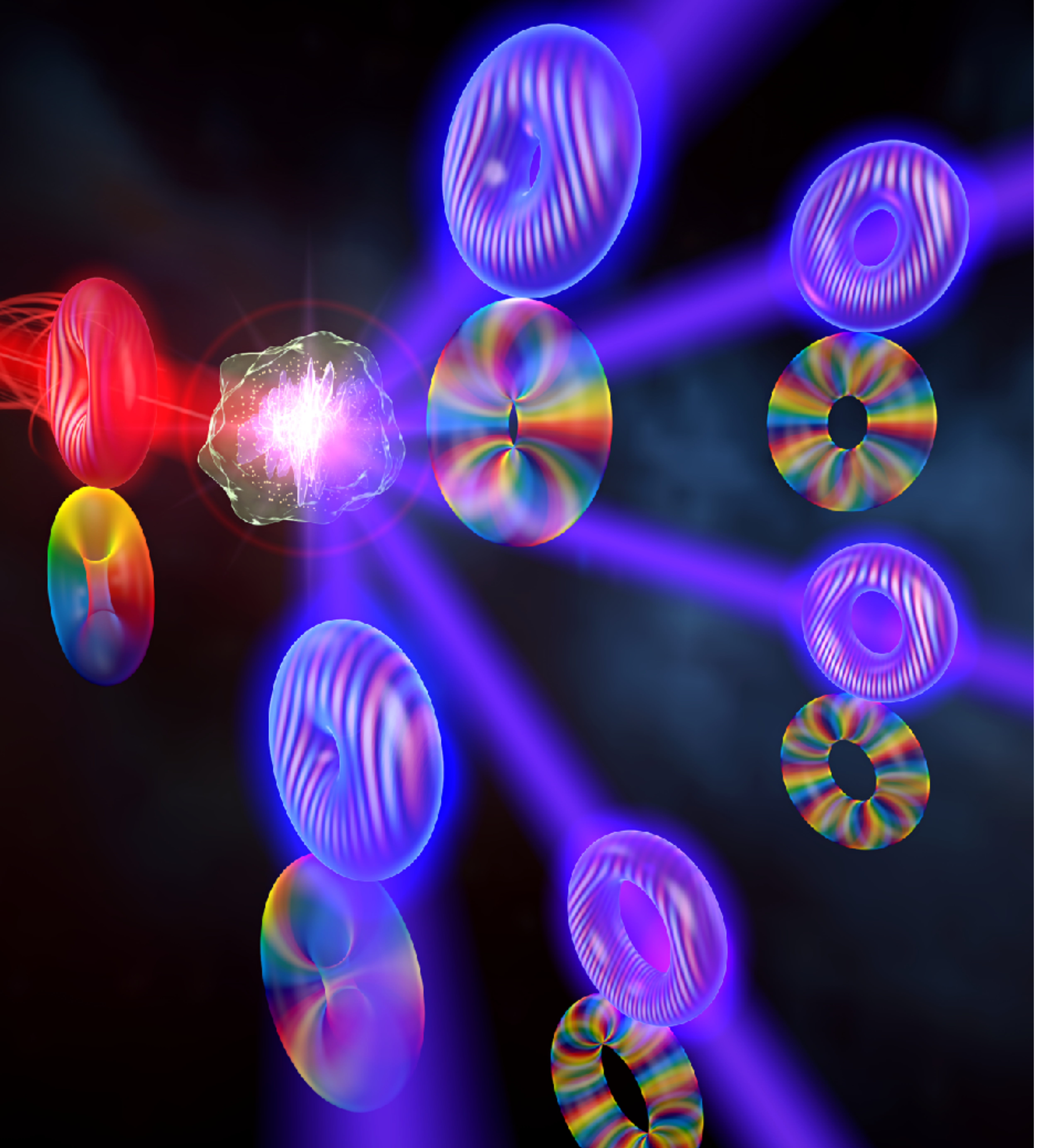

Figure credit: Steven Burrows and KM group, JILA

Generation of EUV attosecond structured pulses

Carlos Hernández-García

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Luz y Materia Estructuradas (LUMES)

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European Research Council

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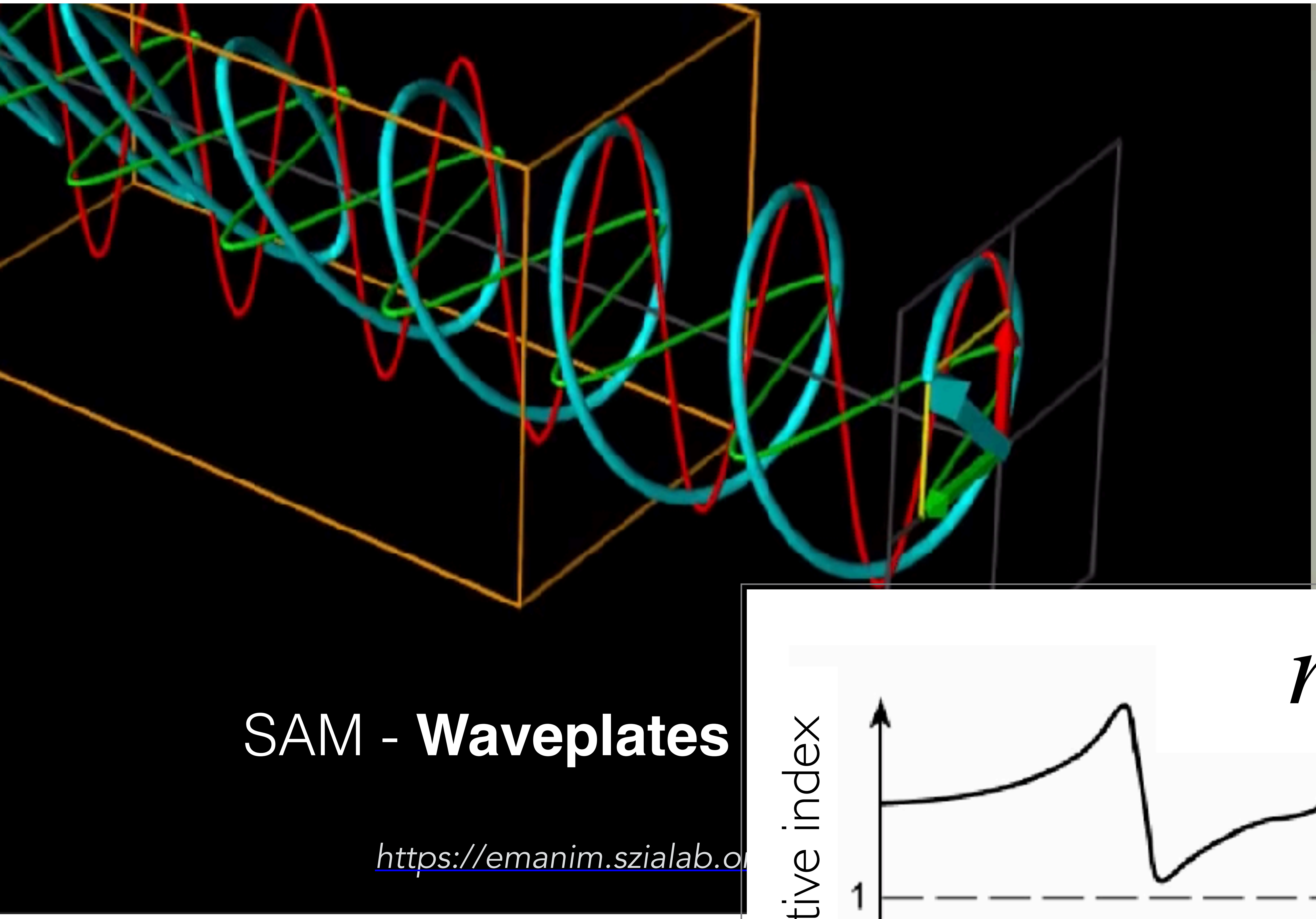
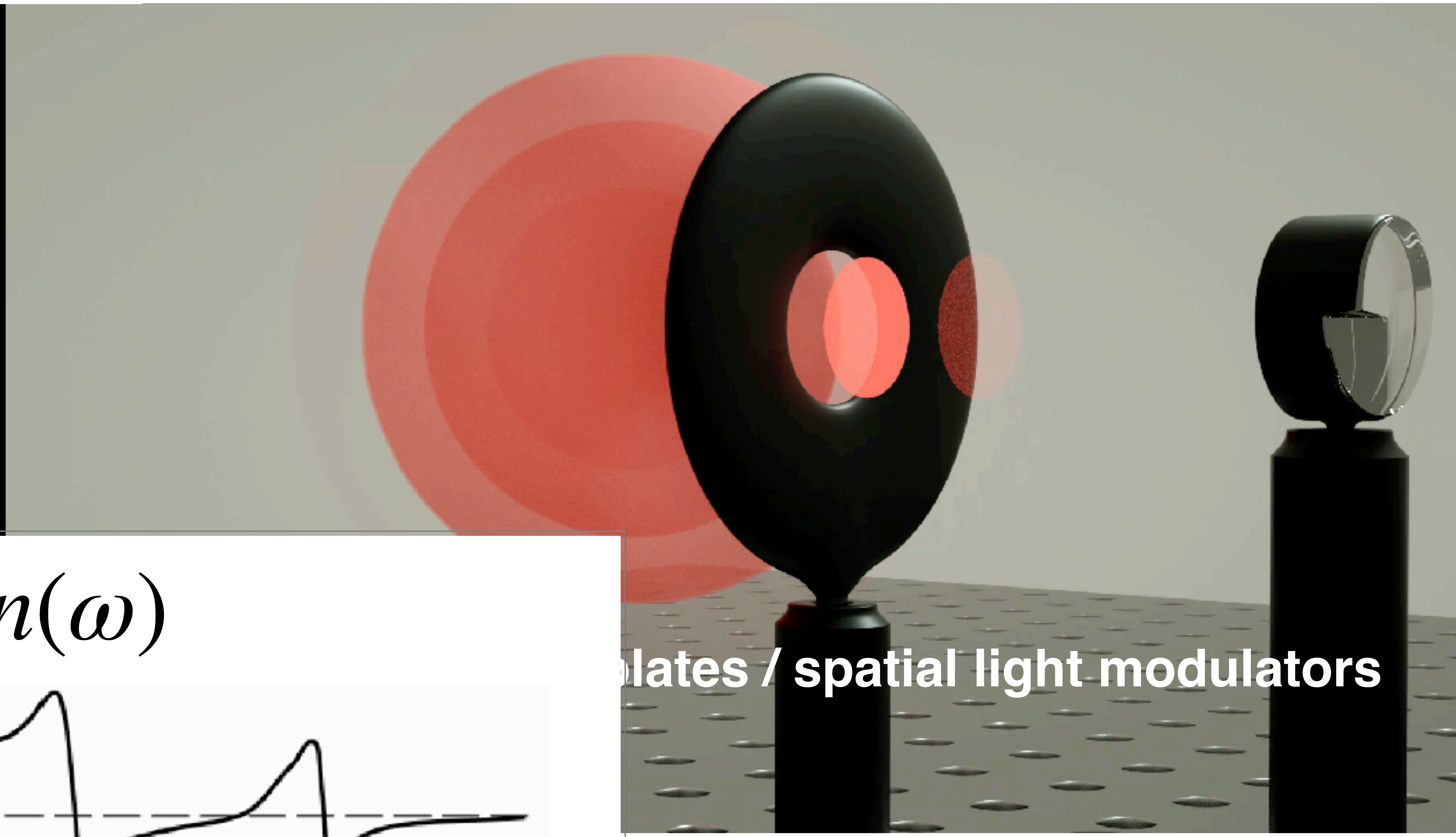
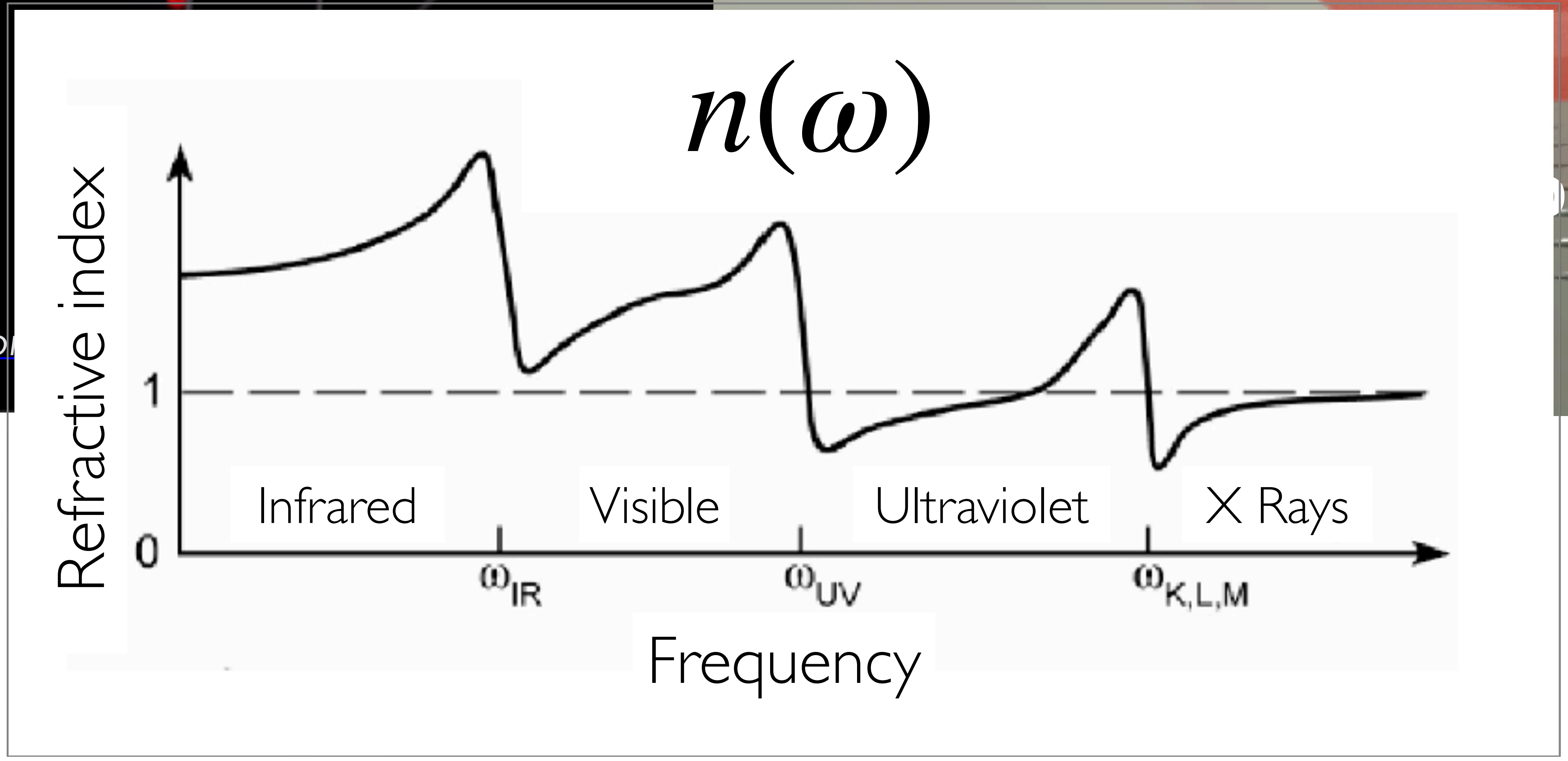
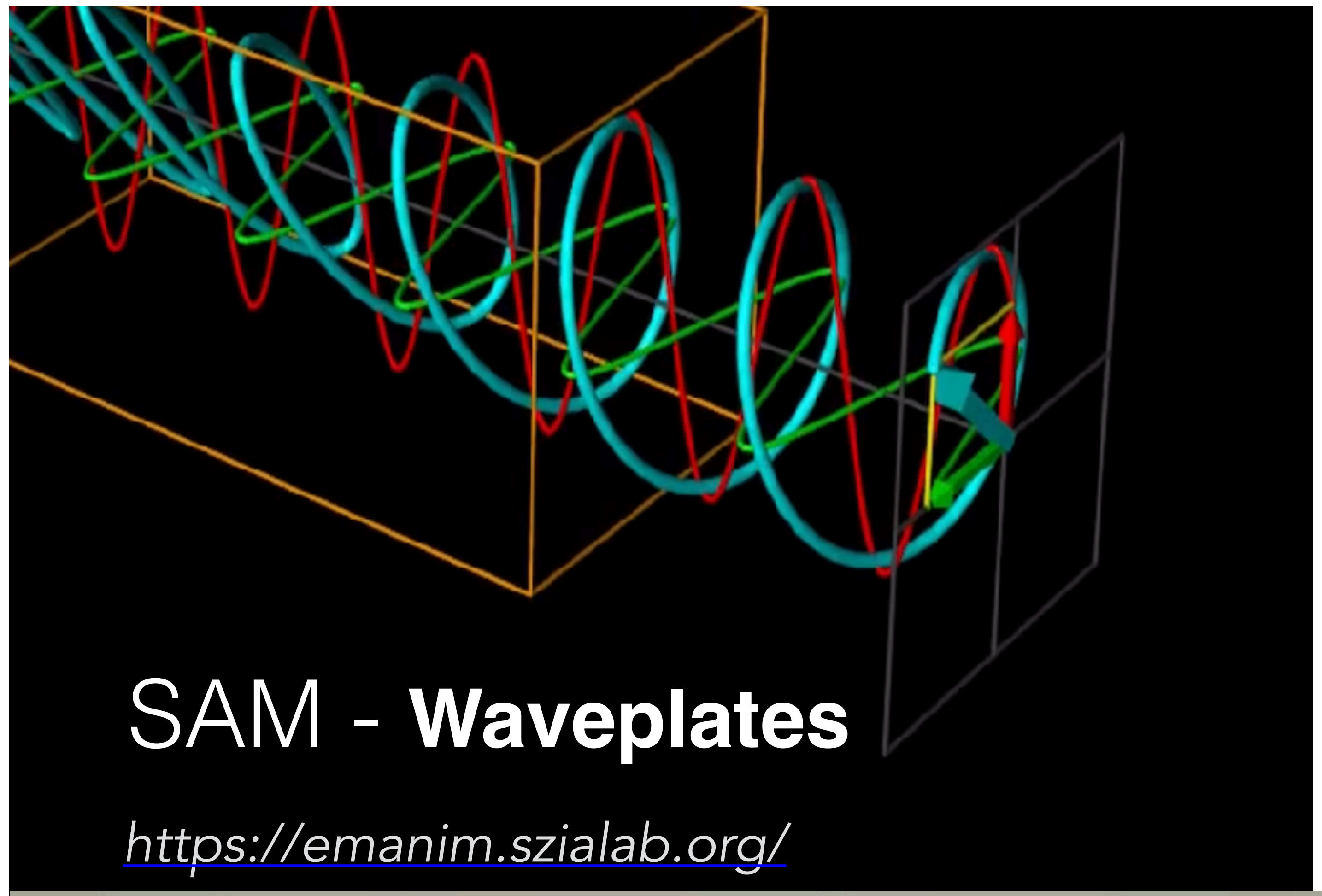
Challenge: bring structured light into the EUV/soft x-rays

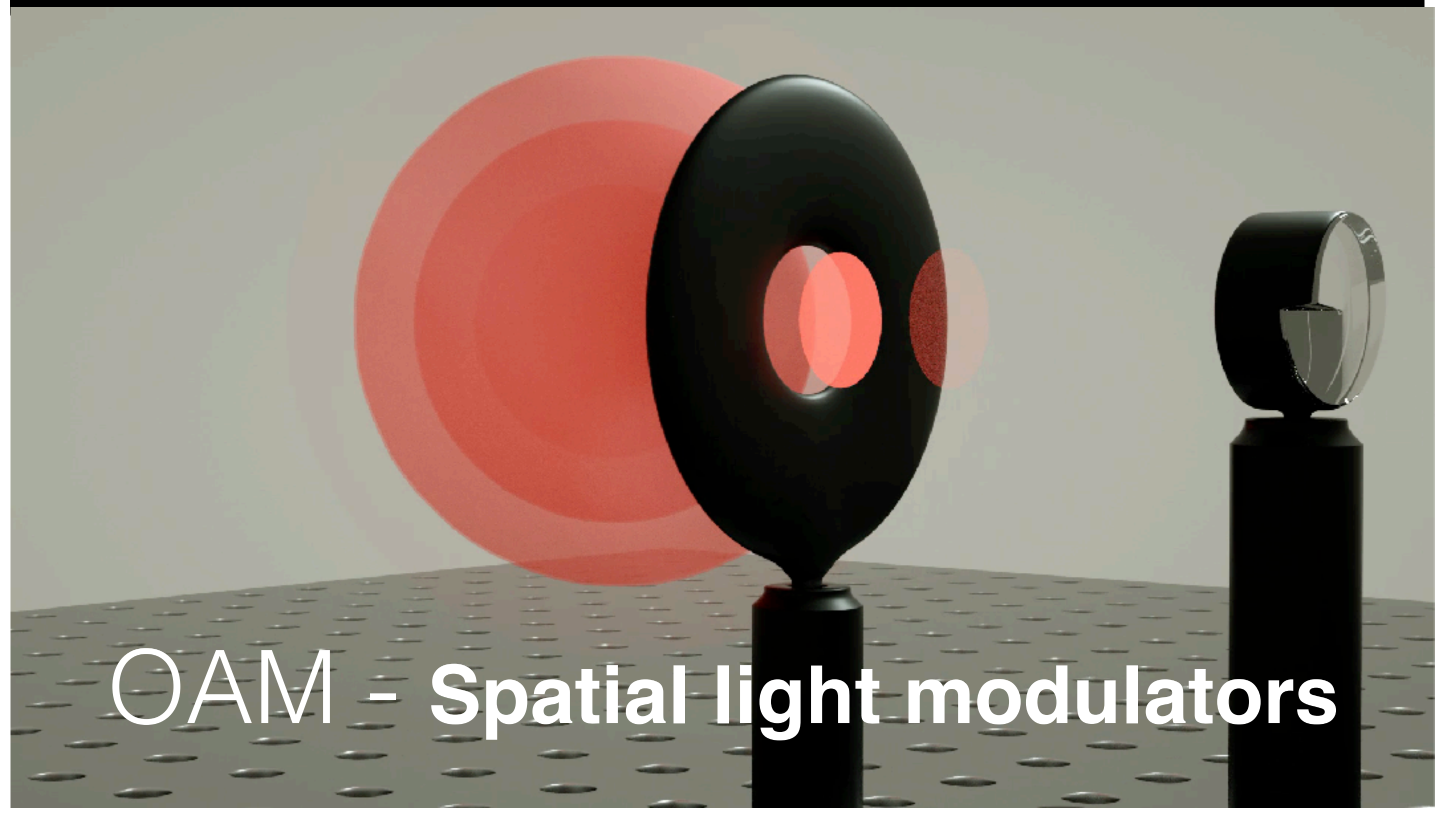


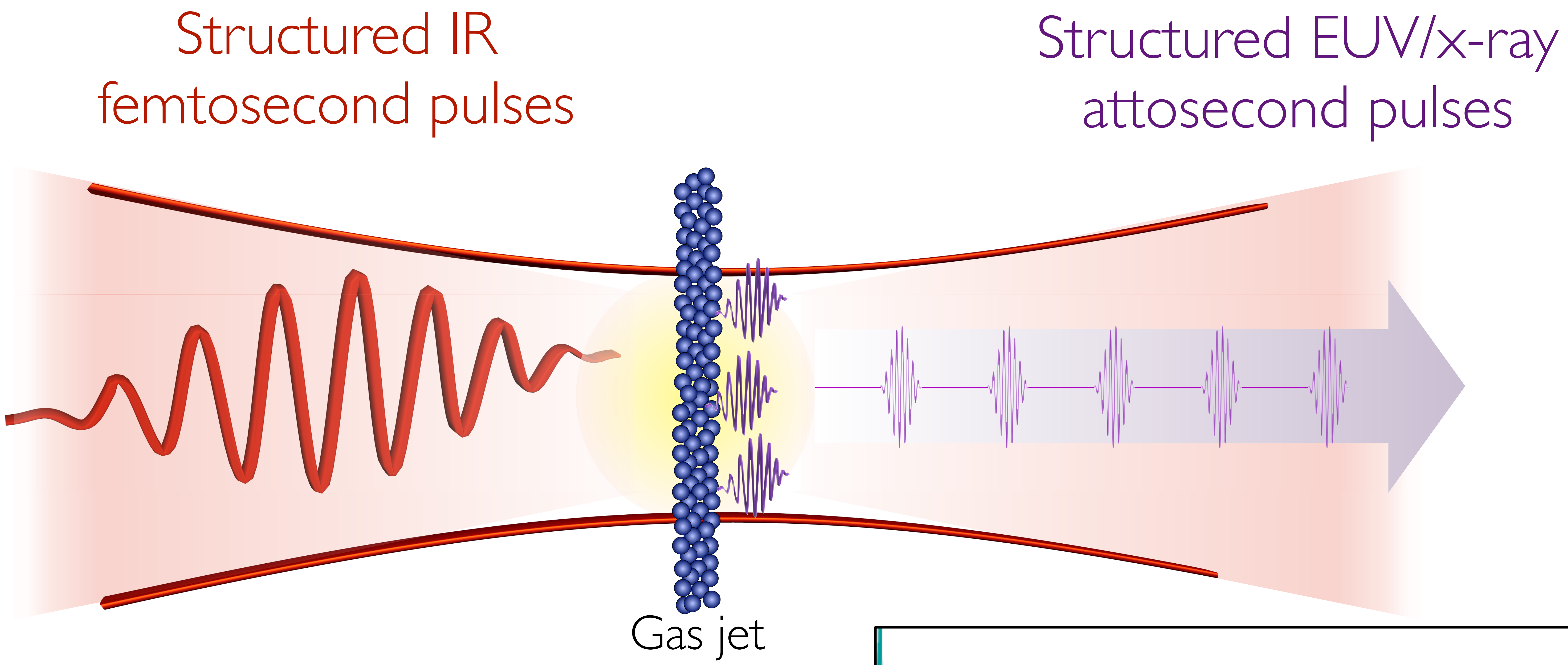


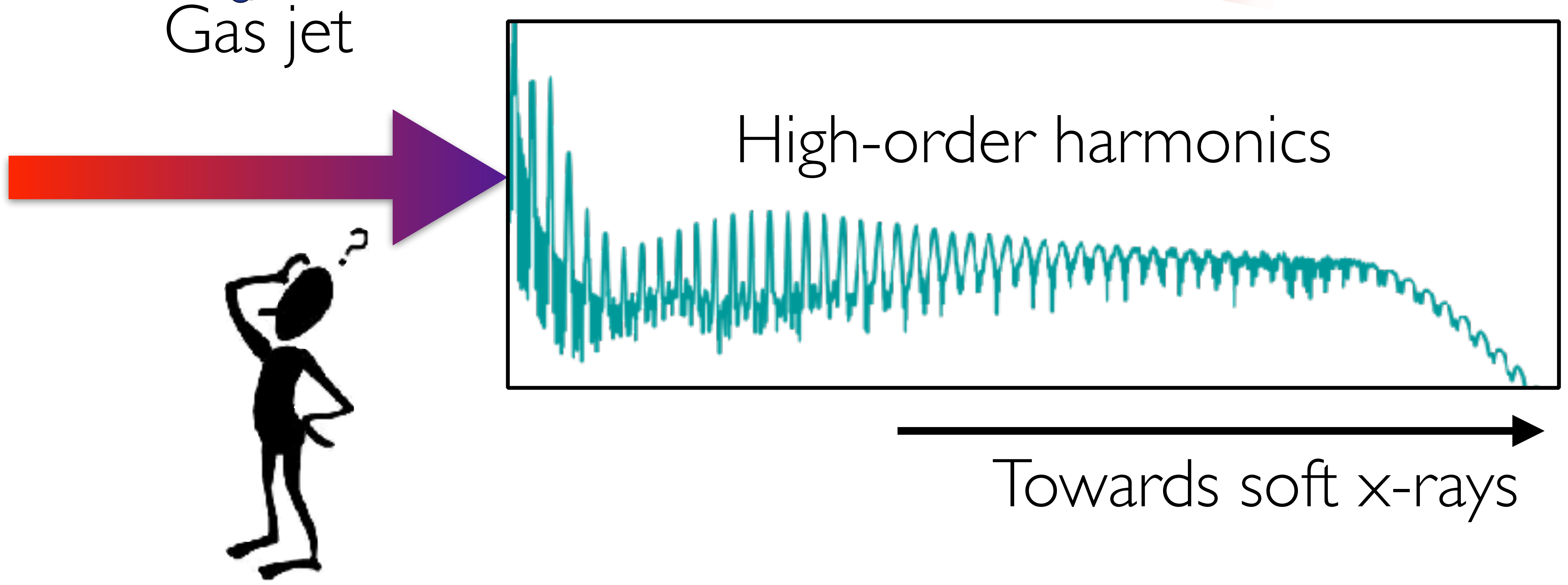


Our approach: highly nonlinear optics

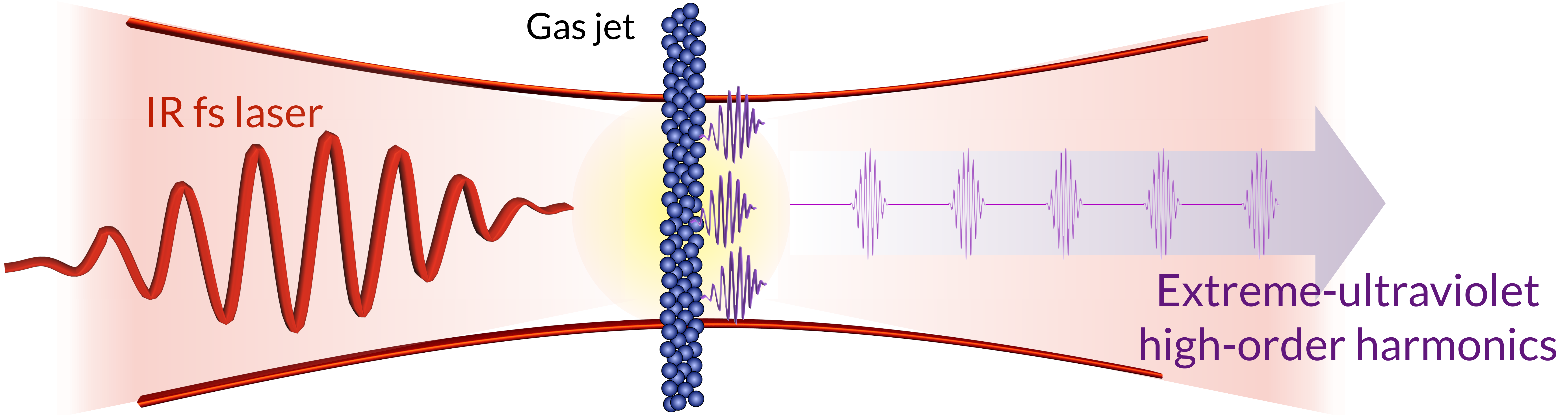




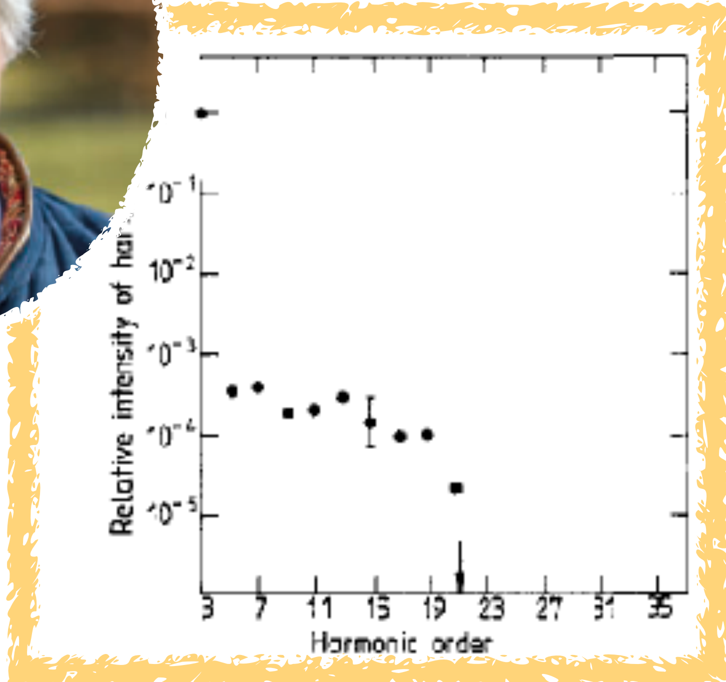


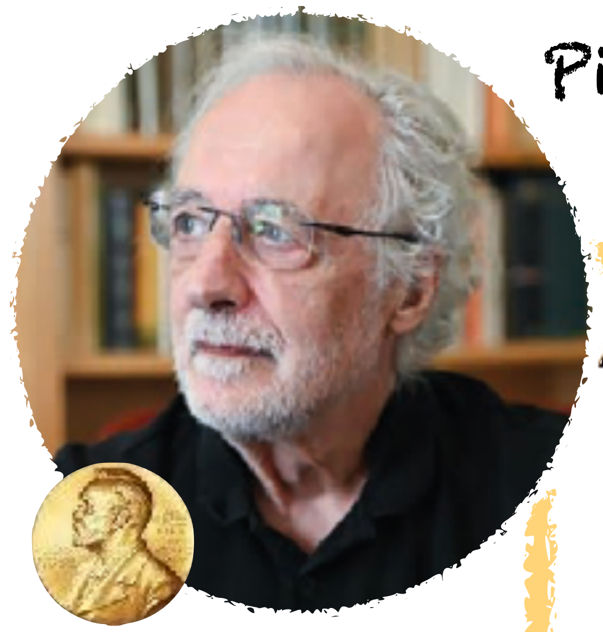


Attosecond pulses and high harmonic generation (HHG)

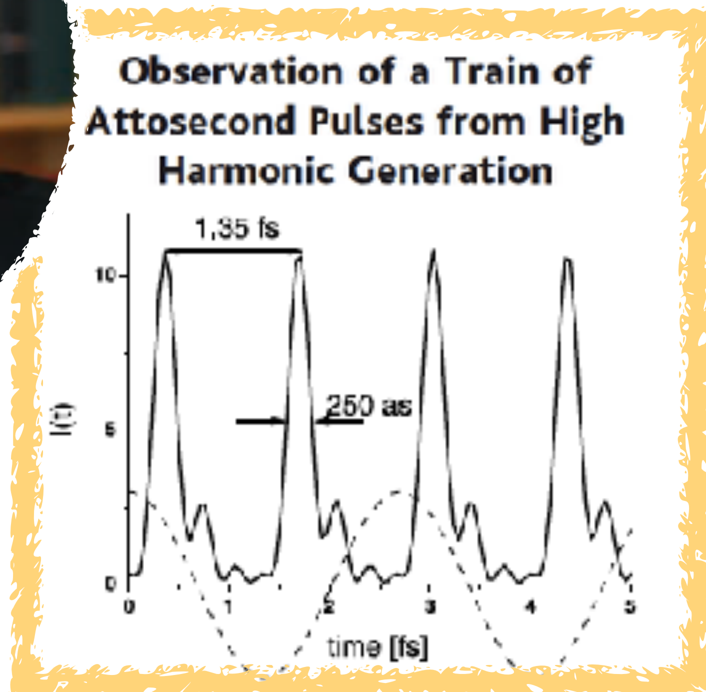


Anne L'Huillier

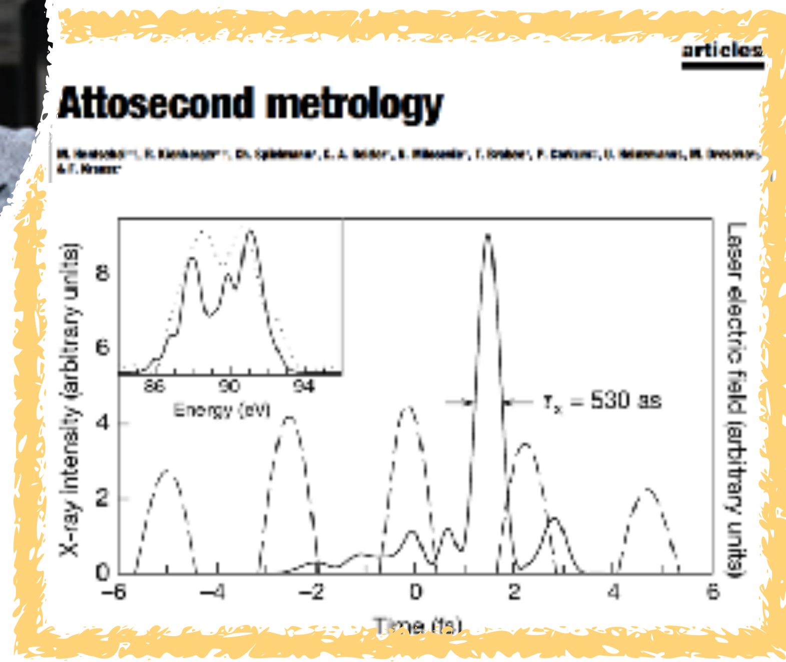


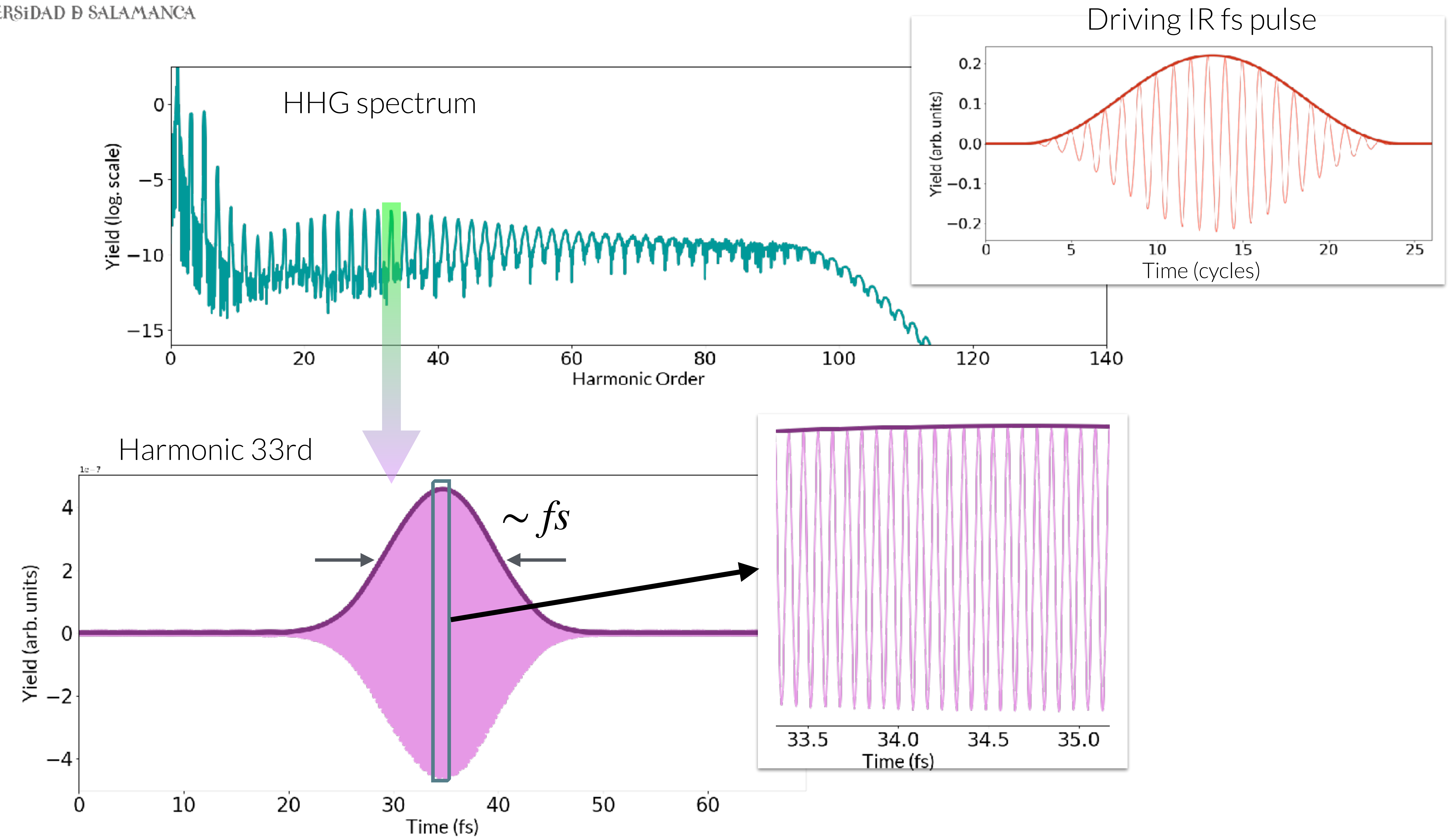


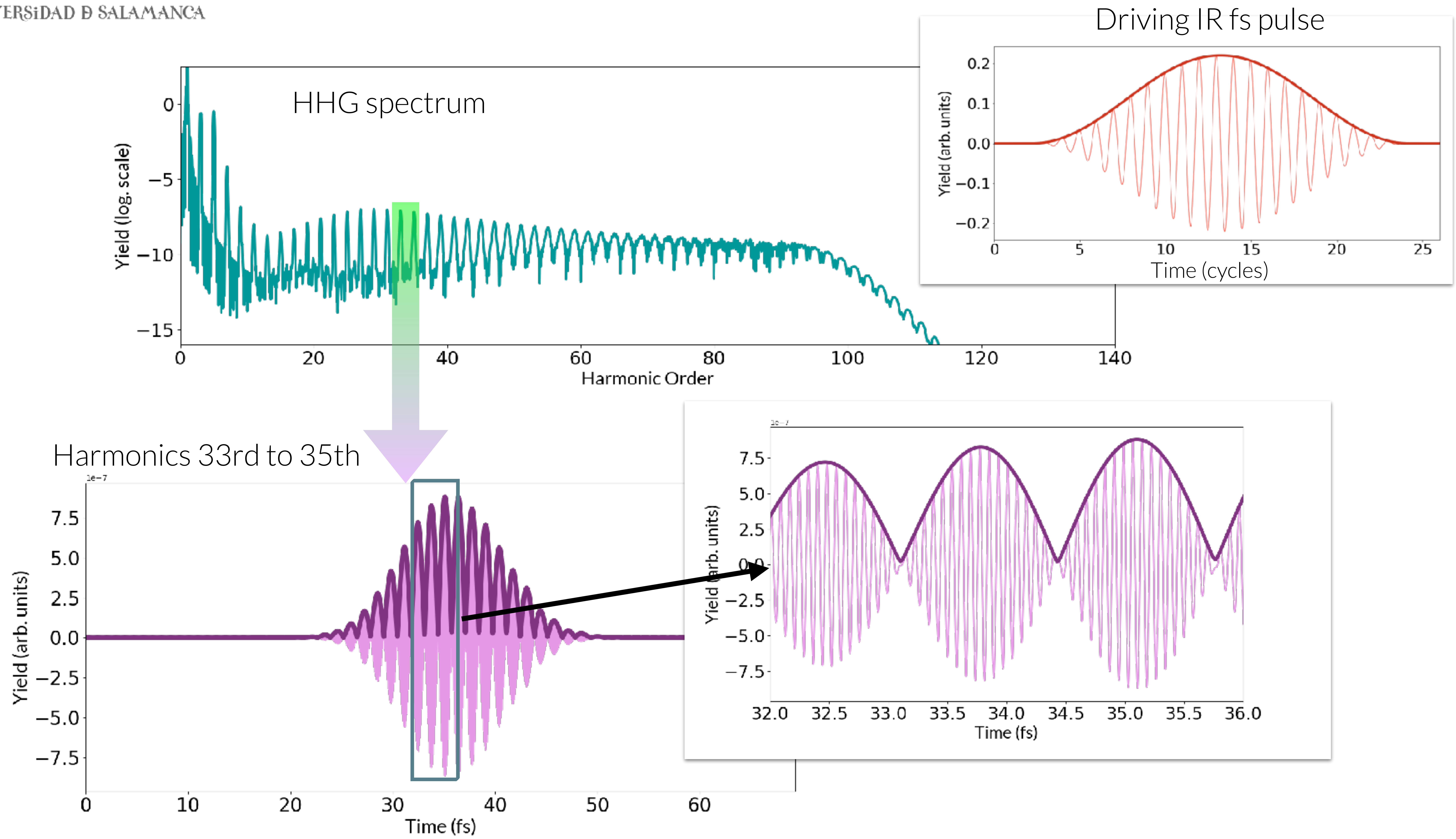
Pierre Agostini

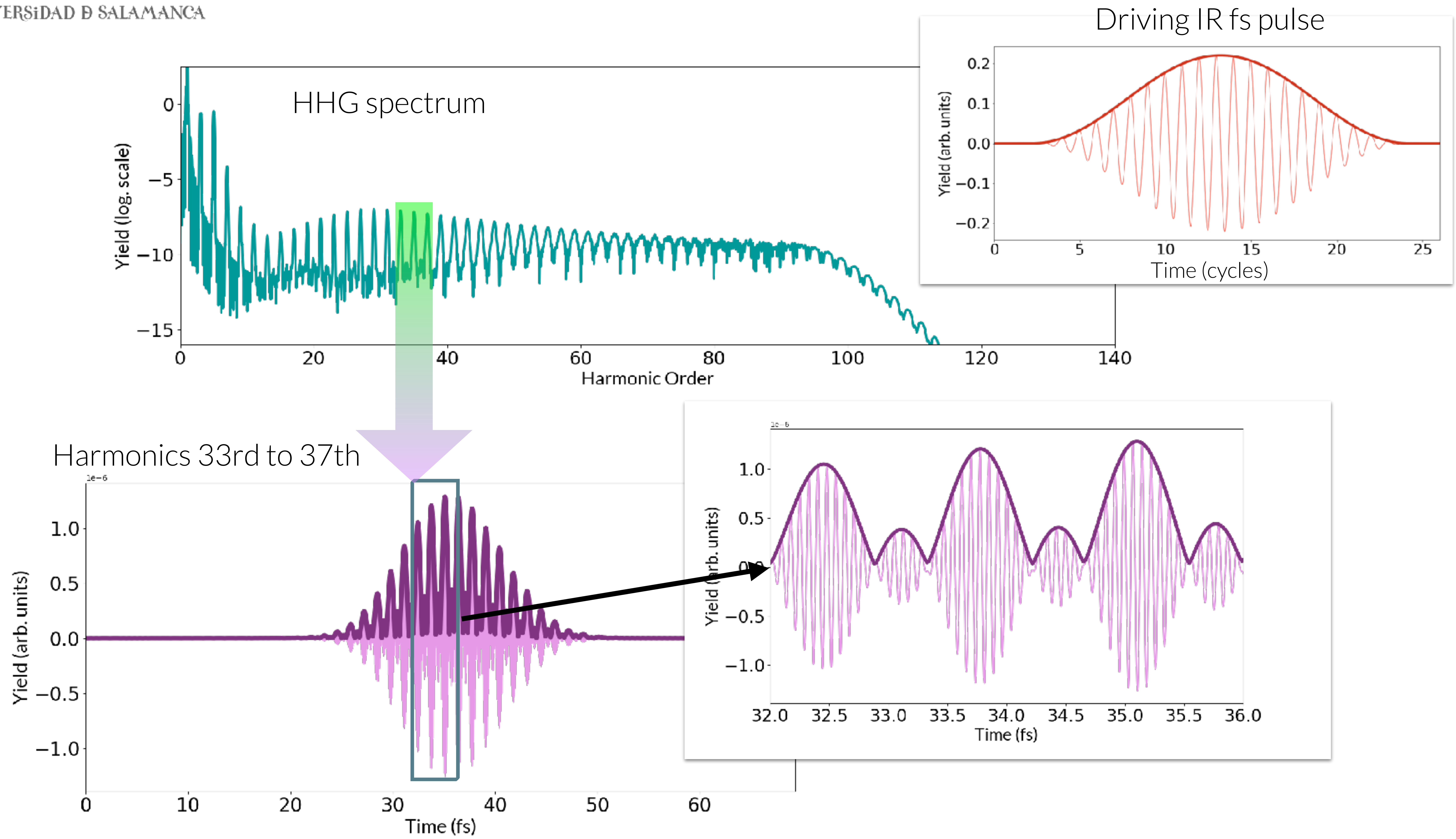


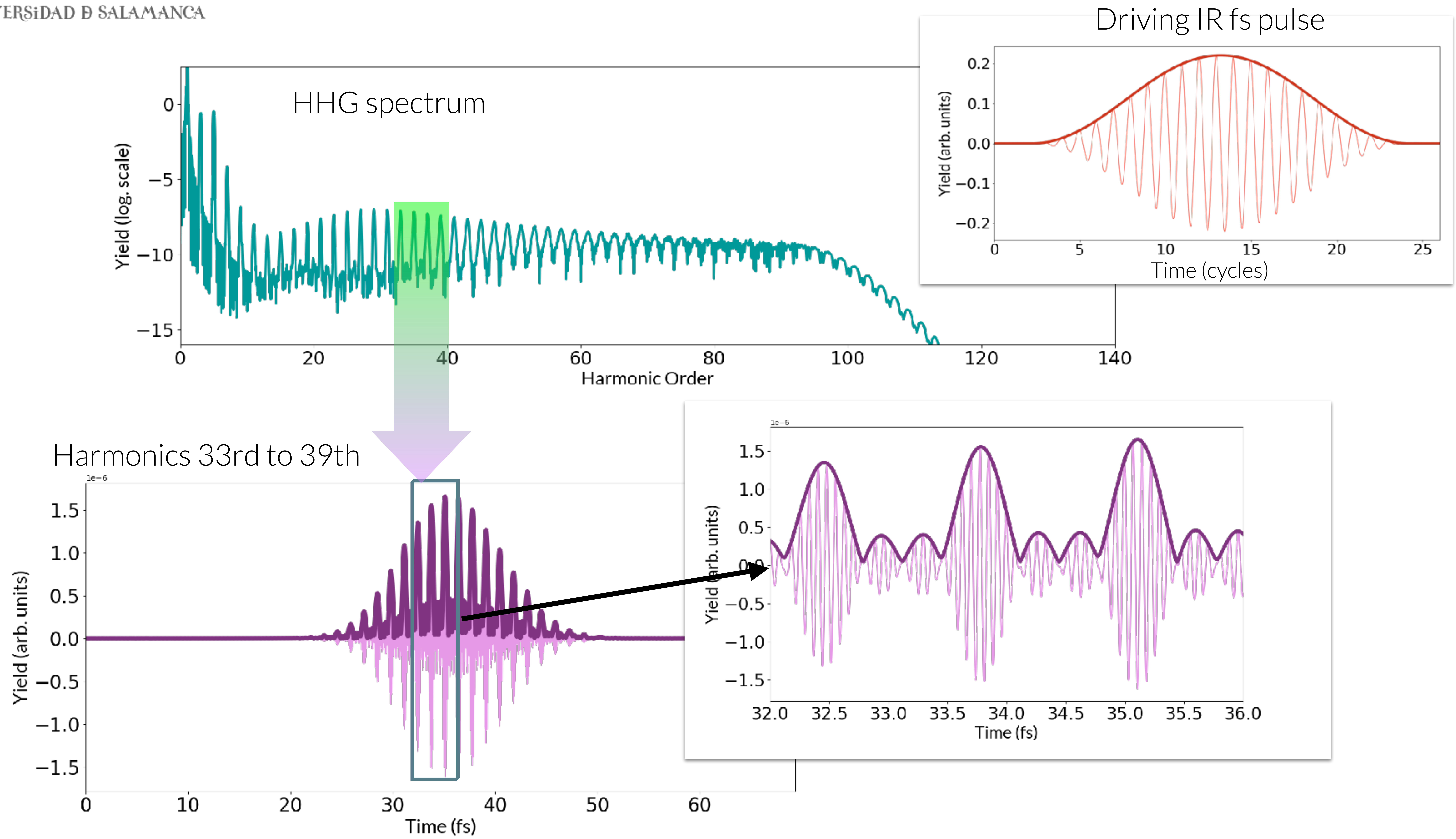
Ferencz Krausz



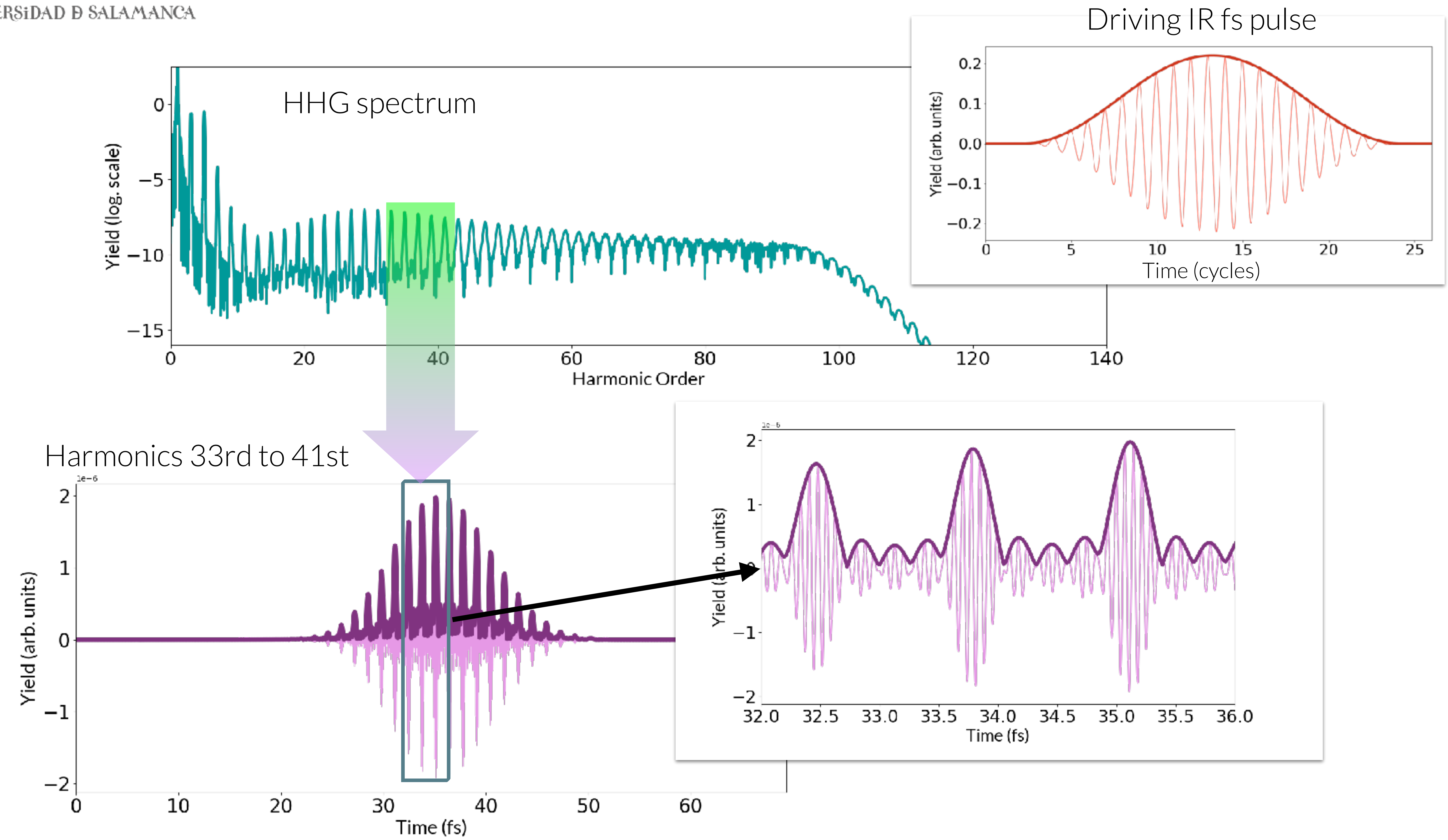

HHG spectrum
Yield (log. scale)
0
−5
−10
−15
0
20
40
60
80
100
120
140
Harmonic Order
Driving IR fs pulse
Yield (arb. units)
0.2
0.1
0.0
−0.1
−0.2
0
5
10
15
20
25
Time (cycles)
Harmonic 33rd
1e−7
4
2
0
−2
−4
Yield (arb. units)
0
10
20
30
40
50
60
Time (fs)
~ fs
33.5
34.0
34.5
35.0
Time (fs)

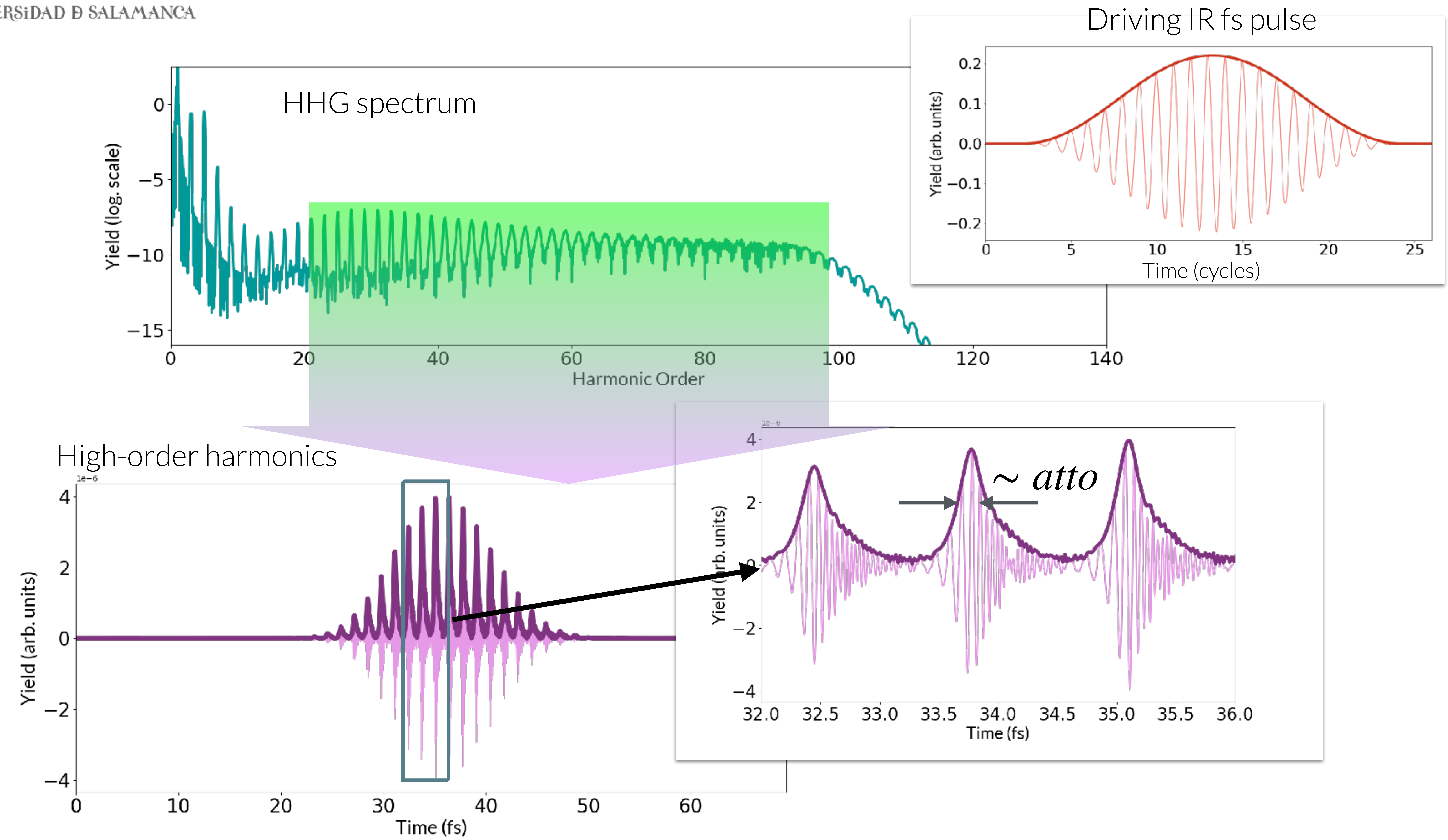

HHG spectrum
Yield (log. scale)
0
−5
−10
−15
0
20
40
60
80
100
120
140
Harmonic Order
Driving IR fs pulse
0.2
0.1
0.0
−0.1
−0.2
Yield (arb. units)
0
5
10
15
20
25
Time (cycles)
Harmonics 33rd to 35th
1e−7
7.5
5.0
2.5
0.0
−2.5
−5.0
−7.5
Yield (arb. units)
0
10
20
30
40
50
60
Time (fs)
32.0
32.5
33.0
33.5
34.0
34.5
35.0
35.5
36.0
Time (fs)


HHG spectrum
Yield (log. scale)
0
−5
−10
−15
0
20
40
60
80
100
120
140
Harmonic Order
Driving IR fs pulse
Yield (arb. units)
0.2
0.1
0.0
−0.1
−0.2
0
5
10
15
20
25
Time (cycles)
Harmonics 33rd to 37th
1e−6
Yield (arb. units)
1.0
0.5
0.0
−0.5
−1.0
0
10
20
30
40
50
60
Time (fs)
1e−6
1.0
0.5
−0.5
−1.0
32.0
32.5
33.0
33.5
34.0
34.5
35.0
35.5
36.0
Time (fs)



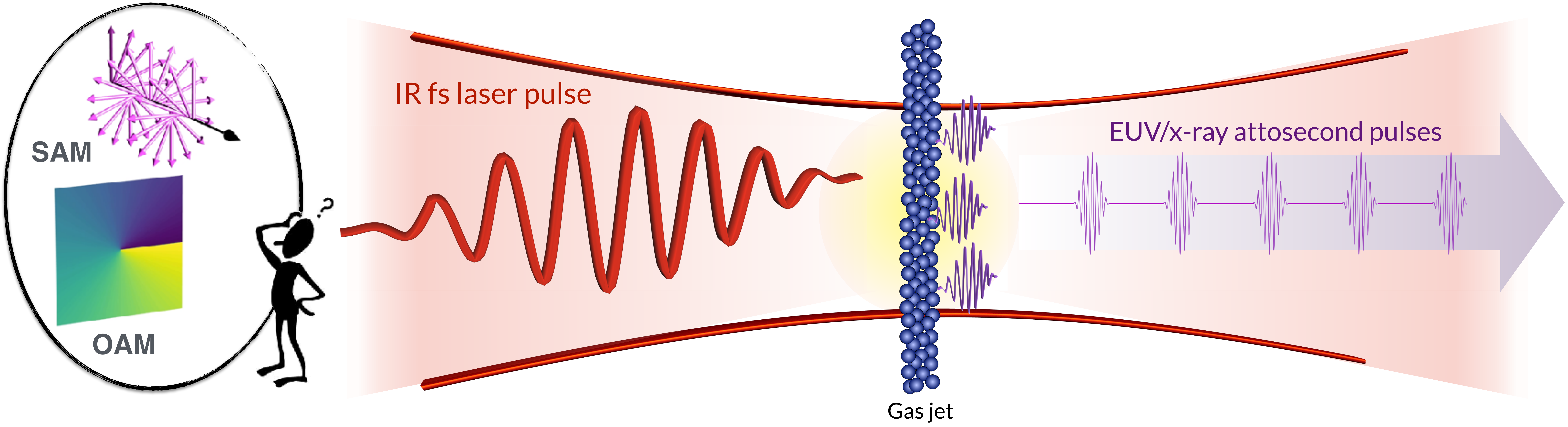
Driving IR fs pulse
Yield (arb. units)
Time (cycles)
HHG spectrum
Yield (log. scale)
Harmonic Order
Harmonics 33rd to 39th
Yield (arb. units)
Time (fs)
Yield (arb. units)
Time (fs)


HHG spectrum
Yield (log. scale)
Harmonic Order
0
−5
−10
−15
0
20
40
60
80
100
120
140
Driving IR fs pulse
Yield (arb. units)
Time (cycles)
0.2
0.1
0.0
−0.1
−0.2
0
5
10
15
20
25
Harmonics 33rd to 41st
1e−6
Yield (arb. units)
Time (fs)
2
1
0
−1
−2
0
10
20
30
40
50
60
1e−6
Yield (arb. units)
Time (fs)
32.0
32.5
33.0
33.5
34.0
34.5
35.0
35.5
36.0



Driving IR fs pulse
Yield (arb. units)
0.2
0.1
0.0
−0.1
−0.2
0
5
10
15
20
25
Time (cycles)
HHG spectrum
Yield (log. scale)
0
−5
−10
−15
0
20
40
60
80
100
120
140
Harmonic Order
High-order harmonics
1e−6
4
2
0
−2
−4
Yield (arb. units)
0
10
20
30
40
50
60
Time (fs)
~ atto
32.0
32.5
33.0
33.5
34.0
34.5
35.0
35.5
36.0
Time (fs)

More than a decade of angular momentum transfer in HHG



Circularly polarized high harmonics

First experiments:

Fleischer, et al. Nat. Photon. 8, 543–549 (2014).
O. Kfir, et al. Nat. Photonics 9, 99–105 (2015).

Previous theory works:

H. Eichmann, et al. Phys. Rev. A, 51, R3414 (1995).
S. Long, et al. Phys. Rev. A 52 2262 (1995).
D. Milosevic, et al. Phys. Rev. A 61 063403 (2000).

High harmonic vortices

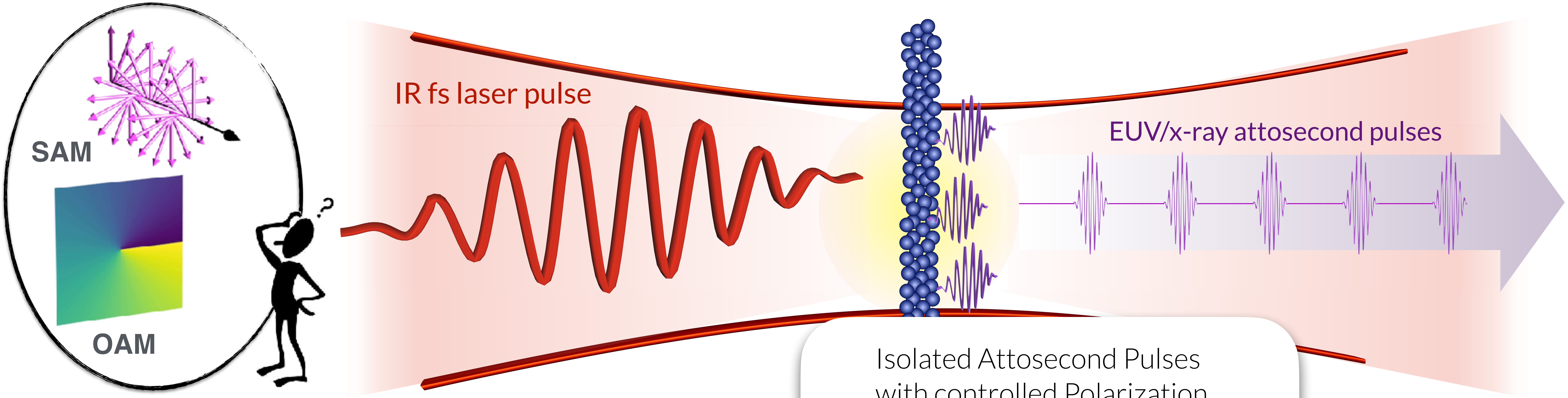
First experiment:

M. Zürch, C. Kern, P. Hansinger, A. Dreischuh, Ch. Spielmann, Nature Phys. 8, 743 (2012).

Understanding picture:

C. Hernández-García, A. Picón, J. San Román, L. Plaja, PRL 111, 083602 (2013).

More than a decade of angular momentum transfer in HHG



Circularly polarized high harmonics

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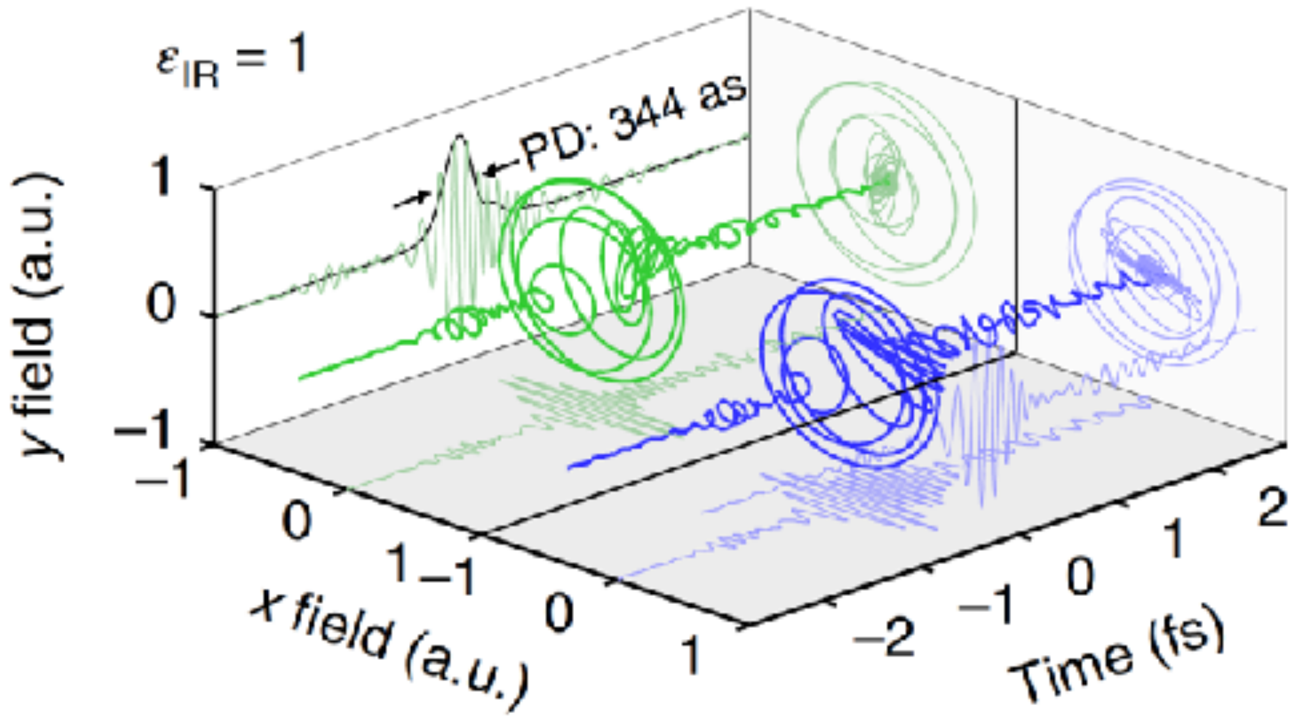
S. Long, et al. Phys. Rev. A 52 2262 (1995).
D. Milosevic, et al. Phys. Rev. A 61 063403 (2000).

Isolated Attosecond Pulses
with controlled Polarization

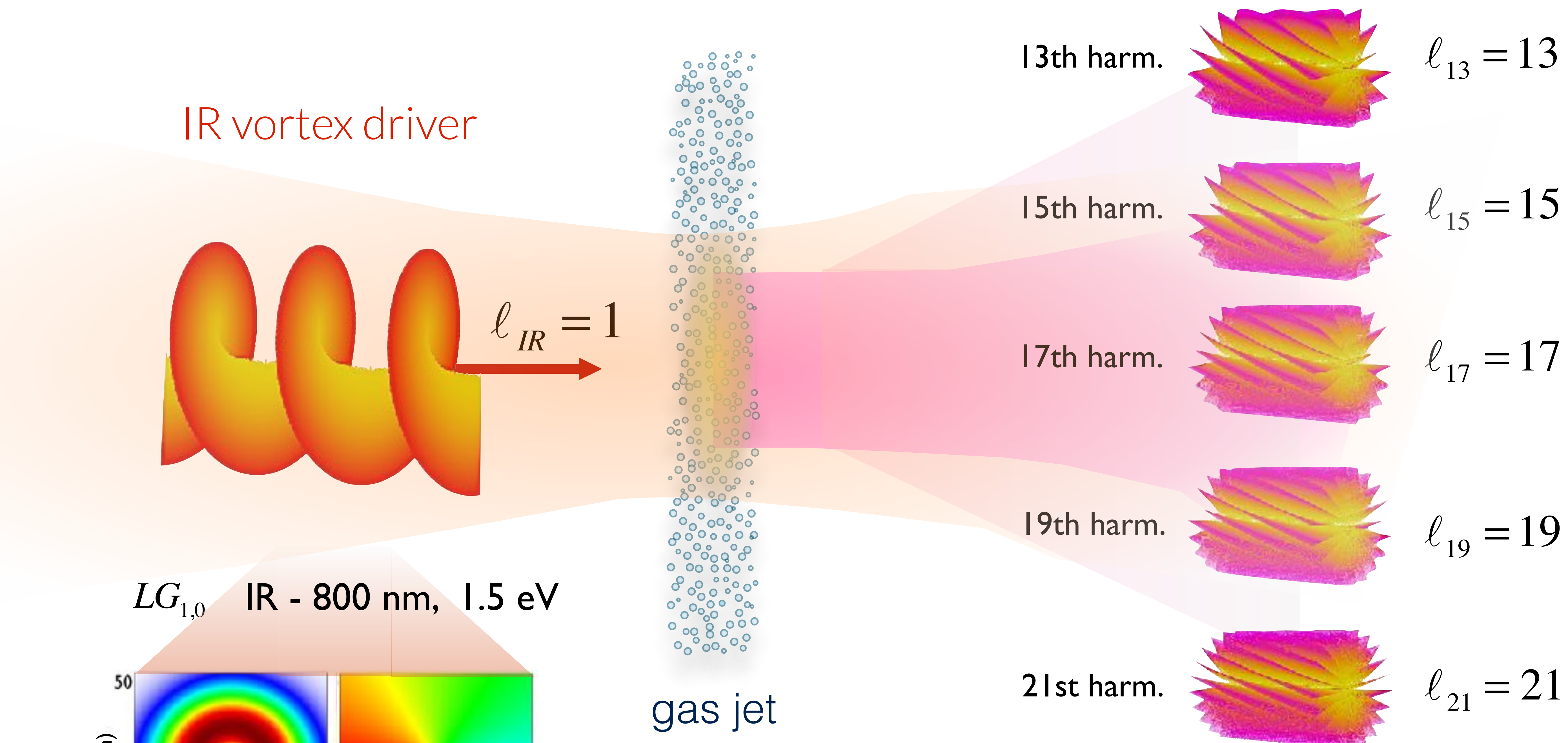


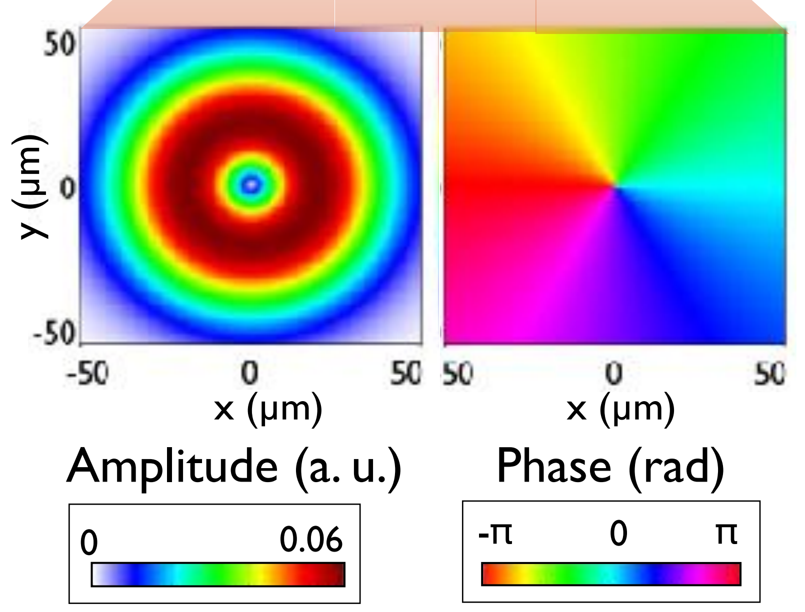
Nature Photonics 12, 349-354 (2018).
Optica 8, 484 (2021).

h, Ch. Spielmann,

n, L. Plaja, PRL 111, 083602 (2013).

Orbital Angular Momentum transfer in HHG



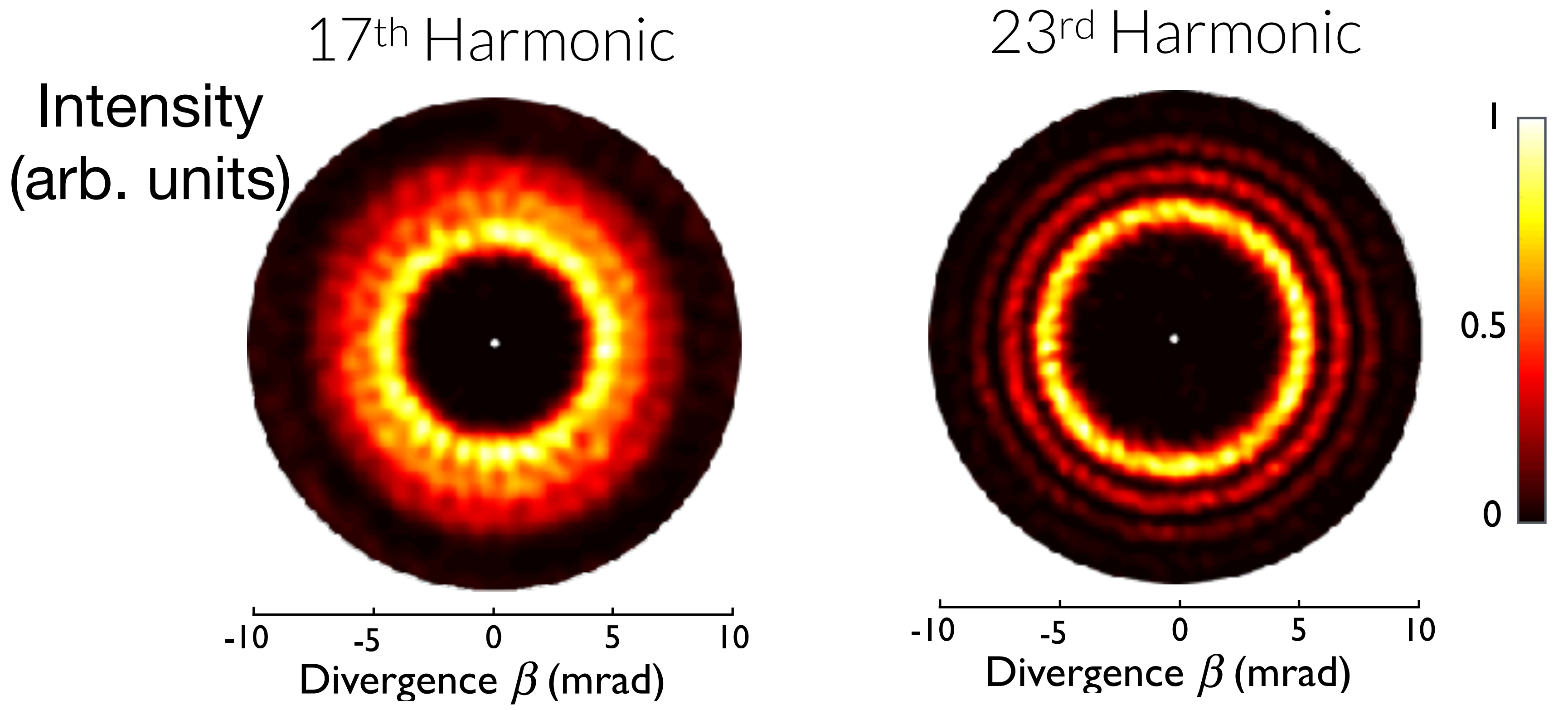


$$\ell_q = q\ell_{IR}$$

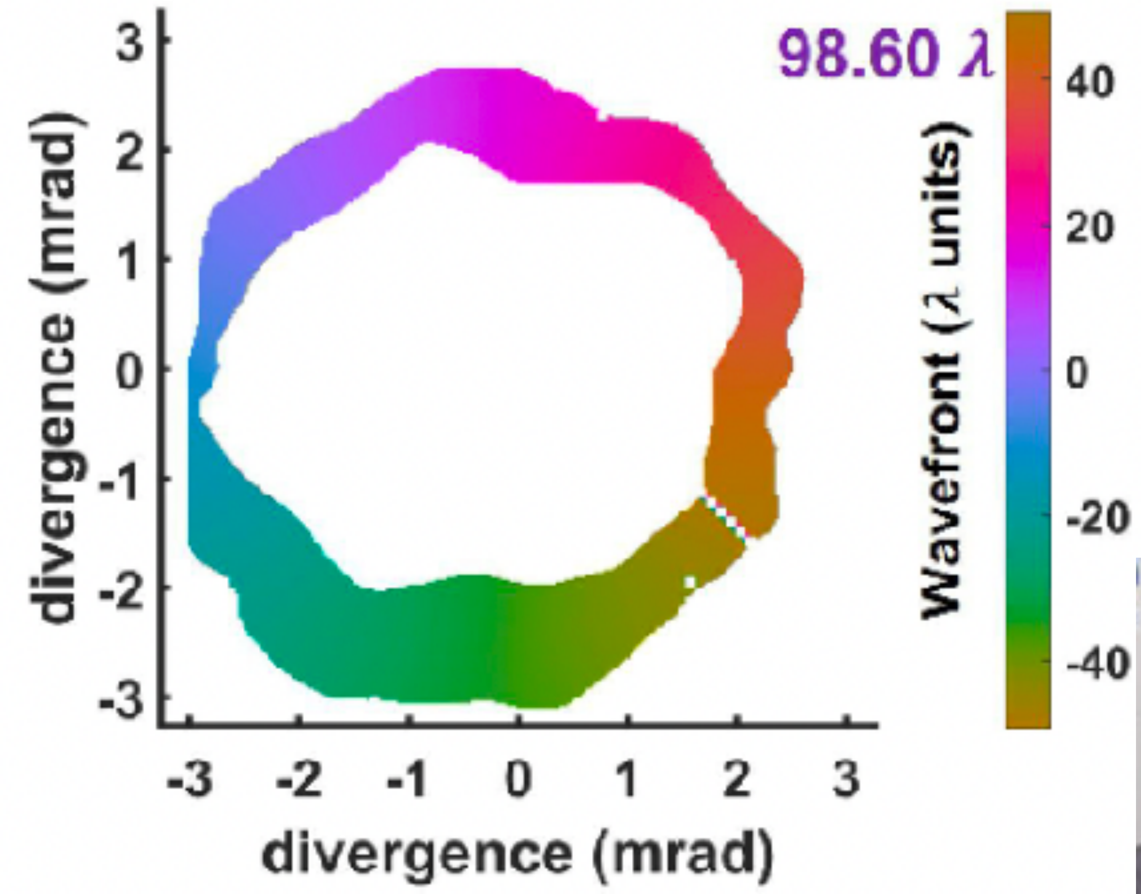
OAM conservation

EUV harmonic vortices

C. Hernández-García, A. Picón, J. San Román, L. Plaja, **Phys. Rev. Lett. 111**, 083602 (2013).



very high OAM



A. Pandey, A. de las Heras, et al.
ACS Photonics 9, 944–951 (2022)

universite PARIS-SACLAY

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Alok K Pandey

Alba de las Heras

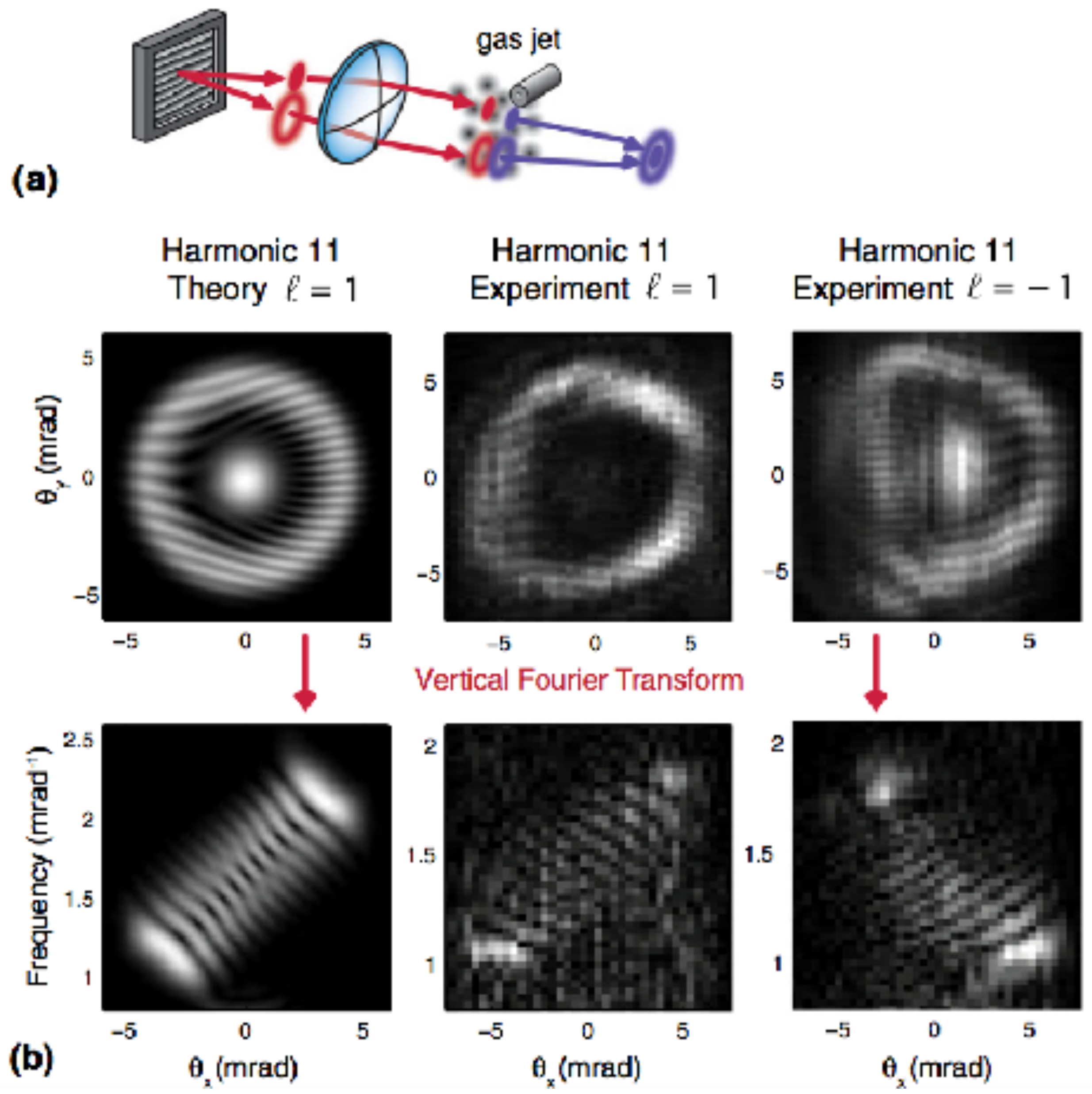
First experiment:

M. Zürch, C. Kern, P. Hansinger, A. Dreischuh, and Ch. Spielmann, **Nature Phys. 8**, 743 (2012).

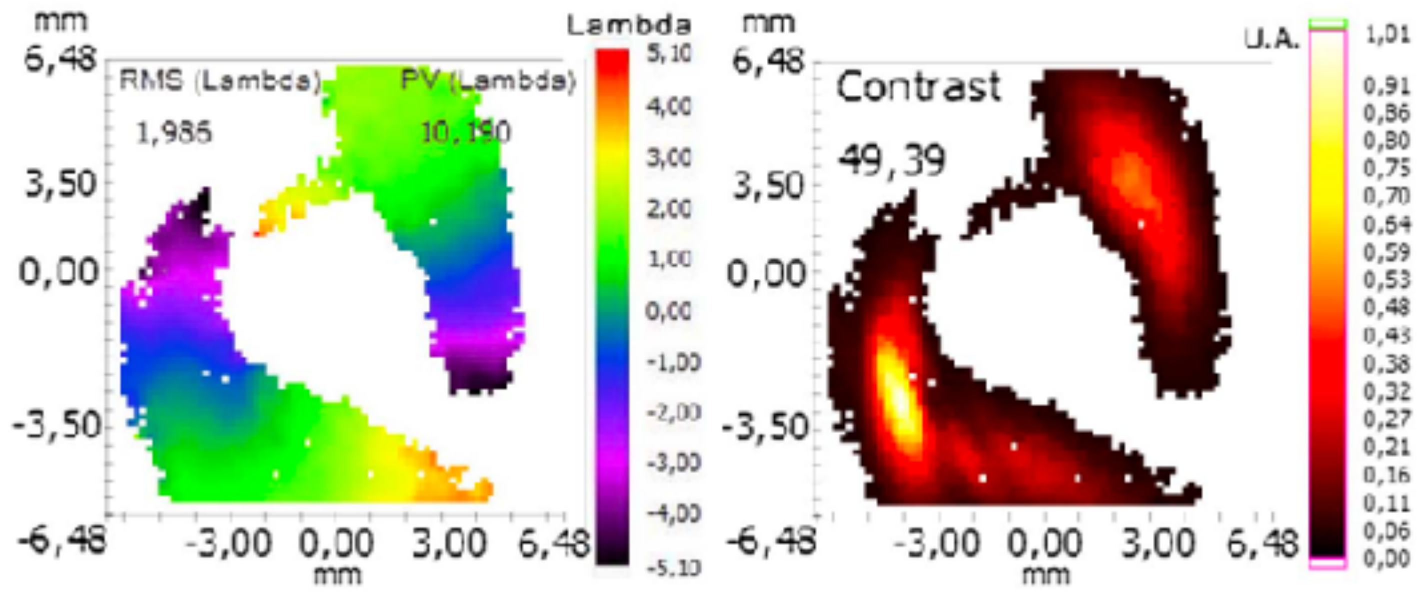
Experimental confirmation:

G. Gariepy, et al. **Phys. Rev. Lett. 113**, 153901 (2014).
R. Géneaux, et al. **Nature Commun. 7**, 12583 (2016).

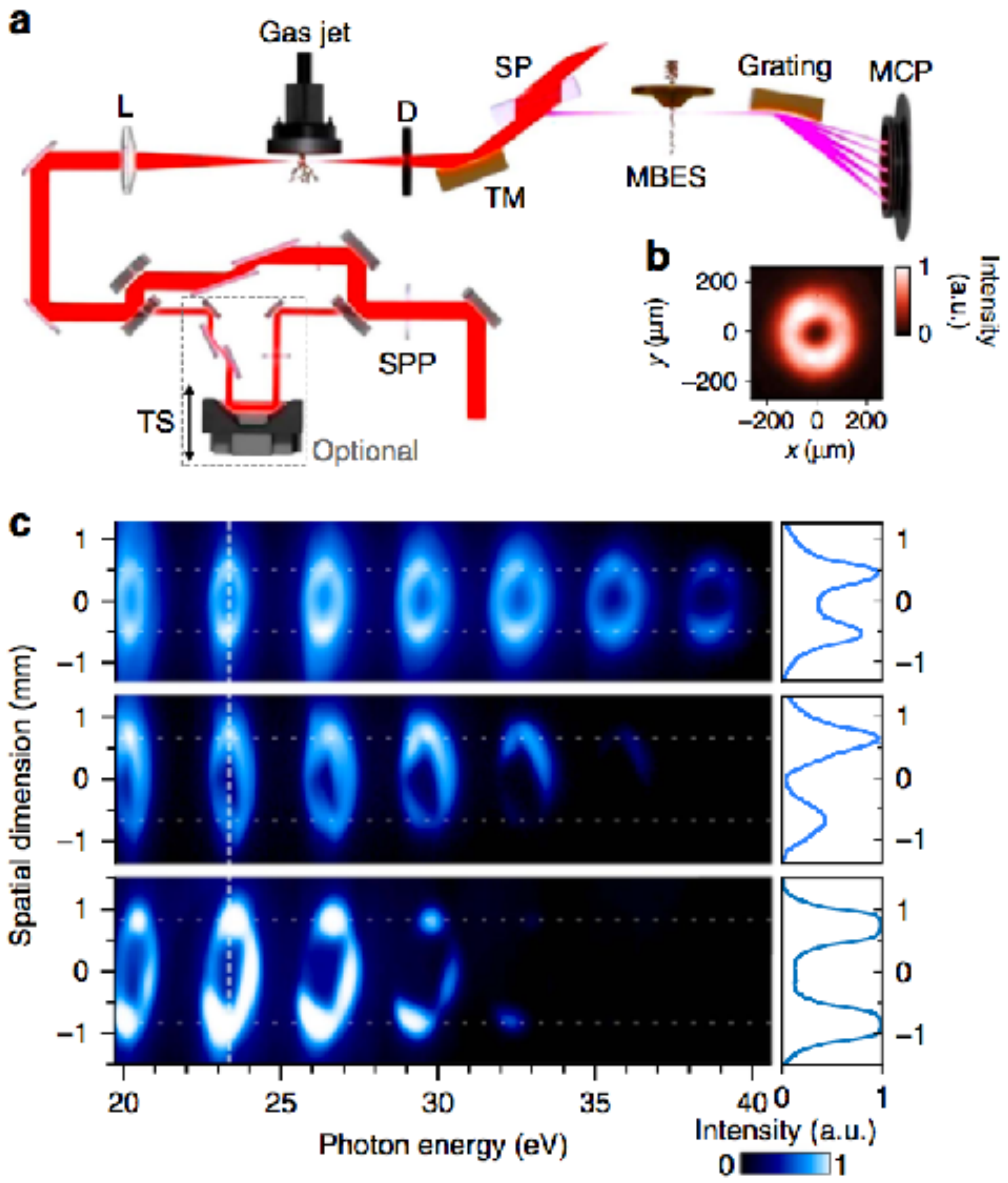
Experimental characterization of EUV harmonic vortices

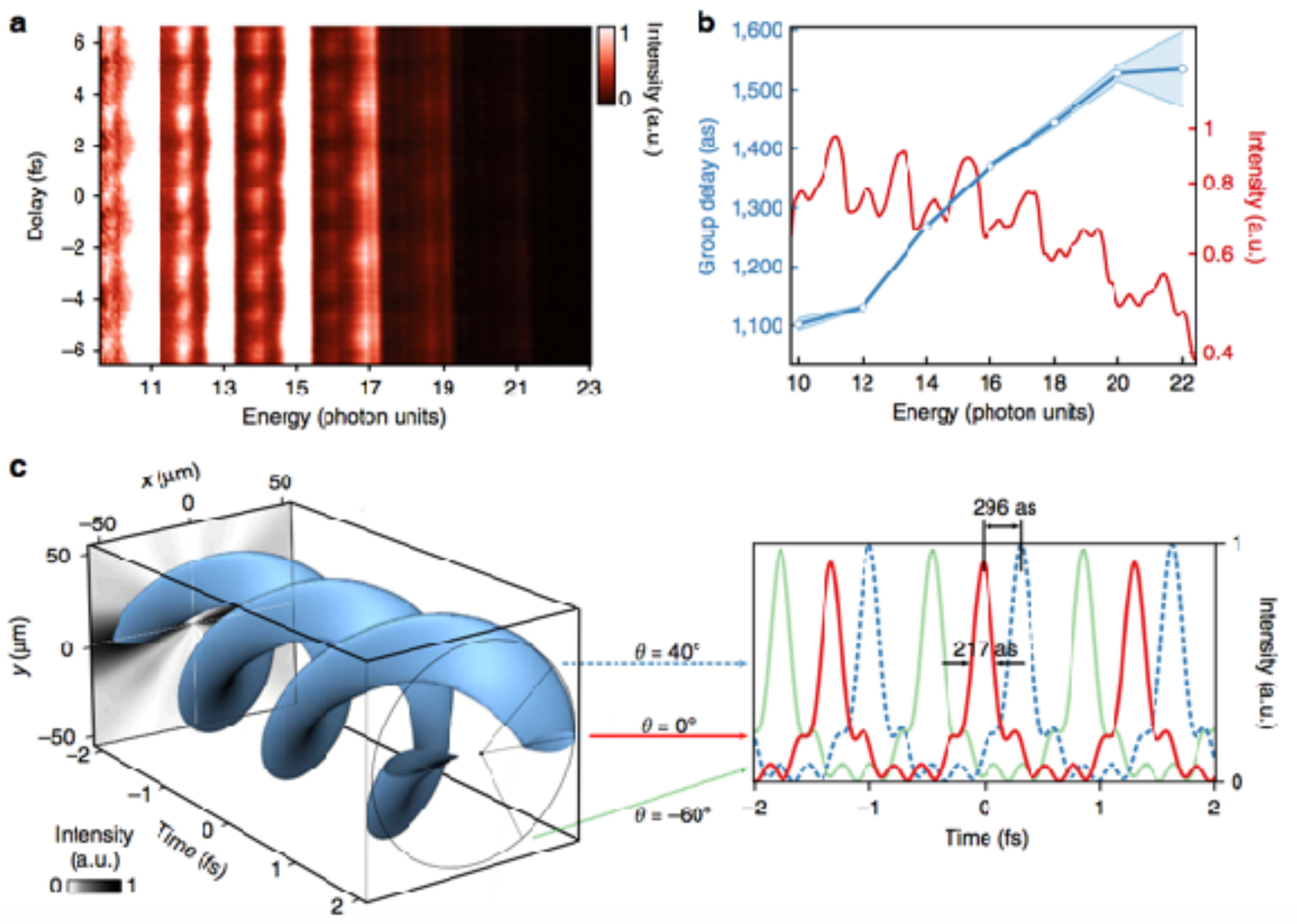


G. Gariepy, J. Leach, K. T. Kim, T. J. Hammond, E. Frumker, R. W. Boyd, and P. B. Corkum, Phys. Rev. Lett. 113, 153901 (2014).

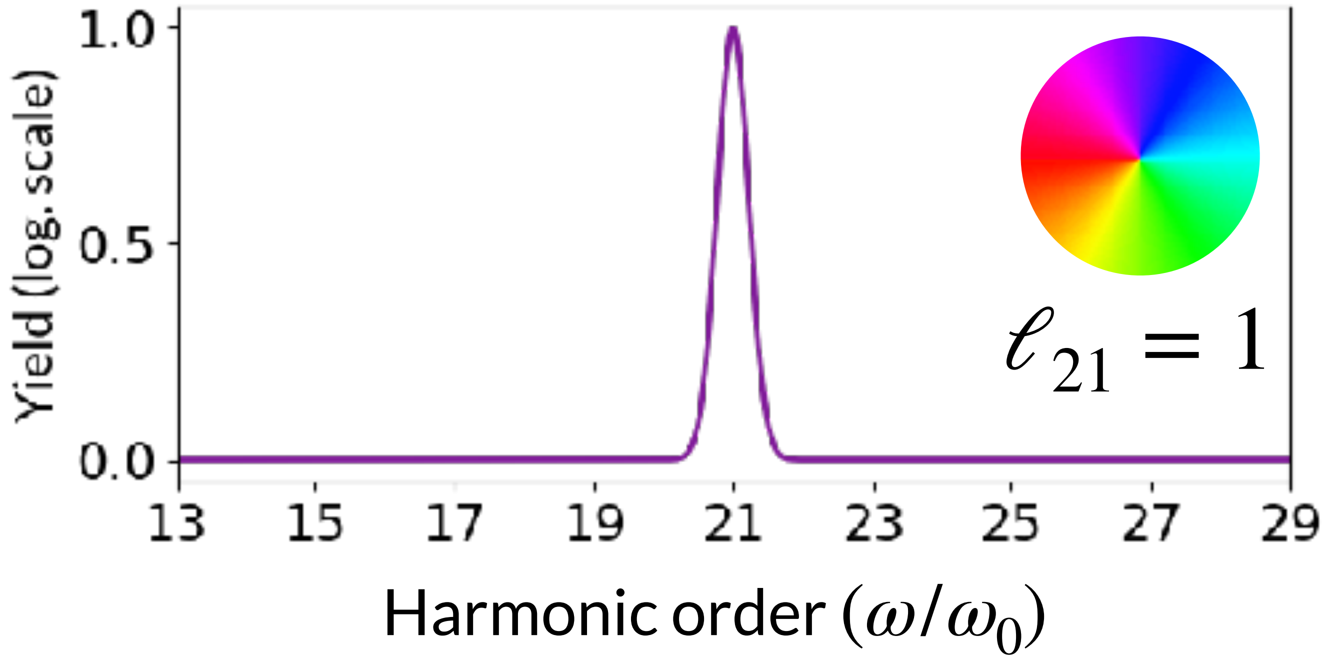


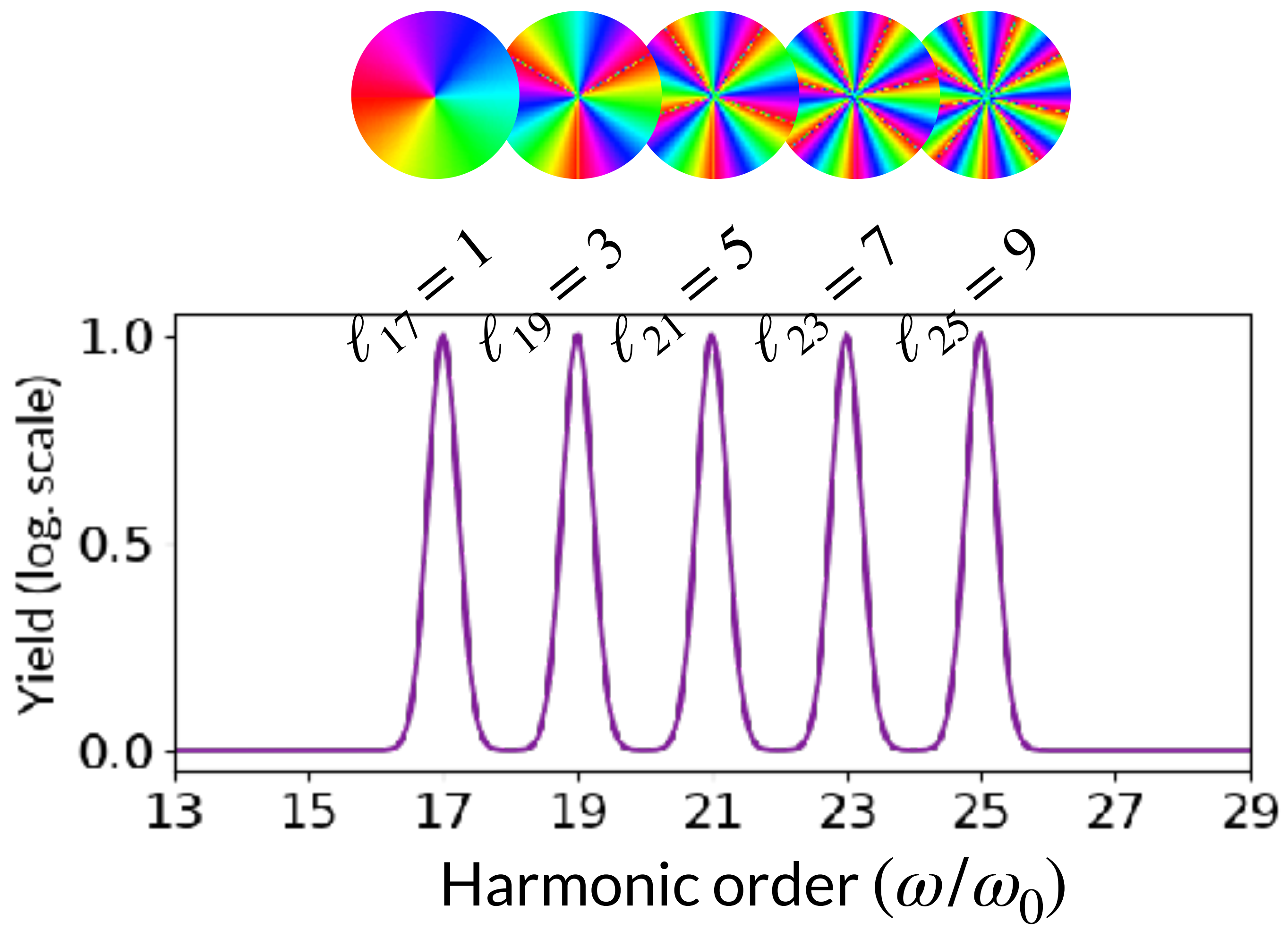
F. Sanson, et al.Optics Letters, 43(12), 2780 (2018).





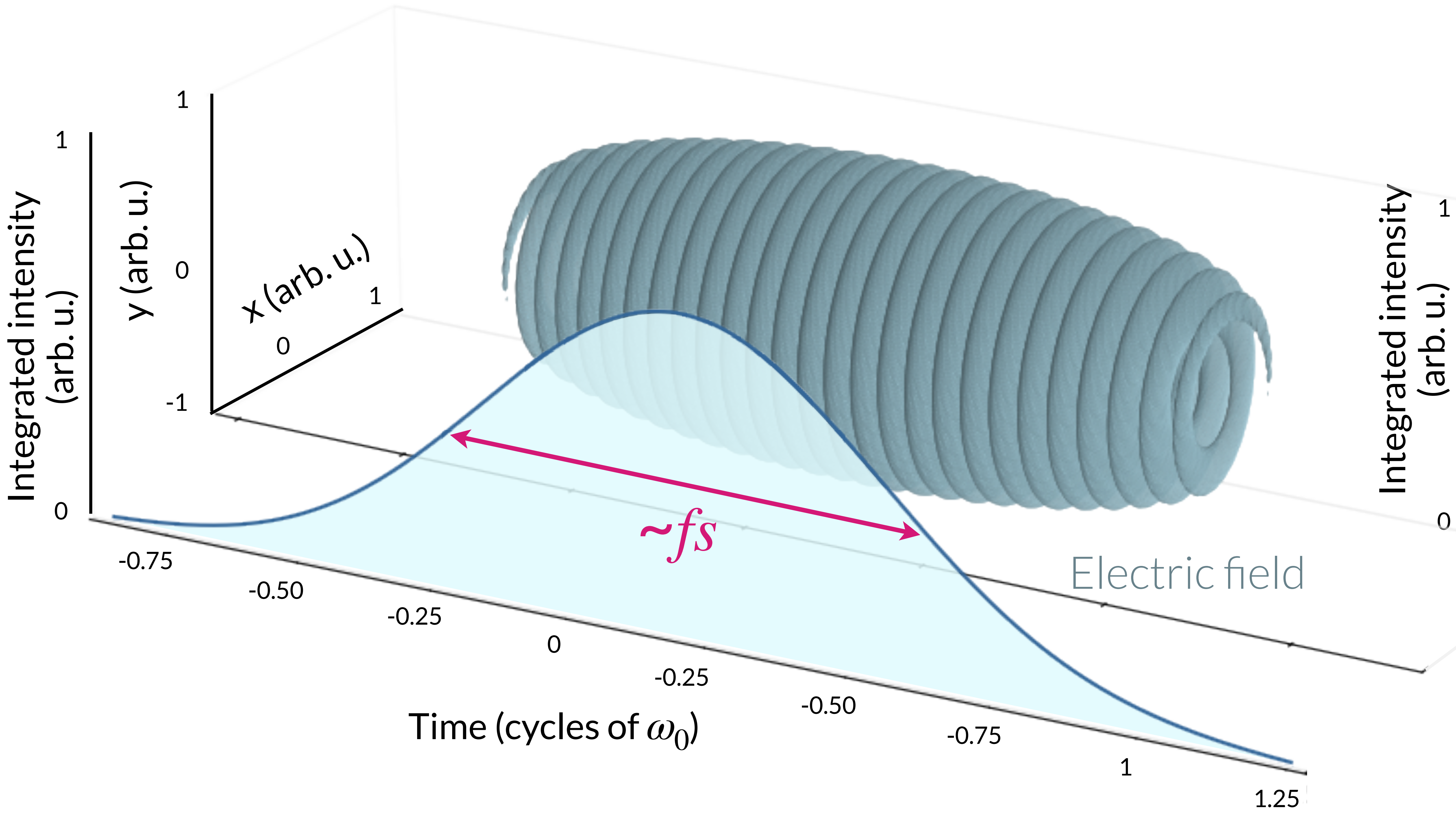
R. Géneaux, A. Camper, T. Auguste, O. Gobert, J. Caillat, R. Taïeb, and T. Ruchon, Nature Commun. 7, 12583 (2016).

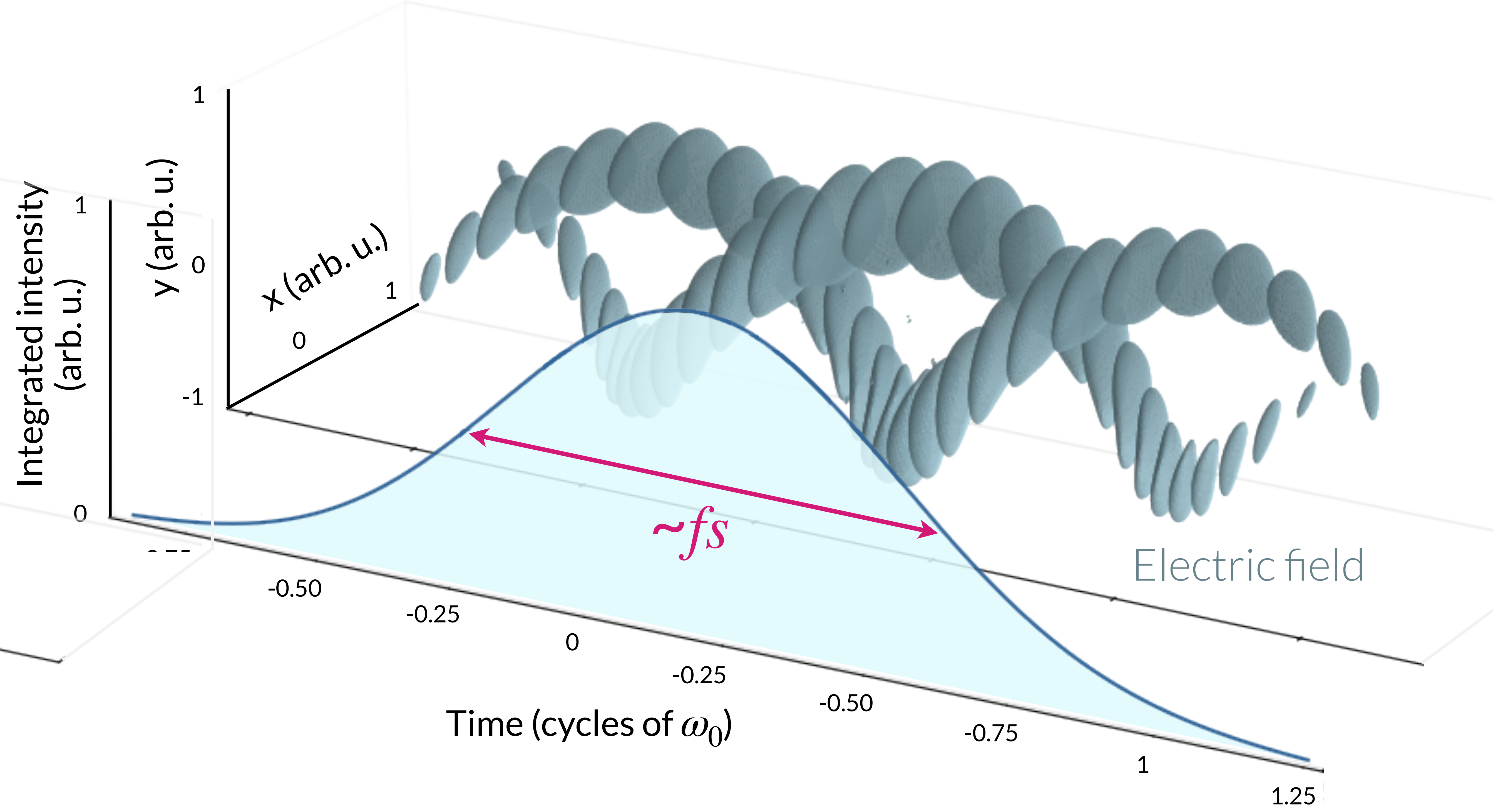




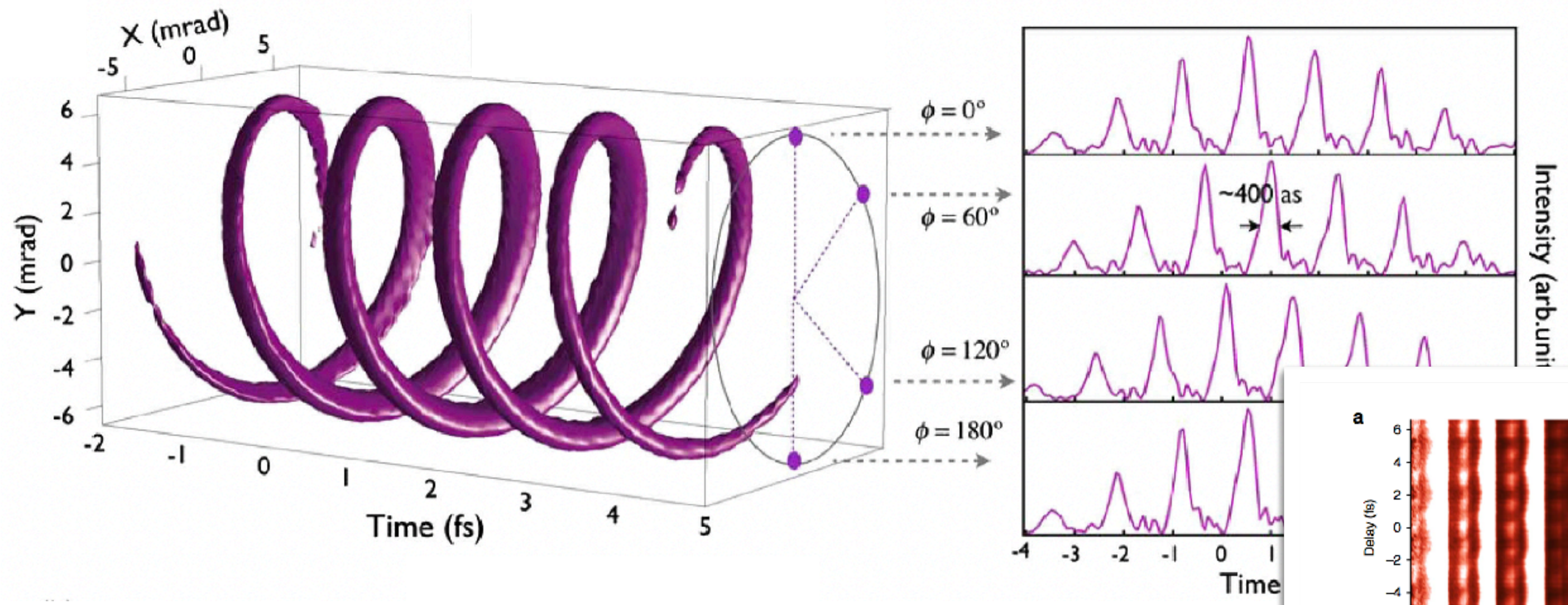
Femtosecond vortex pulse

Attosecond light spring

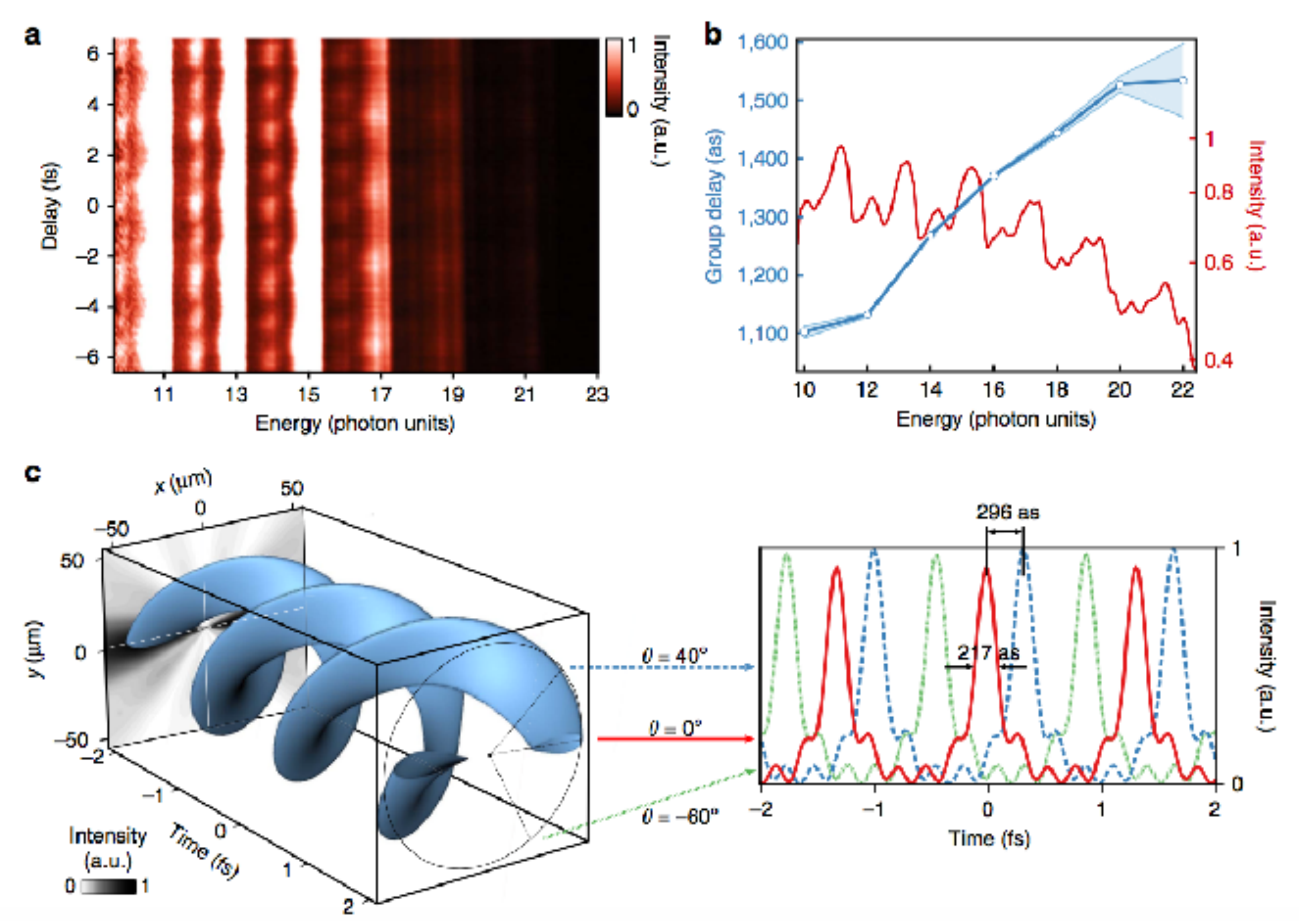




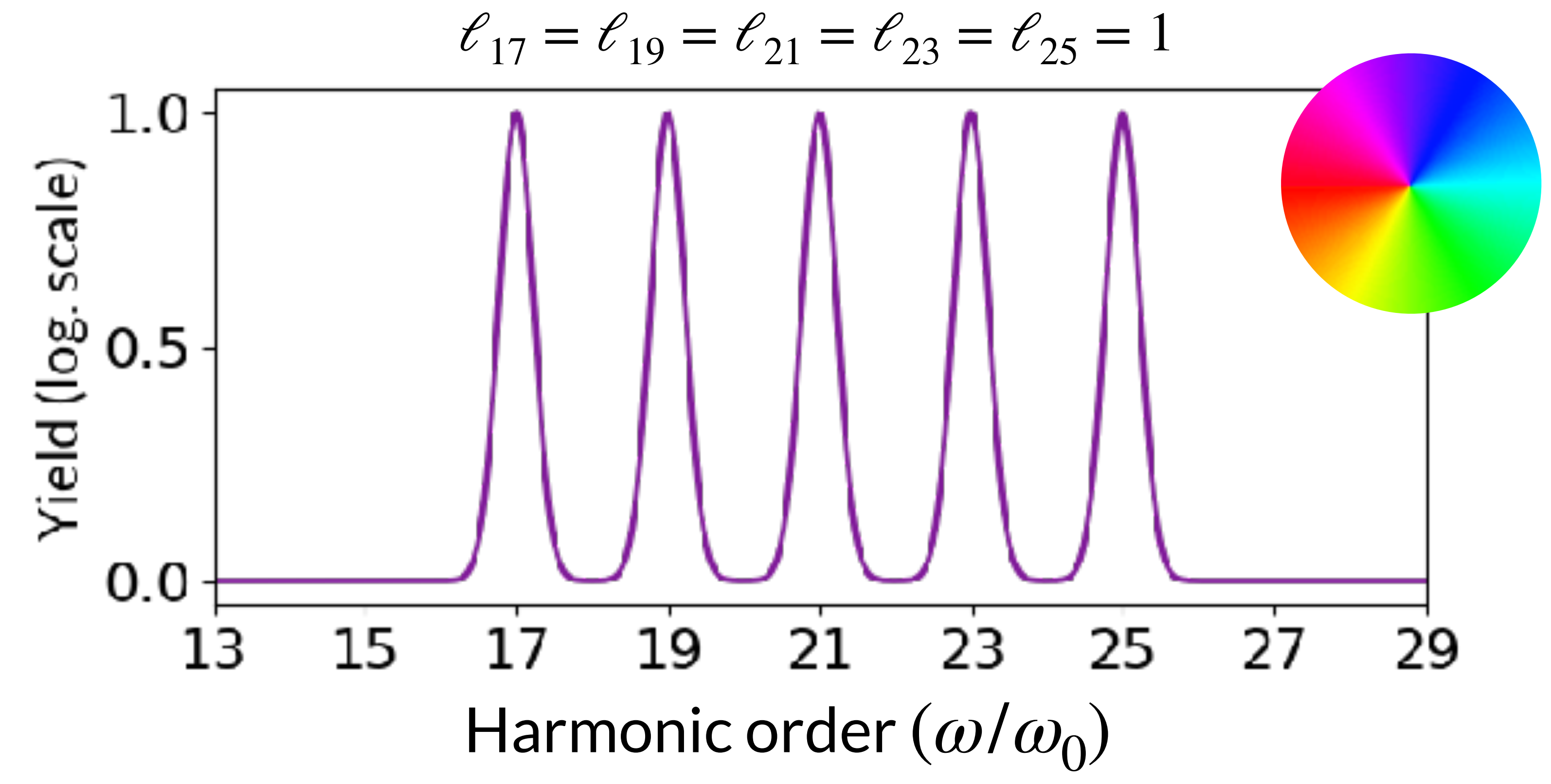
Attosecond light spring



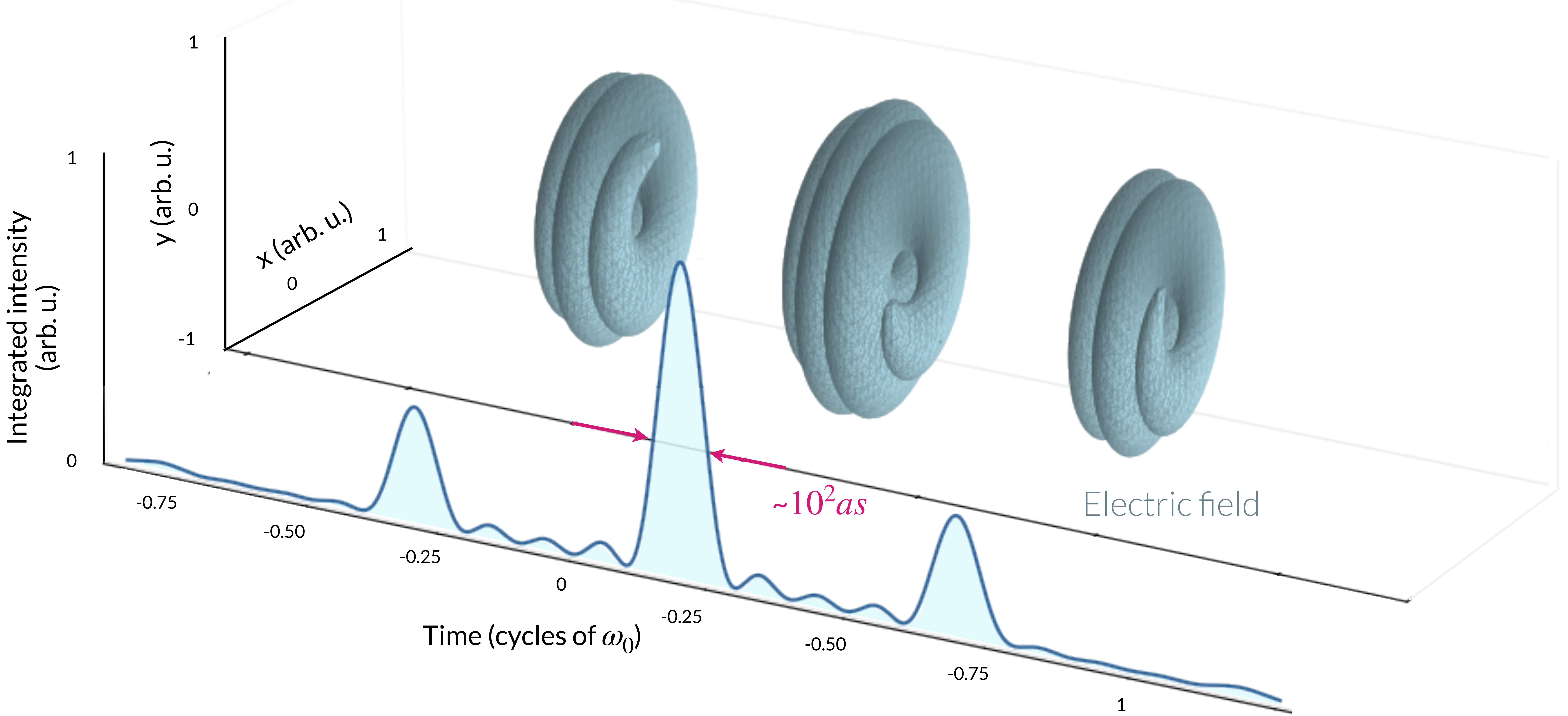
Theory: C. Hernández-García et al. , **Phys. Rev. Lett. 111**, 083602 (2013).



Experiment: R. Géneaux, et al. **Nature Comm. 7**, 12583 (2016).



Attosecond vortex pulse train



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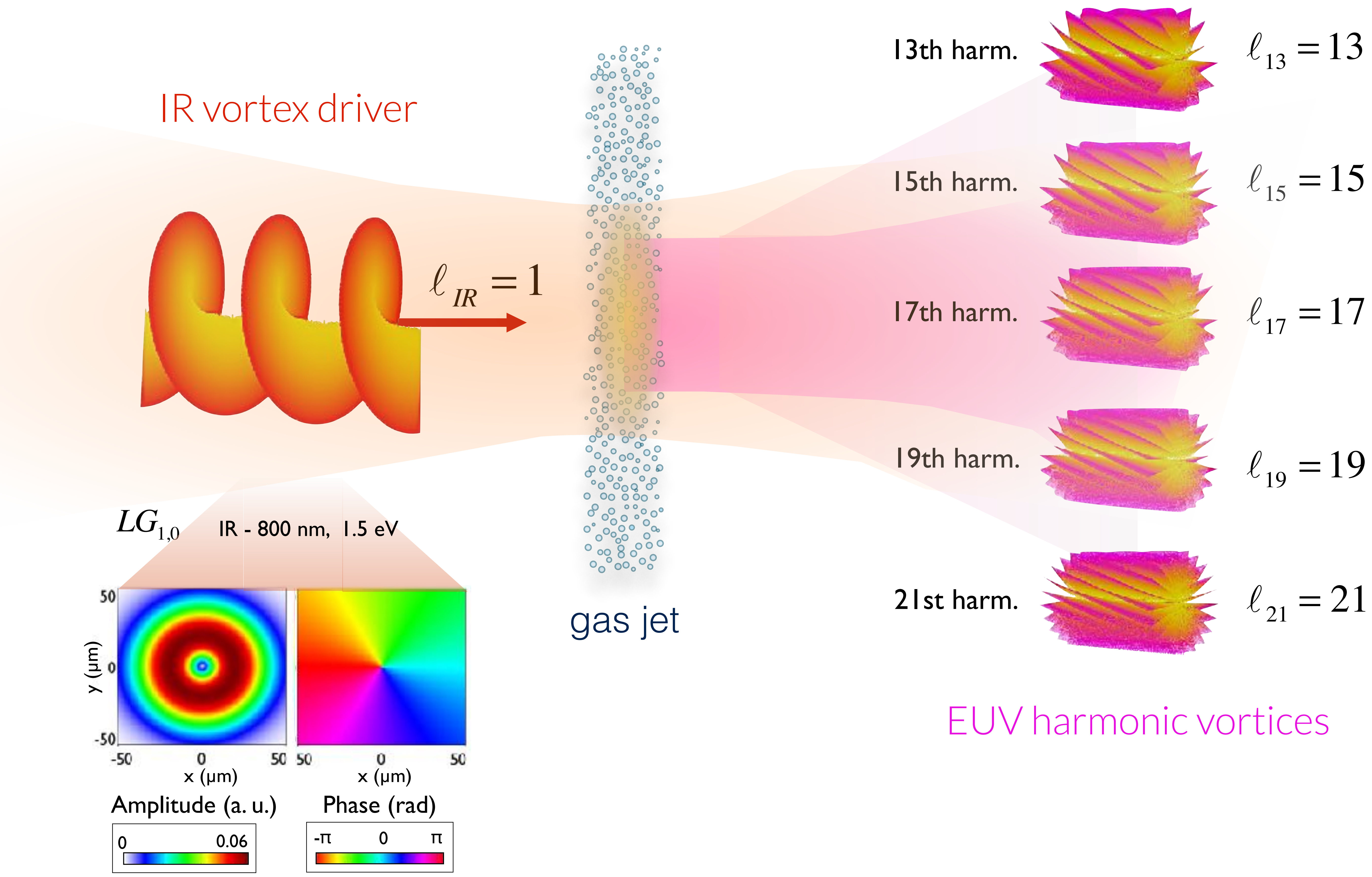
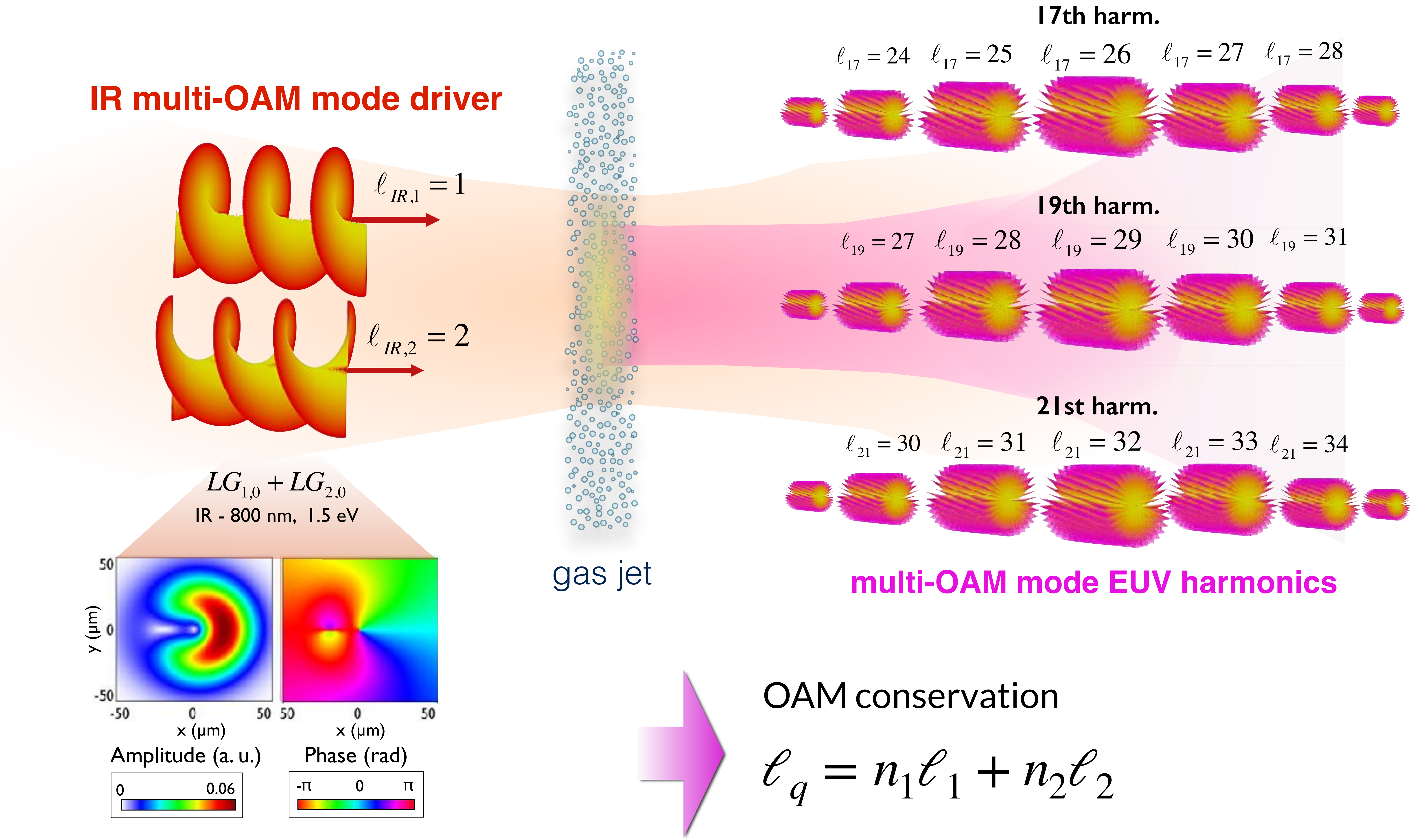
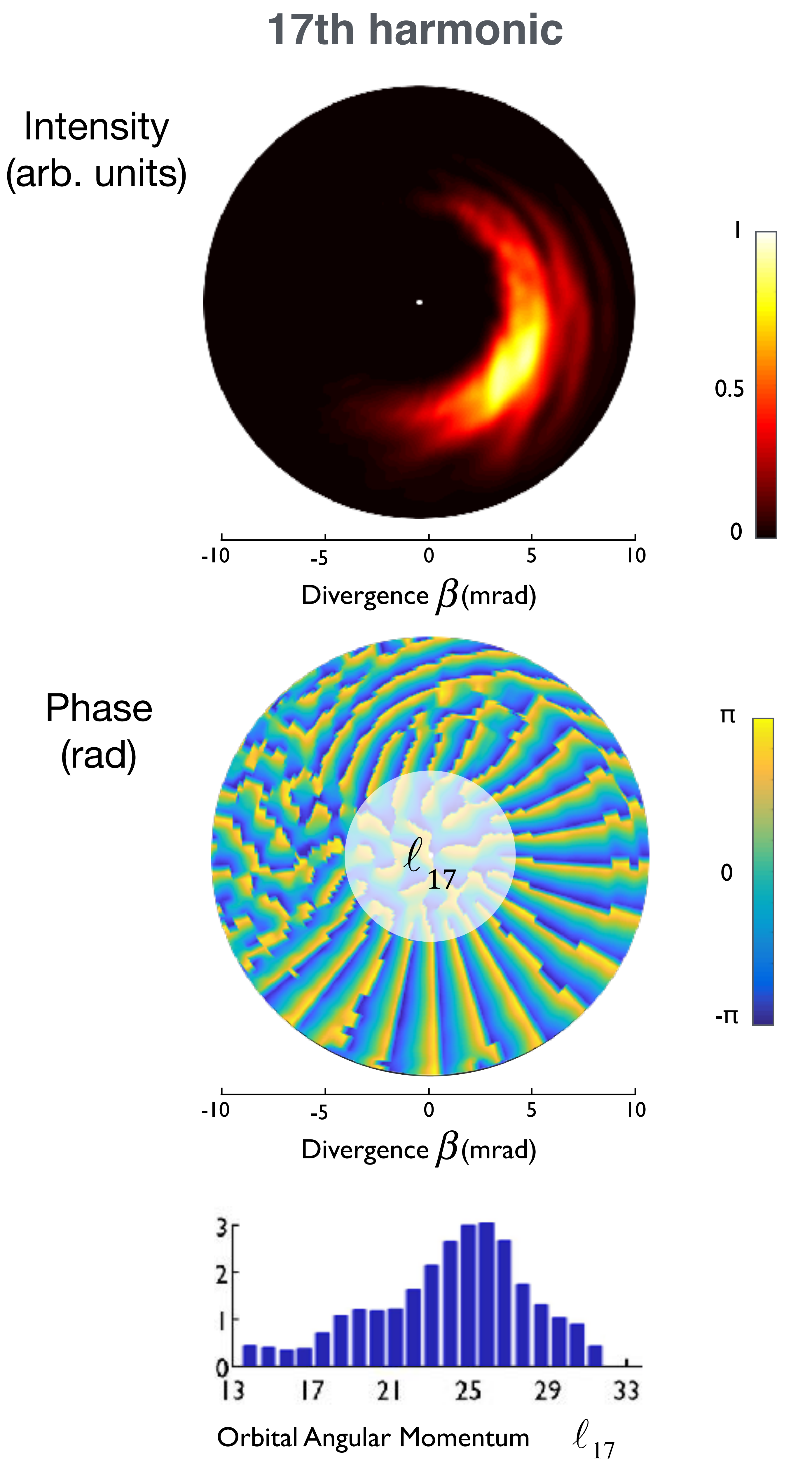
Orbital Angular Momentum transfer in HHG



$$\ell_q = q\ell_{IR}$$





OAM conservation

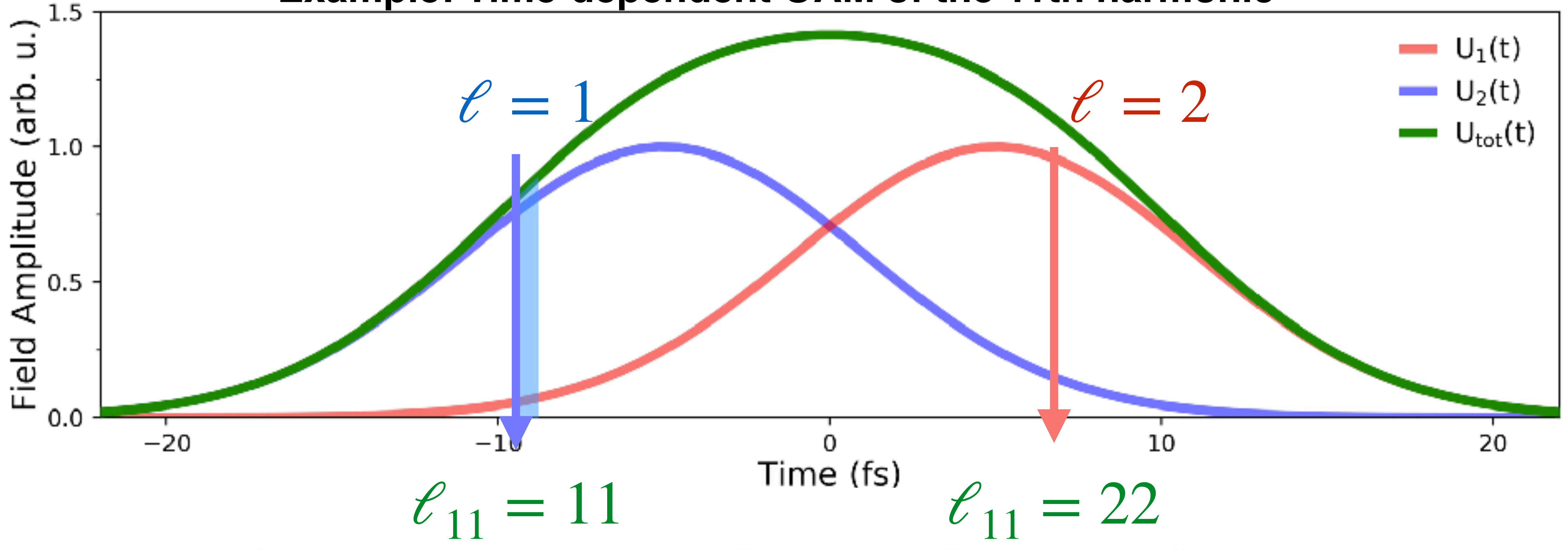
$$\ell_q = n_1 \ell_1 + n_2 \ell_2$$

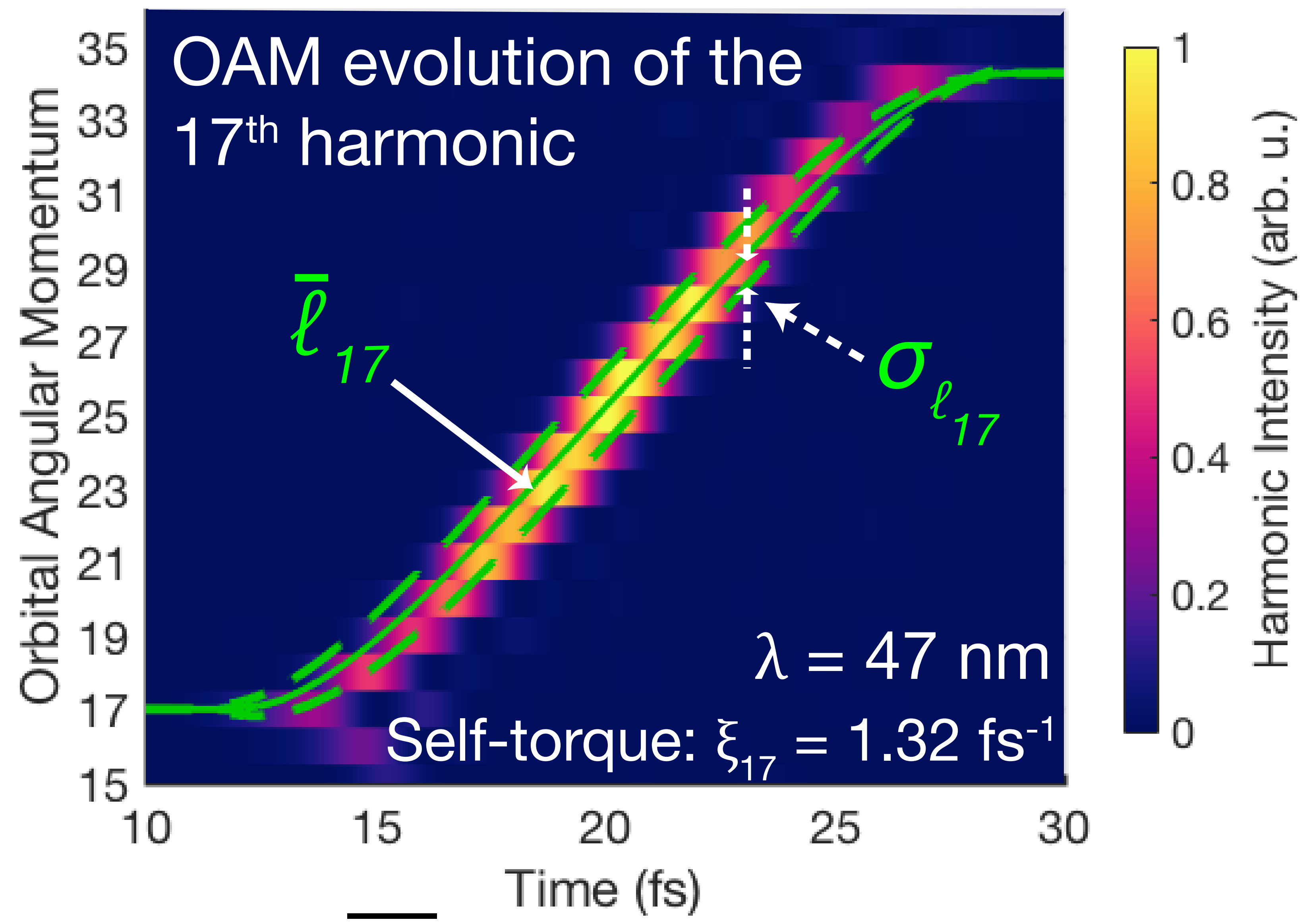
L. Rego, J. San Román, A. Picón, L. Plaja, and C. Hernández-García, **Phys. Rev. Lett. 117**, 163202 (2016).

L. Rego

Time-dependent orbital angular momentum - self-torque

Example: Time-dependent OAM of the 11th harmonic

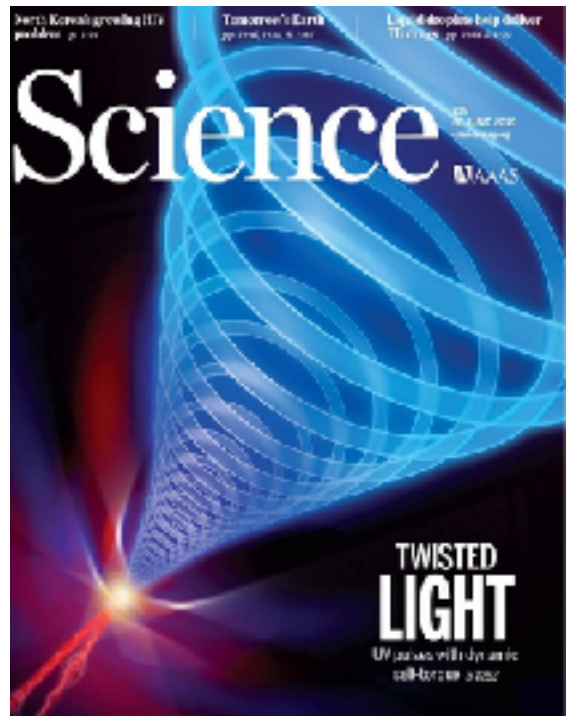




$$\xi_q = \frac{d\overline{\ell}_q(t)}{dt}$$

L. Rego

K. Dorney



L. Rego, K. M. Dorney, N. Brooks, Q. Nguyen, C.-T. Liao, J. San Román, D. Couch, A. Liu, E. Pisanty, M. Lewenstein, L. Plaja, H. C. Kapteyn, M. M. Murnane, and C. Hernández-García, **Science 364**, eaaw9486 (2019)

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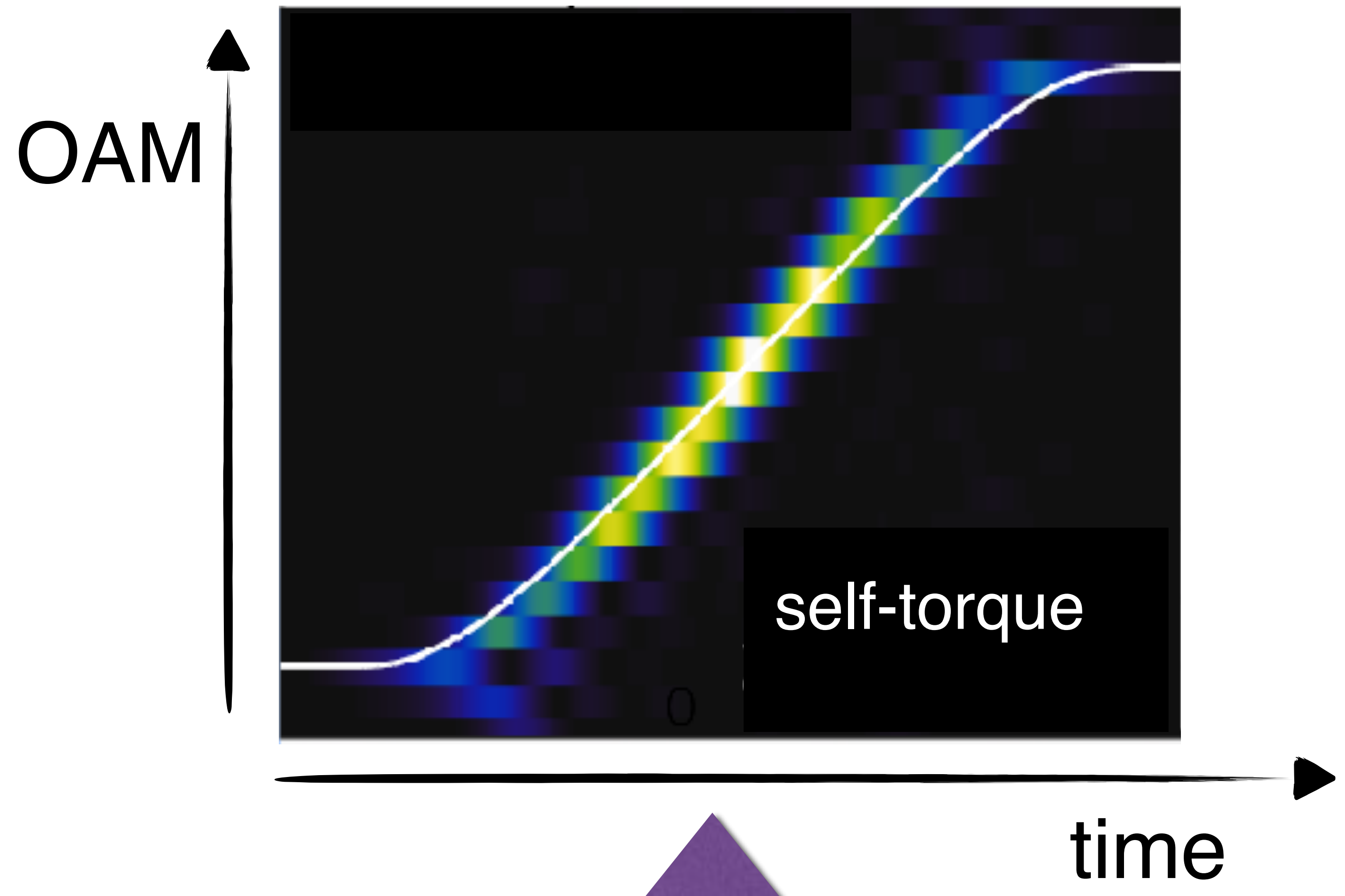
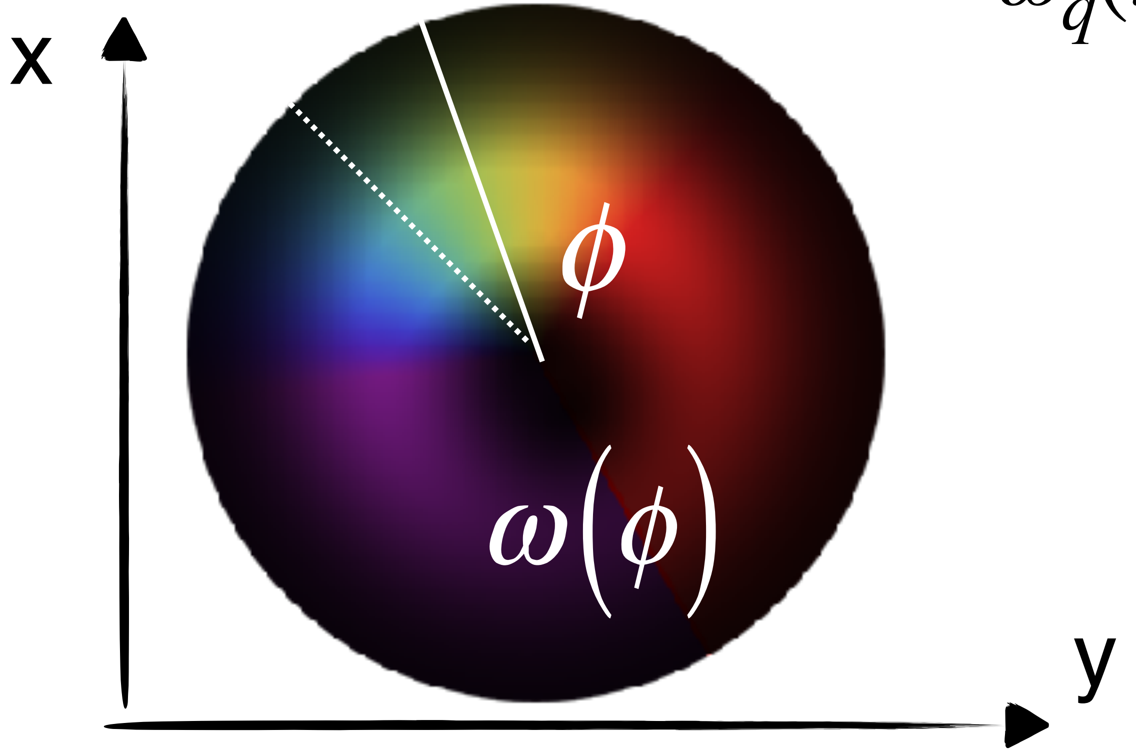
Self torque and azimuthal frequency chirp

Time-dependent OAM

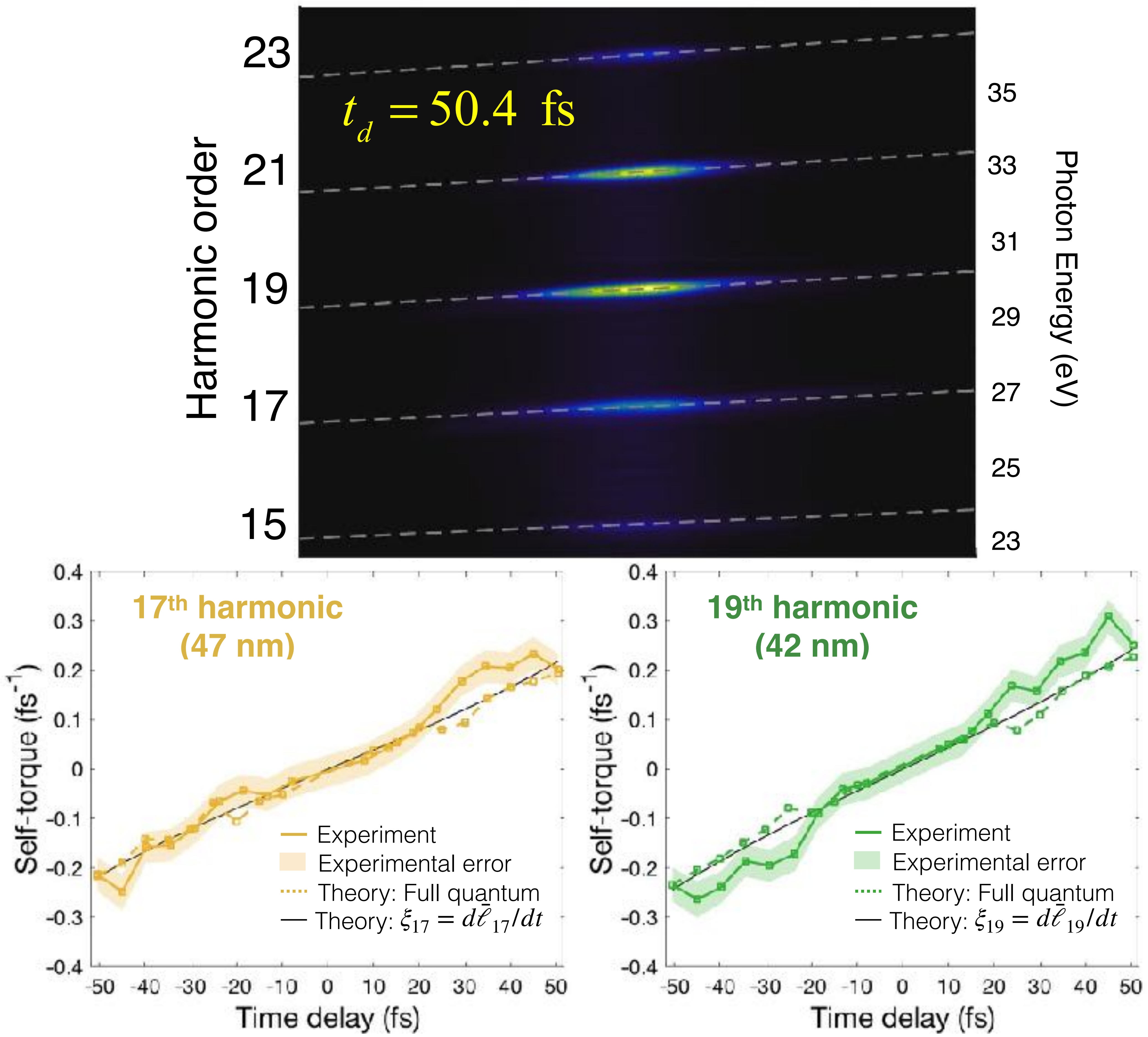


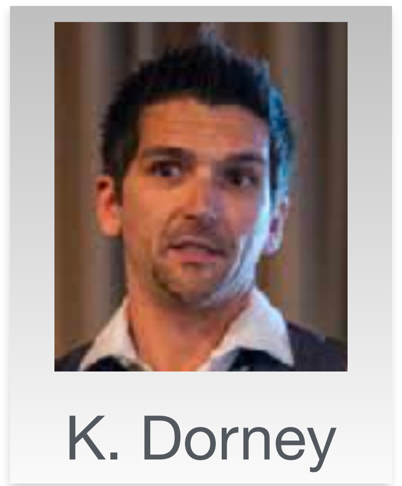
Azimuthal chirp



$$\varphi_q(t,\phi) \propto \ell_q(t)\phi$$

$$\omega_q(t,\phi) = \frac{d\varphi_q(t)}{dt} = \omega_q + \frac{d\overline{\ell}_q(t)}{dt}\phi$$





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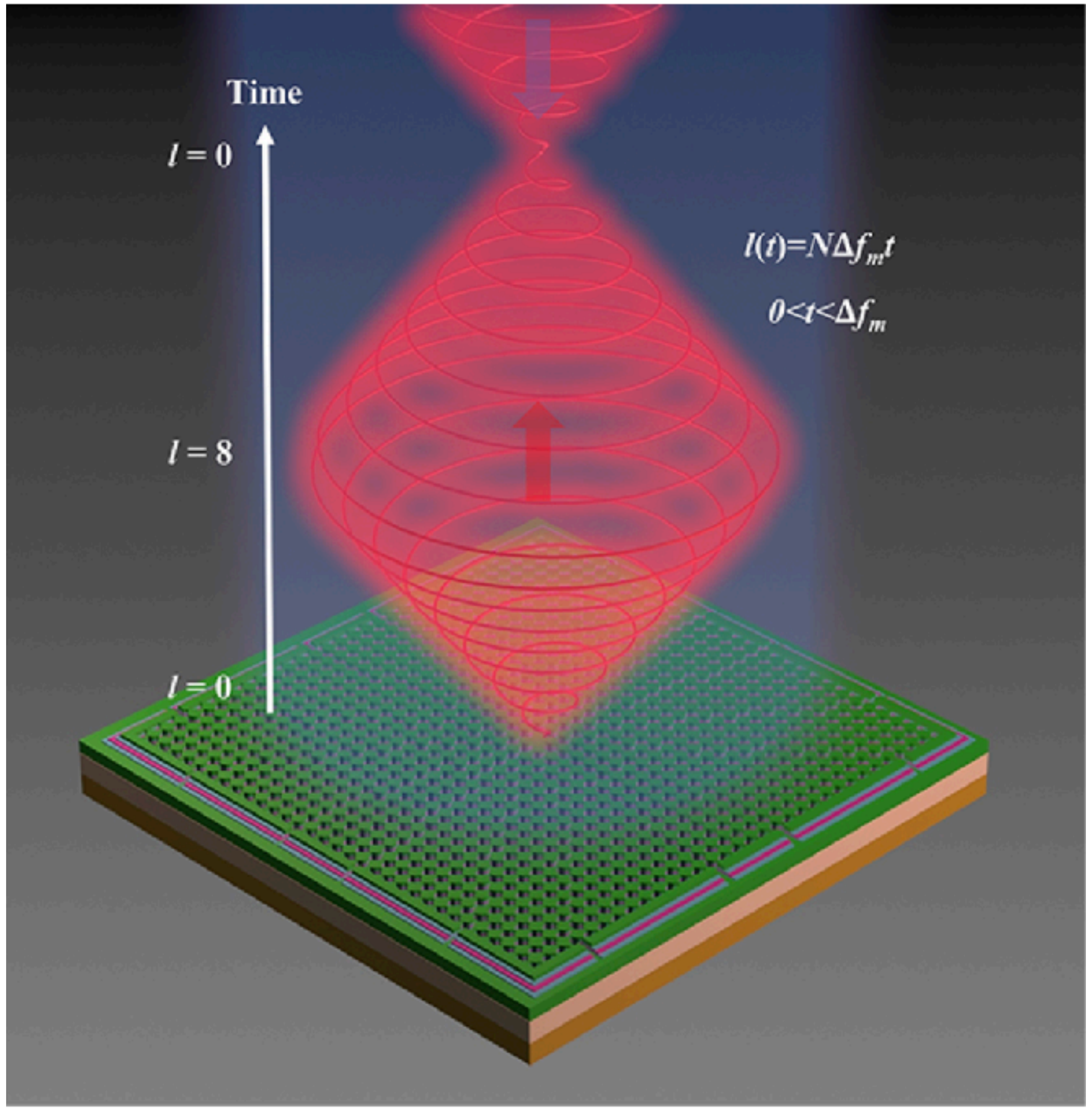
University of Colorado Boulder

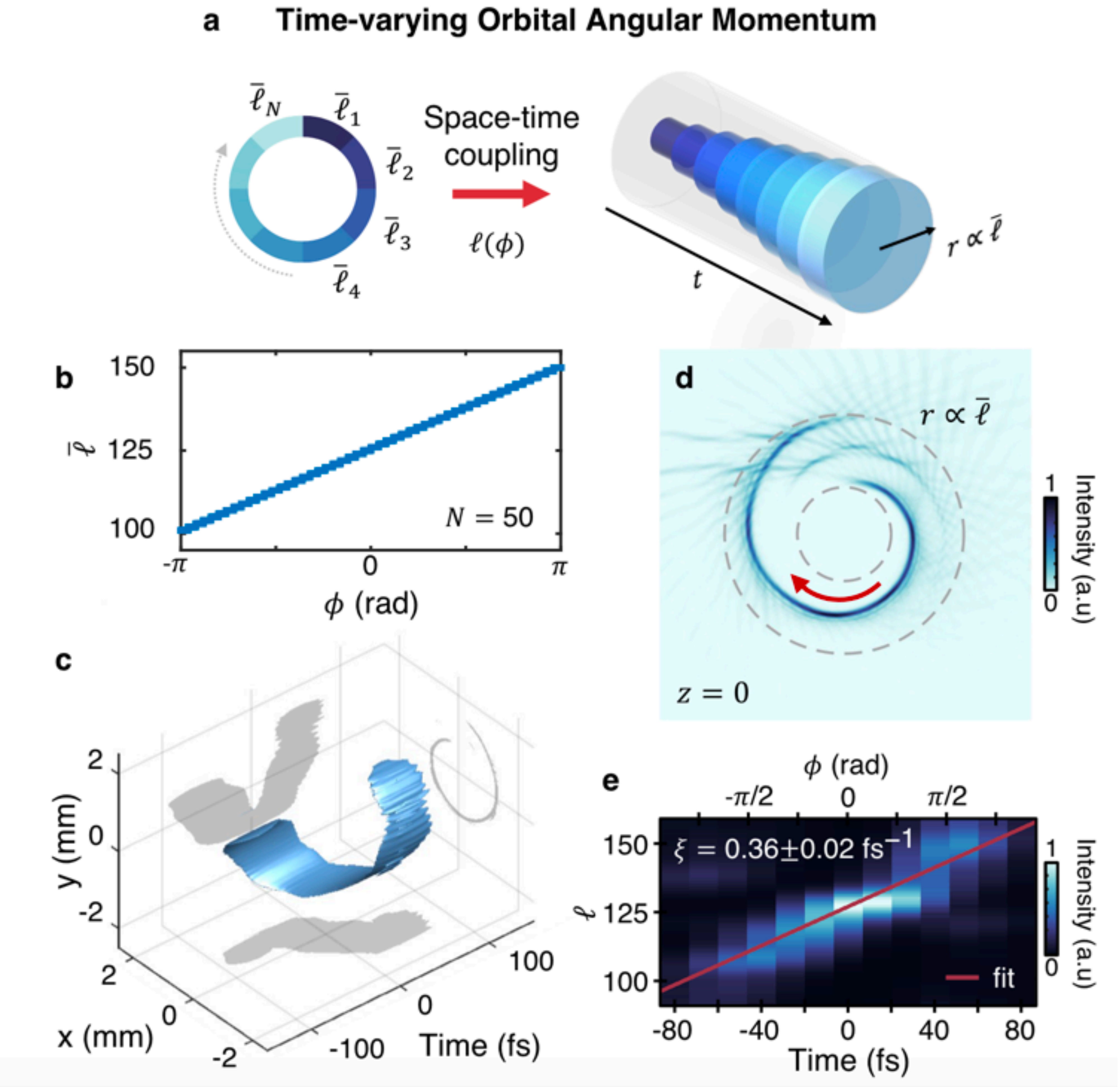
ICFO The Institute of Photonic Sciences

L. Rego, K. M. Dorney, N. Brooks, Q. Nguyen, C.-T. Liao, J. San Román, D. Couch, A. Liu, E. Pisanty, M. Lewenstein, L. Plaja, H. C. Kapteyn, M. M. Murnane, and C. Hernández-García, **Science 364**, eaaw9486 (2019)

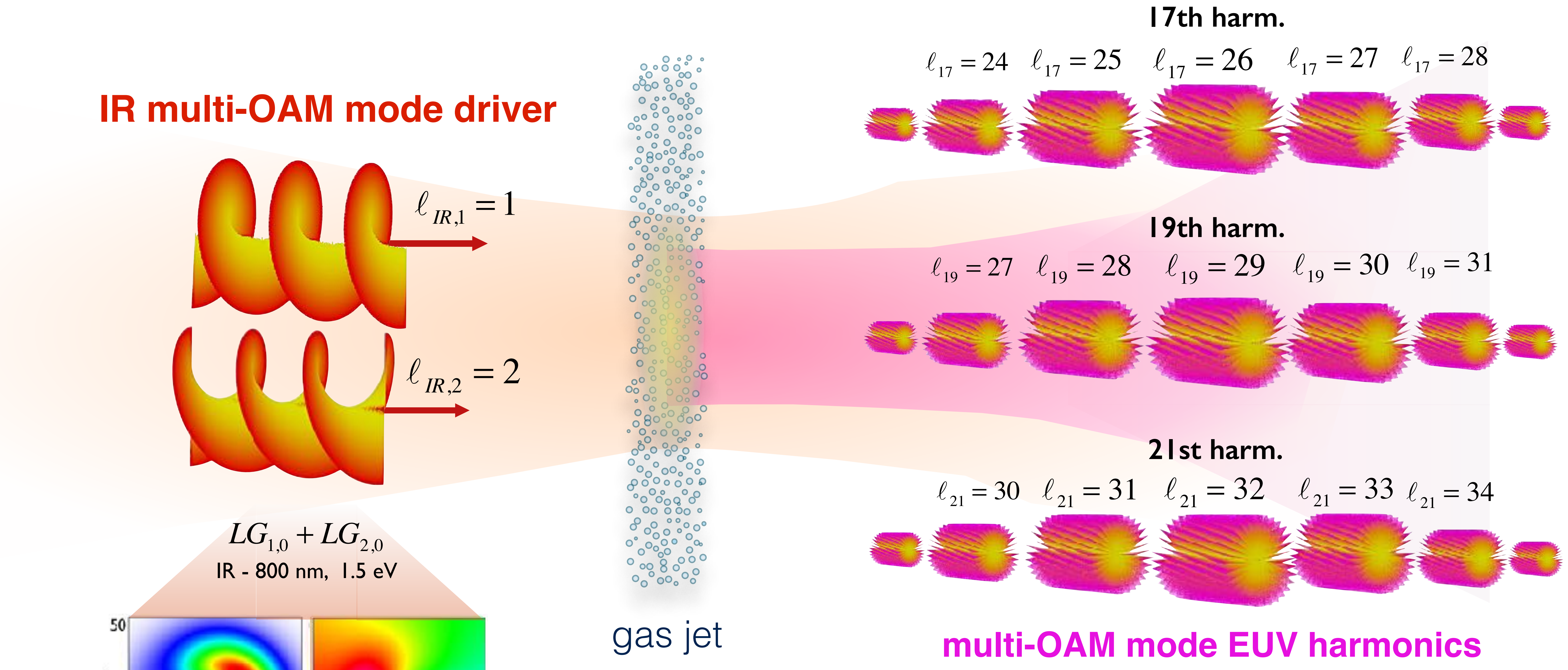
Time-varying OAM or self-torque

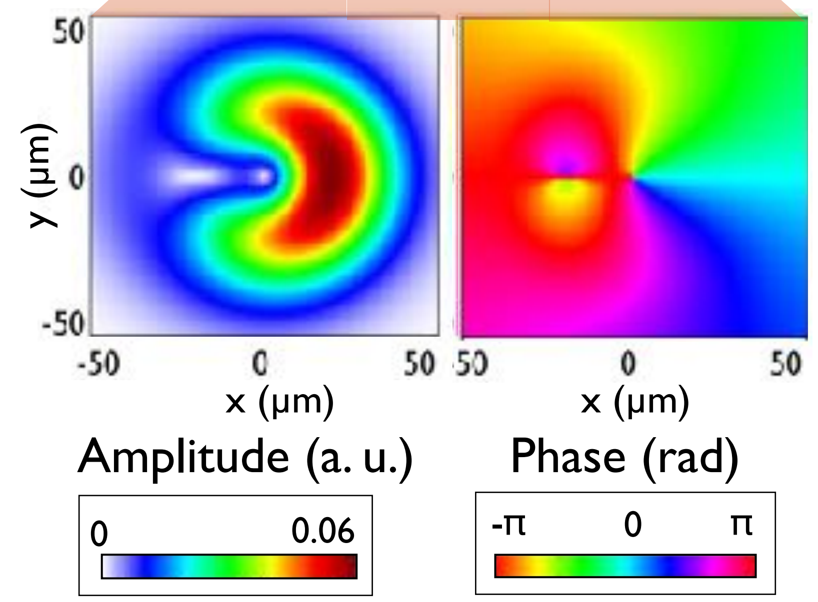


Barati Sedeh, Hooman, et al. Nanophotonics 9, 9 (2020)



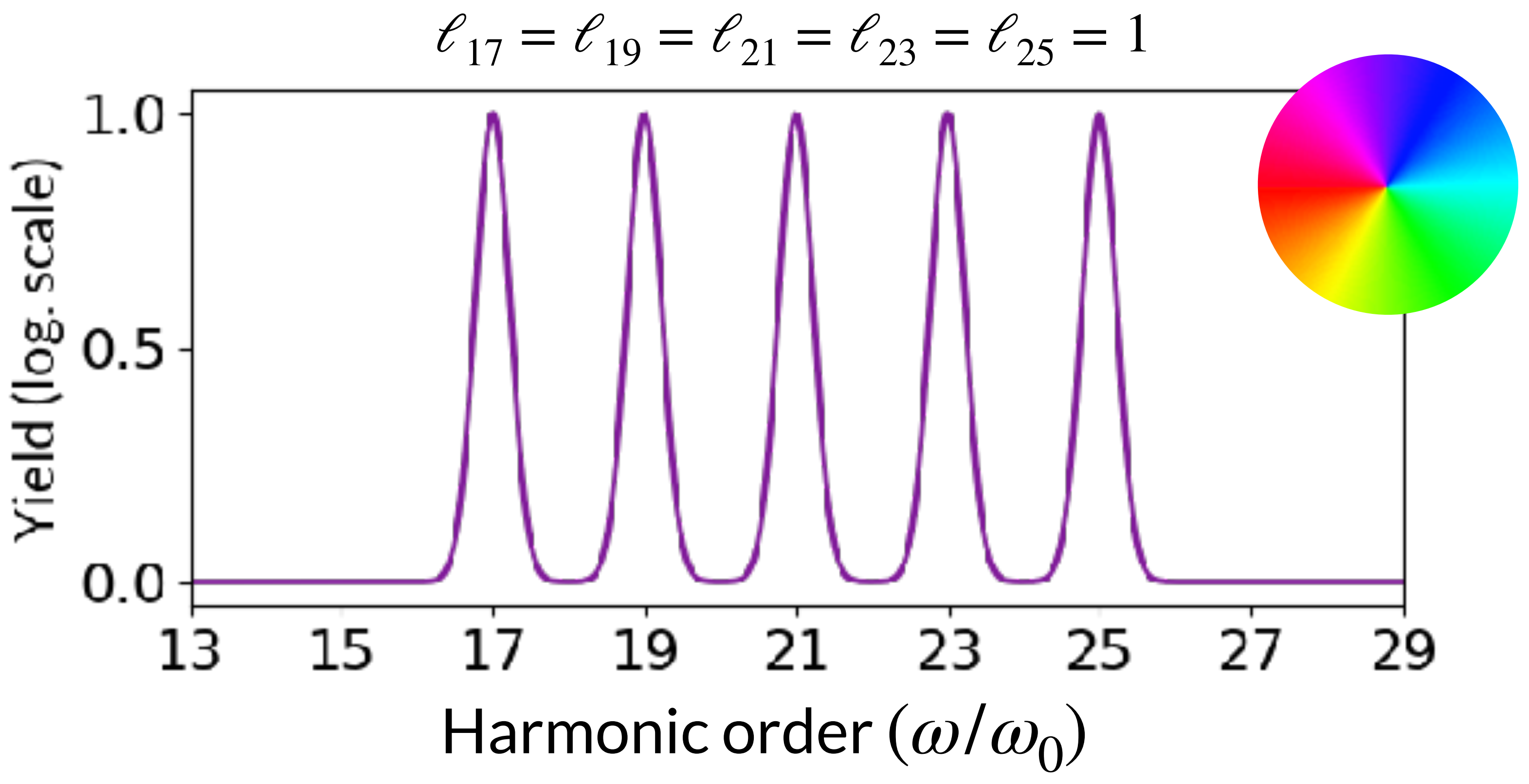
M. de Oliveira, A. Ambrosio, Science Advances 11 (2025)





OAM conservation

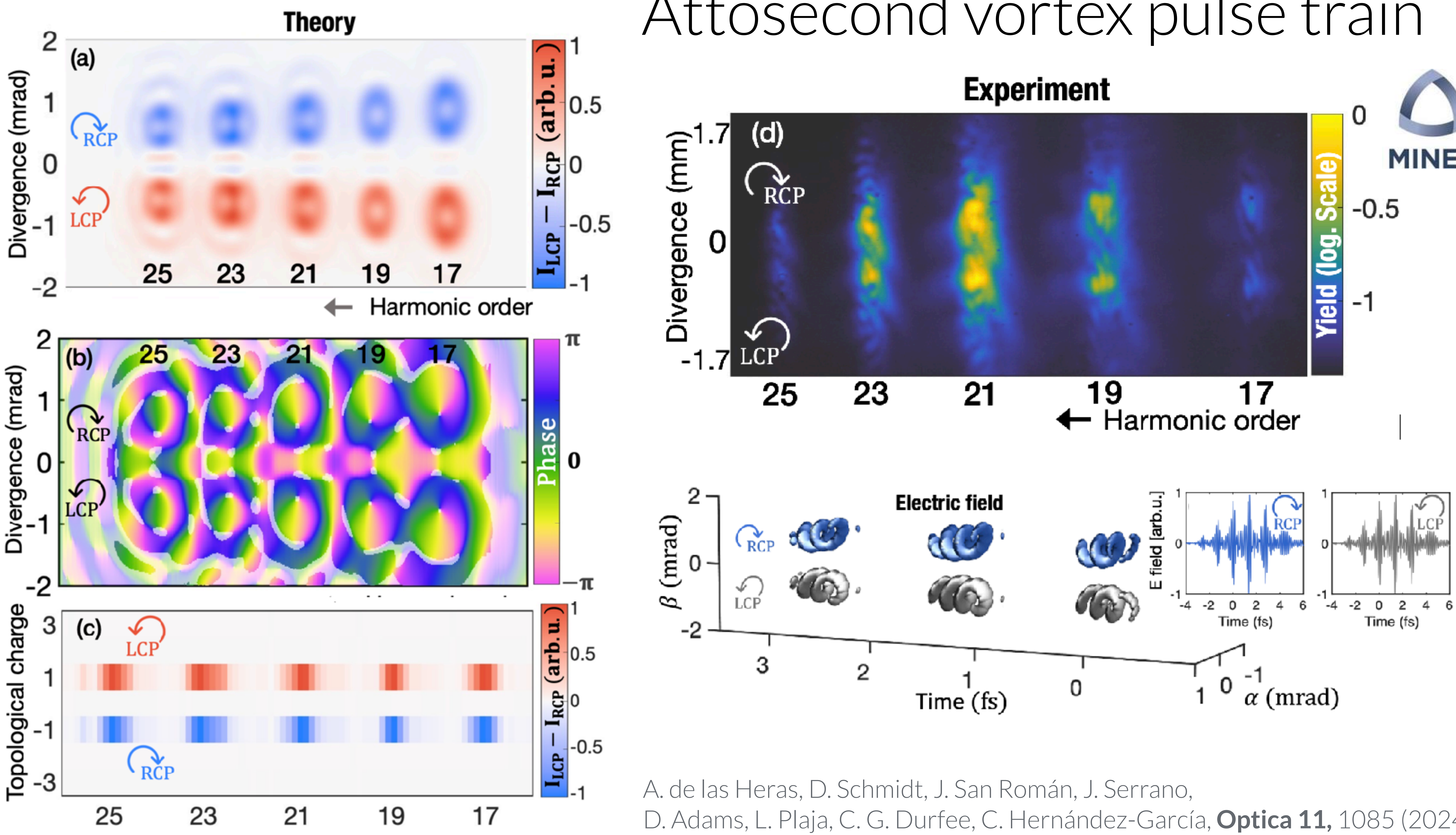
$$\ell_q = n_1\ell_1 + n_2\ell_2$$



L. Rego, J. San Román, A. Picón, L. Plaja, and C. Hernández-García,
Phys. Rev. Lett. 117, 163202 (2016).

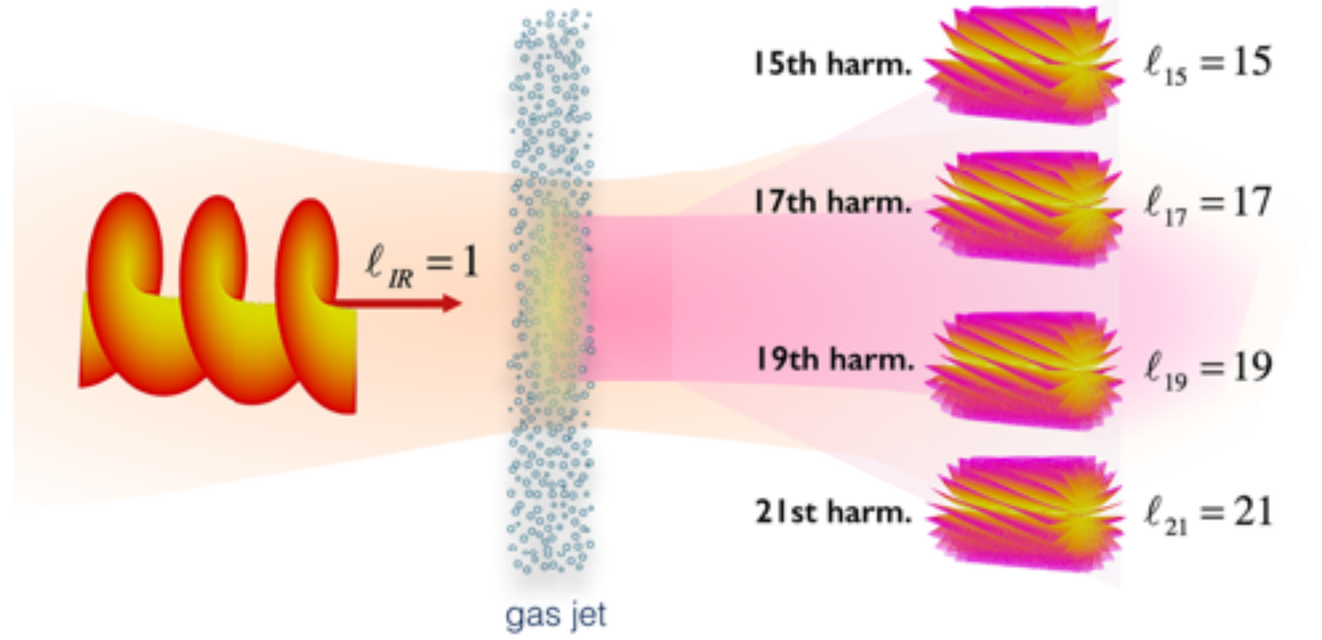

VNiVERSiDAD D SALAMANCA
RCP
$\sigma = 1$
$\ell = 1$
LCP
$\sigma = -1$
$\ell = -1$
IR intensity
IR tilt-angle
(b)
gas jet
High-order harmonics
$\ell = -1$
$\ell = 1$
$H5$
$H7$
$H9$
$H11$
Linear momentum conservation
$\mathbf{k}_q = n_{RCP}\mathbf{k}_{RCP} + n_{LCP}\mathbf{k}_{LCP}$
SAM conservation
$n_{RCP} = n_{LCP} \pm 1$
OAM conservation
$\ell_q = n_{RCP}\ell_{RCP} + n_{LCP}\ell_{LCP}$

Attosecond vortex pulse train



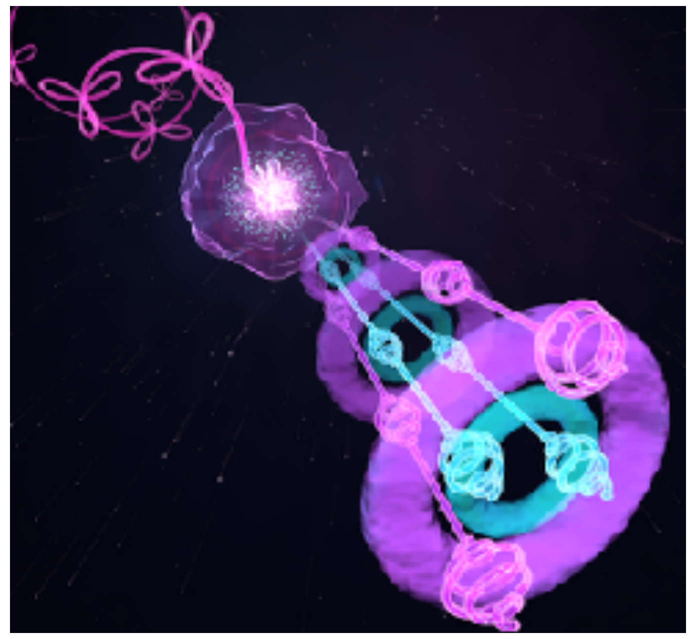
A. de las Heras, D. Schmidt, J. San Román, J. Serrano,
D. Adams, L. Plaja, C. G. Durfee, C. Hernández-García, **Optica 11,** 1085 (2024).

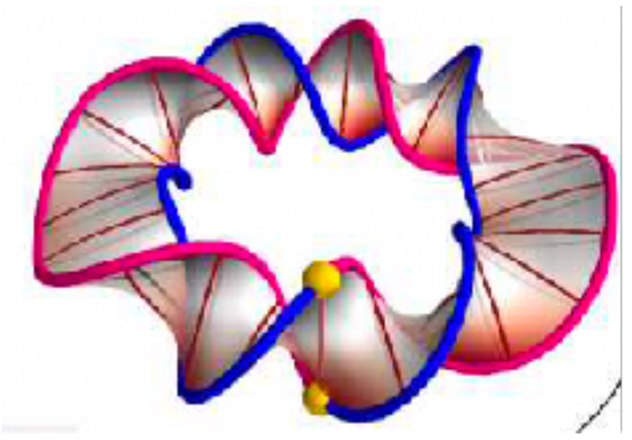
OAM EUV Harmonics



C. Hernández-García, et al. **Phys. Rev. Lett. 111**, 083602 (2013).
G. Gariepy, et al. **Phys. Rev. Lett. 113**, 153901 (2014).
R. Géneaux, et al. **Nature Commun. 7**, 12583 (2016).
L. Rego et al. **Phys. Rev. Lett. 117**, 163202 (2016).

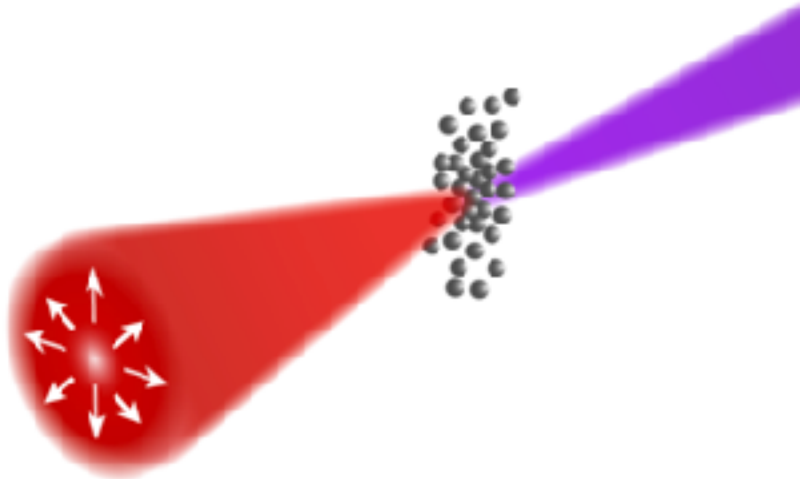
Harmonics with SAM and OAM





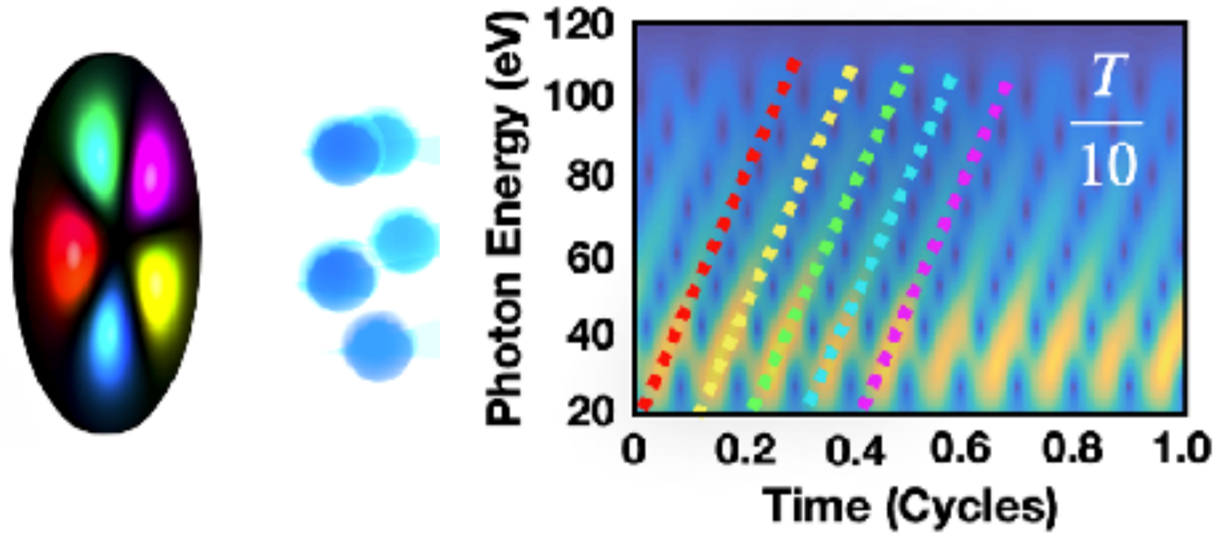
K. Dorney et al **Nature Photonics 13**, 123 (2019).
E. Pisanty et al **Phys. Rev. Lett. 122**, 203201 (2019).
L. Rego et al **Opt. Lett. 45**, 5636 (2020).
A. de las Heras, et al, **Optica 9**, 71-79 (2022).
M. Luttmann, et al., **Sci. Adv. 9**, eadf3486 (2023).
N. Brooks, et al. **ACS Photonics**, 12,,495–504 (2025).

Vector EUV harmonic beams



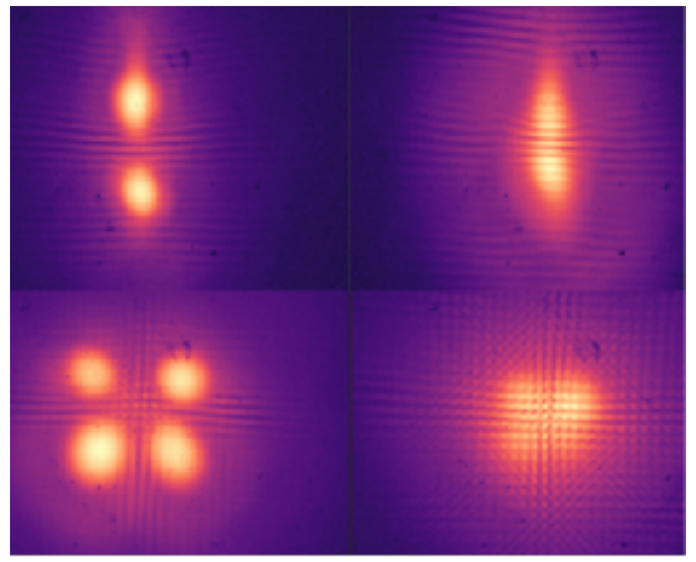
C. Hernández-García et al **Optica** 4, 530 (2017)
A. Turpin et al **Sci Rep 7**, 43888 (2017).

Necklace-driven harmonics



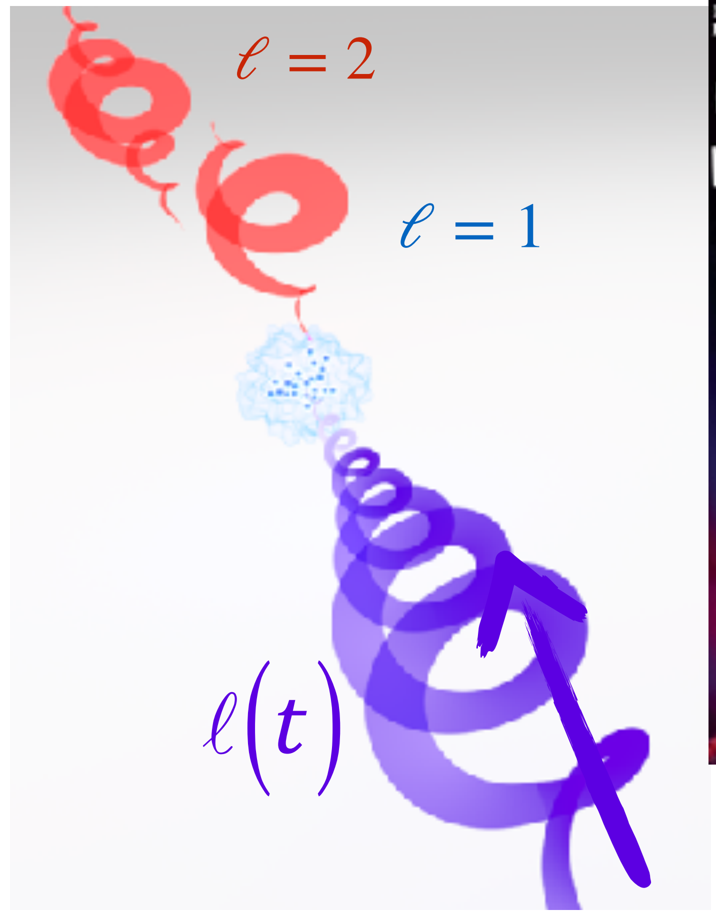
L. Rego et al **Sci. Adv. 8**, eabj7380 (2022).

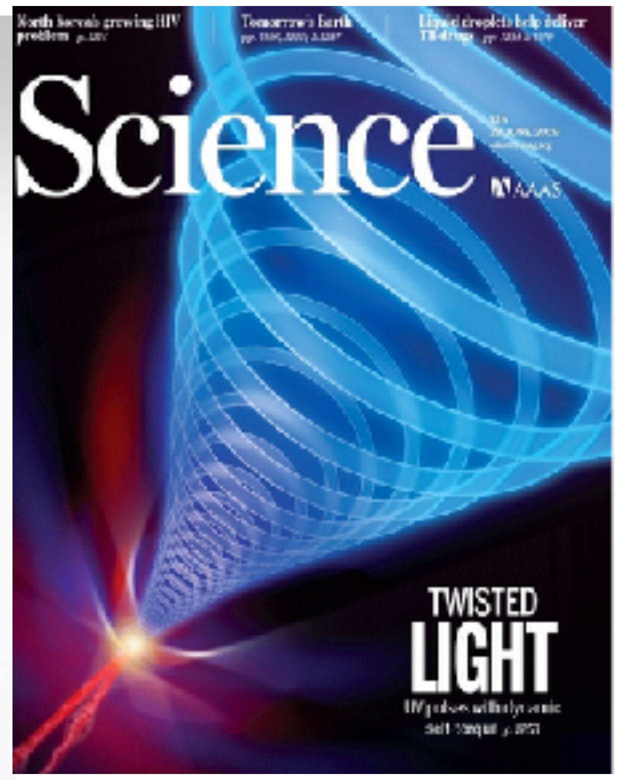
Hermite-Gauss harmonics



D. Schmidt et a. **APL Photonics** 10, 060801 (2025)

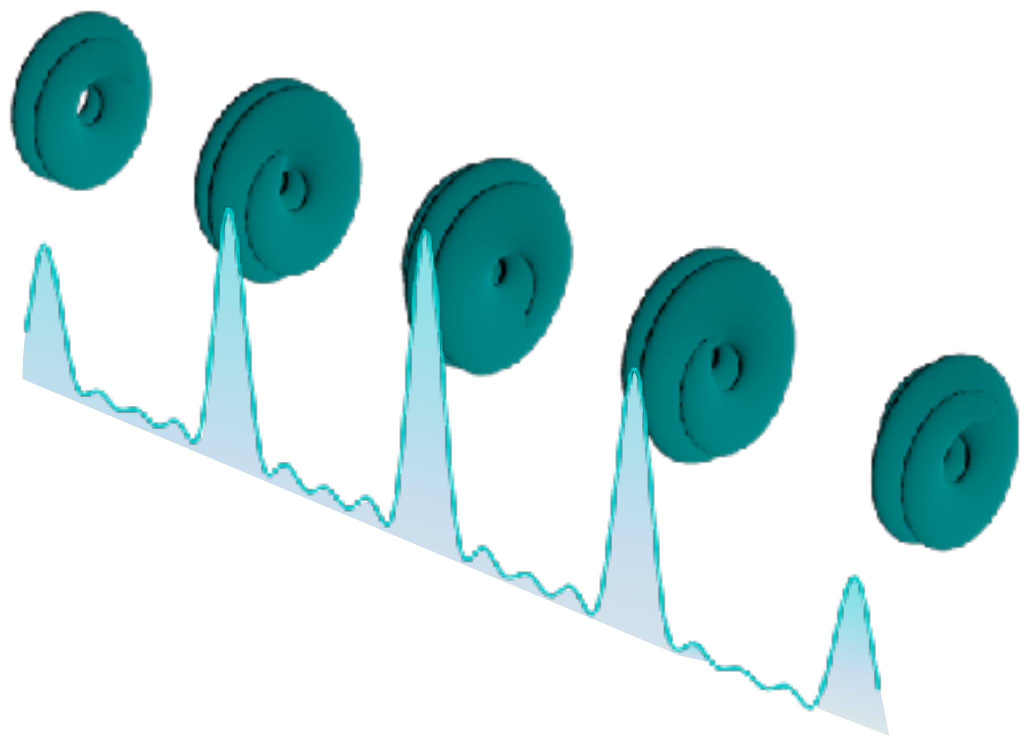
Harmonics with self-torque or time-dependent OAM





L. Rego, et al. **Science 364**, eaaw9486 (2019)
A. de las Heras et al. **ACS Photonics** 11, 4365 (2024).

Attosecond vortex pulse trains



A. de las Heras, D. Schmidt, et al. **Optica 11**, 1085 (2024)

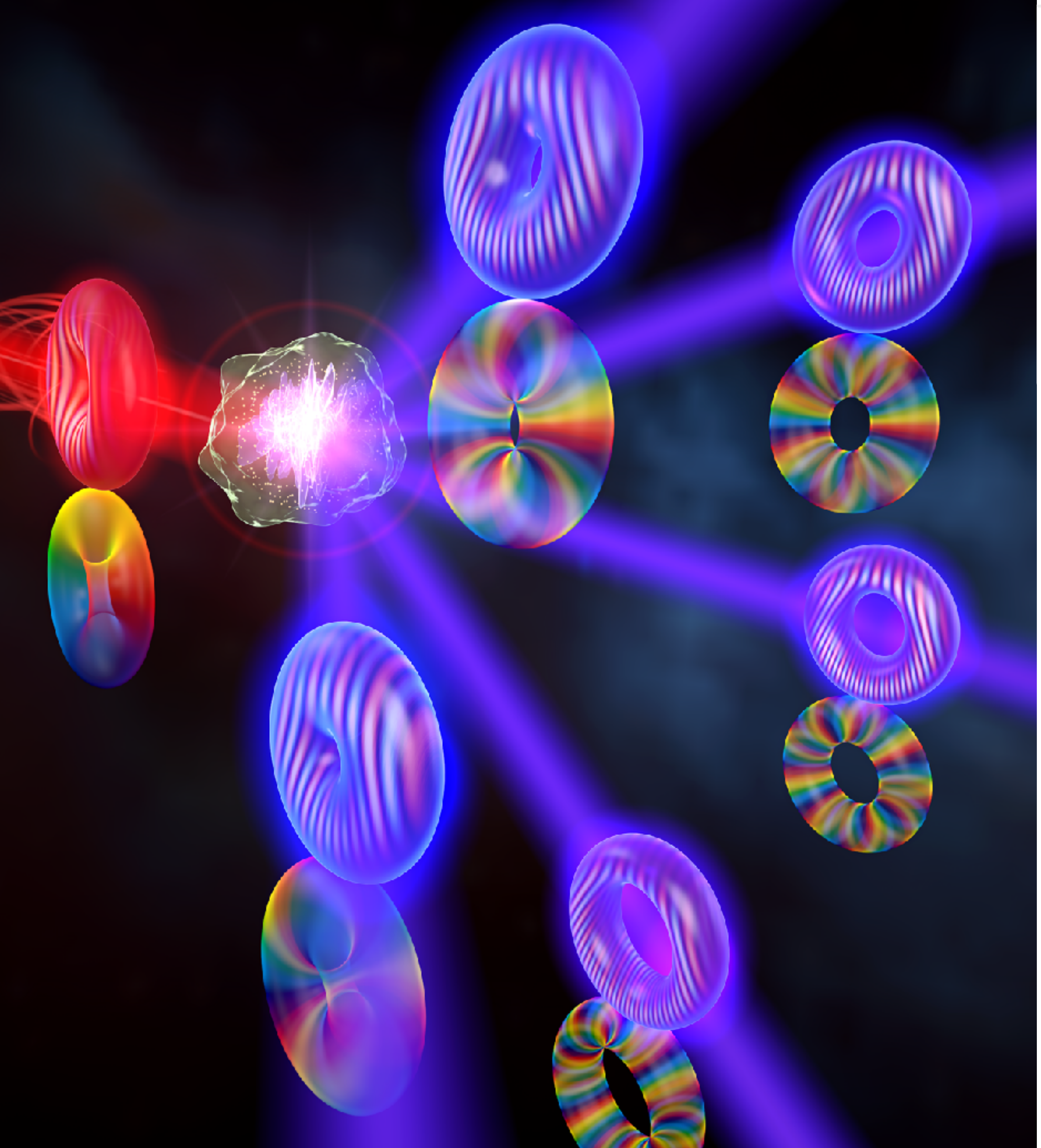


Figure credit: Steven Burrows and KM group, JILA

nature photonics

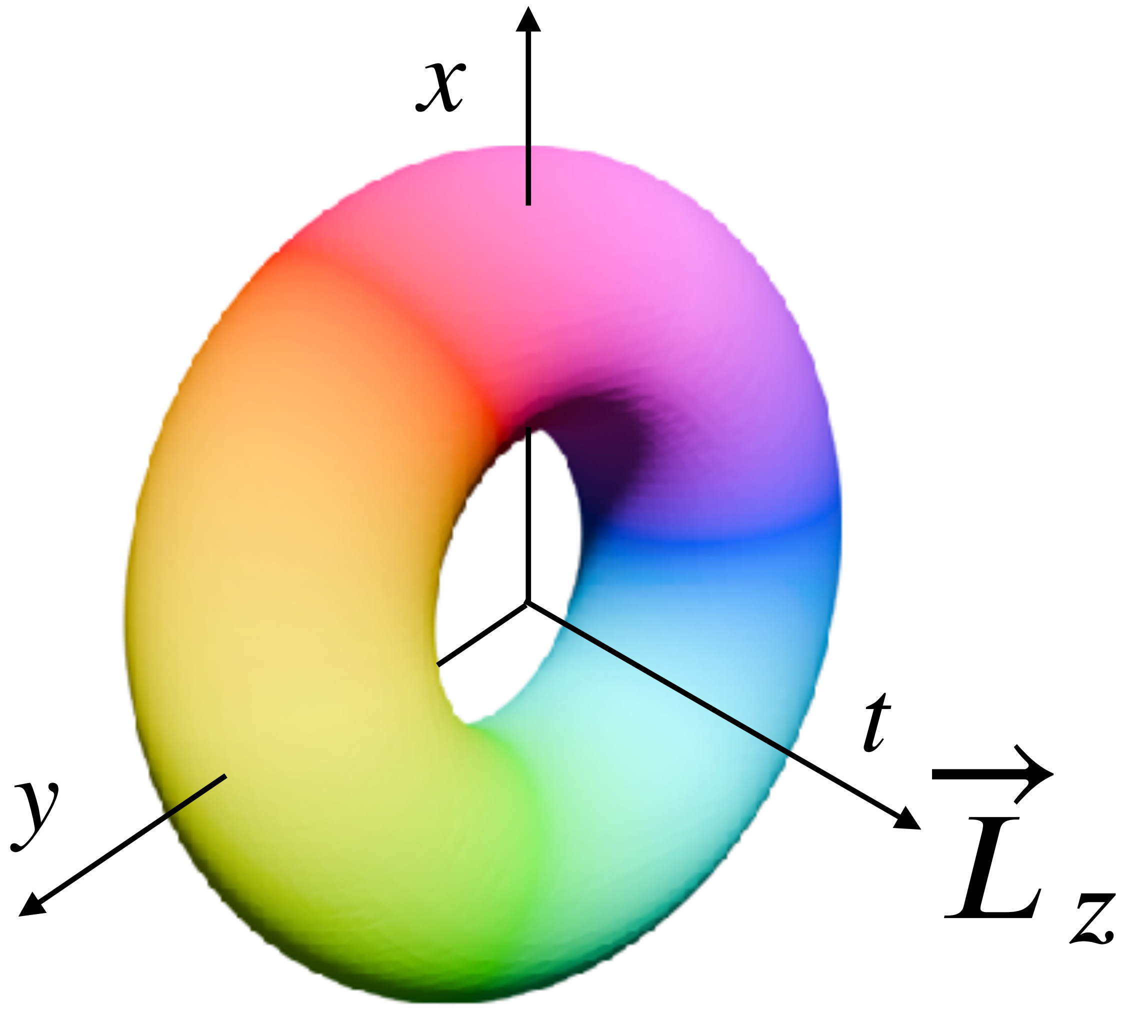
Article

https://doi.org/10.1038/s41566-025-01699-w

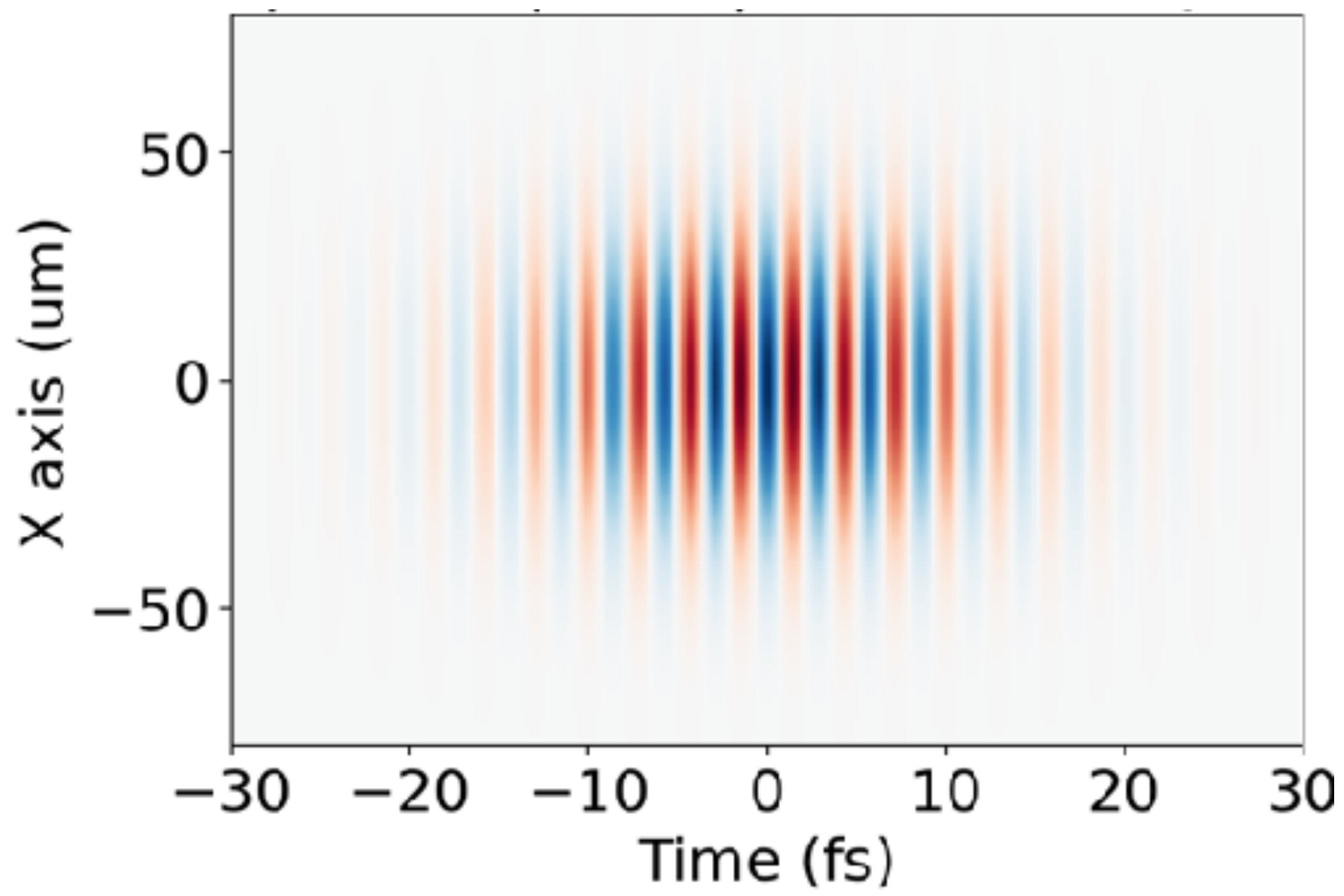
Extreme-ultraviolet spatiotemporal vortices via high harmonic generation

Spatiotemporal optical vortices (STOVs)

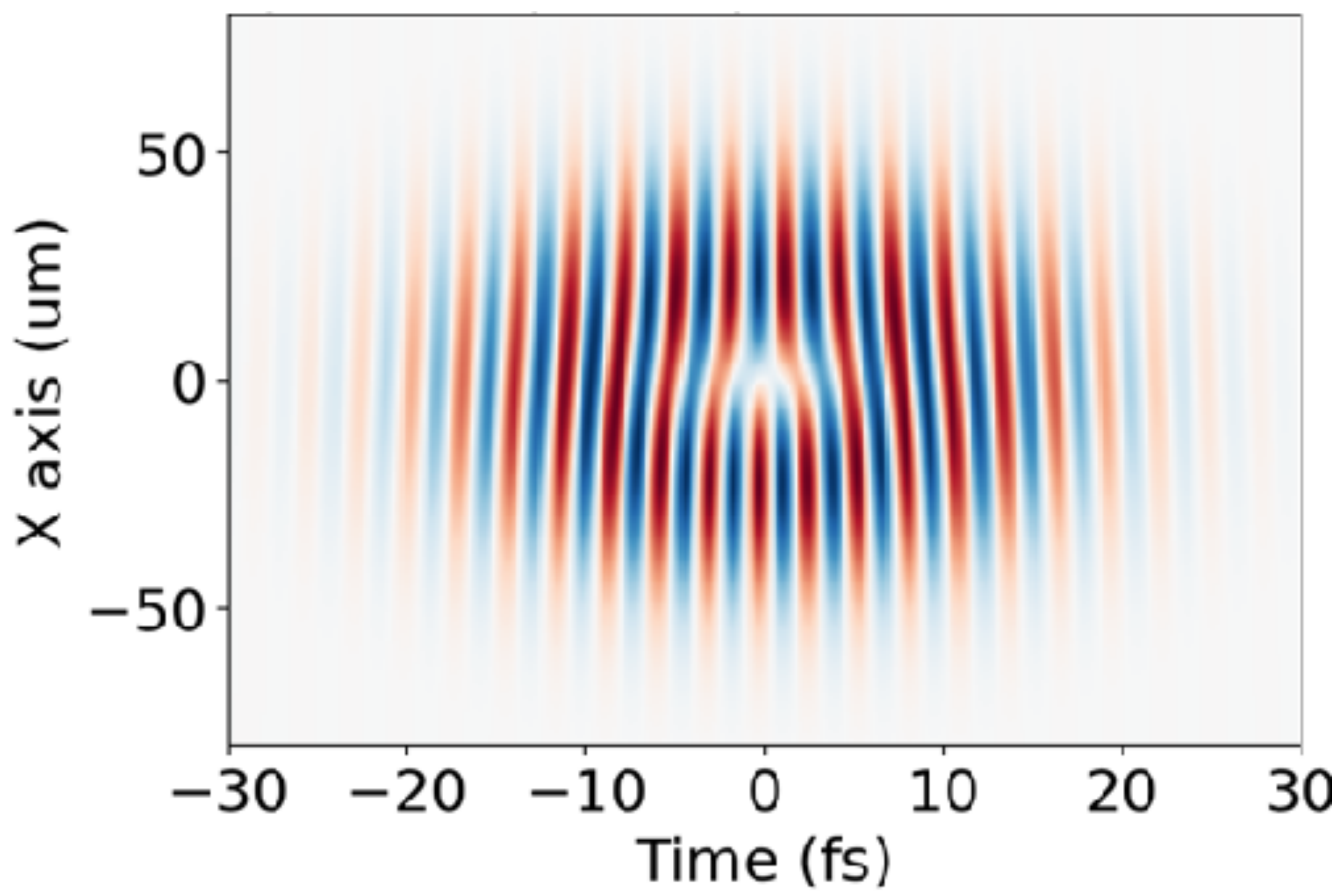
Longitudinal vortex



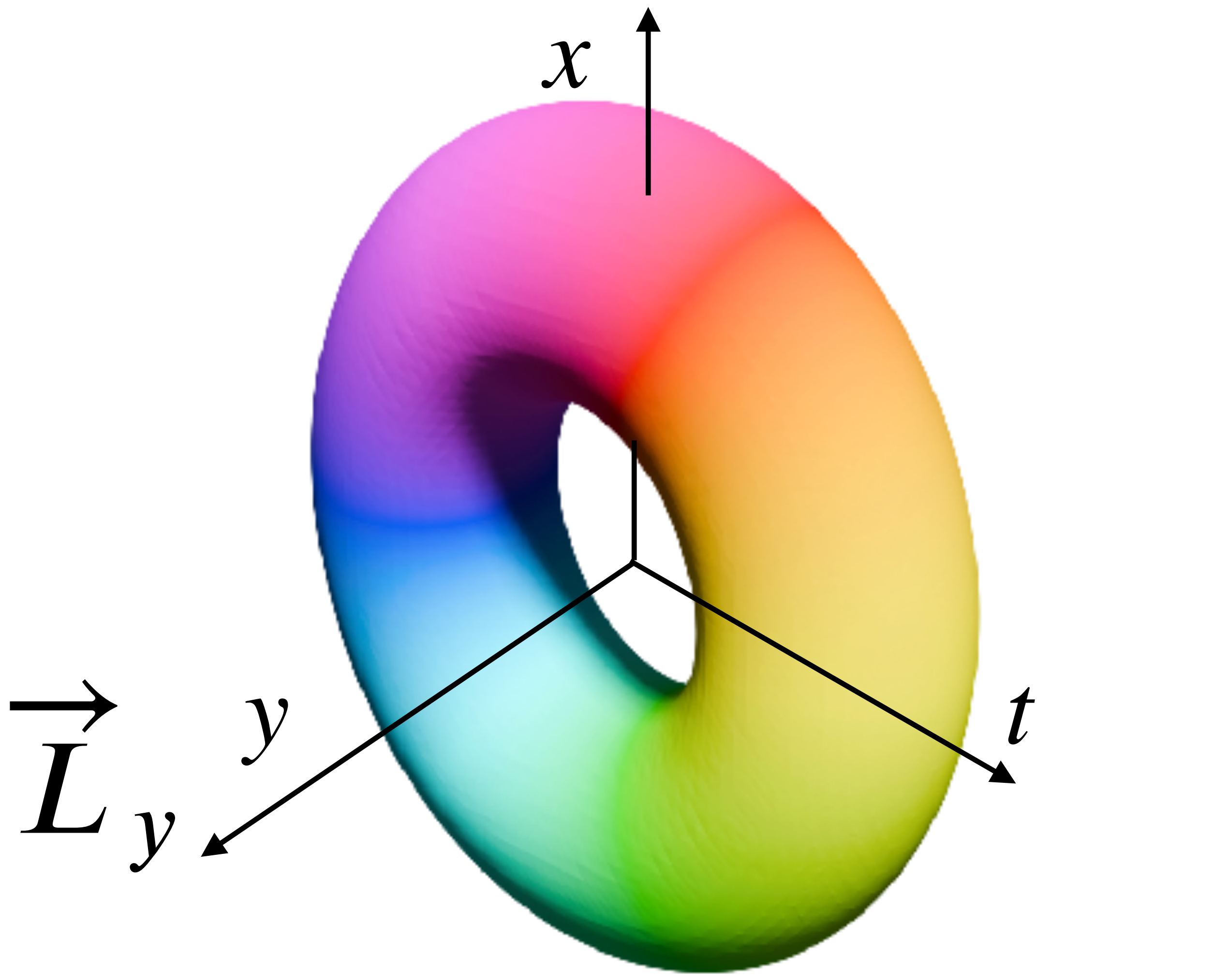
Gaussian beam



Spatiotemporal vortex (STOV)



Spatiotemporal vortex (STOV)



- Twisted phase profile in the spatiotemporal domain
- Topological charge defined as the number of 2π phase jumps
- Non propagating eigenmodes

Fundamentals:
K. Bliokh, F. Nori, Phys. Rev. A 86, 033824 (2012)
N. Jhajj, et al. Phys. Rev. X 6, 031037, (2016)
S. W. Hancock, et al. Optica 6, 1547-1553 (2019)
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G. Gui, et al. Nat. Photon. 15, 608–613 (2021)
S. W. Hancock, et al. Optica 8, 594-597 (2021)
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M. A. Porras, Opt. Lett. 48, 367-370 (2023)
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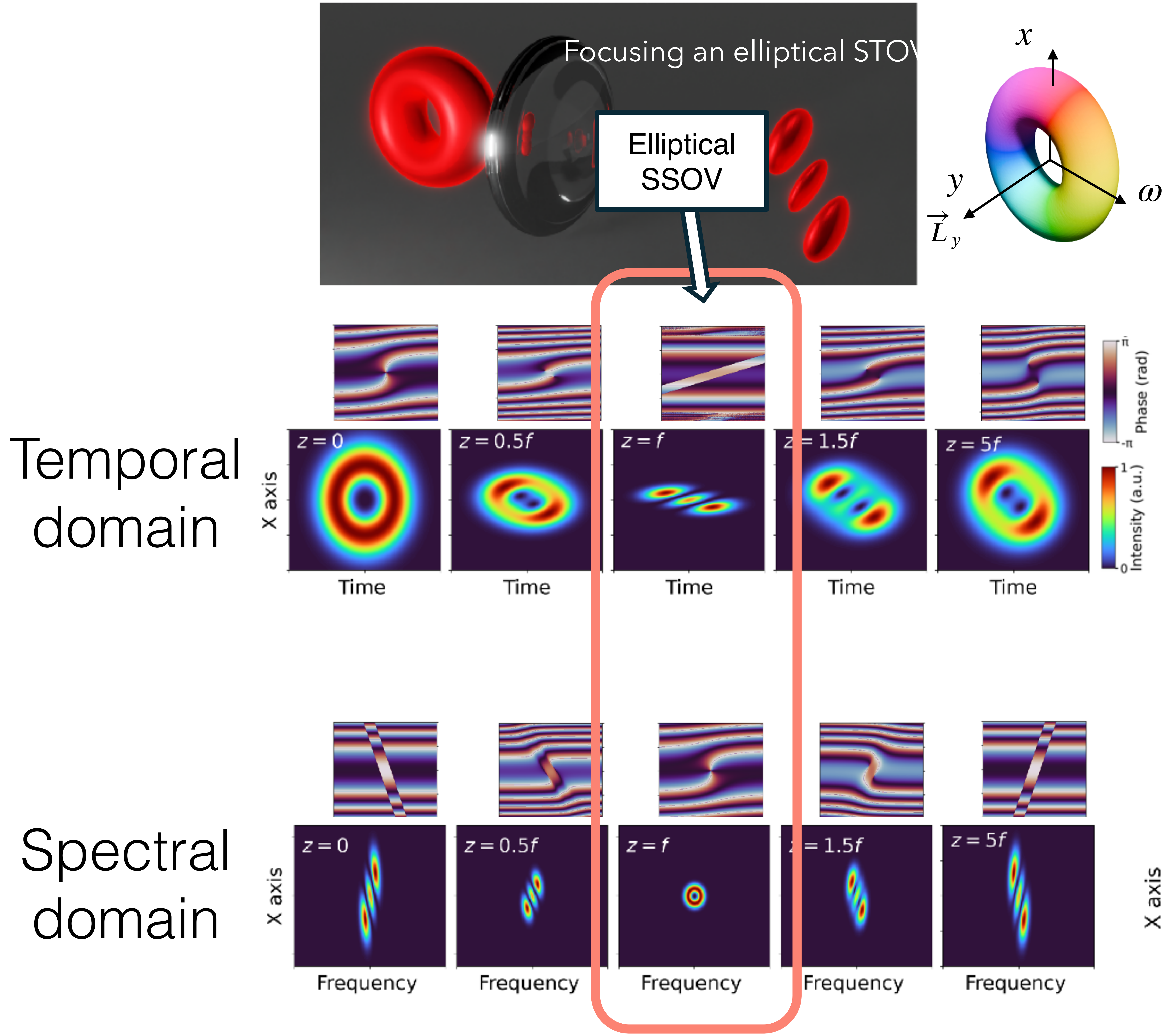
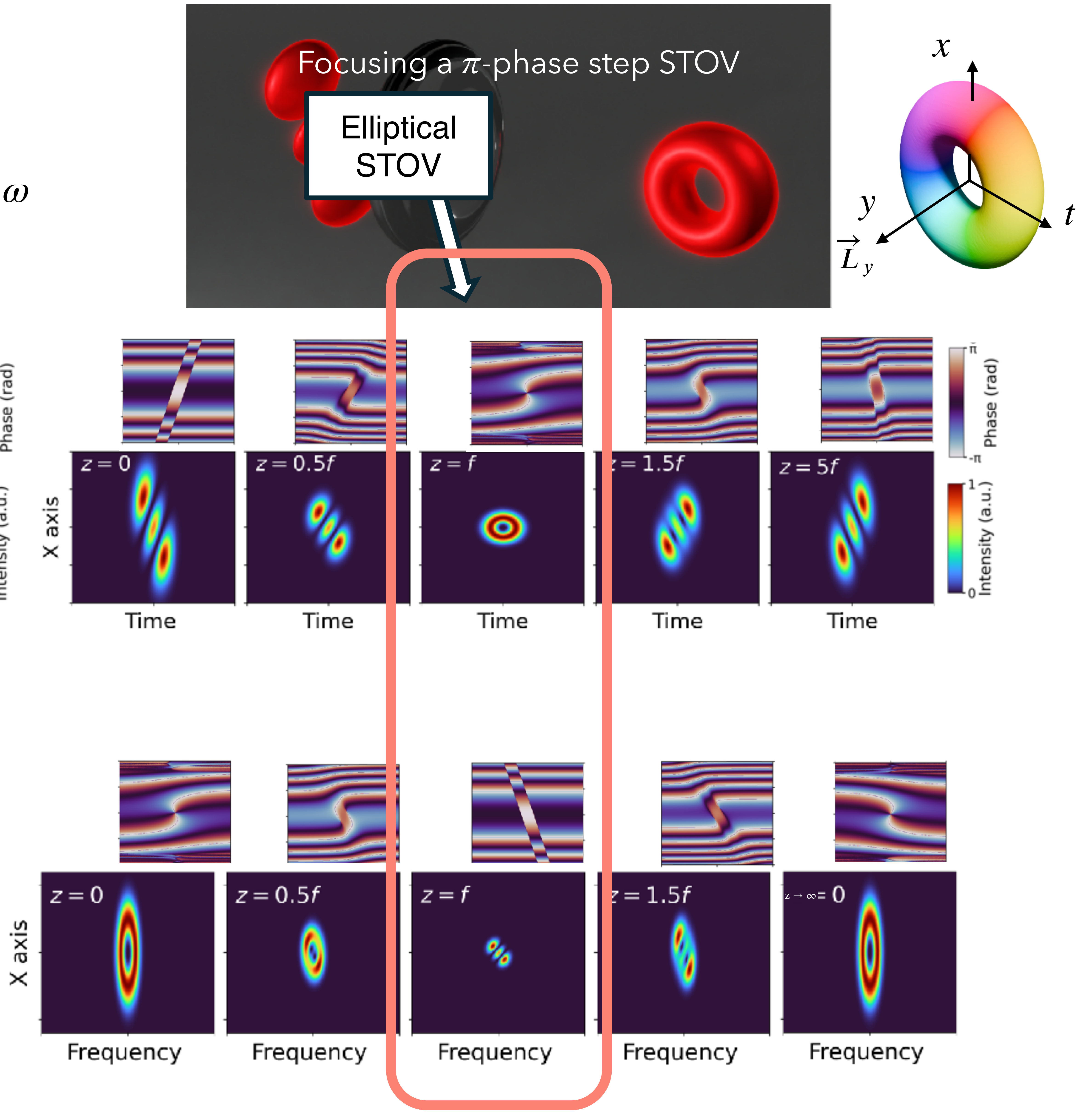
Applications:
J. Huang, et al. . Laser & Photonics Reviews 16, 2100357. (2022)
C. Wan, et al. eLight 2, 22 (2022).
Y. Chen, et al. Phys. Rev. A 107, 033112 (2023)
S. Huang et al..Sci. Adv.10, eadn6206 (2024)

STOV focusing dynamics





Numerical simulation results

$$\ell_q = q\ell_{IR}$$

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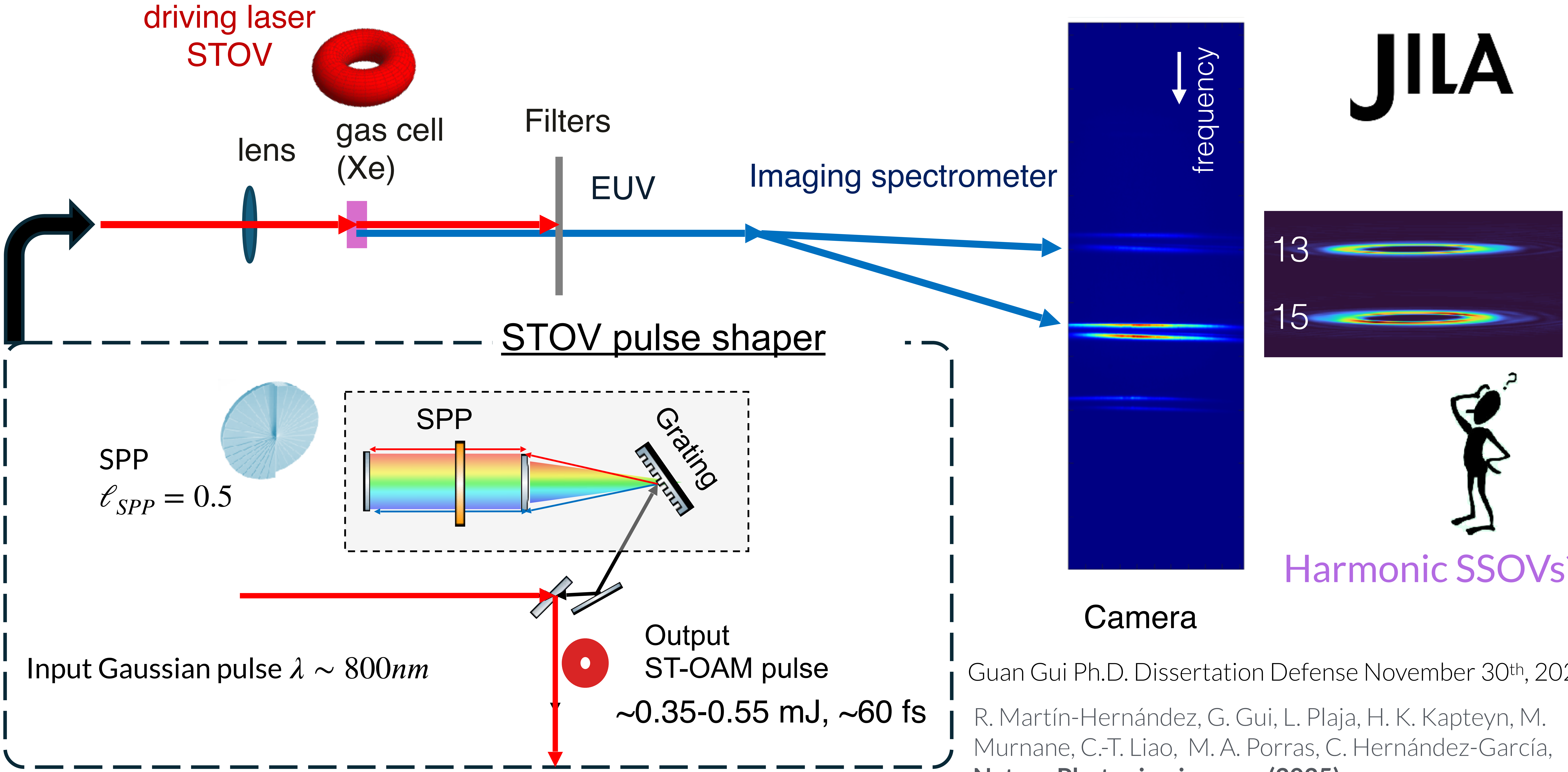
Experimental generation of EUV harmonic STOVs



JILA

Harmonic SSOVs?

Guan Gui Ph.D. Dissertation Defense November 30th, 2022

R. Martín-Hernández, G. Gui, L. Plaja, H. K. Kapteyn, M. Murnane, C.-T. Liao, M. A. Porras, C. Hernández-García, **Nature Photonics, in press (2025)**

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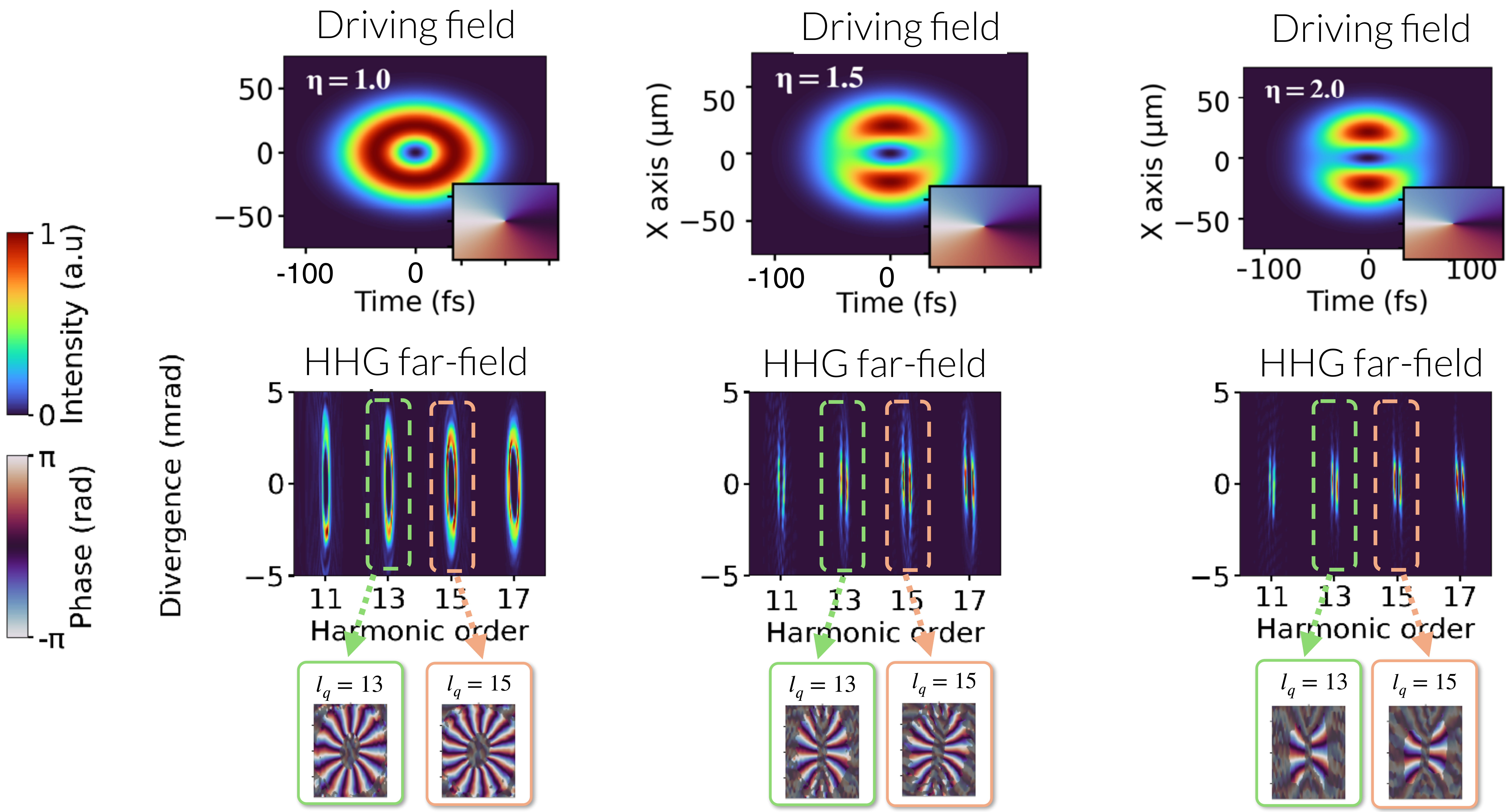
Inhomogeneity of the driving field



R. Martín-Hernández, G. Gui, L. Plaja, H. K. Kapteyn, M. Murnane, C.-T. Liao, M. A. Porras, C. Hernández-García, **Nature Photonics, in press (2025)**

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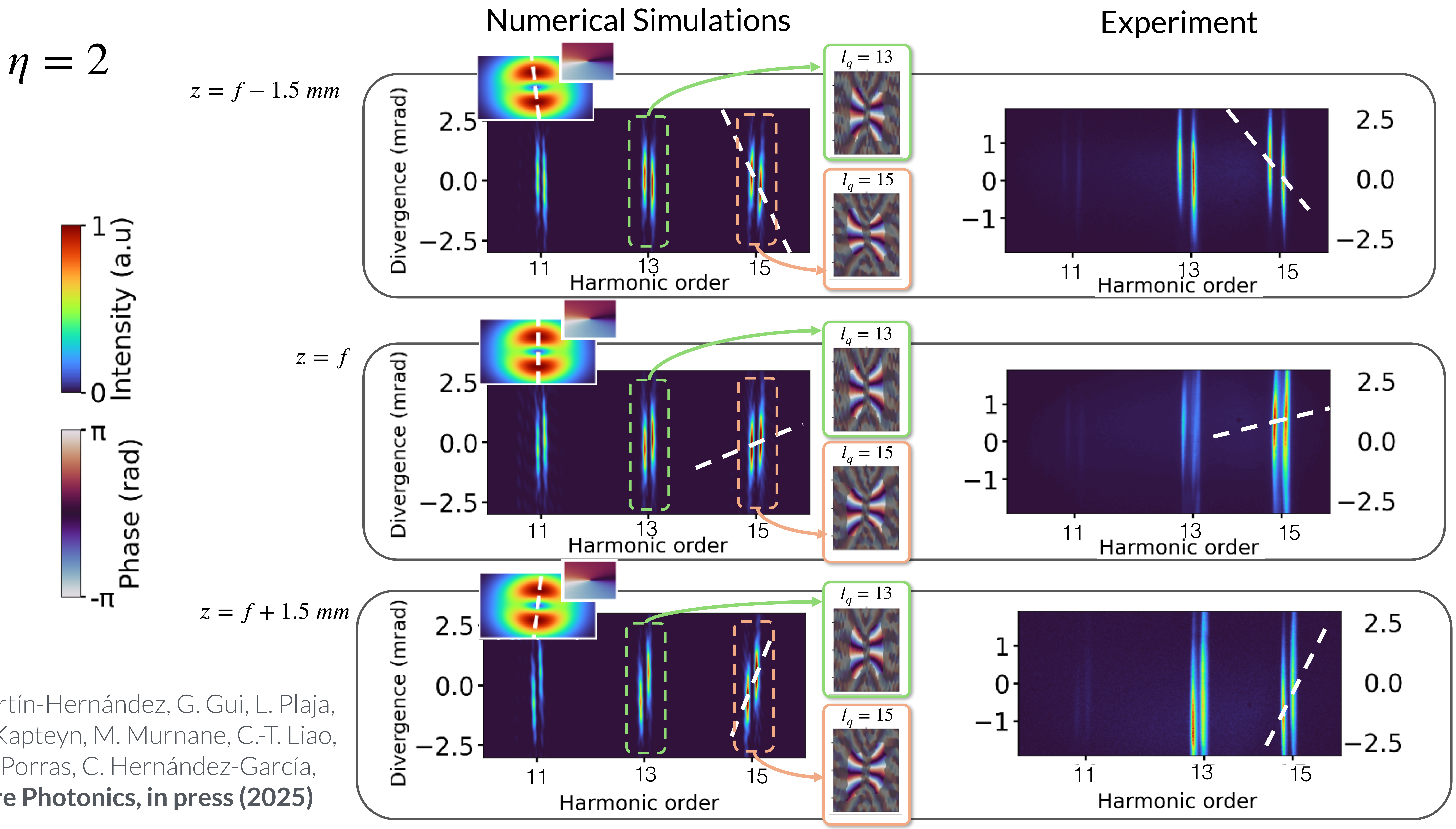
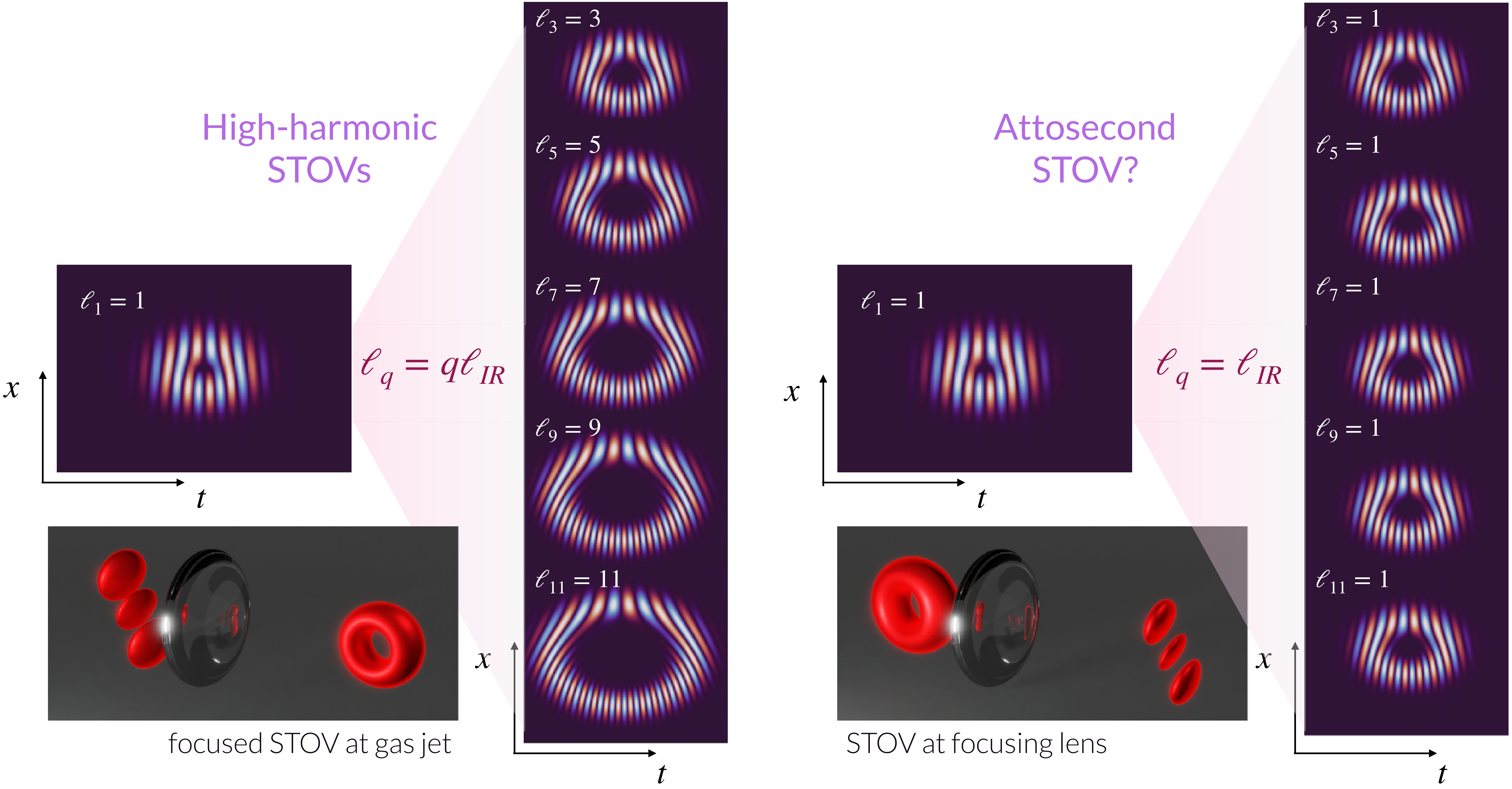
Theory-experiment comparison

$\eta = 2$

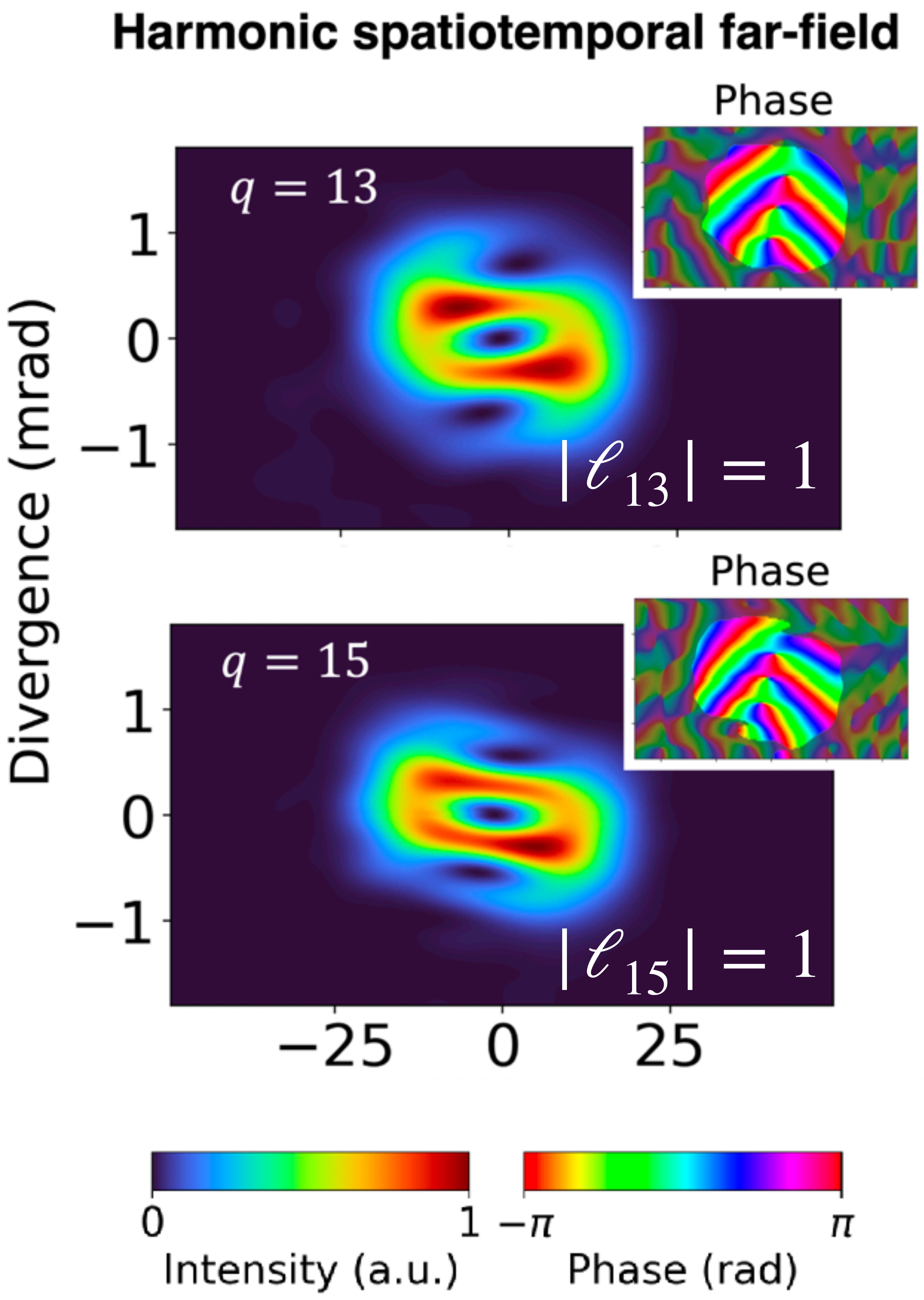


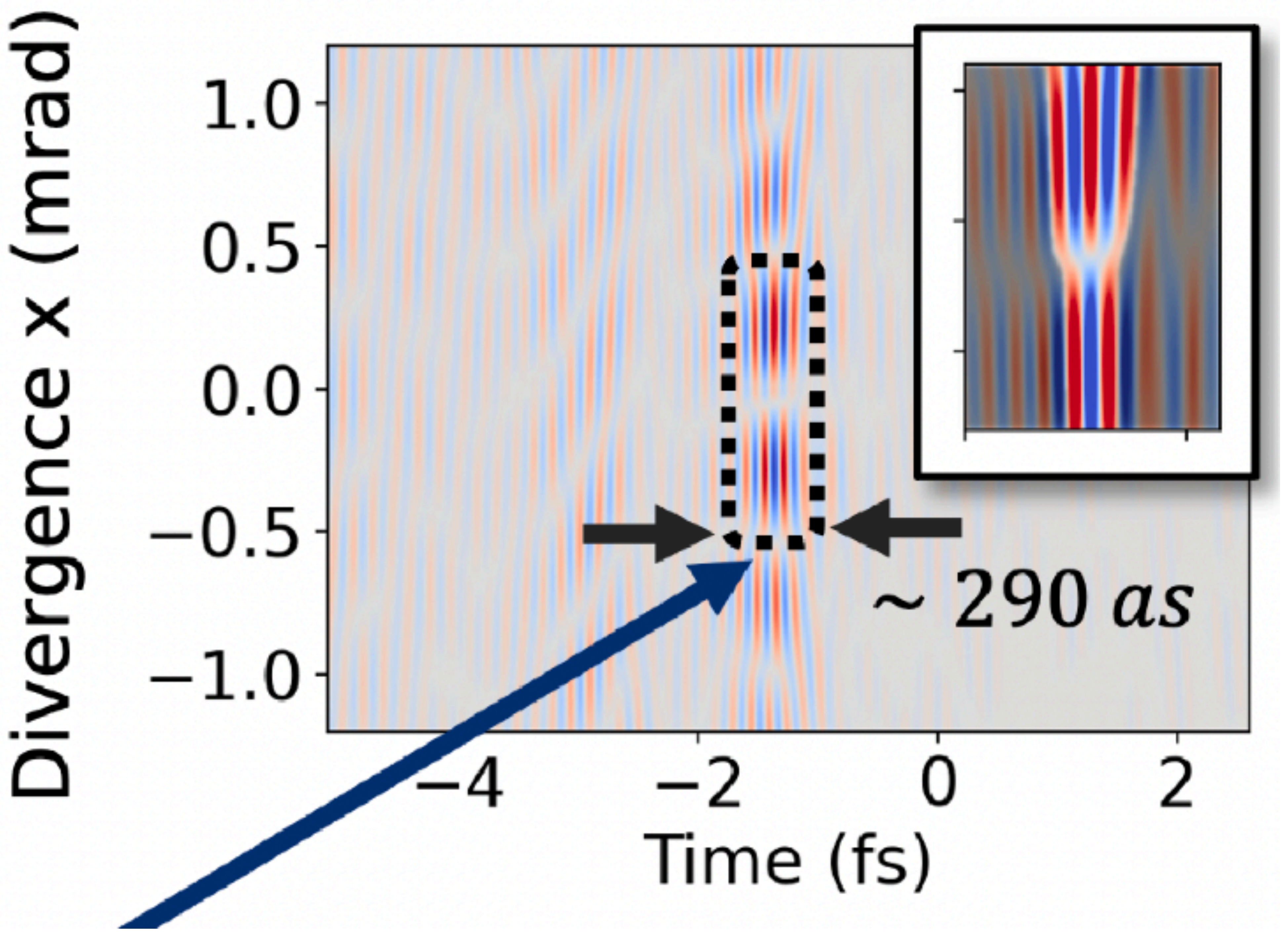
R. Martín-Hernández, G. Gui, L. Plaja, H. K. Kapteyn, M. Murnane, C.-T. Liao, M. A. Porras, C. Hernández-García, **Nature Photonics, in press (2025)**



High-harmonic STOVs
$\ell_1 = 1$
$\ell_q = q\ell_{IR}$
$\ell_3 = 3$
$\ell_5 = 5$
$\ell_7 = 7$
$\ell_9 = 9$
$\ell_{11} = 11$
x
t
focused STOV at gas jet
Attosecond STOV?
$\ell_1 = 1$
$\ell_q = \ell_{IR}$
$\ell_3 = 1$
$\ell_5 = 1$
$\ell_7 = 1$
$\ell_9 = 1$
$\ell_{11} = 1$
STOV at focusing lens

Attosecond STOVs

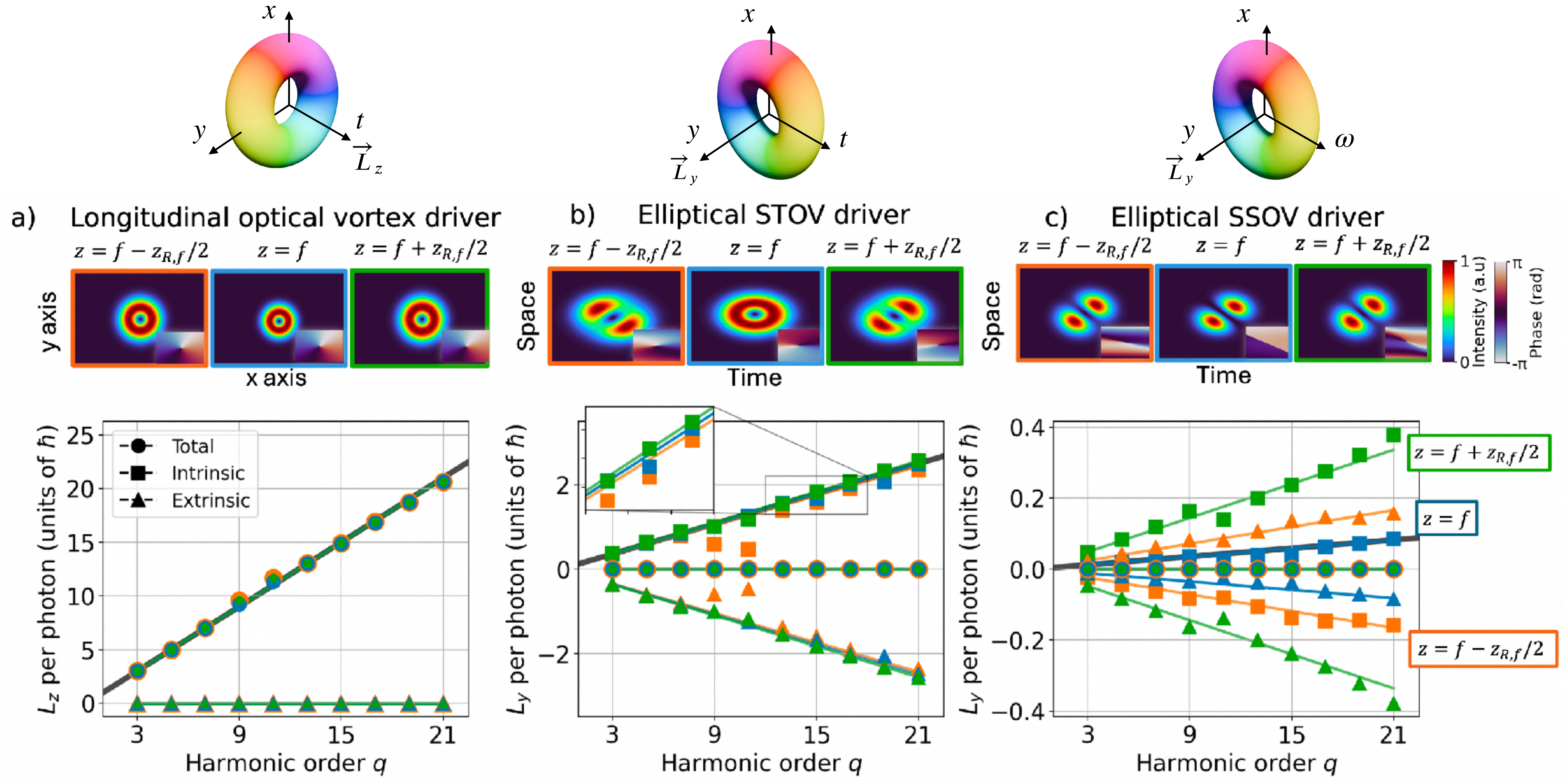




$\ell_q = \ell_{IR}$ Attosecond STOV!

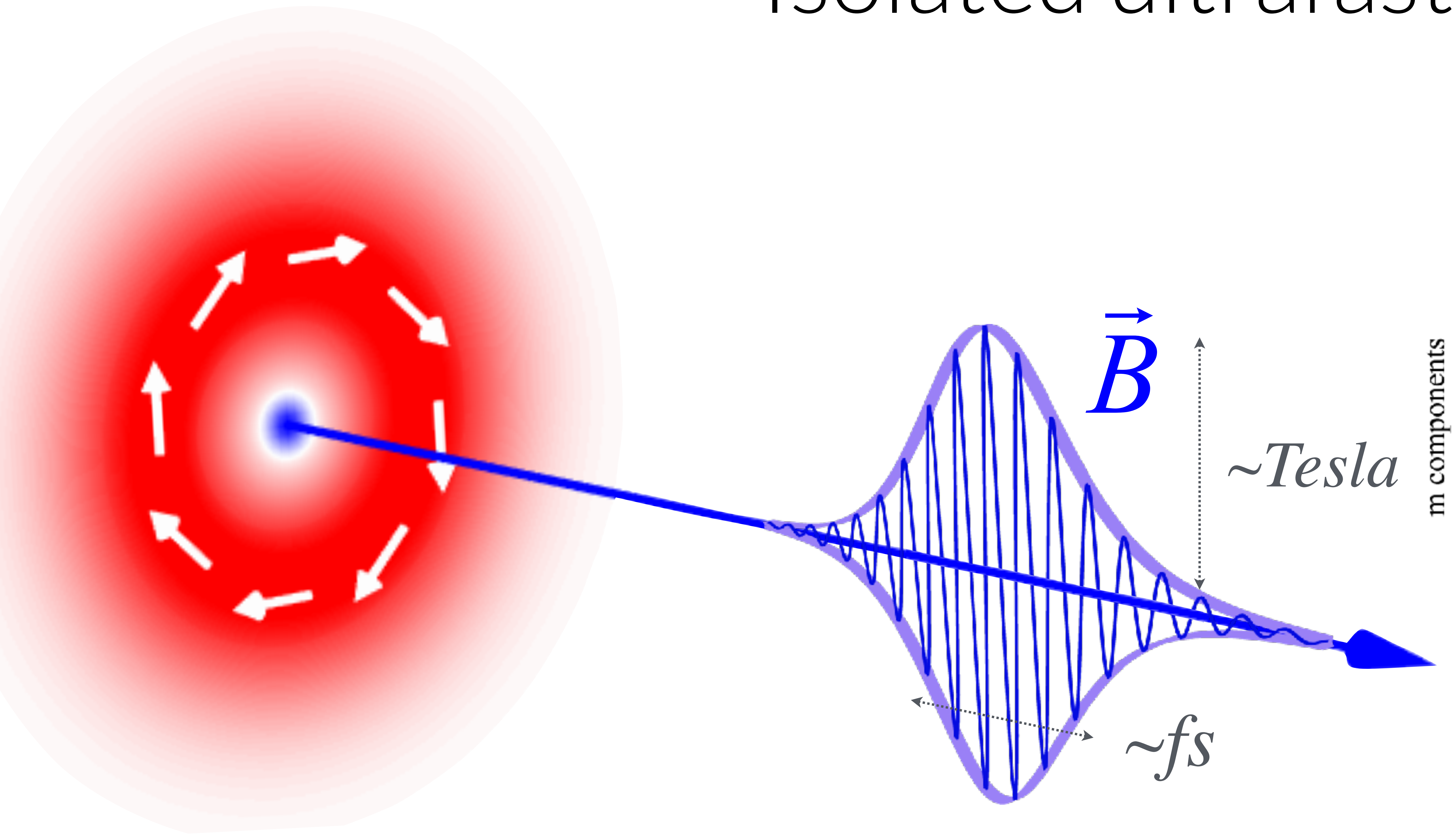
R. Martín-Hernández, L. Plaja, C. Hernández-García, M. A. Porras
arXiv:2506.07465

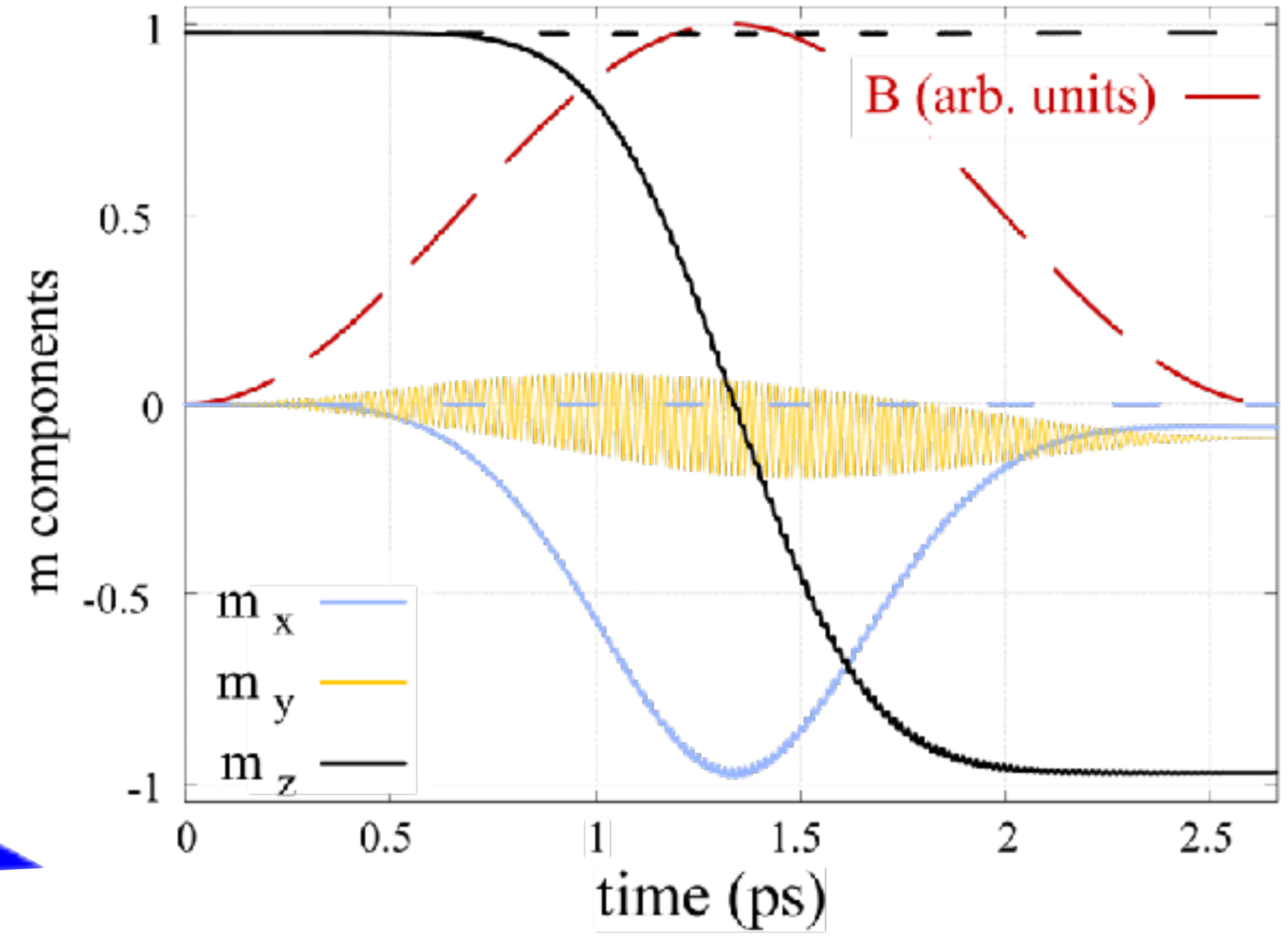
Topological charge scaling vs OAM conservation



R. Martín-Hernández, L. Plaja, C. Hernández-García, M. A. Porras **arXiv:2506.07465**

Isolated ultrafast and ultraintense magnetic fields

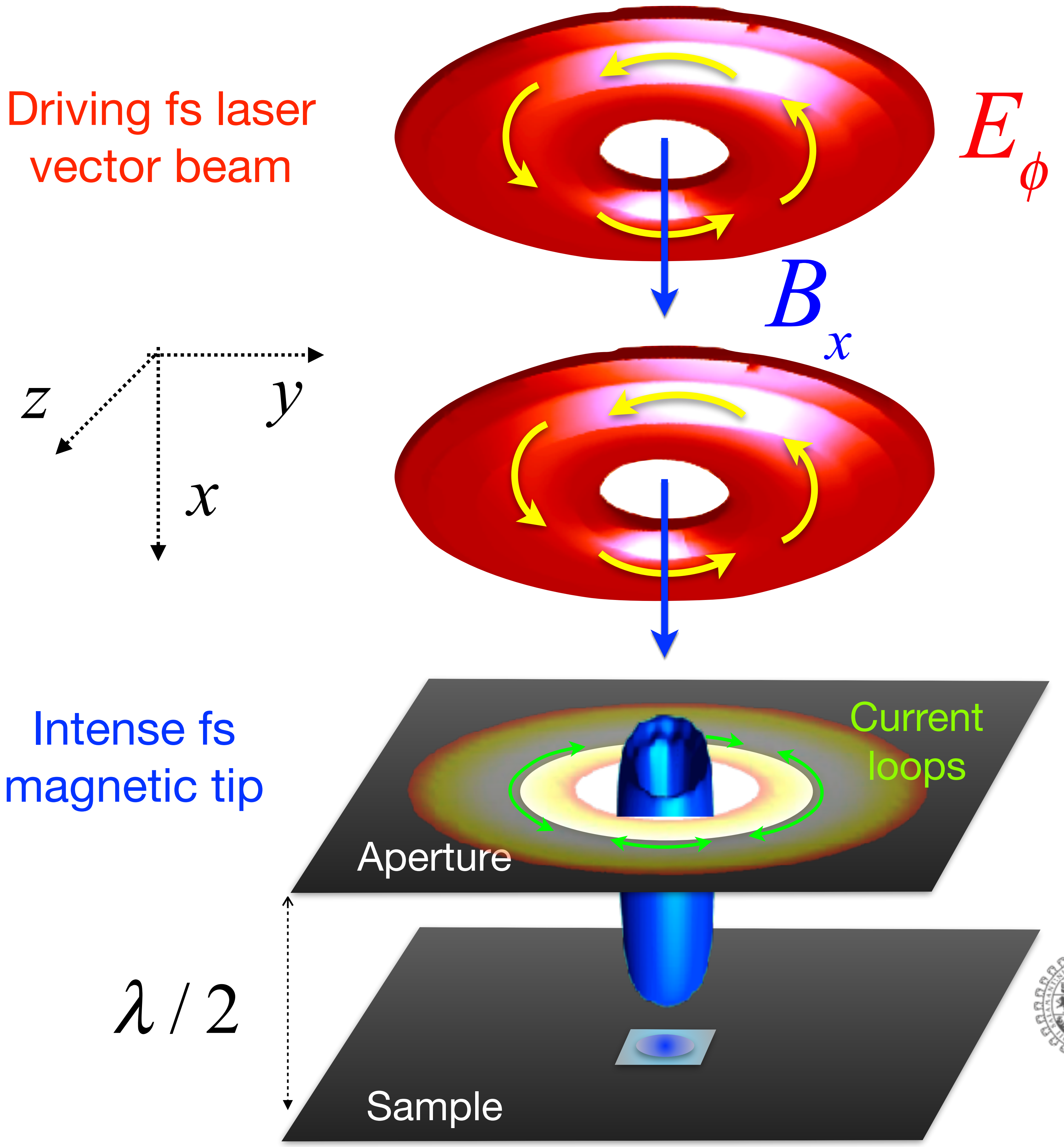




Sergio Martín Domene | Rodrigo Martín-Hernández | Luis Sánchez-Tejerina

M. Blanco, et al., **ACS Photonics 6**, 38-42 (2019).
L. Sánchez-Tejerina, et al. **High Power Laser Science and Engineering 11,** e82 (2023).
R. Martín-Hernández, et al. **Photonics Research 12**(5), 1078 (2024).
S. Martín-Domene, et al. **Appl. Phys. Lett. 124** 211101 (2024)

Generation of intense, ultrafast magnetic fields



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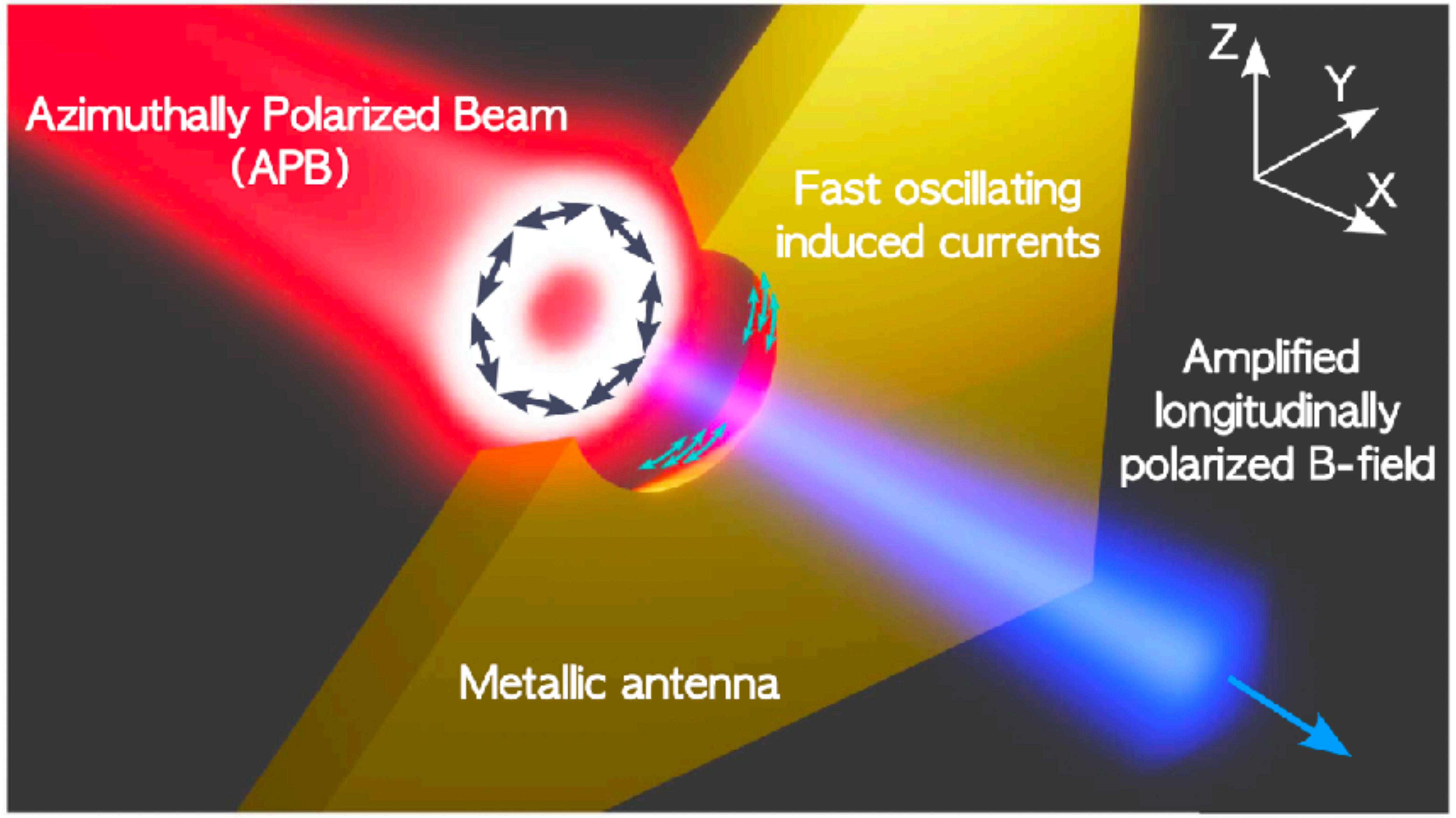
USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

M. Blanco, F. Cambronero, M.T. Flores-Arias, E. Conejero Jarque, L. Plaja and C. Hernández-García, **ACS Photonics 6, 38-42 (2019).**



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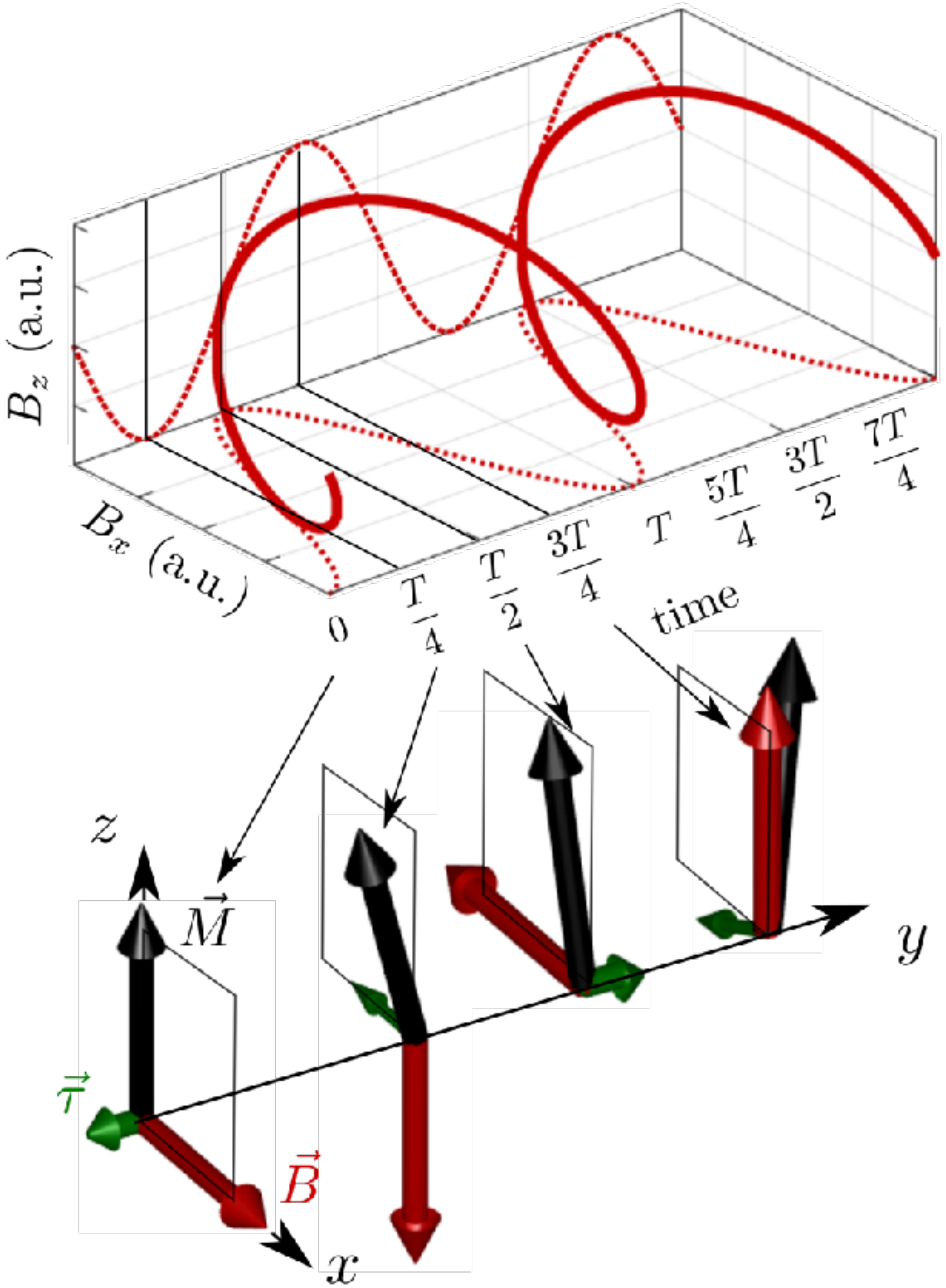
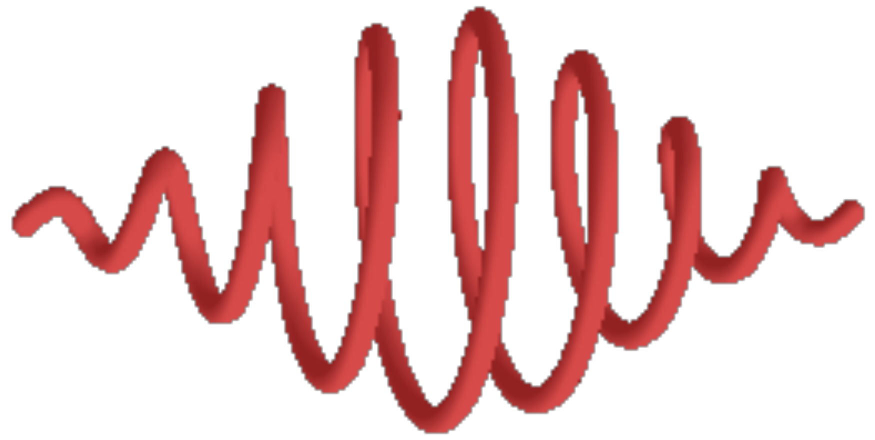
R. Martín-Hernández, L. Grünewald, L. Sánchez-Tejerina, E. Conejero -Jarque, L. Plaja, C. Hernández-García, S. Mai. **Photonics Research 12(5), 1078 (2024).**

Nonlinear B-field driven magnetization dynamics





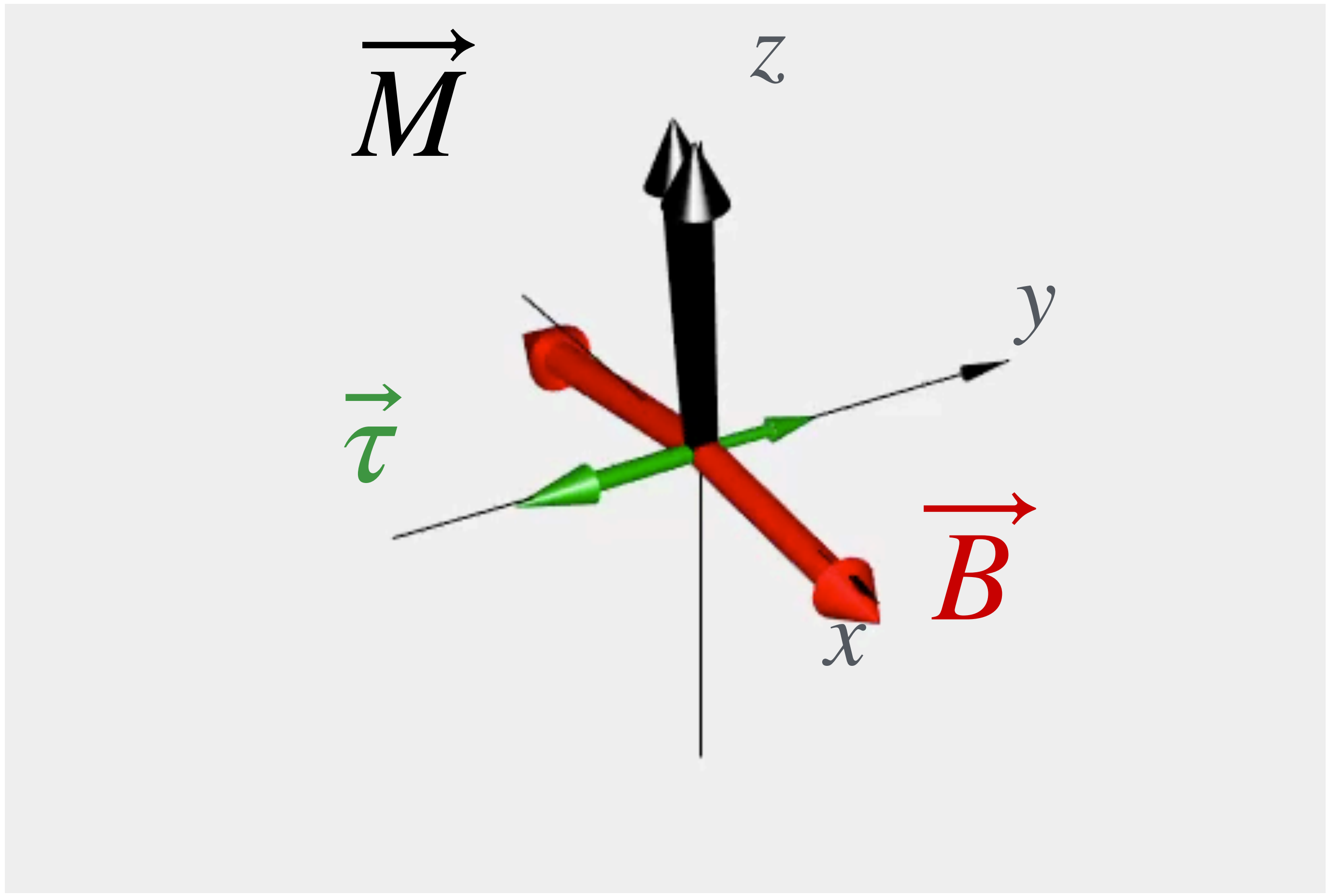
Circularly polarized B field

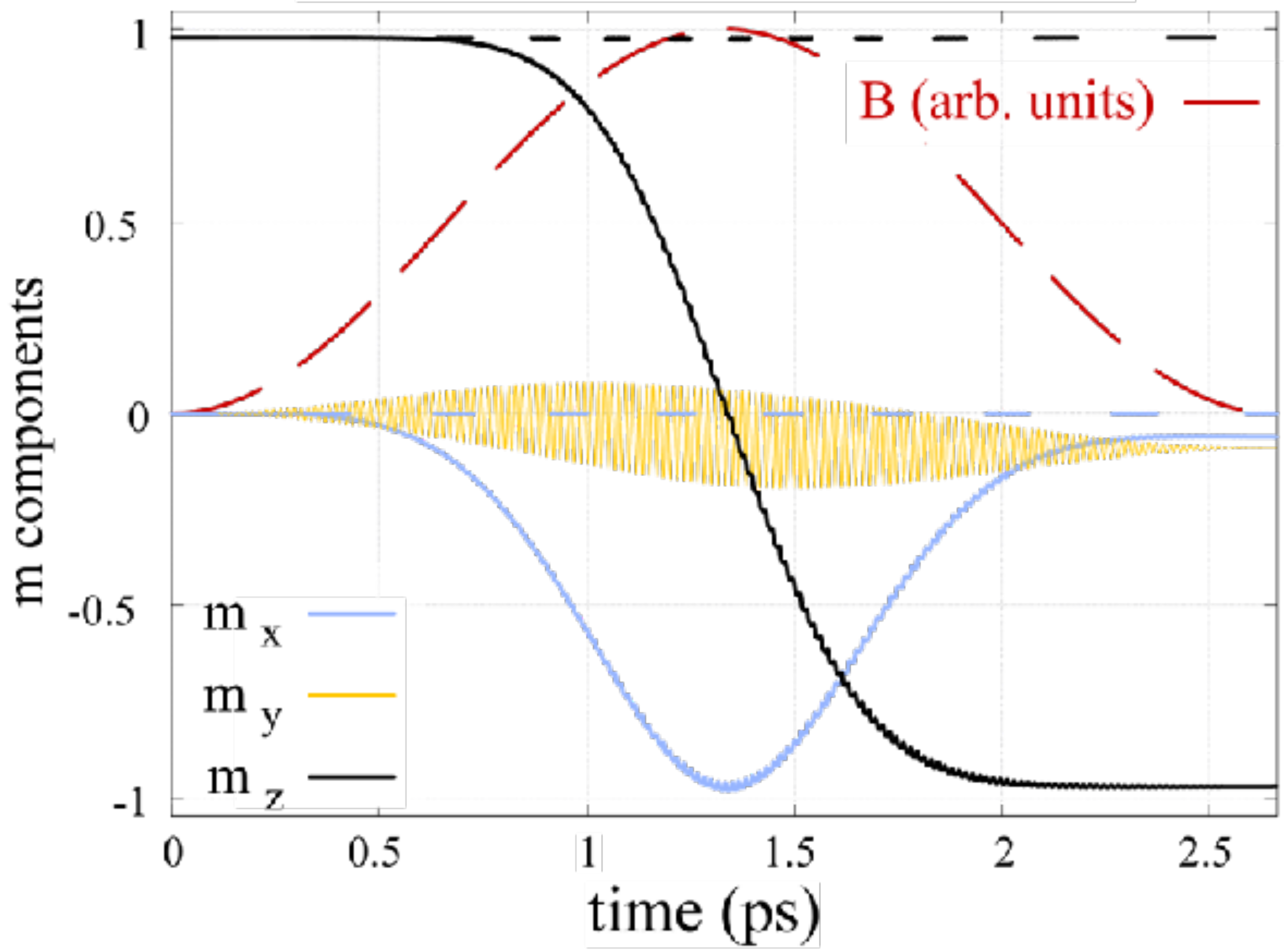
$100THz, \lambda_B = 3\mu m$

$275T$

1 ps (FWHM)

Magnetization dynamics





Simulations: CoFeB, micromagnetic, MuMax3

$$\frac{d\vec{m}_0^{\parallel}(t)}{dt} = -\frac{2i\gamma^2}{\omega}\vec{m}_0^{\parallel}(t) \times \left(\vec{b}(t) \times \vec{b}^*(t)\right)$$

L. Sánchez-Tejerina, R. Hernández-Martín, R. Yanes, L. Plaja, L. López-Díaz and C. Hernández-García,
High Power Laser Science and Engineering 11, e82 (2023).

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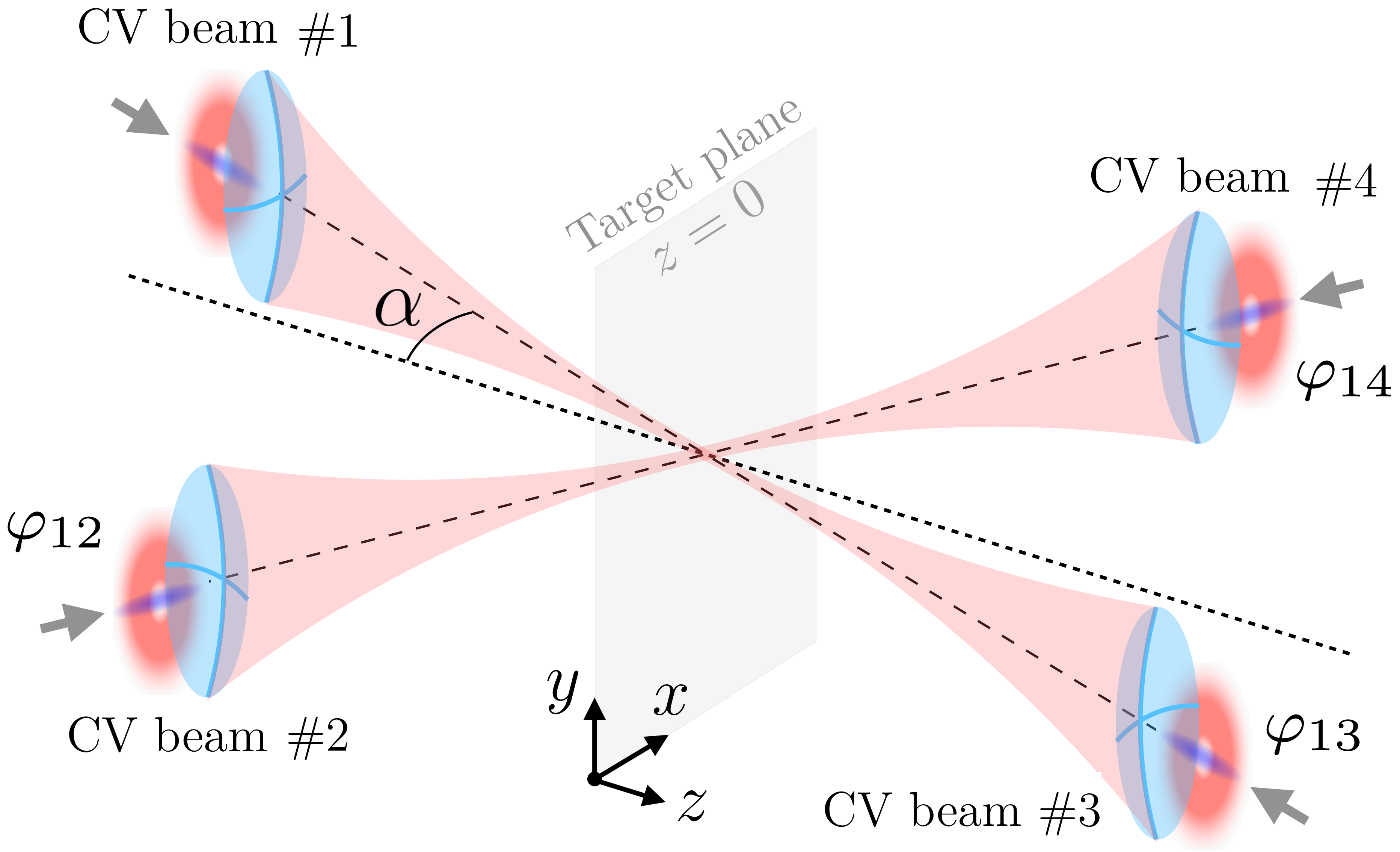
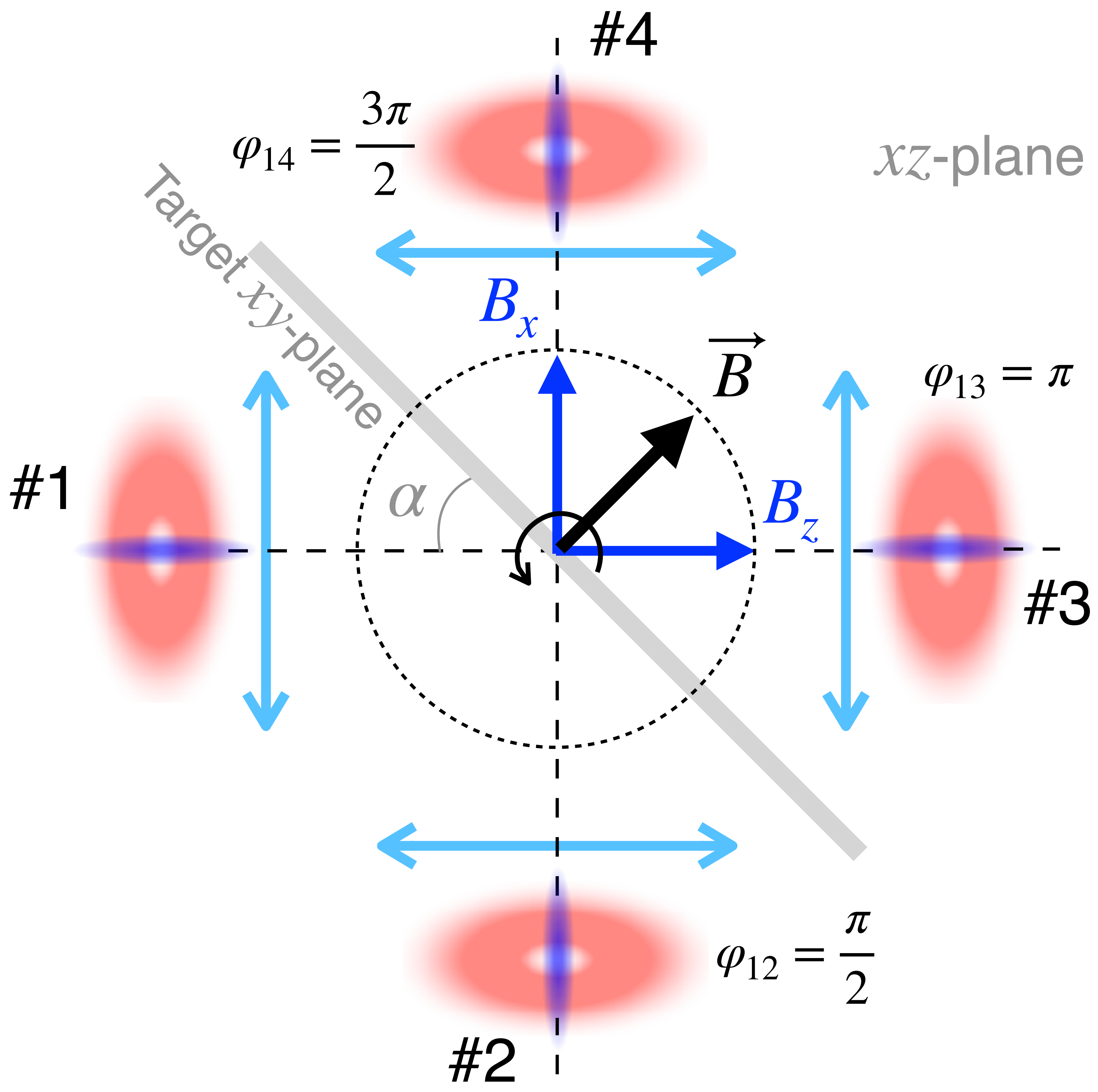
Isolated circularly-polarized B fields

$$B_x(\mathbf{r}) \propto e^{-(x^2+z^2)/w_0^2}$$
$$B_z(\mathbf{r}) \propto e^{-(x^2+z^2)/w_0^2}\, e^{i\pi/2}$$

$\longrightarrow$ **Maxwell's equations: longitudinally polarized E-field vortex**

Our first approach:





S. Martín-Domene, L. Sánchez-Tejerina, R. Martín-Hernández, C. Hernández-García
Appl. Phys. Lett. 124 211101 (2024)

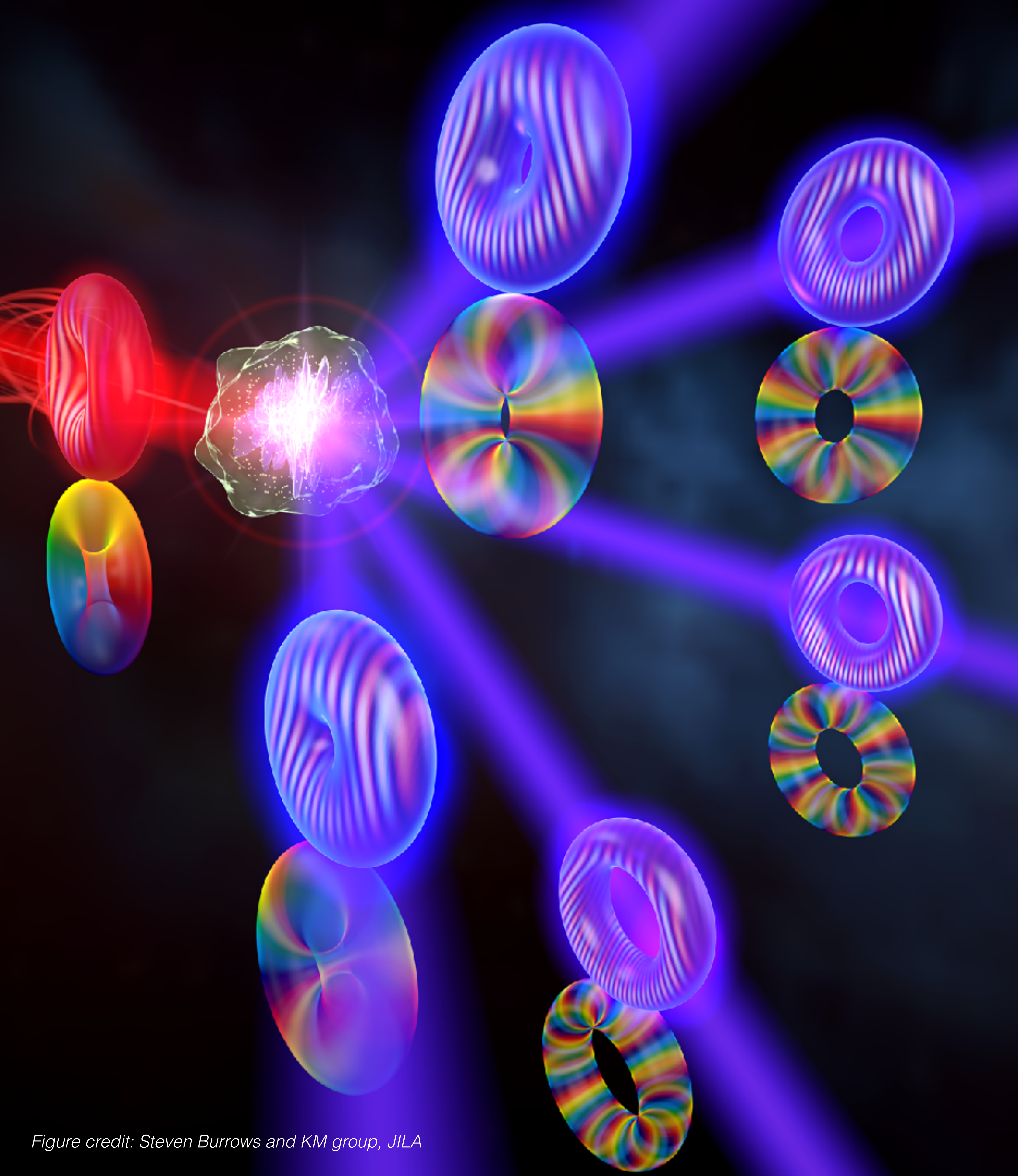


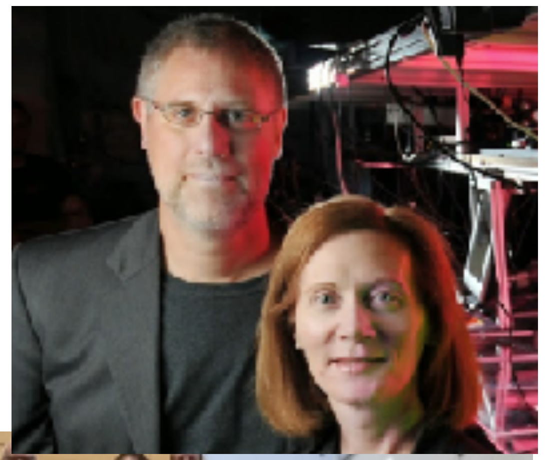
Figure credit: Steven Burrows and KM group, JILA

We can generate many kinds of structured light beams at the attosecond timescale

Exciting future prospects in HHG interacting with solids & generation of isolated B-fields

Collaborators

University of Colorado (USA)



Nathan Brooks
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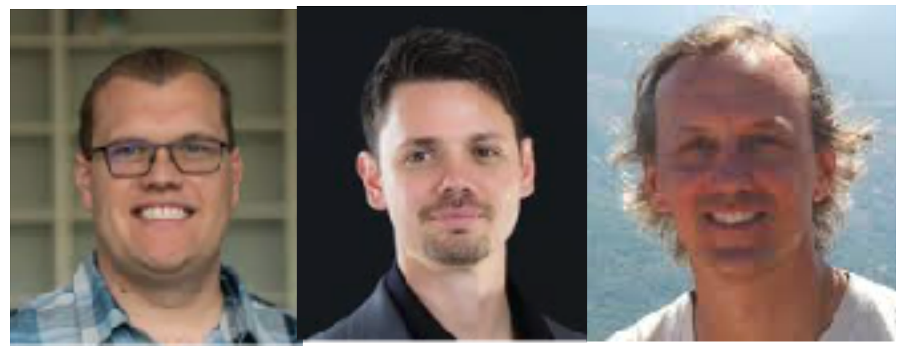
Kevin Dorney
Guan Gui
Chen-Ting Liao
Henry Kapteyn
M. Murnane

Colorado S. Mines (USA)

David Schmidt
Dan Adams
Charles Durfee



U. Politecnica Madrid (Spain)

M. A. Porras

U. Paris-Saclay (France)

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Olivier Guibaud
Sophie Kazamias

Martin Luttman
Matthieu Guer
Thierry Ruchon

Politecnico di Milano (Italy)

Federico Vismarra
Rocío Borrego-Varillas
Matteo Lucchini

Lund University (Sweden)

Melvin Redon
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Peter Kazansky

Univ. Santiago de Compostela (Spain)

M. Blanco
F. Cambronero
M. Flores-Arias

S. Mai
L. Grünewald

U. California San Diego (USA)

Tenio Popmintchev

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Unidad de Excelencia en
Luz y Materia Estructuradas (LUMES)

Laser Applications and Photonics Group

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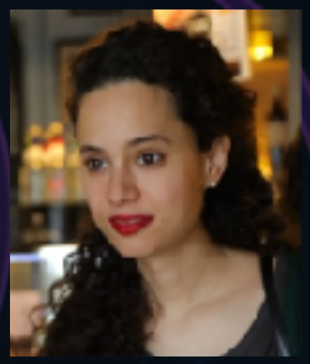
Benjamín Alonso


Enrique Conejero


Aurora Crego


Carlos Hernández-García


Irene Huerta


Ignacio López Quintás

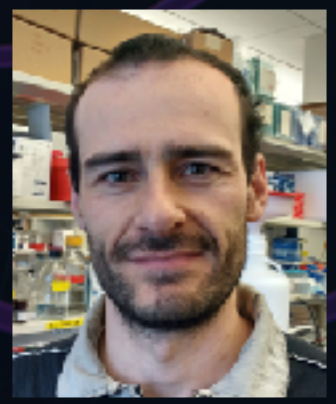

Rosa Merchán


Pablo Moreno

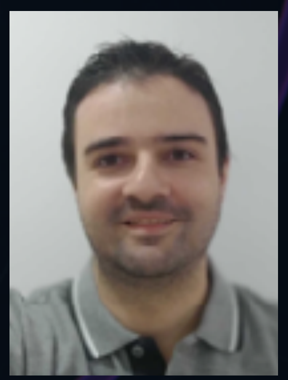

Luis Plaja


Javier Rguez. Vázquez de Aldana


Carolina Romero

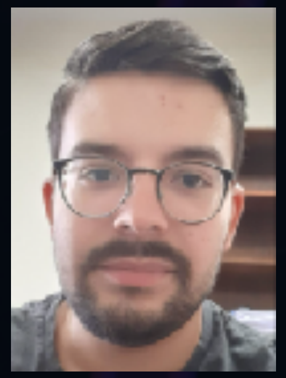

Andrés Sanz

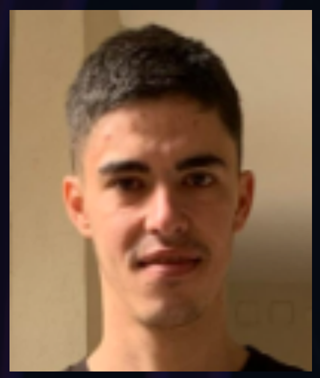

Julio San Román


Javier Serrano


Íñigo Sola


Óscar Zurrón


Víctor Arroyo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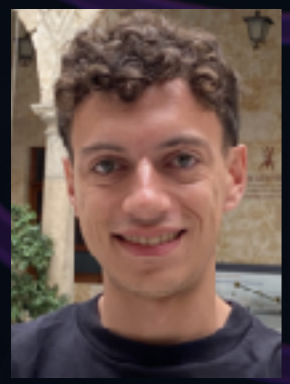
Marina Fernández Galán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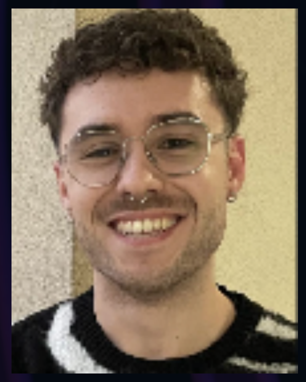
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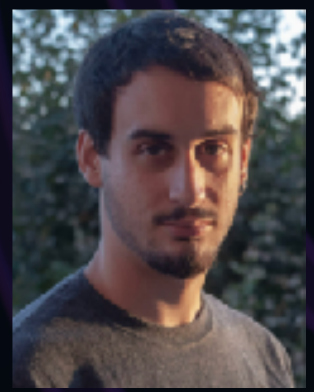
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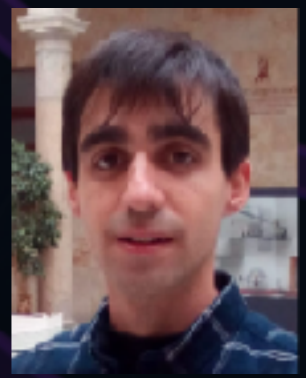
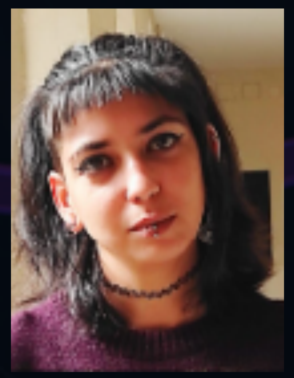

José Miguel Pablos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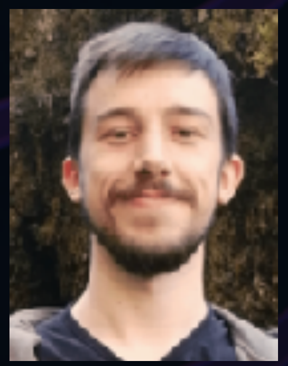
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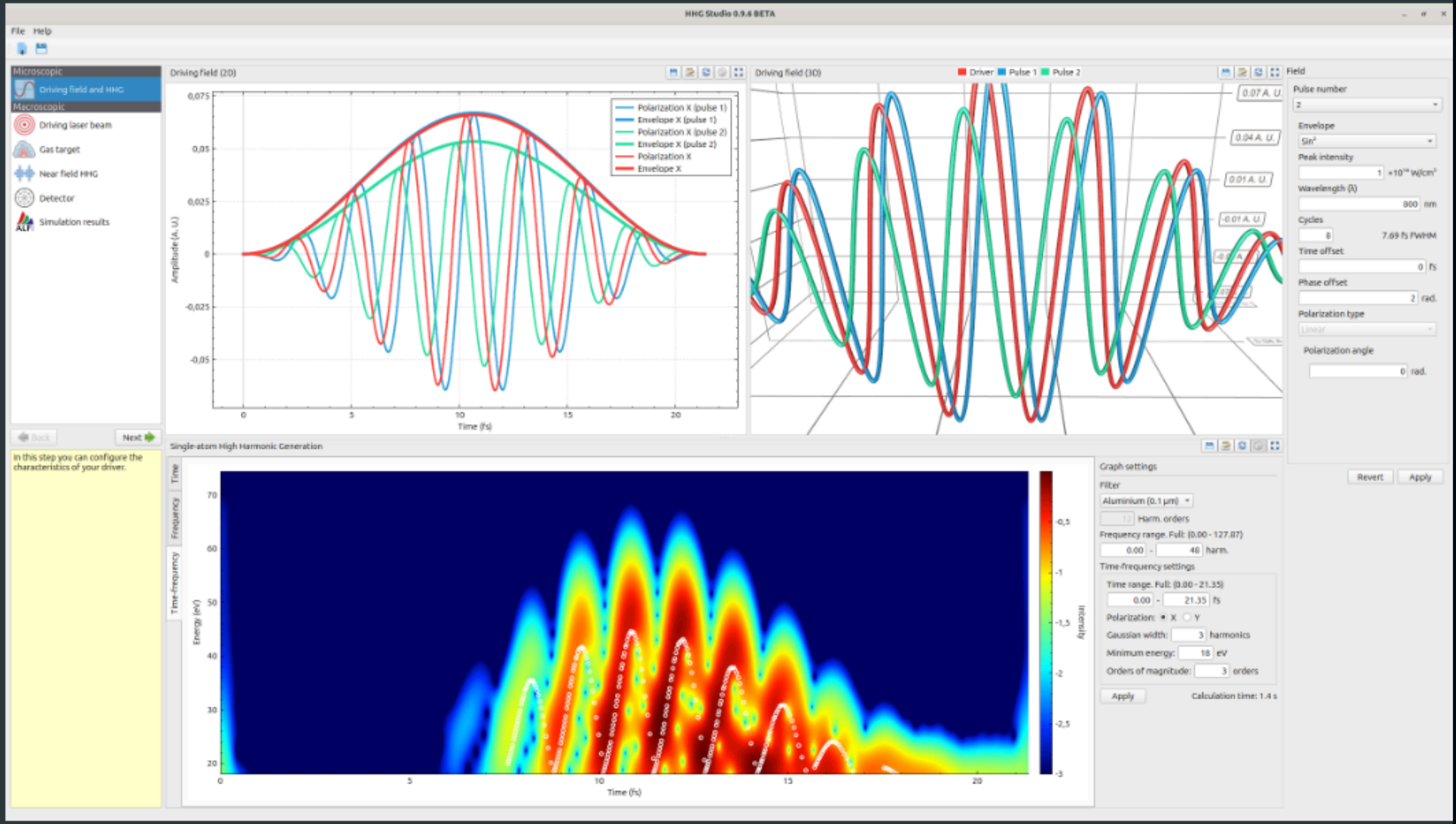

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