Particle acceleration in twisted plasma waves with orbital angular momentum

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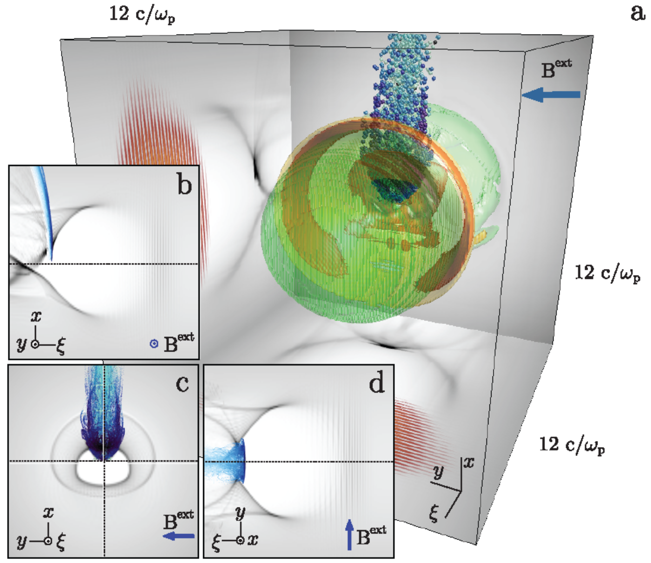
The topological freedom is an unique property of the plasma

cannot be currently found in conventional devices

TÉCNICO LISBOA

Plasma waves can have any shape

Plasma waves are sustained by free electrons



Wakefields in conventional devices are sustained by metallic parts

Implications of wake topology

Plasma waves are ubiquitous

- Fundamental plasma processes wave-particle interactions
- Nonlinear optics
- **Accelerators and light sources**

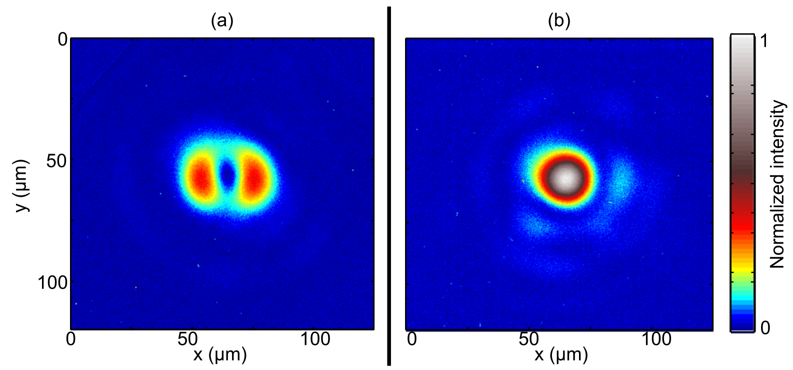
- One-dimensional waves widely explored, require standard Gaussian drivers
- Plasma waves with non-trivial topologies unexplored, require non-Gaussian drivers

Changing the **topology of the plasma can** have deep ramifications **and transform** the outputs of **plasma accelerators and radiation sources**

The orbital angular momentum of light (OAM)

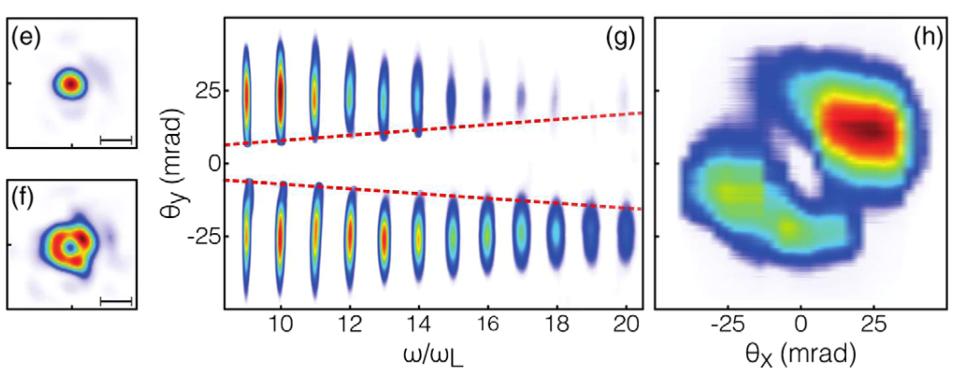
Ultra-intense twisted lasers

PW twisted laser for ion acceleration



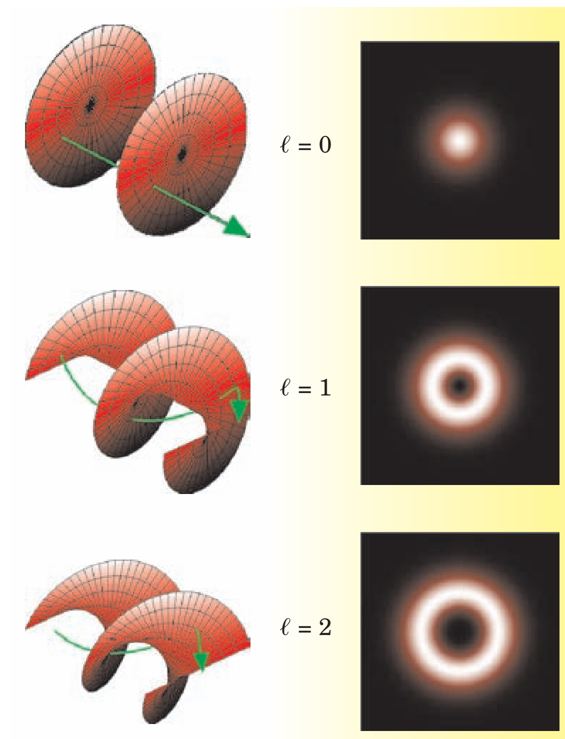
C. Brabetz *et al.*, PoP **22**, 013102 (2015).

High intensity twisted light from plasma mirrors



Denoeud *et al.* PRL **118** 033902 (2017)

Orbital angular momentum



$$E_{\text{laser}} \propto \left(\frac{r}{w_0}\right)^{|\ell|} \mathrm{L}_p^{|\ell|}\left(\frac{r}{w_0}\right) \exp\left(-\frac{r^2}{w_0^2}\right) \times \cos\left(\omega_0 t - k_0 z + \ell\phi\right)$$

M. Padgett *et al.*, Phys. Today 57(5), 35 (2004)

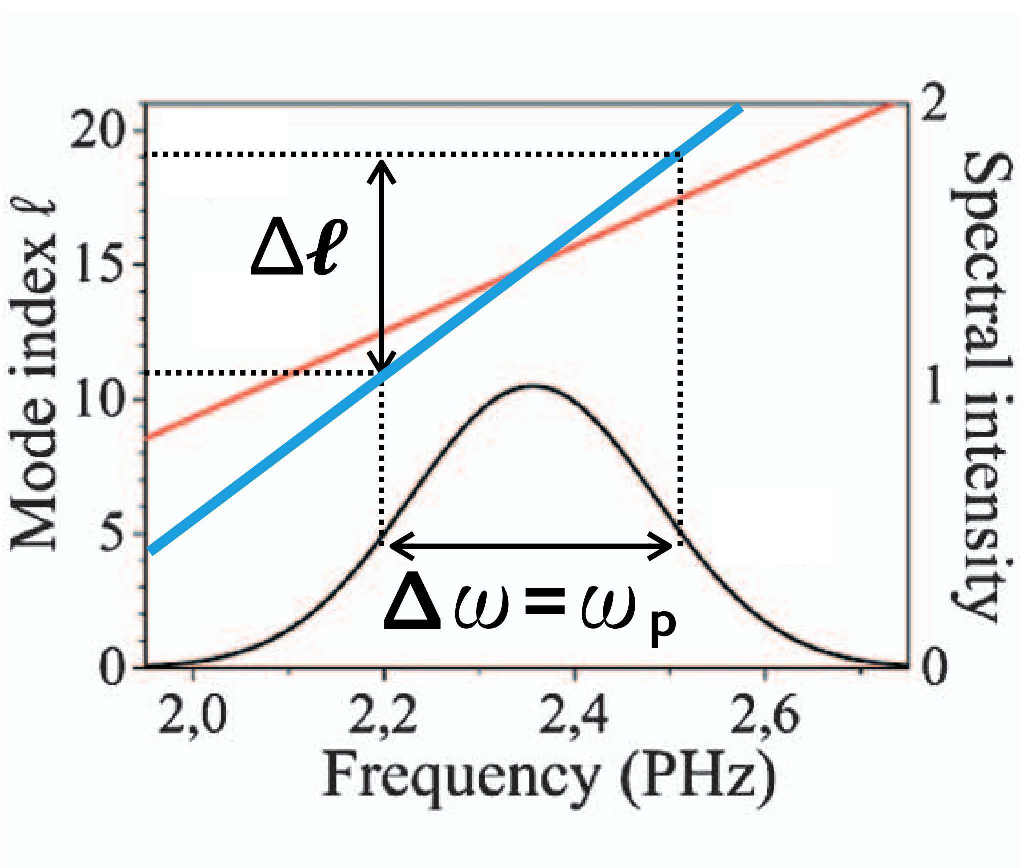
Goal: to propose new configuration that allows **transfer the angular momentum of the laser to a relativistic plasma wakefield** carrying OAM

Conditions to excite a twisted wakefield

(Forward) Raman scattering

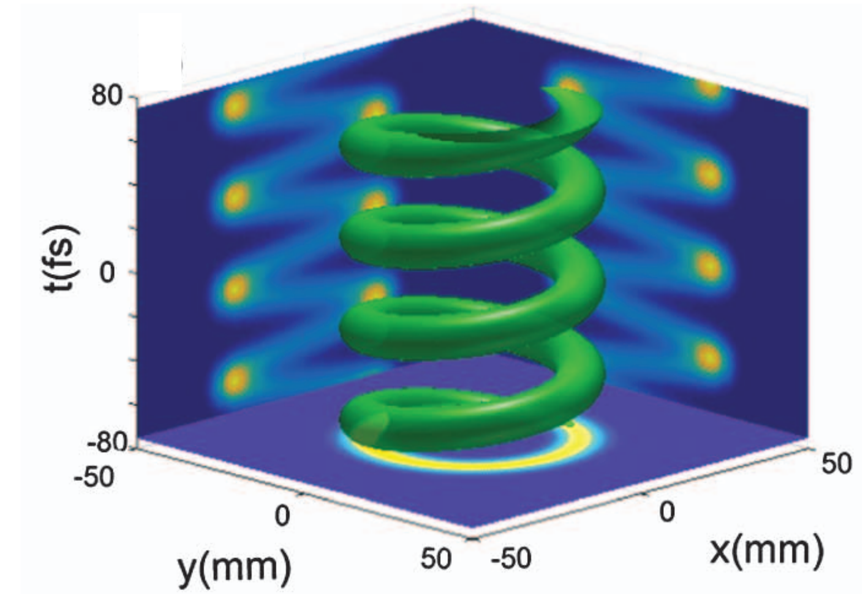
OAM transfer requires different photons (with different frequencies) carrying different OAM levels

Frequency and orbital angular momentum correlation

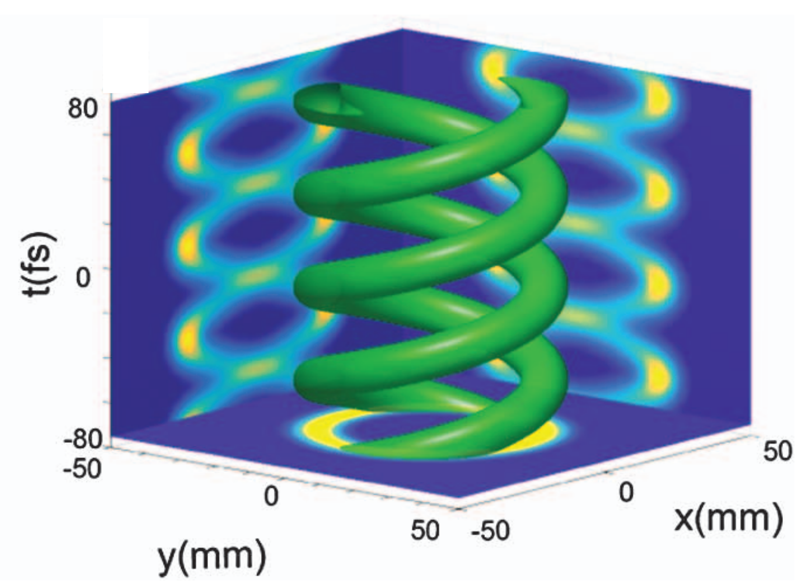


Plasma absorbs OAM $\Delta\ell$

Light spring with $\Delta\ell$ = 1



Light spring with $\Delta\ell$ = 2

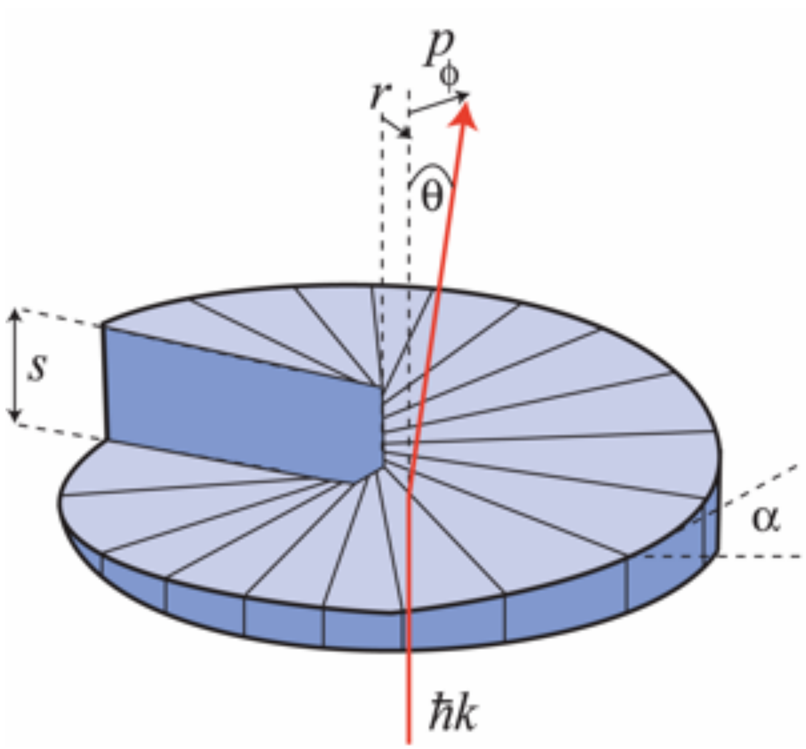


Images adapted from G. Pariente, F. Quéré, Optics Letters **40** 2037 (2015)

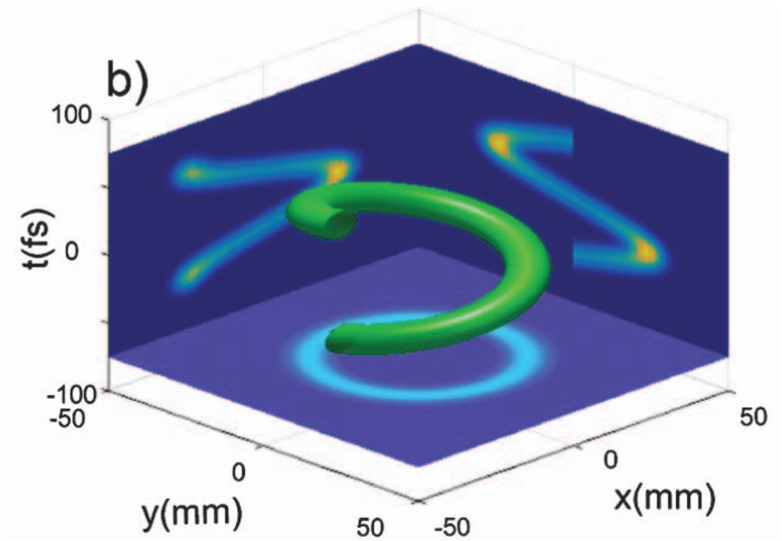
Generation of an ultra-short light spring

Experimental realisation*

spiral phase plate



Light spring forms when thickness ≈ laser duration



angular dependent group velocity dispersion

Mathematical model for simulations and theory

Beating two Laguerre-Gaussian modes

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

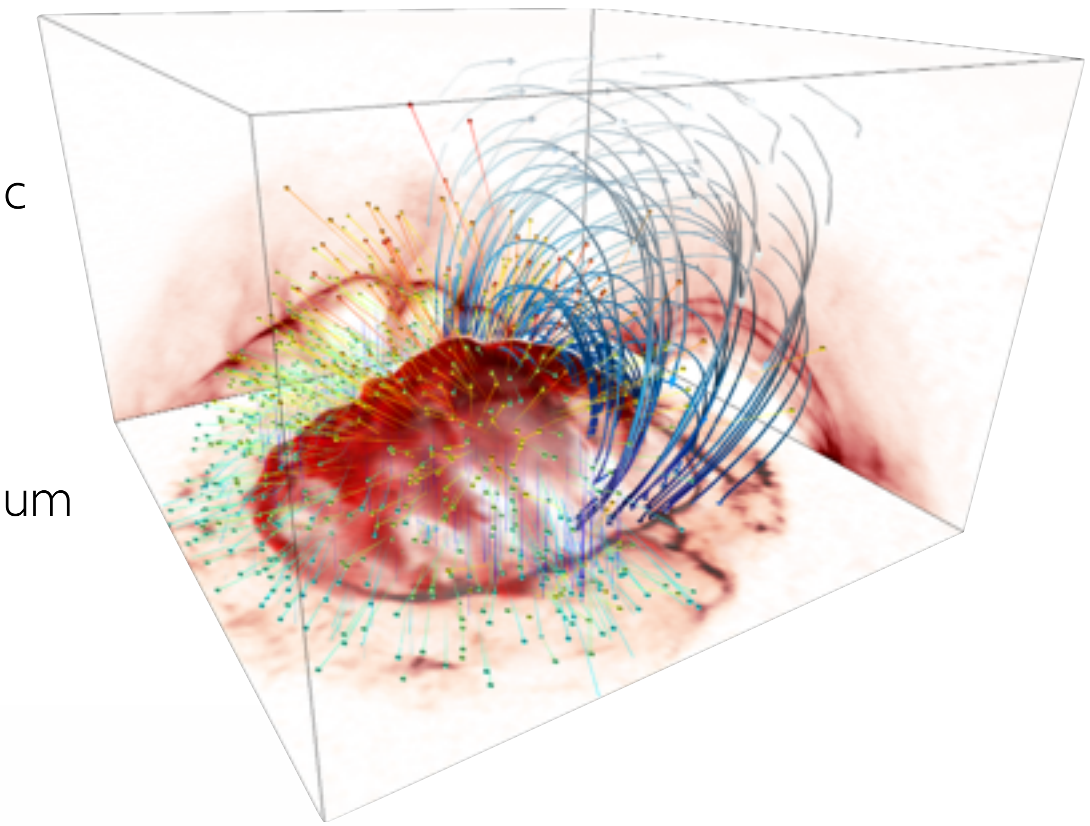
Δl is the OAM difference between the two modes
Δk is the wavenumber difference
Δφ is a phase difference

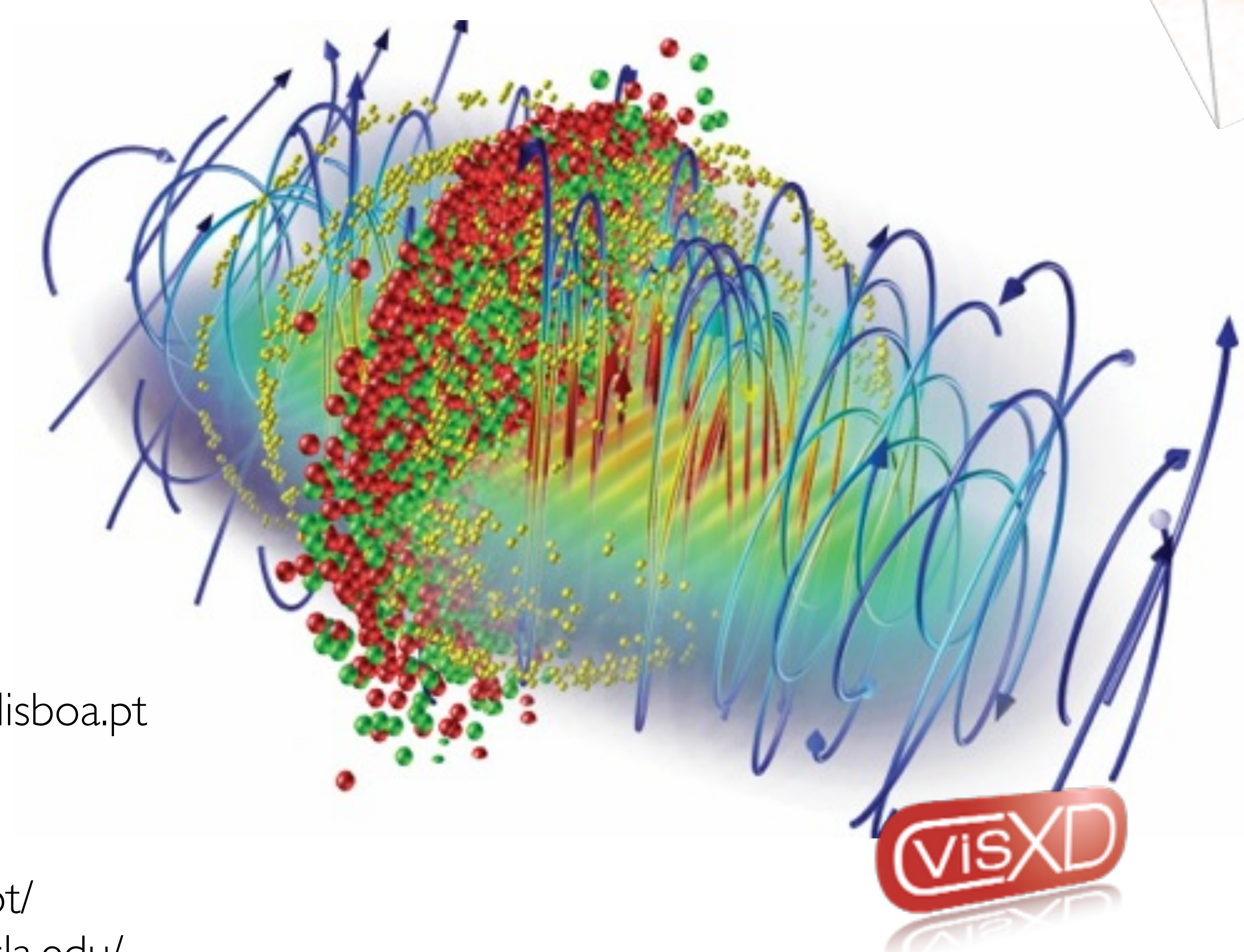
*G. Pariente, F. Quéré, Optics Letters **40** 2037 (2015)

OSIRIS 3.0

osiris framework

- Massivelly Parallel, Fully Relativistic Particle-in-Cell (PIC) Code
- Visualization and Data Analysis Infrastructure
- Developed by the osiris.consortium
  - ⇒ UCLA + IST





code features

- Scalability to ~ 1.6 M cores
- SIMD hardware optimized
- Parallel I/O
- Dynamic Load Balancing
- QED module
- Particle merging
- GPGPU support
- Xeon Phi support

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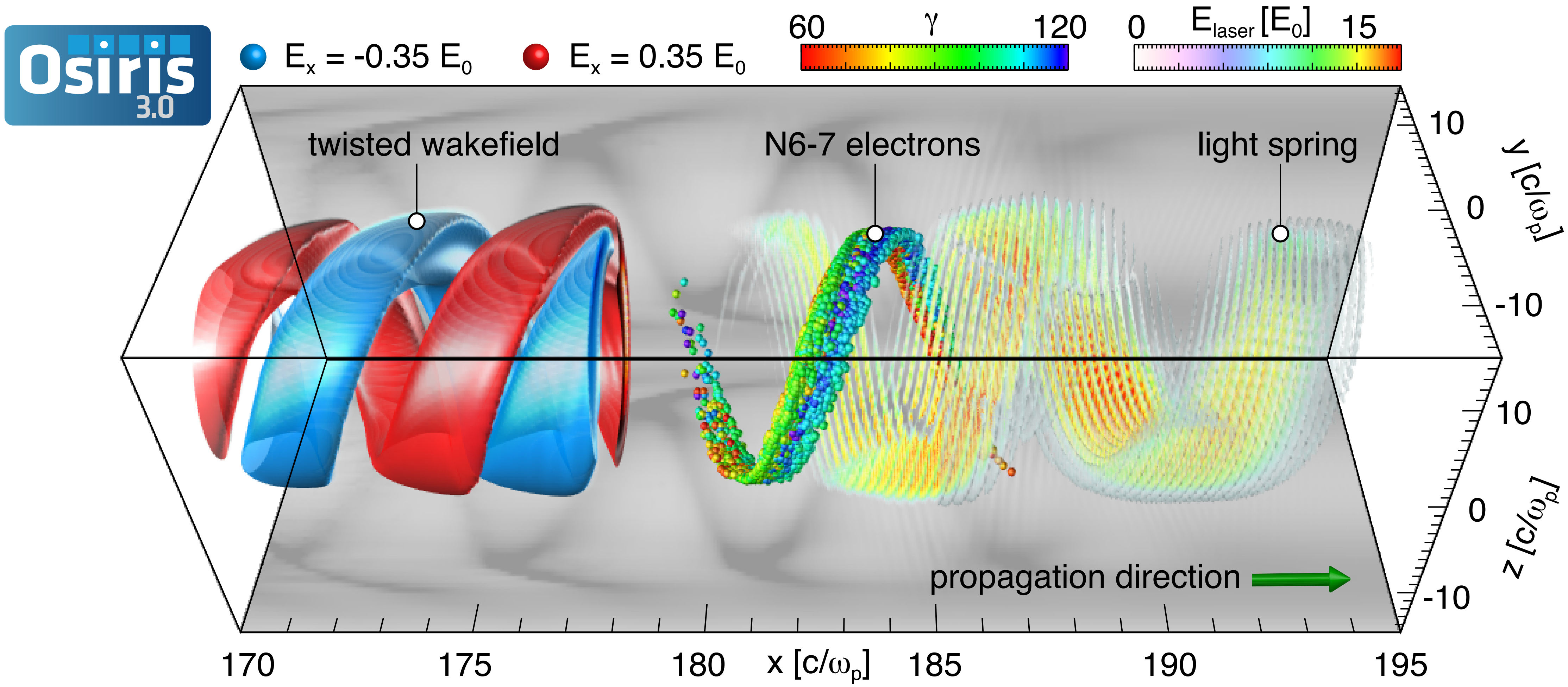
Twisted wakefield structure



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!**

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

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

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

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

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

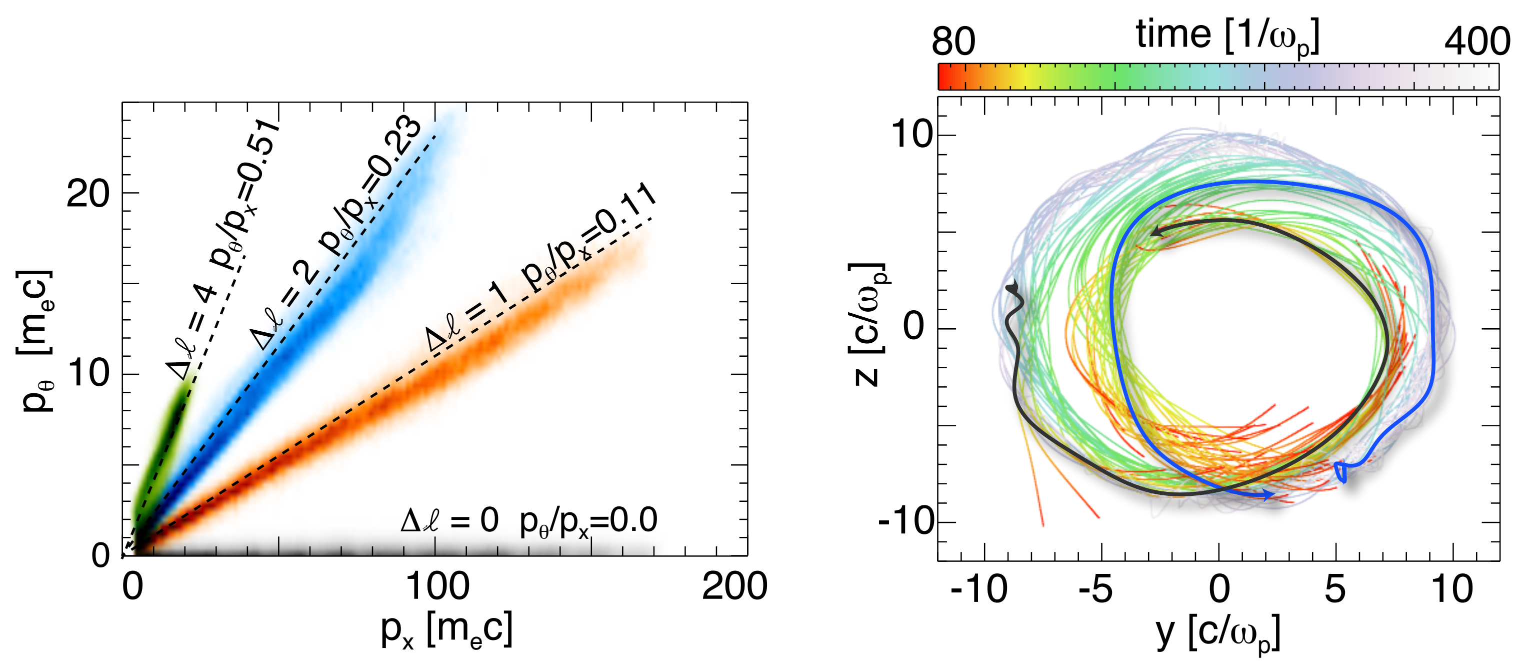
Constants of motion

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

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

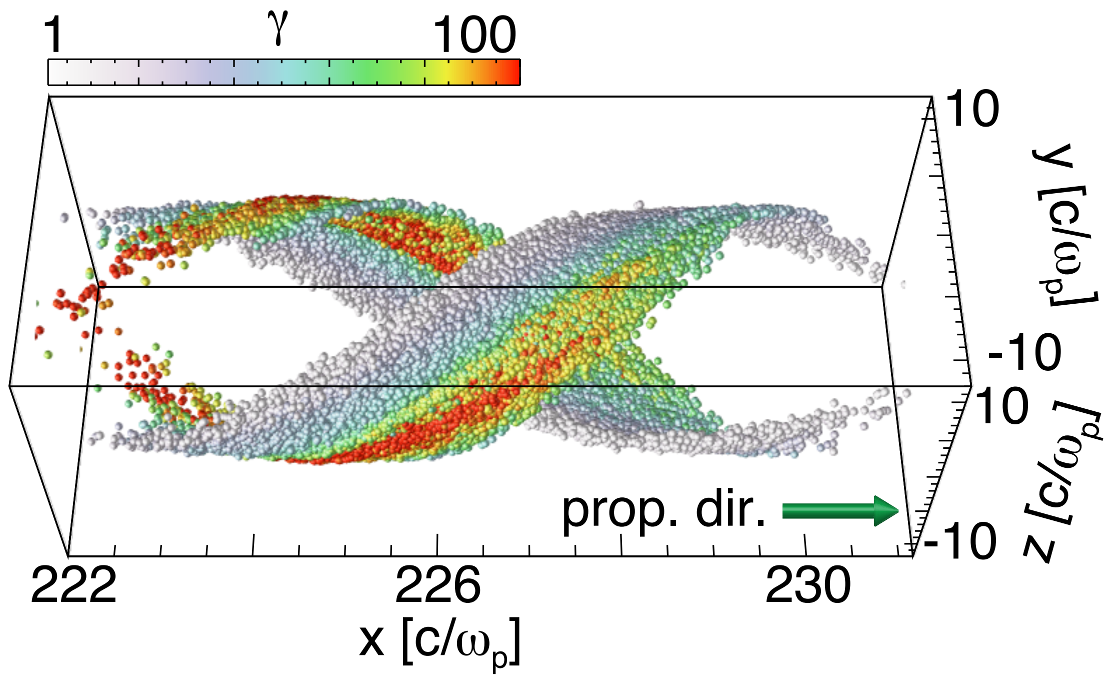
Angular momentum is quantised.

Simulations confirm OAM quantisation

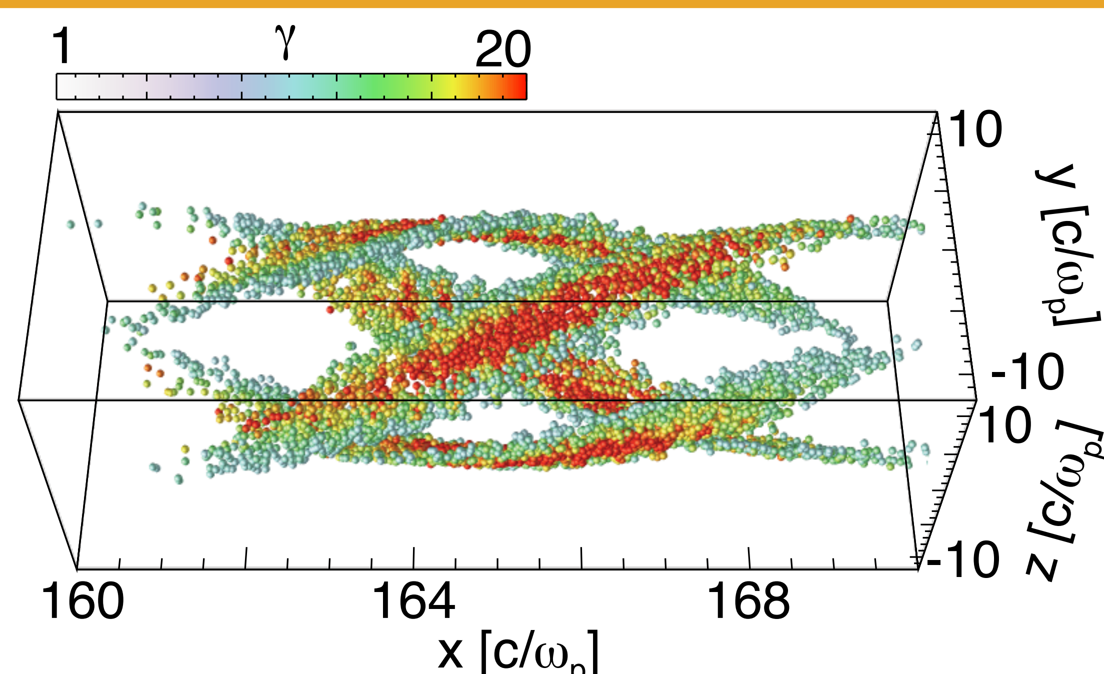


Beams have a vortex density structure

Vortex particle beam with $\ell = 2$



Vortex particle beam with $\ell = 4$



Similar to twisted light

Ratio of angular momentum flux to energy flux for light

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

L. Allen *et al.*, PRA **11** 8185 (1992)

Ratio of angular momentum to energy for beam particle

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

Vortex beam electrons move as a twisted ray of light

Energy gain of the vortex beam

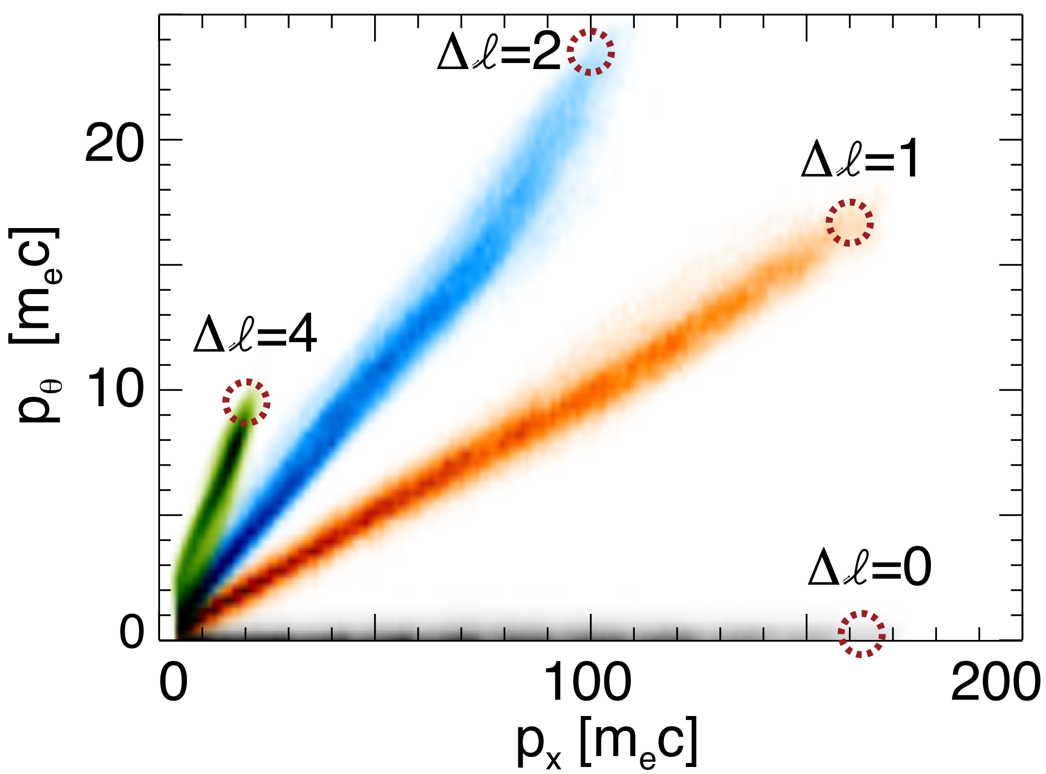
Lower energy gain

Energy gain

$$\Delta\gamma \propto \frac{1}{c^2(1+\Delta\ell^2/r^2) - v_\phi^2} \leq 2\gamma_\phi^2$$

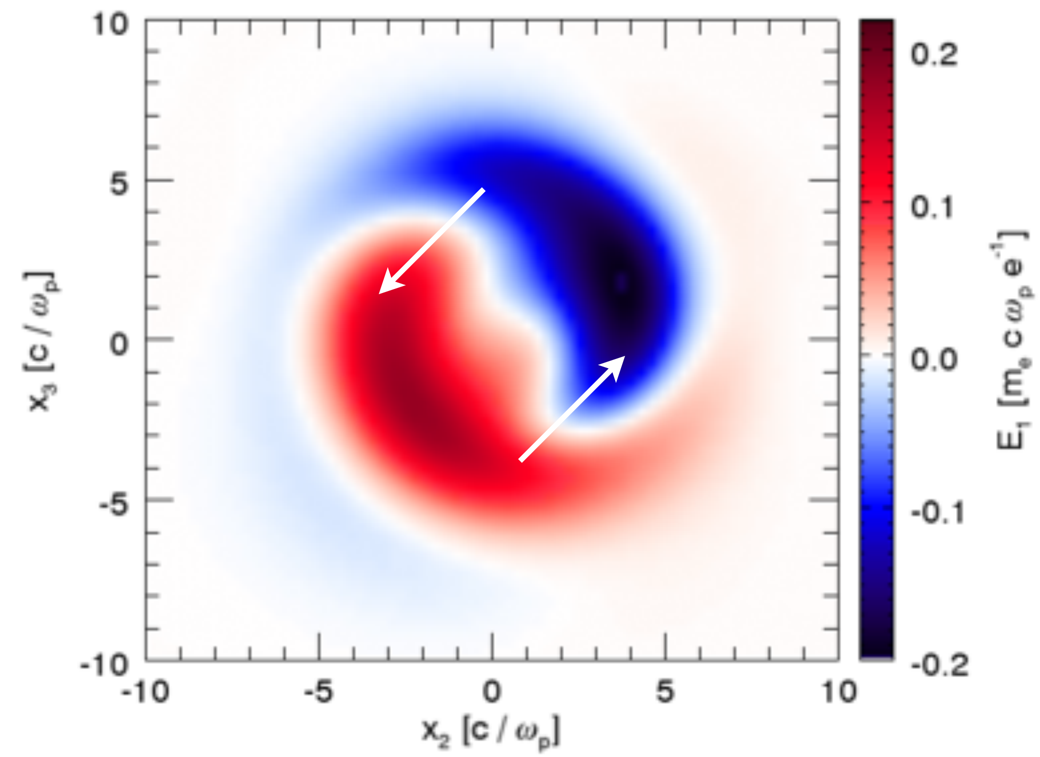
decreases with the plasma wave OAM

Simulation confirmation



Reduced dephasing length

Transverse slide of longitudinal wakefield

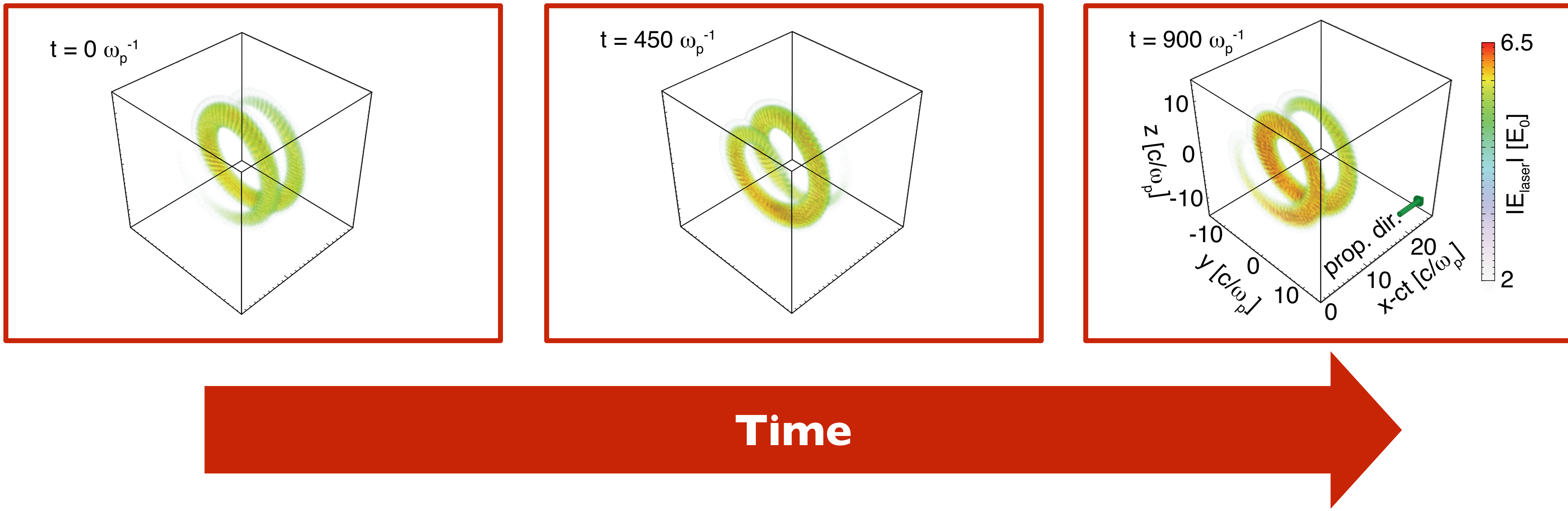


Dephasing along the axial direction and also along the azimutal direction $\mathbf{e}_\theta$

Particles dragged along $\mathbf{e}_\theta$ due to the new azimuthal wakefield component E_θ

Light springs spins in a plasma channel

Twisted wavefronts can spiral in a plasma channel causing the rotation of the light spring



Two key directions set wakefield response:
rotation orientation: set by the OAM of light spring modes
OAM orientation: set by the OAM difference between light spring modes

Wakefield phase velocity depends the relative orientation between these two rotational directions

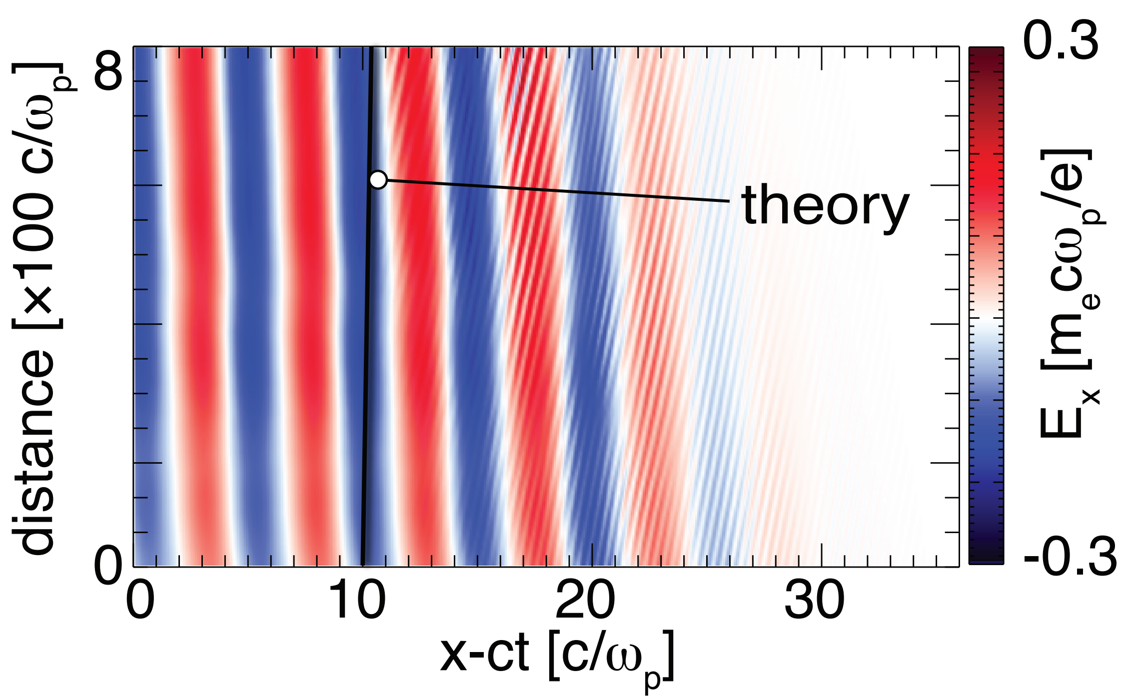
Tuneable phase velocities

Wakefield phase velocity depends the relative sign between ℓ and $\Delta\ \ell$

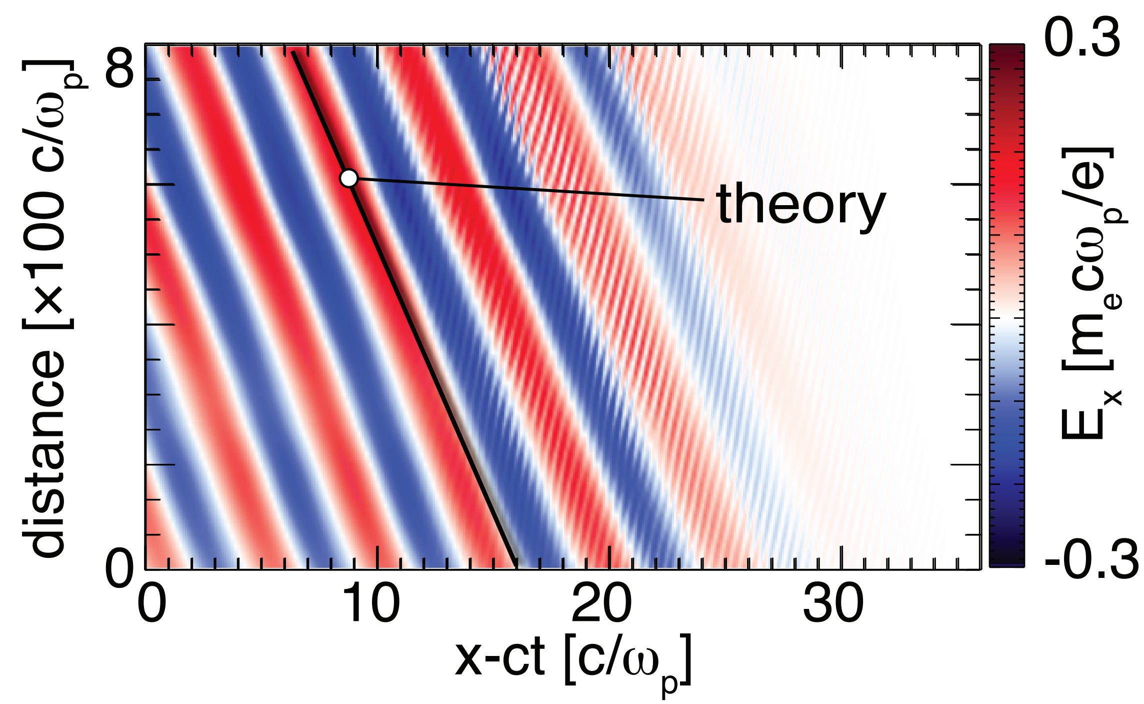
$$\frac{v_{\phi,\mathrm{wake}}}{c} = \left[1 - \frac{k_p(0)^2}{2k_0^2} - \frac{2\left(1+|\ell+\Delta\ell|\right)}{k_0^2 w_0^2} + \frac{2\left(|\ell+\Delta\ell|-|\ell|\right)}{k_0 w_0^2 \Delta k}\right]$$

Phase velocity control

$\Delta\ell > 0$ and $\ell>0$



$\Delta\ell < 0$ and and $\ell>0$

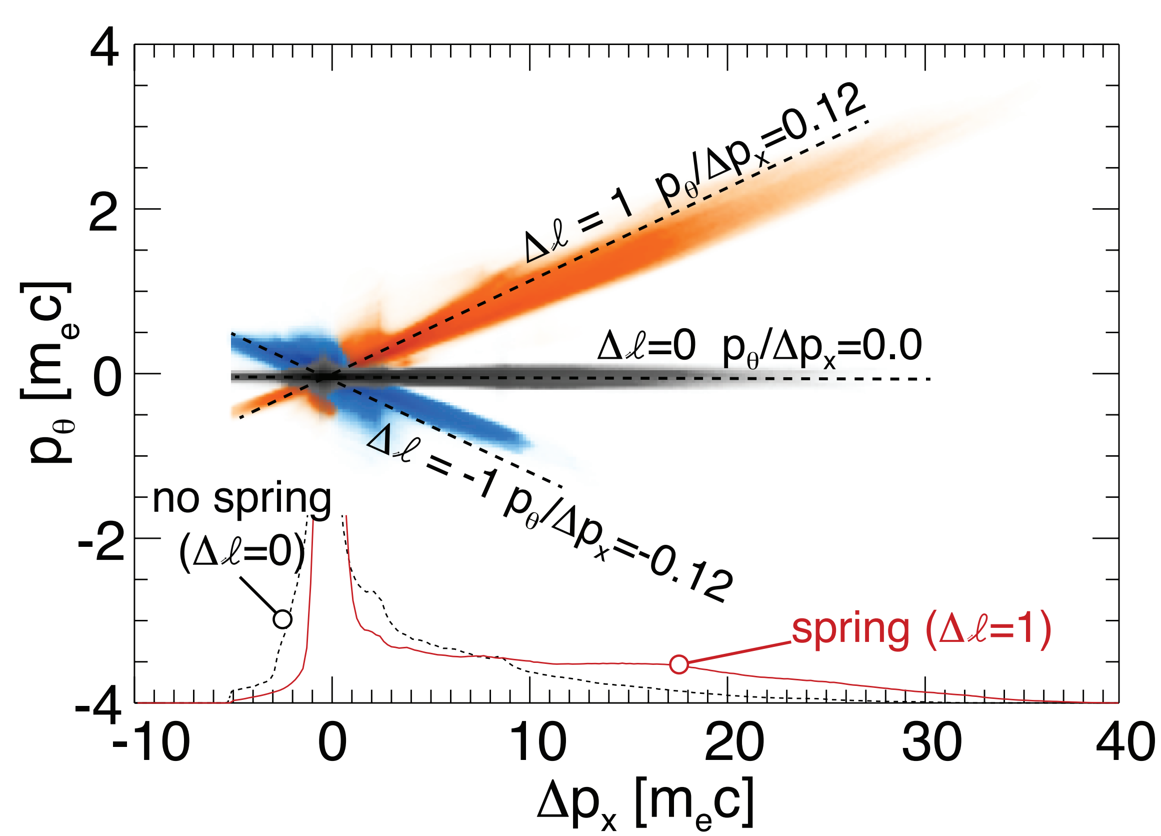


Energy gain control beyond planar wakefields

Wakefield phase velocity depends the relative sign between ℓ and $\Delta\ \ell$

$$\frac{v_{\phi,\mathrm{wake}}}{c} = \left[1 - \frac{k_p(0)^2}{2k_0^2} - \frac{2\left(1+|\ell+\Delta\ell|\right)}{k_0^2 w_0^2} + \frac{2\left(|\ell+\Delta\ell|-|\ell|\right)}{k_0 w_0^2 \Delta k}\right]$$

Energy gain control



Ordering of energy gain with $\Delta\ \ell$ for constant ℓ

$\Delta\ell$

$\Delta\ell$ =1	ΔE^{max}~40
$\Delta\ell$ =0	ΔE^{max}~30
$\Delta\ell$ =-1	ΔE^{max}~10

Energy gain

Conclusions and future directions

Plasma wave topology is a new degree of freedom that impacts accelerators and light sources

- Light spring laser pulses as drivers for twisted plasma waves

- Generation of relativistic vortex bunches with quantised OAM levels

- Rotation of light spring enable all optical control of the wake phase velocity

- Additional questions motivated by this work
  - wakefield excitation by relativistic vortex bunches
  - twisted THz generation using vortex beams
  - vortex bunch magnetic moments and interaction with magnetic fields
  - …

Thank you!