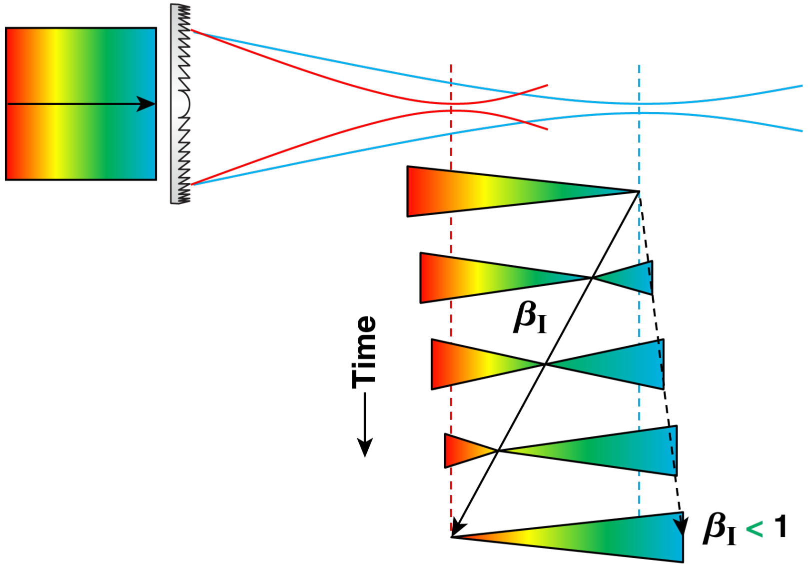
Direct Electron Acceleration and Radiation Generation in Space-Time Structured Laser Pulses



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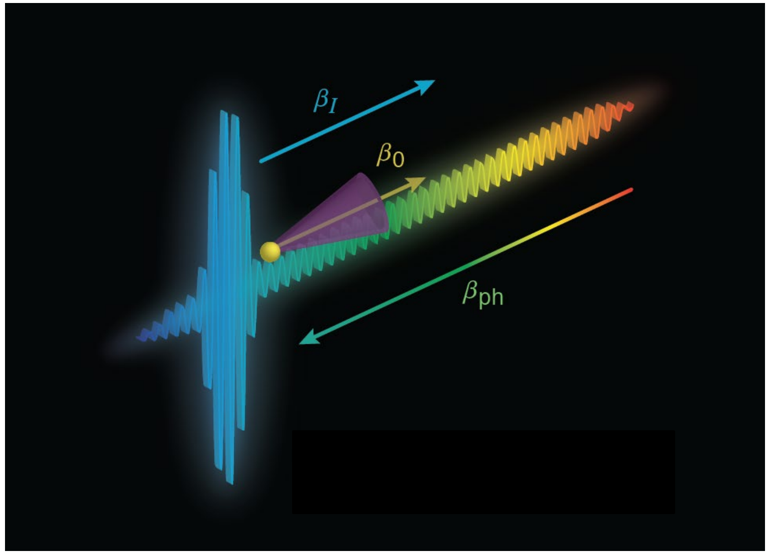

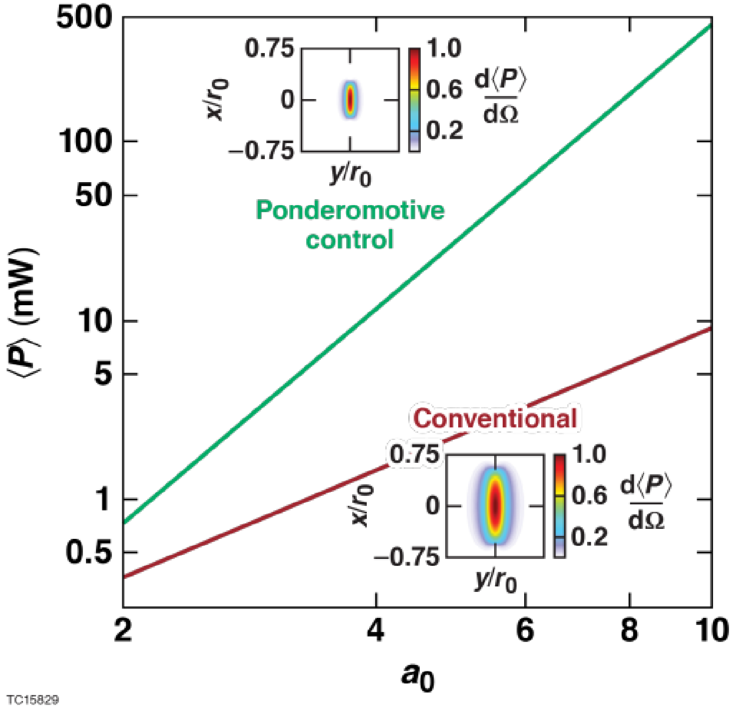

TC15829

Dillon Ramsey
University of Rochester
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17 October 2022

Space-time structured laser pulses enable novel regimes of direct laser acceleration and nonlinear Thomson scattering

UR LLE

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The flying focus offers additional control over the radiation properties of nonlinear Thomson scattering

Collaborators

MAX-PLANCK-INSTITUT FÜR KERNPHYSIK HEIDELBERG

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National Nuclear Security Administration

U.S. DEPARTMENT OF ENERGY

Office of Science

Outline

1. Space-time structured laser pulses

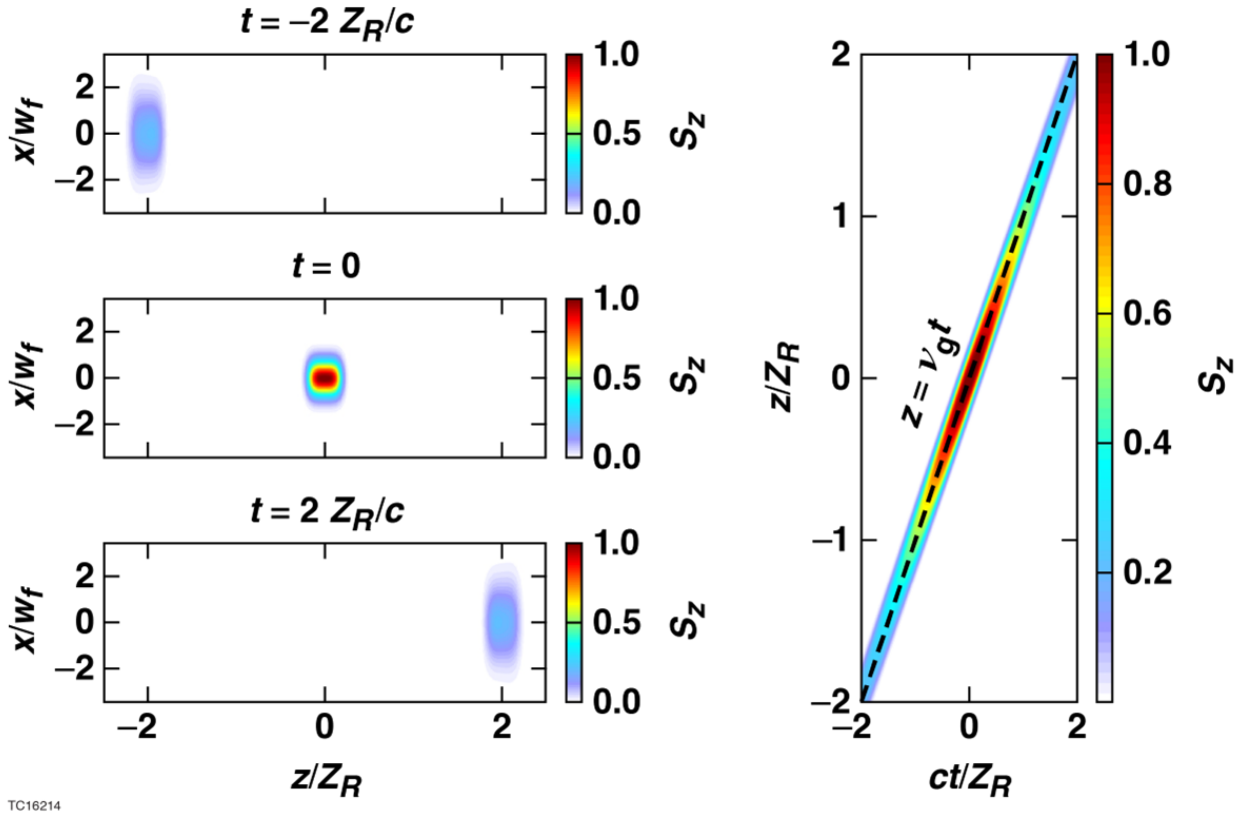
2. Exact electromagnetic fields of a flying focus

3. Vacuum laser acceleration

4. Nonlinear Thomson scattering

Conventional optical configurations have constraints that can limit laser-matter interactions

- The intensity peak travels at the group velocity
  - Difficult to velocity match a physical process of interest



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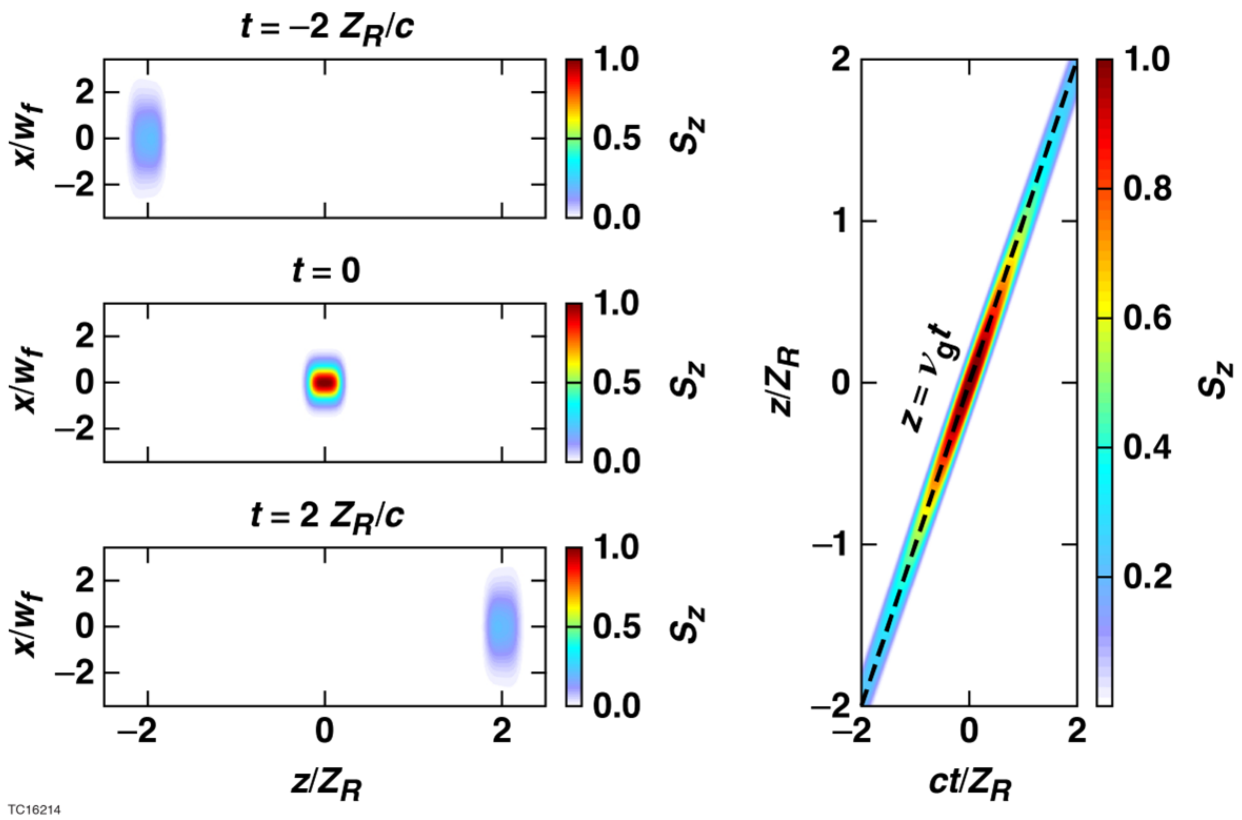

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- The intensity peak travels at the group velocity
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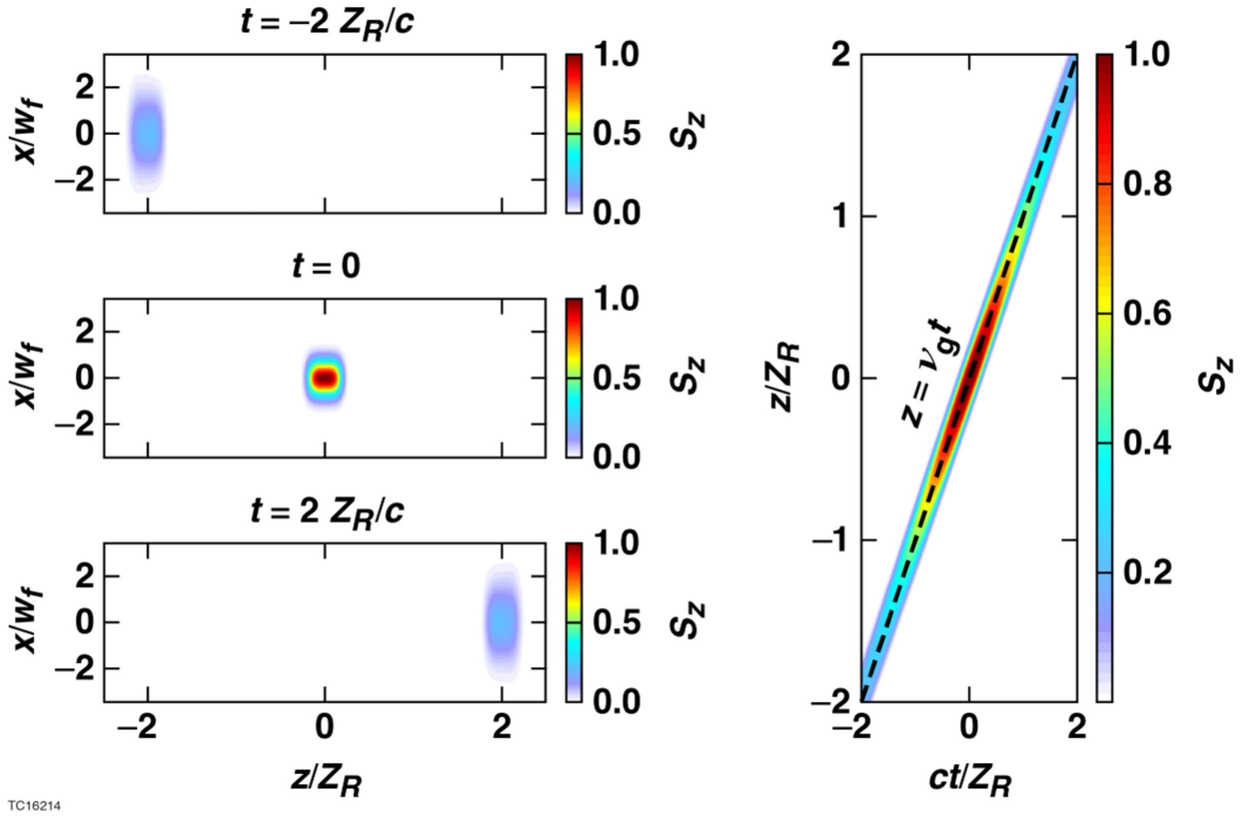
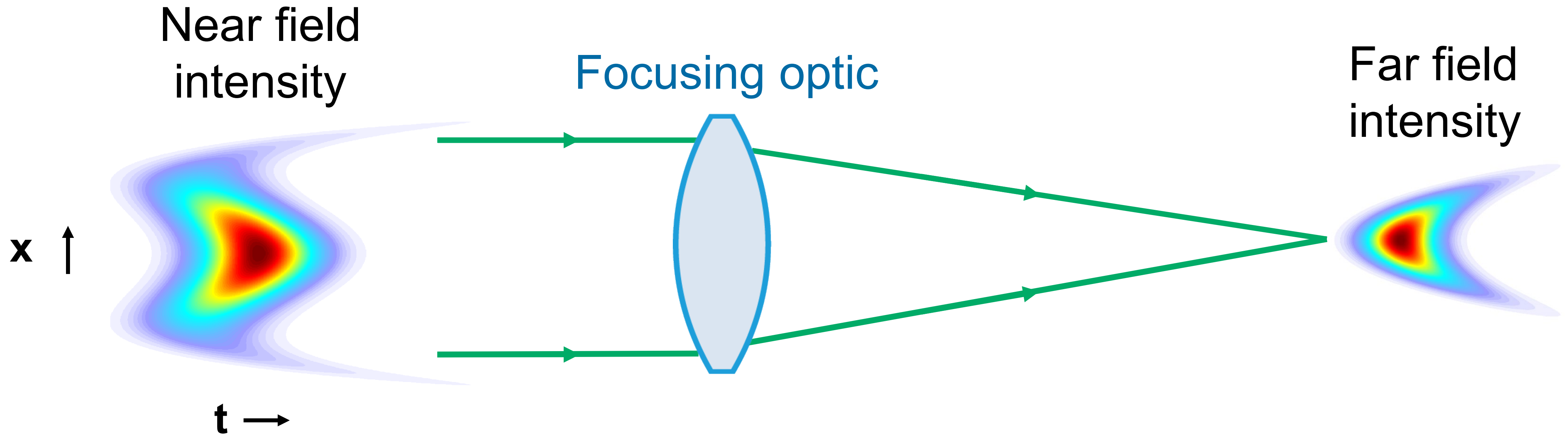
- The intensity drops over a Rayleigh range
  - – Limits interaction lengths
- The transverse profile evolves through the focus
  - – Nonuniform profile



Space-time structured laser pulses have coupled space-time dependent properties that can be tailored to an application



Space-time structuring provides additional flexibility that mitigates the constraints of conventional optical configurations

The "flying" focus is a space-time structuring technique that produces a moving focus

A flying focus has three advantageous properties:

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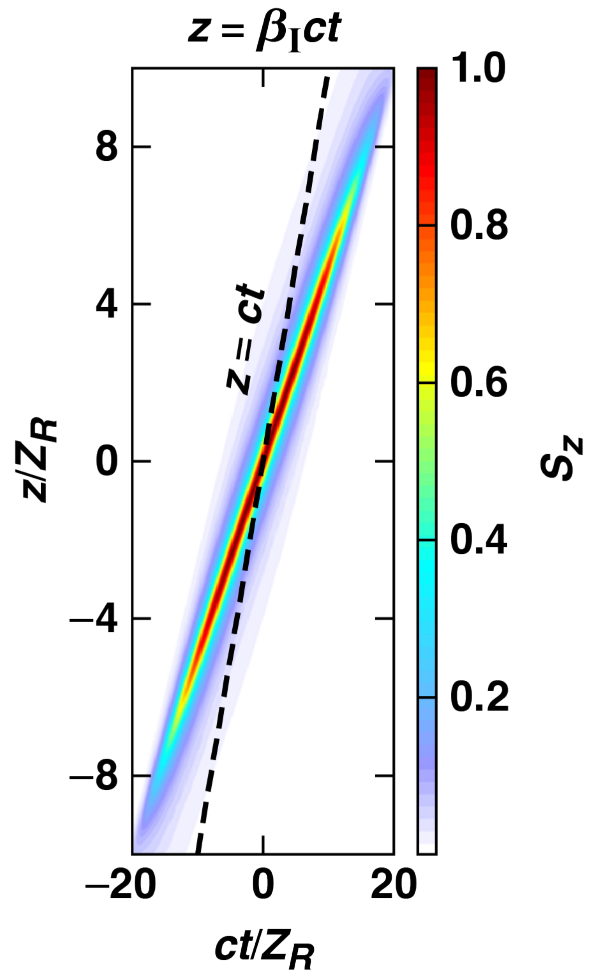
- A programable-velocity intensity peak



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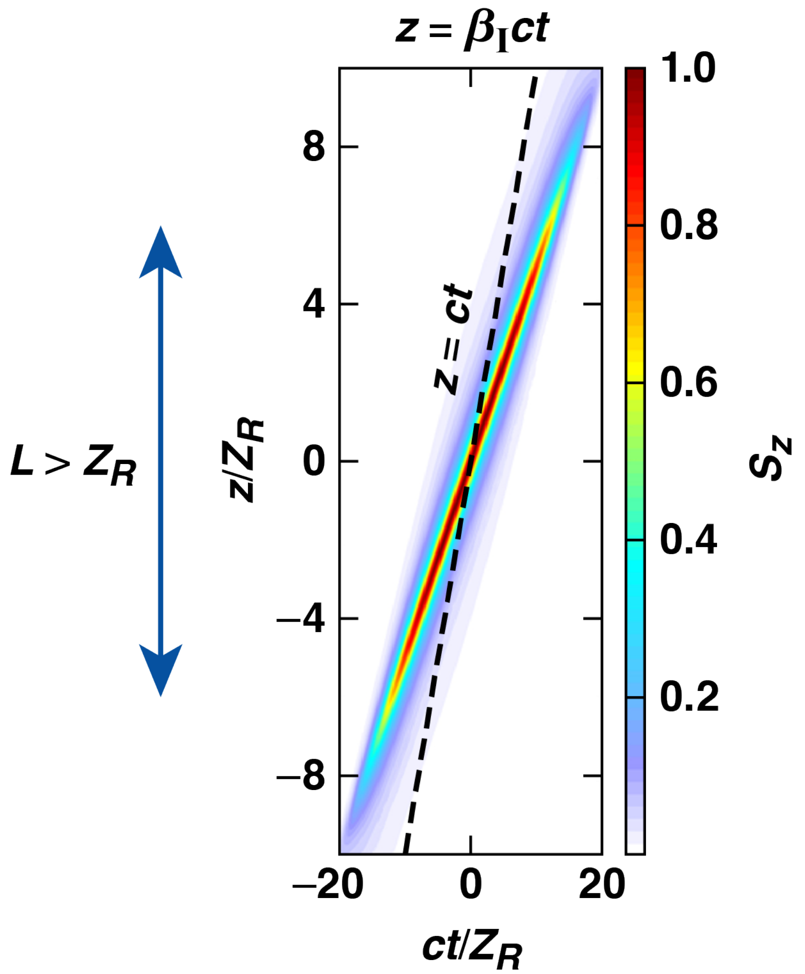
The “flying” focus is a space-time structuring technique that produces a moving focus

A flying focus has three advantageous properties:

- A programable-velocity intensity peak
- A peak intensity that persists for many Rayleigh ranges



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The "flying" focus is a space-time structuring technique that produces a moving focus

A flying focus has three advantageous properties:

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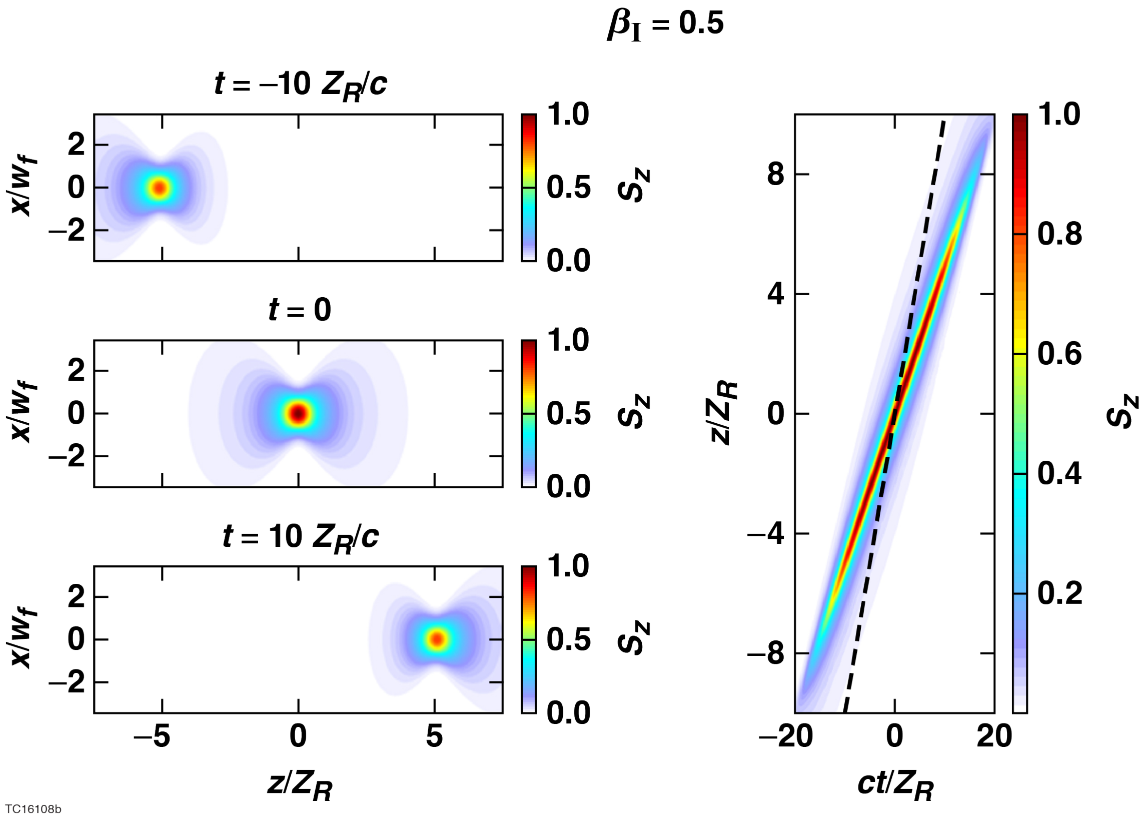

TC16108b

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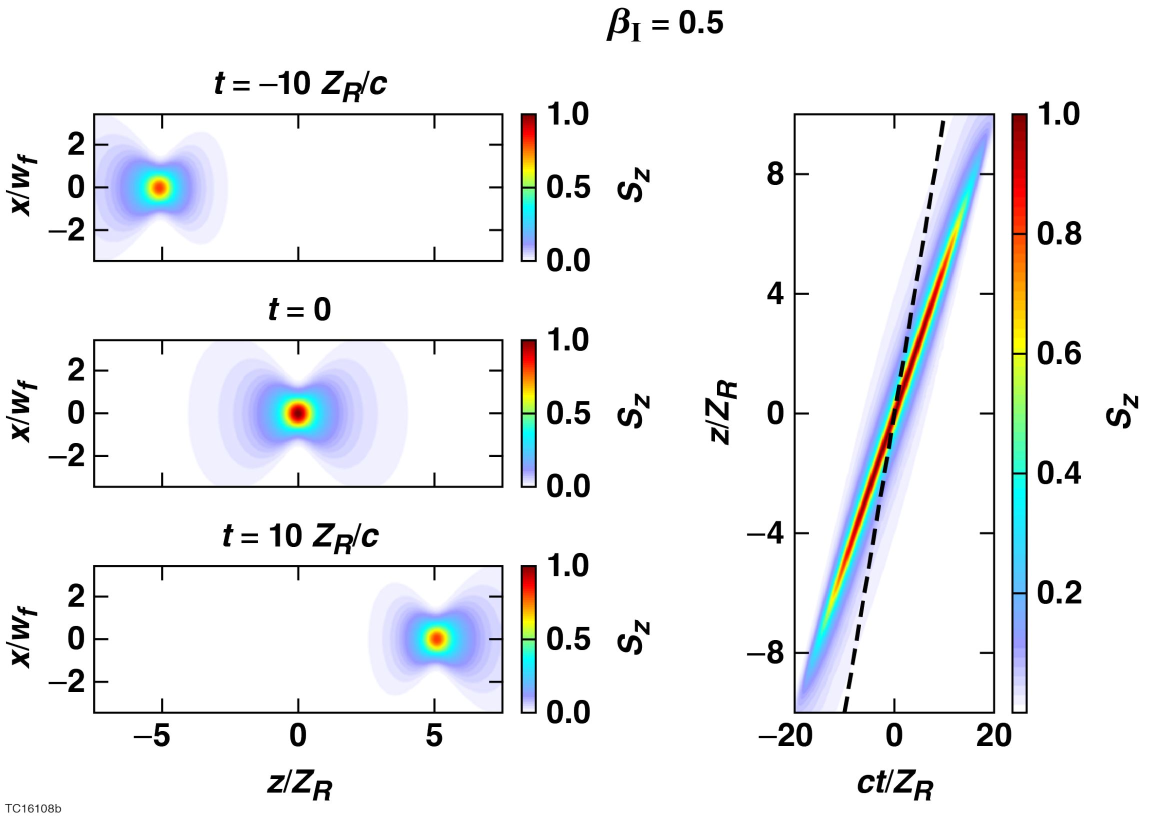
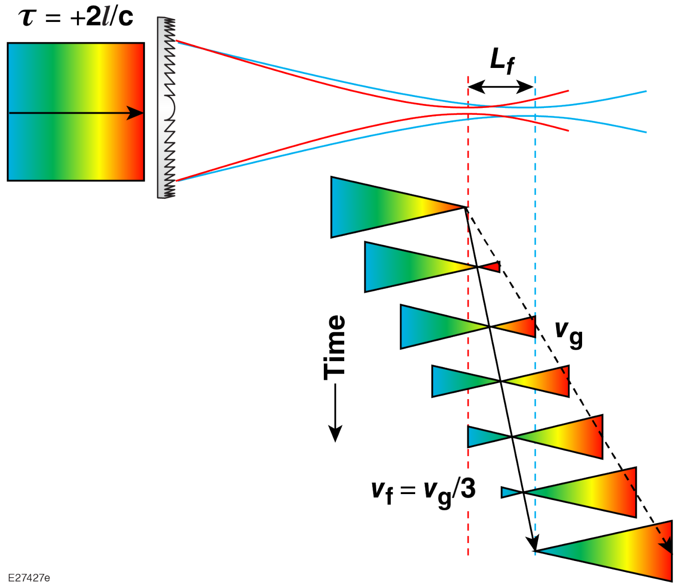


These features can enable or enhance laser-based applications

Several techniques have been developed to produce flying focus pulses, each with advantages and tradeoffs

"Chromatic" flying focus

Diffractive optic and chirped pulse*



J.R. Pierce
NO08 10:42AM

J.P. Palastro
TO08 11:18AM

*Froula *et al.* (2018)

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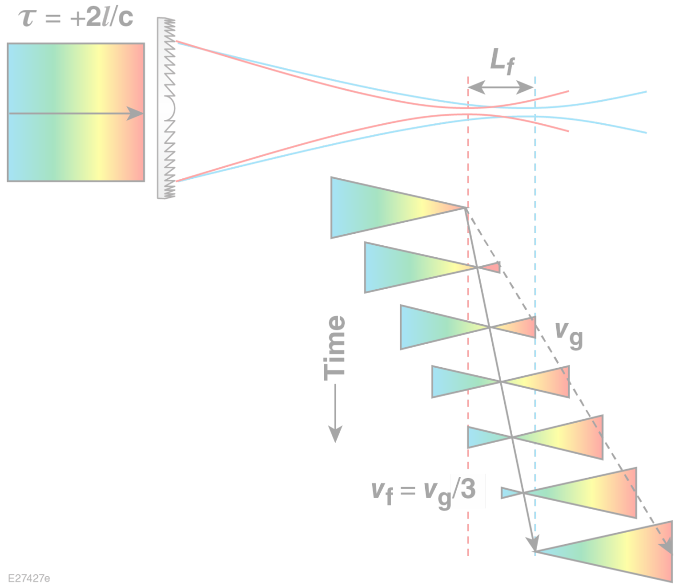
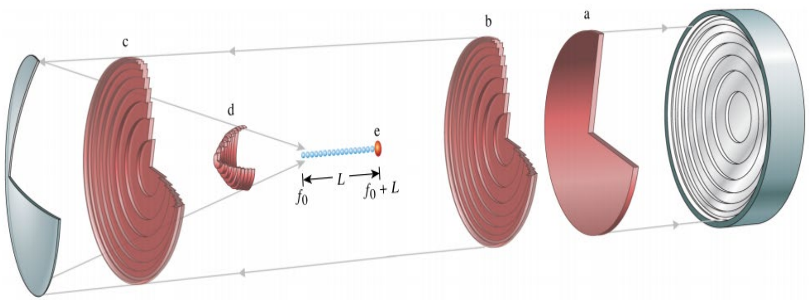


“Achromatic” flying focus

Spherical aberration and a radial delay**



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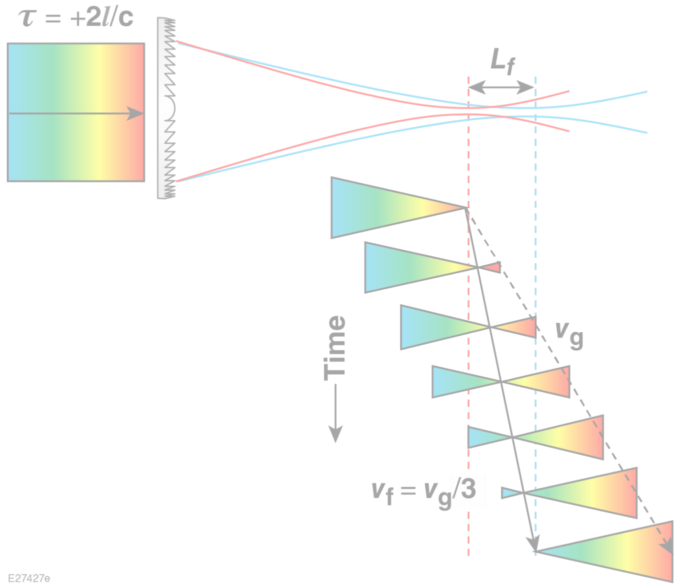

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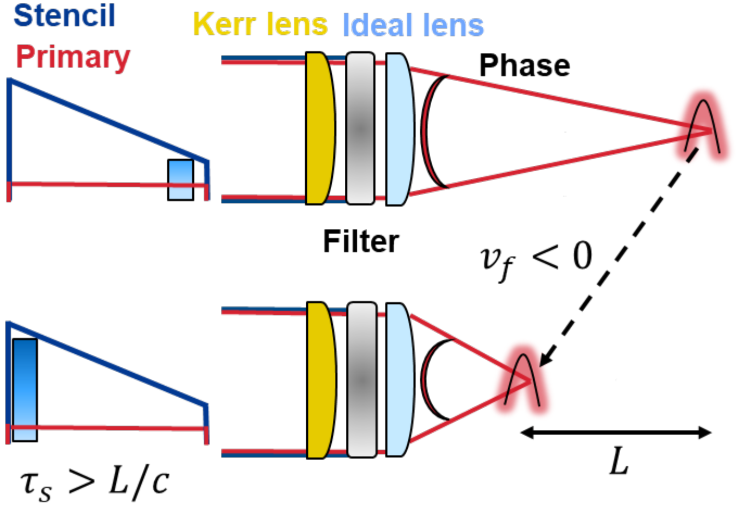
Flying focus X

Kerr lens and cross phase modulation†



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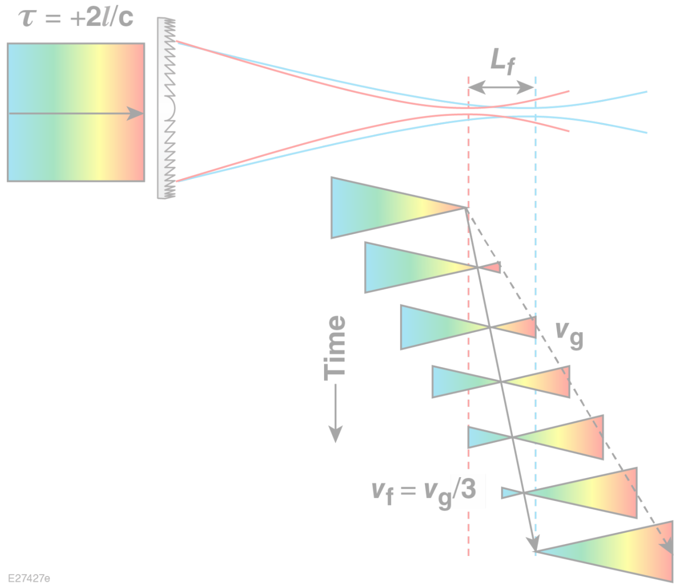

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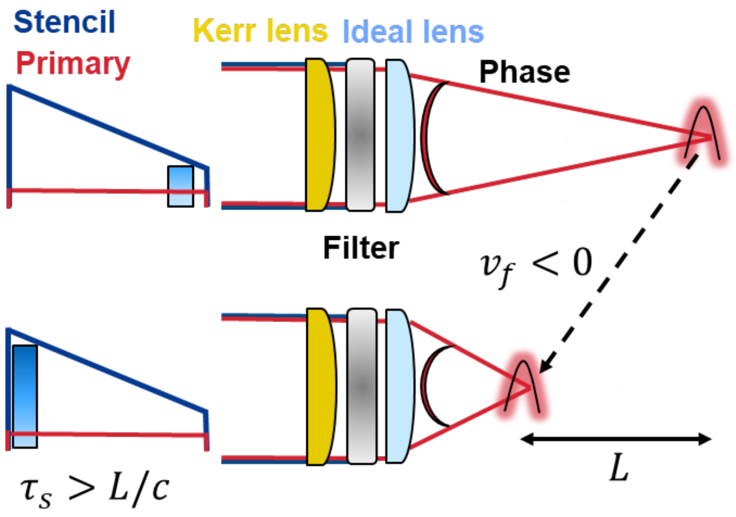

Assessing the extent to which the flying focus can improve applications requires an accurate description of the electromagnetic field

*Froula *et al.* (2018); **Palastro *et al.* (2020); †**Simpson *et al.* (2021)**

Outline

1. Space-time structured laser pulses

2. Exact electromagnetic fields of a flying focus

3. Vacuum laser acceleration

4. Nonlinear Thomson scattering

The Hertz vectors provide a natural, closed form representation for waves driven by dipole sources

Consider magnetic and electric dipole sources,

$$(\nabla^2 - \partial_{tt})\Pi_e \hat{\mathbf{e}} = \delta(\mathbf{r}) e^{-i\kappa t} \qquad (\nabla^2 - \partial_{tt})\Pi_m \hat{\mathbf{m}} = \delta(\mathbf{r}) e^{-i\kappa t}$$

$$\boldsymbol{\Pi}_e = \frac{e^{i\kappa(r-t)}}{4\pi r}\hat{\mathbf{e}} \qquad \boldsymbol{\Pi}_m = \frac{e^{i\kappa(r-t)}}{4\pi r}\hat{\mathbf{m}}$$

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$$\Phi = -\nabla \cdot \mathbf{\Pi}_e$$

$$\mathbf{A} = \partial_t \mathbf{\Pi}_e + \nabla \times \mathbf{\Pi}_m$$

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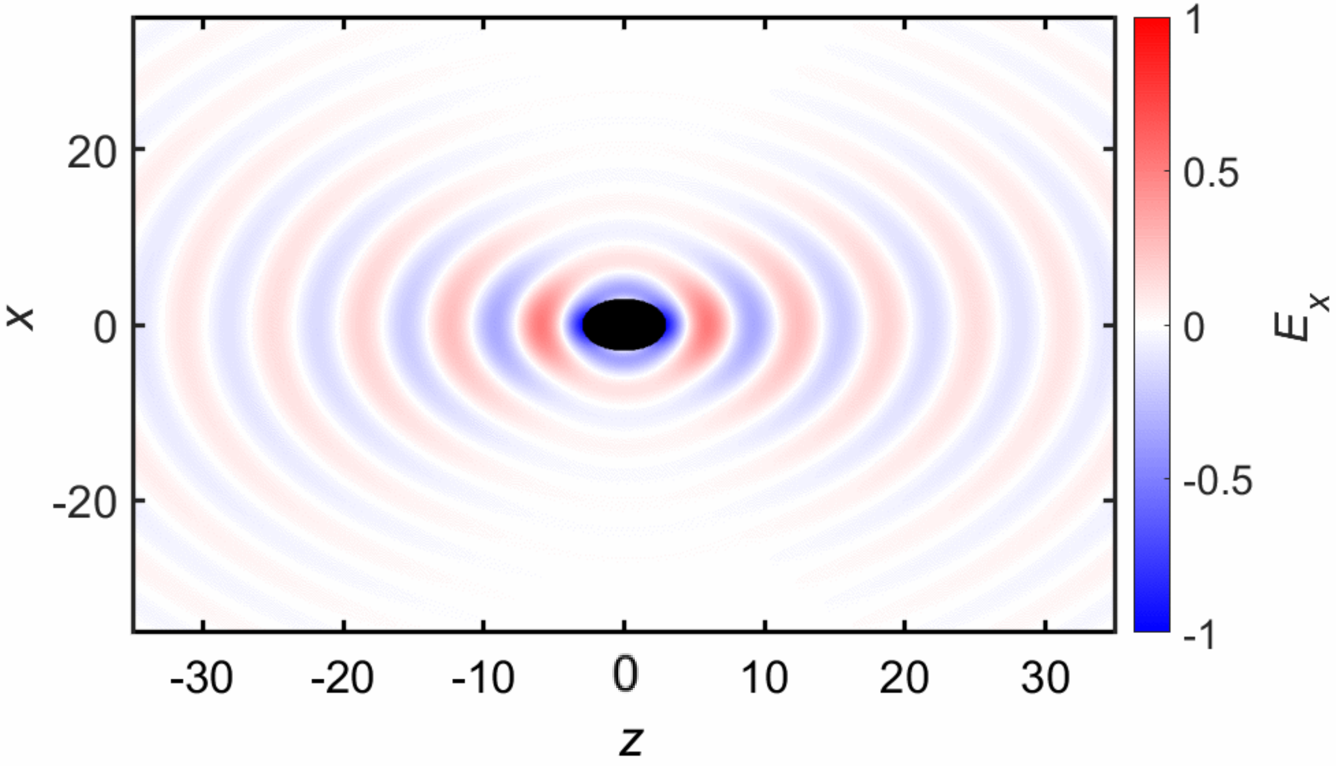
The fields,

$$\mathbf{E} = -\partial_t \mathbf{A} - \nabla \Phi$$

$$\mathbf{B} = \nabla \times \mathbf{A}$$

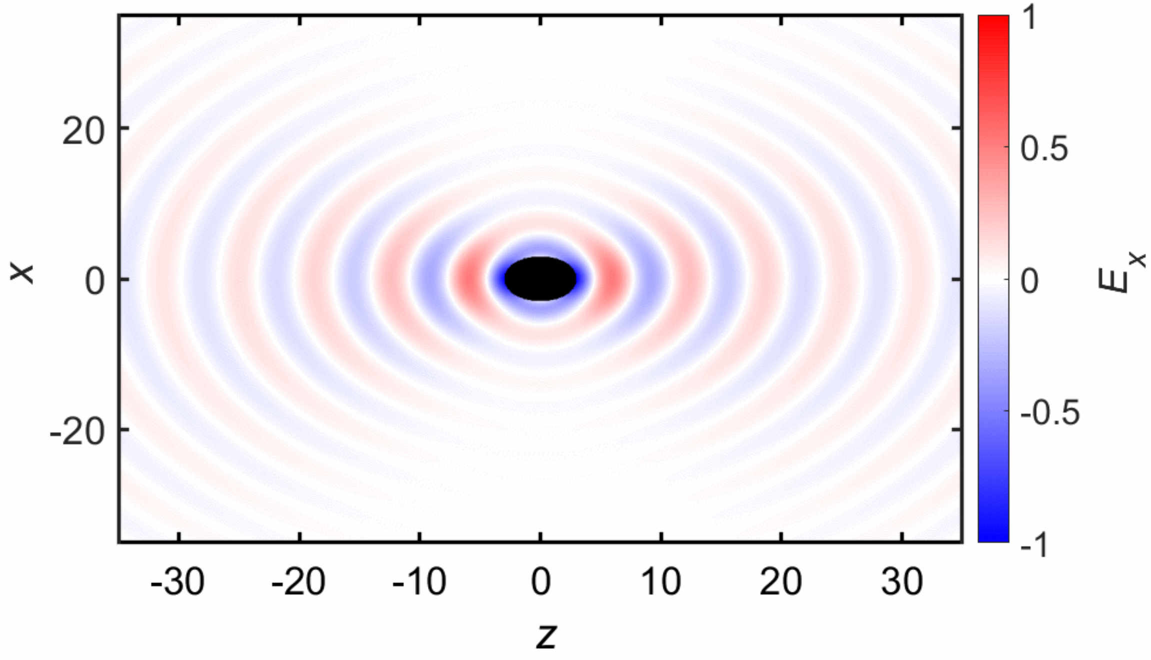


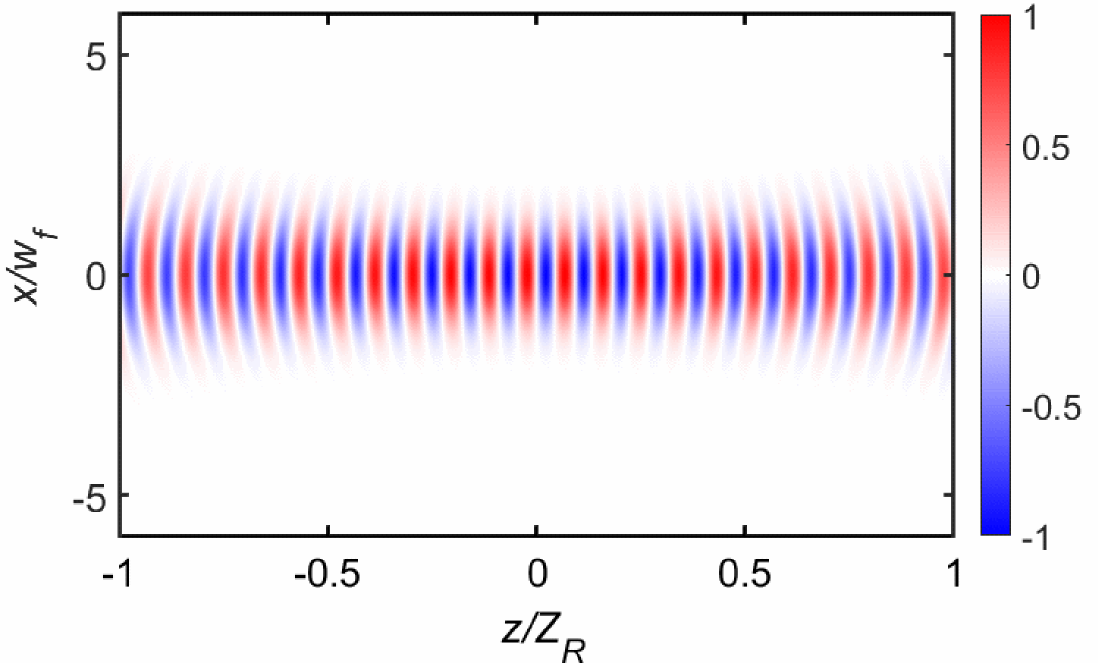
The exact fields of a flying focus can be calculated by combining the complex source point method with a Lorentz transformation

Solutions to Maxwell's equations remain solutions under coordinate translations along the real or *imaginary* axis

$$z \rightarrow z - iZ_R$$

Spherical wave → Focused continuous wave





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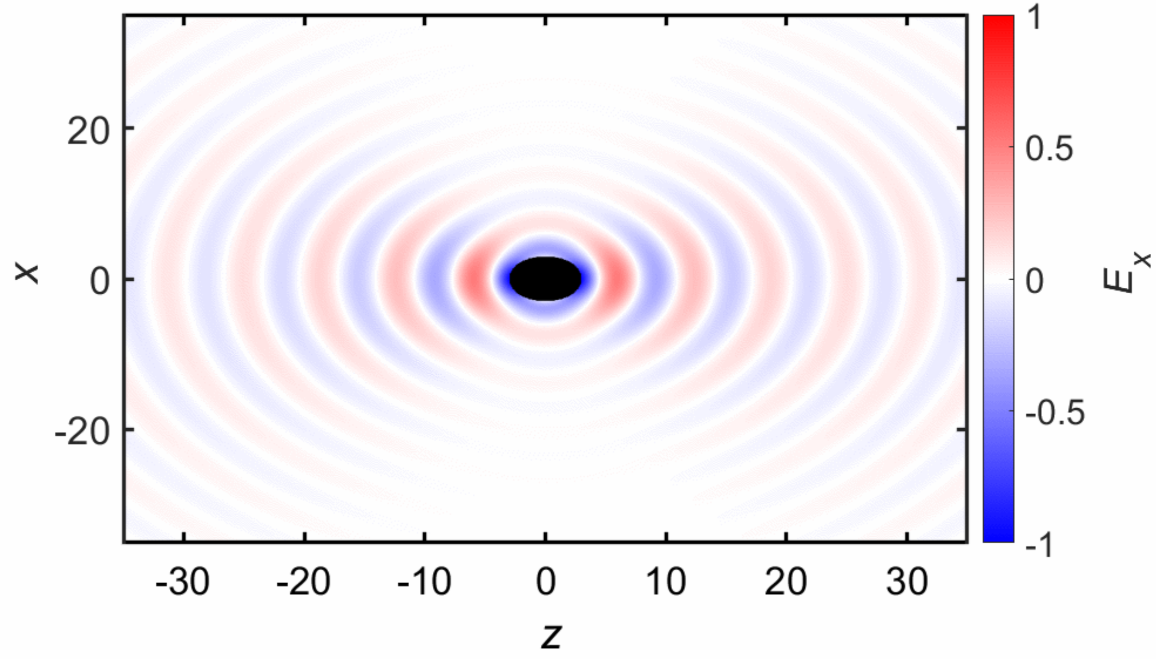

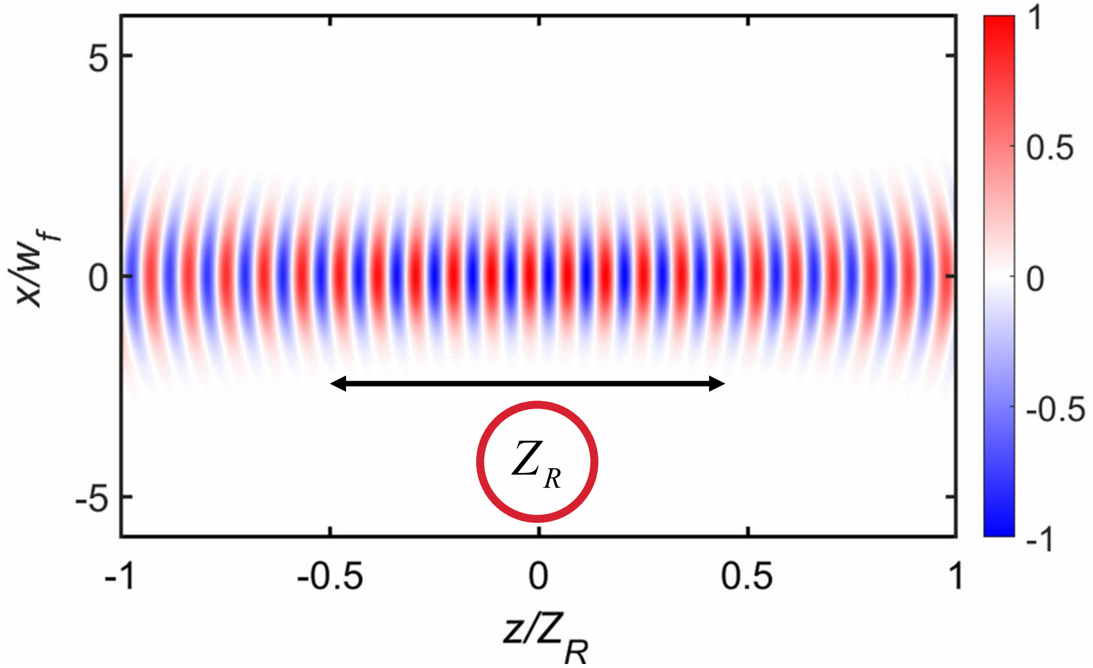

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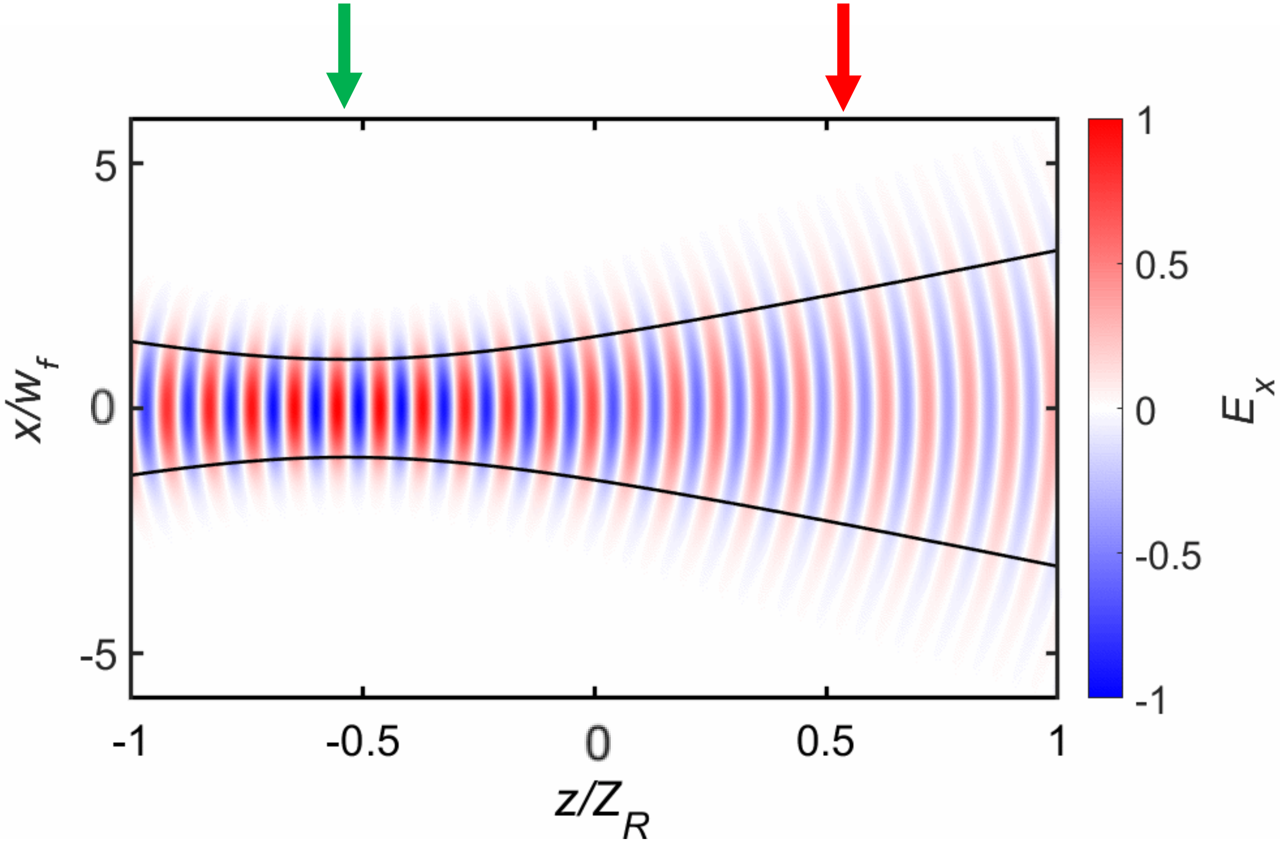
Maxwell's equations are invariant under a Lorentz coordinate transformation

$$t' = \gamma(t - \beta z)$$
$$z' = \gamma(z - \beta t) - iZ_R$$

β is the velocity of the focus

with the 4-potential transformation

$$\Phi = \gamma(\Phi' + \beta A_z')$$
$$A_z = \gamma(A_z' + \beta\Phi')$$



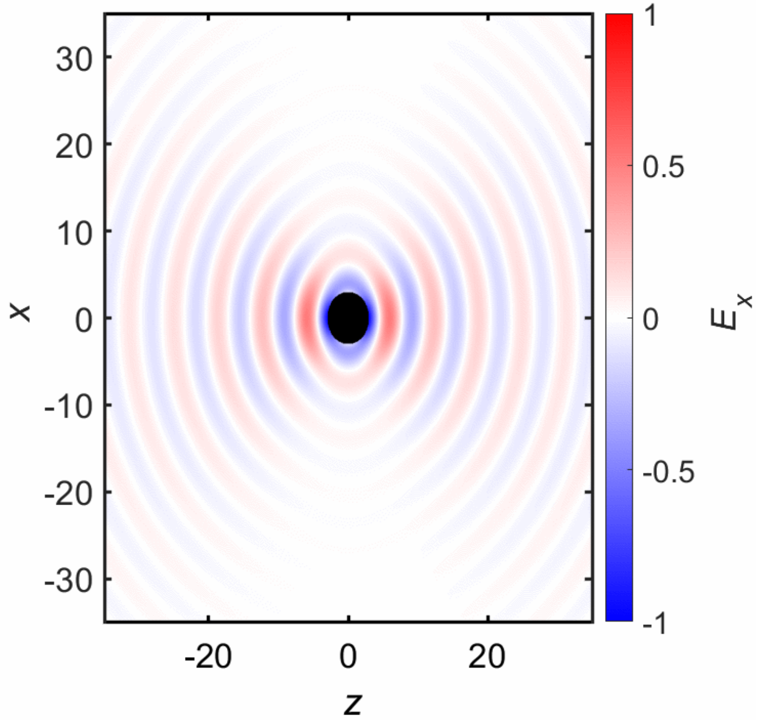
The resulting fields are a flying focus

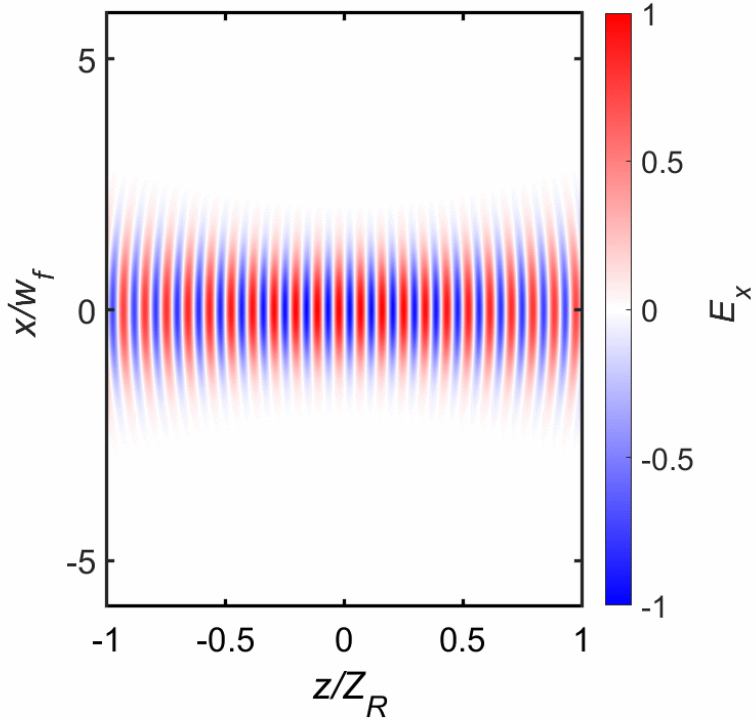
The exact fields of a flying focus can be calculated by combining the complex source point method with a Lorentz transformation

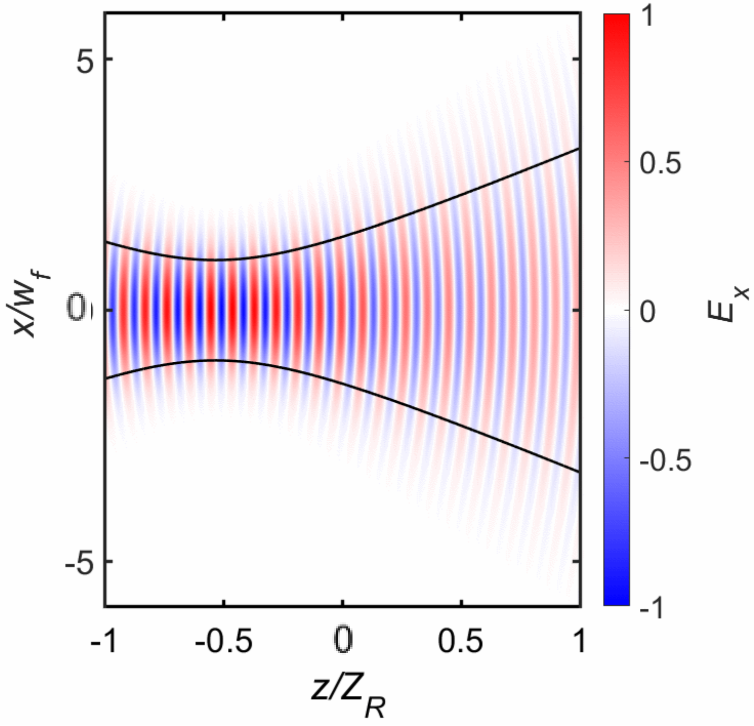
Spherical wave → Focused wave → Flying focus

Complex coordinate translation

Lorentz transformation

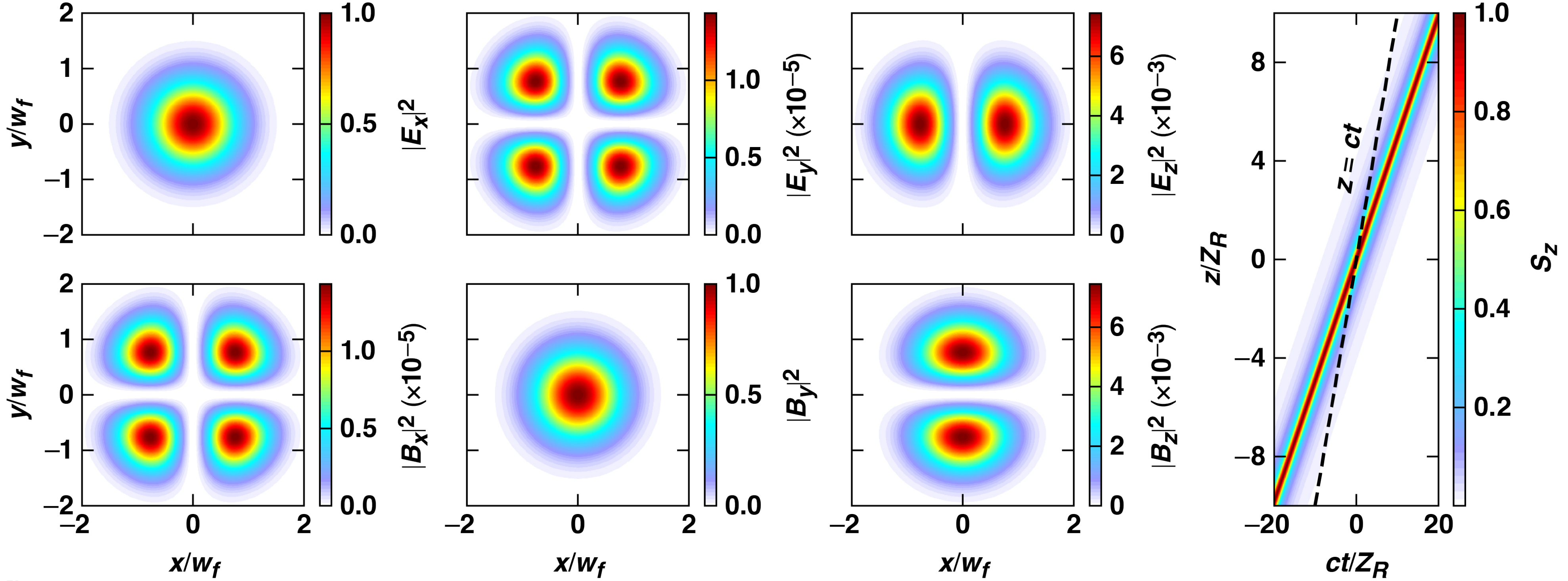






This method generates **all six components** of the electromagnetic field for arbitrary polarization and orbital angular momentum

Forward subluminal ($\beta_I = 0.5$), linearly polarized ($\hat{\mathbf{x}}$), $\ell = 0$



Complete field expressions enable calculations of vacuum acceleration and nonlinear Thomson scattering in a flying focus

Outline

1. Space-time structured laser pulses

2. Exact electromagnetic fields of a flying focus

3. Vacuum laser acceleration

4. Nonlinear Thomson scattering

Lawson-Woodward Theorem: The net energy gain for an electron in a laser pulse is zero

For net energy gain, one of the assumptions of the LWT needs to be violated:

1. No static fields

2. Infinite interaction region

3. No non-linear effects (ponderomotive)

Esarey et al., Phys. Rev. E 52, 5443 (1995)

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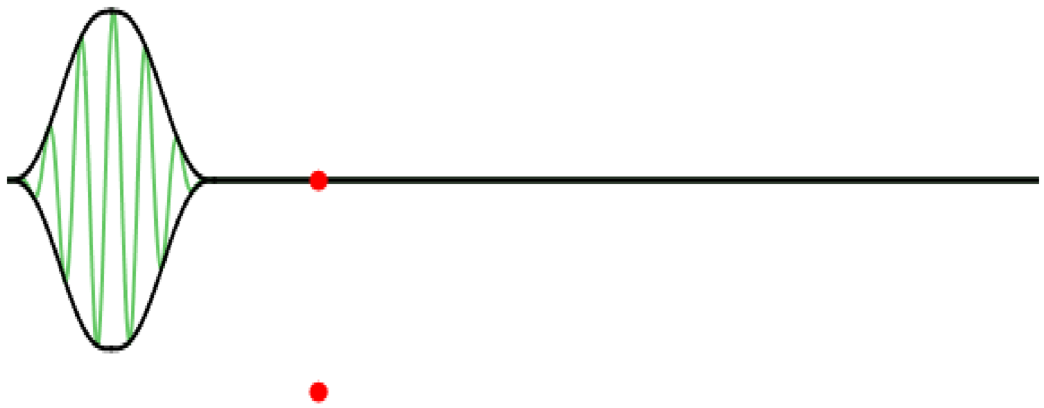
Standard Focus

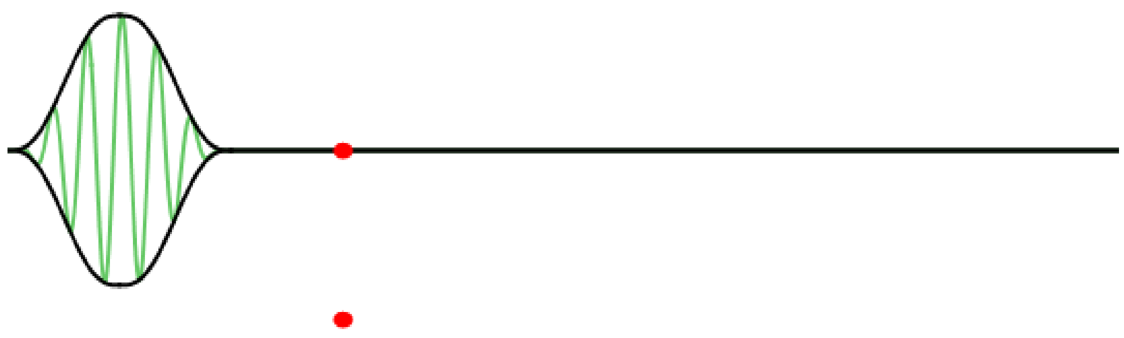


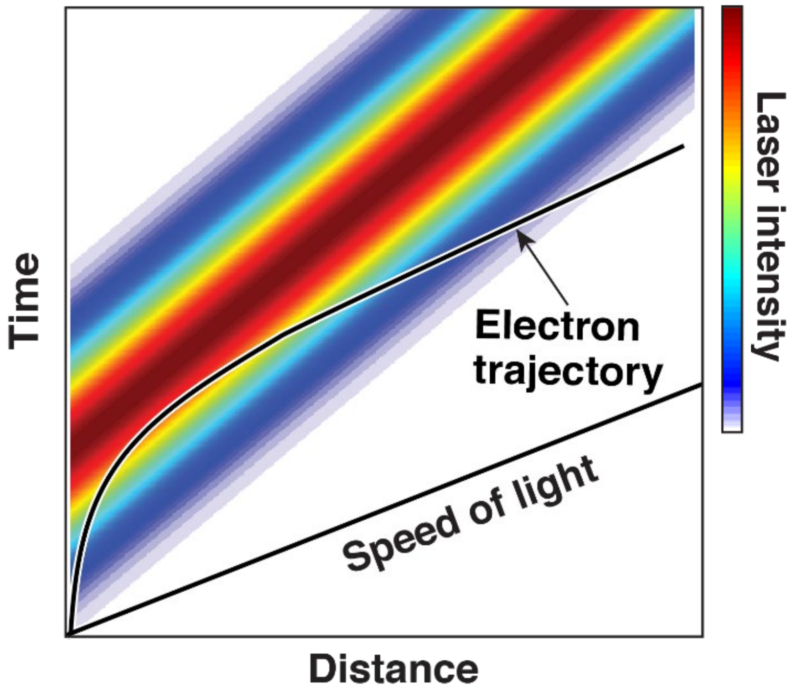
Electrons cannot outrun the ponderomotive force of an intensity peak moving at c

The flying focus enables enables a novel mechanism for vacuum acceleration

Electrons can outrun the ponderomotive force of an intensity peak moving at $v_f < c$

Flying Focus





The electron retains its momentum when the ponderomotive force is strong enough to accelerate the electron beyond the flying focus velocity

In the Lorentz frame of the intensity peak, the energy gain corresponds to a reflection from the ponderomotive potential

In the intensity peak frame, the ponderomotive potential is time-independent, implying the electron energy is conserved: $\gamma_i = \gamma_f$

There are two ways this can occur

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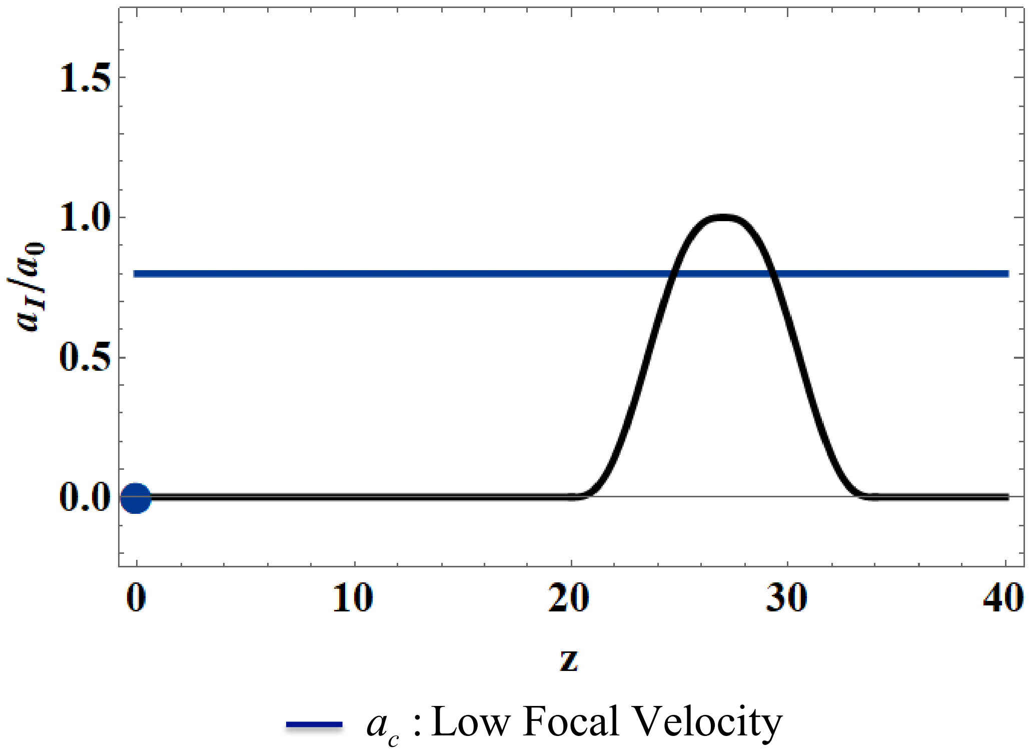
There are two ways this can occur

1. $v_f = -v_i$

   The initial kinetic energy of the electron is insufficient to overcome the ponderomotive potential hill



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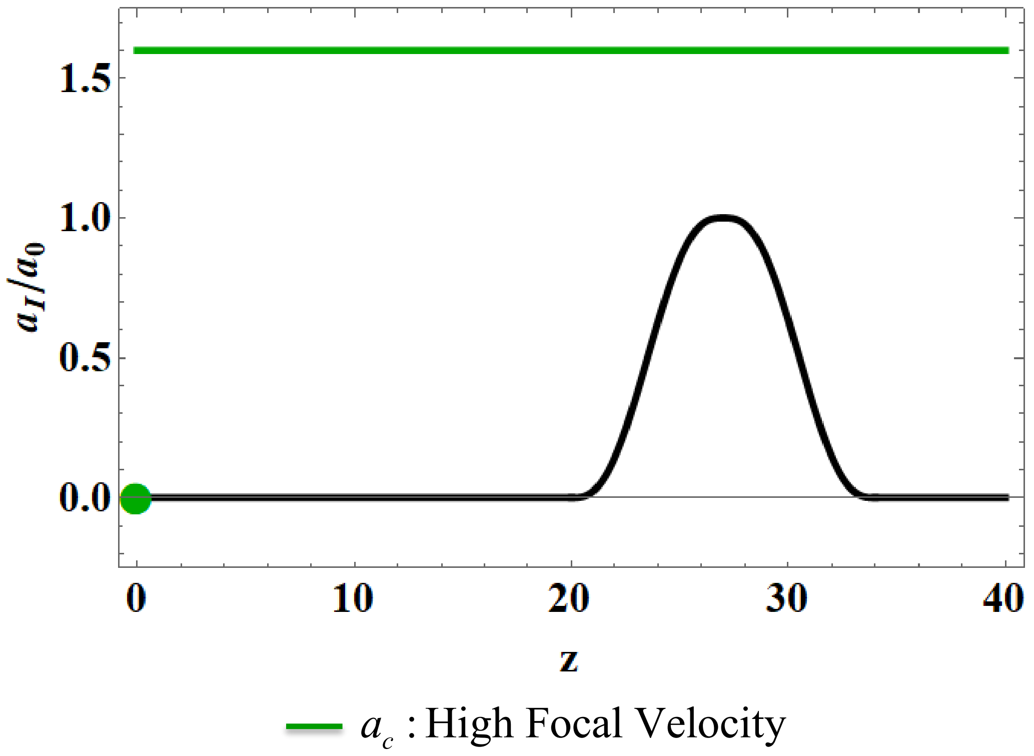
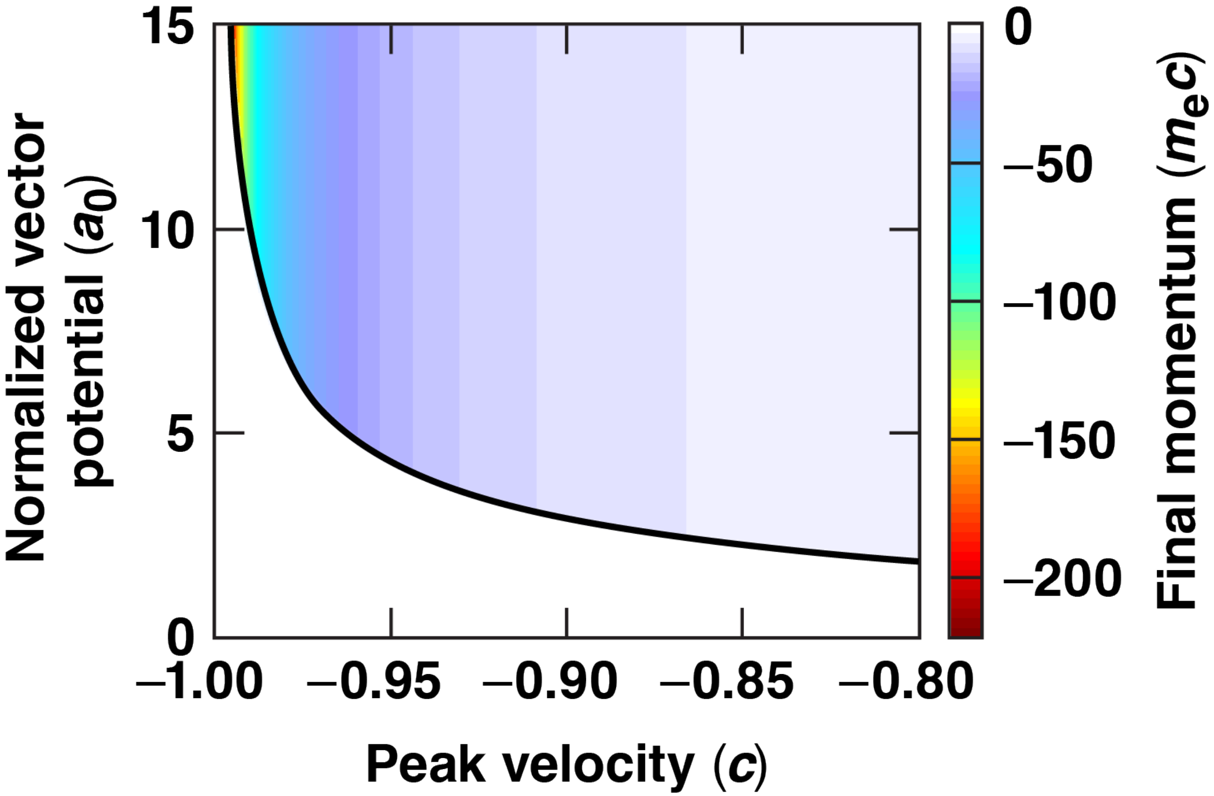


The flying focus can accelerate electrons in the opposite direction of the laser pulse and its phase fronts



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This backwards acceleration enables a unique configuration of nonlinear Thomson scattering

D. Ramsey *et al.* Phys. Rev. E (2020)

Outline

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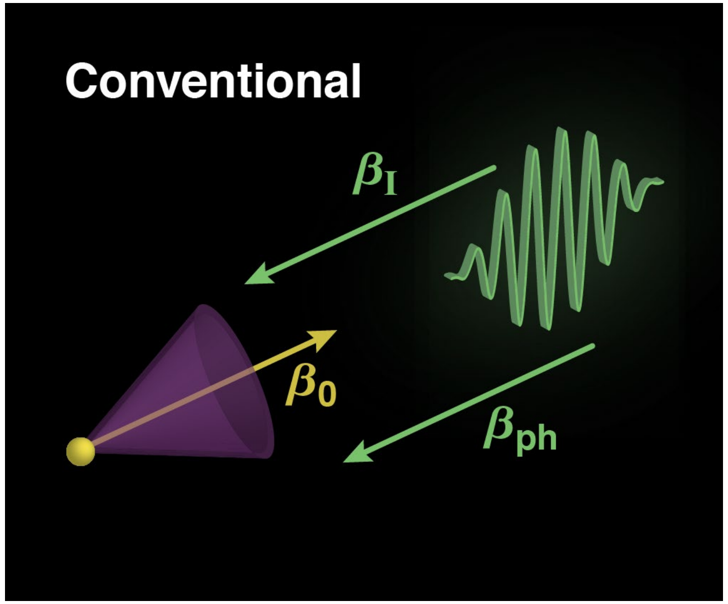
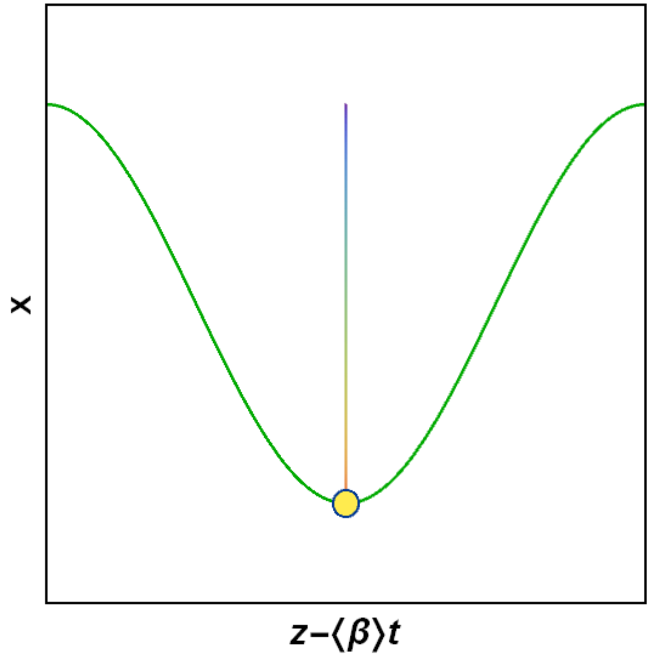
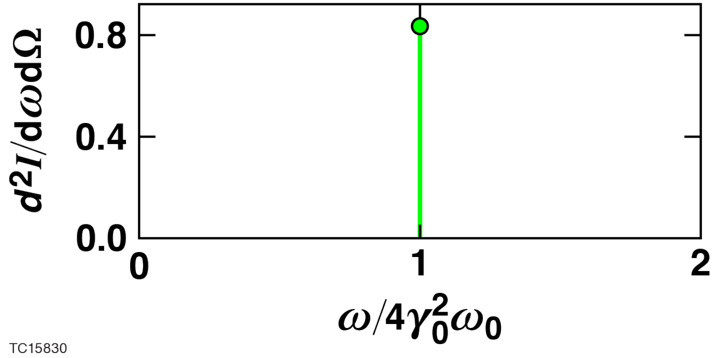
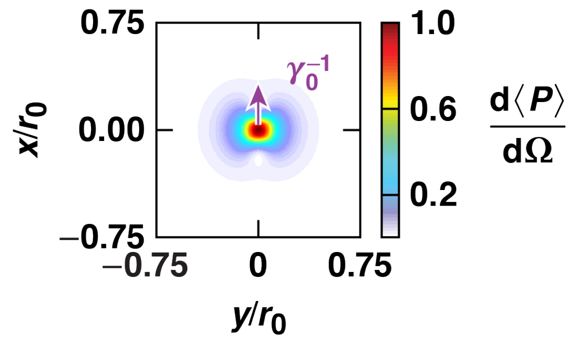
When a relativistic electron collides with a counter-propagating laser pulse, it radiates light at an upshifted frequency

Low intensity ($I < 2\times10^{18}$ W/cm^2, $a_0<1$)





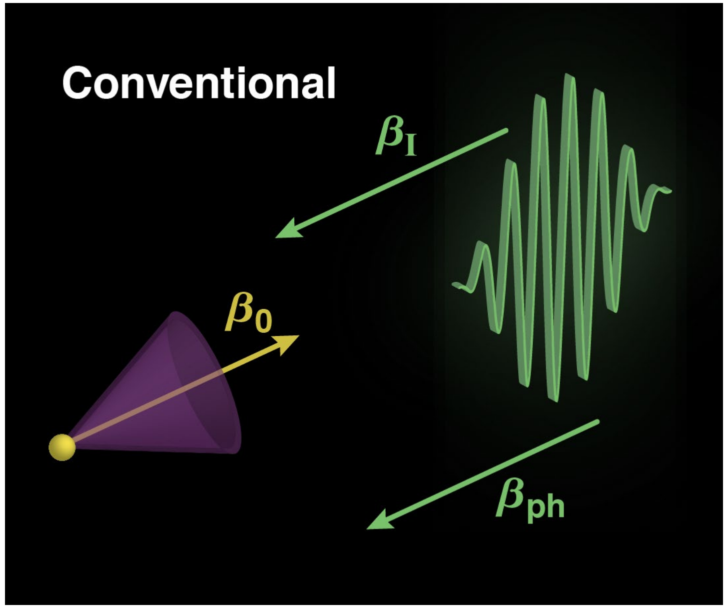


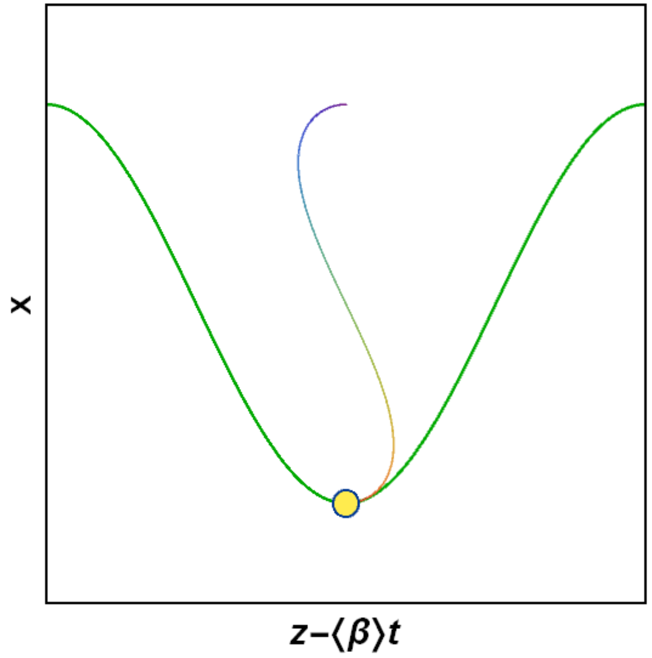


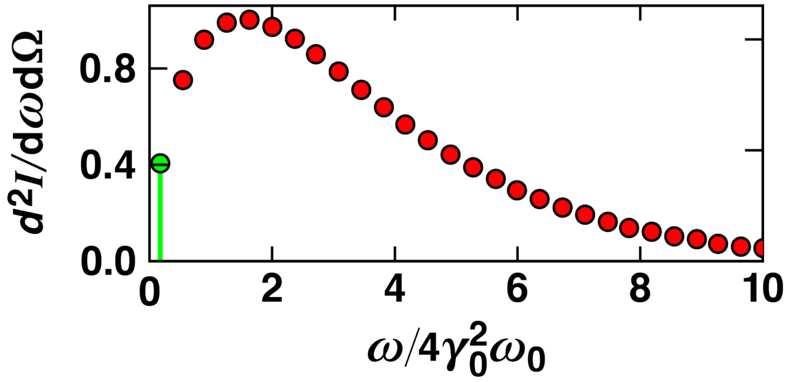
Linear oscillations result in emission at a single frequency and into an angle determined by the electron energy

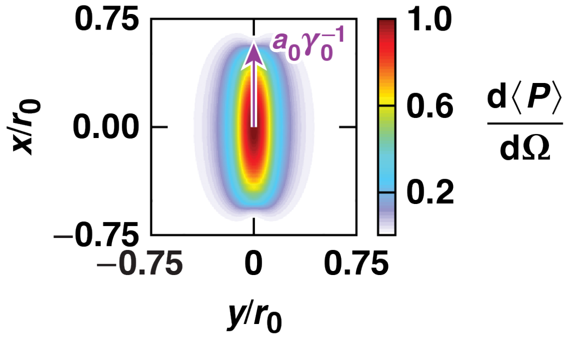
At high intensity, the electron motion becomes nonlinear

High intensity (I > 2×10^{18} W/cm^2, $a_0>1$)





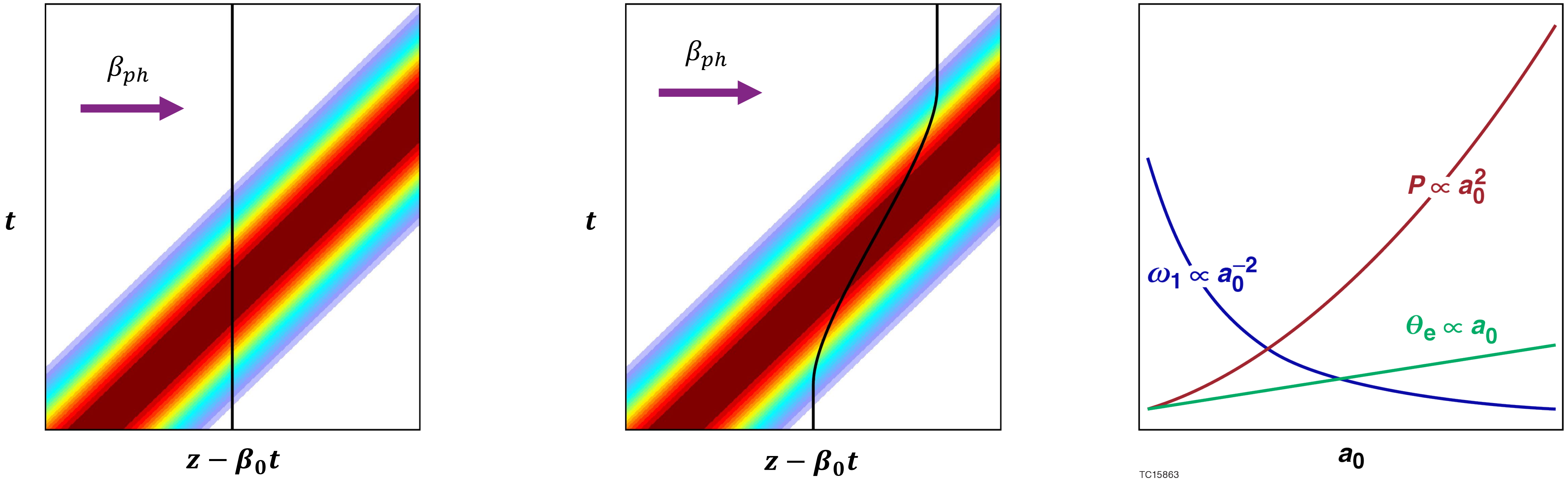




The nonlinear motion results in broadband emission into several harmonics and into a much wider cone

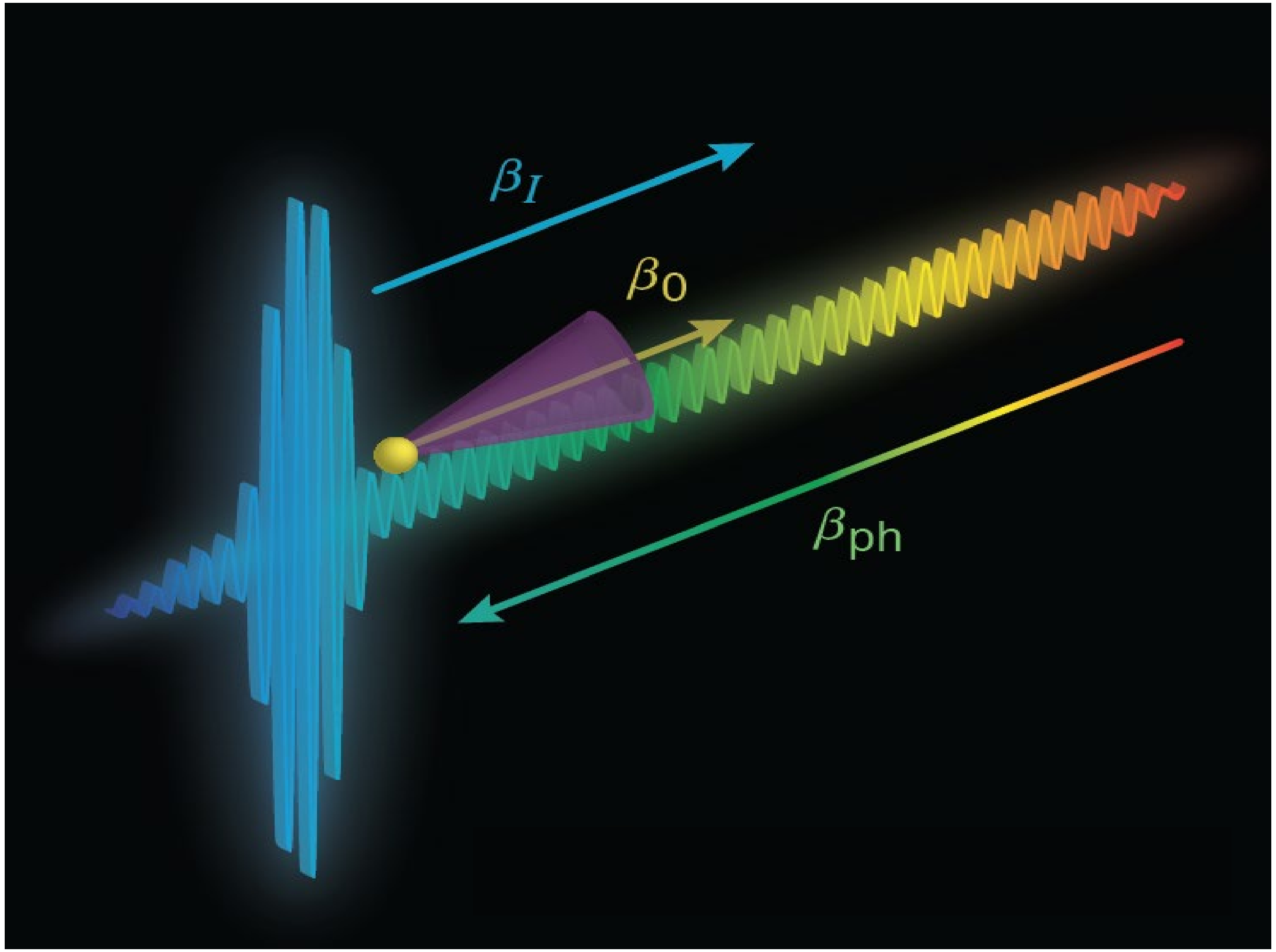
In a high-intensity laser pulse, electrons undergo an appreciable ponderomotive deceleration, which modifies the radiation properties

Low intensity (a_0<1) High intensity (a_0>1)



A higher intensity provides more radiated power, but significantly redshifts the harmonic frequencies and increases the emission angle

In nonlinear Thomson scattering with ponderomotive control (NPC), a flying focus is used to ponderomotively accelerate the electrons



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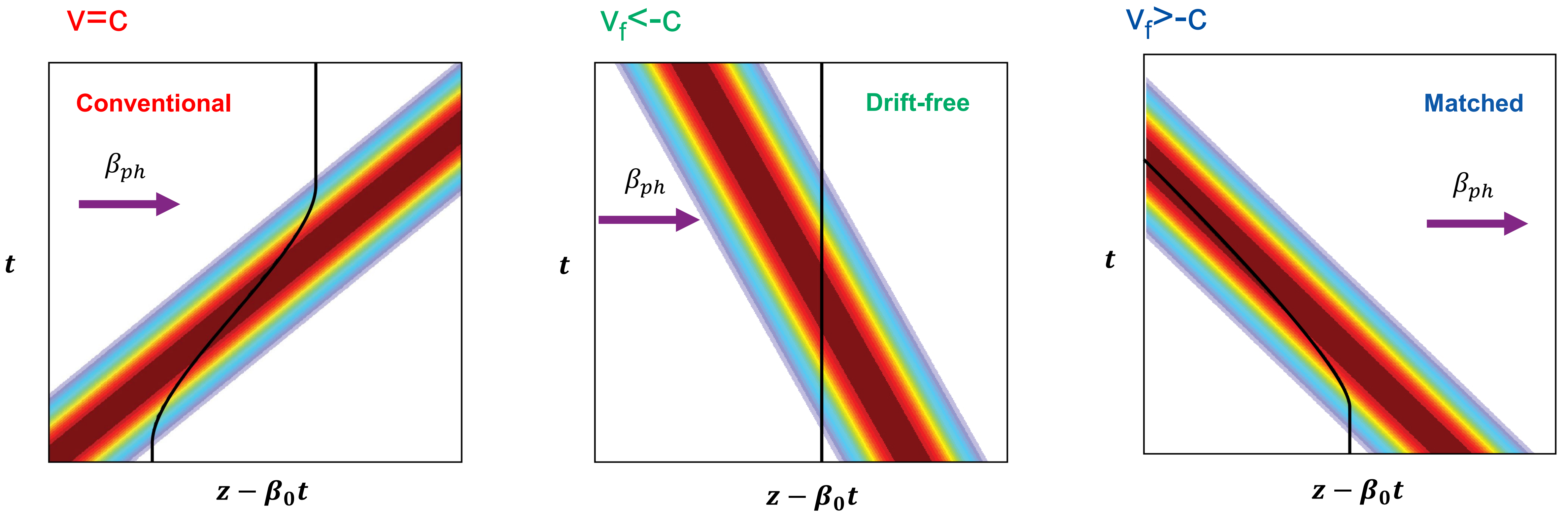
The programmable velocity of the intensity peak provides control over the electron trajectory

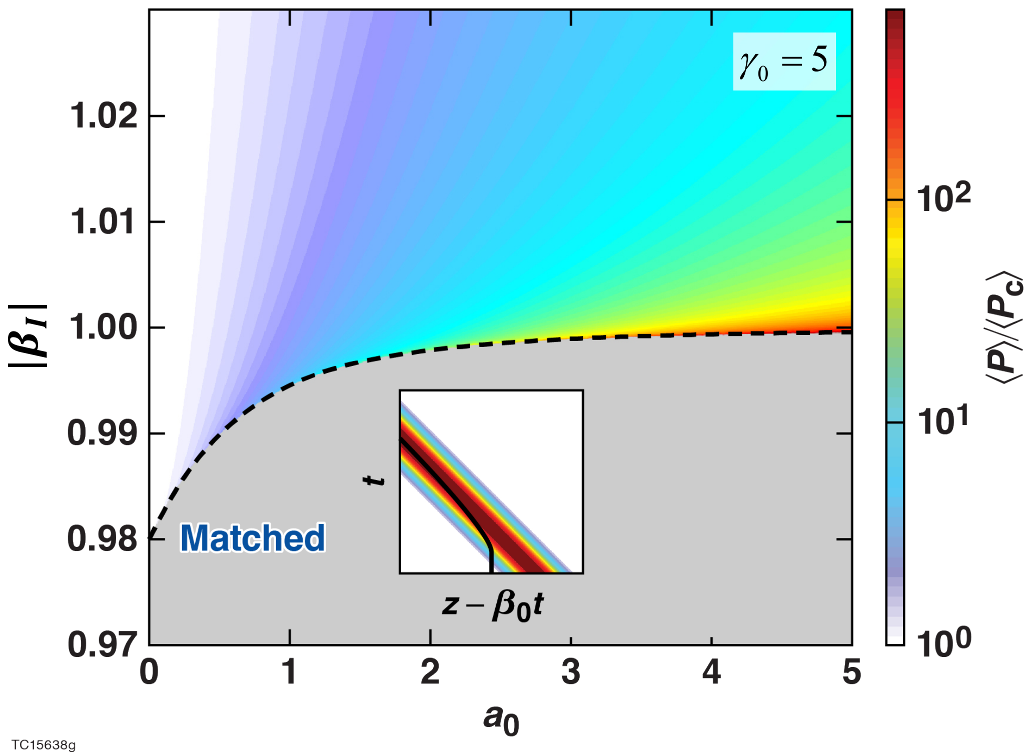


A counter-travelling intensity peak decelerates the electron

A **super**luminal, co-travelling intensity peak leaves the electron velocity unaffected

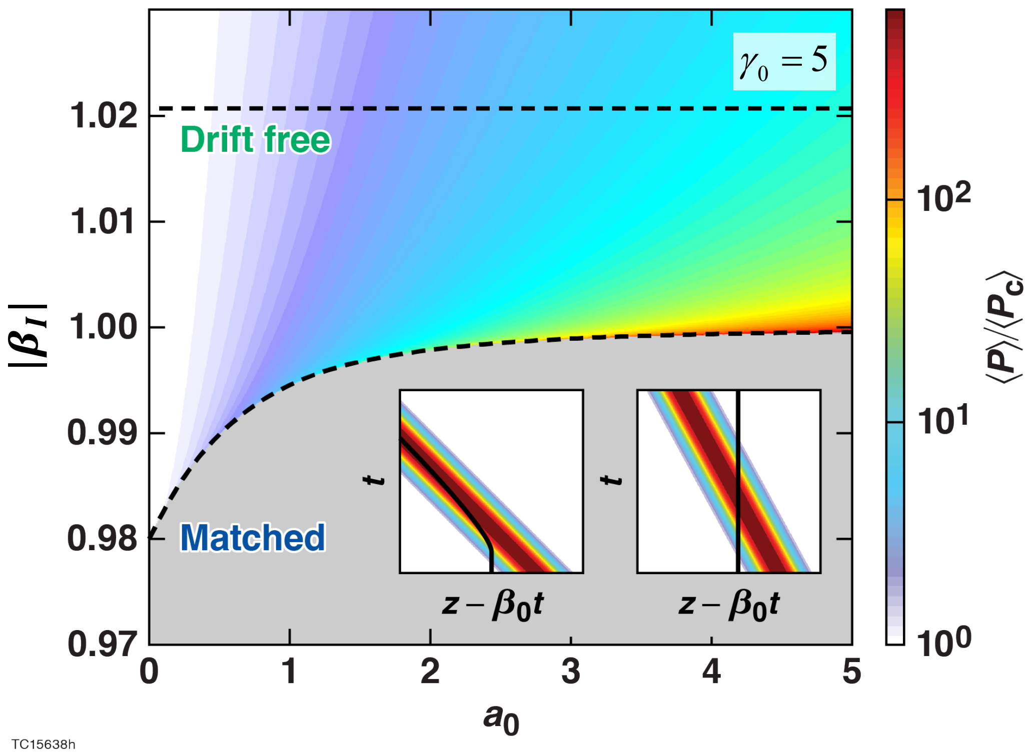
A **sub**luminal, co-travelling intensity peak accelerates the electron up to its velocity

A flying focus can increase the power radiated in nonlinear Thomson scattering by orders of magnitude while decreasing the emission angle



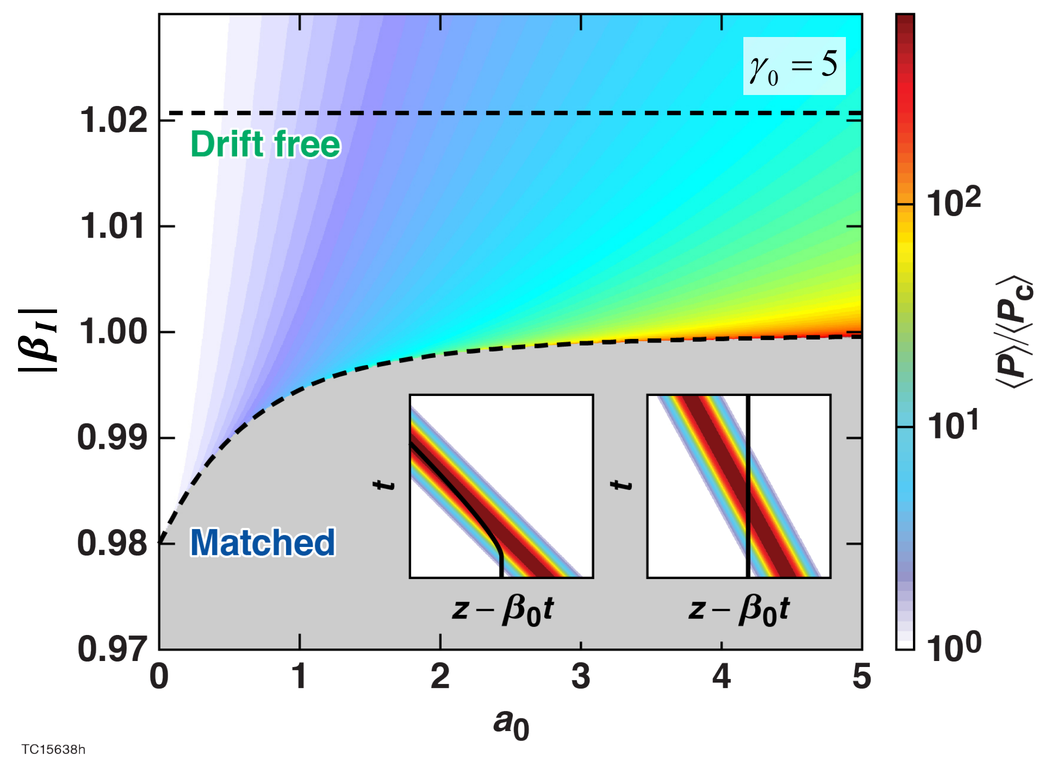
TC15638g

A flying focus can increase the power radiated in nonlinear Thomson scattering by orders of magnitude while decreasing the emission angle

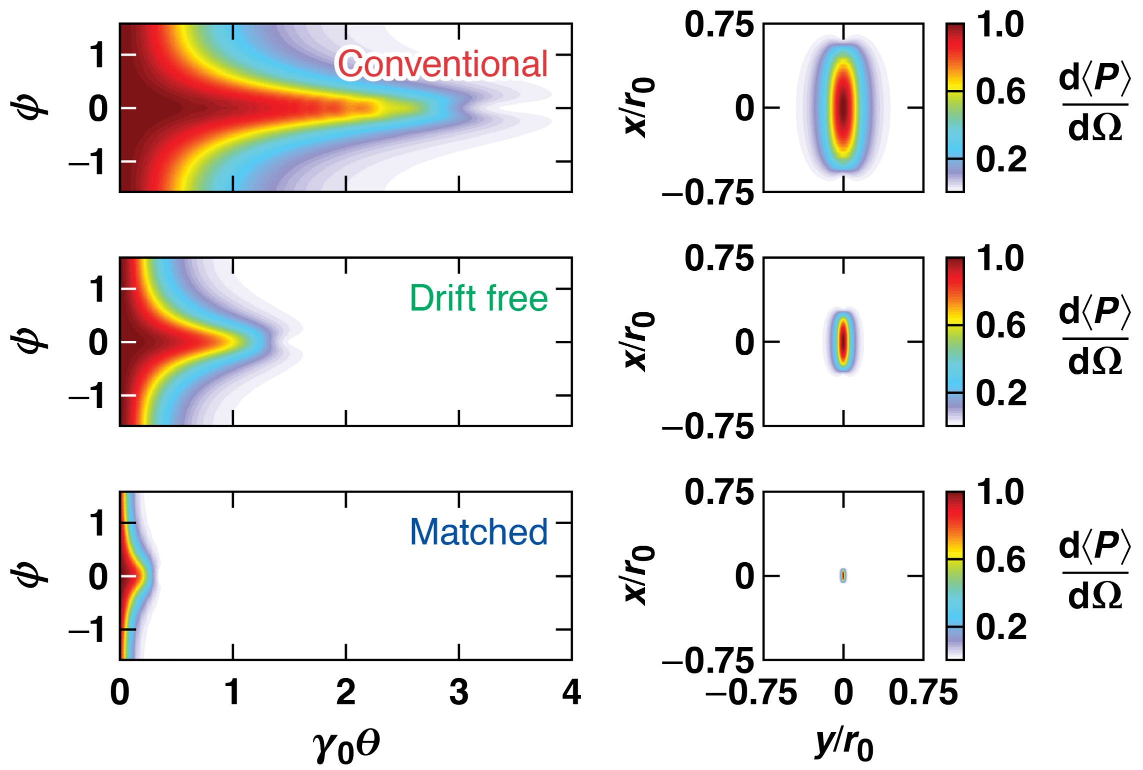


TC15638h

A flying focus can increase the power radiated in nonlinear Thomson scattering by orders of magnitude while decreasing the emission angle



TC15638h



TC15639b

Both drift-free and matched NLTS result in more radiated power into a smaller angle than conventional NLTS

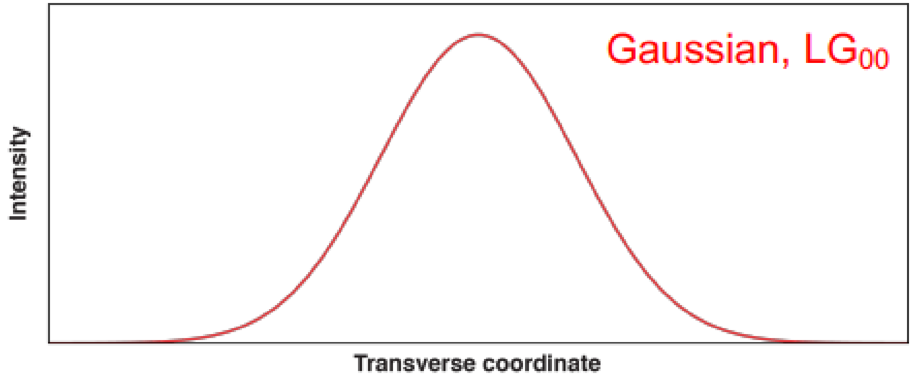
Space-time structured laser pulses enable novel regimes of direct laser acceleration and nonlinear Thomson scattering

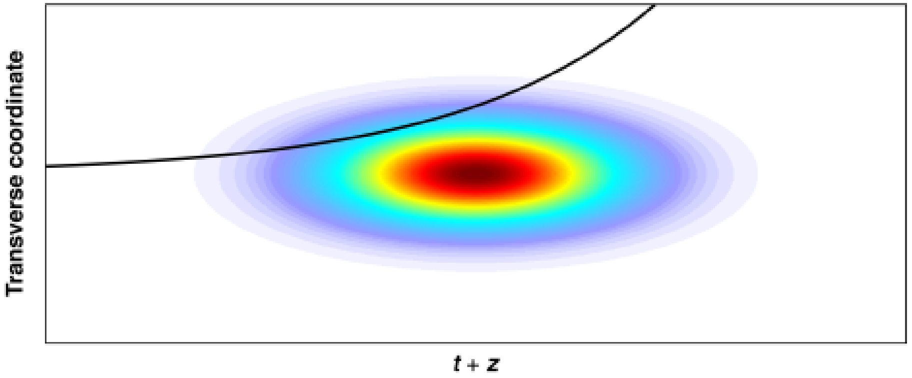
- Flying focus pulses feature a programmable-velocity intensity peak that travels distances much greater than a Rayleigh range while maintaining a near-constant profile
- The exact fields of a flying focus pulse can be derived by Lorentz transforming a pulse with a stationary focus
- A flying focus pulse can impart net energy and accelerate electrons to relativistic momenta either parallel or antiparallel to the phase velocity
- Accelerating electrons against the phase velocity enables a novel regime of nonlinear Thomson scattering that increases the radiated power by orders of magnitude

The flying focus offers additional control over the radiation properties of nonlinear Thomson scattering

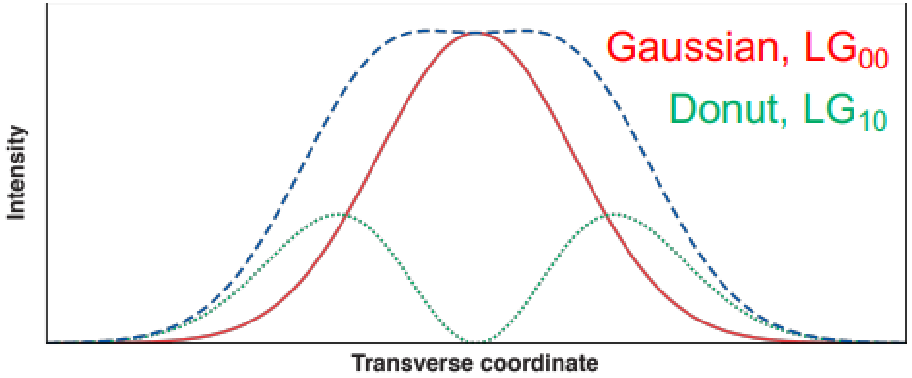
A transverse ponderomotive well eliminates transverse ponderomotive scattering

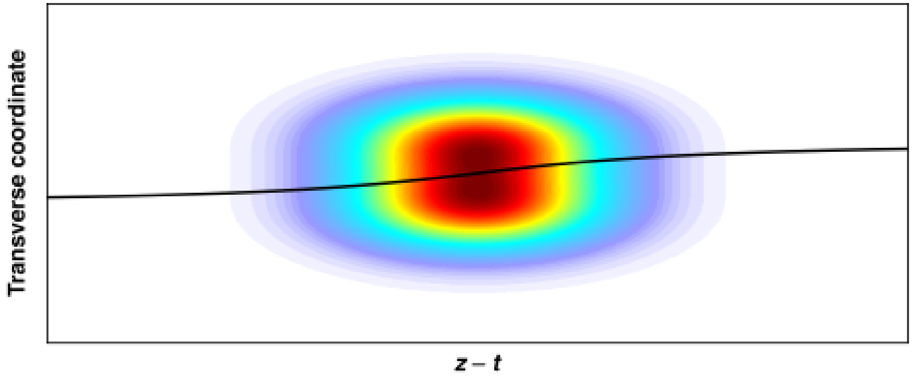
Conventional NLTS





NPC

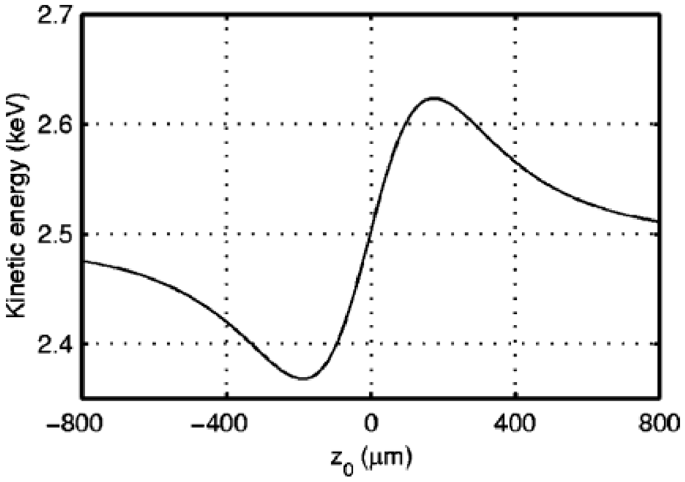


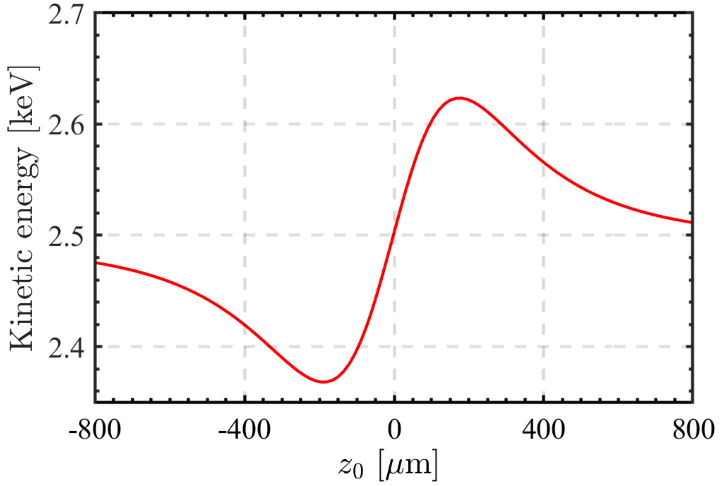


The accuracy of the derived laser fields and pusher was benchmarked against Quesnel and Mora (1998)

Demonstration of net energy gain (loss) due to axial ponderomotive force depending on initial position

$$a_0 = 0.30$$





Interaction of relativistic laser pulse with relativistic electron

$$a_0 = 3.41$$