Thomson scattering for producing spatiotemporal optical vortices

R.R. Almeida [1]

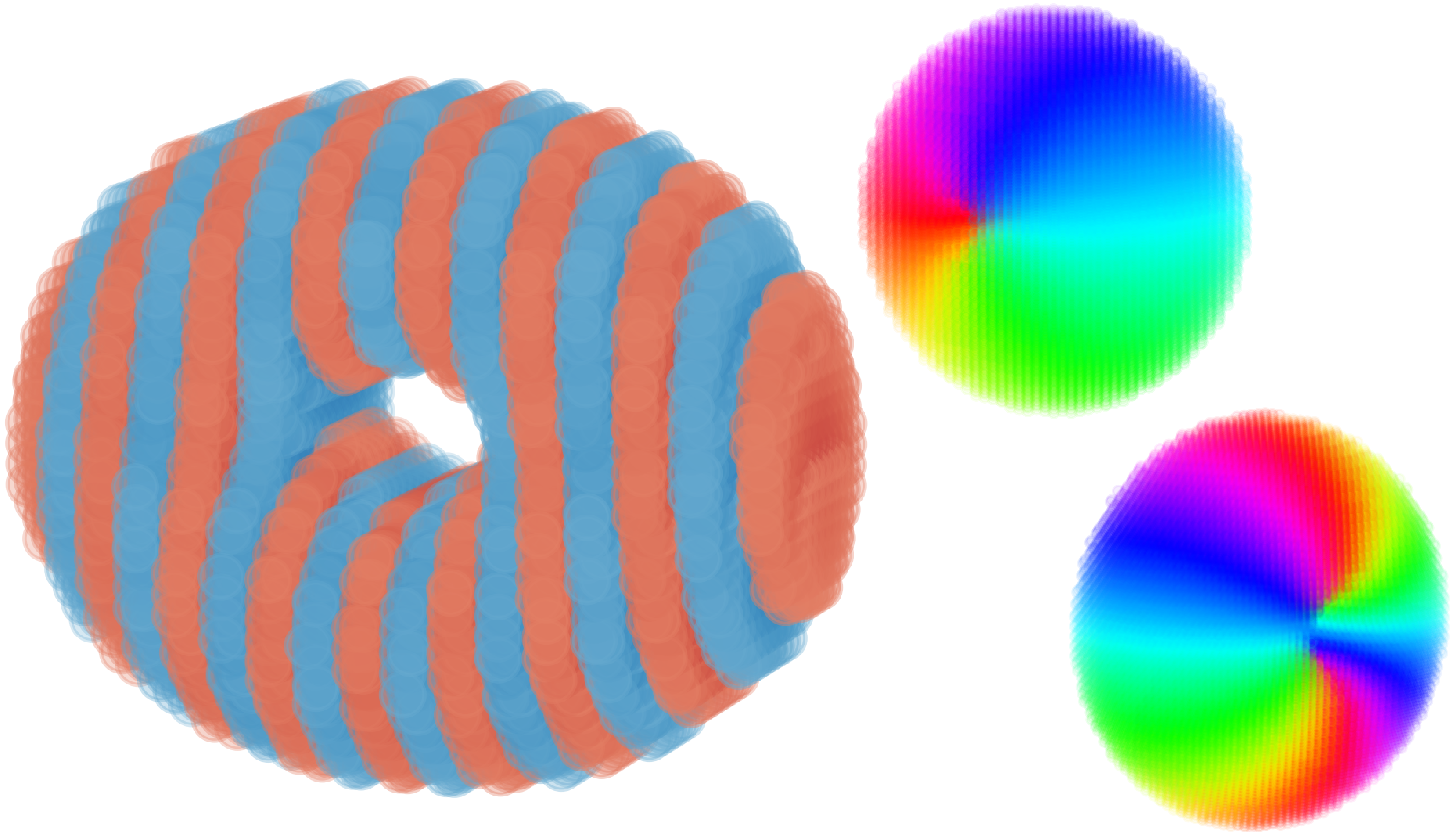
J.P. Palastro [2], R. Fonseca [1,3], J. Vieira [1]

[1] GoLP / Instituto de Plasmas e Fusão Nuclear
Instituto Superior Técnico, Lisbon, Portugal

[2] University of Rochester, Laboratory for Laser Energetics
Rochester, New York, 14623 USA

[3] DCTI/ISCTE University Institute of Lisbon, 1649-026
Lisbon, Portugal

epp.tecnico.ulisboa.pt || **golp**.tecnico.ulisboa.pt



Introduction

Main Goal

Thomson Scattering as a light structure manipulation tool

Thomson Scattering can be used to both **upshift radiation frequency**

but also to accurately **manipulate and structure light fields**

* Allen, L., et.al Physical Review A 45, 8185–8189 (1992)
Pariente, G. & Quéré, F. , Opt. Lett. 40, 2037 (2015)
Jhajj, N. et al. , Phys. Rev. X 6, 031037 (2016)
Froula, D. H. et al. , Physics of Plasmas 26, 032109–032109 (2019)

Introduction

Main Goal

Thomson Scattering as a light structure manipulation tool

Thomson Scattering can be used to both **upshift radiation frequency** but also to accurately **manipulate and structure light fields**

Structured light *

New and exciting area of research

Traditionally, **high order couplings** in laser beams were seen as a **negative** aspect

More recently, **coupling the spatial and temporal components of light** has brought a plethora of new applications

Particle acceleration with OAM lasers and spatiotemporal couplings

High Magnetic Field generation

* Allen, L., et.al Physical Review A 45, 8185–8189 (1992)
Pariente, G. & Quéré, F. , Opt. Lett. 40, 2037 (2015)
Jhajj, N. et al. , Phys. Rev. X 6, 031037 (2016)
Froula, D. H. et al. , Physics of Plasmas 26, 032109–032109 (2019)

Introduction

Main Goal
Thomson Scattering as a light structure manipulation tool

Thomson Scattering can be used to both **upshift radiation frequency** but also to accurately **manipulate and structure light fields**

Structured light *
New and exciting area of research

Traditionally, **high order couplings** in laser beams were seen as a **negative** aspect

More recently, **coupling the spatial and temporal components of light** has brought a plethora of new applications

Particle acceleration with OAM lasers and spatiotemporal couplings
High Magnetic Field generation

Accurate description of laser beams
Accurate injection is key

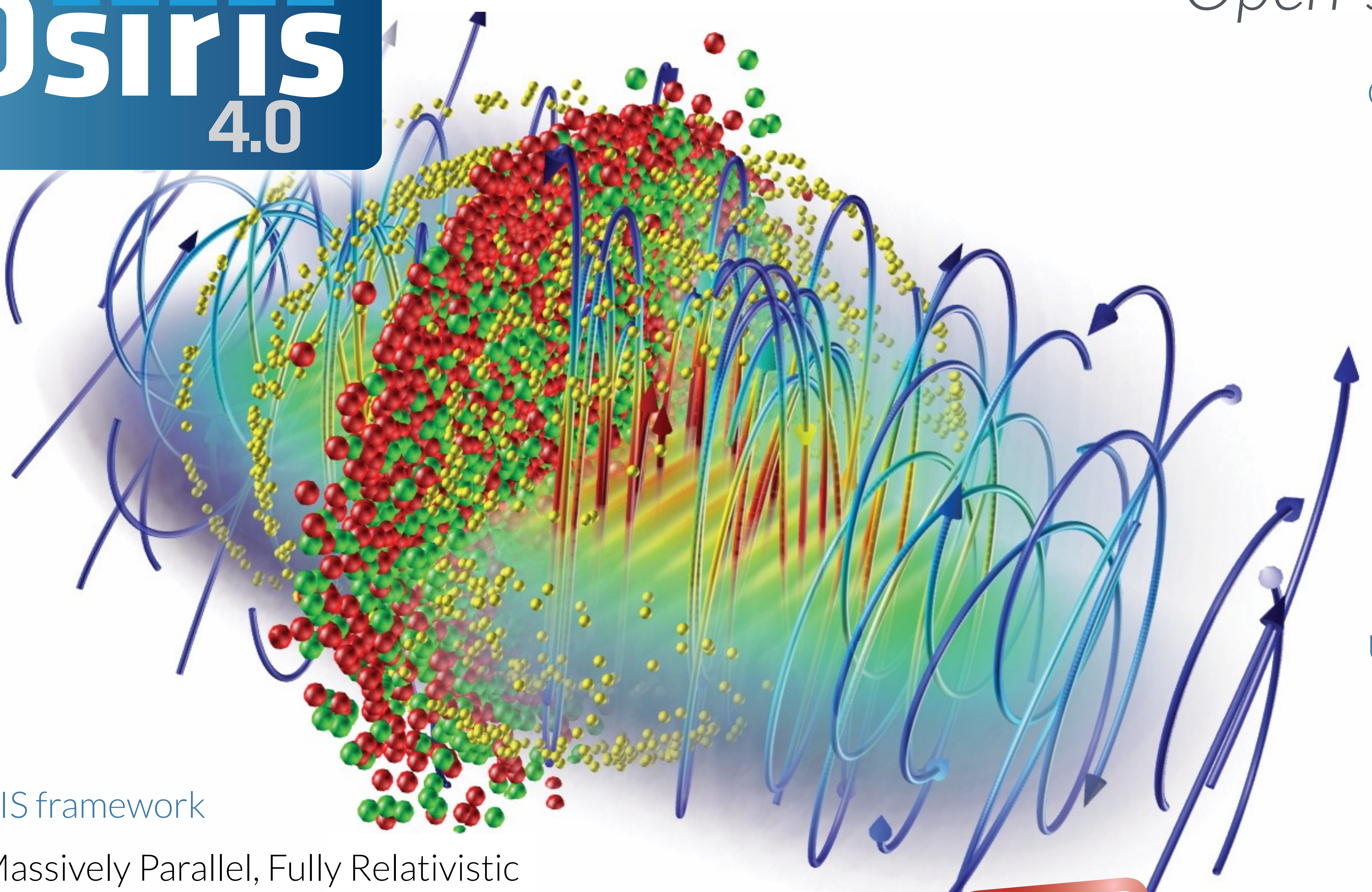
Traditional laser beams have **well known analytical solutions** that can be modelled in simulations

These new, more complex light structures **do not have simple descriptions** and thus no straight forward way of describing them

Accurate, intuitive and easily tunnable description and injection tools are necessary

* Allen, L., et.al Physical Review A 45, 8185–8189 (1992)
Pariente, G. & Quéré, F. , Opt. Lett. 40, 2037 (2015)
Jhajj, N. et al. , Phys. Rev. X 6, 031037 (2016)
Froula, D. H. et al. , Physics of Plasmas 26, 032109–032109 (2019)

Open-source version available



OSIRIS framework

- Massively Parallel, Fully Relativistic Particle-in-Cell Code
- Support for advanced CPU / GPU architectures
- Extended physics/simulation models
- AI/ML surrogate models and data-driven discovery

Open-access model

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

Using OSIRIS 4.0

- The code can be used freely by research institutions after signing an MoU
- Open-source version at:

https://osiris-code.github.io/

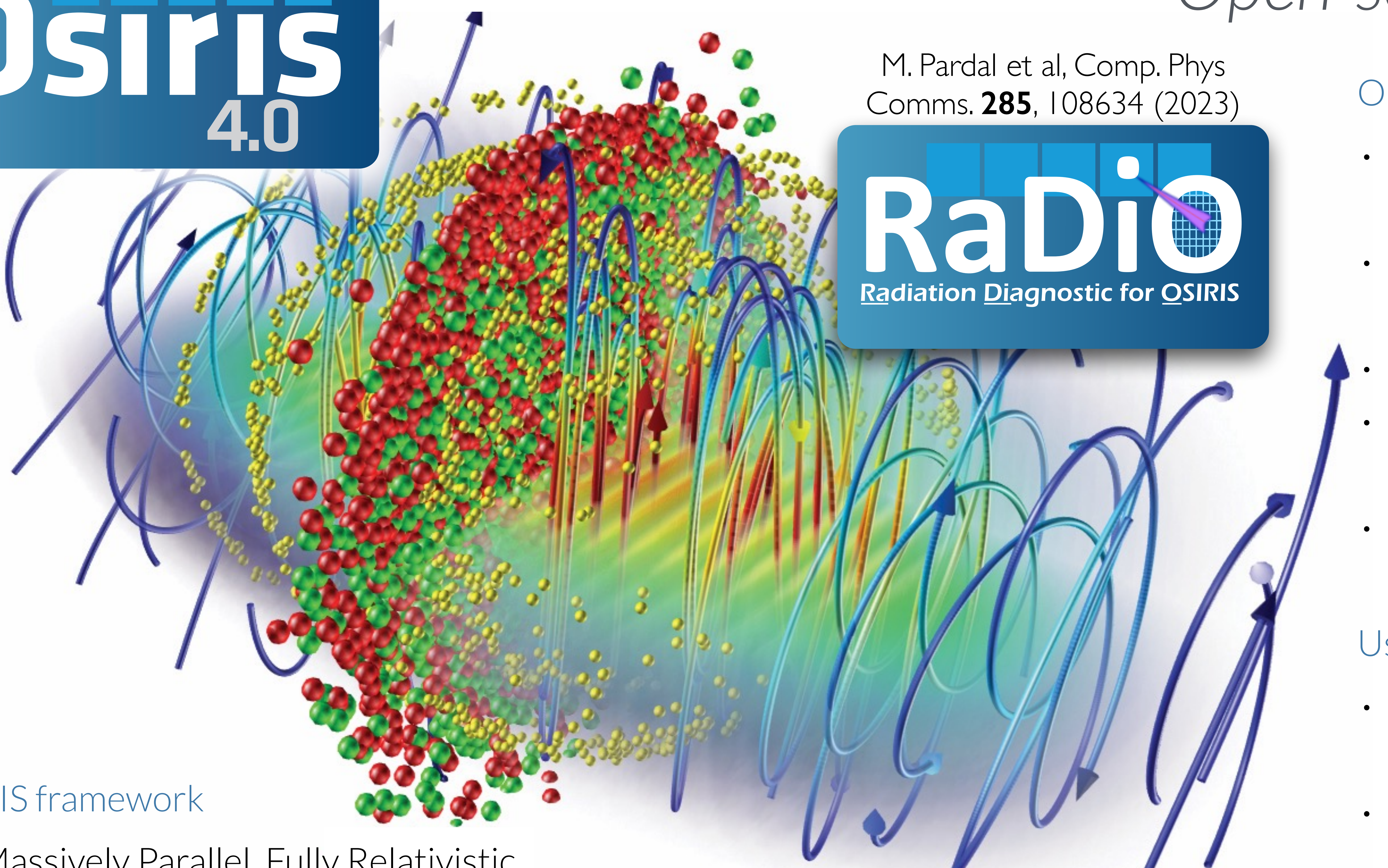
Ricardo Fonseca: ricardo.fonseca@tecnico.ulisboa.pt

Open-source version available

OSIRIS 4.0

M. Pardal et al, Comp. Phys Comms. **285**, 108634 (2023)

RaDiO
Radiation Diagnostic for OSIRIS



Open-access model

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

Using OSIRIS 4.0

- The code can be used freely by research institutions after signing an MoU
- Open-source version at:

https://osiris-code.github.io/

OSIRIS framework

- Massively Parallel, Fully Relativistic Particle-in-Cell Code
- Support for advanced CPU / GPU architectures
- Extended physics/simulation models
- AI/ML surrogate models and data-driven discovery

visXD

University of Michigan · UCLA · Técnico Lisboa

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

Describing arbitrarily complex laser beams

How laser beams are normally theoretically described
Sometimes oversimplified

Using known simple analytical solutions to Maxwell's Equations (example: gaussian beam) under some approximations:

- **Paraxial approximation**: laser spot size much bigger than wavelength
- **Slowly varying envelope approximation**: temporal duration much bigger than period

These restrictions can be, and **are, limiting**!

Describing arbitrarily complex laser beams

How laser beams are normally theoretically described

Sometimes oversimplified

Using known simple analytical solutions to Maxwell's Equations (example: gaussian beam) under some approximations:

- **Paraxial approximation**: laser spot size much bigger than wavelength
- **Slowly varying envelope approximation**: temporal duration much bigger than period

These restrictions can be, and **are, limiting**!

The solution: even simpler solutions

Plane waves can be summed to achieve any pulse

Plane waves are exact solutions to Maxwell's Eqs.

$$\hat{\mathbf{e}}_{\mathbf{k}}(\mathbf{r}, t) = \hat{\mathbf{e}}_0 e^{i(\mathbf{k}\cdot\mathbf{r} - c|\mathbf{k}|t)}$$ (identically for $\hat{\mathbf{b}}_{\mathbf{k}}$)

Maxwell's Eqs are linear $\Rightarrow$ sum of solutions is solution

$$\mathbf{E}(\mathbf{r}, t) \equiv \sum_{\mathbf{k}} \tilde{E}(\mathbf{k})\ \hat{\mathbf{e}}_{\mathbf{k}}(\mathbf{r}, t)$$

Describe any pulse by its Fourier transform

$$\tilde{E}(\mathbf{k}) \equiv \int E(\mathbf{r}, t)\ e^{-i\mathbf{k}\cdot\mathbf{r}} d\mathbf{r}, \forall_t : \omega = c\,|\,\mathbf{k}\,|$$

Describing arbitrarily complex laser beams

TÉCNICO LISBOA

How laser beams are normally theoretically described
Sometimes oversimplified

Using known simple analytical solutions to Maxwell's Equations (example: gaussian beam) under some approximations:

- **Paraxial approximation**: laser spot size much bigger than wavelength
- **Slowly varying envelope approximation**: temporal duration much bigger than period

These restrictions can be, and **are, limiting**!

The solution: even simpler solutions
Plane waves can be summed to achieve any pulse

Plane waves are exact solutions to Maxwell's Eqs.

$\hat{\mathbf{e}}_{\mathbf{k}}(\mathbf{r}, t) = \hat{\mathbf{e}}_0 e^{i(\mathbf{k}\cdot\mathbf{r} - c|\mathbf{k}|t)}$ (identically for $\hat{\mathbf{b}}_{\mathbf{k}}$)

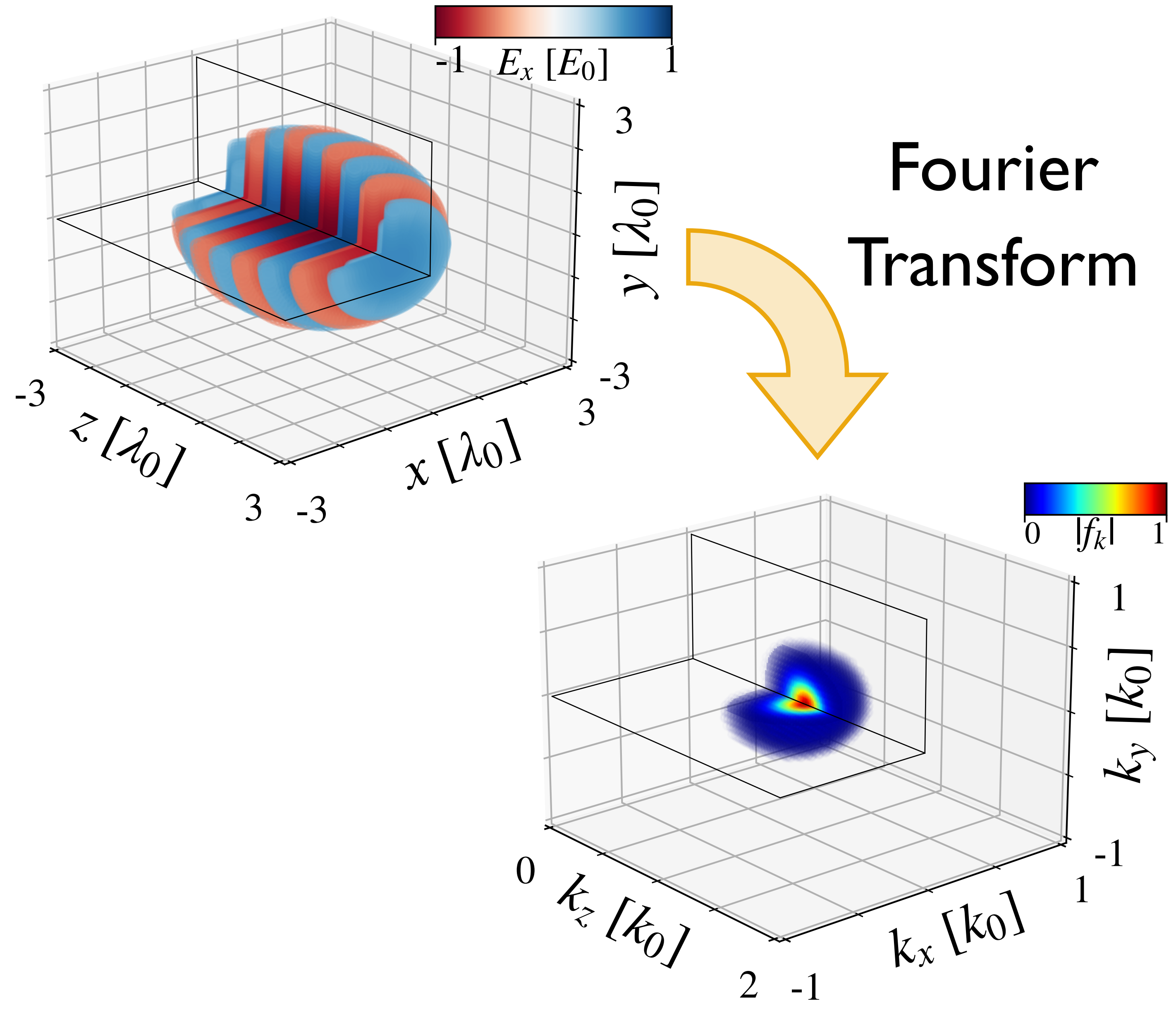
Maxwell's Eqs are linear $\Rightarrow$ sum of solutions is solution

$$\mathbf{E}(\mathbf{r}, t) \equiv \sum_{\mathbf{k}} \tilde{E}(\mathbf{k})\ \hat{\mathbf{e}}_{\mathbf{k}}(\mathbf{r}, t)$$

Describe any pulse by its Fourier transform

$$\tilde{E}(\mathbf{k}) \equiv \int E(\mathbf{r}, t)\ e^{-i\mathbf{k}\cdot\mathbf{r}} d\mathbf{r}, \forall_t : \omega = c\,|\,\mathbf{k}\,|$$

Thinking of lasers as their Fourier representation
Visualising the individual plane waves in k-space



Laser propagating in $+z$

$\Downarrow$

Spectrum centered at $\mathbf{k} = k_0\hat{\mathbf{k}}_\mathbf{z}$

Fourier Transform also includes phase information

It is a complex function

Describing arbitrarily complex laser beams

TÉCNICO LISBOA

How laser beams are normally theoretically described

Sometimes oversimplified

Using known simple analytical solutions to Maxwell's Equations (example: gaussian beam) under some approximations:

- **Paraxial approximation**: laser spot size much bigger than wavelength
- **Slowly varying envelope approx** eriod

These restrictions can be, and **are, limit**

The solution: even simpler solution

Plane waves can be summed to achieve any

Plane waves are exact solutions to Max

$\hat{\mathbf{e}}_{\mathbf{k}}(\mathbf{r},t) = \hat{\mathbf{e}}_0 e^{i(\mathbf{k}\cdot\mathbf{r}-c|\mathbf{k}|t)}$ (identically f

Maxwell's Eqs are linear ⇒ sum of so

solution

$$\mathbf{E}(\mathbf{r},t) \equiv \sum_{\mathbf{k}} \tilde{E}(\mathbf{k})\ \hat{\mathbf{e}}_{\mathbf{k}}(\mathbf{r},t)$$

Describe any pulse by its Fourier transform

$$\tilde{E}(\mathbf{k}) \equiv \int E(\mathbf{r},t)\ e^{-i\mathbf{k}\cdot\mathbf{r}} d\mathbf{r}, \forall_t : \omega = c\,|\,\mathbf{k}\,|$$

Algorithm already available

Accurate and arbitrary injection of lasers

Osiris 4.0

R.R.Almeida, et.al. (2025, in preparation)

urier representation

in k-space

urier

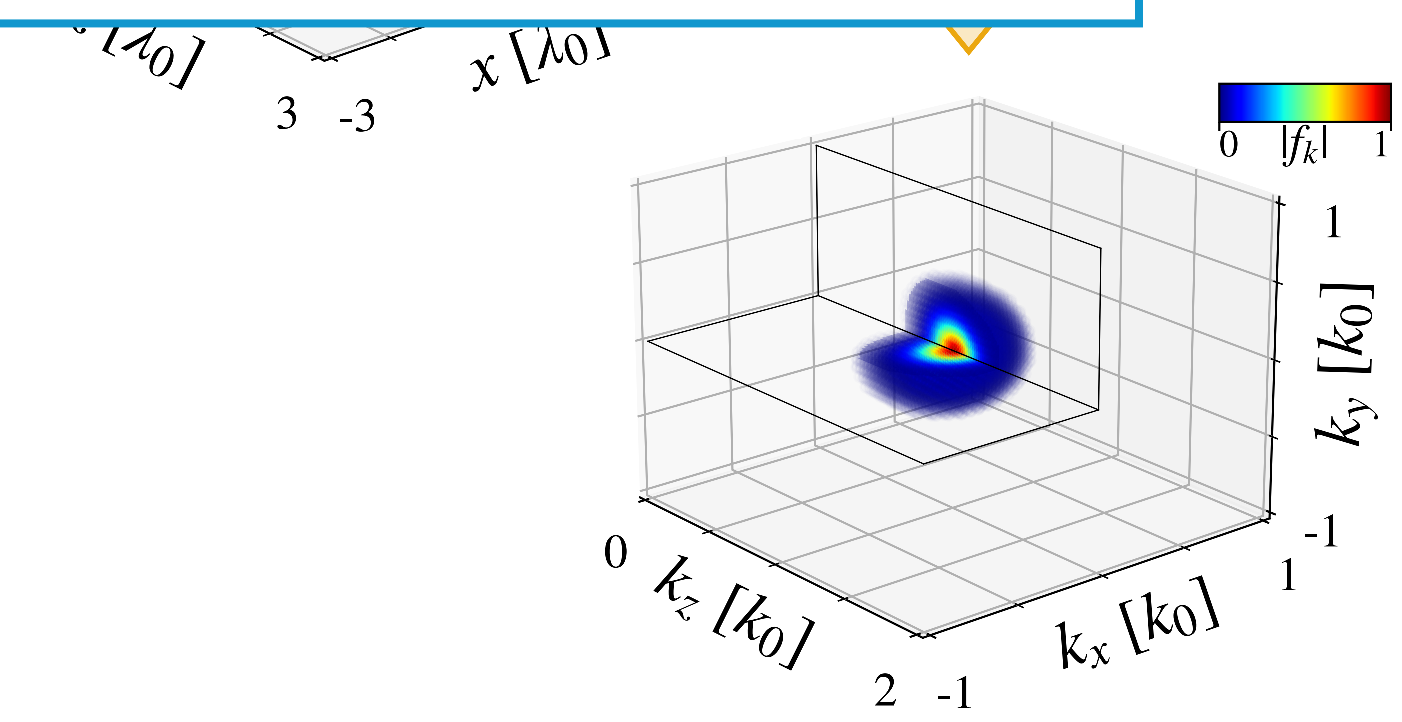
nsform

Laser propagating in $+z$

⇓

Spectrum centered

at $\mathbf{k} = k_0\hat{\mathbf{k}}_\mathbf{z}$



Fourier Transform also includes phase information

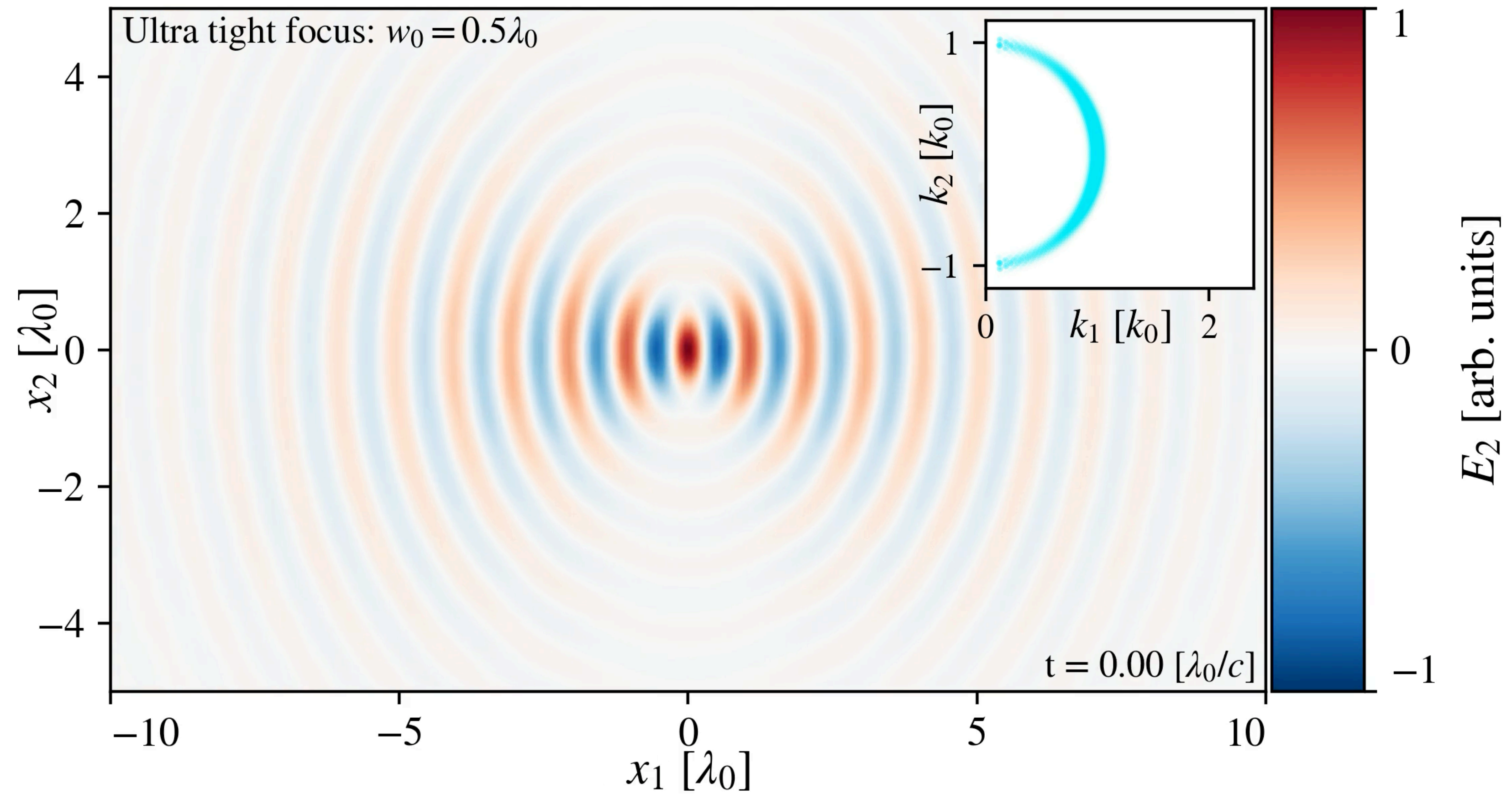
It is a complex function

What the tool allows us to do

What the tool allows us to do

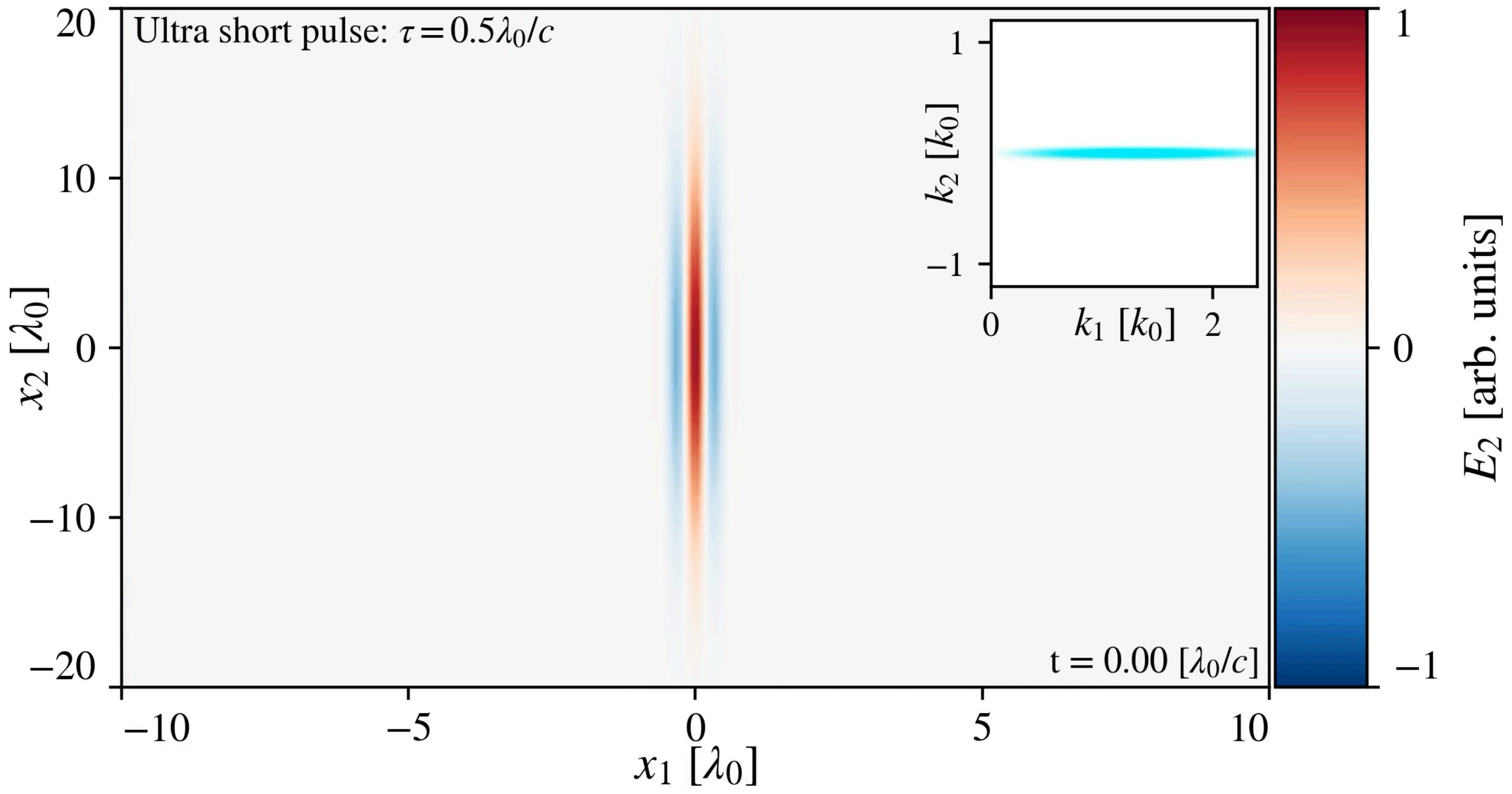
Ultra tightly focused laser beams

Spot size of the order of the wavelength



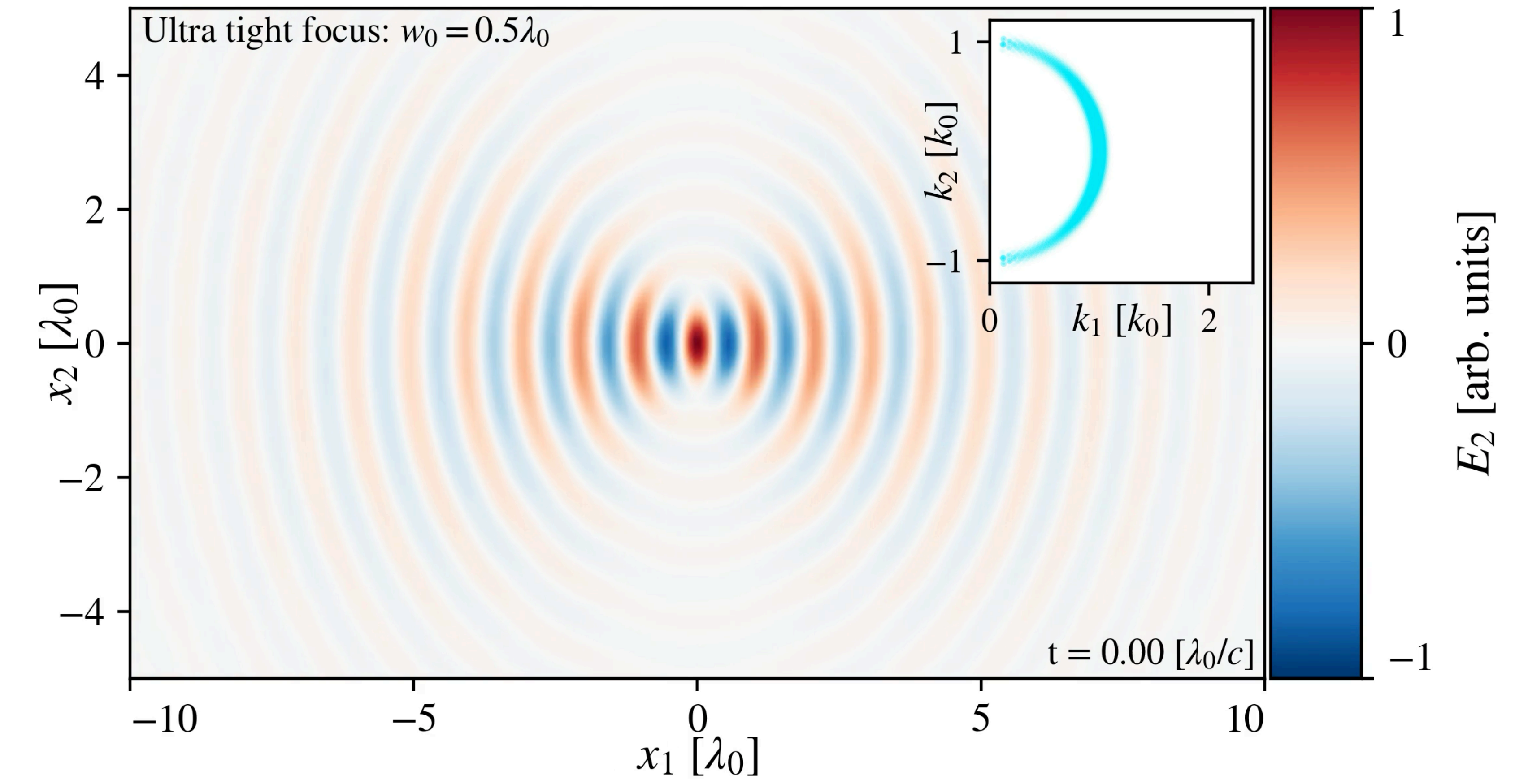
Ultra short pulses

Duration of the order of the period

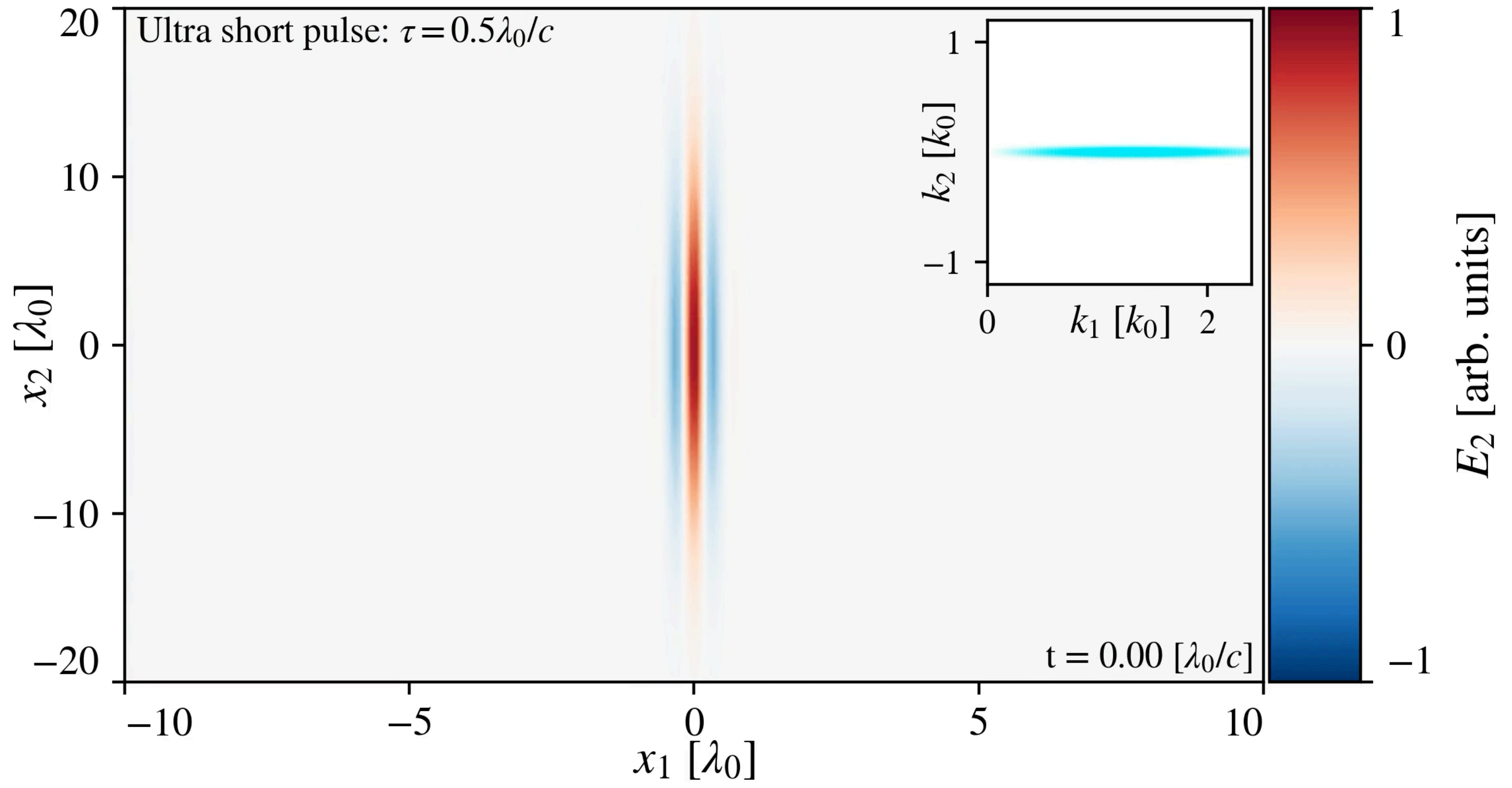


What the tool allows us to do

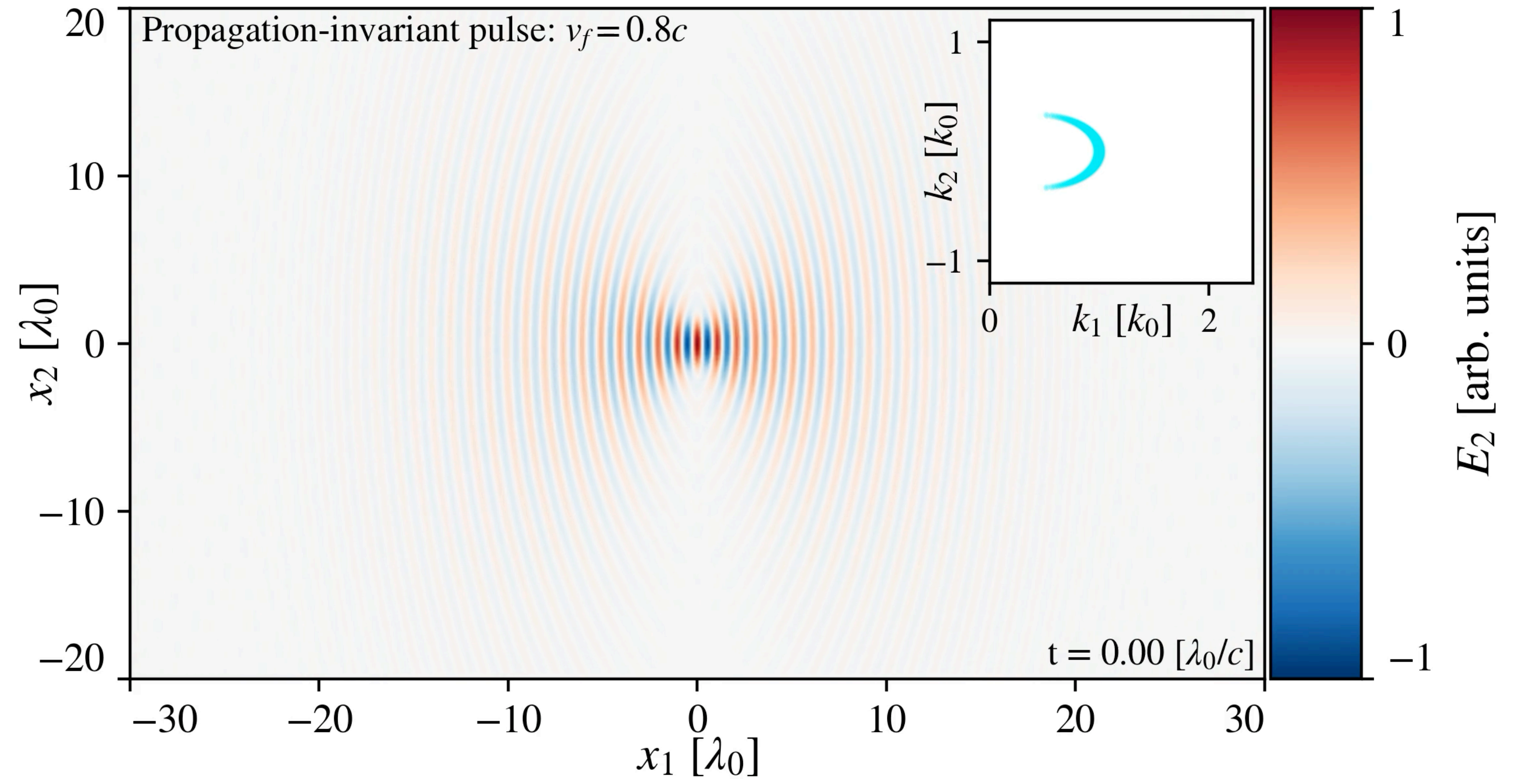
Ultra tightly focused laser beams
Spot size of the order of the wavelength



Ultra short pulses
Duration of the order of the period

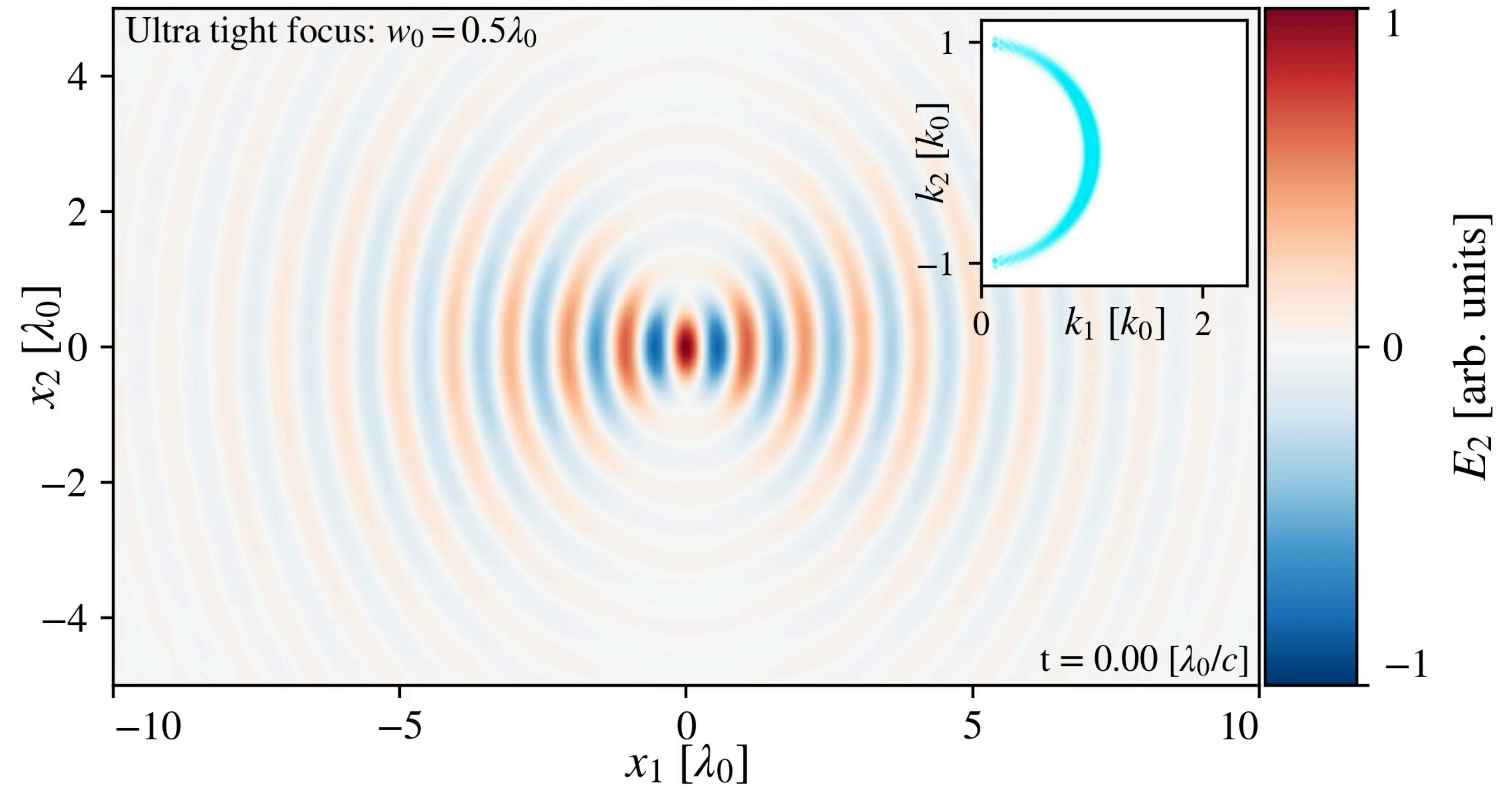


Propagation-invariant constant velocity pulses
Arbitrary control on the velocity of the intensity peak

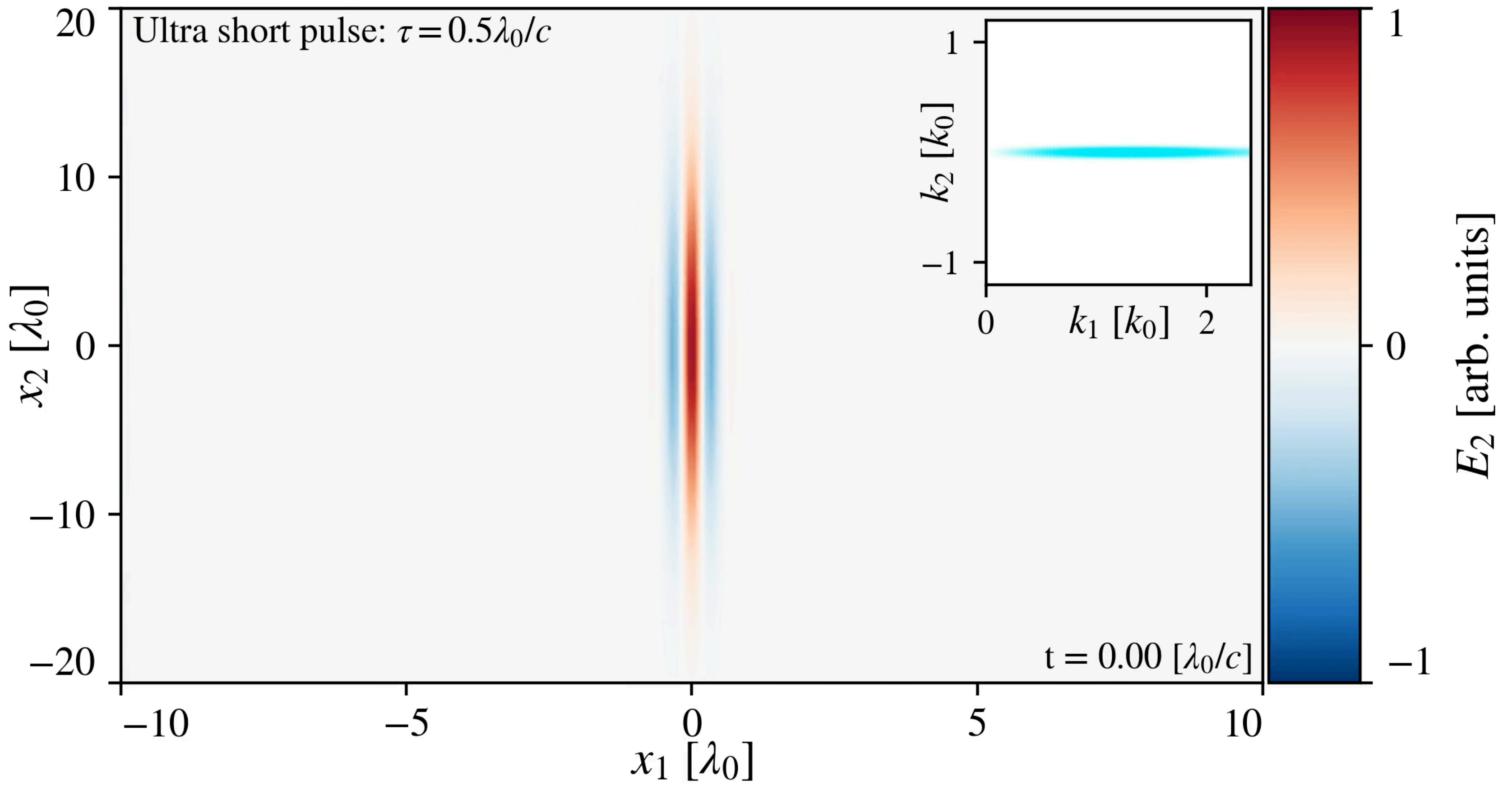


What the tool allows us to do

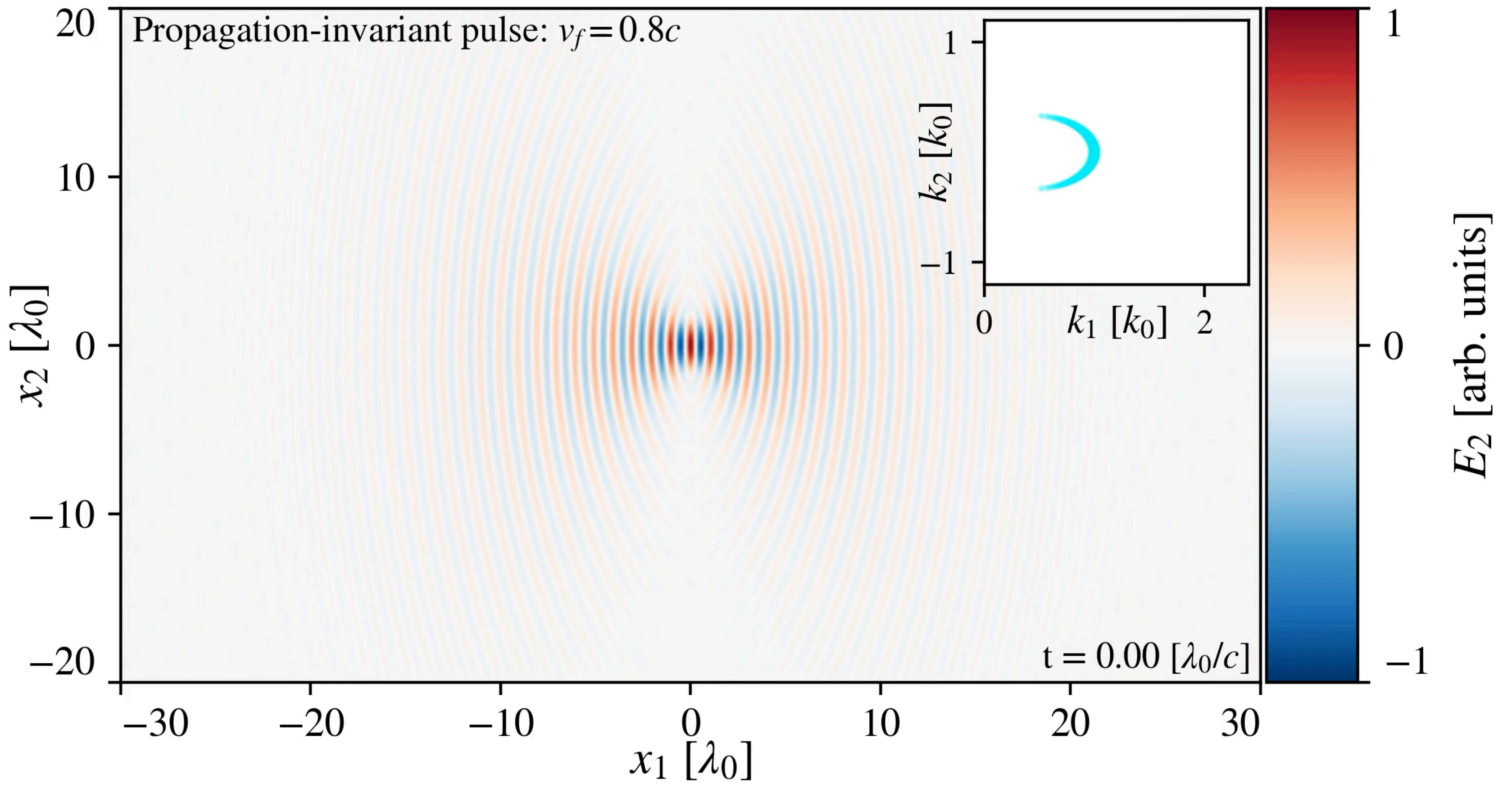
Ultra tightly focused laser beams
Spot size of the order of the wavelength



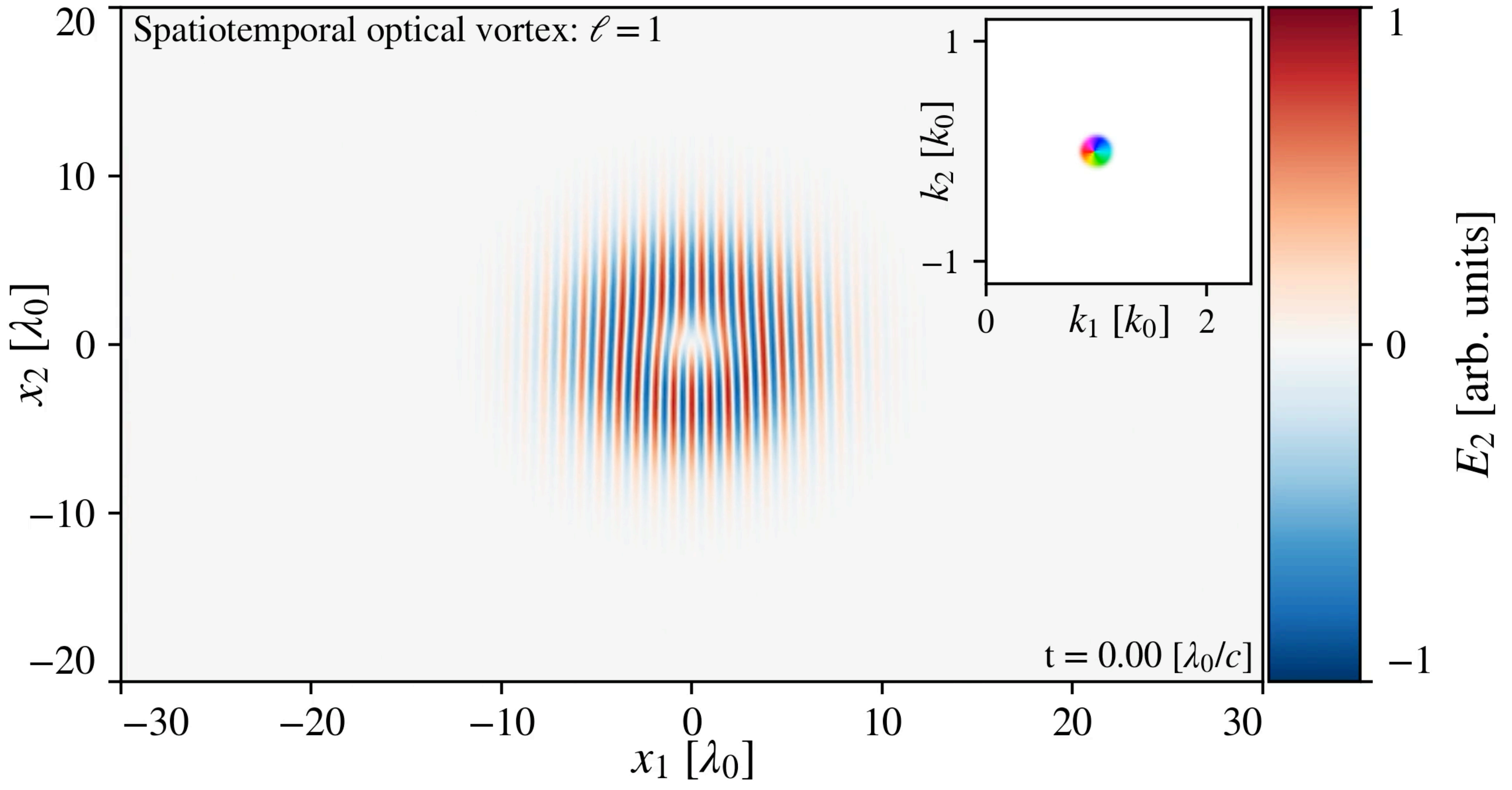
Ultra short pulses
Duration of the order of the period



Propagation-invariant constant velocity pulses
Arbitrary control on the velocity of the intensity peak

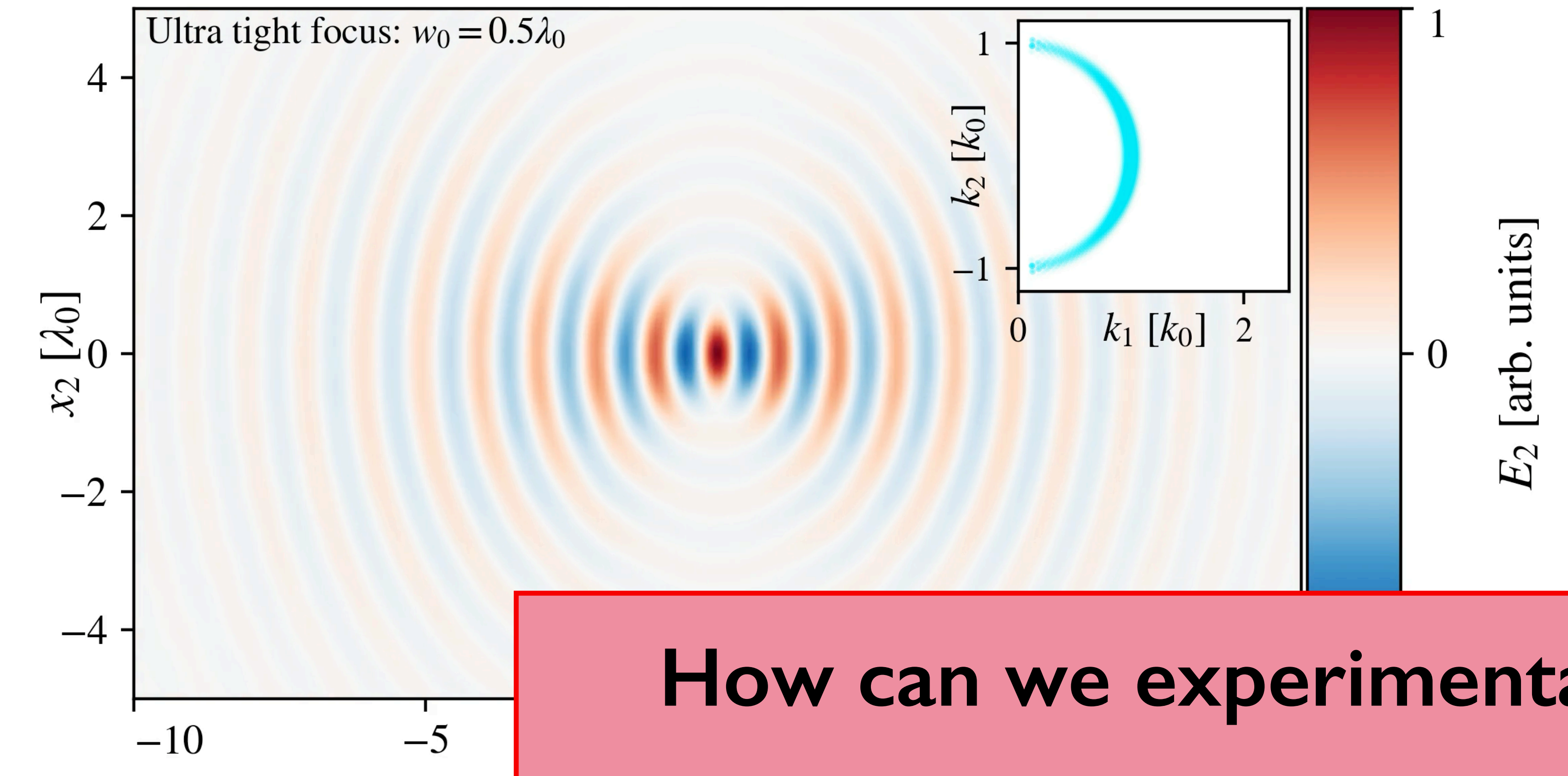


Complex structured light
Full control over the frequency and phase of spectrum

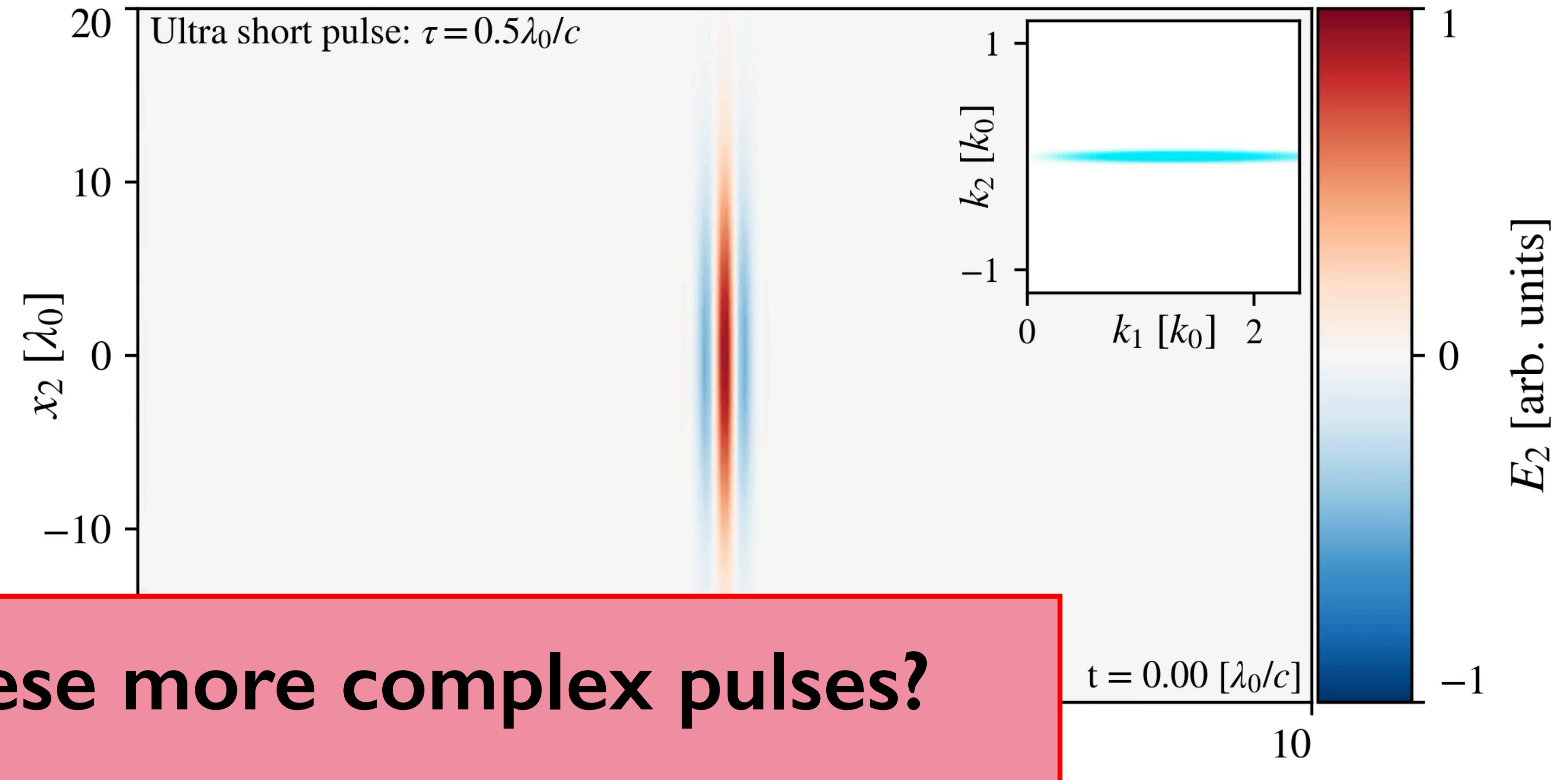


What the tool allows us to do

Ultra tightly focused laser beams
Spot size of the order of the wavelength



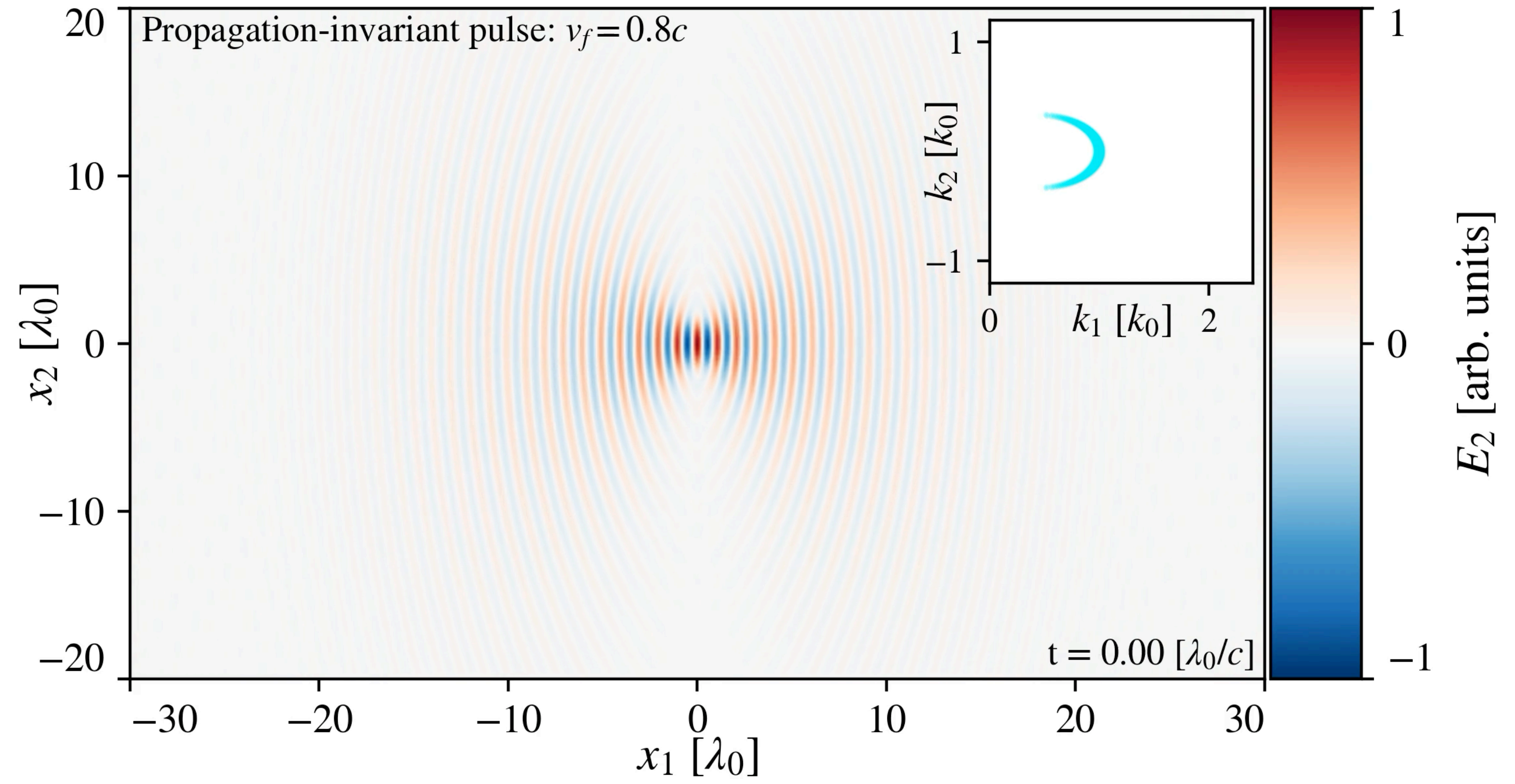
Ultra short pulses
Duration of the order of the period



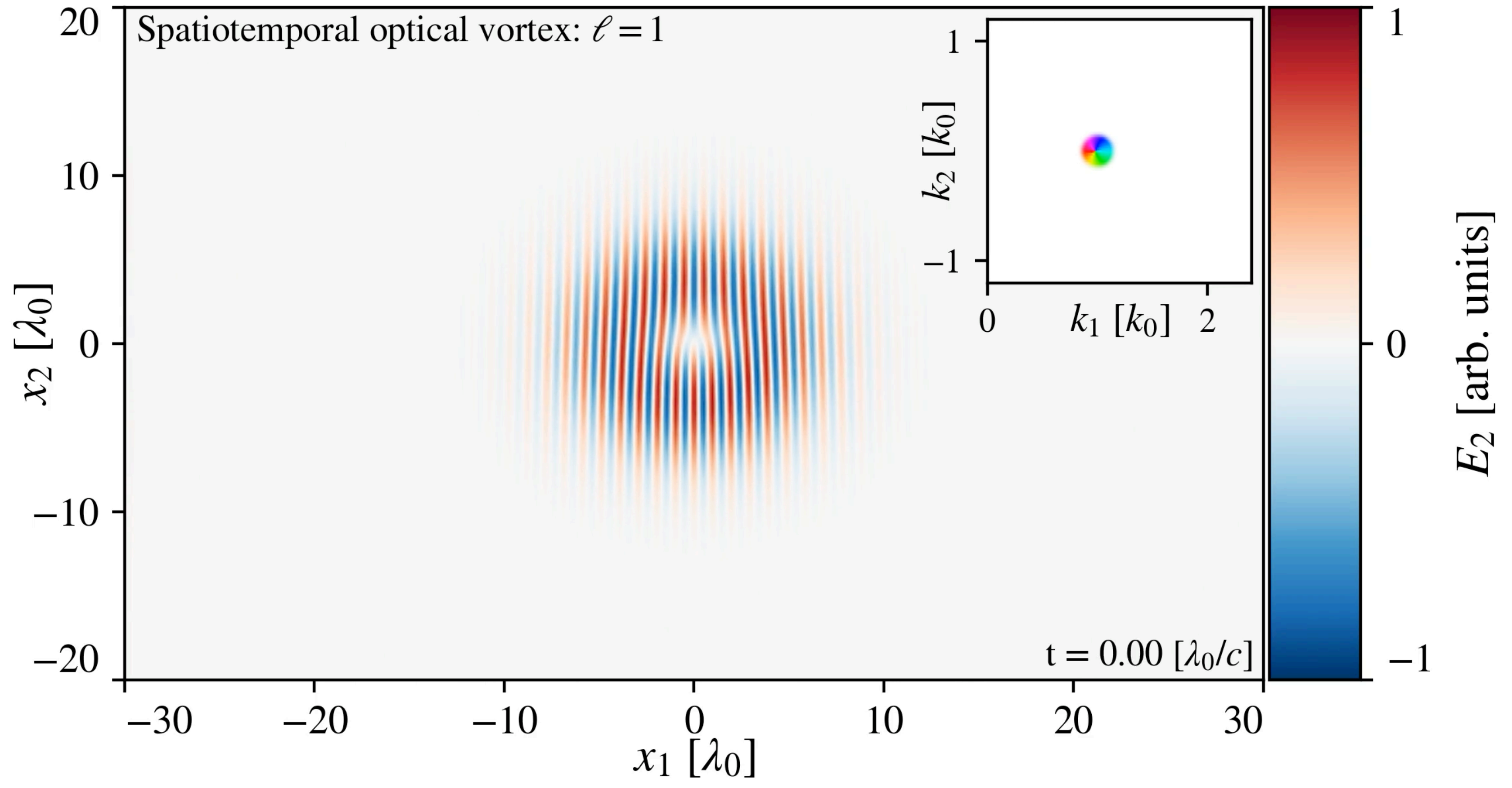
How can we experimentally create these more complex pulses?

Can we directly shape their spectrum?
Can we use laser-plasma interactions to synthesise them?

Propagation-inv
Arbitrary control on the velocity of the intensity peak



Full control over the frequency and phase of spectrum



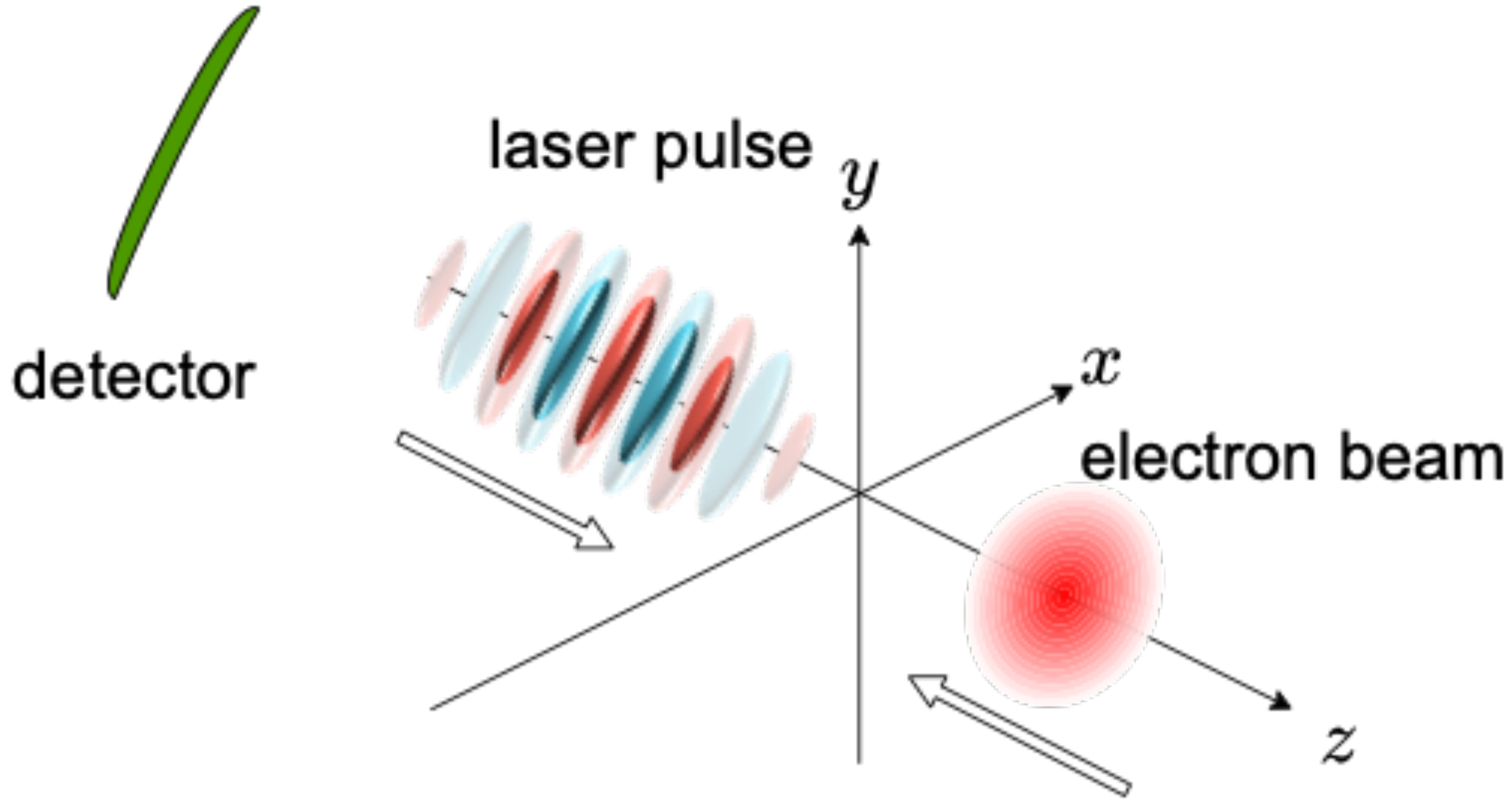
Normal usage of Thomson Scattering

Standard Thomson Scattering Setup

Collinear collision between charged particle beam and laser pulse

Relativistic particle beam collides with an intense electromagnetic beam (usually simple laser)

Interaction results in burst of high frequency radiation in the direction of propagation of the particle beam

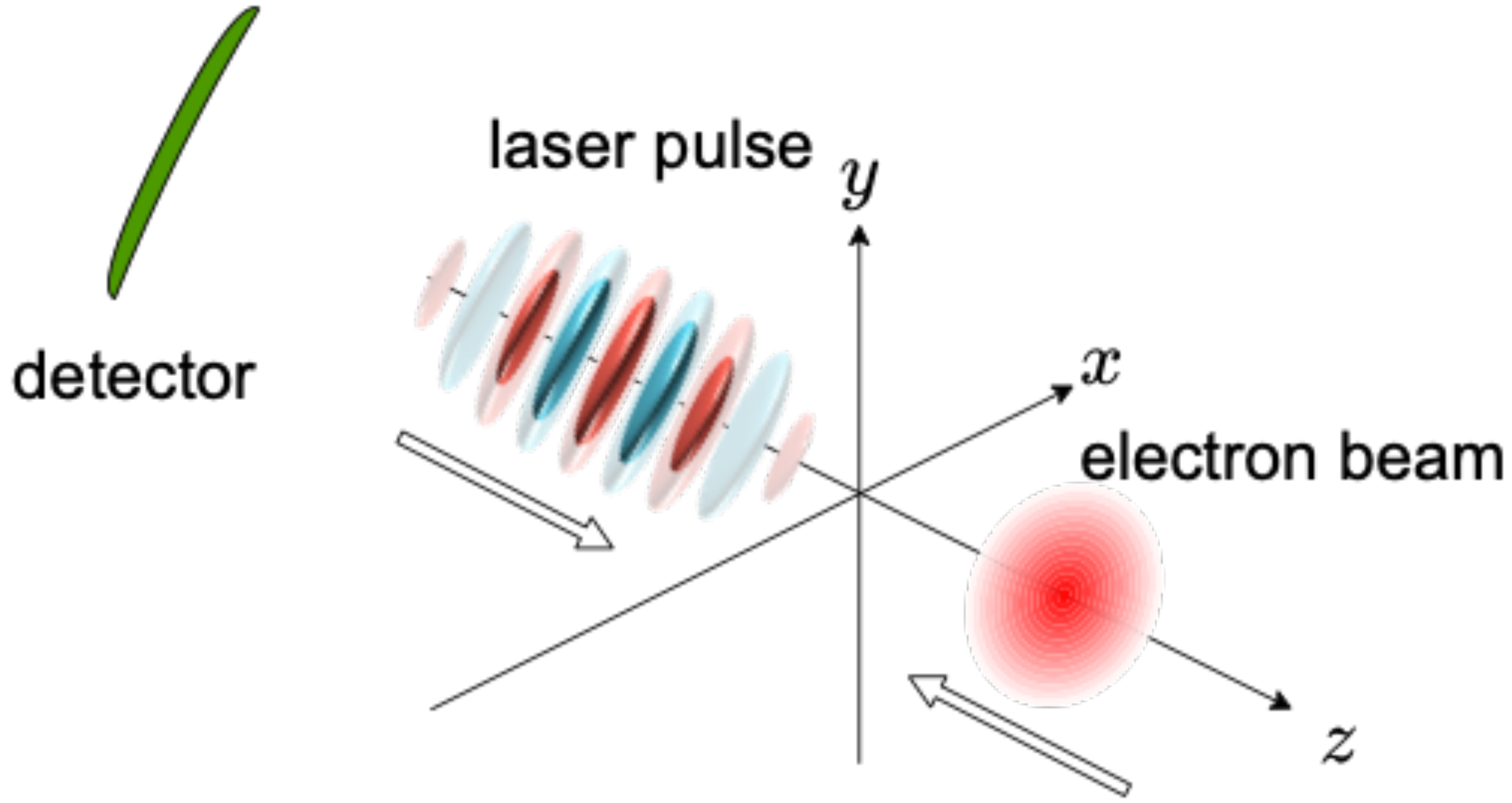


Normal usage of Thomson Scattering

Standard Thomson Scattering Setup
Collinear collision between charged particle beam and laser pulse

Relativistic particle beam collides with an intense electromagnetic beam (usually simple laser)

Interaction results in burst of high frequency radiation in the direction of propagation of the particle beam



Our goal is to generalised this setup
Pushing the boundaries of this interaction

Thomson Scattering at arbitrary angles with complex laser beams
Upshift frequency and control spectrum of resulting radiation

A generalised radiation formula

Radiation of distribution of currents

Derived from Liénard–Wiechert potentials

$$\tilde{\mathbf{A}}(\omega, \mathbf{n}) \equiv \frac{\omega}{2\pi c^{3/2}} \int \mathbf{dr} \int dt \;\mathbf{n} \times [\mathbf{n} \times \mathbf{J}(\mathbf{r}, t)] e^{i\omega(t - \mathbf{n}\cdot\mathbf{r}/c)}$$

with $\tilde{\mathbf{A}}(\omega, \mathbf{n})$ the Fourier transform of the vector potential of the radiation. This is the **spectrum with phase information.**

Assuming:

1) that the current is given by $\mathbf{J}(\mathbf{r}, t) \approx -eS(\mathbf{r} - c\boldsymbol{\beta}_0 t)\mathbf{v}(\mathbf{r}, t)$

2) that the **particles conserve their canonical momentum**

3) **Fourier transforms** for both the laser field $\mathbf{A}_\mathrm{L}(\mathbf{r}, t) \to \tilde{\mathbf{A}}_\mathrm{L}(\mathbf{k})$ and shape $S(\mathbf{r}) \to \tilde{S}(\mathbf{k})$

A generalised radiation formula

Radiation of distribution of currents
Derived from Liénard–Wiechert potentials

$$\tilde{\mathbf{A}}(\omega, \mathbf{n}) \equiv \frac{\omega}{2\pi c^{3/2}} \int \mathbf{dr} \int dt \;\; \mathbf{n} \times [\mathbf{n} \times \mathbf{J}(\mathbf{r}, t)] e^{i\omega(t - \mathbf{n}\cdot\mathbf{r}/c)}$$

with $\tilde{\mathbf{A}}(\omega, \mathbf{n})$ the Fourier transform of the vector potential of the radiation. This is the **spectrum with phase information.**

Assuming:

1) that the current is given by $\mathbf{J}(\mathbf{r}, t) \approx -eS(\mathbf{r} - c\boldsymbol{\beta}_0 t)\mathbf{v}(\mathbf{r}, t)$

2) that the **particles conserve their canonical momentum**

3) **Fourier transforms** for both the laser field $\mathbf{A}_\mathrm{L}(\mathbf{r}, t) \to \tilde{\mathbf{A}}_\mathrm{L}(\mathbf{k})$ and shape $S(\mathbf{r}) \to \tilde{S}(\mathbf{k})$

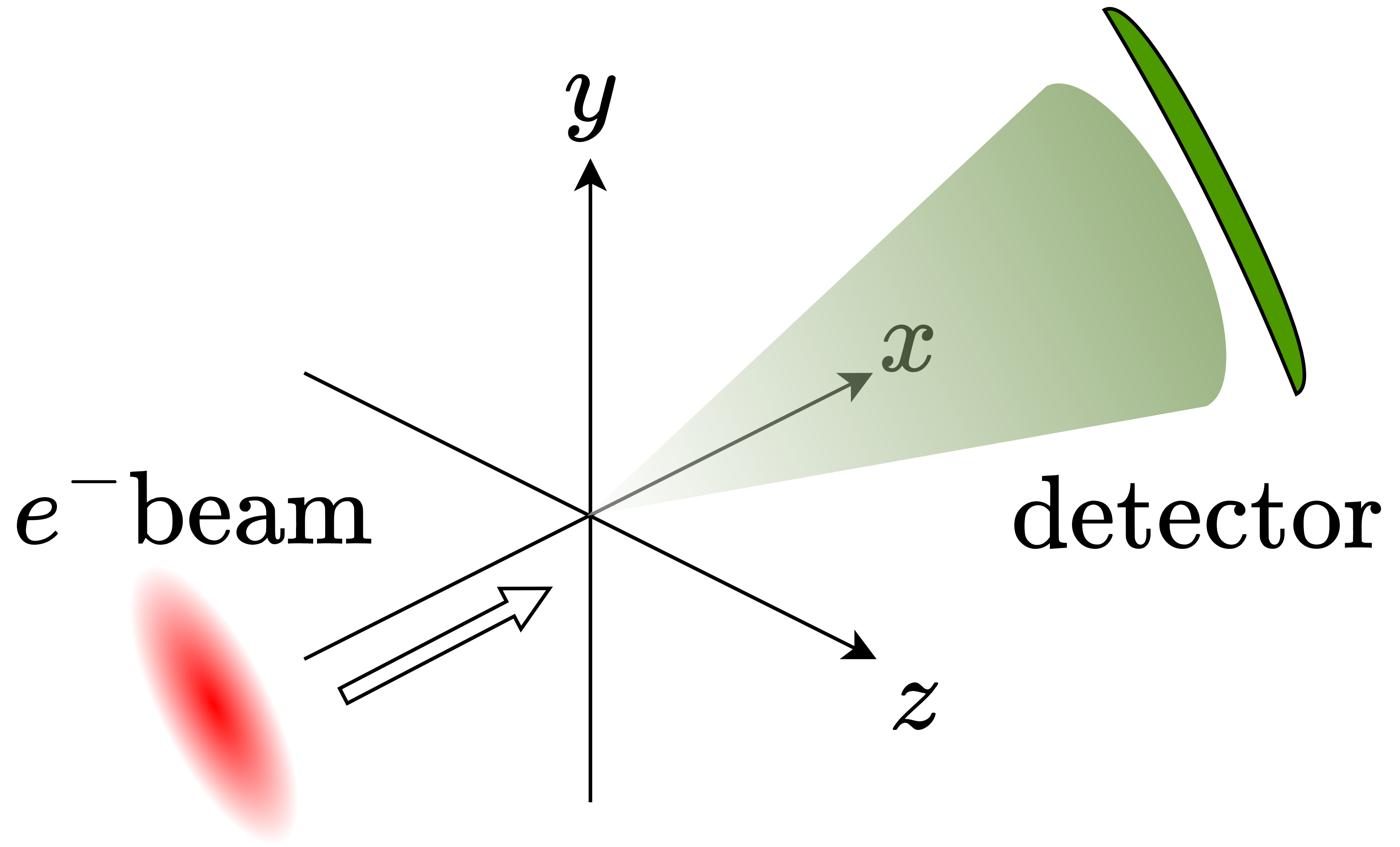
Generalised Radiation from Laser - Particle Beam Interaction
Simplified analysis is achieved in Fourier, or k-space

$$\tilde{\mathbf{A}}(\omega, \mathbf{n}) \approx \frac{1}{(2\pi)^4} \frac{-e^2\omega}{4\pi c^{5/2} m_e \gamma_0} \mathbf{n} \times \mathbf{n} \times \int d\mathbf{q} \; \tilde{S}(\mathbf{k} - \mathbf{q}) \; \tilde{\mathbf{A}}_\mathrm{L}(\mathbf{q}) \; \delta[\,|\mathbf{k}| - |\mathbf{q}| - (\mathbf{k} - \mathbf{q}) \cdot \boldsymbol{\beta}_0]$$

"Wave mixing" of **particle beam** and **laser** spectra restricted to the **Dirac-delta constraint**

A simplified radiation formula

A simplified model
"Pancake" electron beam
Very short and wide electron beam: $S(\mathbf{r}) \approx \delta(x) \Rightarrow \tilde{S}(\mathbf{q}) = \delta(q_y)\delta(q_z)$ Travelling along $\hat{\mathbf{x}}$ with $\boldsymbol{\beta}_0 = \beta_0 \hat{\mathbf{x}}$
Linearly polarised laser
Laser polarised in $\hat{\mathbf{y}}$ With $\mathbf{n} \equiv \dfrac{c\mathbf{k}}{\omega}$, the radiation will be mostly along $\hat{\mathbf{x}} \Rightarrow \mathbf{n} \times \mathbf{n} \times \hat{\mathbf{y}} \approx -\hat{\mathbf{y}}$



A simplified radiation formula

A simplified model

"Pancake" electron beam

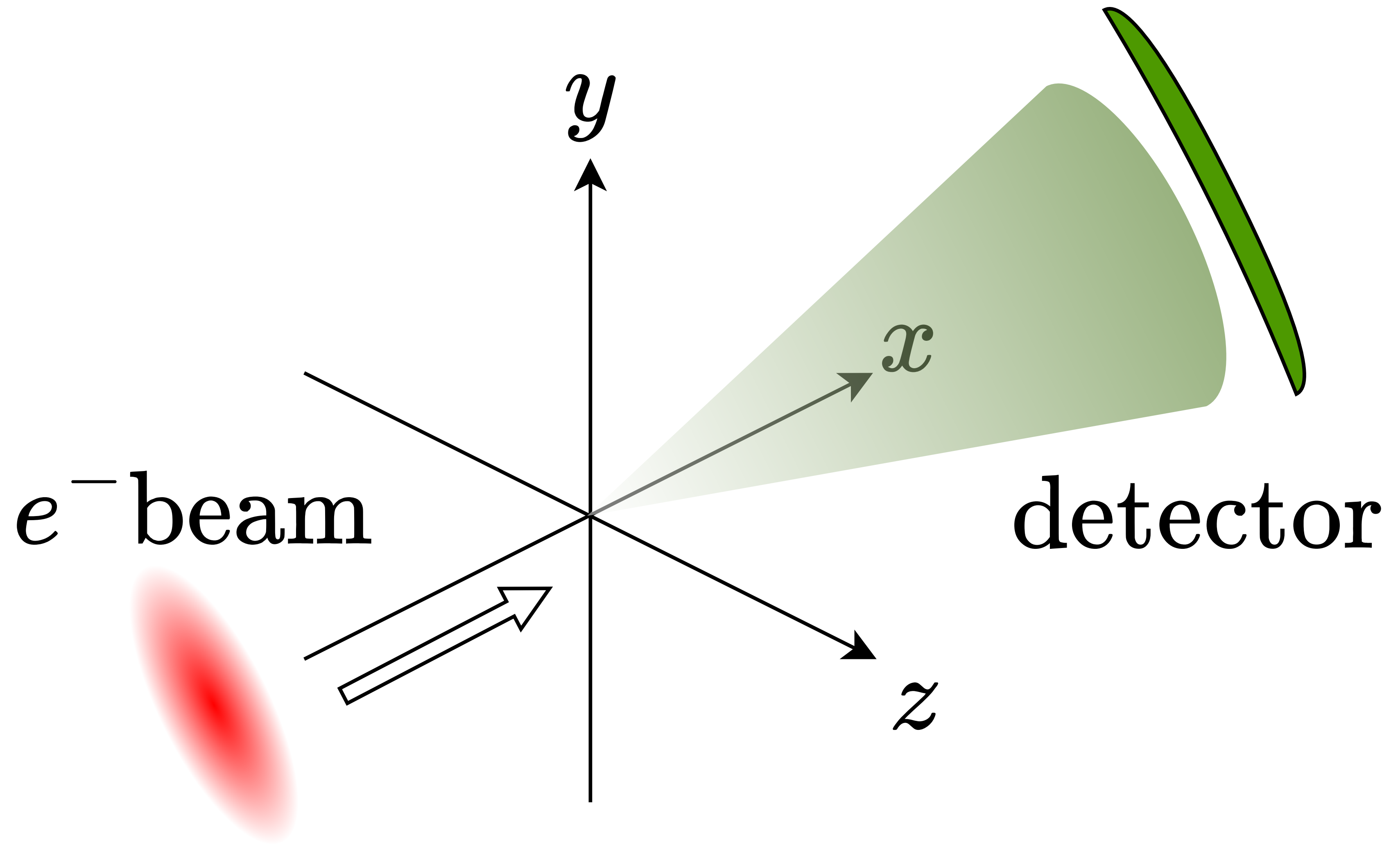
Very short and wide electron beam: $S(\mathbf{r}) \approx \delta(x) \Rightarrow \tilde{S}(\mathbf{q}) = \delta(q_y)\delta(q_z)$

Travelling along $\hat{\mathbf{x}}$ with $\boldsymbol{\beta}_0 = \beta_0\hat{\mathbf{x}}$

Linearly polarised laser

Laser polarised in $\hat{\mathbf{y}}$

With $\mathbf{n} \equiv \dfrac{c\mathbf{k}}{\omega}$, the radiation will be mostly along $\hat{\mathbf{x}} \Rightarrow \mathbf{n} \times \mathbf{n} \times \hat{\mathbf{y}} \approx -\hat{\mathbf{y}}$



Resulting simplified formula for the radiation

Copy of the original laser beam!

$$\tilde{\mathbf{A}}(\mathbf{k}) \approx \frac{e^2\omega}{4^3\pi^5 c^{5/2} m_e \gamma_0} \tilde{A}_L\left(\kappa(\mathbf{k}, \beta_0), k_y, k_z\right)\hat{\mathbf{y}}$$

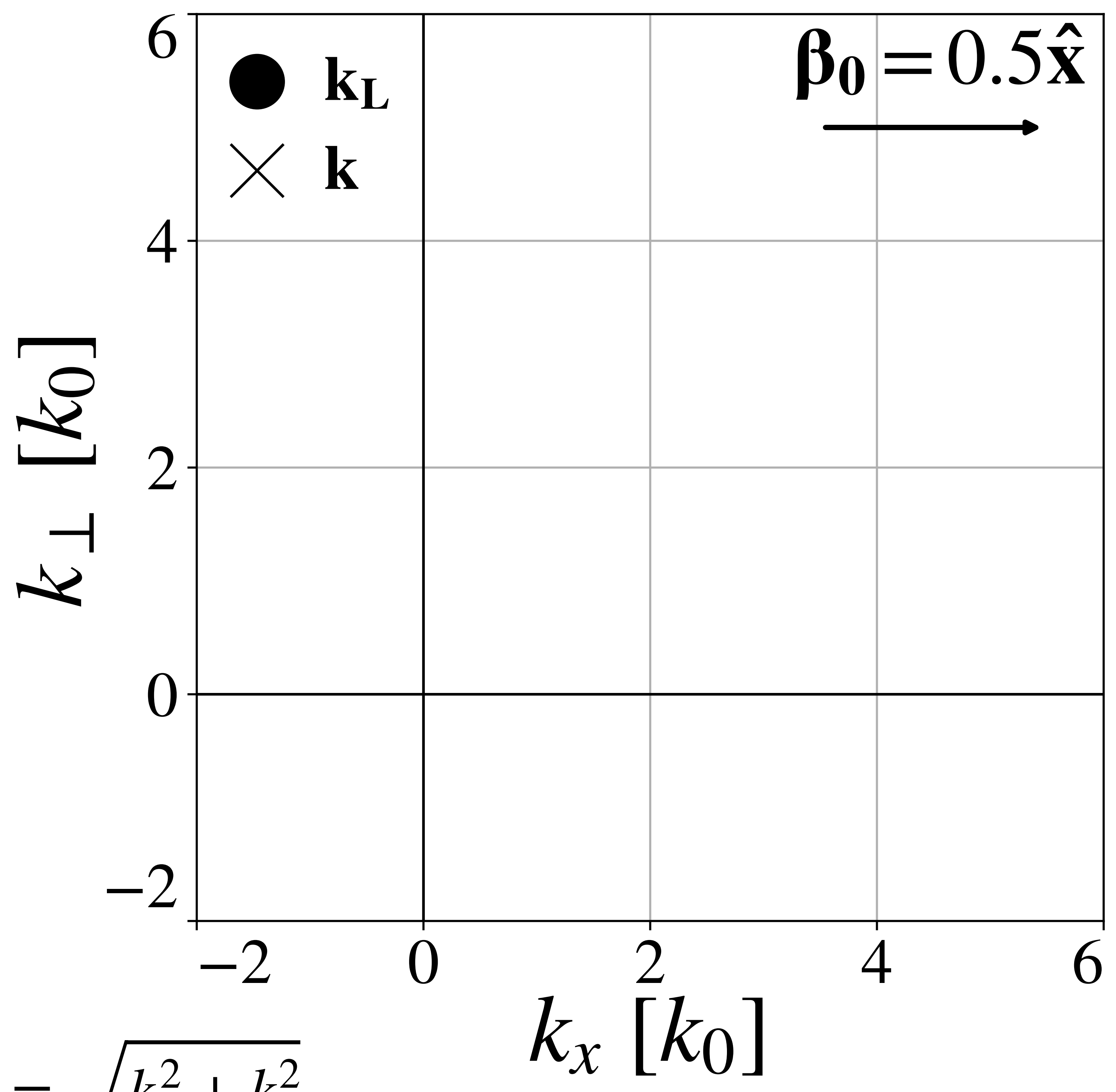
Remapping the original laser beam spectrum ($\mathbf{k_L}$) to a new set of wave vectors ($\mathbf{k}$)

$$k_y = k_y^L \text{ and } k_z = k_z^L \text{ and } k_x^L = \kappa(\mathbf{k}, \beta_0) \Rightarrow k_x = \frac{k_x^L(\beta_0^2 + 1) \pm 2\beta_0 |\mathbf{k_L}|}{\beta_0^2 - 1}$$

What happens to each wave of a laser beam?

Radiation Formula
Original laser beam copy

$$\tilde{\mathbf{A}}(\mathbf{k}) \propto \frac{\omega}{\gamma_0} \tilde{\mathbf{A}}_{\mathbf{L}} \left(\kappa(\mathbf{k}, \beta_0), k_y, k_z \right)$$

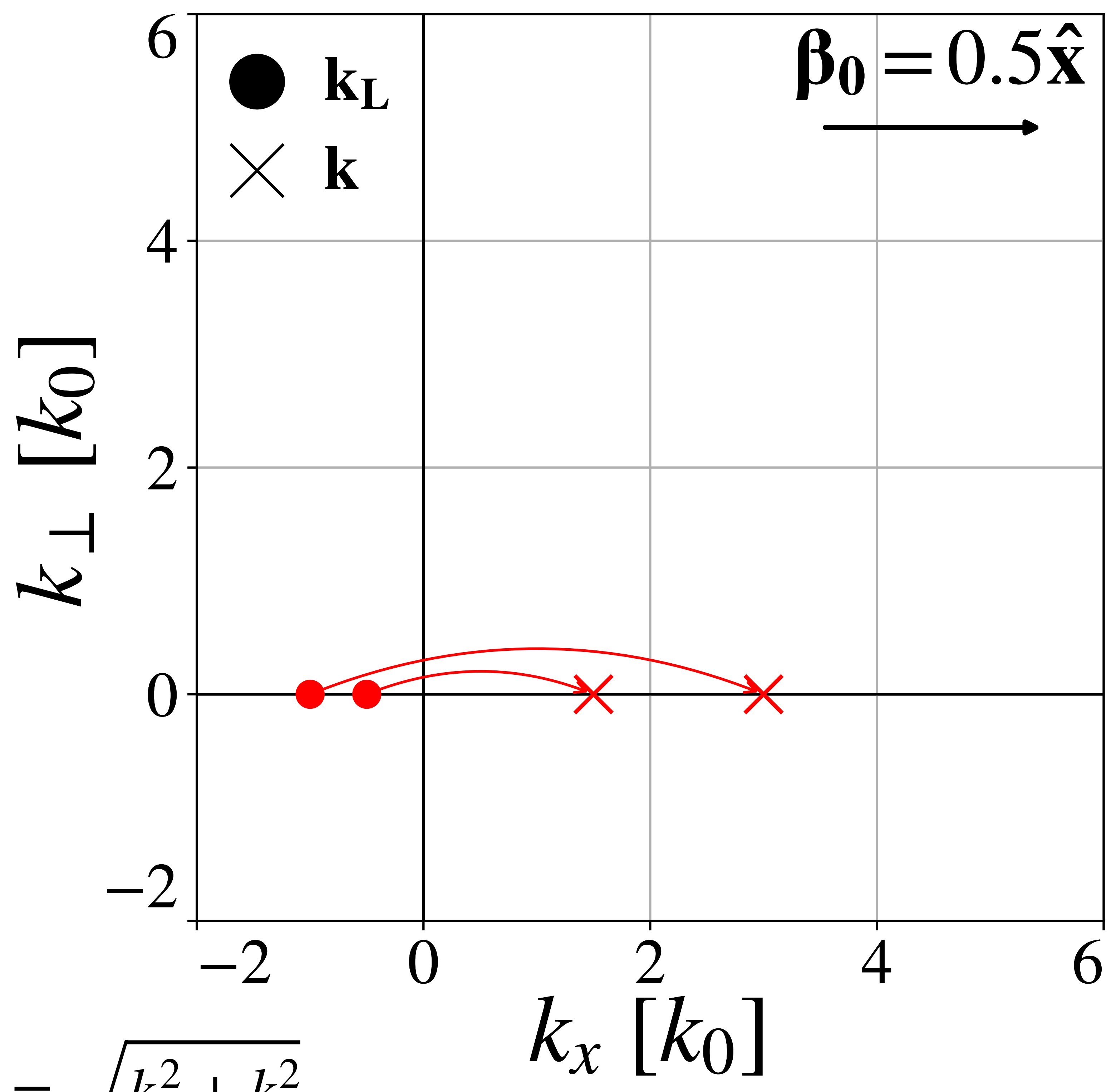


$$k_\perp = \sqrt{k_y^2 + k_z^2}$$

What happens to each wave of a laser beam?

Radiation Formula
Original laser beam copy

$$\tilde{\mathbf{A}}(\mathbf{k}) \propto \frac{\omega}{\gamma_0}\tilde{\mathbf{A}}_{\mathbf{L}}\left(\kappa(\mathbf{k},\beta_0),k_y,k_z\right)$$



$k_\perp = \sqrt{k_y^2 + k_z^2}$

Head on collision
Laser propagating in $-x$ direction

$$k_x^L = -k_0 \text{ and } k_z^L = k_y^L = 0$$

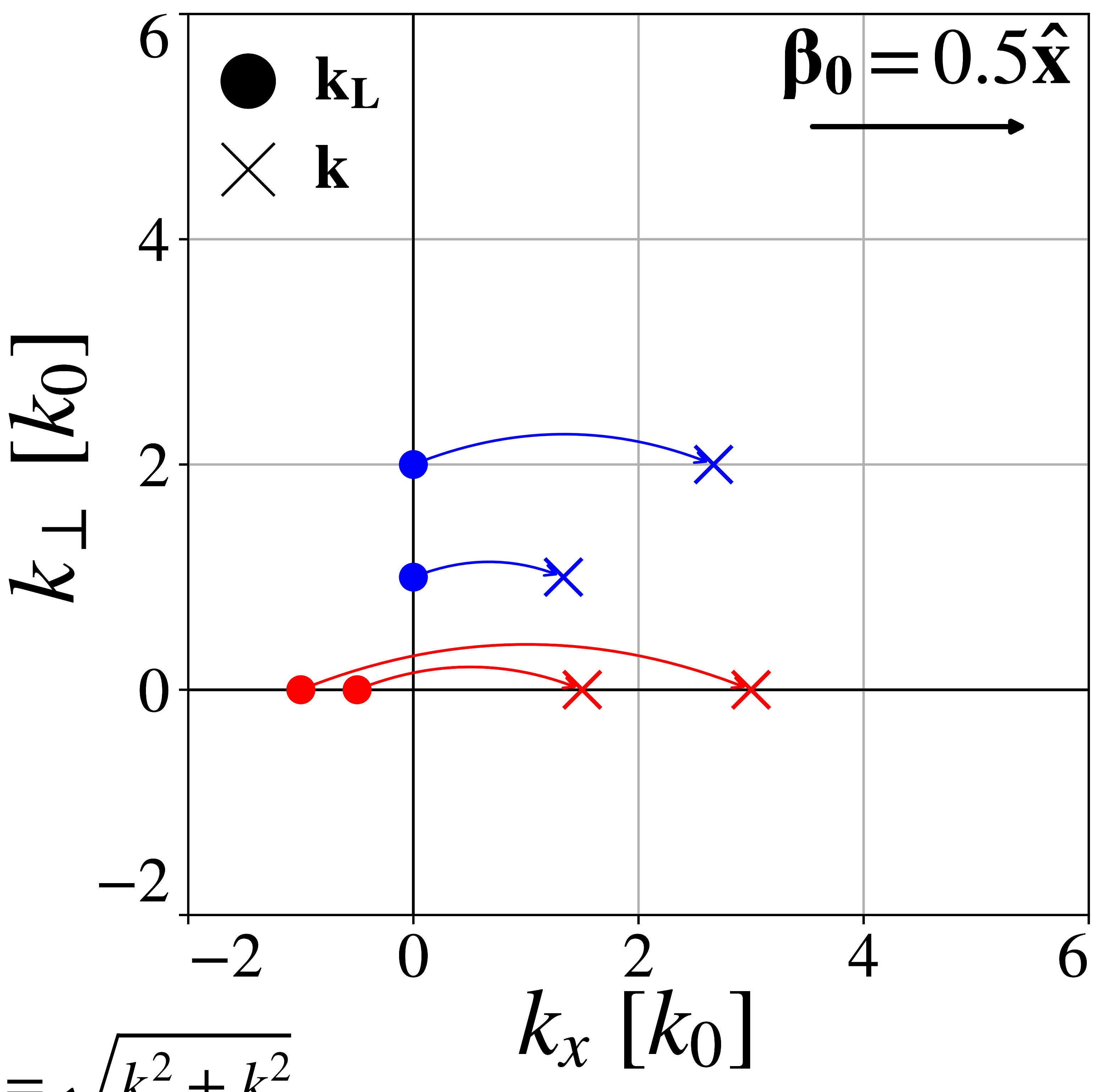
Yields: $k_x = k_0\dfrac{1+\beta_0}{1-\beta_0} \approx 4\gamma_0^2 k_0 \vee \ldots$ and $k_z = k_y = 0$

which is the **standard Thomson result**!

What happens to each wave of a laser beam?

Radiation Formula
Original laser beam copy

$$\tilde{\mathbf{A}}(\mathbf{k}) \propto \frac{\omega}{\gamma_0}\tilde{\mathbf{A}}_{\mathbf{L}}\left(\kappa(\mathbf{k},\beta_0), k_y, k_z\right)$$



$k_\perp = \sqrt{k_y^2 + k_z^2}$

Head on collision
Laser propagating in $-x$ direction

$$k_x^L = -k_0 \text{ and } k_z^L = k_y^L = 0$$

Yields: $k_x = k_0\dfrac{1+\beta_0}{1-\beta_0} \approx 4\gamma_0^2 k_0 \vee \ldots$ and $k_z = k_y = 0$

which is the **standard Thomson result**!

Perpendicular collision
Laser propagating in z direction

$$k_z^L = k_0 \text{ and } k_x^L = k_y^L = 0$$

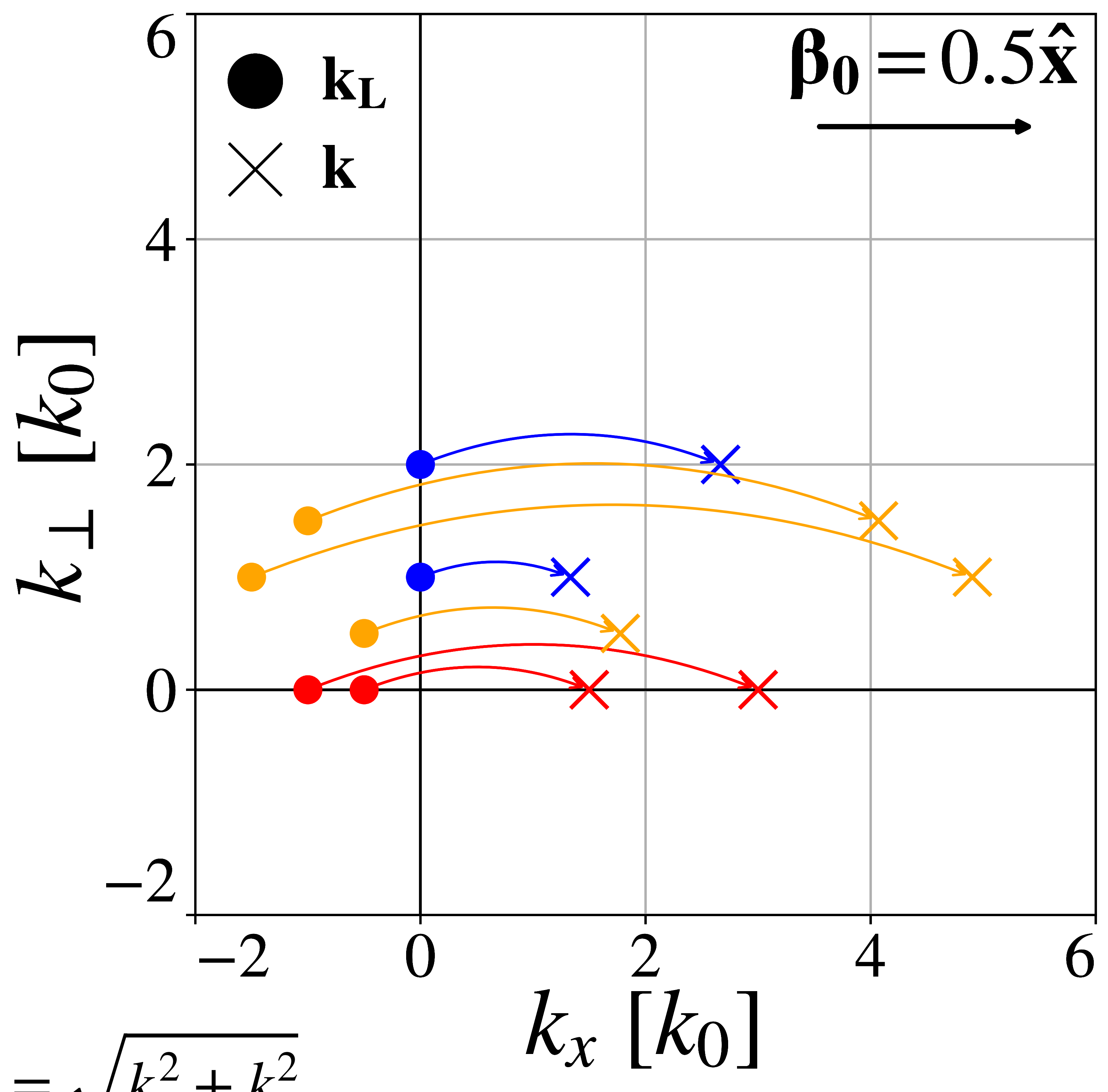
Yields $k_x = \dfrac{2\beta_0 k_0}{1-\beta_0^2} \approx 2\gamma_0^2 k_0 \vee \ldots$ and $k_z = k_0$ and $k_y = 0$

upshift is smaller but still **arbitrarily large**

What happens to each wave of a laser beam?

Radiation Formula
Original laser beam copy

$$\tilde{\mathbf{A}}(\mathbf{k}) \propto \frac{\omega}{\gamma_0}\tilde{\mathbf{A}}_\mathbf{L}\left(\kappa(\mathbf{k},\beta_0),k_y,k_z\right)$$



$k_\perp = \sqrt{k_y^2 + k_z^2}$

Head on collision
Laser propagating in $-x$ direction

$$k_x^L = -k_0 \text{ and } k_z^L = k_y^L = 0$$

$$\text{Yields: } k_x = k_0\frac{1+\beta_0}{1-\beta_0} \approx 4\gamma_0^2 k_0 \vee \dots \text{ and } k_z = k_y = 0$$

which is the **standard Thomson result**!

Perpendicular collision
Laser propagating in z direction

$$k_z^L = k_0 \text{ and } k_x^L = k_y^L = 0$$

$$\text{Yields } k_x = \frac{2\beta_0 k_0}{1-\beta_0^2} \approx 2\gamma_0^2 k_0 \vee \dots \text{ and } k_z = k_0 \text{ and } k_y = 0$$

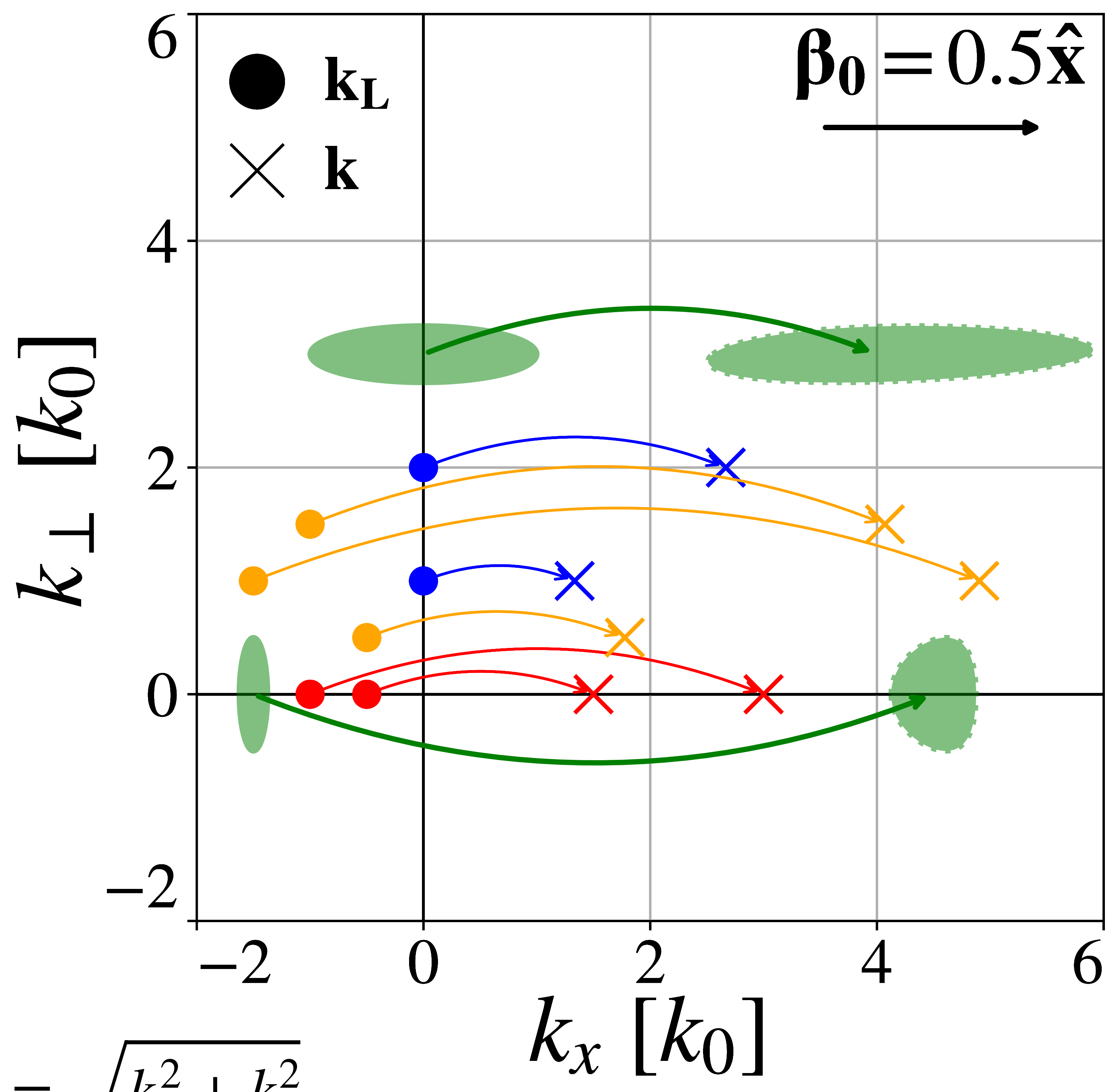
upshift is smaller but still **arbitrarily large**

One to one mapping of every $\mathbf{k}$ vector
Arbitrary angle and magnitude

What happens to each wave of a laser beam?

Radiation Formula
Original laser beam copy

$$\tilde{\mathbf{A}}(\mathbf{k}) \propto \frac{\omega}{\gamma_0}\tilde{\mathbf{A}}_\mathbf{L}\left(\kappa(\mathbf{k},\beta_0), k_y, k_z\right)$$



$k_\perp = \sqrt{k_y^2 + k_z^2}$

Head on collision
Laser propagating in $-x$ direction

$$k_x^L = -k_0 \text{ and } k_z^L = k_y^L = 0$$

$$\text{Yields: } k_x = k_0\frac{1+\beta_0}{1-\beta_0} \approx 4\gamma_0^2 k_0 \vee \ldots \text{ and } k_z = k_y = 0$$

which is the **standard Thomson result**!

Perpendicular collision
Laser propagating in z direction

$$k_z^L = k_0 \text{ and } k_x^L = k_y^L = 0$$

$$\text{Yields } k_x = \frac{2\beta_0 k_0}{1-\beta_0^2} \approx 2\gamma_0^2 k_0 \vee \ldots \text{ and } k_z = k_0 \text{ and } k_y = 0$$

upshift is smaller but still **arbitrarily large**

One to one mapping of every $\mathbf{k}$ vector
Arbitrary angle and magnitude

Remapping also of full patches in k space
Complete laser profiles are patches

An illustrative example: OAM Laser

Lasers with Orbital Angular Momentum [1]
Spiral wavefronts in real space - angular phase dependence in k-space

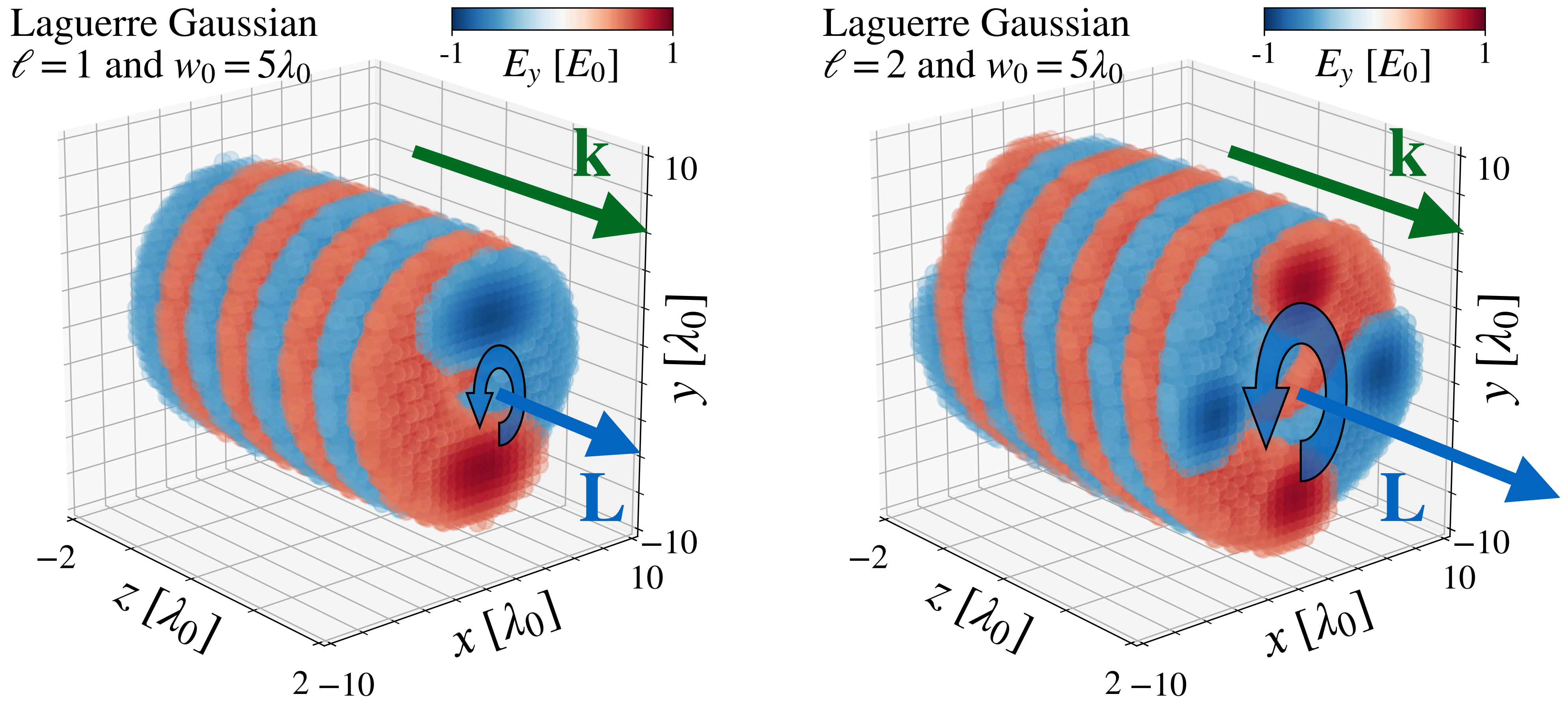
Laser field given by

$$A_L(\mathbf{r},t) \propto \left(\frac{r\sqrt{2}}{w_0}\right)^{|\ell|} e^{-r^2/w_0^2}\, e^{i\ell\phi - ik_0(z-ct)}\, f(z-ct)$$

where $r \equiv \sqrt{x^2+y^2}$ and $\phi \equiv \arctan x/y$

- orbital angular momentum $\mathbf{L}$ that is $|\mathbf{L}| \propto \ell$ and $\mathbf{L} \parallel \mathbf{k}$

In real space, ℓ controls the number of spiral wavefronts



[1] Allen, L., et.al Physical Review A 45, 8185–8189 (1992)

An illustrative example: OAM Laser

Lasers with Orbital Angular Momentum [1]

Spiral wavefronts in real space - angular phase dependence in k-space

Laser field given by

$$A_L(\mathbf{r},t) \propto \left(\frac{r\sqrt{2}}{w_0}\right)^{|\ell|} e^{-r^2/w_0^2}\, e^{i\ell\phi - ik_0(z-ct)}\, f(z-ct)$$

where $r \equiv \sqrt{x^2+y^2}$ and $\phi \equiv \arctan x/y$

- orbital angular momentum $\mathbf{L}$ that is $|\mathbf{L}| \propto \ell$ and $\mathbf{L} \parallel \mathbf{k}$

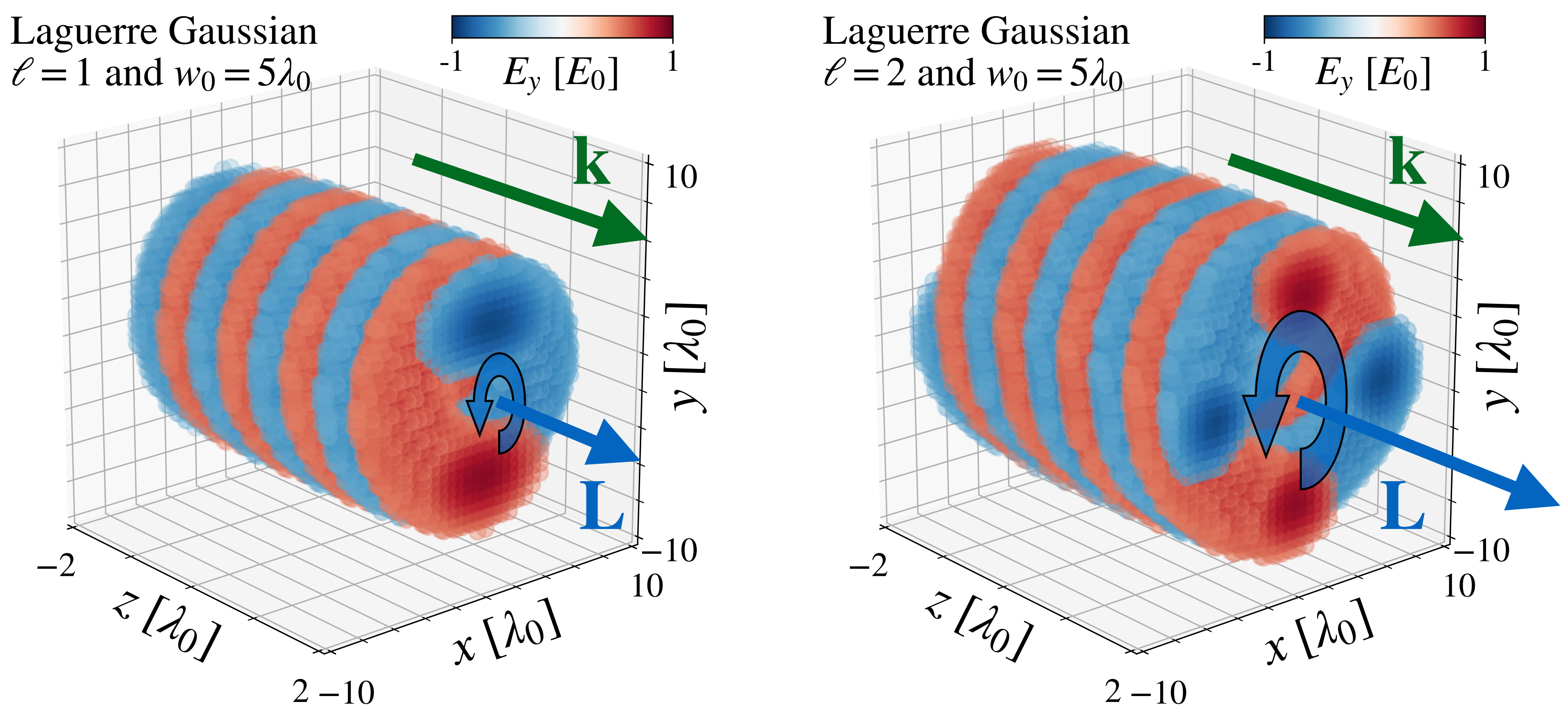
Describing the pulse in k-space yields

$$\tilde{A}_L(\mathbf{k}) \propto \left(\frac{k_r w_0}{\sqrt{2}}\right)^{|\ell|} e^{-k_r^2 w_0^2/4}\, e^{i\ell k_\phi}\, \tilde{f}(k_z - k_0)$$

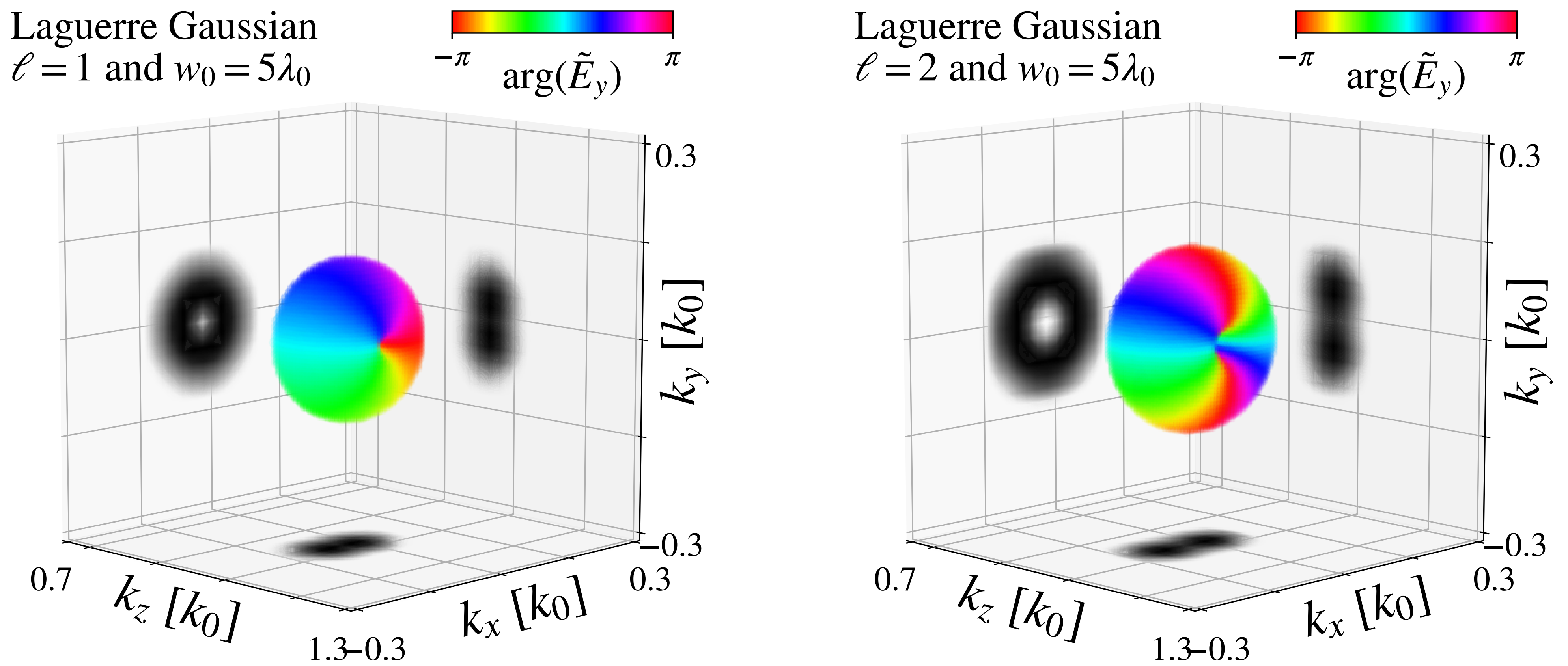
where $k_r \equiv \sqrt{k_x^2+k_y^2}$ and $k_\phi \equiv \arctan k_x/k_y$

- "donut" - like spectral intensity with $\ell \times 2\pi$ phase shifts

In real space, ℓ controls the number of spiral wavefronts



In k-space, ℓ controls the number of 2π phase shifts



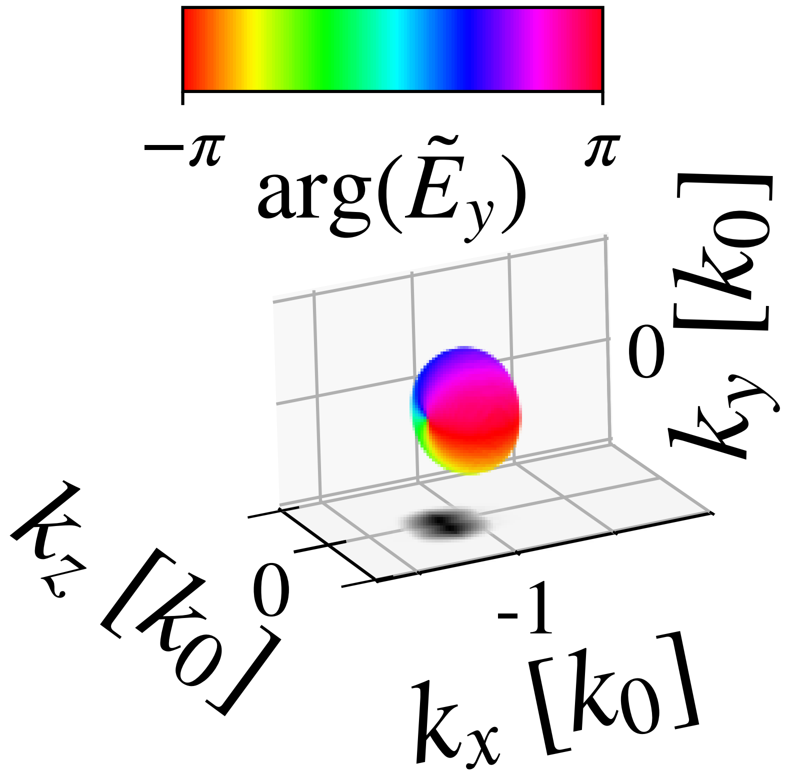
[1] Allen, L., et.al Physical Review A 45, 8185–8189 (1992)

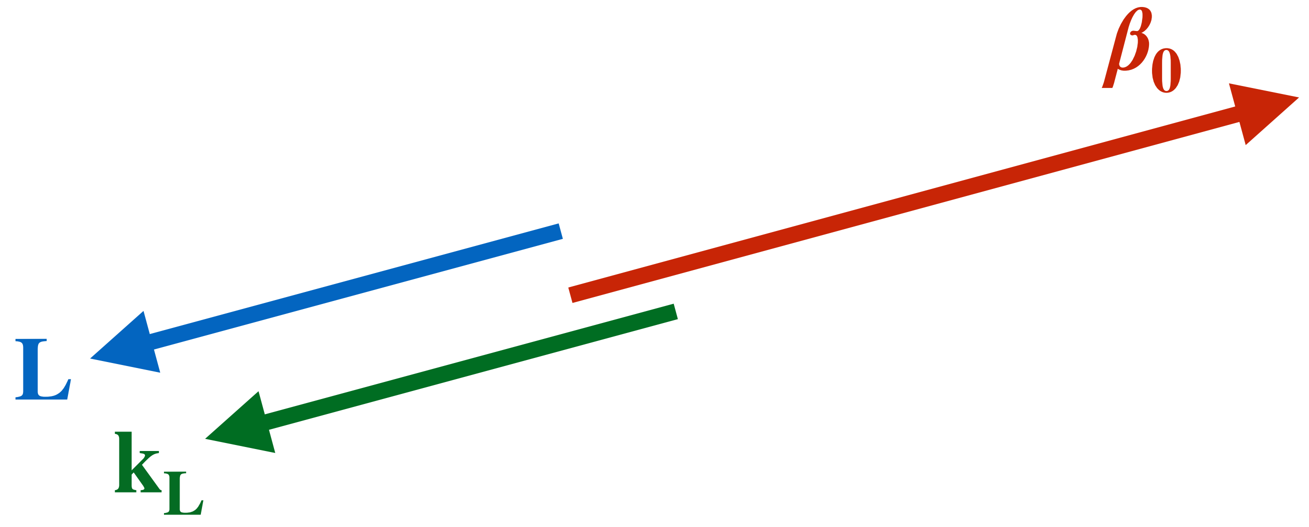
Radiation from an OAM Laser

Radiation from an OAM Laser

Radiation from head on collision
Spectral structure is kept, frequency is upshifted

Laser propagates along $-x$ and beam along $+x$





Radiation from an OAM Laser

Radiation from head on collision
Spectral structure is kept, frequency is upshifted

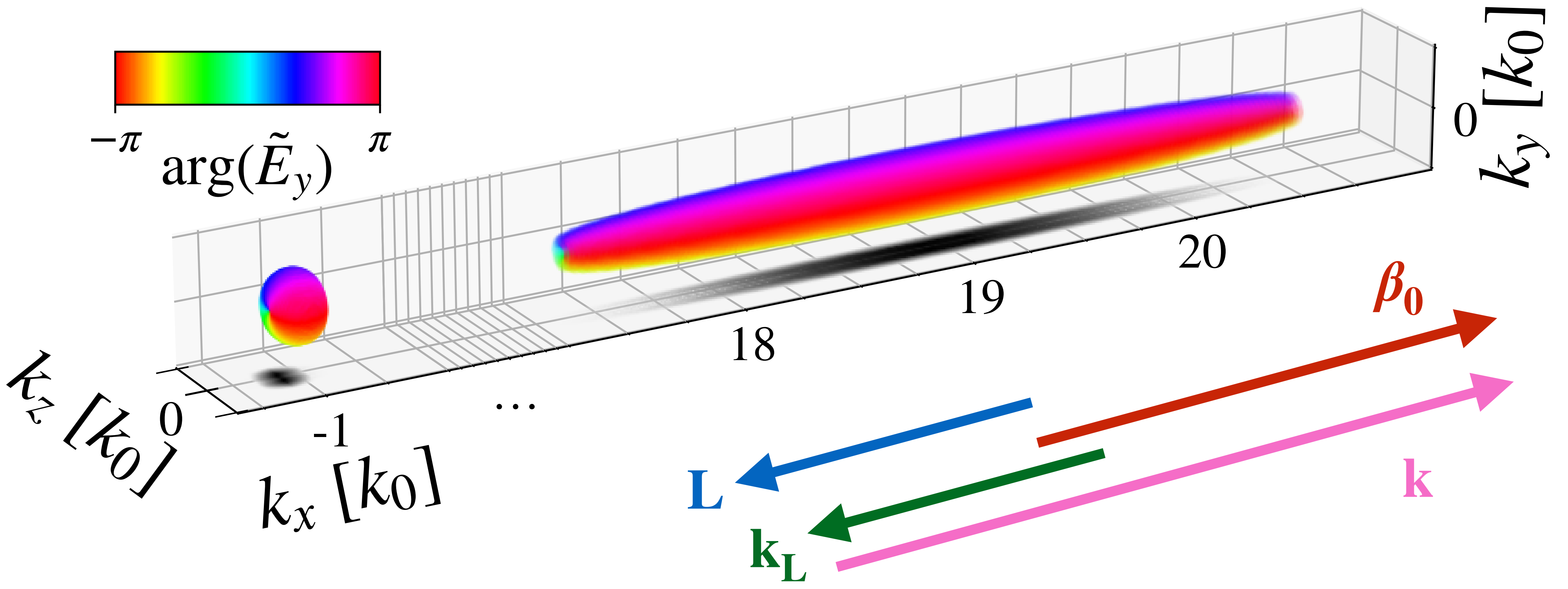
Laser propagates along $-x$ and beam along $+x$

Spectrum is **shifted** and **stretched** along k_x

Radiation travels along $+x$

Still a LG Beam ($\mathbf{k} \parallel \mathbf{L}$) but

upshifted in frequency: $|\mathbf{k}| \approx 4\gamma_0^2 |\mathbf{k_L}|$



Radiation from an OAM Laser

Radiation from head on collision

Spectral structure is kept, frequency is upshifted

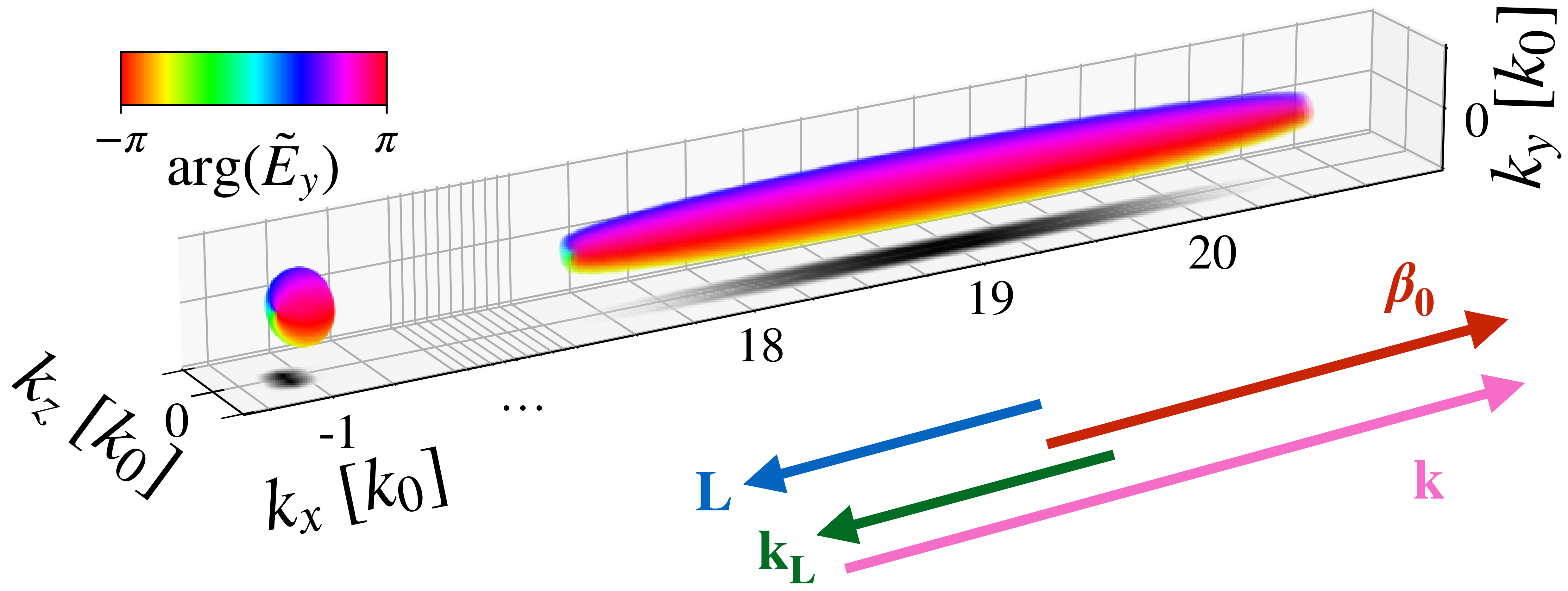
Laser propagates along $-x$ and beam along $+x$

Spectrum is **shifted** and **stretched** along k_x

Radiation travels along $+x$

Still a LG Beam ($\mathbf{k} \parallel \mathbf{L}$) but

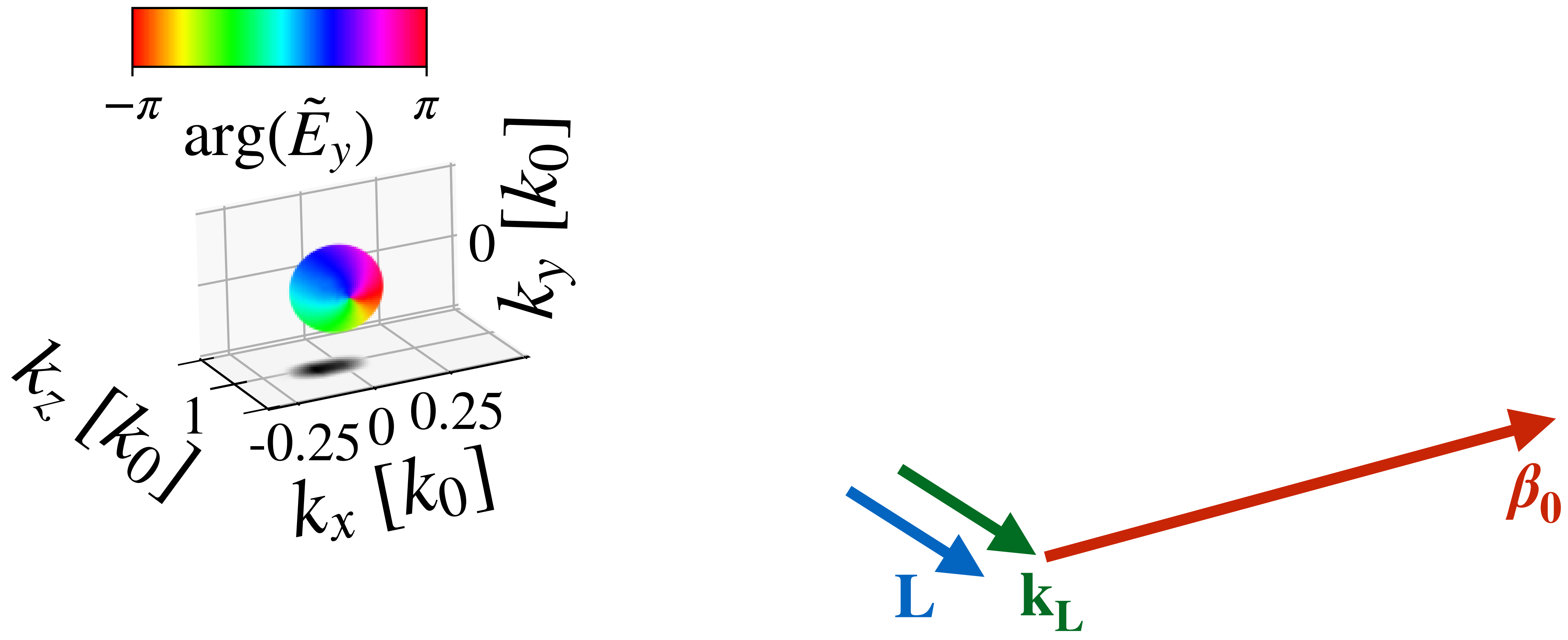
upshifted in frequency: $|\mathbf{k}| \approx 4\gamma_0^2 |\mathbf{k_L}|$



Radiation from perpendicular colliding

Spectrum is shifted and spectral structure is changed

Laser propagates along $+z$ and beam along $+x$



Radiation from an OAM Laser

Radiation from head on collision
Spectral structure is kept, frequency is upshifted

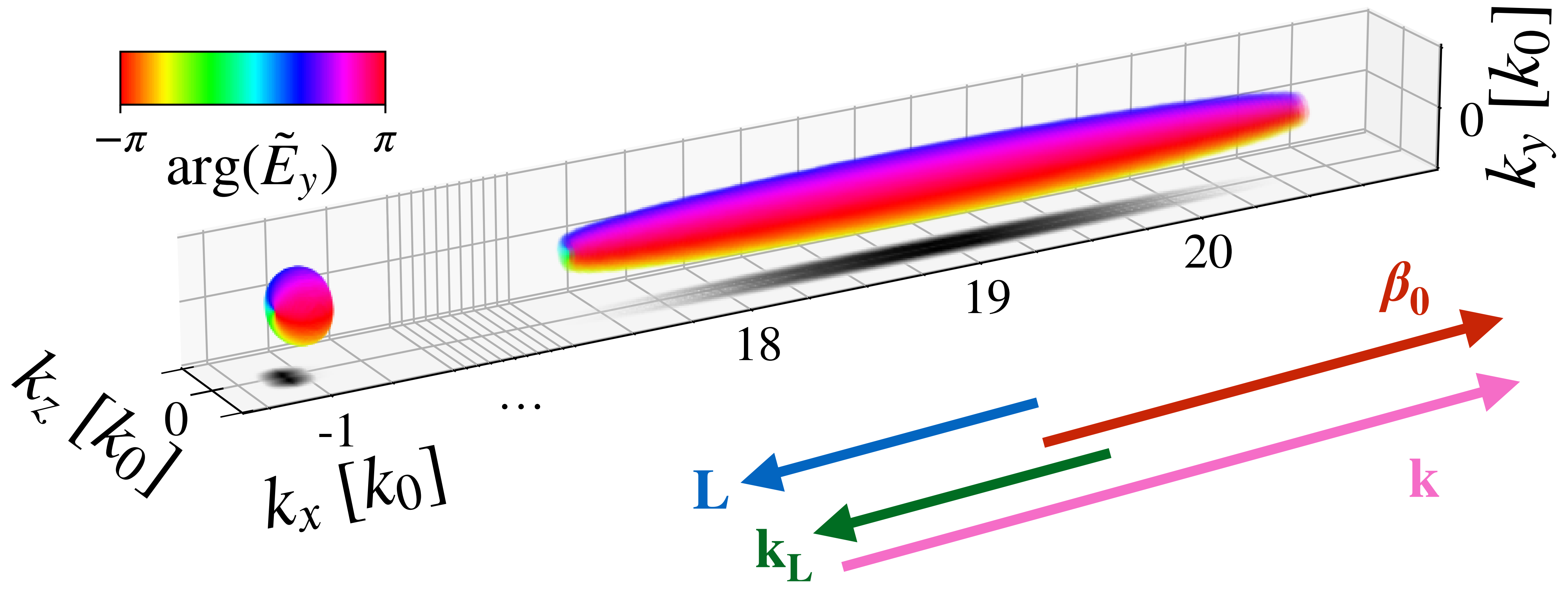
Laser propagates along $-x$ and beam along $+x$

Spectrum is **shifted** and **stretched** along k_x

Radiation travels along $+x$

Still a LG Beam ($\mathbf{k} \parallel \mathbf{L}$) but

upshifted in frequency: $|\mathbf{k}| \approx 4\gamma_0^2 |\mathbf{k_L}|$



Radiation from perpendicular colliding
Spectrum is shifted and spectral structure is changed

Laser propagates along $+z$ and beam along $+x$

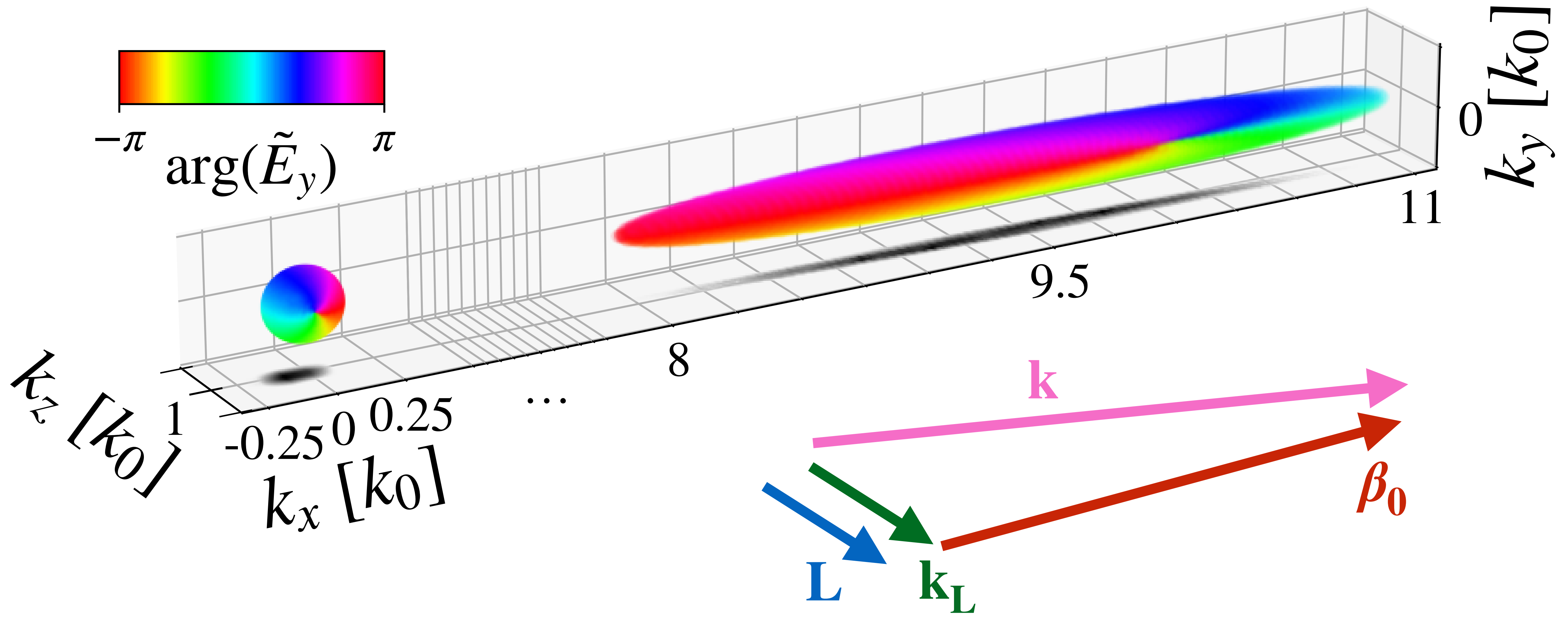
Spectrum is **shifted** and **stretched** along k_x

Radiation travels mainly along $+x$

(actually small angle in the z direction)

Fundamental spectral structure is different ($\mathbf{k} \perp \mathbf{L}$)

SpatioTemporal Optical Vortex - STOV



What is a SpatioTemporal Optical Vortex?

STOV: SpatioTemporal Optical Vortex [1,2]

Equivalent to the OAM but with Transverse Optical Angular Momentum

[1] Jhajj, N. et al. Phys. Rev. X 6, 031037 (2016)
[2] Bliokh, K.Y. Phys. Rev. Lett. 126, 243601 (2021)

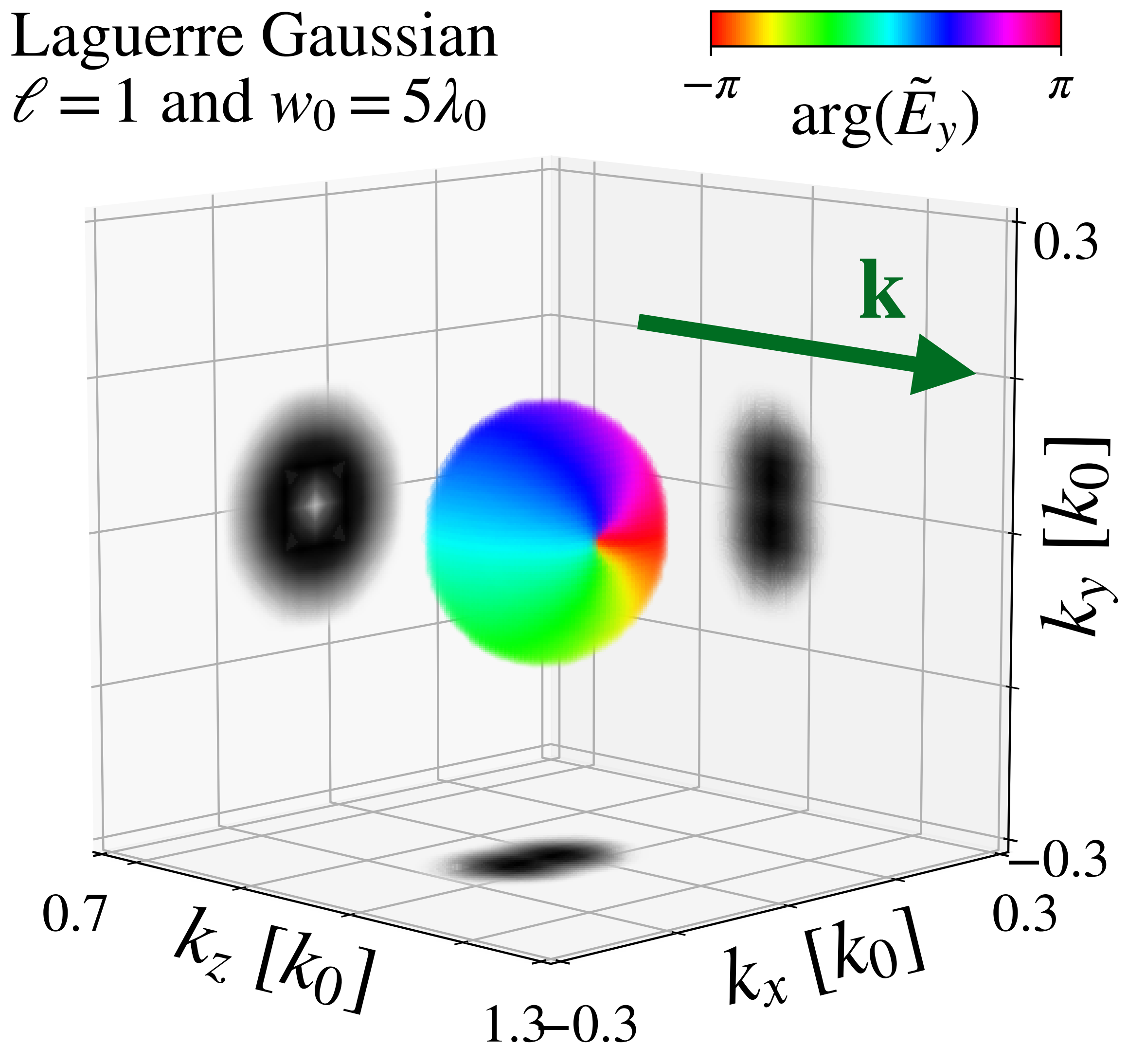
What is a SpatioTemporal Optical Vortex?

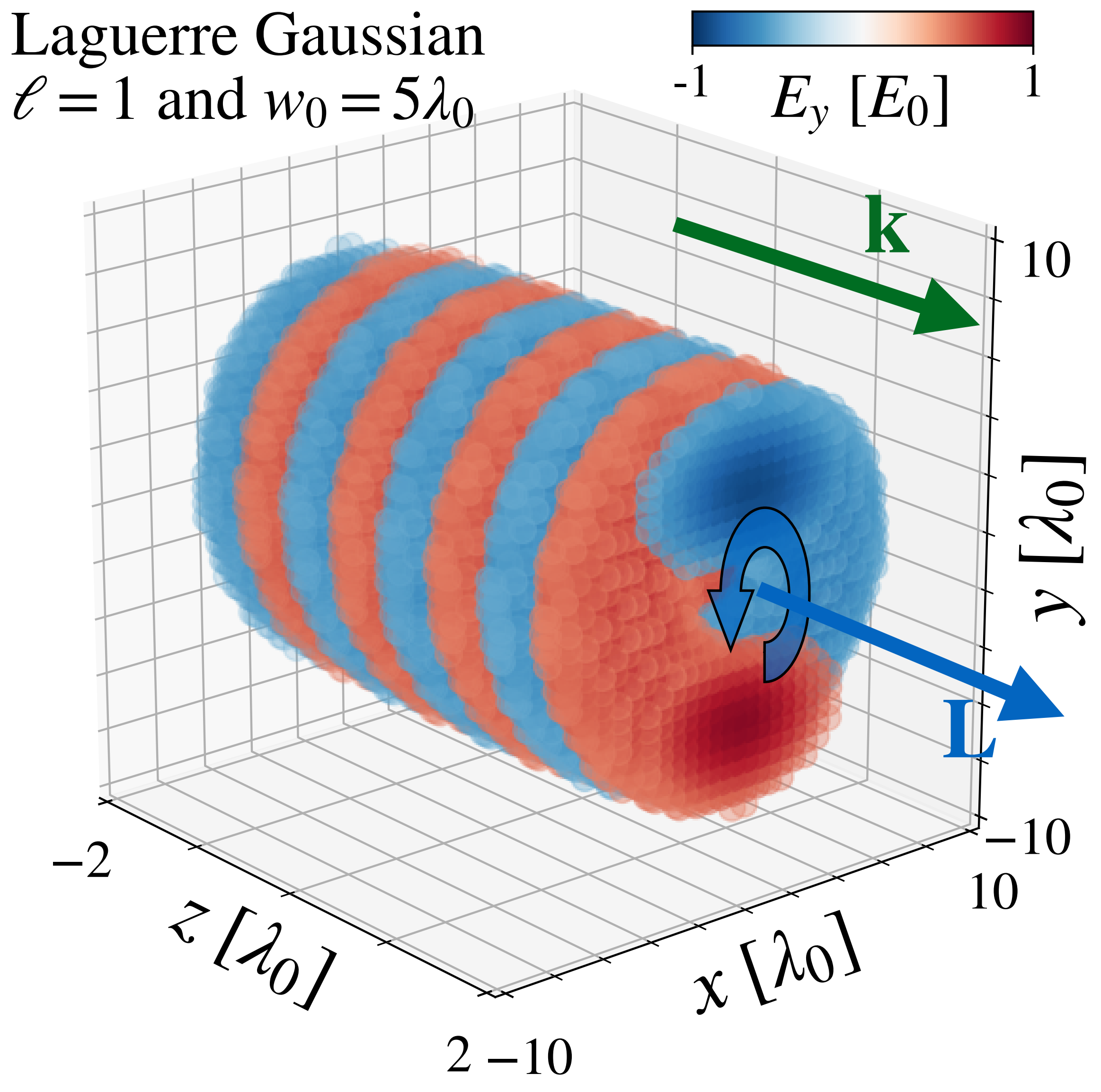
STOV: SpatioTemporal Optical Vortex [1,2]

Equivalent to the OAM but with Transverse Optical Angular Momentum

A LG Beam has angular momentum **parallel** to the propagation direction

(Normal) Orbital Angular Momentum - k || L





[1] Jhajj, N. et al. Phys. Rev. X 6, 031037 (2016)
[2] Bliokh, K.Y. Phys. Rev. Lett. 126, 243601 (2021)

What is a SpatioTemporal Optical Vortex?

TÉCNICO LISBOA

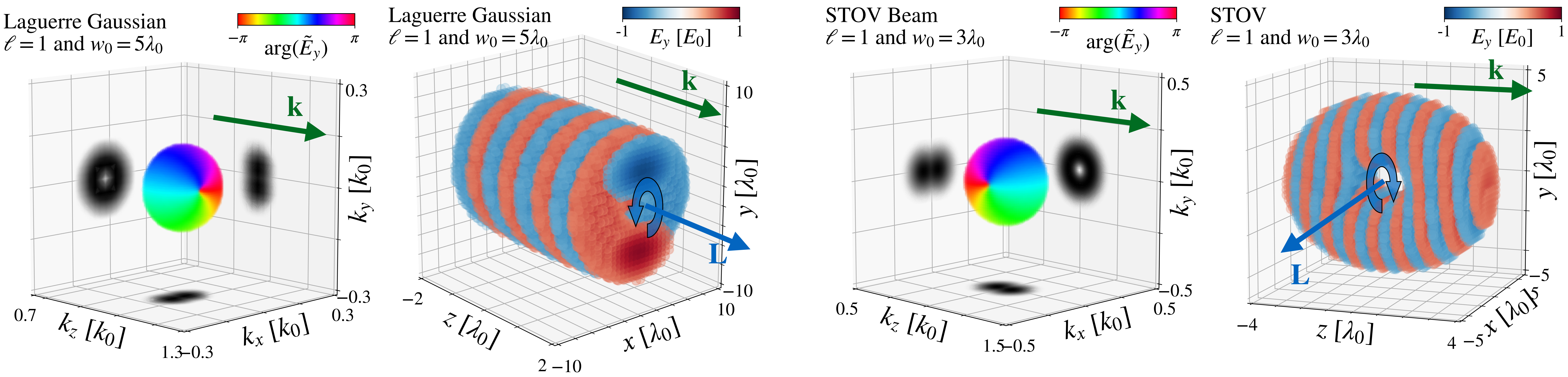
STOV: SpatioTemporal Optical Vortex [1,2]
Equivalent to the OAM but with Transverse Optical Angular Momentum

A LG Beam has angular momentum **parallel** to the propagation direction

A STOV has angular momentum **perpendicular** to the propagation direction

(Normal) Orbital Angular Momentum - $\mathbf{k} \parallel \mathbf{L}$

Transverse Orbital Angular Momentum - $\mathbf{k} \perp \mathbf{L}$



[1] Jhajj, N. et al. Phys. Rev. X 6, 031037 (2016)
[2] Bliokh, K.Y. Phys. Rev. Lett. 126, 243601 (2021)

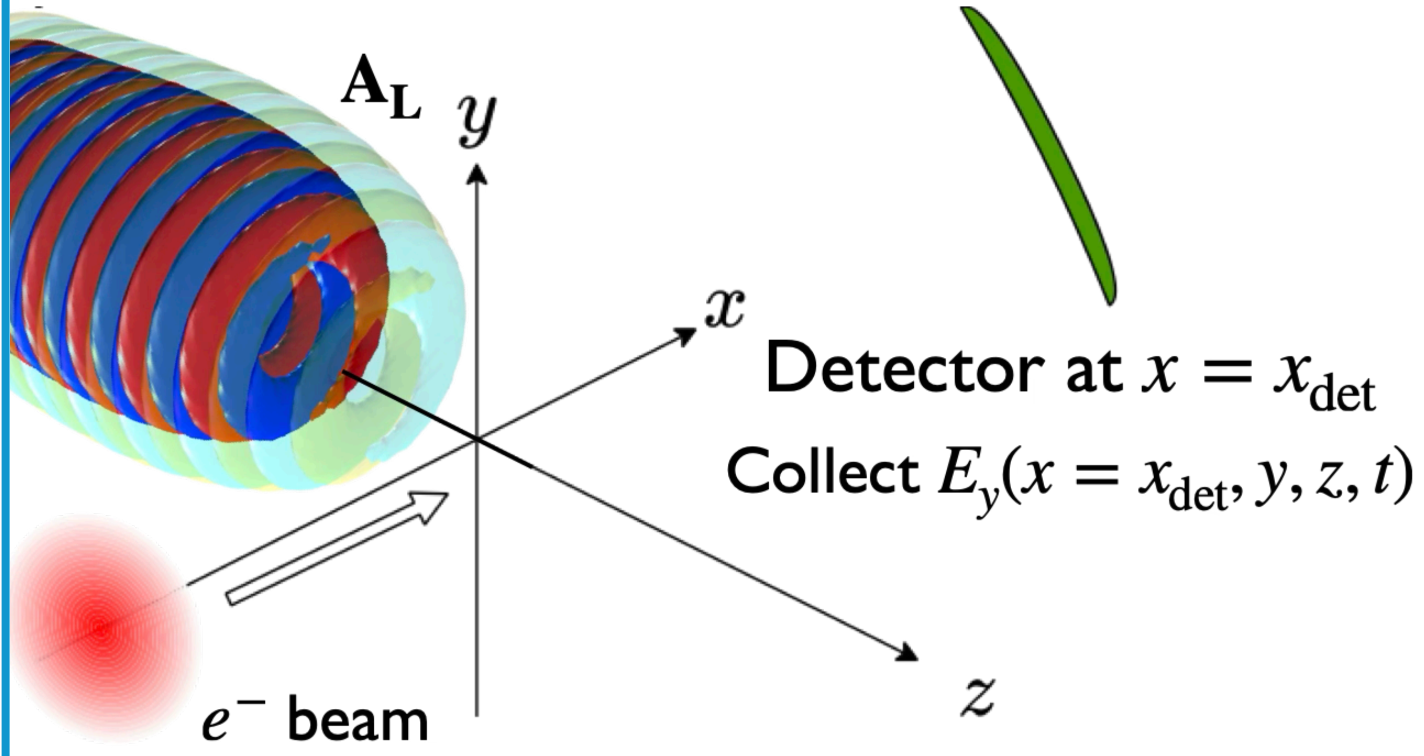
Osiris and RaDiO set-up and simulation results

Simulation setup
Fully self consistent results

Laser:
- Laguerre Gauss ($\ell = 1, w_0 = 5\lambda_0$)
- injected with plane wave algorithm

Electron beam:
- underdense, cold and collimated
- gaussian transversely, $\sigma = 5\lambda_0$
- 1 particle thick longitudinally
- momentum $p_0 = 50\ m_e c$

Detector at $x_{\text{det}} = 50000\lambda_0$



[1] Osiris 4.0 [2] RaDiO Radiation Diagnostic for OSIRIS

[1] R.A. Fonseca et al, LNCS. Issue: PART 3. Springer Verlag, 2002, pp. 342–351
[2] M. Pardal et al, Comp. Phys Comms. **285**, 108634 (2023)

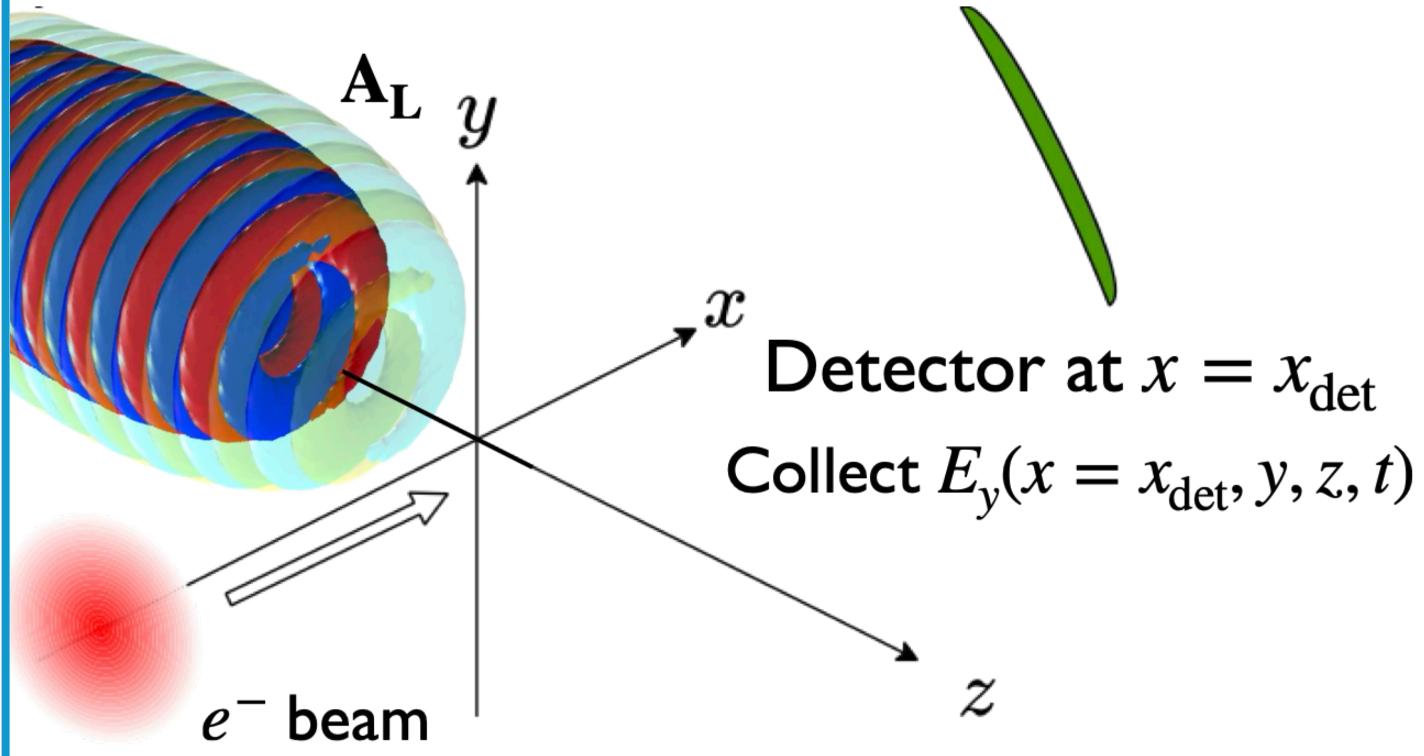
Osiris and RaDiO set-up and simulation results

Simulation setup
Fully self consistent results

Laser:
- Laguerre Gauss ($\ell = 1, w_0 = 5\lambda_0$)
- injected with plane wave algorithm

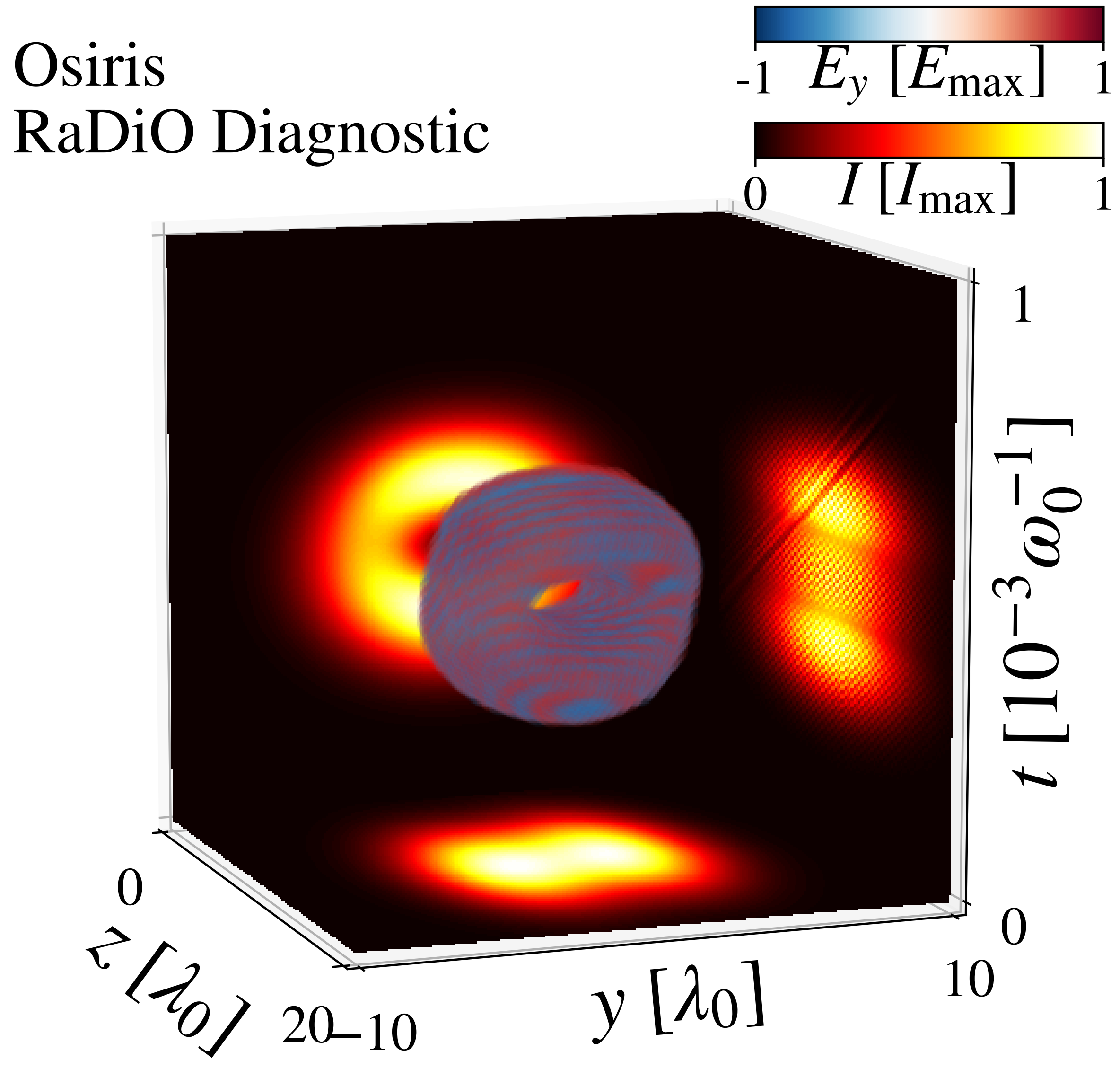
Electron beam:
- underdense, cold and collimated
- gaussian transversely, $\sigma = 5\lambda_0$
- 1 particle thick longitudinally
- momentum $p_0 = 50\ m_e c$

Detector at $x_{det} = 50000\lambda_0$



[1] [2]

Radiation captured by RaDiO
Energy radiated by all simulation particles



[1] R.A. Fonseca et al, LNCS. Issue: PART 3. Springer Verlag, 2002, pp. 342–351

[2] M. Pardal et al, Comp. Phys Comms. **285**, 108634 (2023)

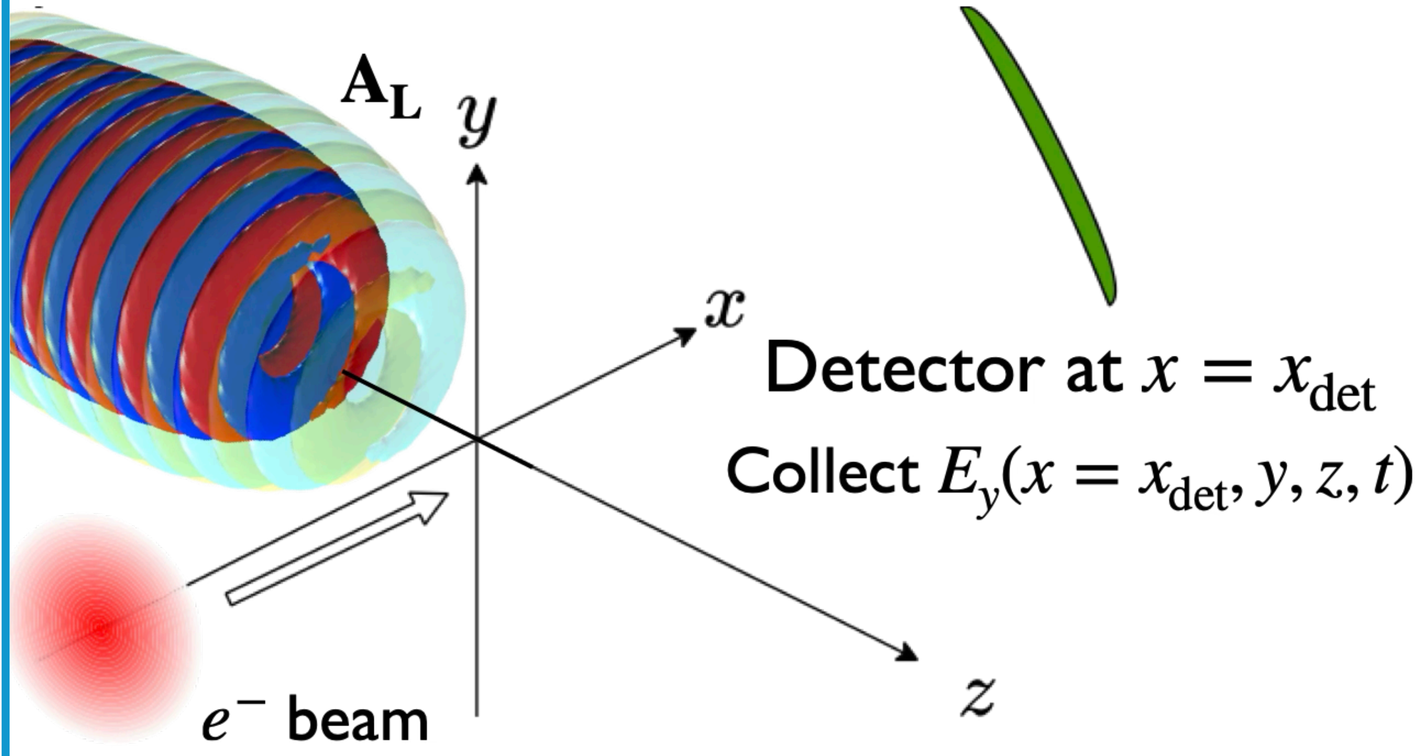
Osiris and RaDiO set-up and simulation results

Simulation setup
Fully self consistent results

Laser:
- Laguerre Gauss ($\ell = 1, w_0 = 5\lambda_0$)
- injected with plane wave algorithm

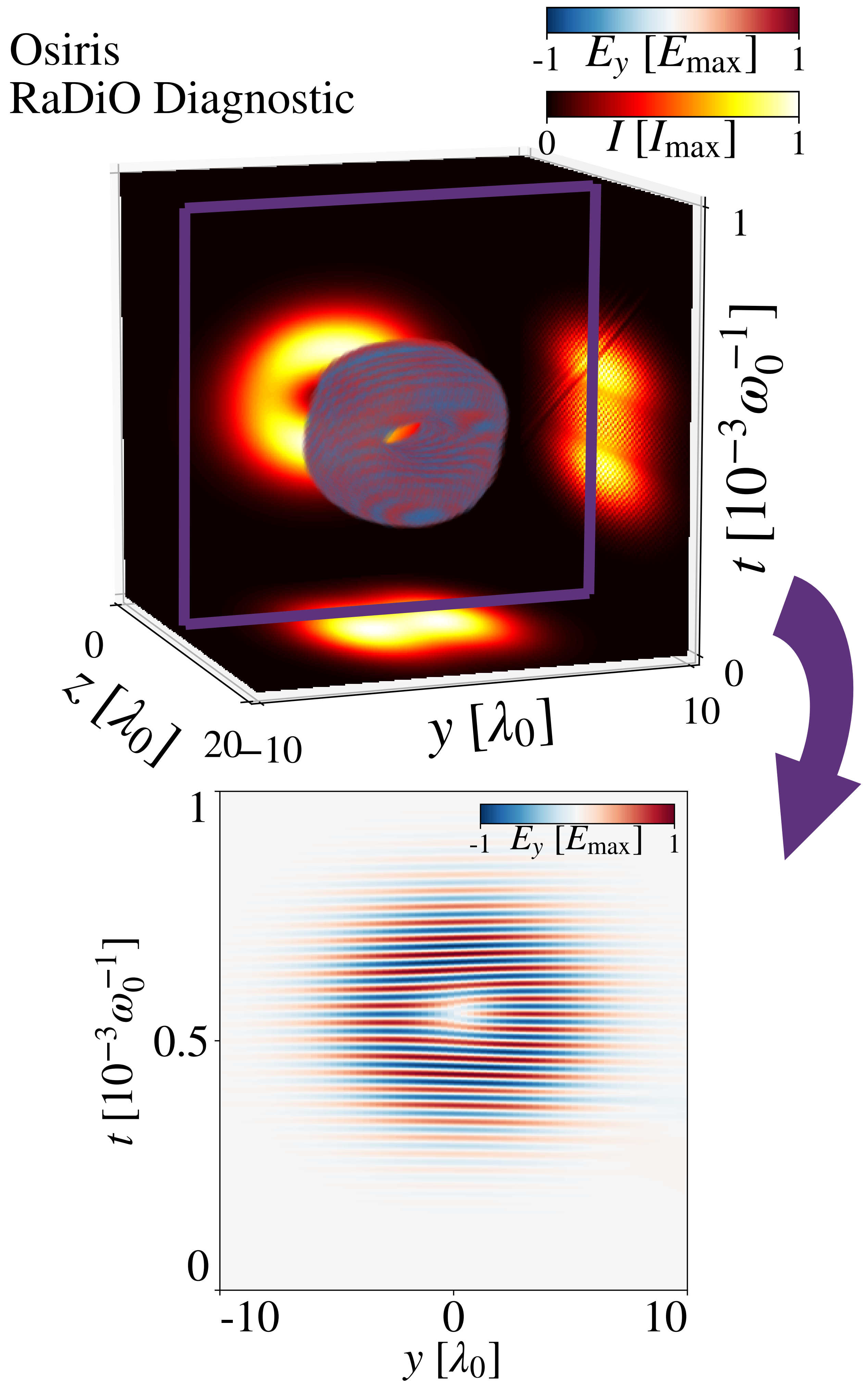
Electron beam:
- underdense, cold and collimated
- gaussian transversely, $\sigma = 5\lambda_0$
- 1 particle thick longitudinally
- momentum $p_0 = 50\ m_e c$

Detector at $x_{det} = 50000\lambda_0$



[1] Osiris 4.0 [2] RaDiO Radiation Diagnostic for OSIRIS

Radiation captured by RaDiO
Energy radiated by all simulation particles



[1] R.A. Fonseca et al, LNCS. Issue: PART 3. Springer Verlag, 2002, pp. 342–351
[2] M. Pardal et al, Comp. Phys Comms. **285**, 108634 (2023)

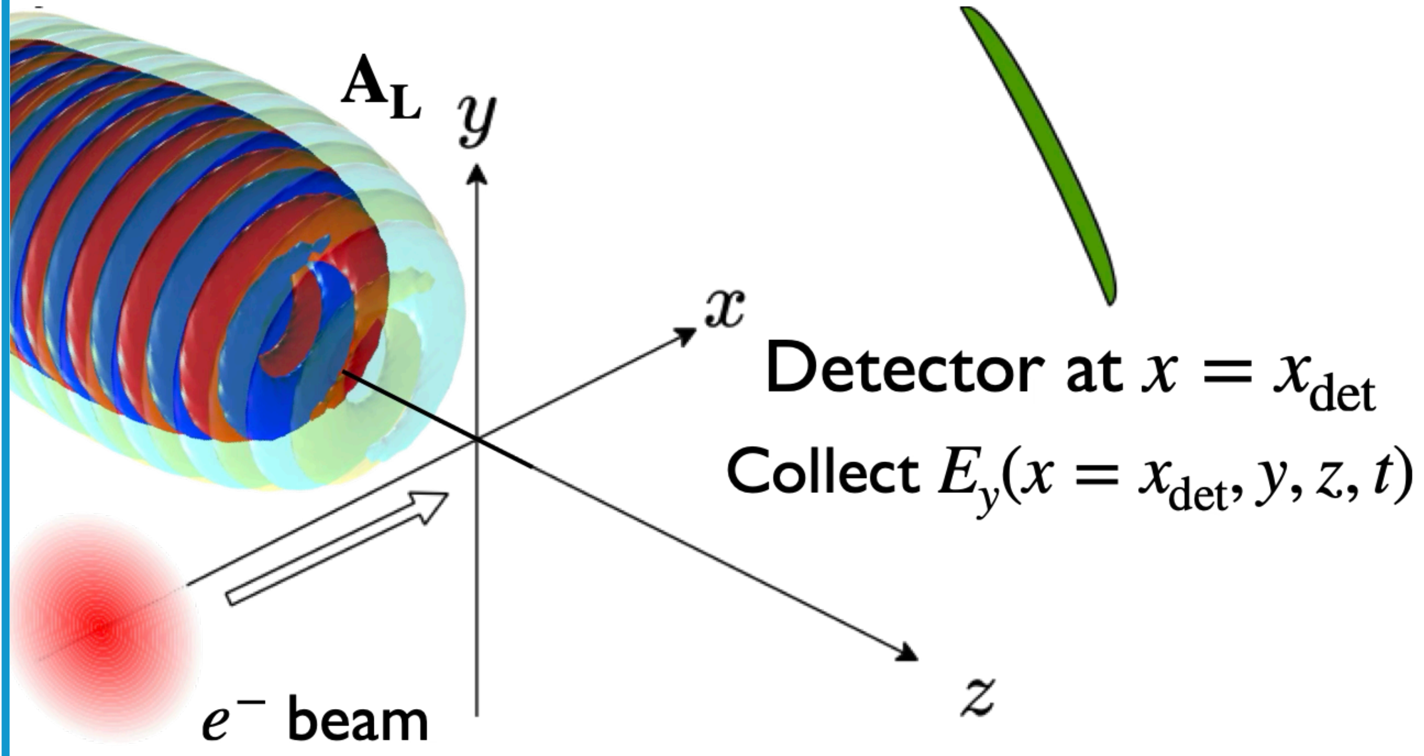
Osiris and RaDiO set-up and simulation results

Simulation setup
Fully self consistent results

Laser:
- Laguerre Gauss ($\ell = 1, w_0 = 5\lambda_0$)
- injected with plane wave algorithm

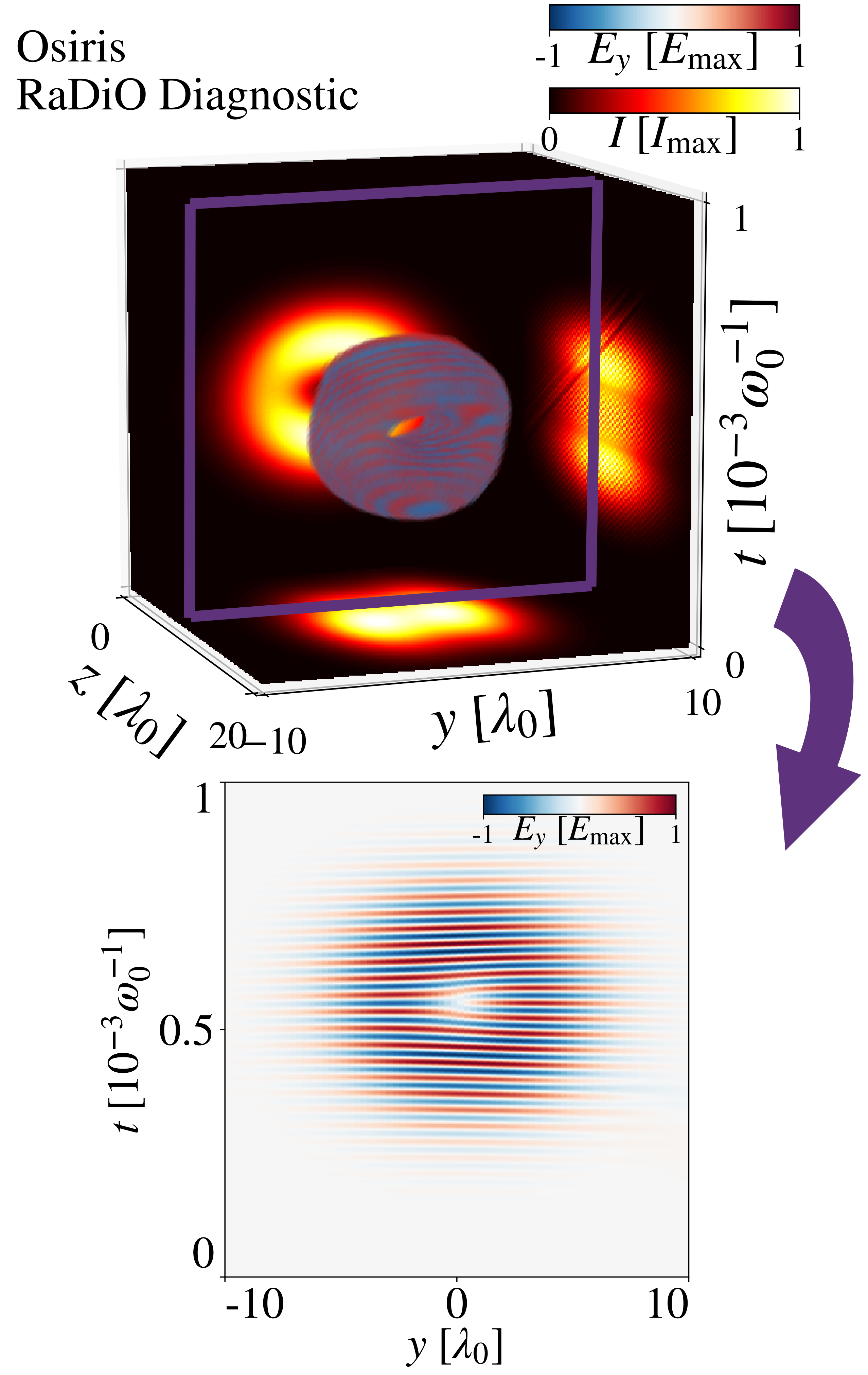
Electron beam:
- underdense, cold and collimated
- gaussian transversely, $\sigma = 5\lambda_0$
- 1 particle thick longitudinally
- momentum $p_0 = 50\ m_e c$

Detector at $x_{\rm det} = 50000\lambda_0$



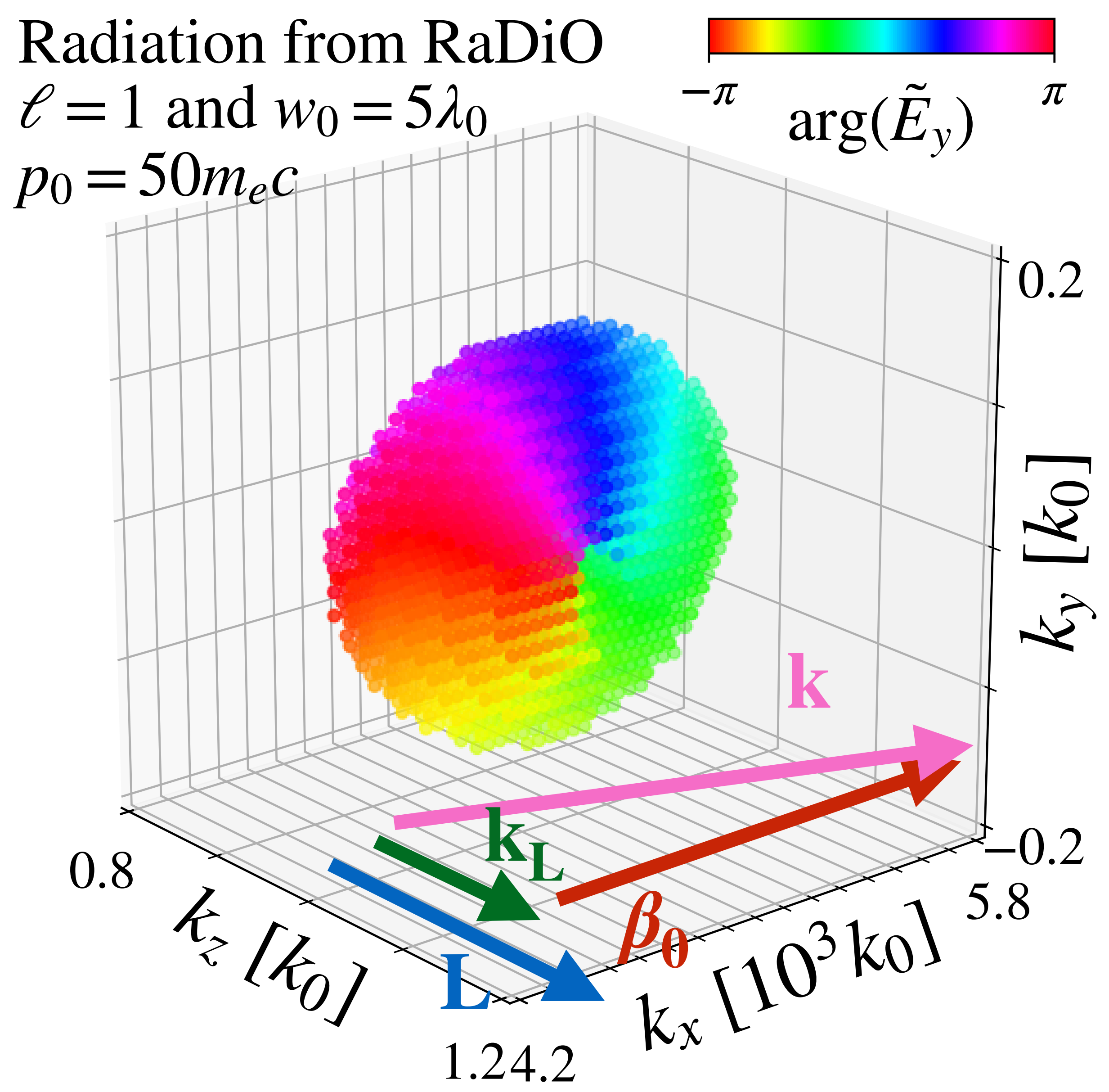
[1] Osiris 4.0 [2] RaDiO Radiation Diagnostic for OSIRIS

Radiation captured by RaDiO
Energy radiated by all simulation particles



Radiation spectrum
Perpendicular collision

$$\gamma_0 \approx 50 \Rightarrow k_x \approx 2\gamma_0^2 k_0 \approx 5000 k_0$$



Spectrum as predicted - $\mathbf{k} \perp \mathbf{L}$

[1] R.A. Fonseca et al, LNCS. Issue: PART 3. Springer Verlag, 2002, pp. 342–351

[2] M. Pardal et al, Comp. Phys Comms. **285**, 108634 (2023)

Conclusions and Future Work

Thomson Scattering can be a light shaping tool
Spectrum of resulting radiation can be manipulated and controlled

Generalised Radiation Formula from Laser - Beam Interaction
Simplified analysis is achieved in k-space using Fourier Transforms

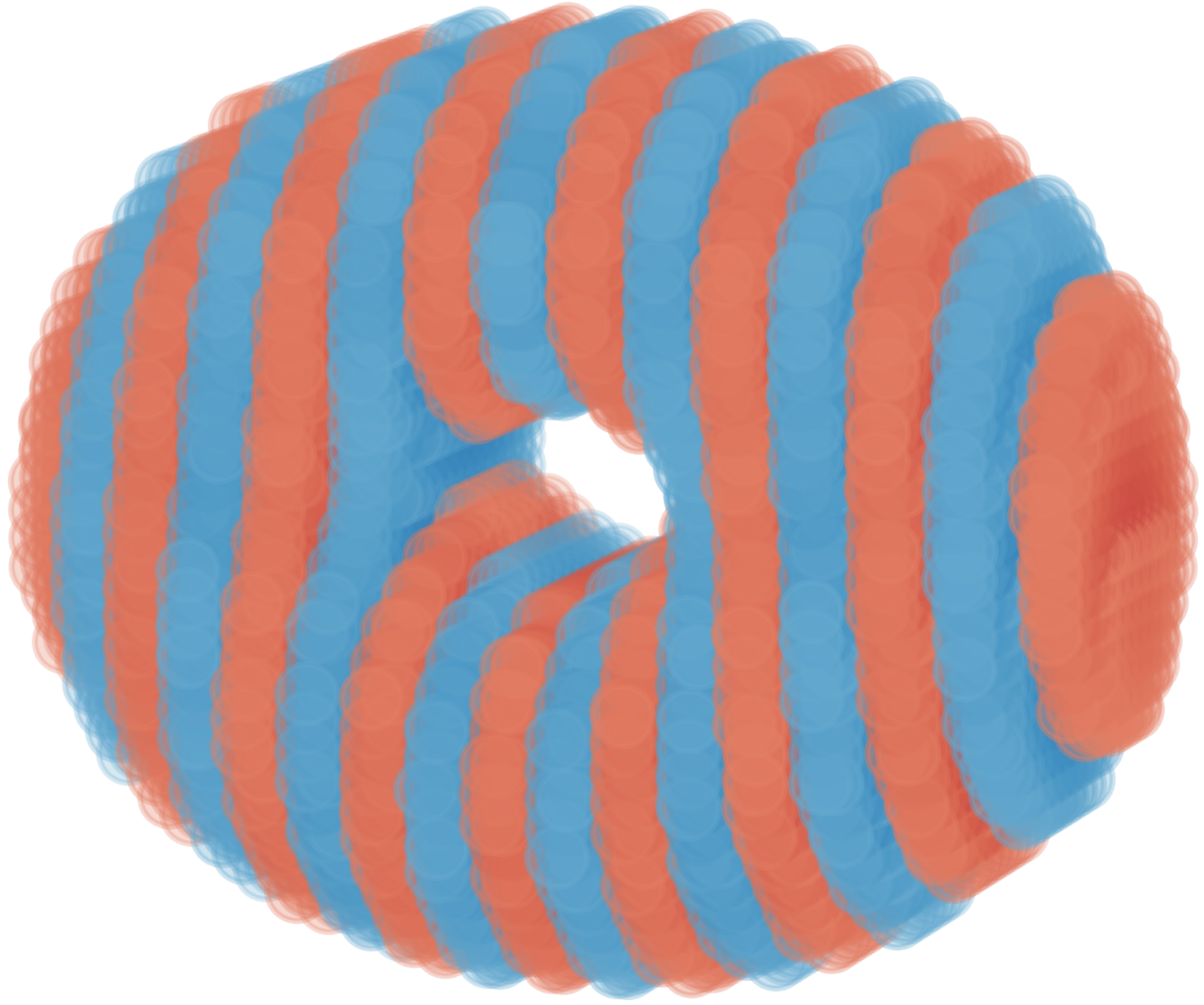
Generated SpatioTemporal Optical Vortex from Laguerre Gaussian Beam
Normal orbital angular momentum was converted to transverse

Next steps towards more realistic setups

- Particle beam shape
- Particle beam characteristics
- Laser polarisations
- Radiation efficiency

Radiation Formula
Original laser beam copy

$$\tilde{\mathbf{A}}(\mathbf{k}) \propto \frac{\omega}{\gamma_0} \tilde{\mathbf{A}}_{\mathbf{L}} \left(\kappa(\mathbf{k}, \beta_0), k_y, k_z \right)$$



Fundação para a Ciência e a Tecnologia

Grant UI/BD/154677/2022

Barcelona Supercomputing Center
Centro Nacional de Supercomputación