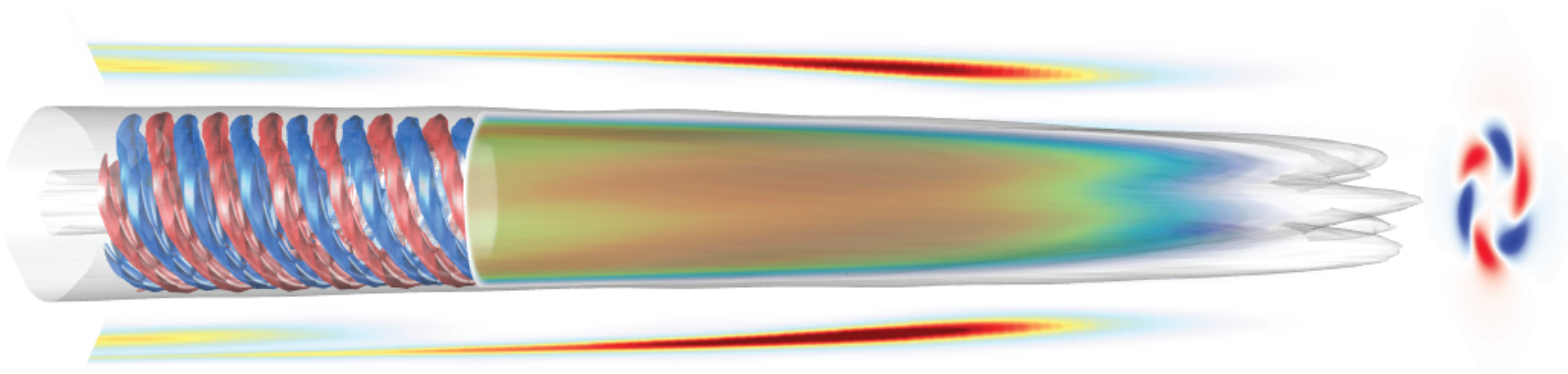
Plasma accelerators driven by exotic light beams

Jorge Vieira
GoLP / IPFN, Instituto Superior Técnico, Lisbon, Portugal



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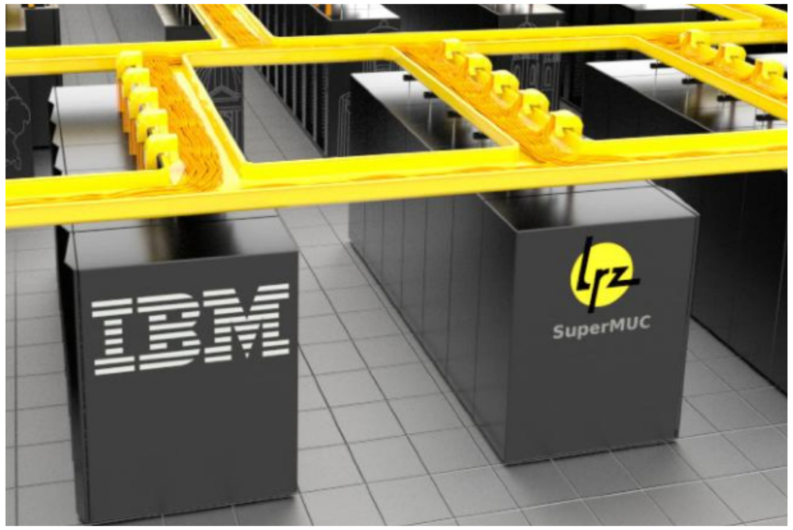
ipfn INSTITUTO DE PLASMAS E FUSÃO NUCLEAR

Acknowledgements

Work in collaboration with:

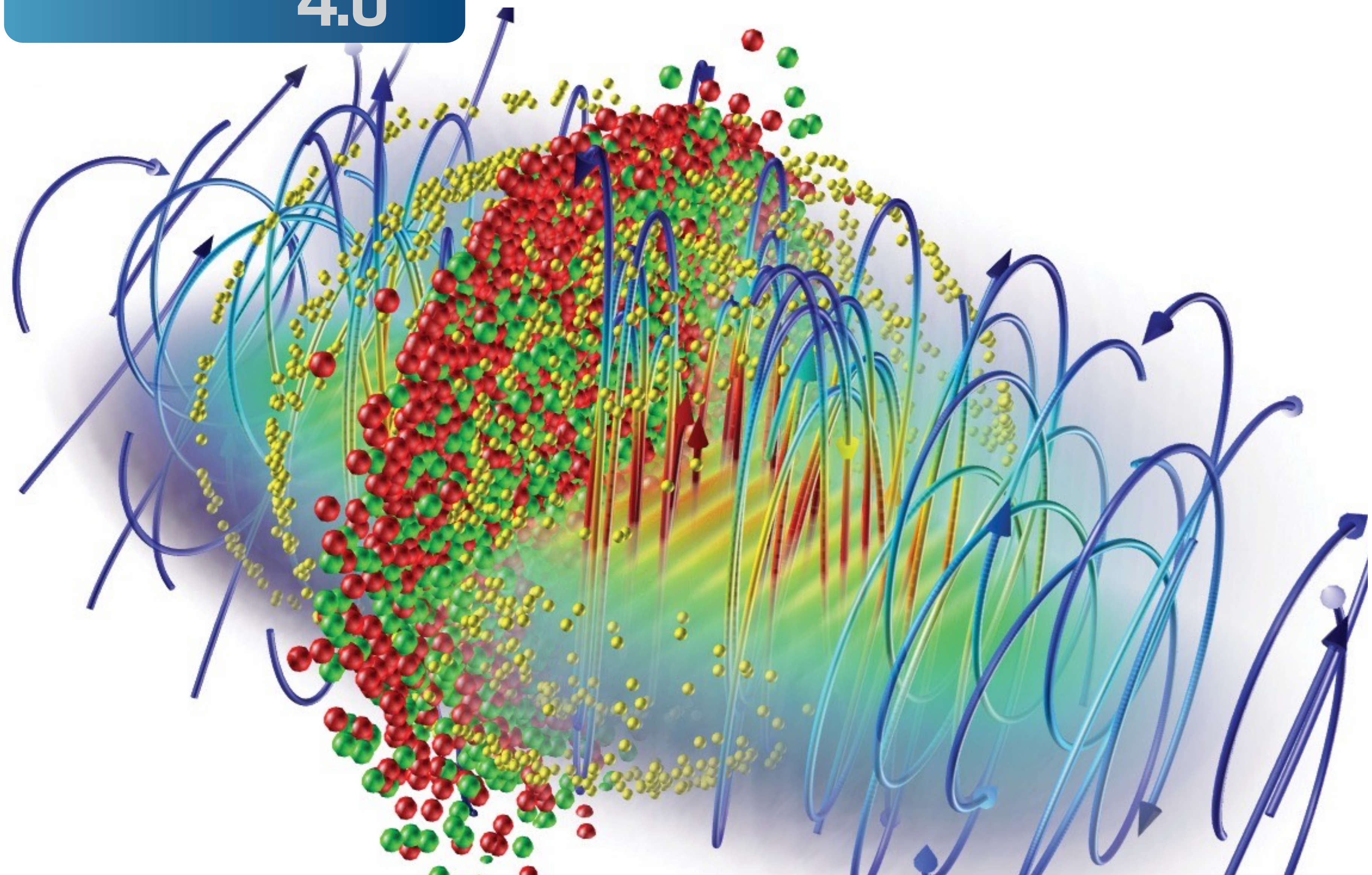
M. Pardal, J.T. Mendonça, R.A. Fonseca, L.O. Silva (IST); **E.P. Alves** (SLAC)
F. Quéré (CEA); **R. Bingham, R. Trines** (RAL,STFC), **Y. Shi, R. Kingham** (Imperial College)

Simulation results obtained at the SuperMUC supercomputer in Garching, Germany.



OSIRIS 4.0

Committed to open science



Open-access model

- 40+ research groups worldwide are using OSIRIS
- 300+ publications in leading scientific journals
- Large developer and user community
- Detailed documentation and sample inputs files available

Using OSIRIS 4.0

- The code can be used freely by research institutions after signing an MoU
- Find out more at:

http://epp.tecnico.ulisboa.pt/osiris

OSIRIS framework

- Massively Parallel, Fully Relativistic Particle-in-Cell Code
- Parallel scalability to 2 M cores
- Explicit SSE / AVX / QPX / Xeon Phi / CUDA support
- Extended simulation/physics models

visXD

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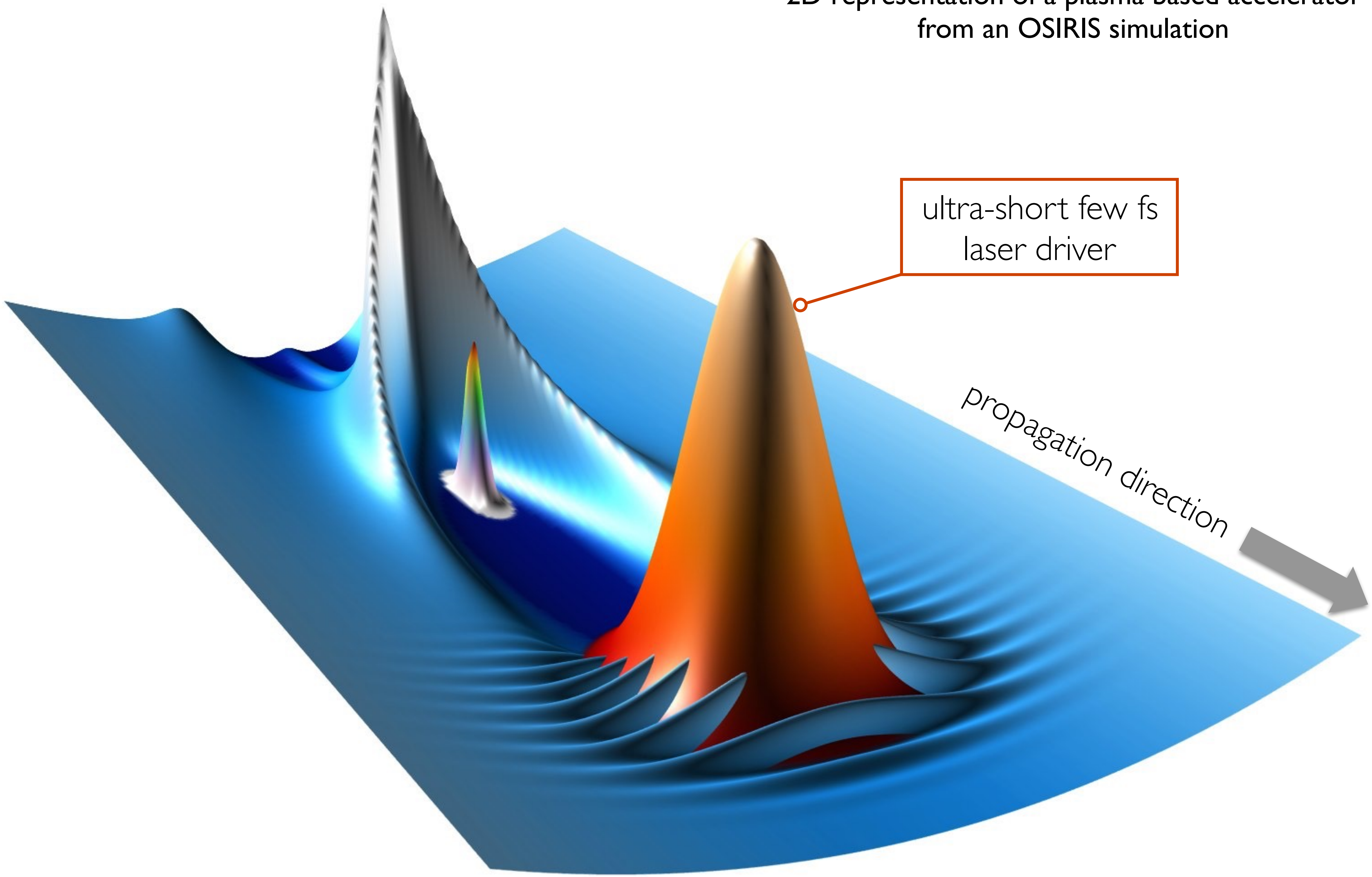
Ricardo Fonseca: ricardo.fonseca@tecnico.ulisboa.pt

How do plasma accelerators work?

2D representation of a plasma based accelerator
from an OSIRIS simulation



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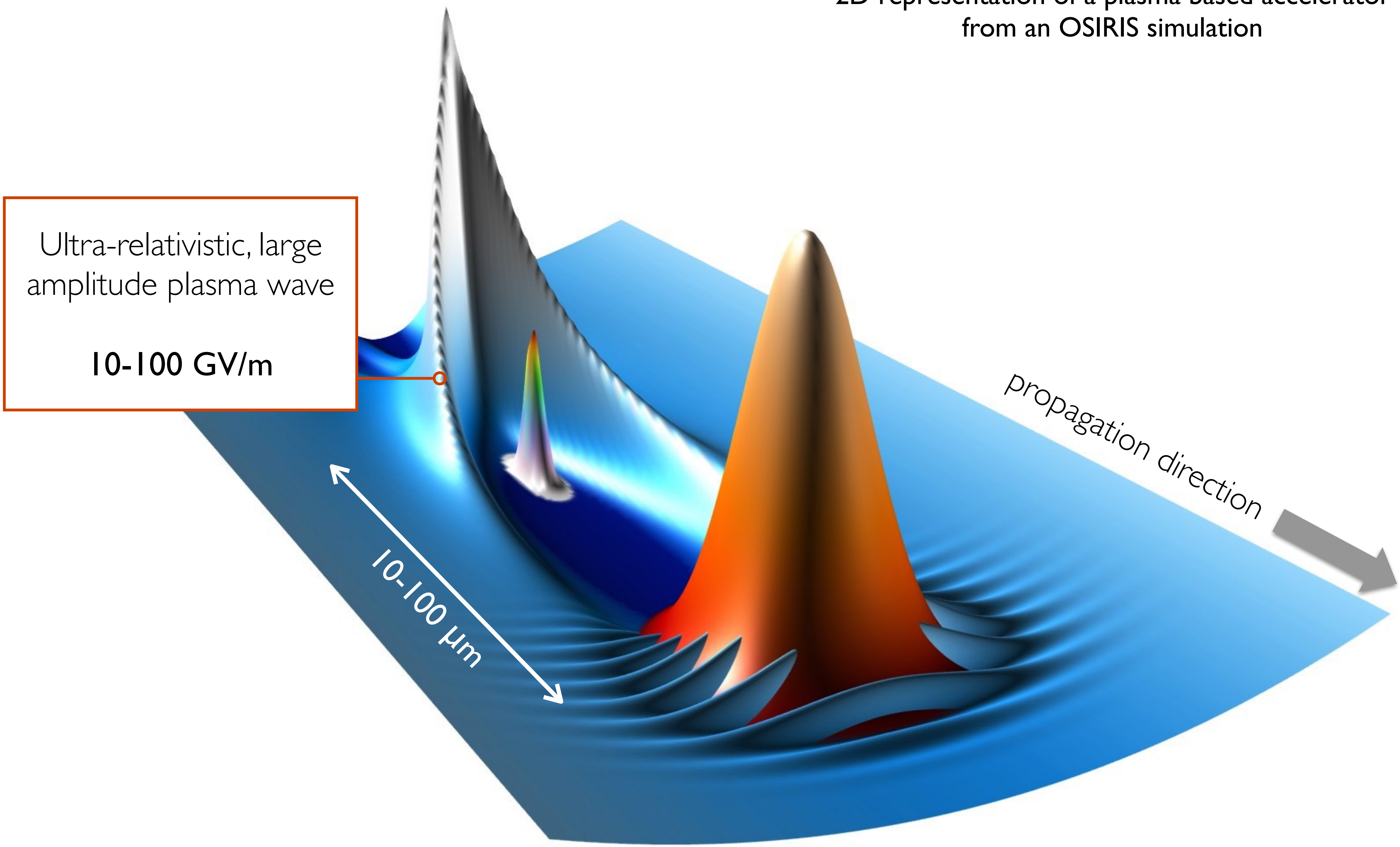

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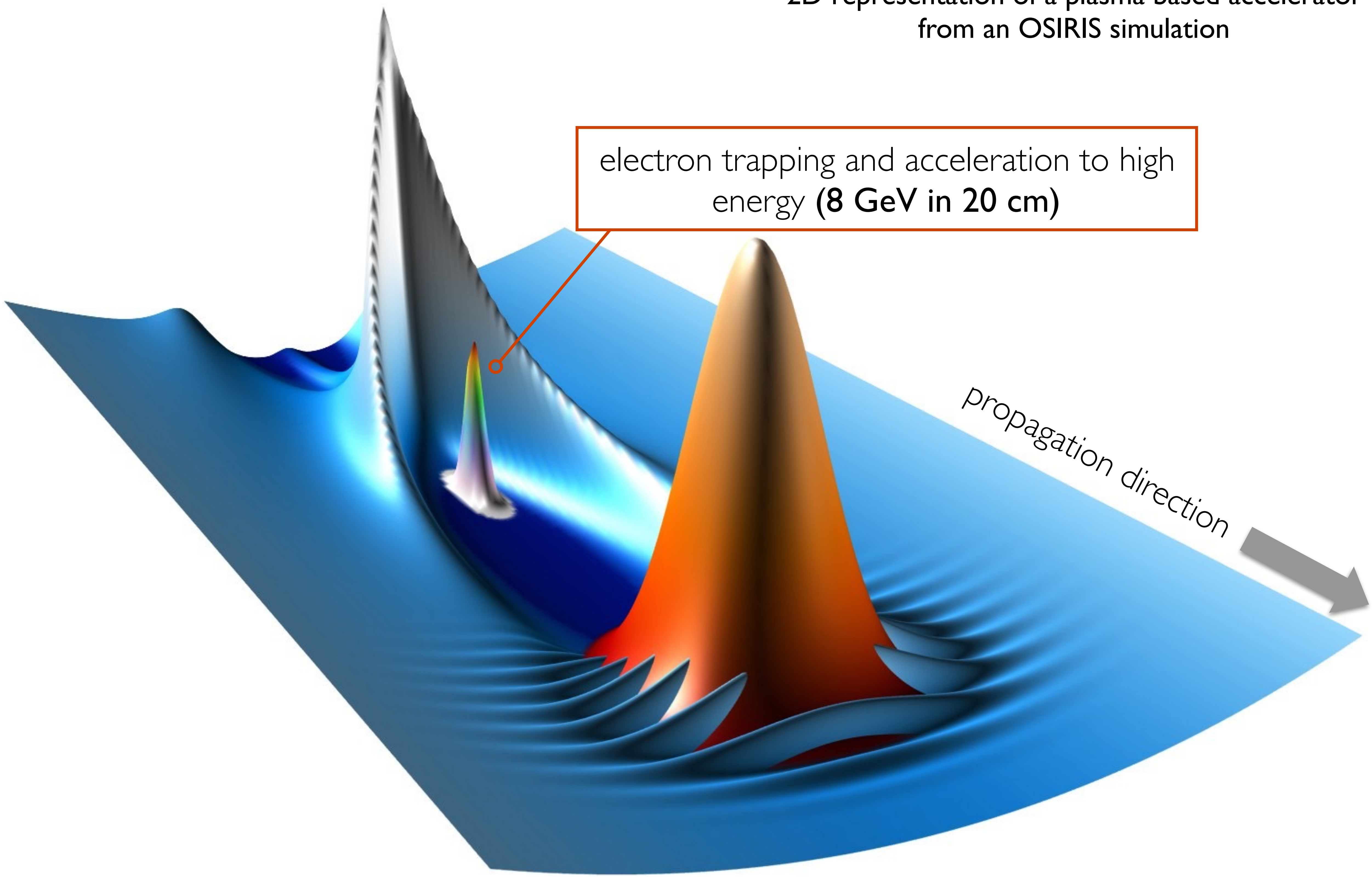

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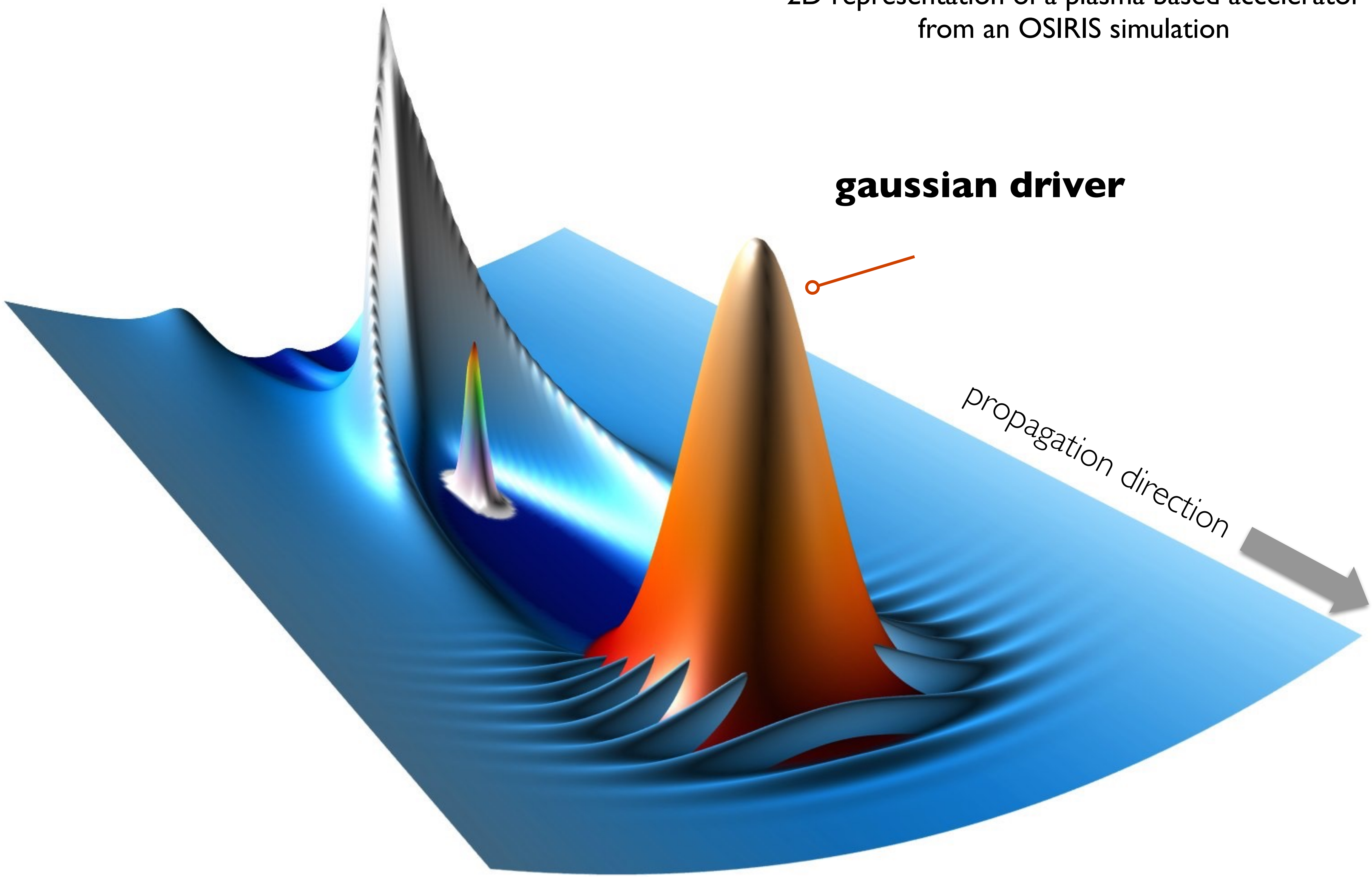

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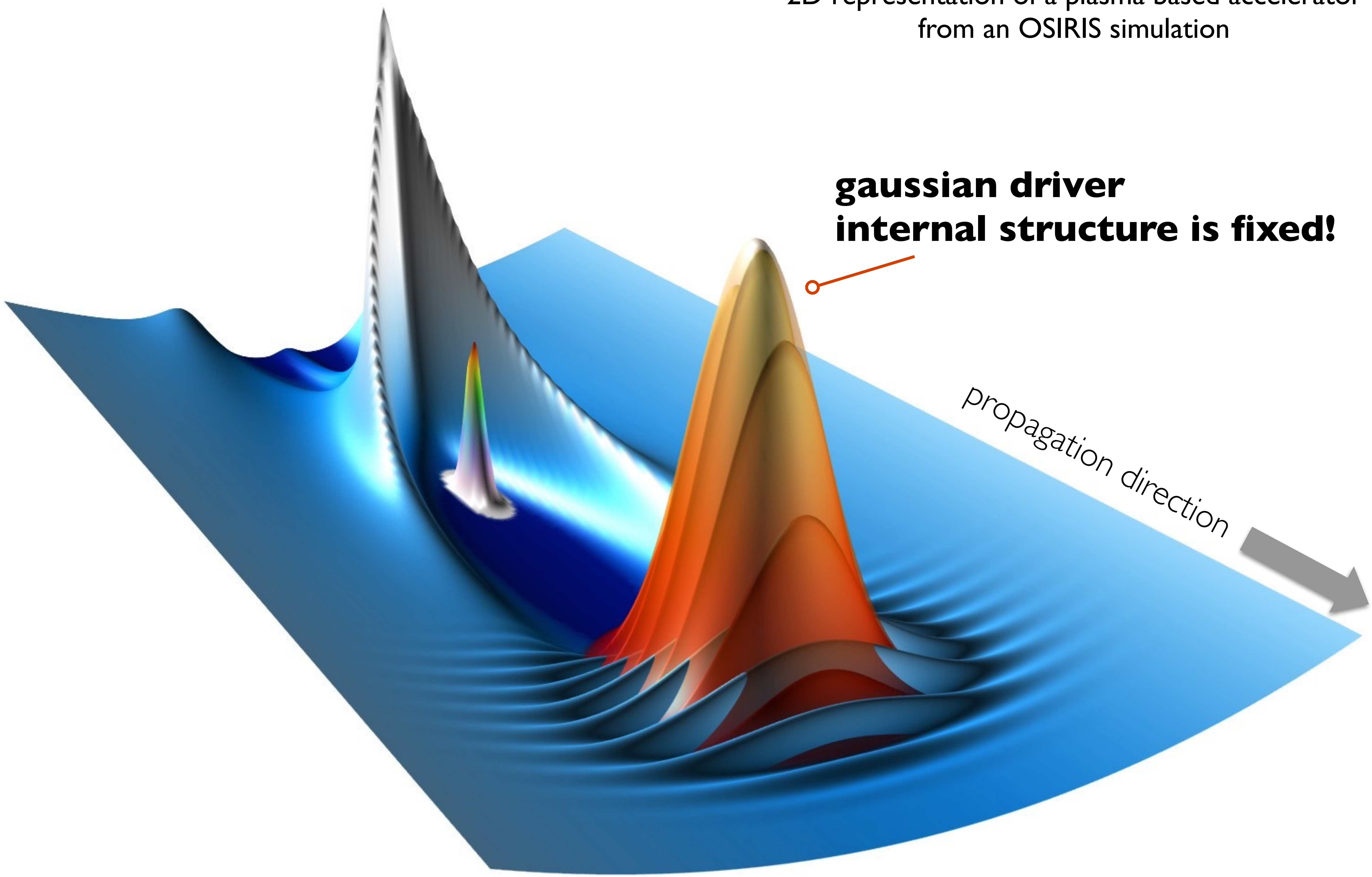
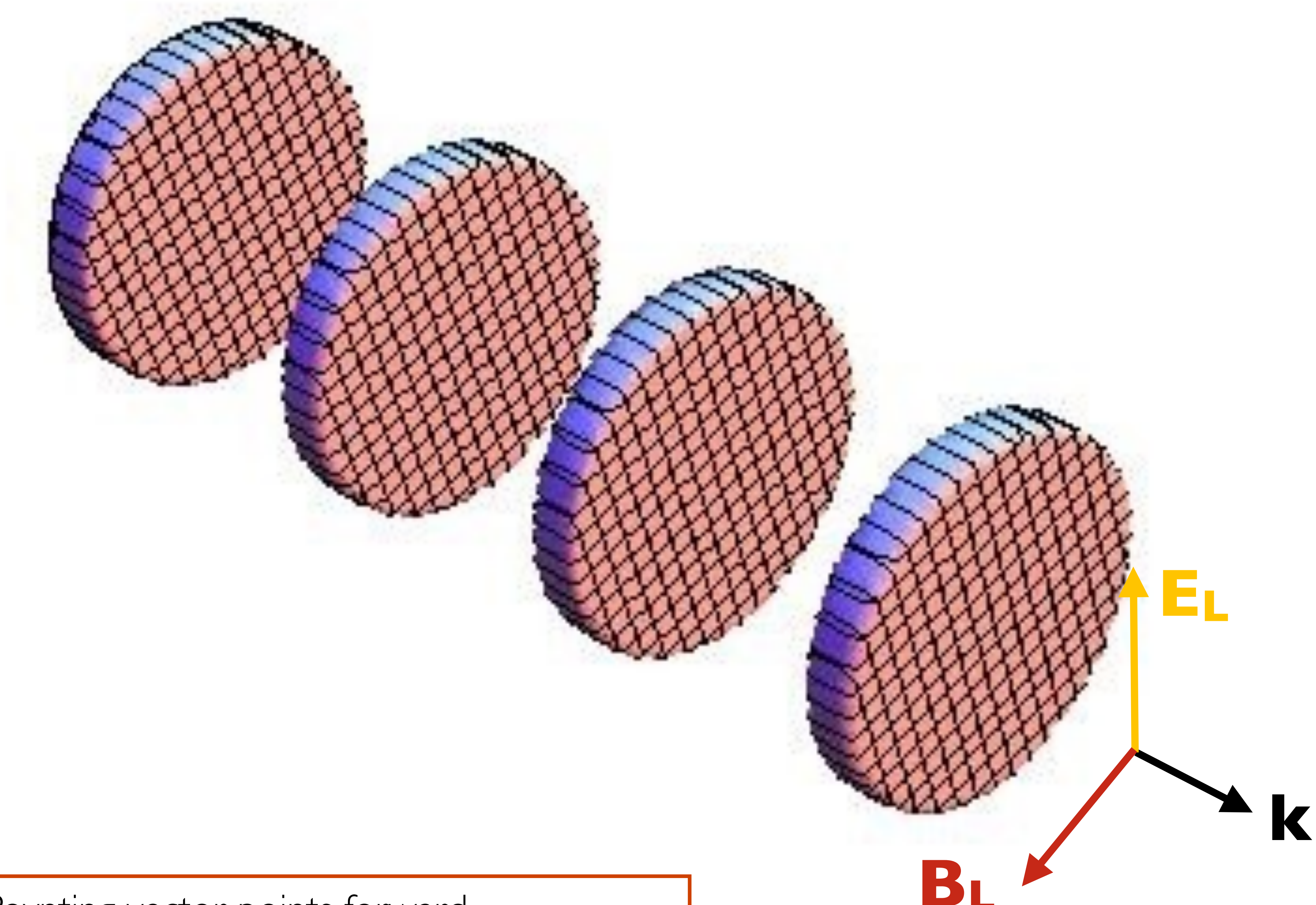


The Orbital Angular Momentum (OAM) of light

representation of a *plane* wave



Poynting vector points forward
Transfer *linear* momentum to matter: **optical tweezers**

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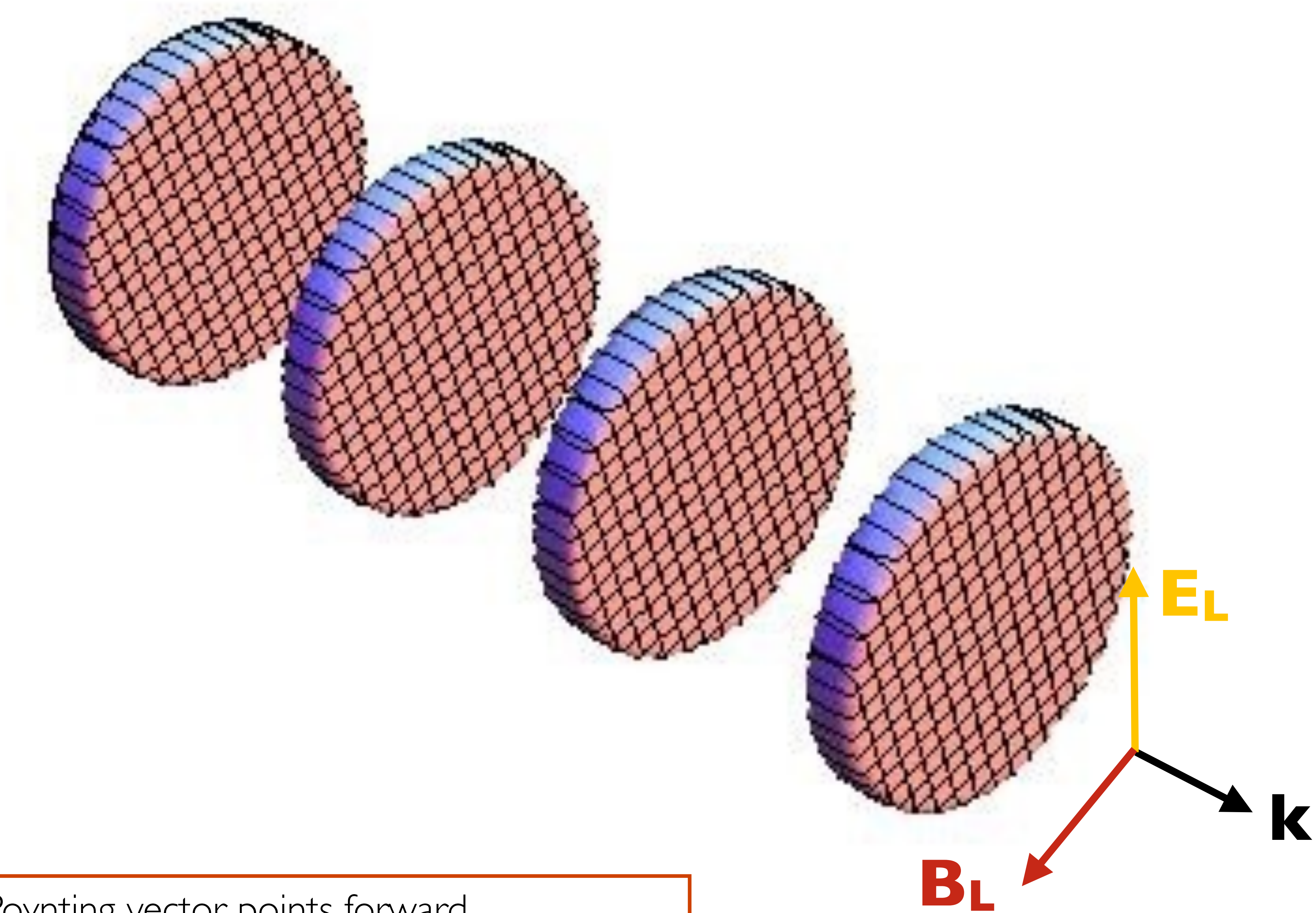

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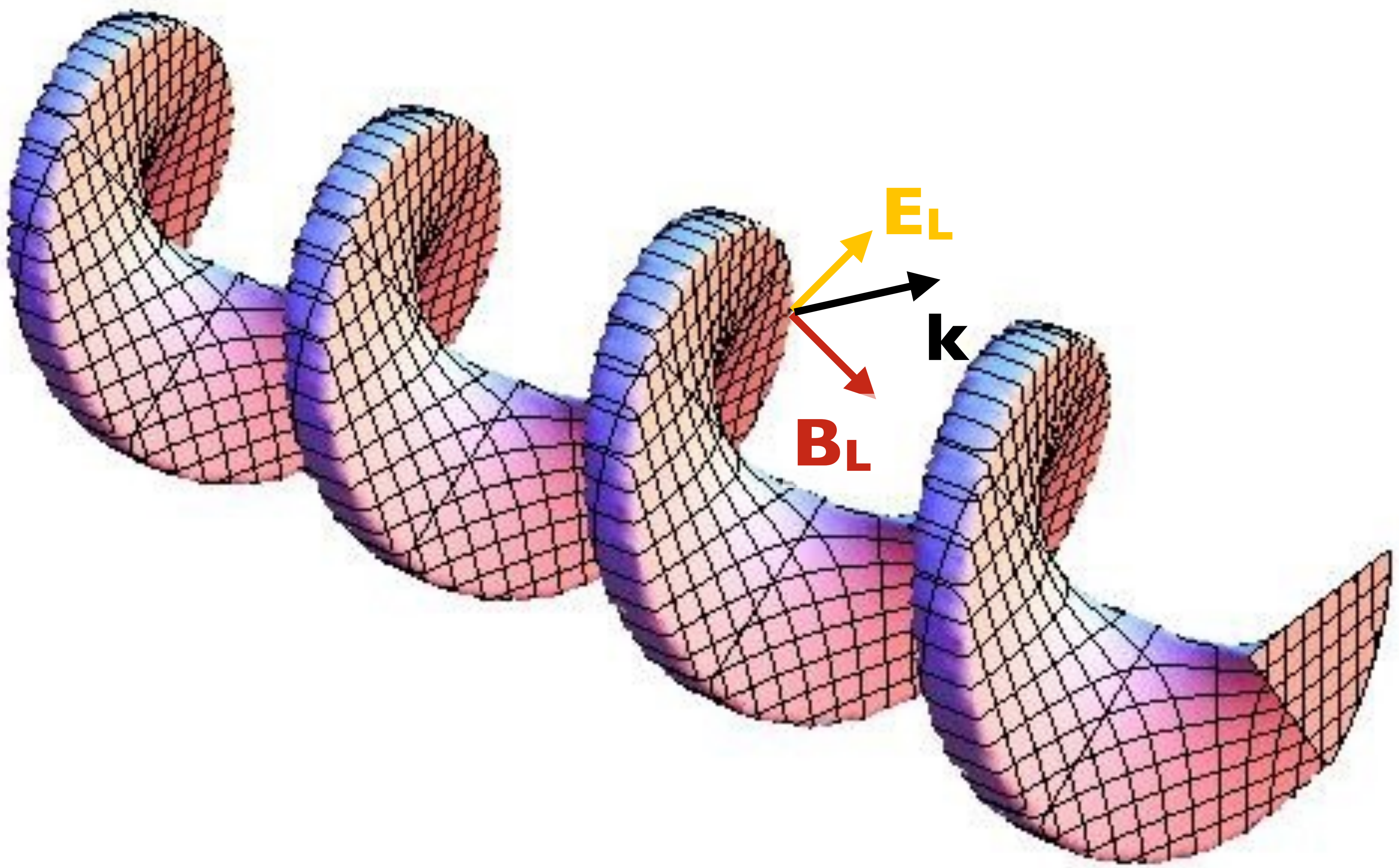

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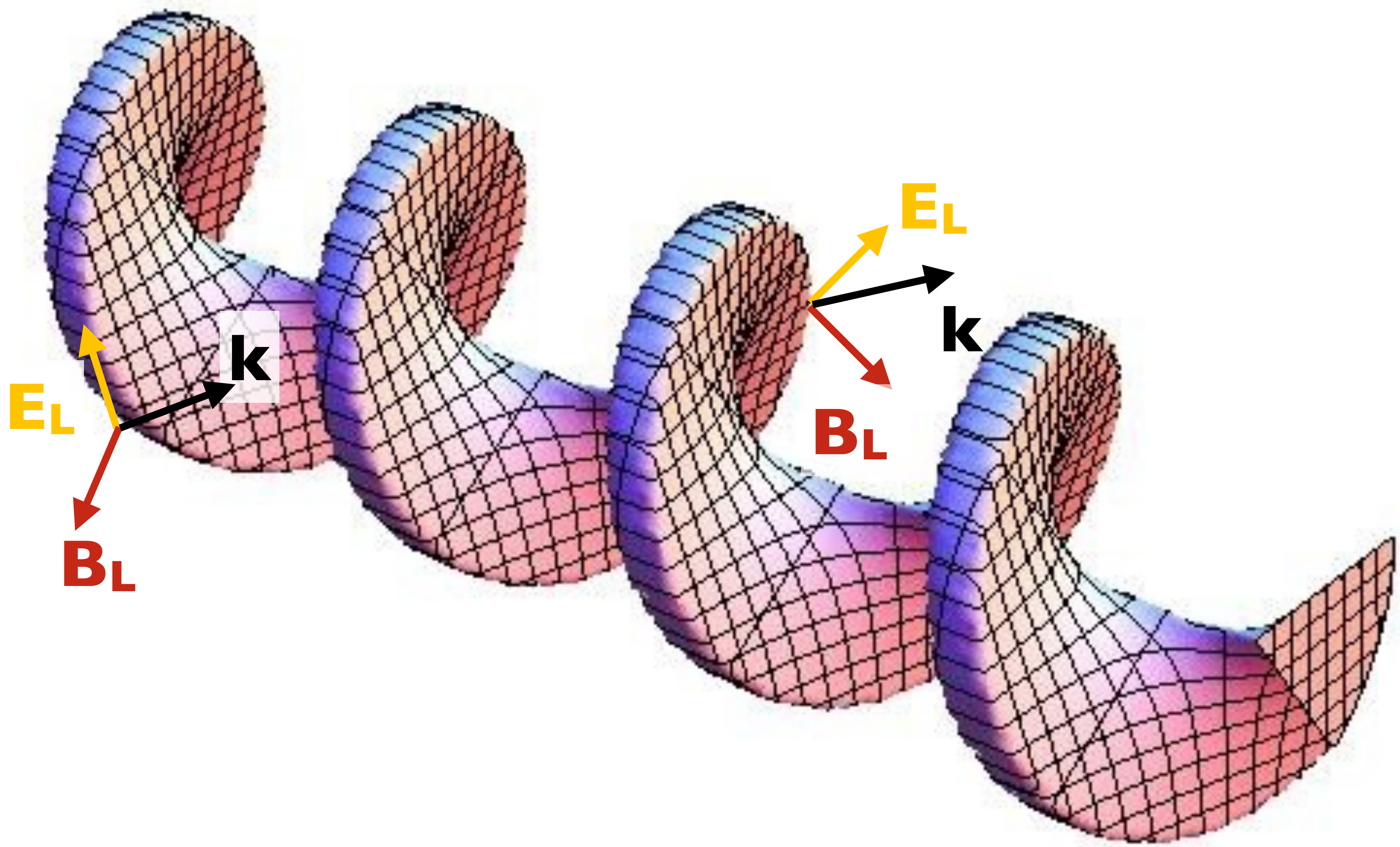

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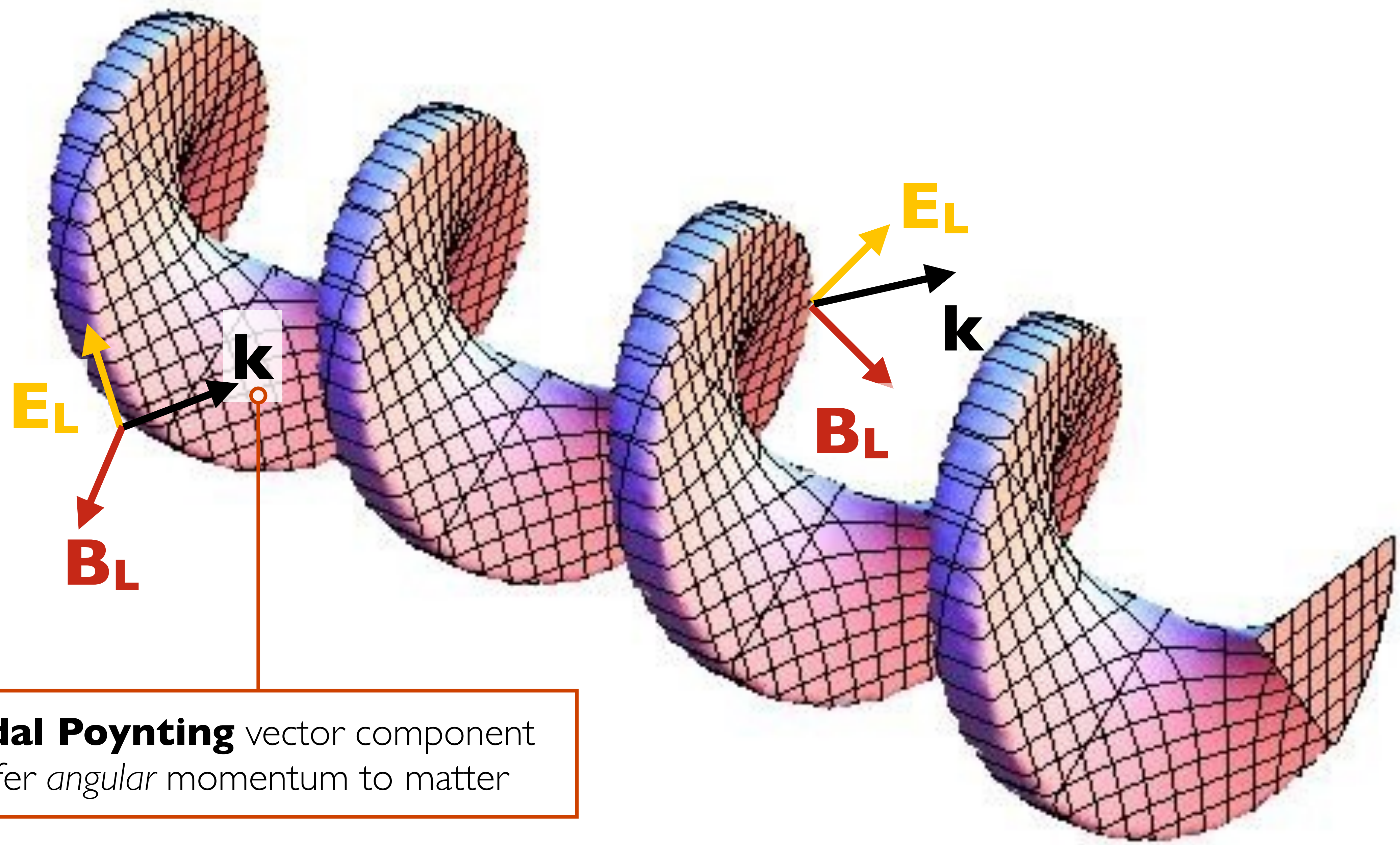
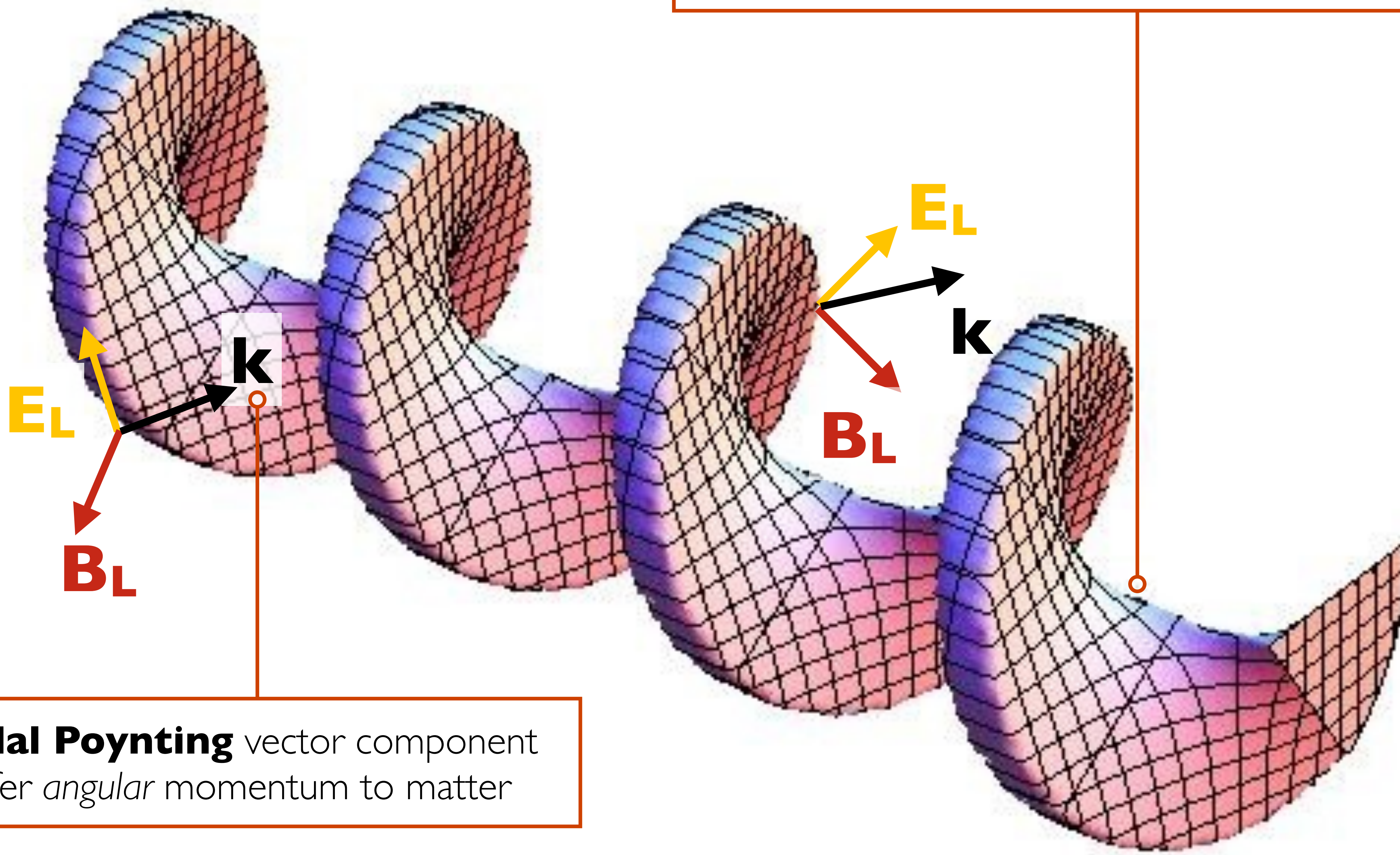


Poloidal Poynting vector component
Transfer *angular* momentum to matter

The Orbital Angular Momentum (OAM) of light

representation of a *twisted* wave

Phase singularity on axis - doughnut intensity profile
Higher order Laguerre-Gaussian modes



Poloidal Poynting vector component
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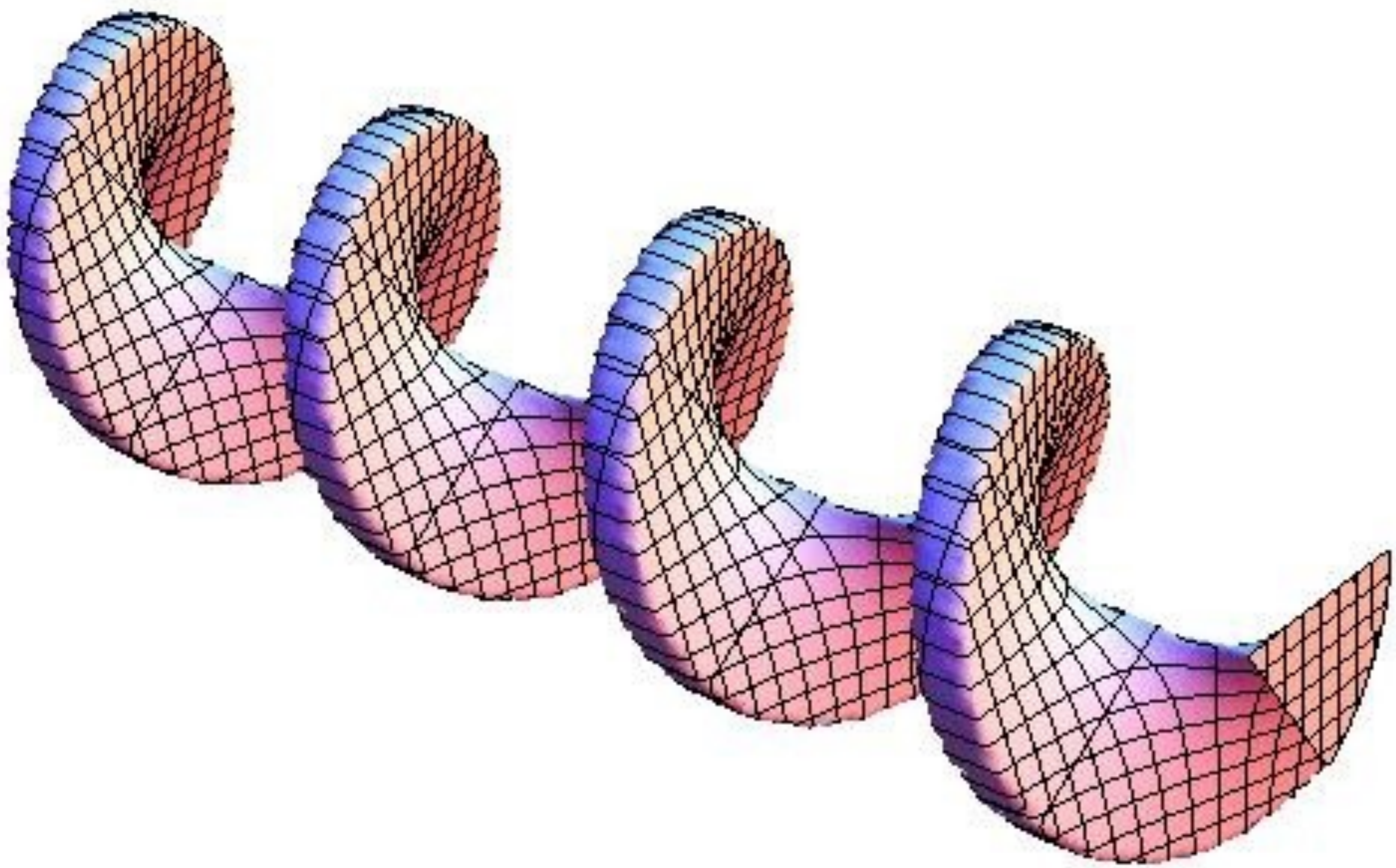
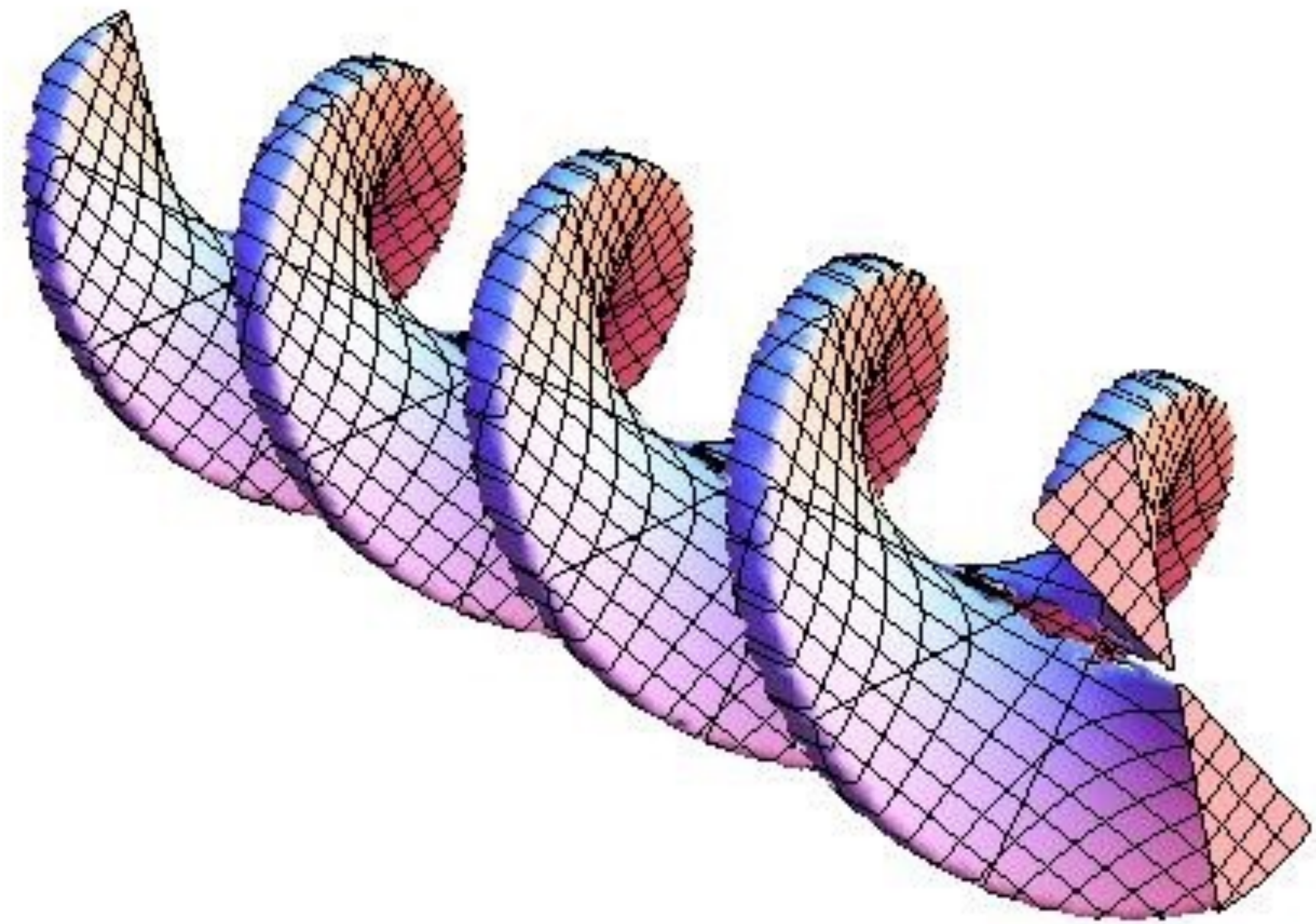
The Orbital Angular Momentum (OAM) of light

representation of a *twisted* wave **1 helix - OAM (ℓ) is 1**



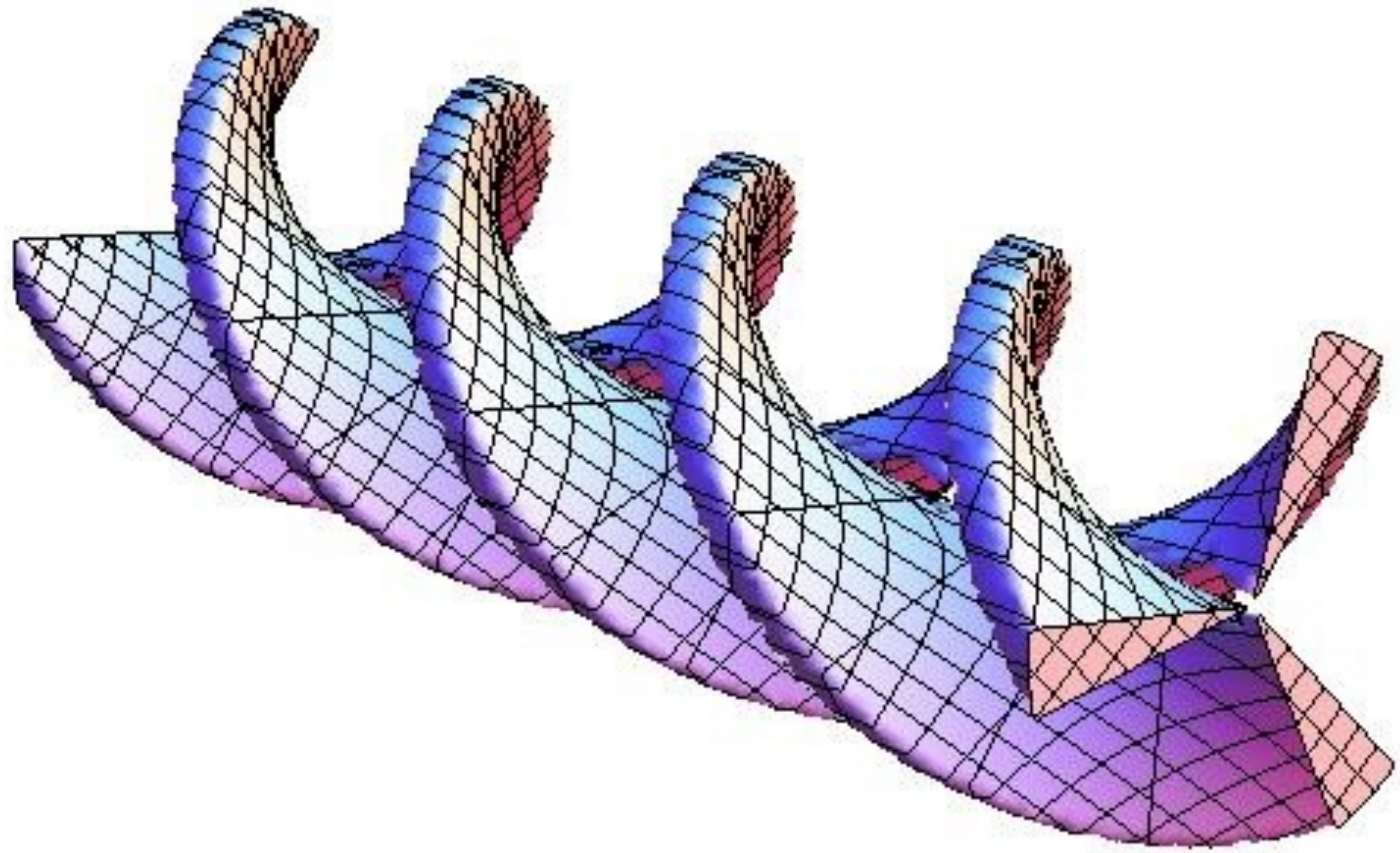
The orbital angular momentum of light

representation of a *twisted* wave **2 helixes - OAM (ℓ) is 2**



The orbital angular momentum of light

representation of a *twisted* wave **3 helixes - OAM (ℓ) is 3**



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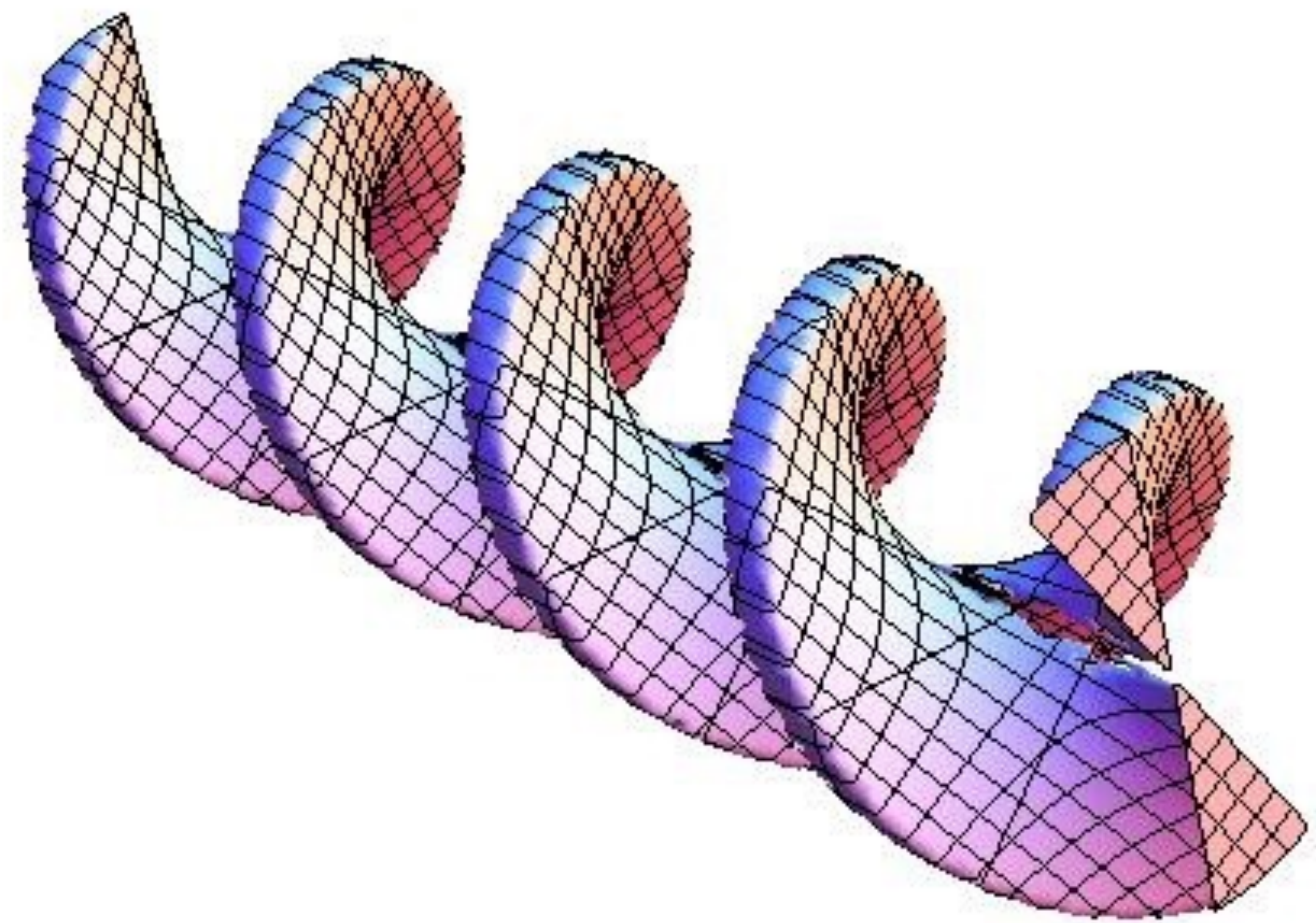

Interesting examples of double helixes

adapted from M. Padgett *et al.*

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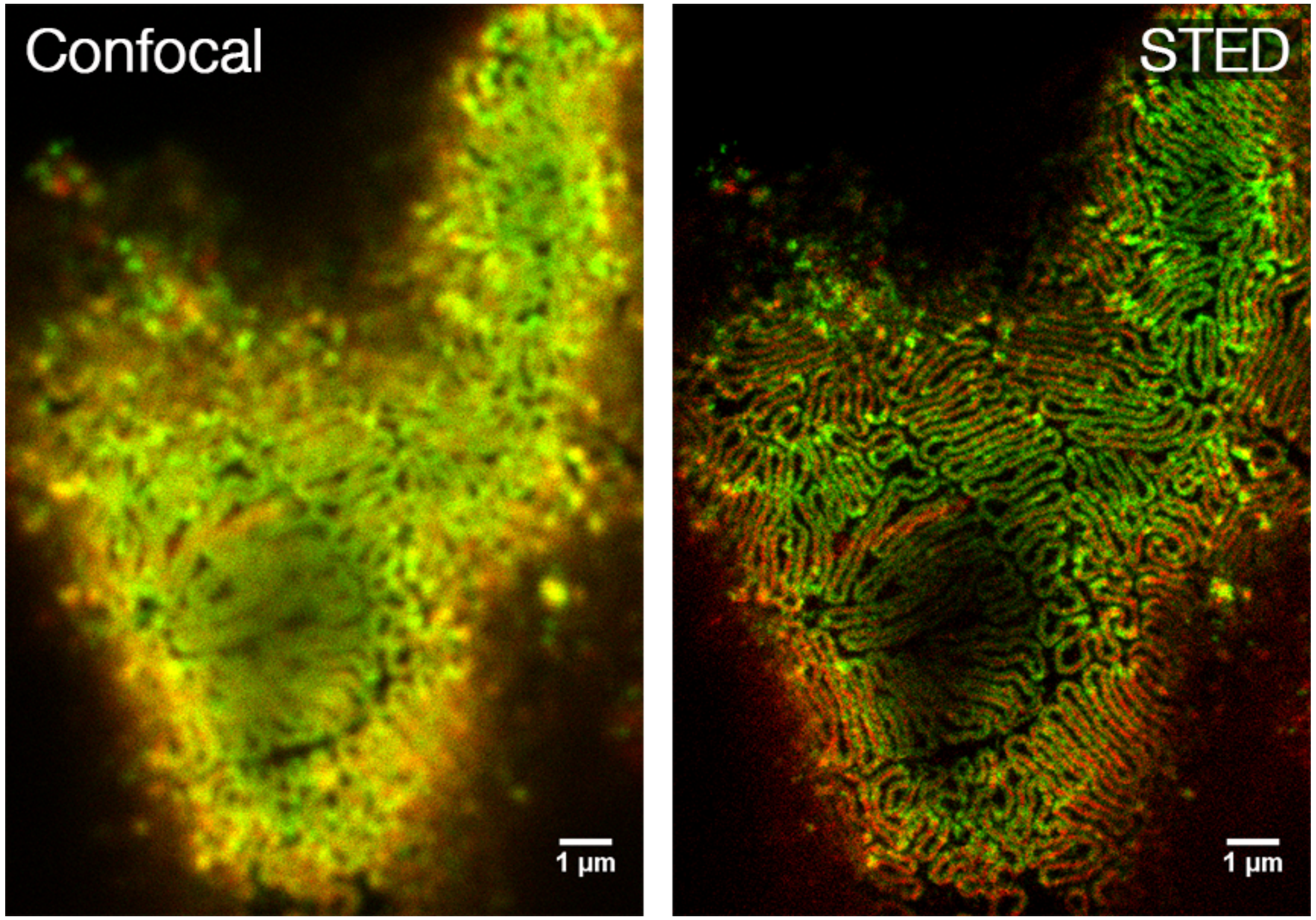
Applications of twisted light

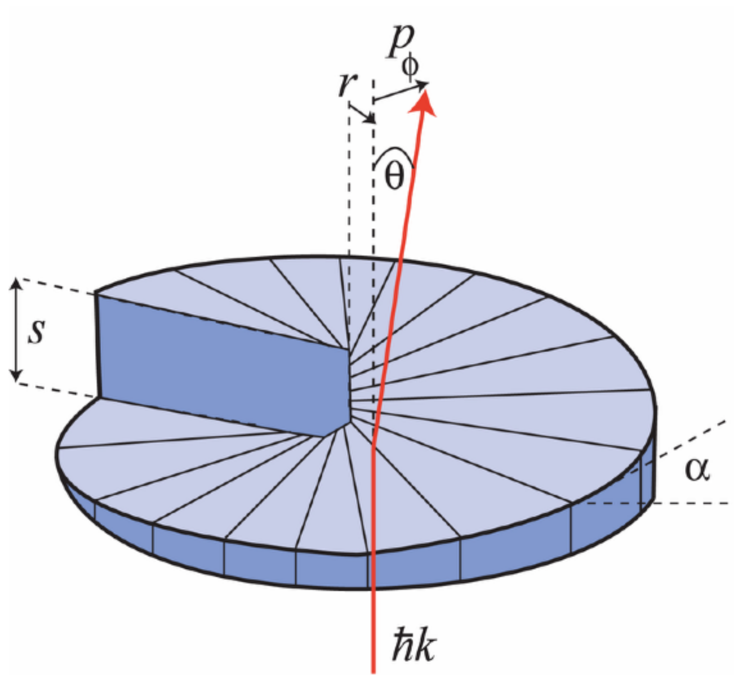
Super-resolution microscopy is a notable example where OAM beams revolutionised science and technology [S. Hell et al. Optics Lett. 19, 780-782 (1994)]



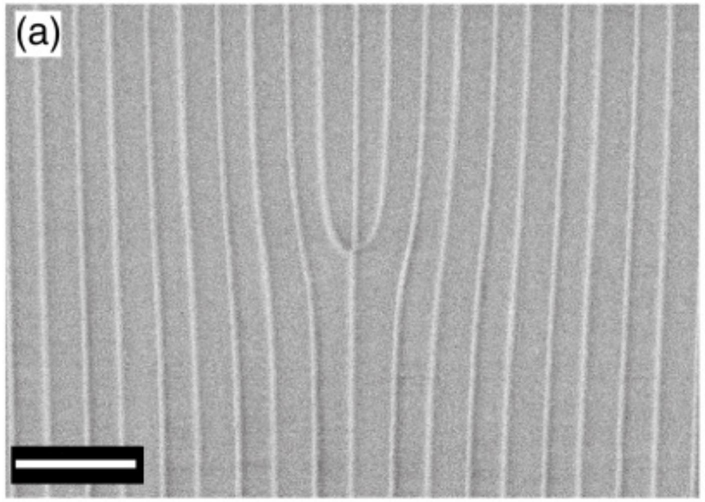
- **Optical communications** TB/s data transfer in free space [J. Wang et al. Nat. Ph. 6 488 (2012)]
- **Quantum computing** Very large base of entangled states [A. Mair et al., Nature 412, 313 (2001)]

Generation of twisted light

Spiral phase plate

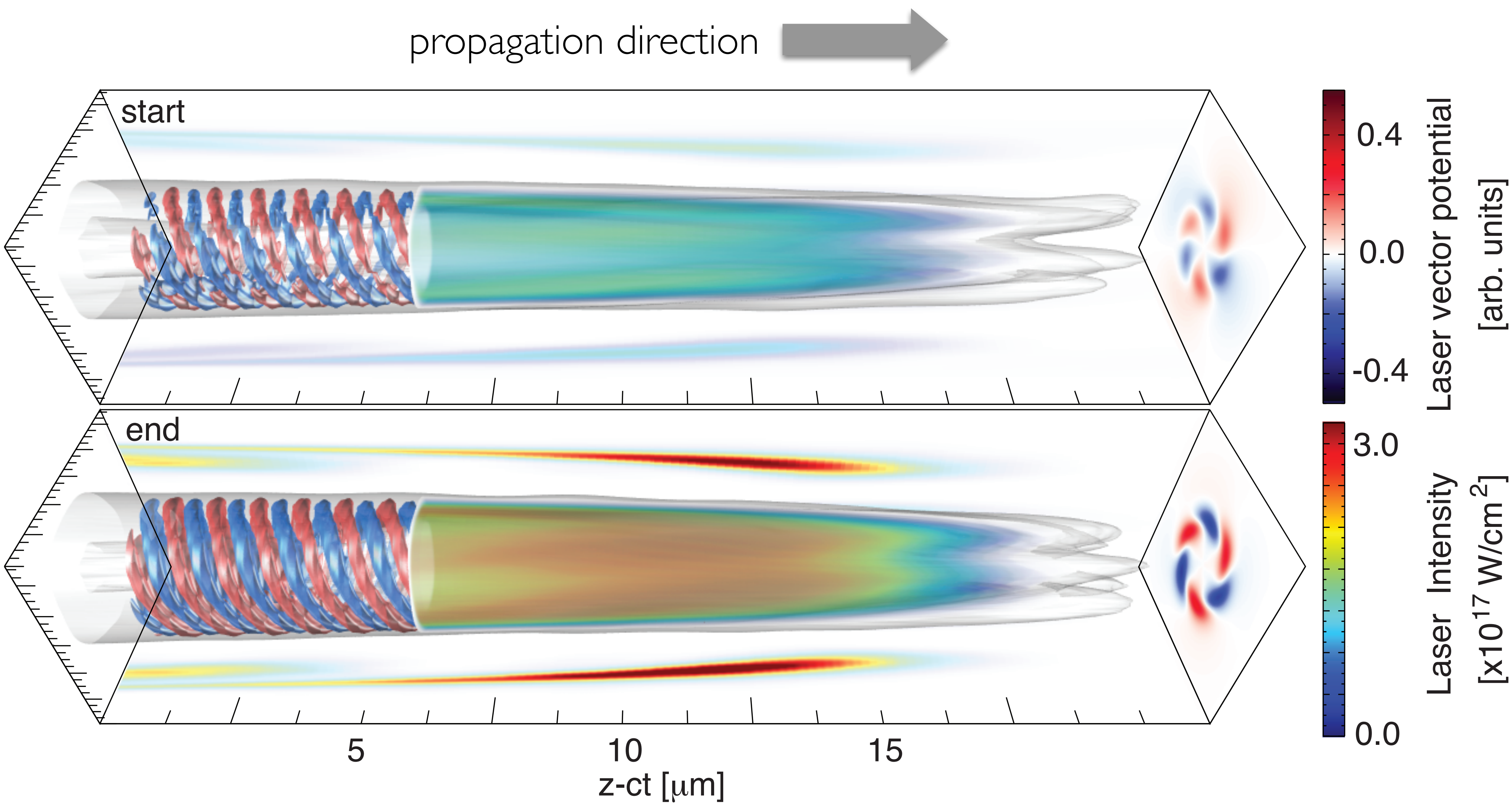


Computer generated hologram



Ultra-fast spatiotemporal beam shaping

Producing these beams at ultra-high intensity is the goal of several experimental teams



J. Vieira et al PRL 117, 265001 (2016); Nat. Comms 7:10371 (2016).

Contents

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Conclusions and future directions

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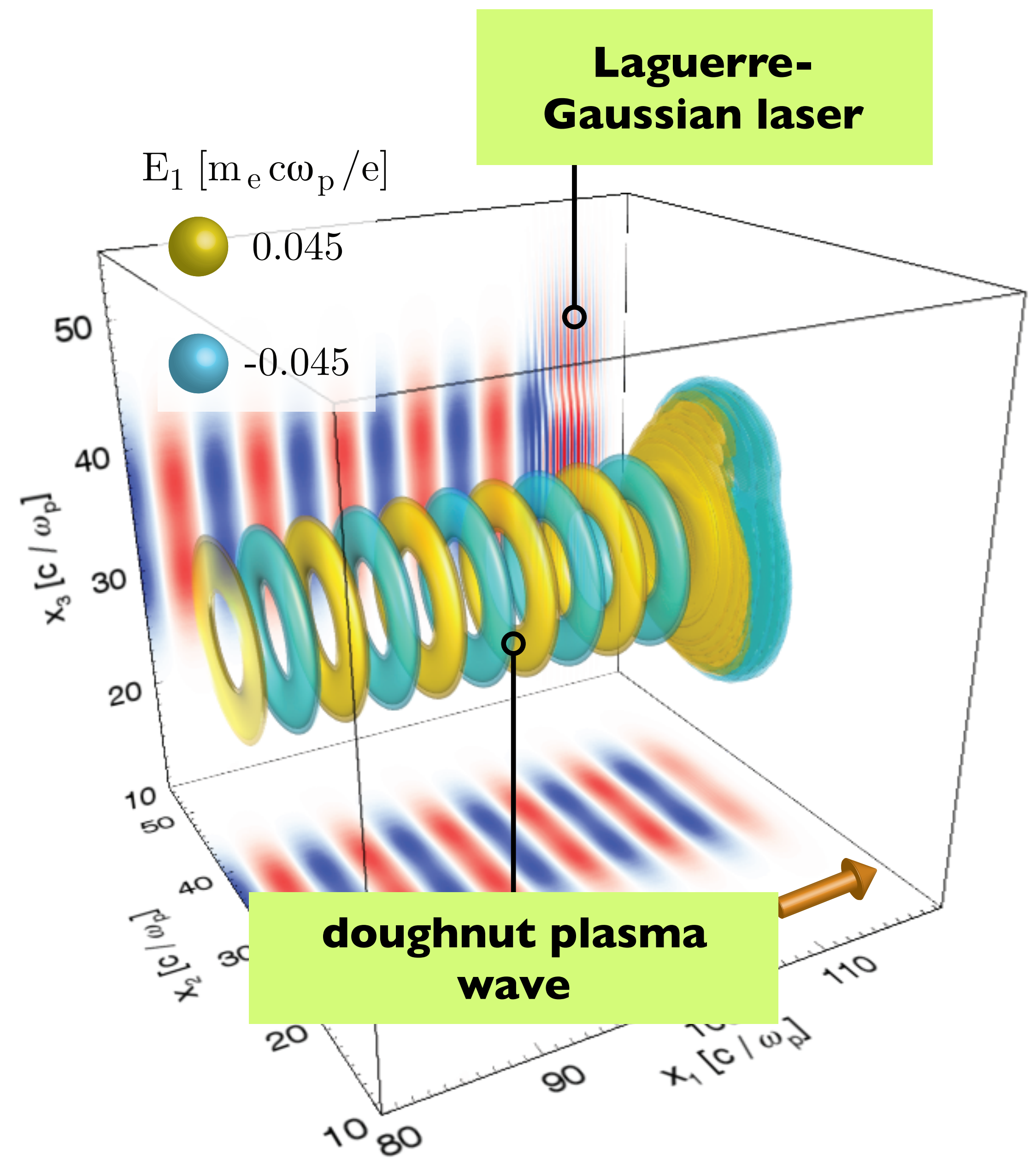
OAM lasers can drive doughnut-shaped plasma waves

Linear doughnut wakefields



J.T. Mendonça and J. Vieira, PoP 21, 033107 (2014)

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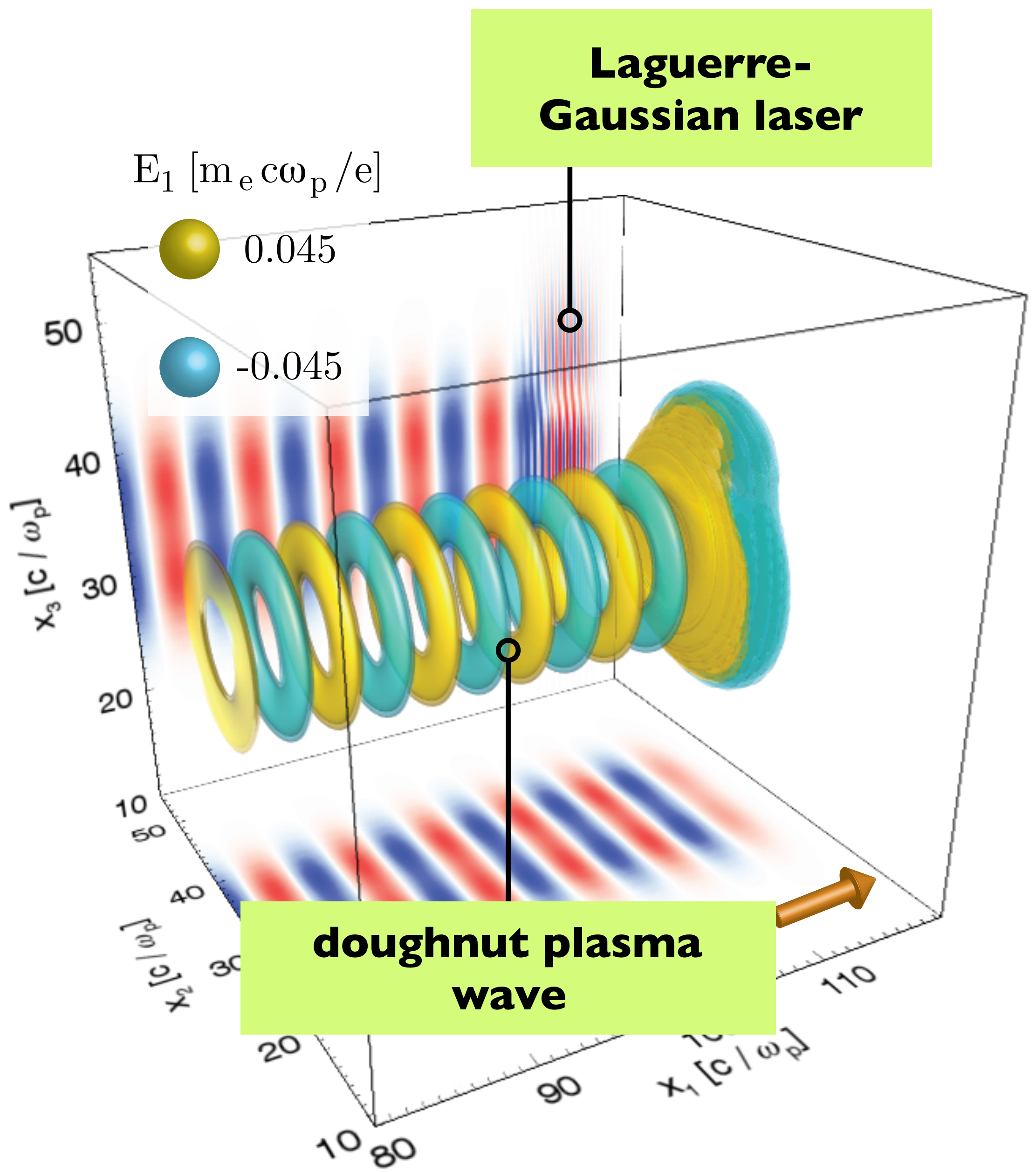
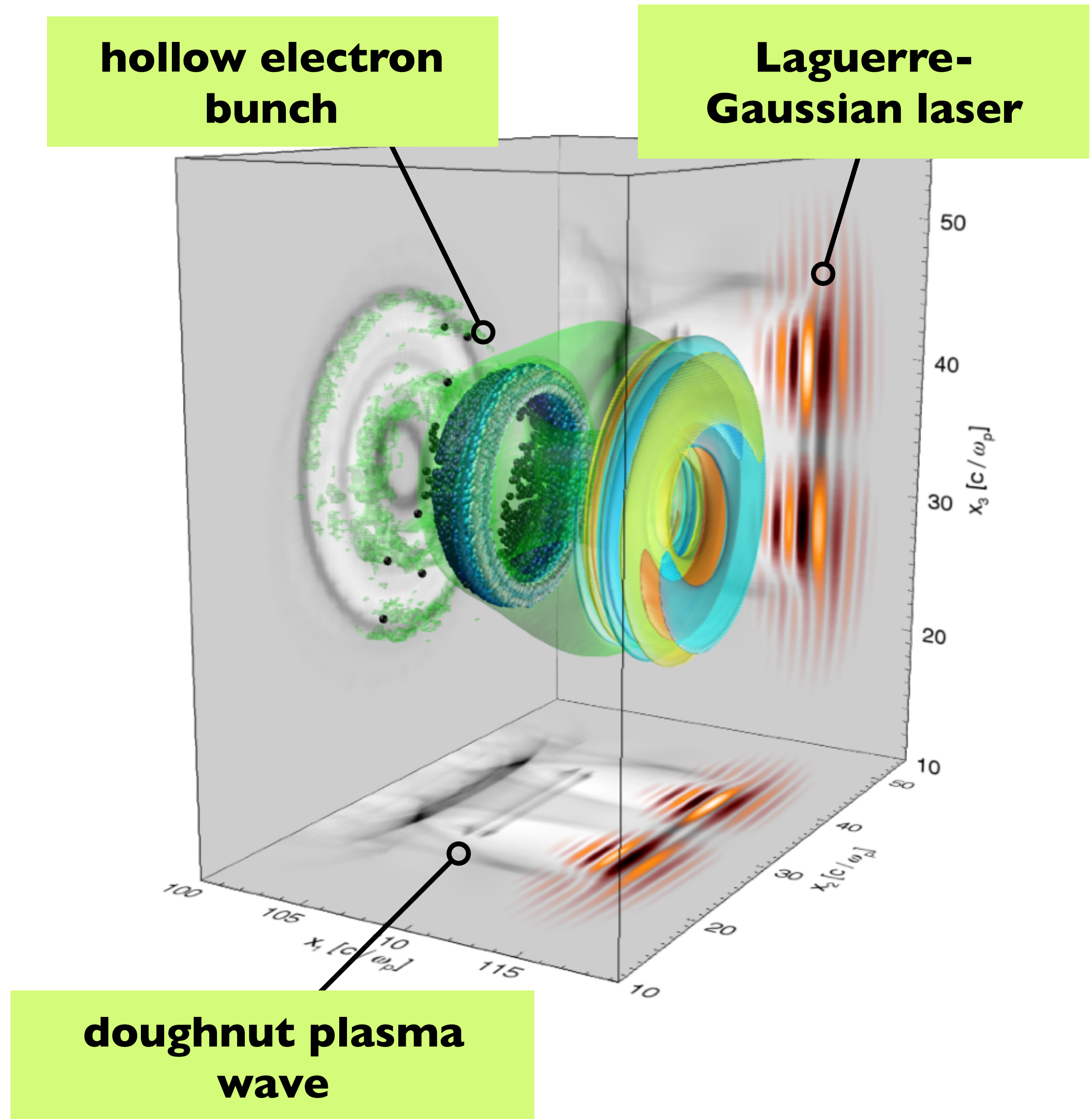


J.T. Mendonça and J. Vieira, PoP 21, 033107 (2014)

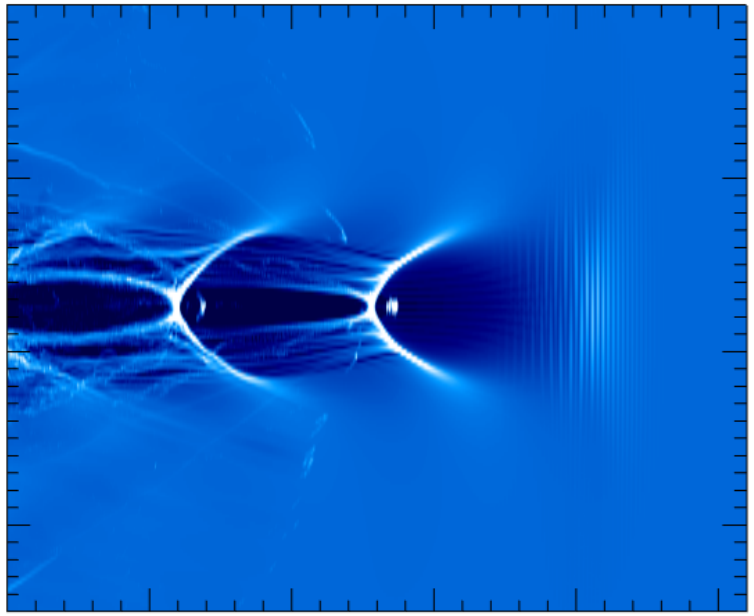
Non-linear doughnut blowout



J. Vieira and J.T. Mendonça PRL 112, 215001 (2014)

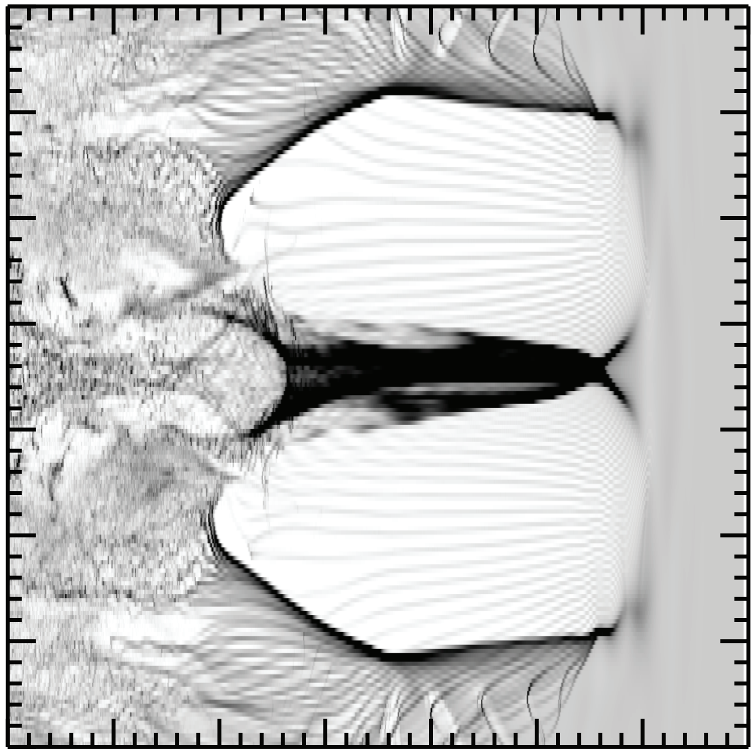
Why doughnut plasma waves are interesting:
Positron acceleration in the non-linear blowout regime

conventional blowout regime



- laser expels electrons outwards
- pure ion channel focuses electrons
- positron acceleration ***not possible***

doughnut plasma wave



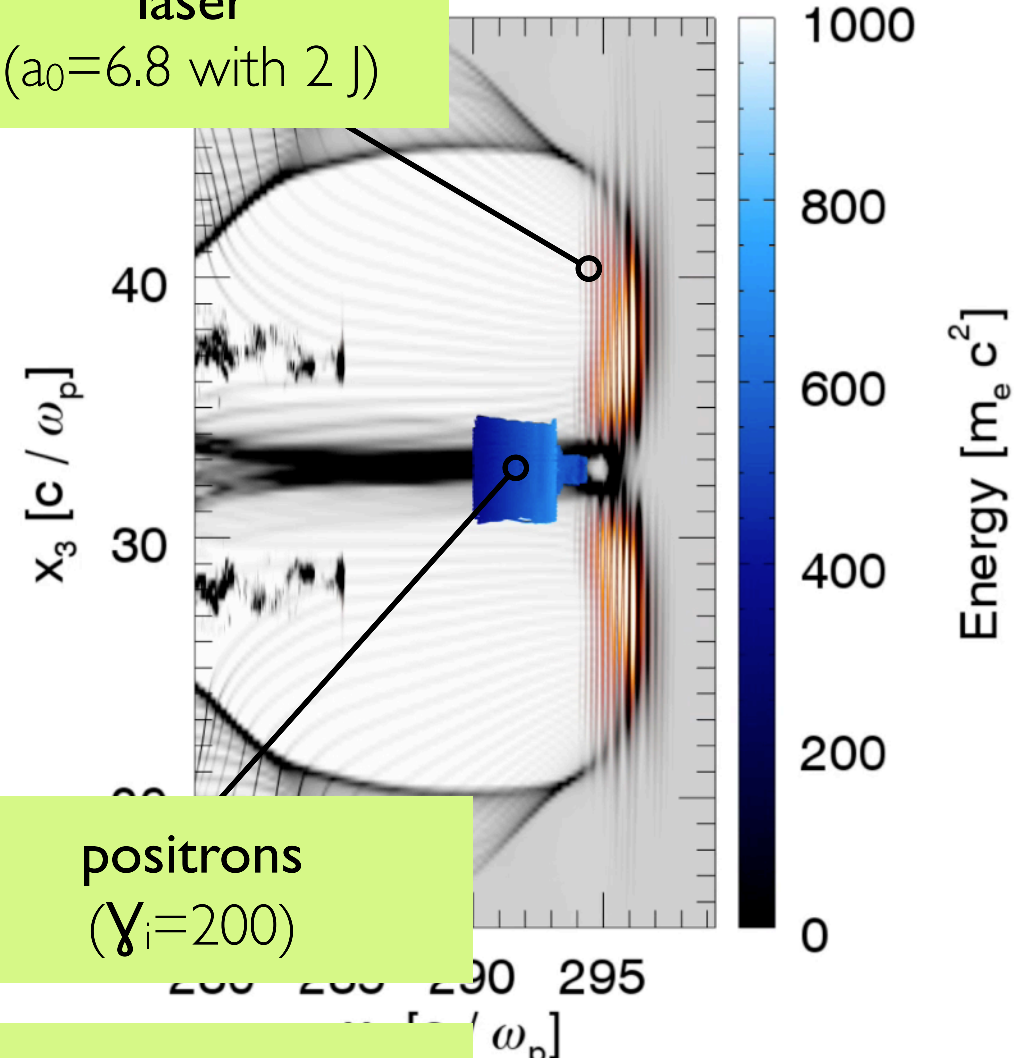
- laser pushes electrons inwards
- electron filament focuses positrons
- positron acceleration ***is possible***

3D simulations show positron acceleration in strongly non-linear regimes

3D simulation of positron acceleration

laser and plasma parameters within experimental reach

laser (a_0=6.8 with 2 J)



positrons (γ_i=200)

plasma ($n_0=7.7\times10^{18}cm^{-3}$)

simulation box zoom

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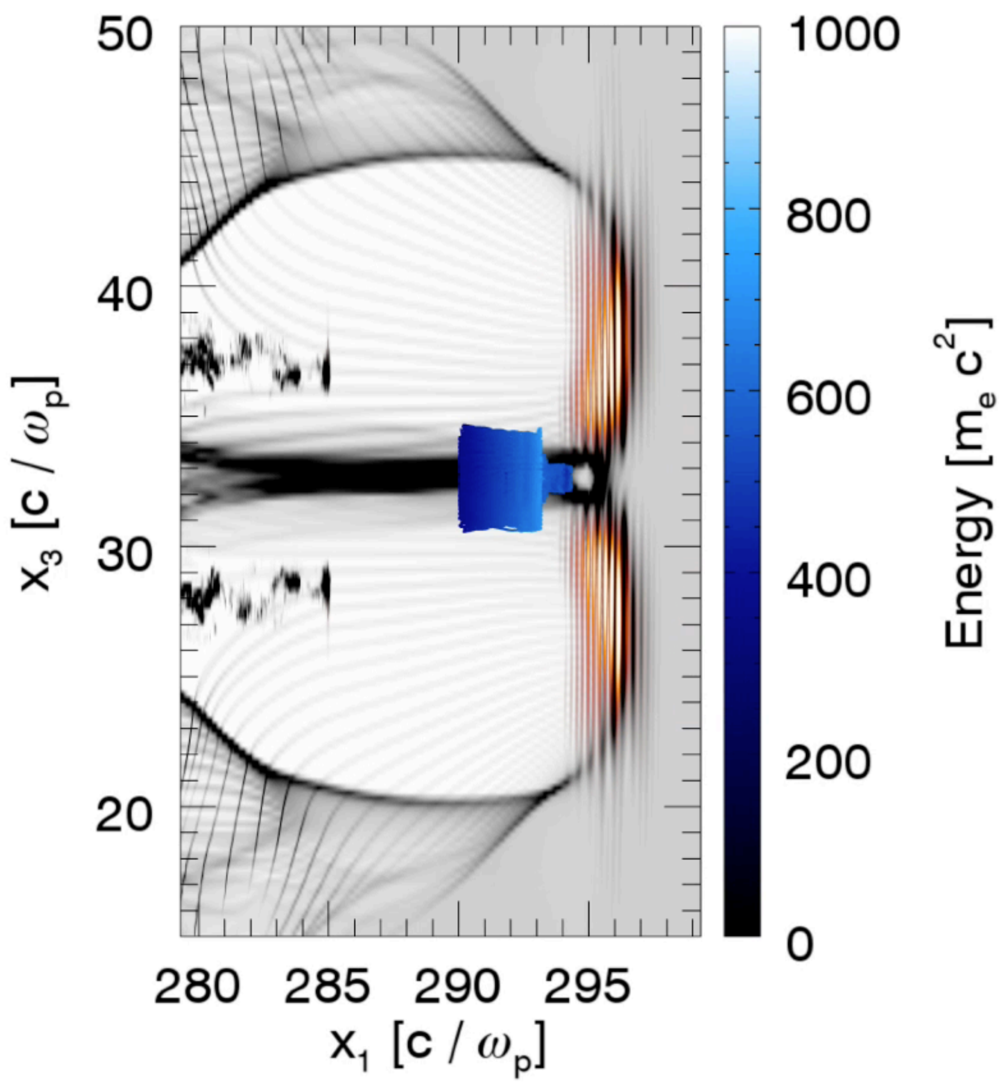
3D simulation of positron acceleration

laser and plasma parameters within experimental reach



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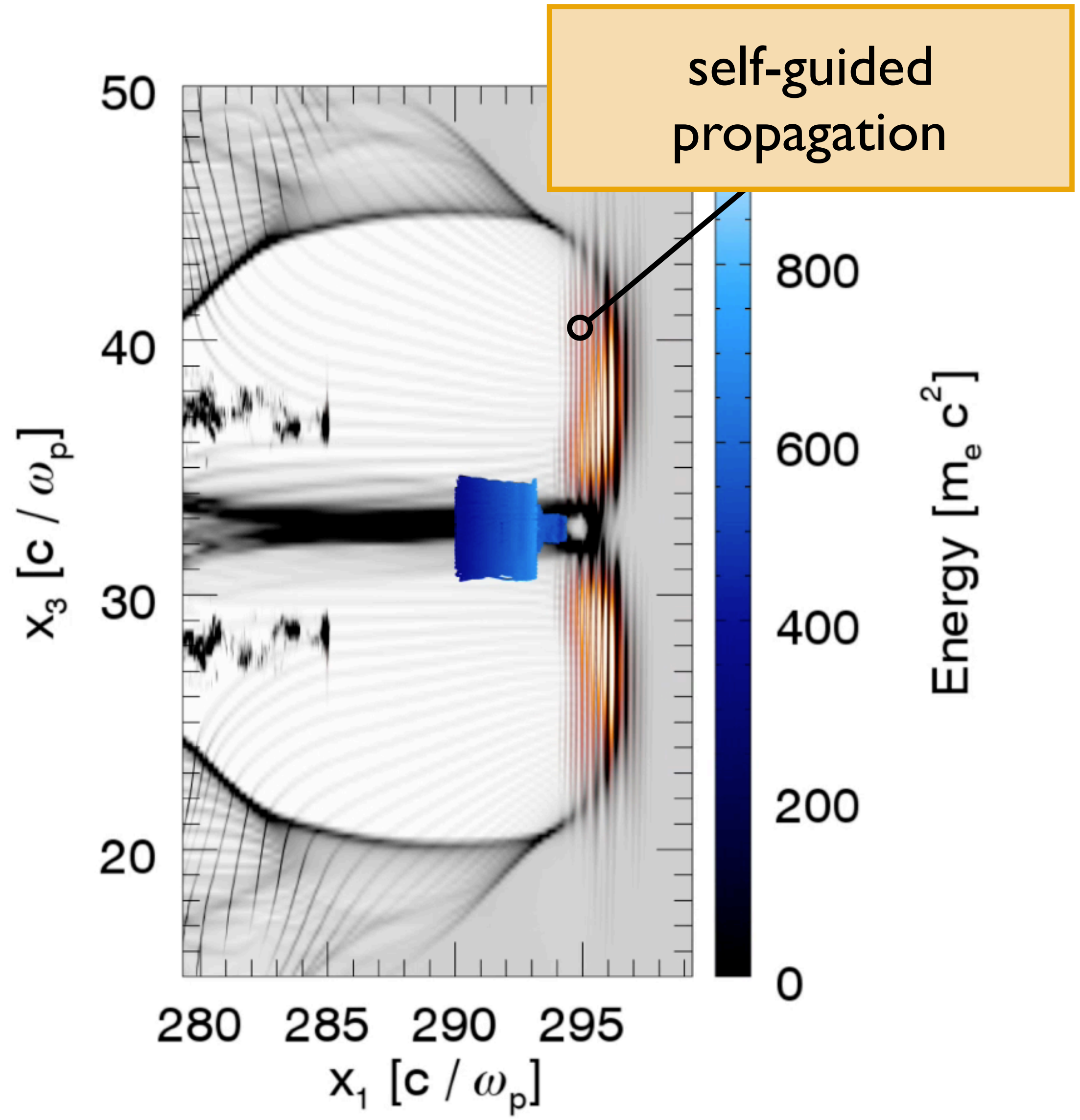

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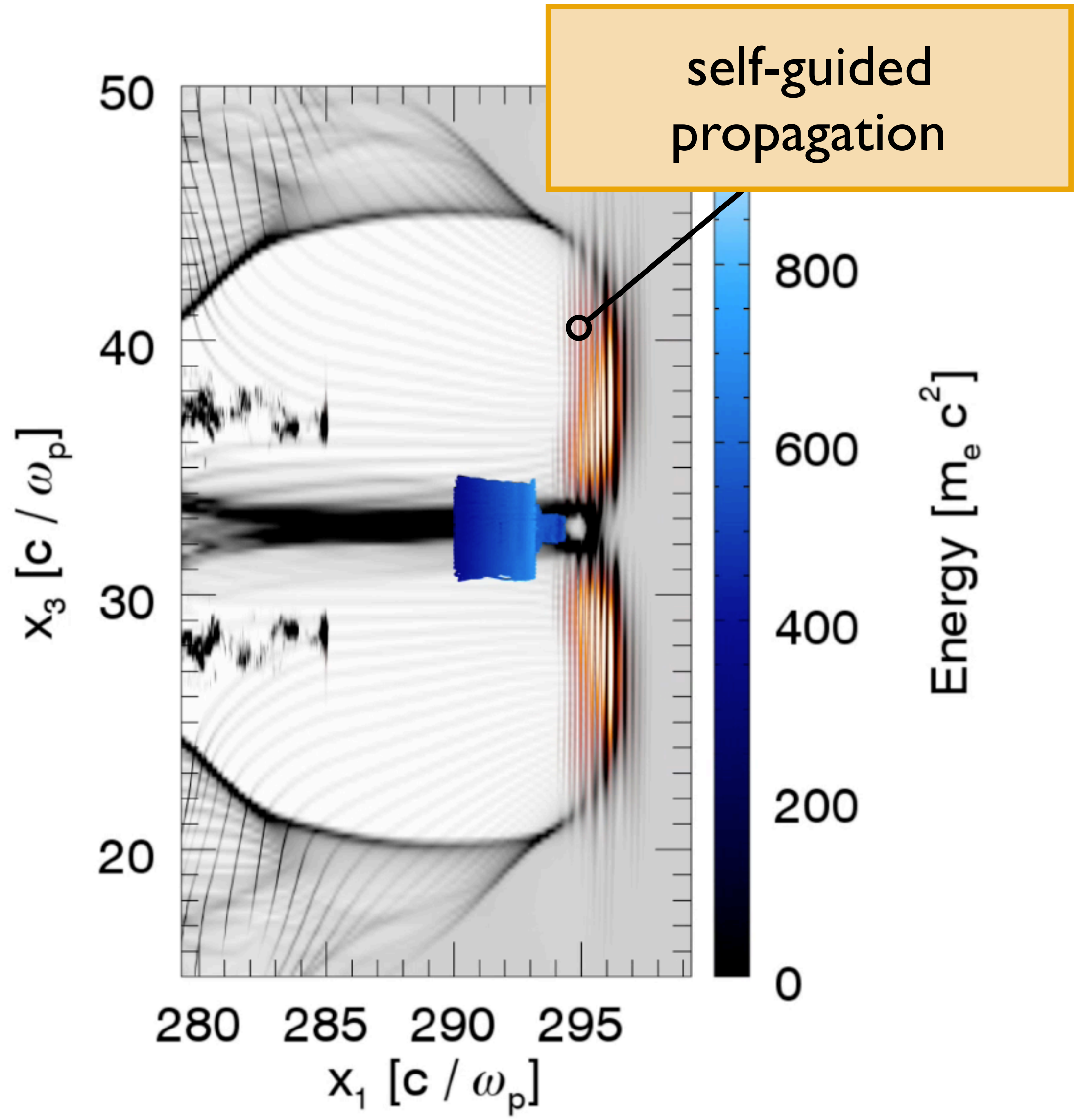

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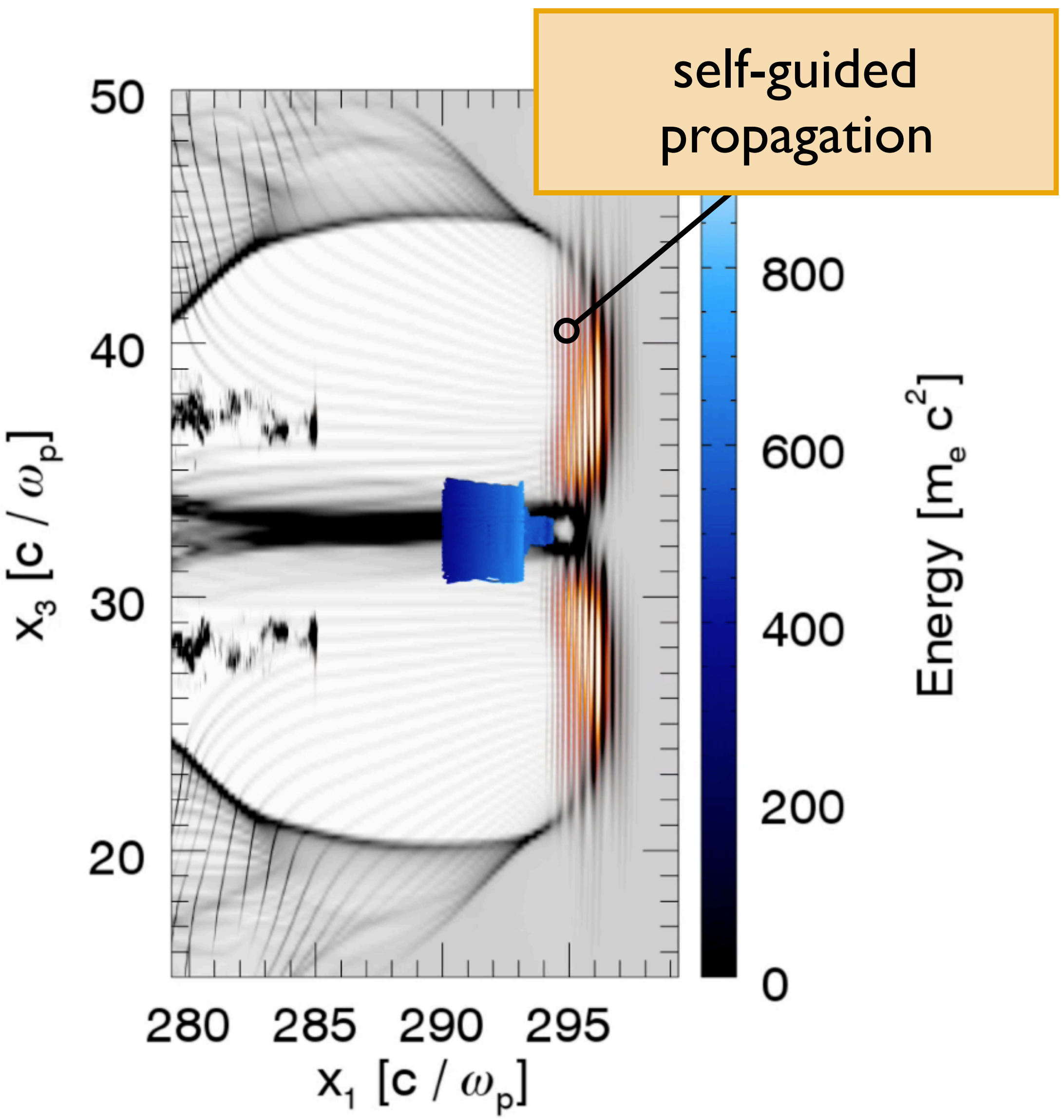
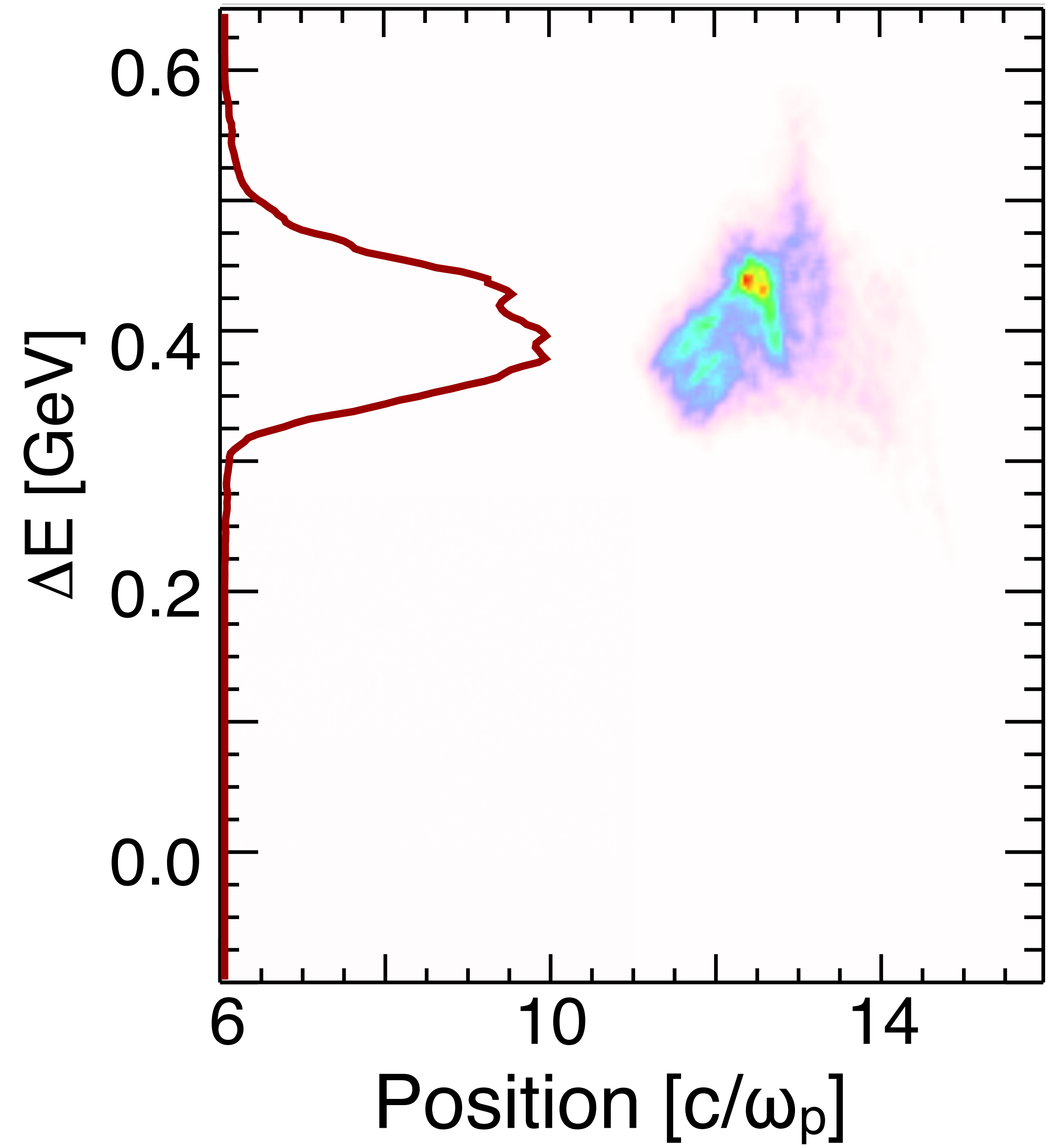


simulation box zoom

Positron bunch is quasimonoenergetic



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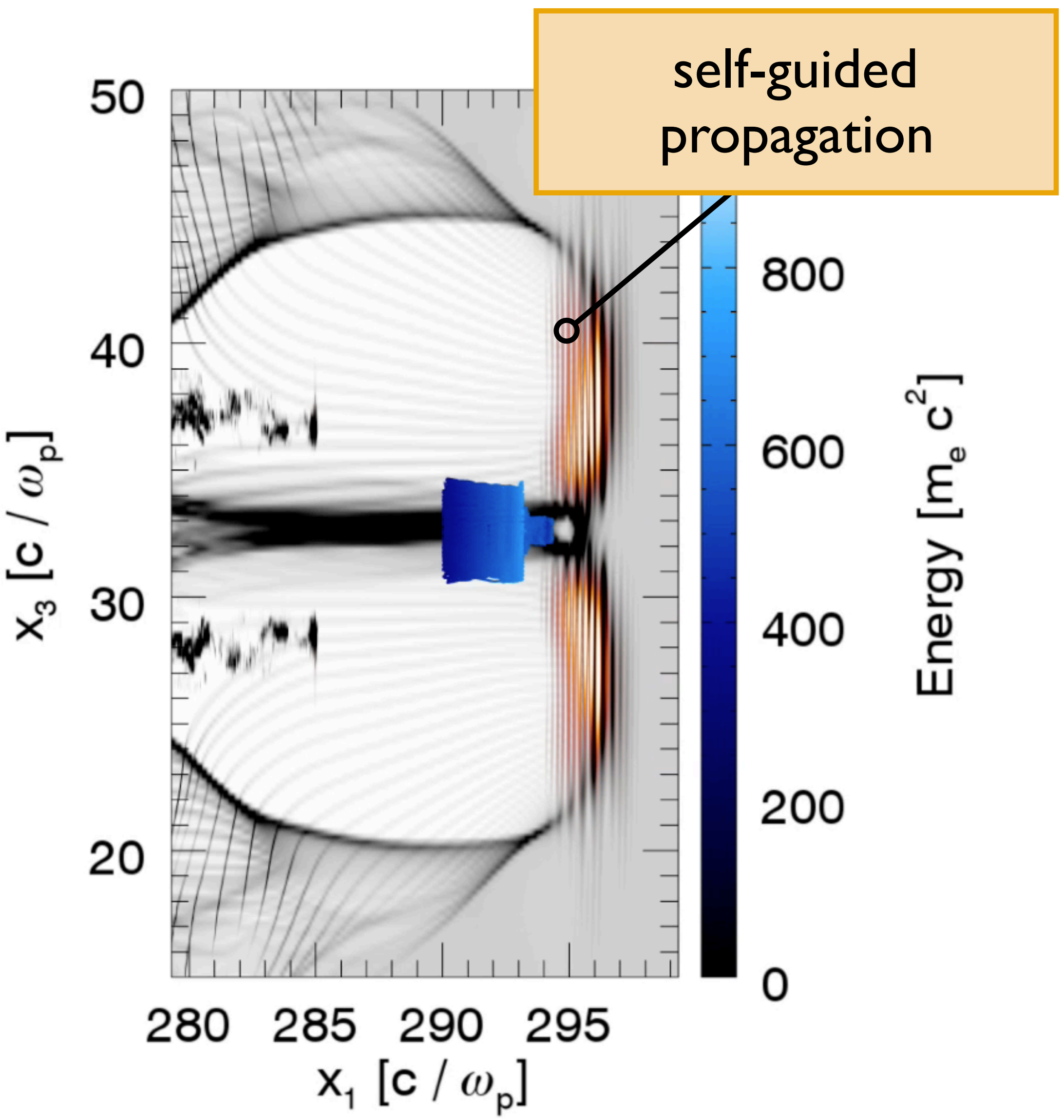

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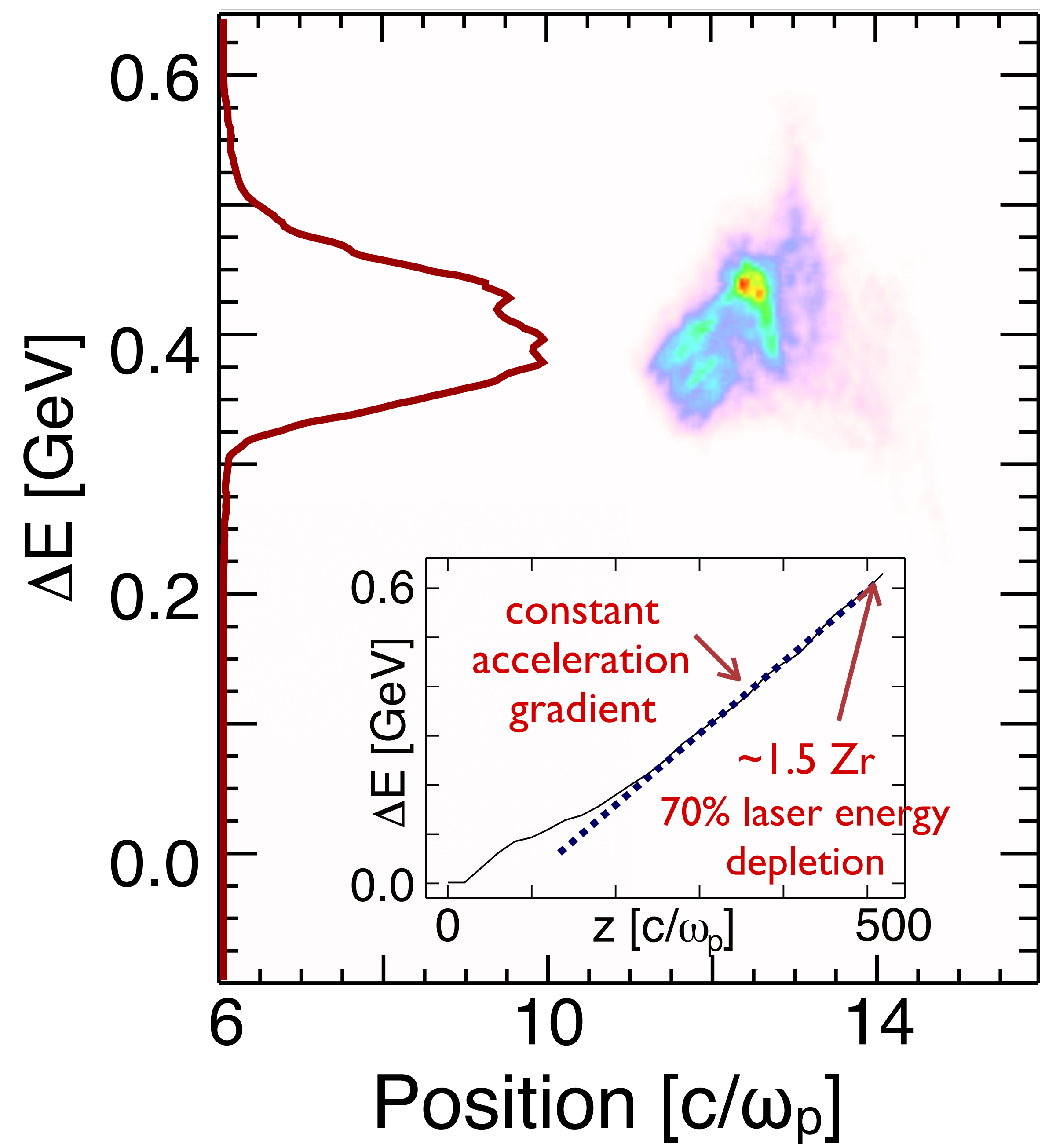

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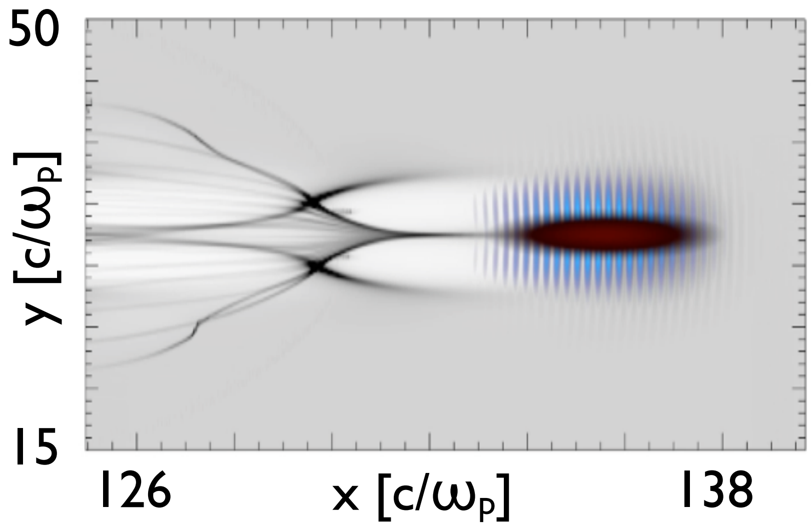
Related configurations using Gaussian lasers are possible

On-axis filament

positrons attract e⁻ towards the axis



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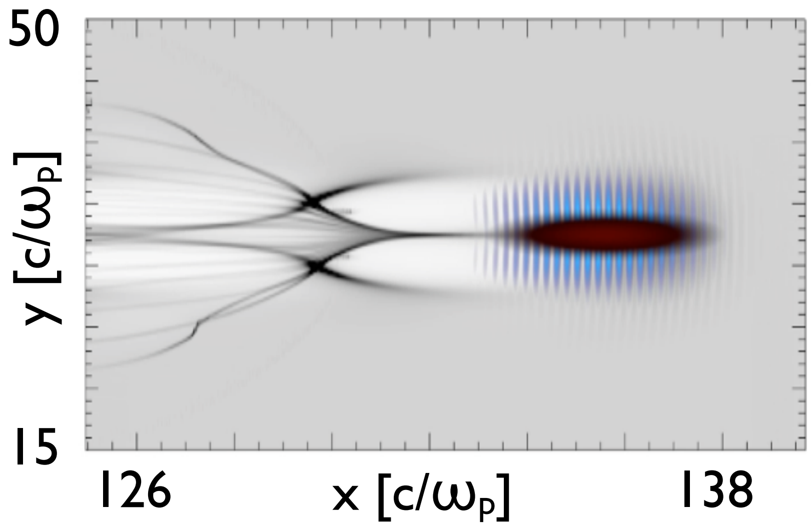
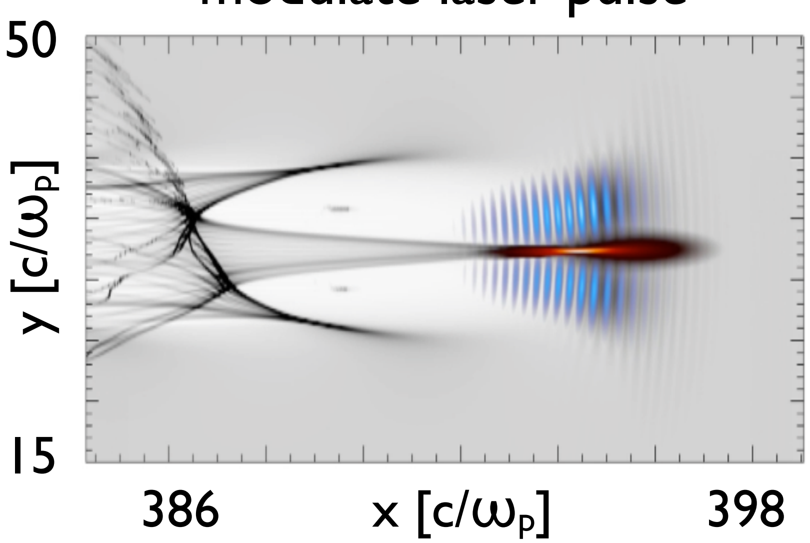


Doughnut laser

plasma refractive index gradients modulate laser pulse



Related configurations using Gaussian lasers are possible

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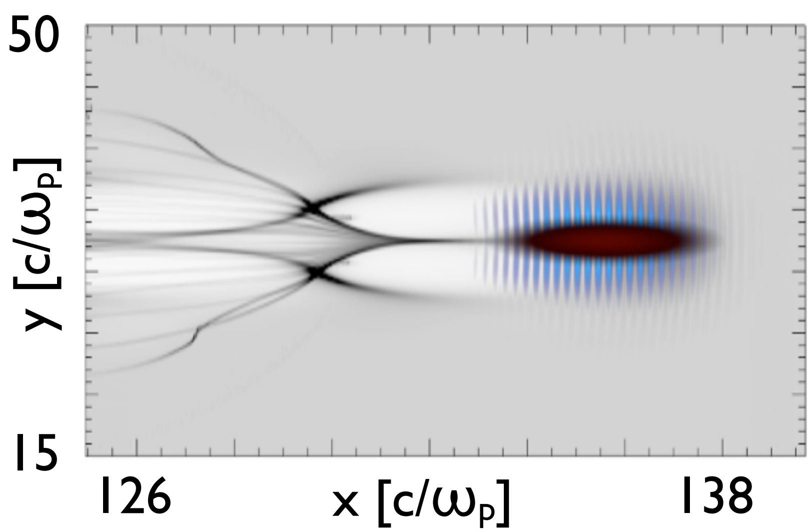

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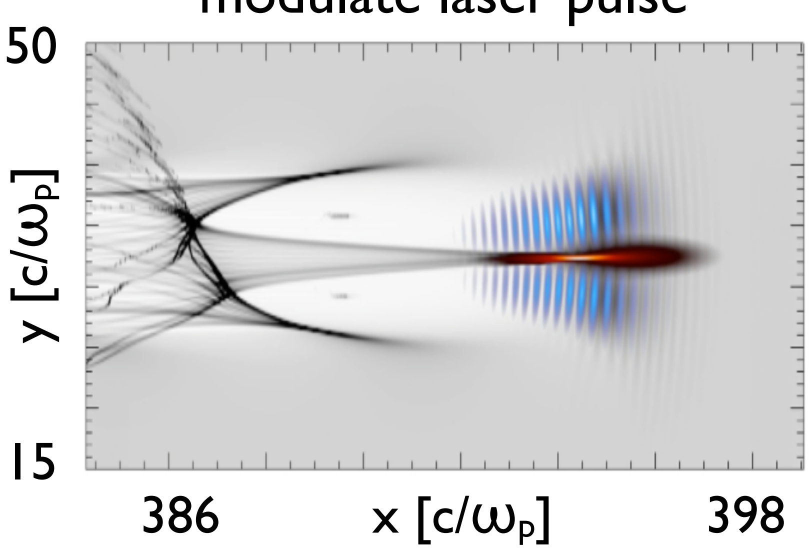
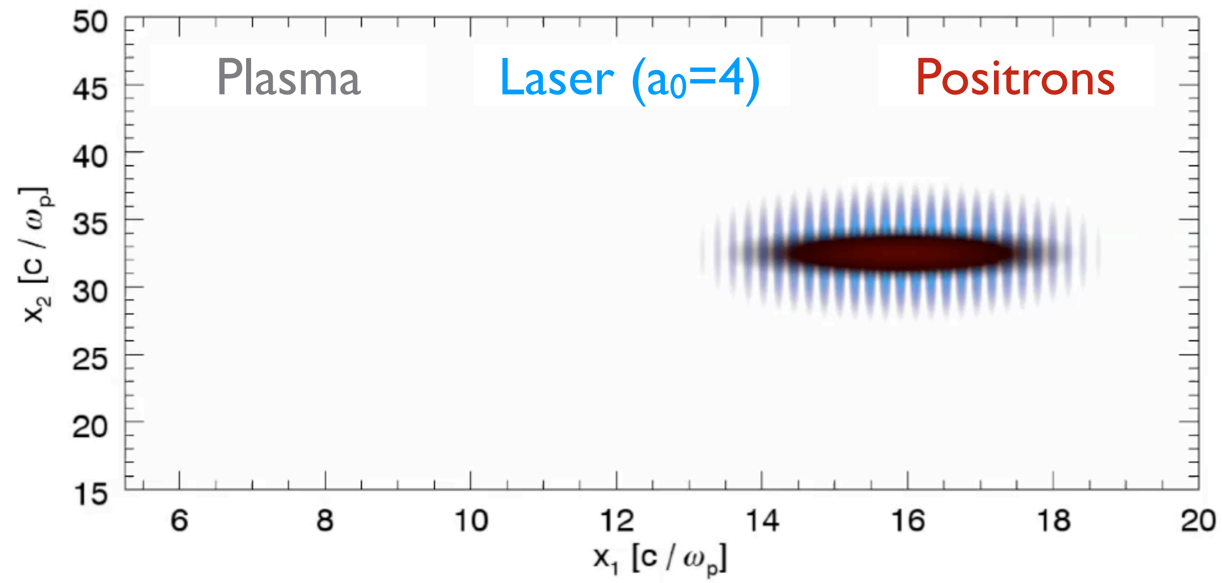


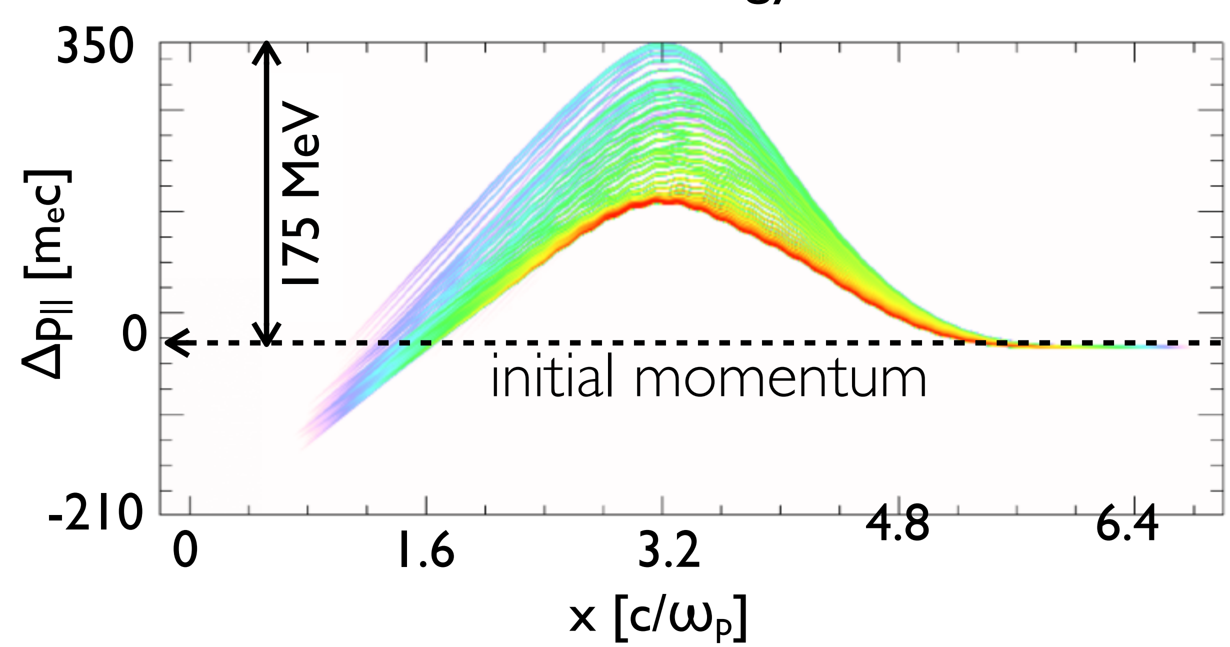
Proof-of-concept simulations

Positron beam loading required



balance laser ponderomotive force with positron attraction

Positrons extract energy from wakefield



J.Vieira et al to be submitted (2019).

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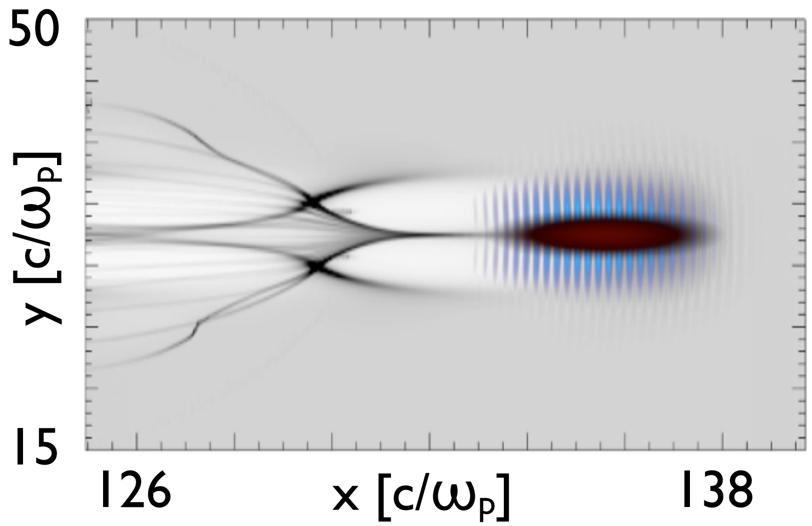

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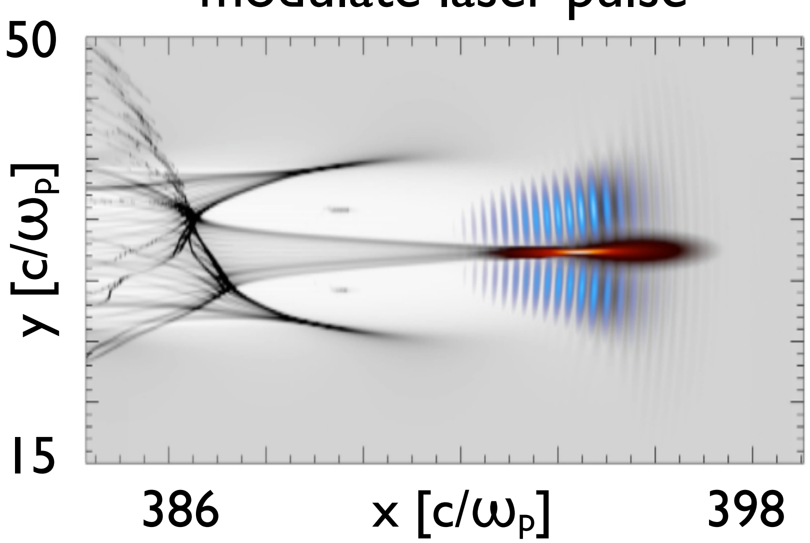

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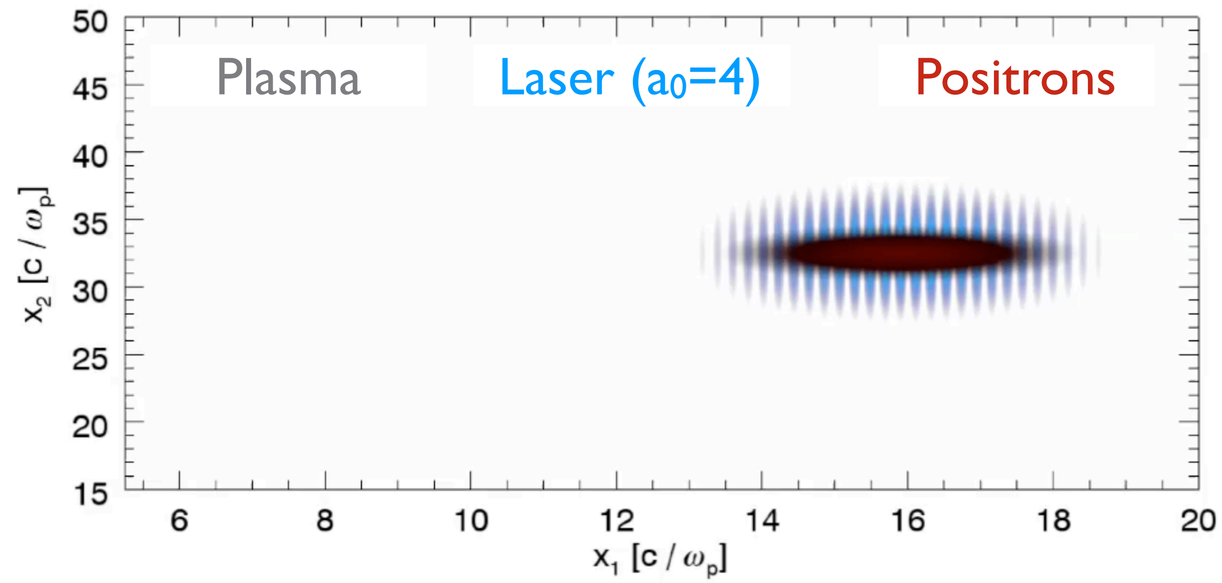

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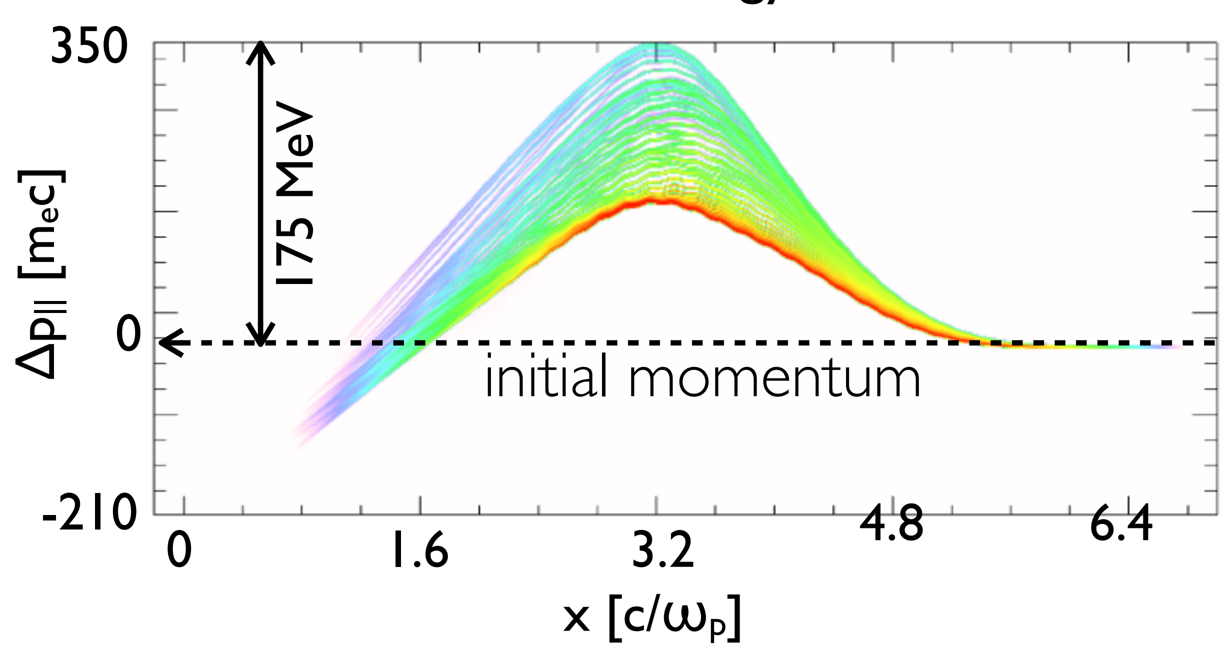

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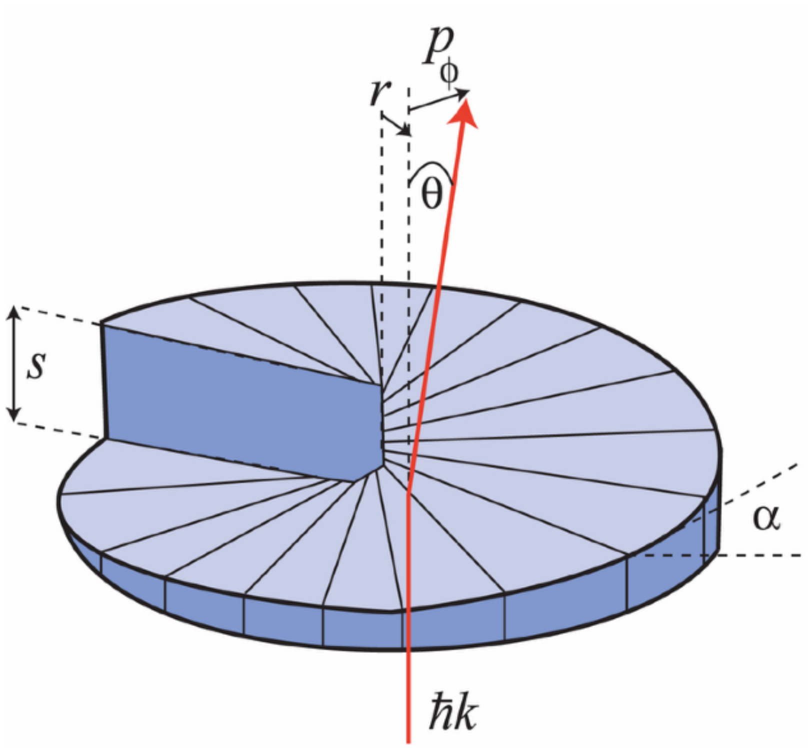
Conclusions and future directions

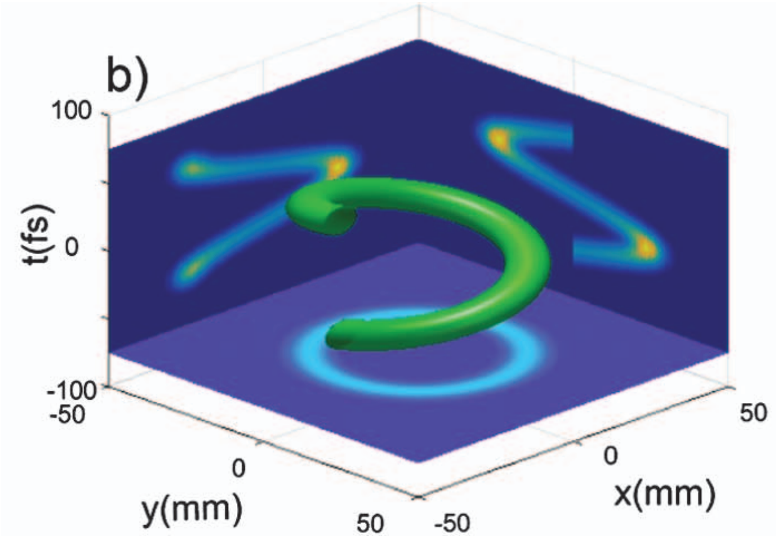
Transfer optical angular momentum to plasma

Experimental realisation*

spiral phase plate



Light spring forms when thickness ≈ laser duration



angular dependent group velocity dispersion

*G. Pariente, F. Quéré, Optics Letters **40** 2037 (2015)

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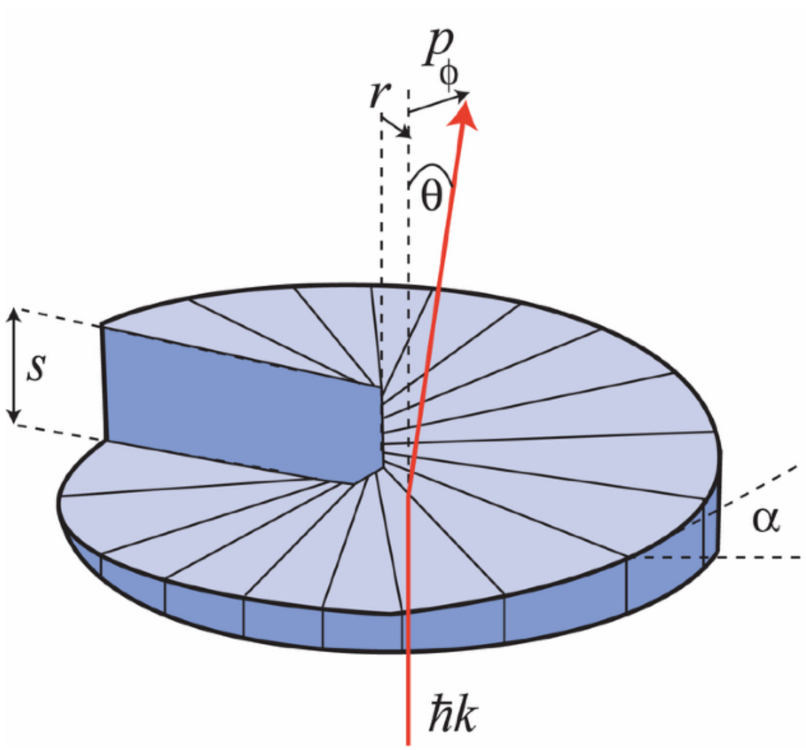

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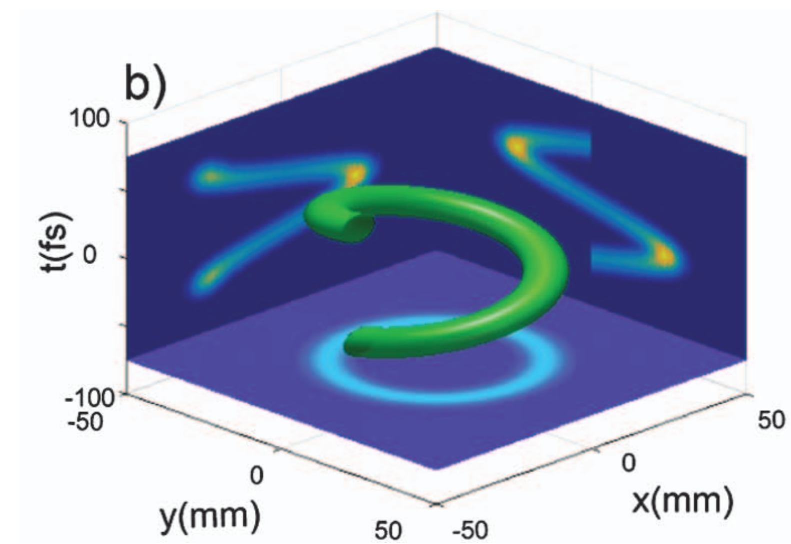


angular dependent group velocity dispersion

Mathematical model for simulations and theory

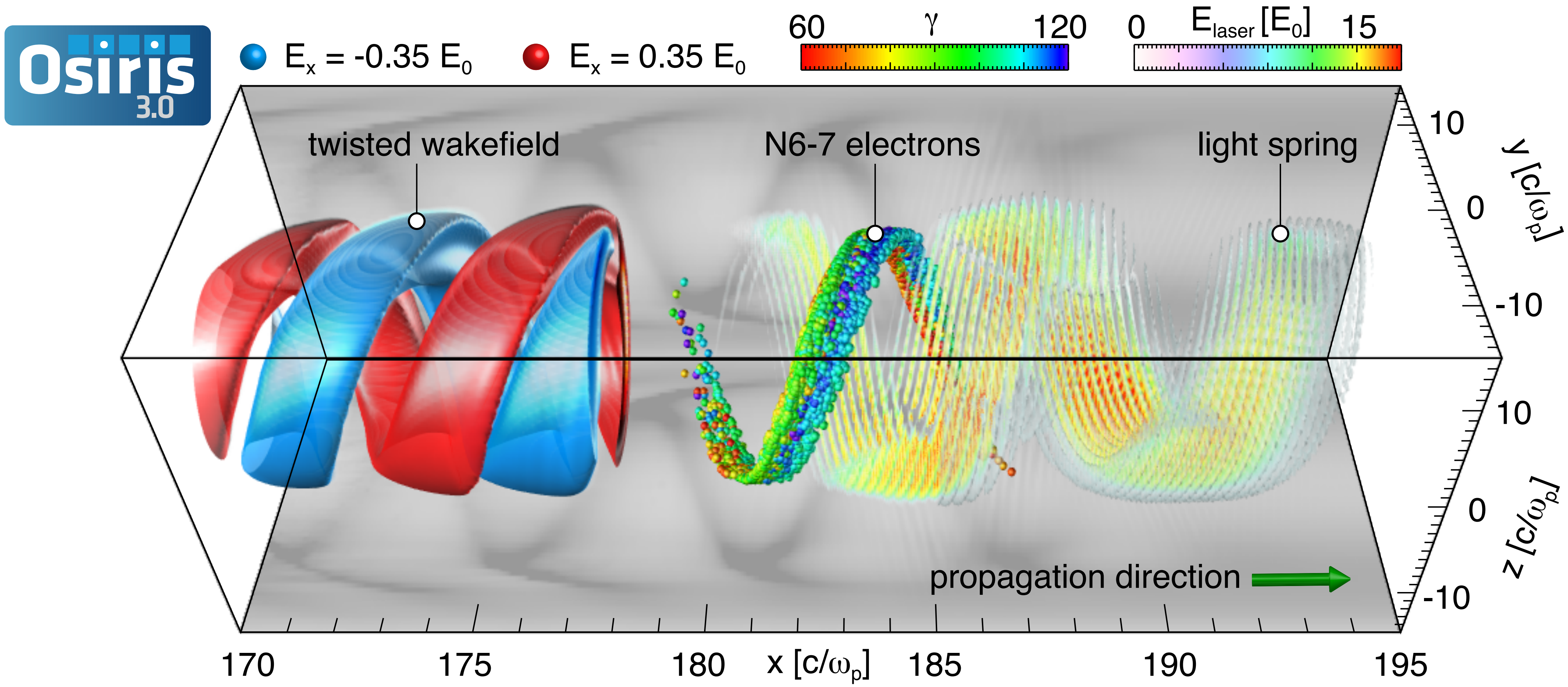
Beating two Laguerre-Gaussian modes

$$a^2 \propto a_{r,\ell}^2 + a_{r,\ell+\Delta\ell}^2 +$$
$$+2a_{r,\ell}a_{r,\ell+\Delta\ell}\cos\left[\Delta k(ct-x) + \Delta\ell\theta + \Delta\varphi(x)\right]$$

Δl is the OAM difference between the two modes
Δk is the wavenumber difference
Δφ is a phase difference

*G. Pariente, F. Quéré, Optics Letters **40** 2037 (2015)

Twisted wakefield structure



Panofksy-Wenzel theorem

Transverse force acting on relativistic particle

$$\nabla_\perp E_x = \frac{\partial \mathbf{W}_\perp}{\partial \xi}$$

Transverse wakefield

$$\mathbf{W}_\perp = \mathbf{E}_\perp + (\mathbf{e}_x \times \mathbf{B})_\perp$$

OAM wakefield

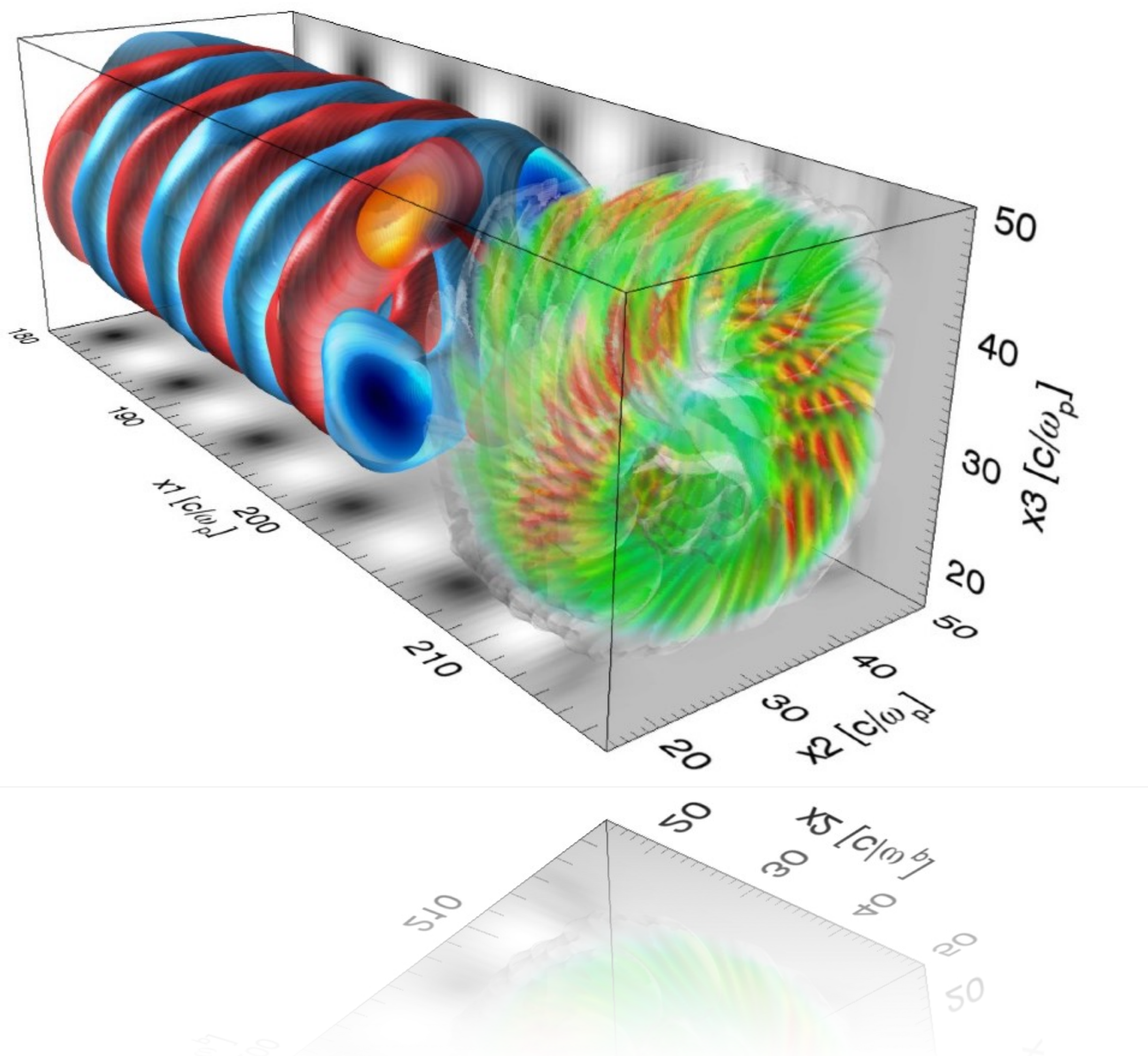
Radial focusing (betatron motion)

$$\frac{\partial E_x}{\partial r} = \frac{\partial W_r}{\partial \xi} \propto \frac{\partial \phi}{\partial r}$$

Azimuthal force **new!**

$$\frac{1}{r}\frac{\partial E_x}{\partial \theta} = \frac{\partial W_\theta}{\partial \xi} \propto \frac{\ell_p}{r}\phi$$

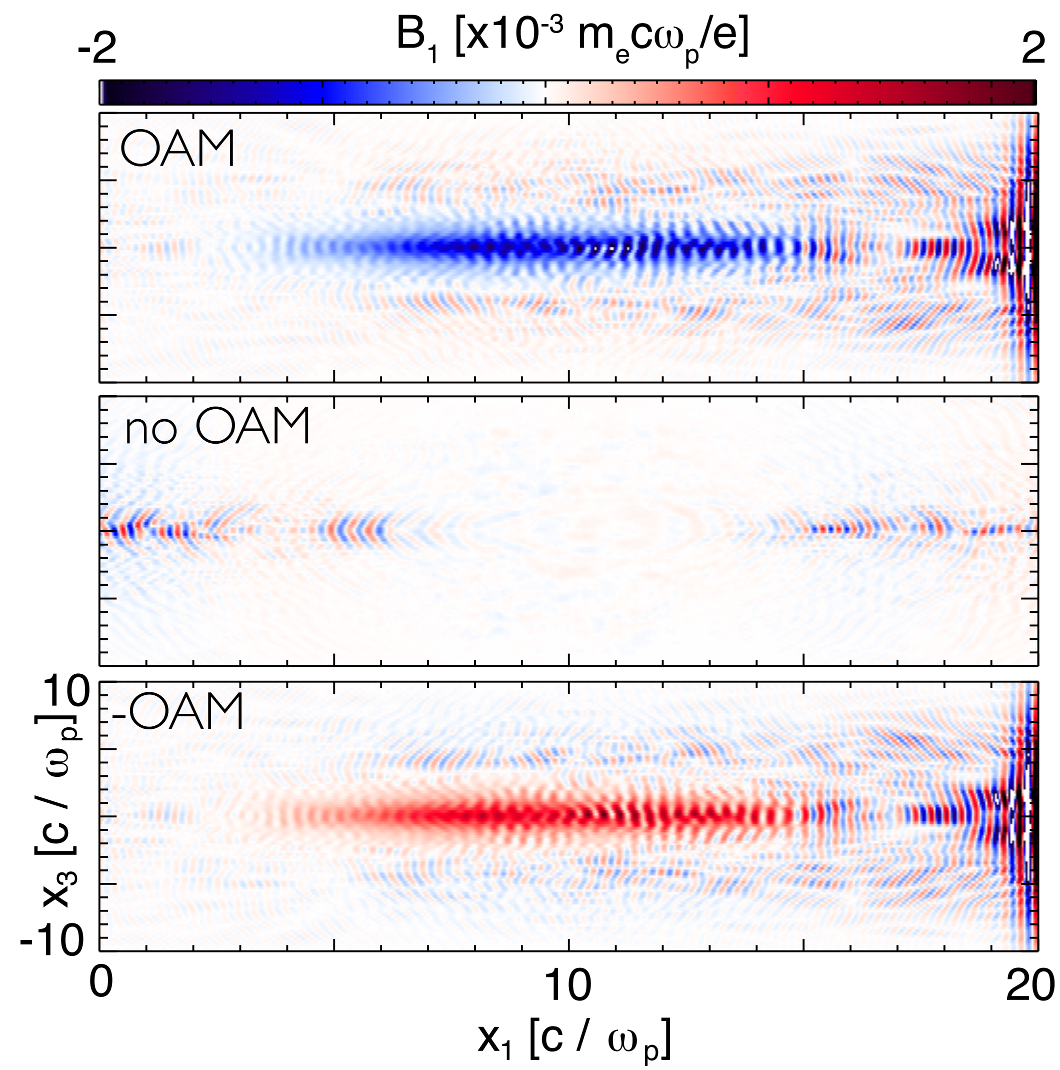
Simulations confirm new field components



Y. Shi et al PRL 121, 145002 (2018).

Longitudinal B fields

A new longitudinal B fields appear
when wakefields become nonlinear



(OAM plasma wave driven in a
Raman backscatter configuration)

Contents

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- **Conclusions and future directions**

Relativistic beams accelerated in OAM wakes

Hamiltonian formulation

Hamiltonian of a charged particle

$$\mathcal{H} = m_e c^2 \gamma + e\phi(r, \theta, \xi)$$

Twisted wakefield structure

$$\phi = \phi(v_\phi t - x + \ell_p \theta) = \phi(u)$$

Hamilton's equations

$$\frac{\mathrm{d}\mathcal{P}_x}{\mathrm{d}t} \simeq \frac{\mathrm{d}p_x}{\mathrm{d}t} = -\frac{\partial \mathcal{H}}{\partial x} = \phi'(u)$$

$$\frac{\mathrm{d}\mathcal{P}_\theta}{\mathrm{d}t} \simeq \frac{\mathrm{d}L_x}{\mathrm{d}t} = -\frac{\partial \mathcal{H}}{\partial \theta} = -\ell_p \phi'$$

$$\frac{\mathrm{d}\mathcal{H}}{\mathrm{d}t} = \frac{\partial \mathcal{H}}{\partial t} = v_g \phi'$$

J.Vieira et al PRL 121, 054801 (2018)

Relativistic beams accelerated in OAM wakes

TÉCNICO LISBOA

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Constants of motion

Energy $\gamma\left(1 - v_\phi v_x / c^2\right) = 1 + \Delta\phi / m_e c^2$

Ratio of angular momentum flux to energy $\dfrac{\Delta L_x}{\Delta p_x} = \dfrac{\ell_p}{k_p} \Rightarrow \dfrac{\Delta L_x}{E} = \dfrac{\ell_p}{\omega_p}$

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Angular momentum is quantised.

J. Vieira et al PRL 121, 054801 (2018)

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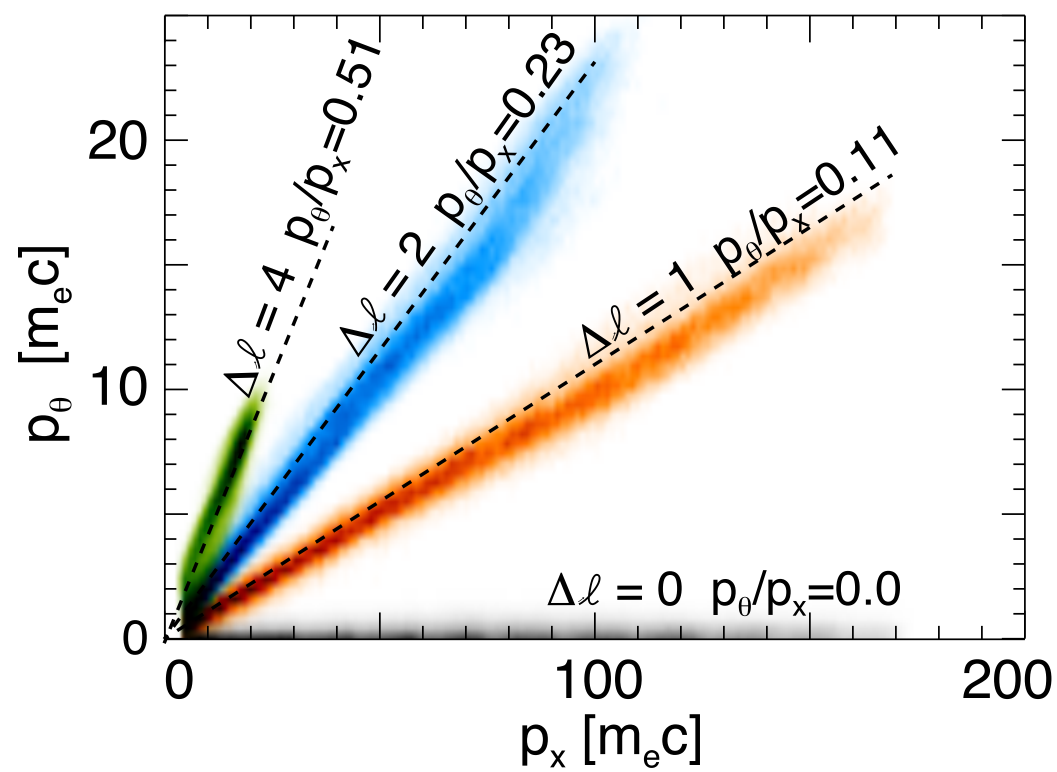
Simulations confirm OAM quantisation

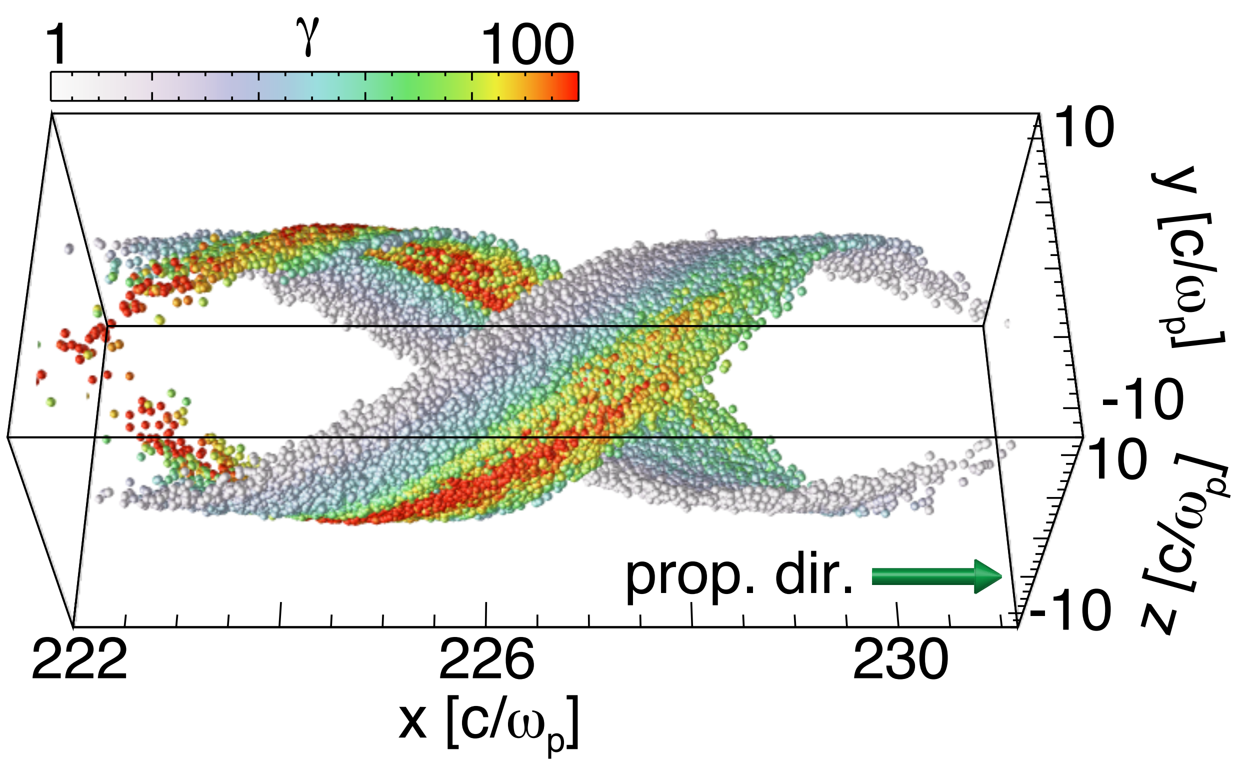


J.Vieira et al PRL 121, 054801 (2018)

Relativistic bunches have a vortex spatial structure

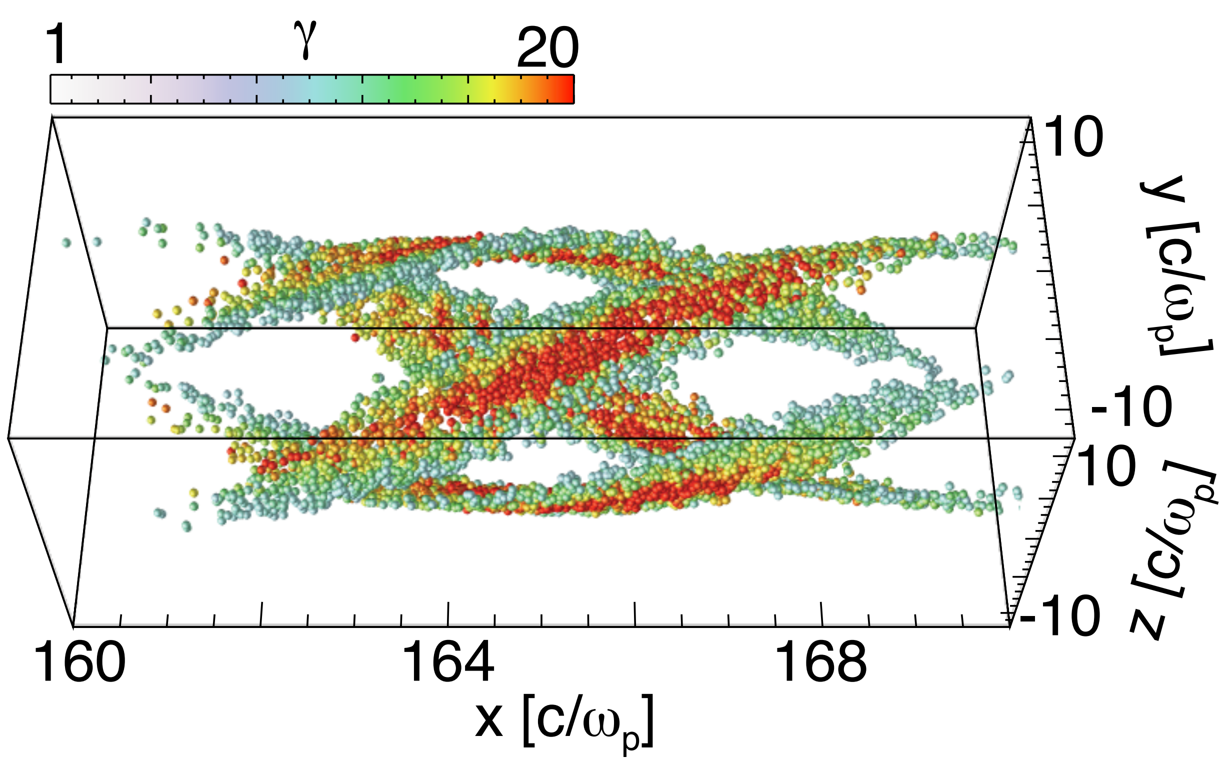
TÉCNICO LISBOA

$\ell = 2$



double start helix

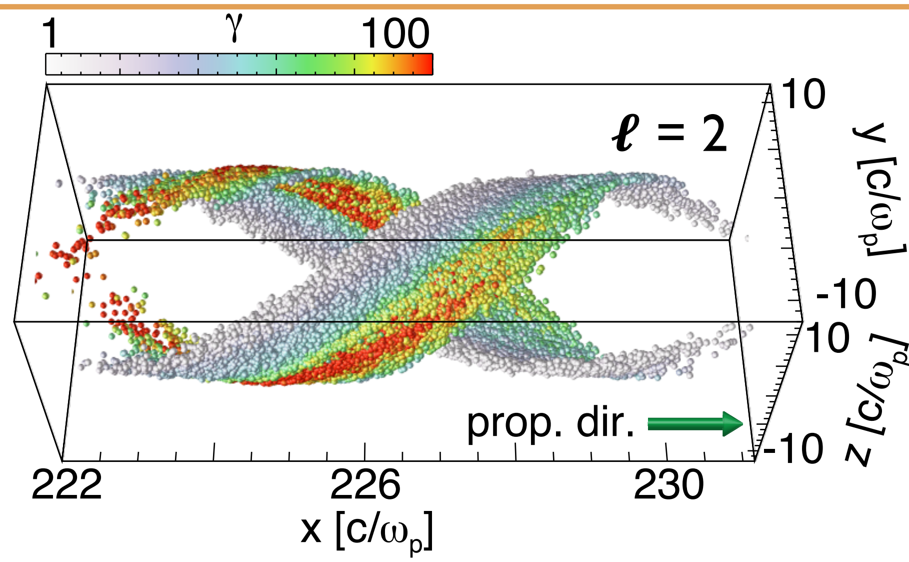
$\ell = 4$



four intertwined helixes

Beams have a vortex density structure

Classical

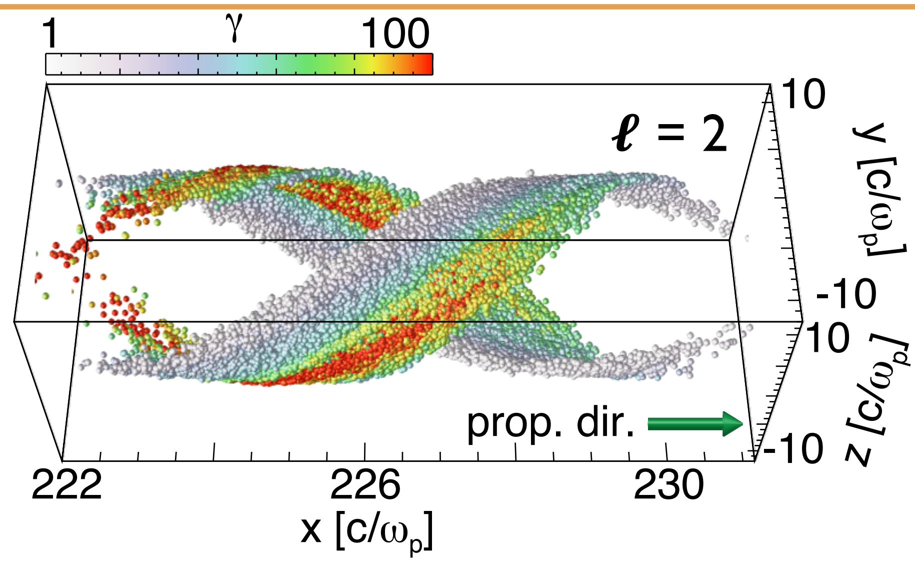


Ratio of angular momentum
to energy gain

$$\frac{\Delta L_x}{E} = \frac{\ell}{\omega_p}$$

Beams have a vortex density structure

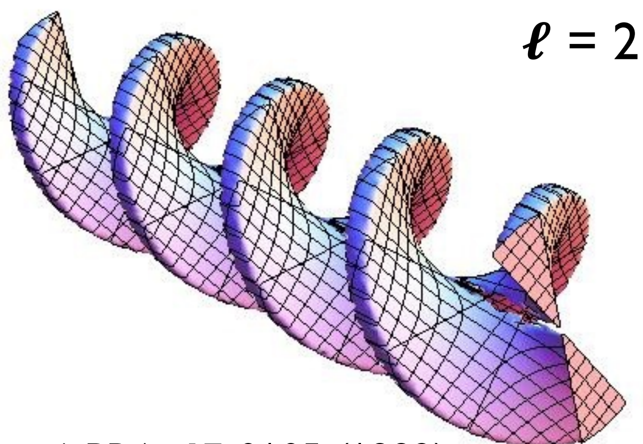
Classical



Ratio of angular momentum to energy gain

$$\frac{\Delta L_x}{E} = \frac{\ell}{\omega_p}$$

Light



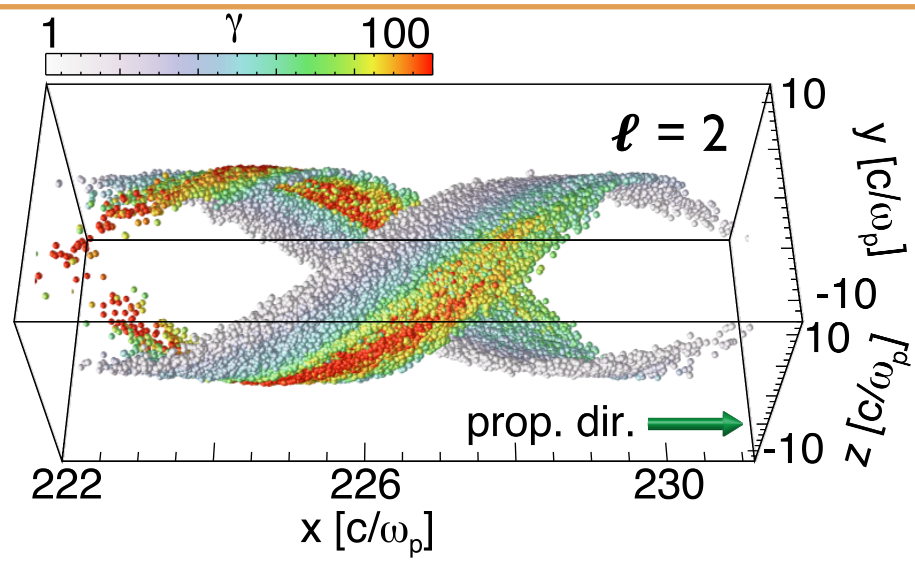
Ratio of angular momentum flux to energy flux for the vortex beams*

$$\frac{\mathbf{J}}{c\mathbf{P}} = \frac{\ell}{\omega_0}$$

*L. Allen *et al.* PRA, **45** 8185 (1992)

Beams have a vortex density structure

Classical



Ratio of angular momentum
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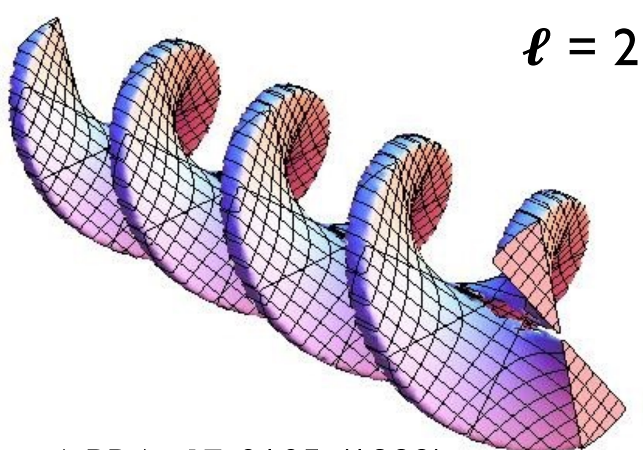
Light



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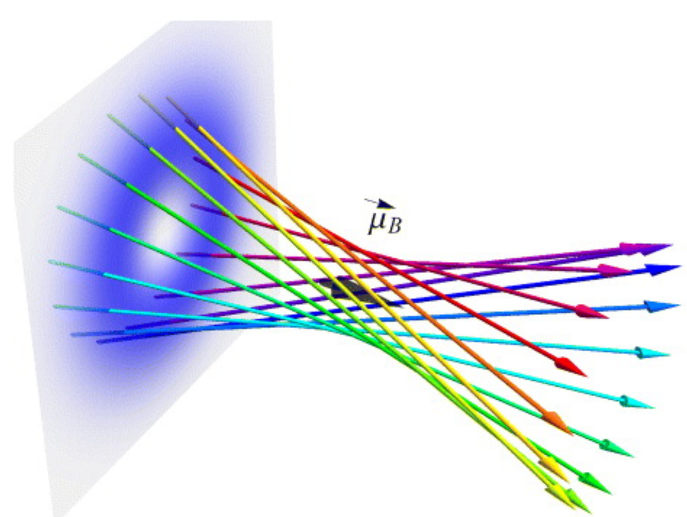
Quantum



Ratio of wave packet
angular momentum flux to longitudinal momentum

$$\frac{L_z}{p_z} = \frac{\ell}{k_z}$$

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Conclusions and future directions

Conclusions and future perspectives

TÉCNICO LISBOA

Twisted light provides new degrees of freedom to control plasma acceleration

positron acceleration and beam phase space manipulation

Positron acceleration in the non-linear blowout regime

on-axis positron focusing force in doughnut shaped plasma waves

Generation of vortex electron bunches

electrons with quantised orbital angular momentum levels in twisted plasma waves