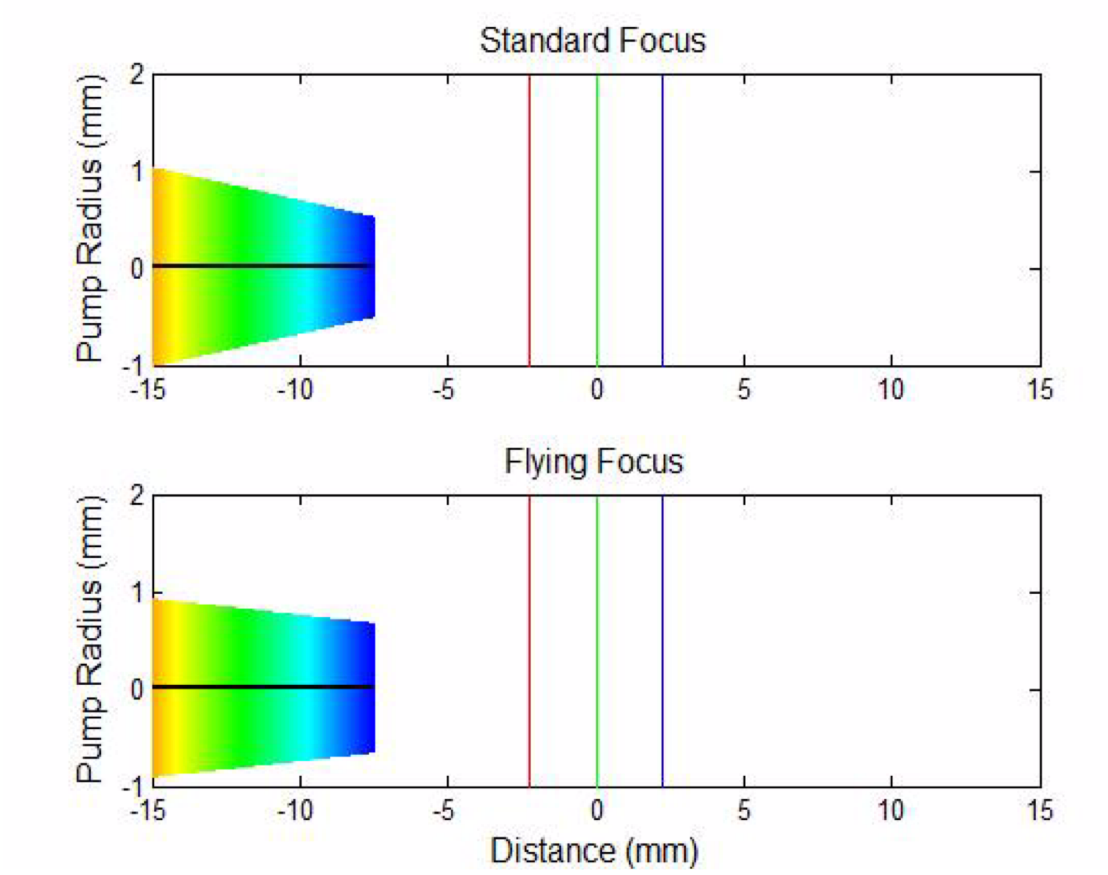
Nonlinear Self-Focusing of Flying Focus Pulses



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Summary

Self-focusing can reduce the effective duration of flying focus pulses

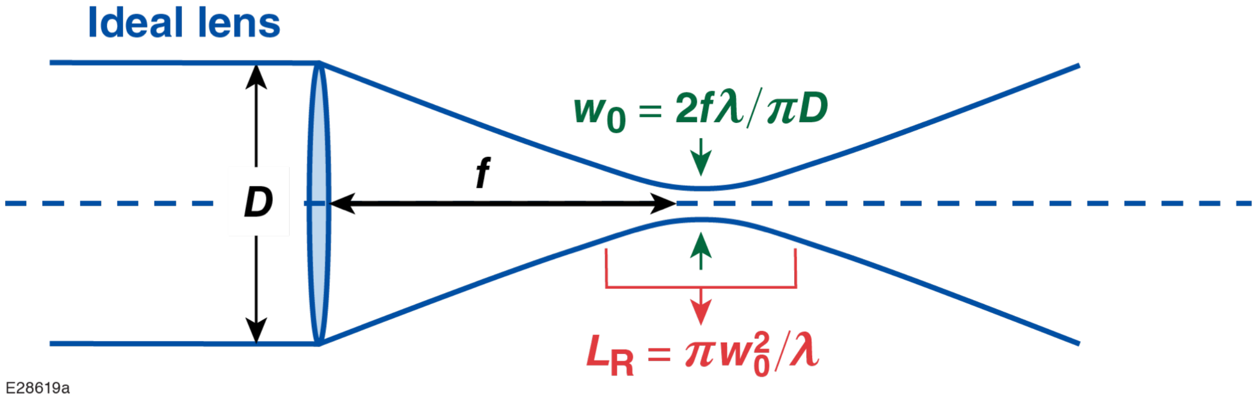
- A “flying focus,” a chirped pulse focused through a chromatic lens, exhibits a high-intensity peak that can travel at an arbitrary velocity over distances much greater than the Rayleigh range

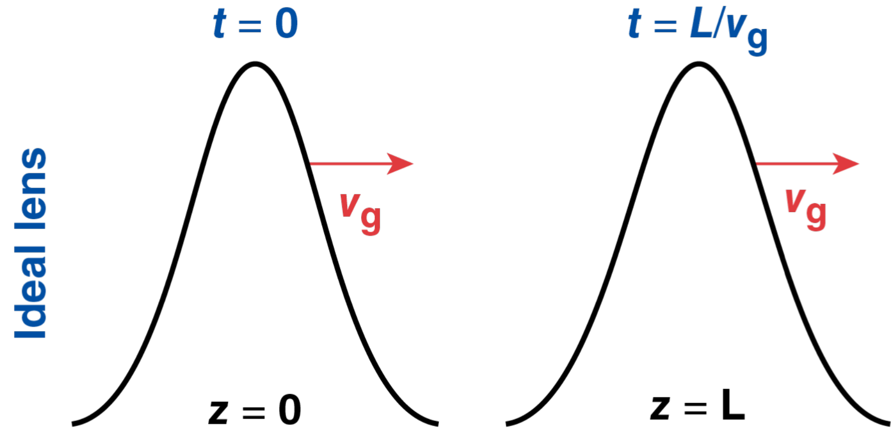
- The effective duration of the intensity peak is limited by the distance it takes adjacent frequencies to come in and out of focus

- By decreasing this distance, self-focusing acts to reduce the duration of the intensity peak

- A shorter duration intensity peak can improve several flying-focus based applications, including terahertz generation, photon acceleration, and wakefield acceleration

Multiple laser applications require (1) a high intensity over an extended distance and (2) phase matching



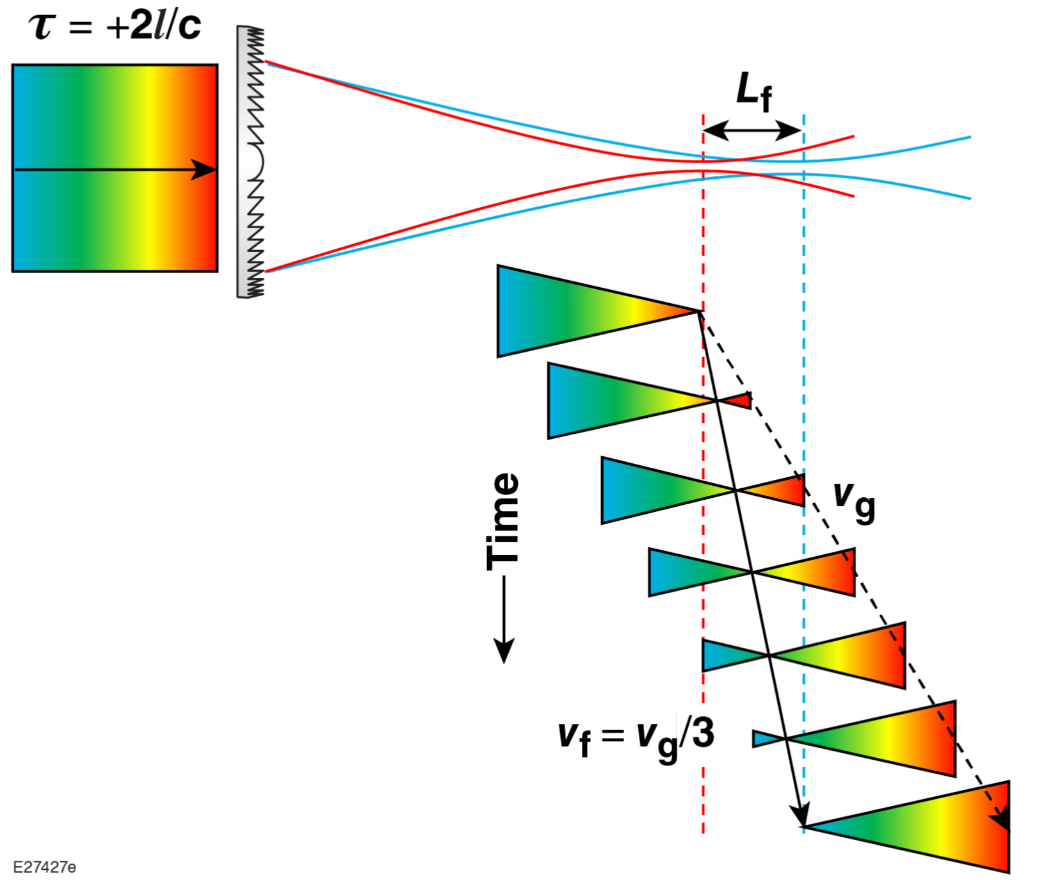


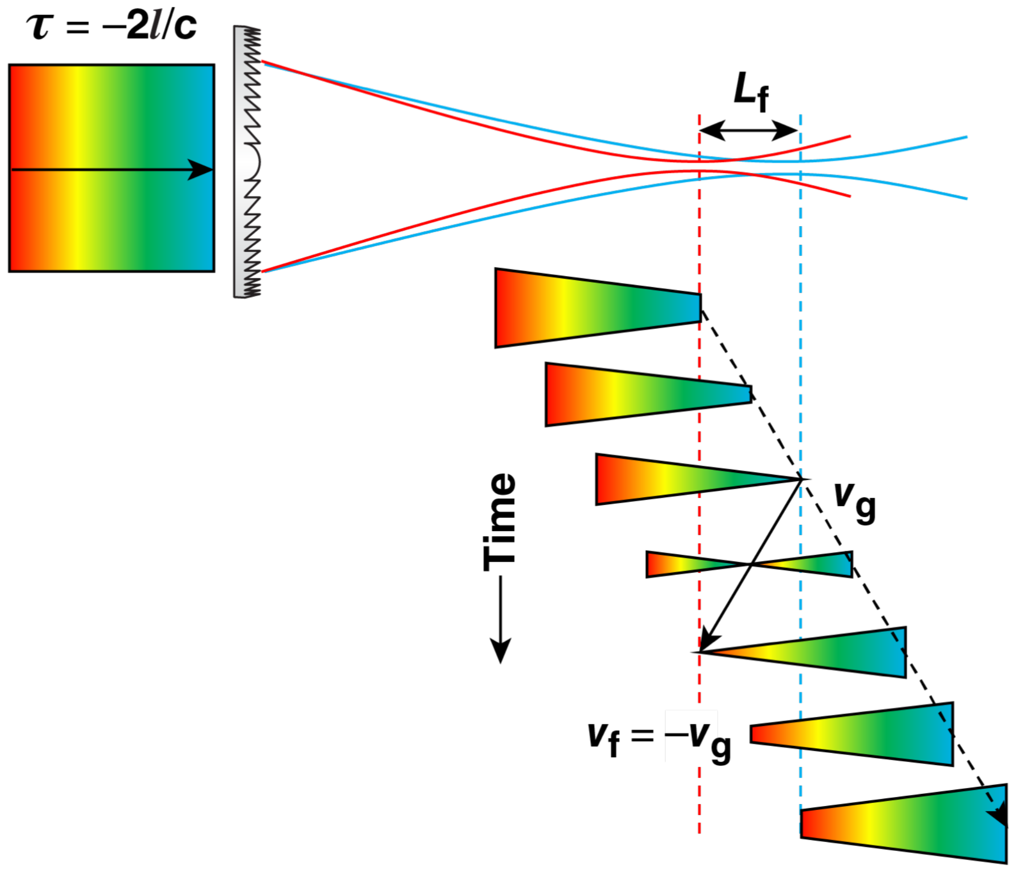
1. For an ideal lens, the region of high intensity is limited to the Rayleigh range, L_R

2. The peak intensity is restricted to travel at the group velocity, v_g, of the pulse

Conventional optics limit the efficacy of different laser-based applications.

The flying focus overcomes both constraints by spatiotemporally structuring the laser pulse

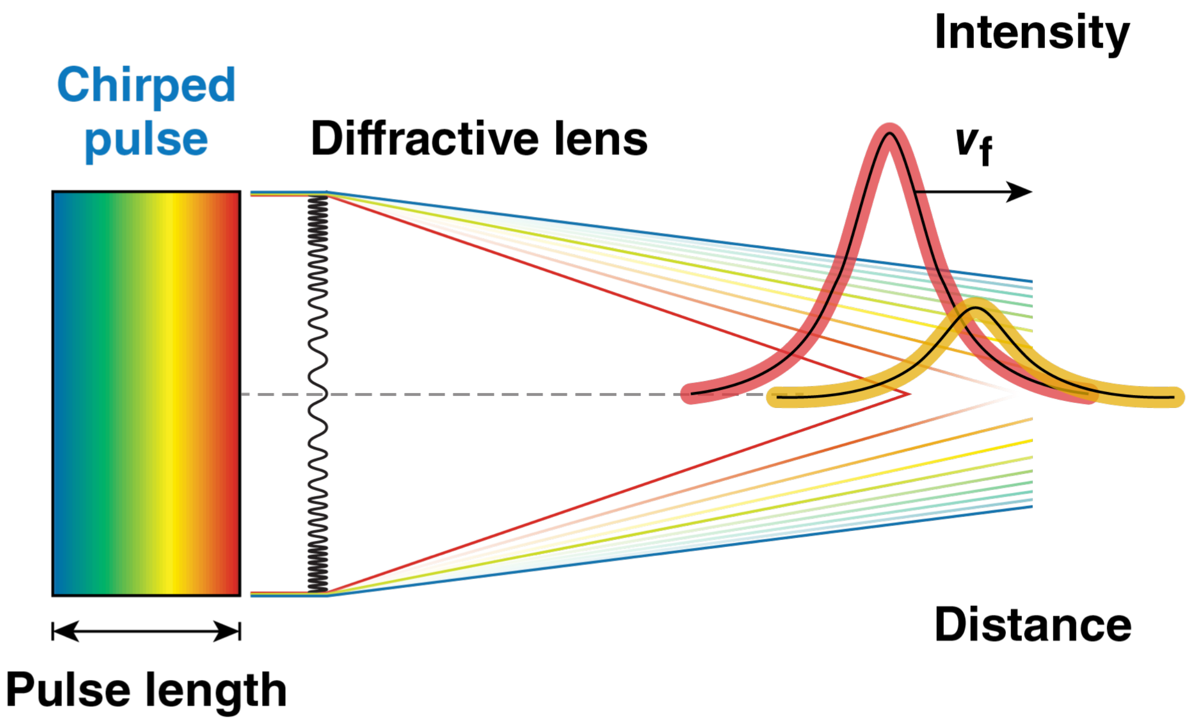




By adjusting the chirp, the intensity peak can move at any velocity over a distance much greater than the Rayleigh range.

D. H. Froula *et al.*, Nat. Photonics 12, 262 (2018).

The effective duration of the flying focus intensity peak is limited by the distance over which adjacent frequencies come in and out of focus



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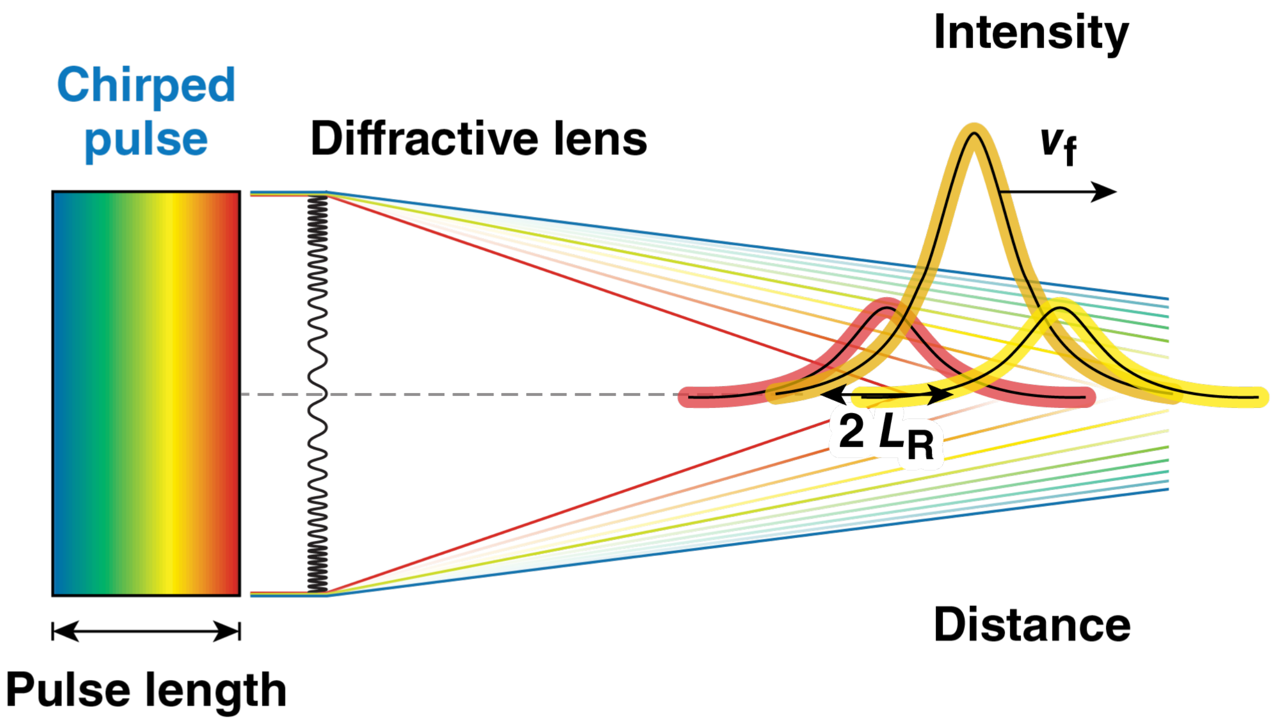
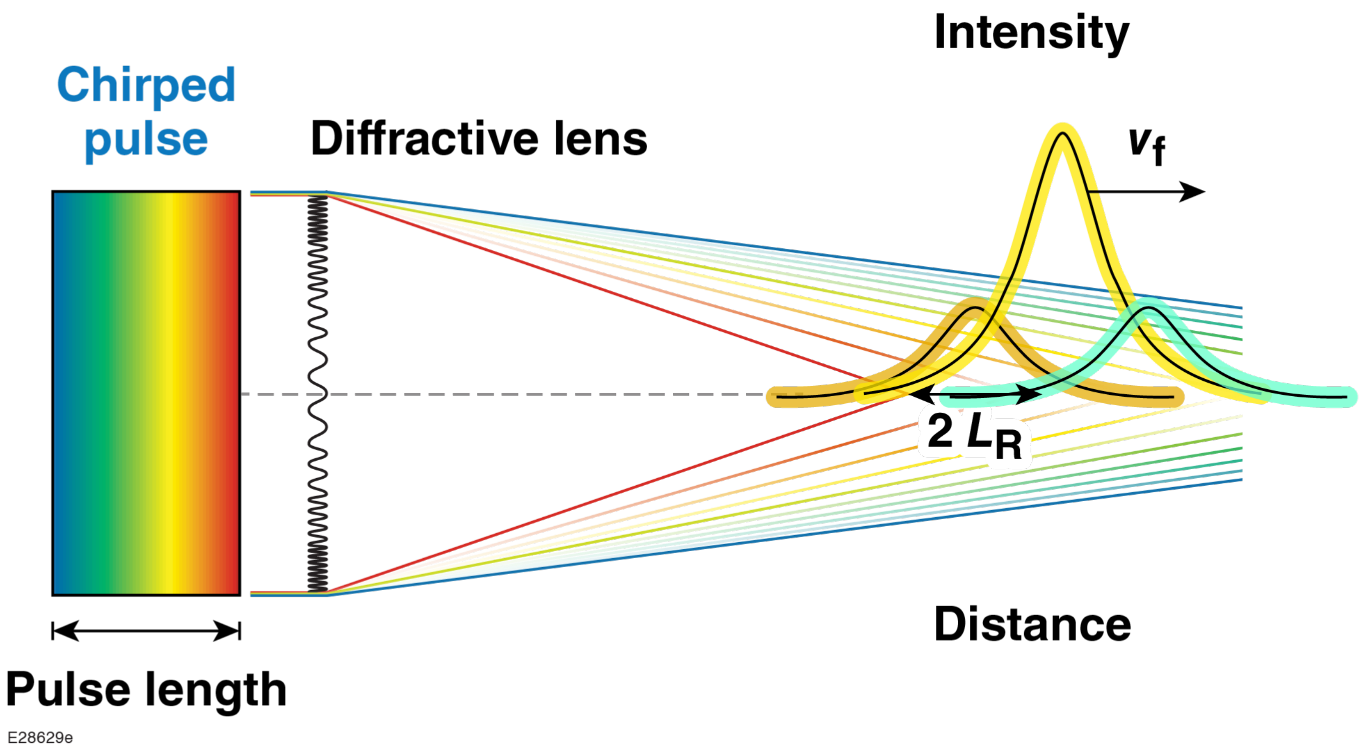
The effective duration of the flying focus intensity peak is limited by the distance over which adjacent frequencies come in and out of focus

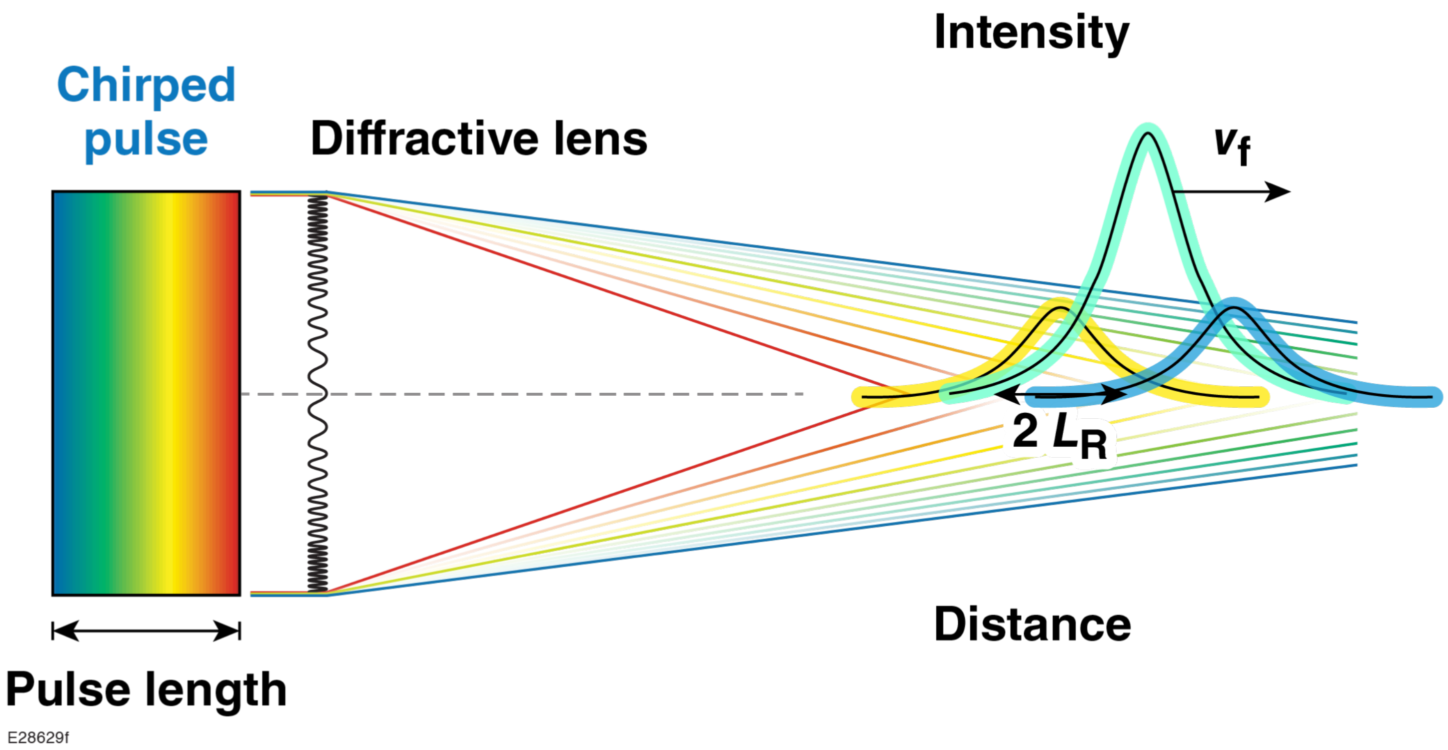


E28629d

The effective duration of the flying focus intensity peak is limited by the distance over which adjacent frequencies come in and out of focus



The effective duration of the flying focus intensity peak is limited by the distance over which adjacent frequencies come in and out of focus



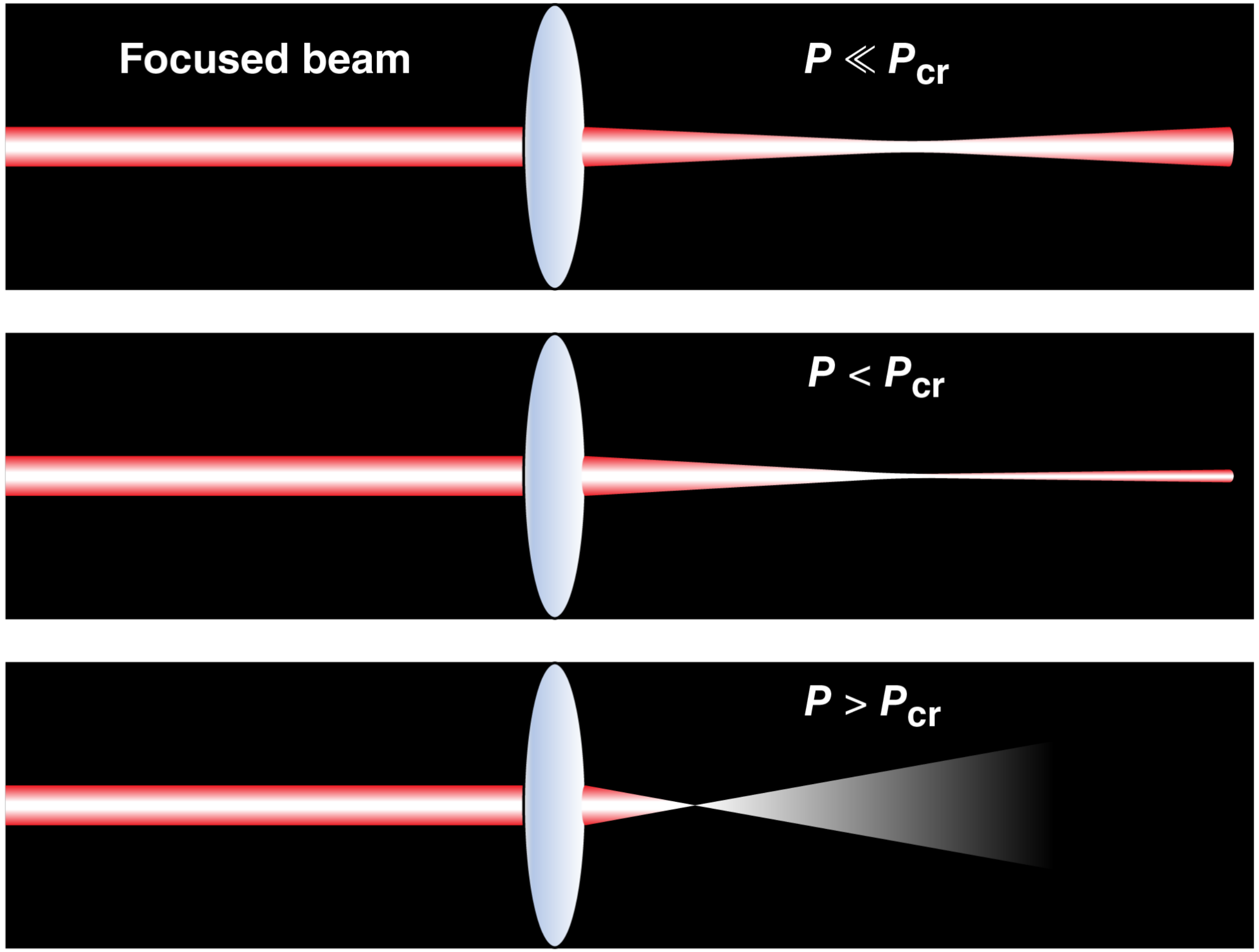
$\Delta t \sim L_R/v_f$

The effective duration is limited by the Rayleigh range

For an $f/7$ lens and a focal velocity of $-c$, $\Delta t \approx 2$ ps

Several applications that could benefit from a tunable focal velocity require an ultrashort-duration intensity peak.

Self-focusing can modify the propagation of high-power flying focus laser pulses in nonlinear media



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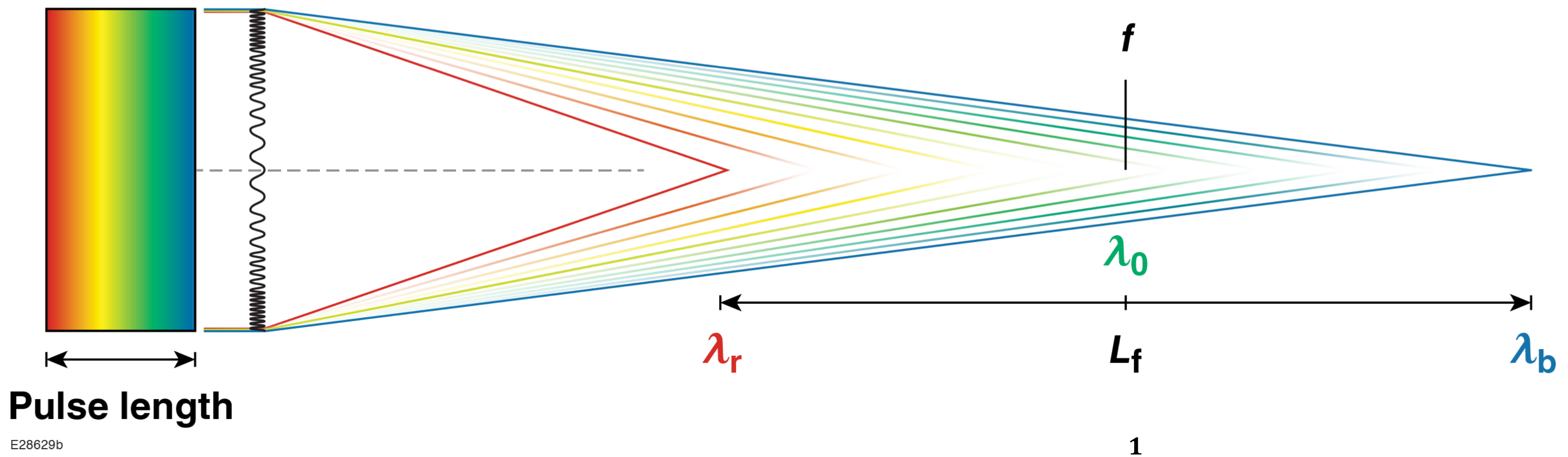
Minimal effect

Smaller spot size, lessened diffraction

Minimal spot size, ceased propagation, shifted focus

J. H. Marburger, Prog. Quantum Electron. 4, 35 (1975).

The self-focusing of flying focus pulses can be modeled with a "frequency by the slice" picture

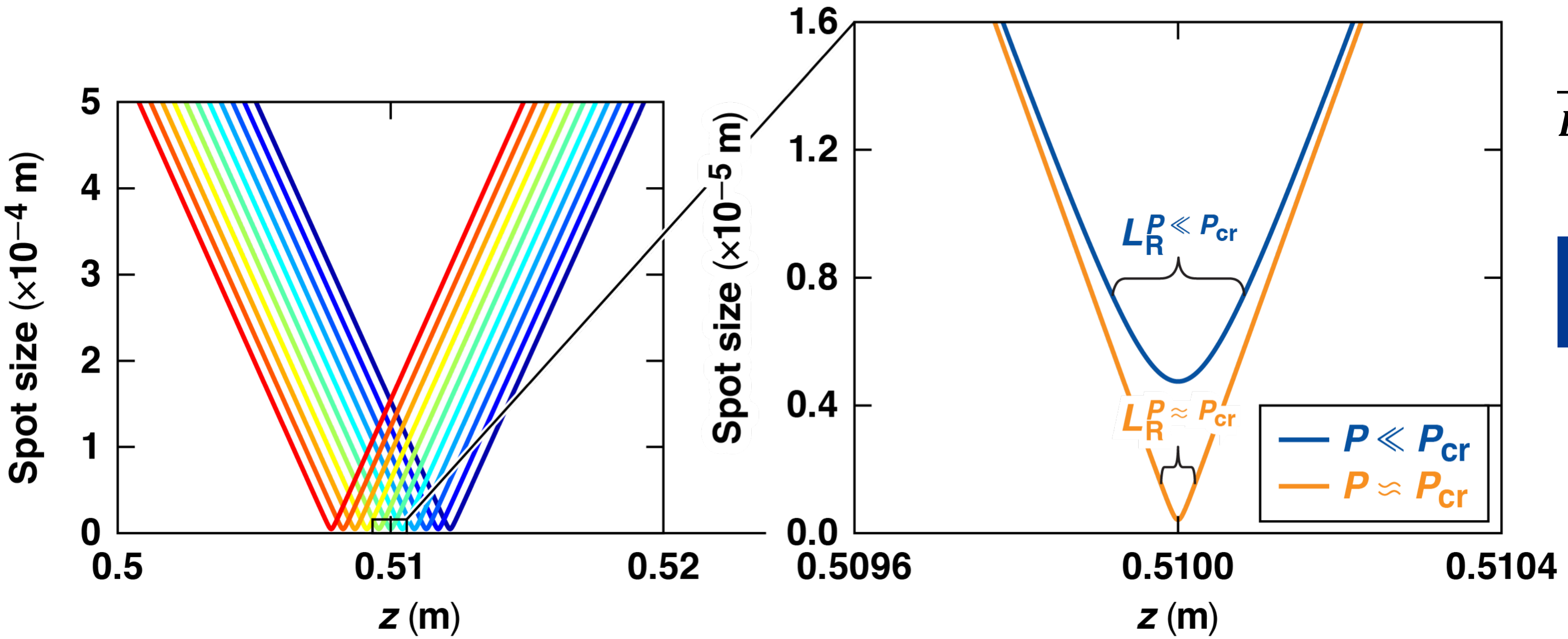


$$w_\lambda(z) = w_i\left[\left(1 - \frac{\lambda}{\lambda_0}\frac{z}{f}\right)^2 + \left(1 - \frac{P}{P_{cr}}\right)\left(\frac{\lambda}{\pi w_i^2} z\right)^2\right]^{\frac{1}{2}}$$

Spot size evolution

P. Sprangle, J. R. Peñano, and B. Hafizi, Phys. Rev. E 66, 046418 (2002).

The self-focusing of flying focus pulses can be modeled with a "frequency by the slice" picture



$$\frac{L_R^{P=0}}{L_R^{P=P_{cr}}} \propto \frac{\Delta t^{P=0}}{\Delta t^{P=P_{cr}}} = \frac{1}{1 - P/P_{cr}}$$

Rayleigh range

Effective duration

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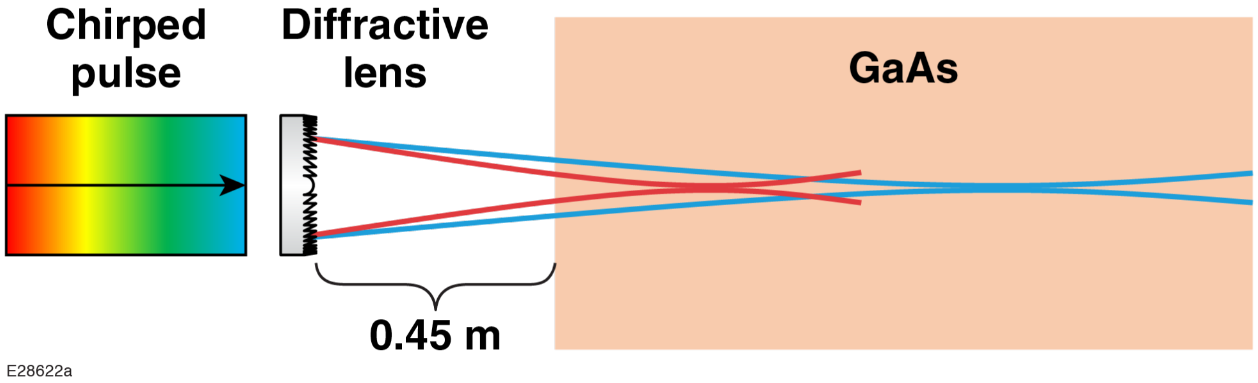
Self-focusing decreases the Rayleigh range for each frequency, which shortens the effective duration of the flying focus intensity peak.

To demonstrate pulse shortening, simulations were run for the parameters of the Multi-Terawatt laser at the Laboratory for Laser Energetics



$$\left[2\left(ik_0 - \frac{\partial}{\partial \xi}\right)\frac{\partial}{\partial z} + \nabla_\perp^2\right]E_\perp = \varepsilon_0 c n_2 \left(ik_0 - \frac{\partial}{\partial \xi}\right)^2 |E_\perp|^2 E_\perp$$

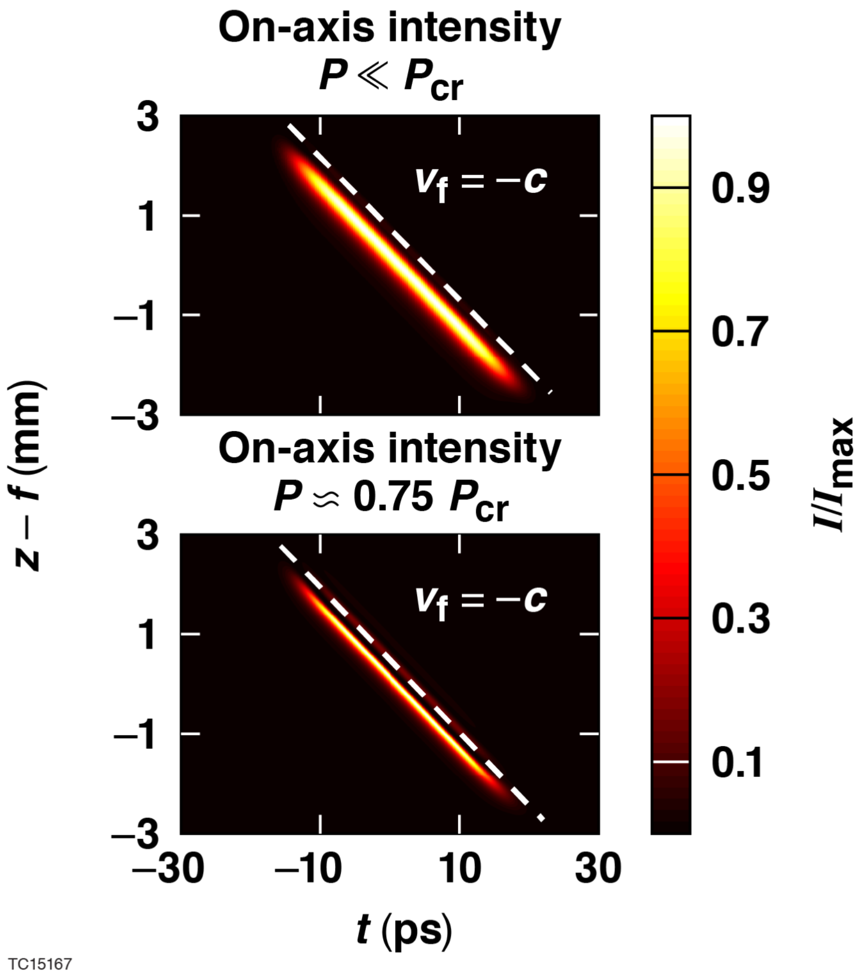
Spatiotemporal modification | **Diffraction** | **Self-phase modulation** | **Self-steepening**

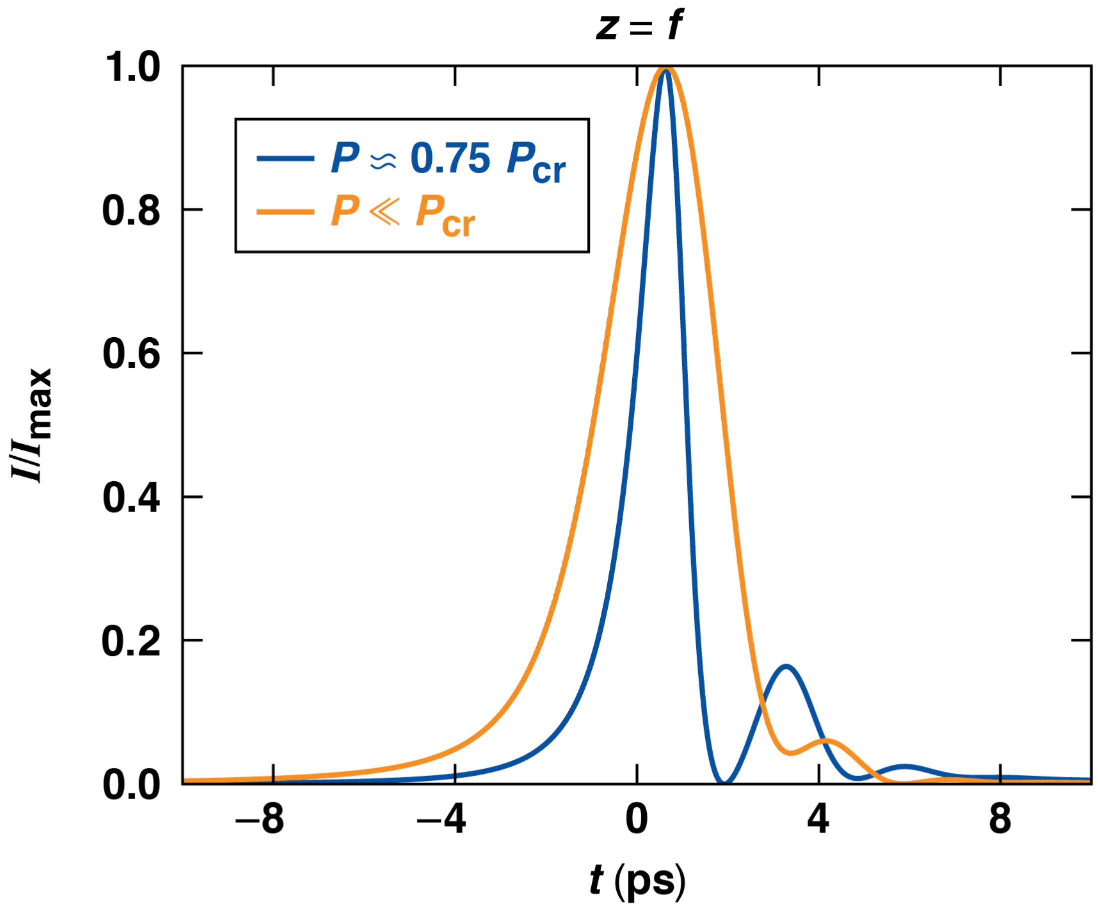
$$\xi = \frac{c}{n_0}t - z$$

Pulse frame coordinate

Pulse Parameters	Value
λ_0 (μm)	1.054
$\Delta\lambda$ (nm)	9.0
τ (ps)	16
P (KW)	<1.2
Lens Parameters	**Value**
$f^{\#}$	7
f (cm)	51
Material Parameters	**Value**
P_{cr} (KW)	1.4
Damage threshold (W/cm^{-2})	2×10^{11}

The simulations agree with the model: the on-axis intensity is spatially and temporally shortened





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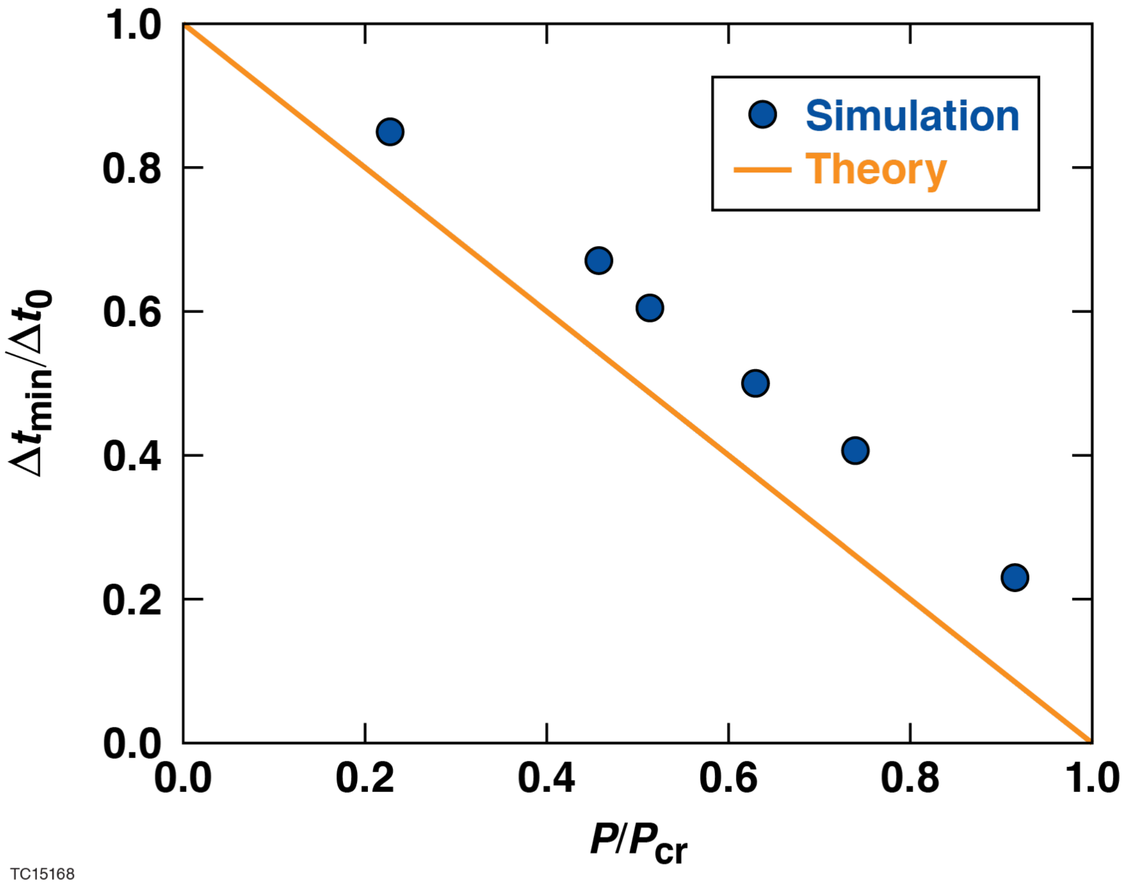
The simulations agree with the model: the on-axis intensity is spatially and temporally shortened



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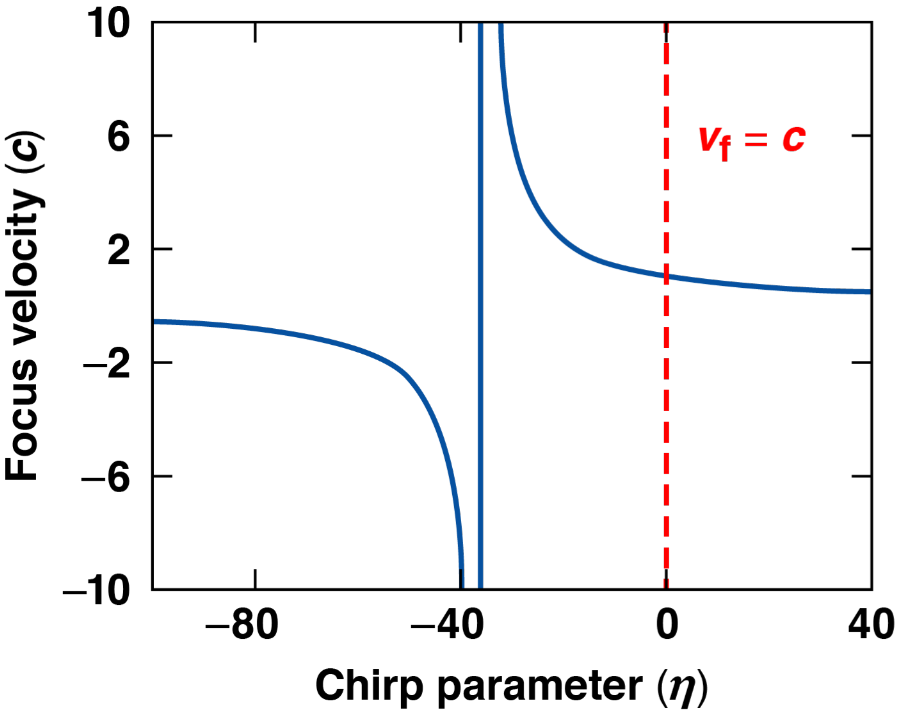
- Increasing the laser power can substantially reduce the effective duration of the intensity peak
- Eventually another process will prevent the spot size from getting too small (e.g., ionization)

Self-focusing can reduce the effective duration of flying focus pulses

- A “flying focus,” a chirped pulse focused through a chromatic lens, exhibits a high-intensity peak that can travel at an arbitrary velocity over distances much greater than the Rayleigh range
- The effective duration of the intensity peak is limited by the distance it takes adjacent frequencies to come in and out of focus
- By decreasing this distance, self-focusing acts to reduce the duration of the intensity peak
- A shorter duration intensity peak can improve several flying-focus based applications, including terahertz generation, photon acceleration, and wakefield acceleration

Backup

Self-focusing will modify the propagation of flying focus pulses differently, depending on the focal velocity



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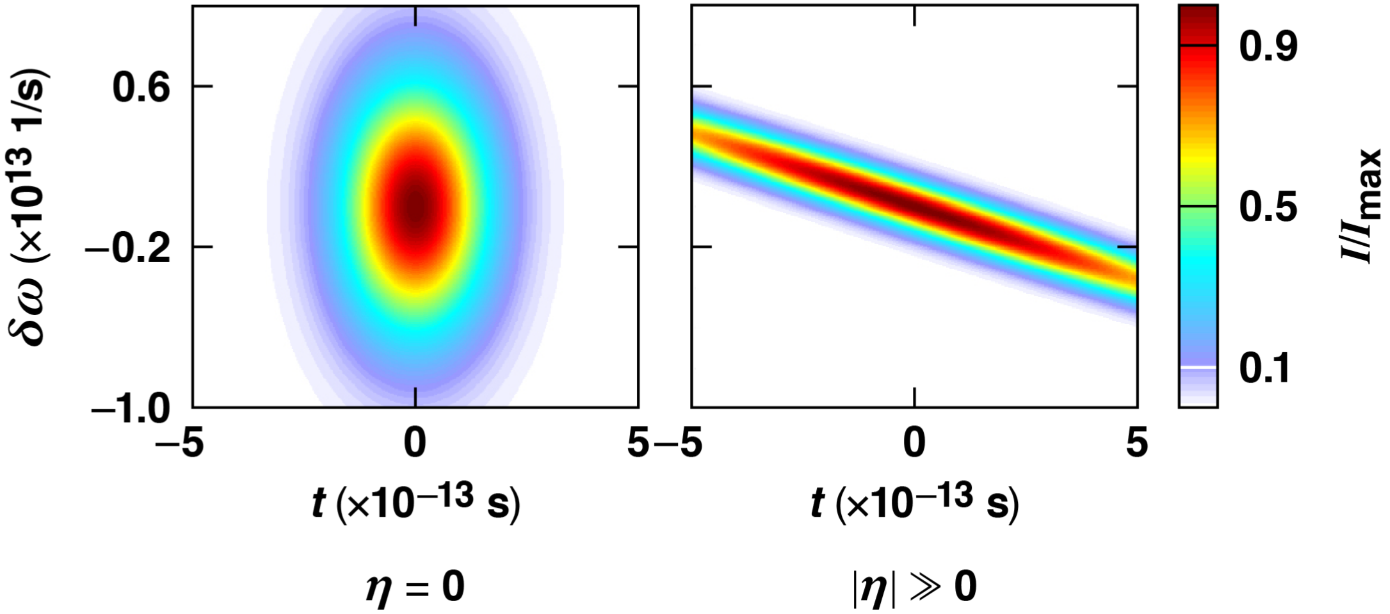
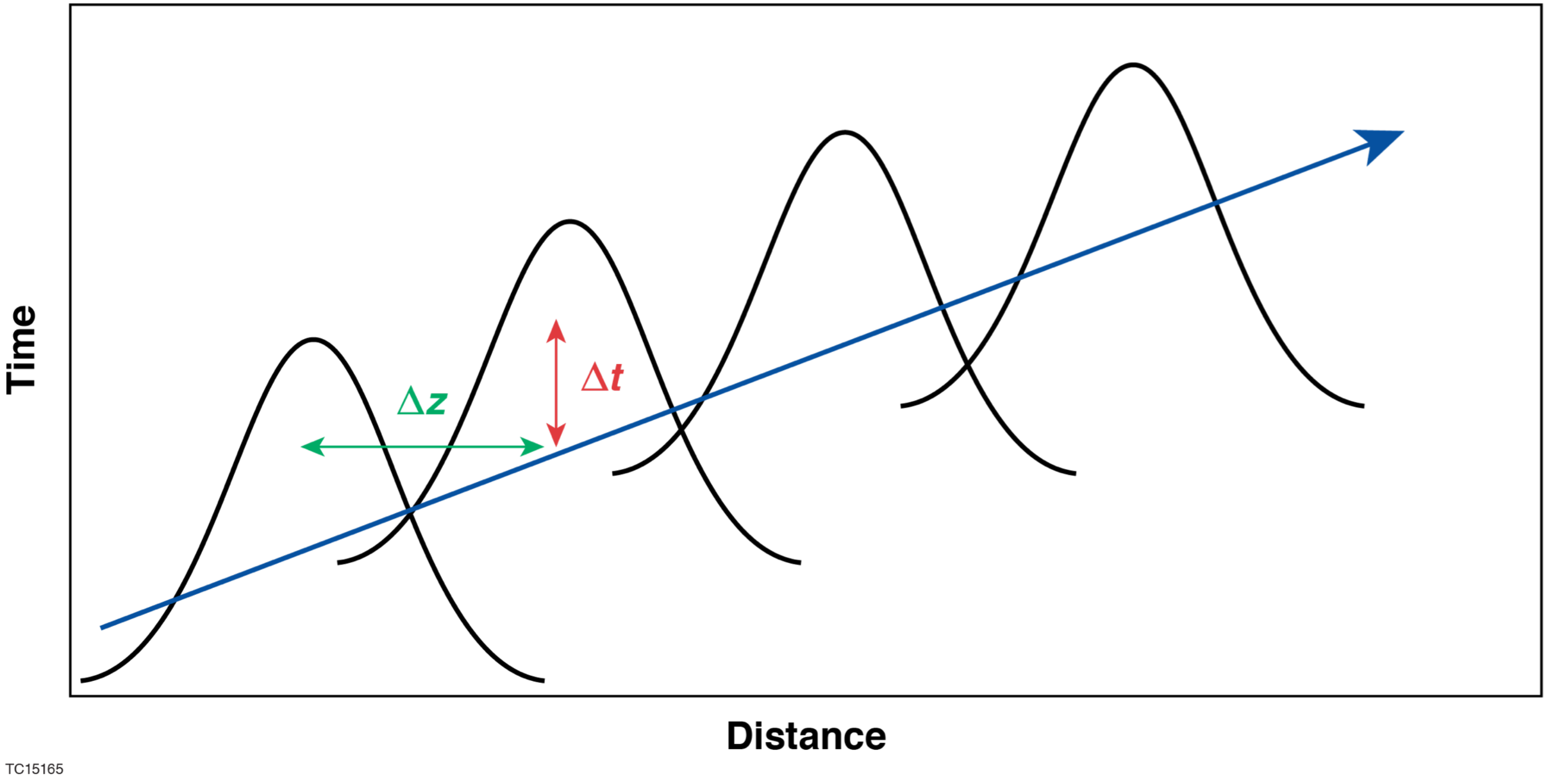
Wigner distribution



- For large chirps ($v_f \approx c$), each frequency essentially propagates independently
- For small chirps ($v_f \approx c$), each frequency component will interact with one another

The effective duration of the flying focus intensity peak is limited by the distance over which adjacent frequencies come in and out of focus



$$\Delta t = \frac{\Delta z}{v_f} \sim \frac{Z_R}{v_f}$$

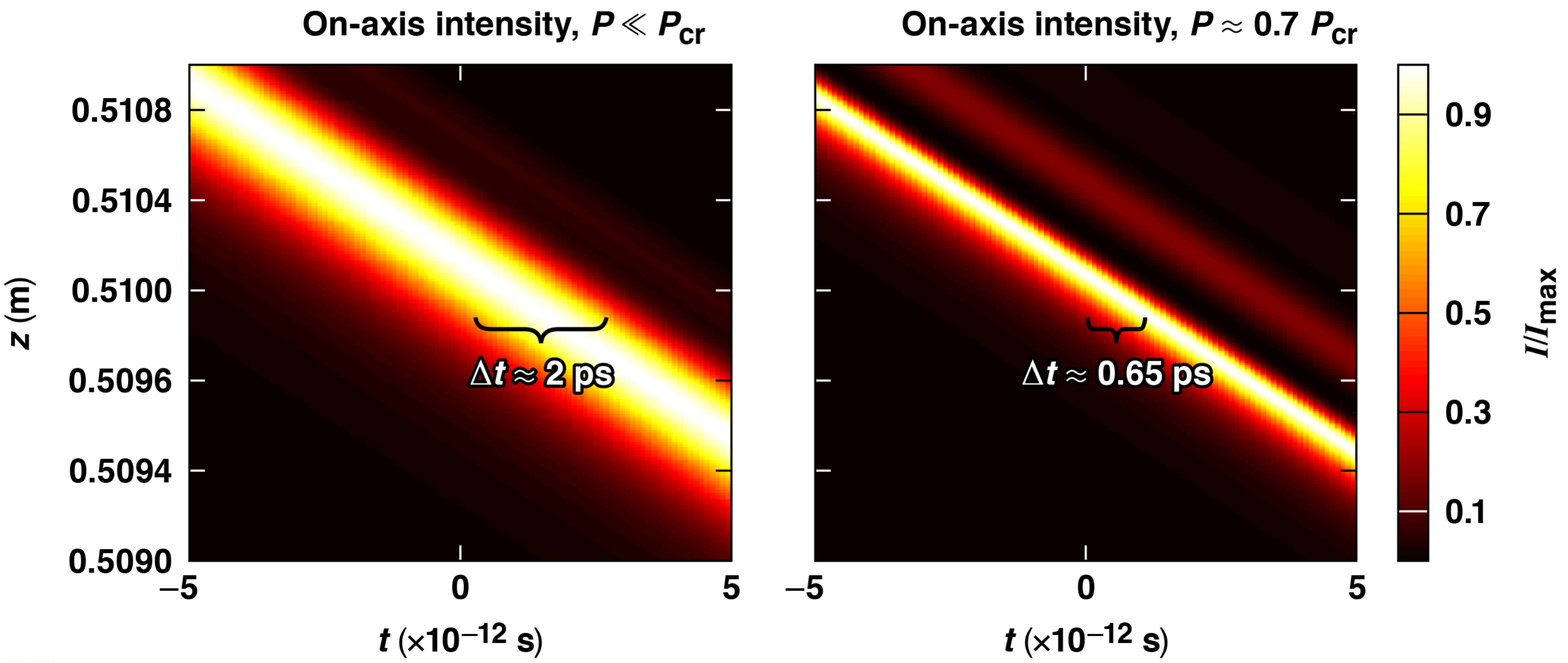
The time required for adjacent frequencies to come in and out of focus is related to the Rayleigh range

For an $f/7$ lens and a focal velocity of $-c$, $\Delta t \approx 2$ ps

Several applications that could benefit from a tunable focal velocity require an ultrashort-duration intensity peak.

D. H. Froula *et al.*, Phys. Plasma 26, 032109 (2019).

For a large negative chirp, the simulations agree with the model: the on-axis intensity is spatially and temporally sharpened



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Self-focusing could allow for sharper ionization fronts.