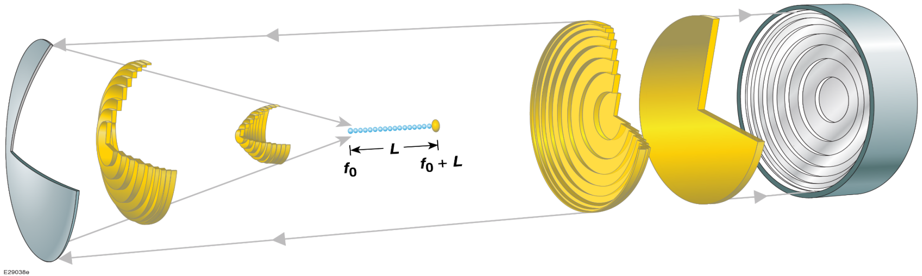
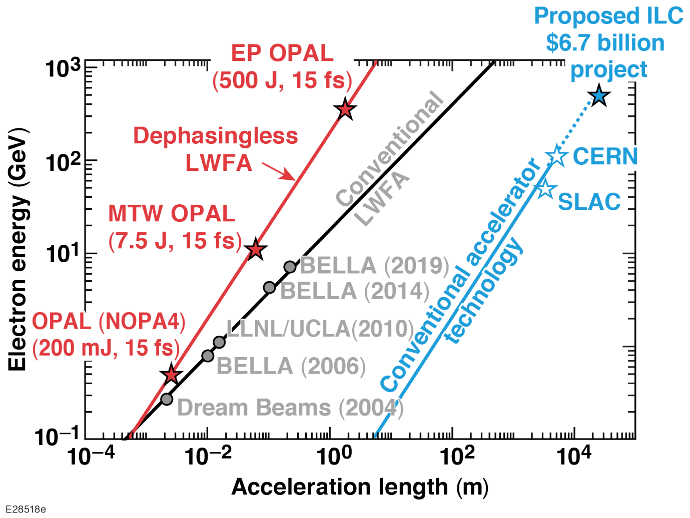
Laser-plasma interactions driven by spatiotemporally structured light pulses





John P. Palastro
University of Rochester
Laboratory for Laser Energetics

APS DPP
November, 9th -13th 2020

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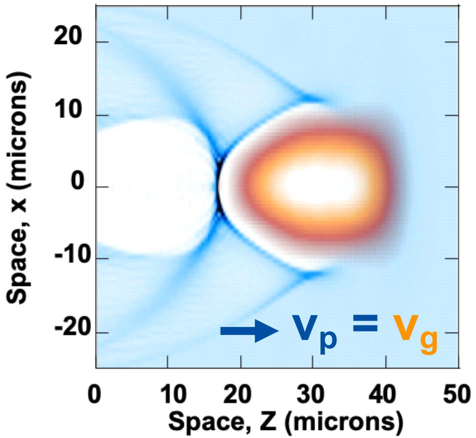

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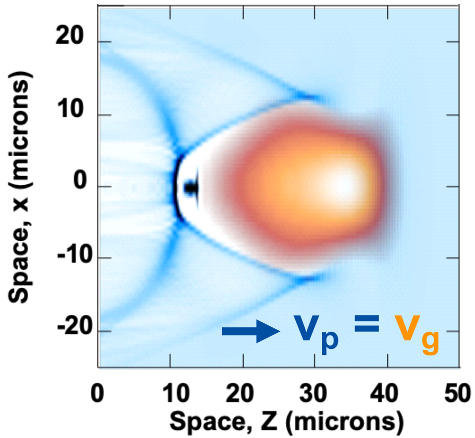

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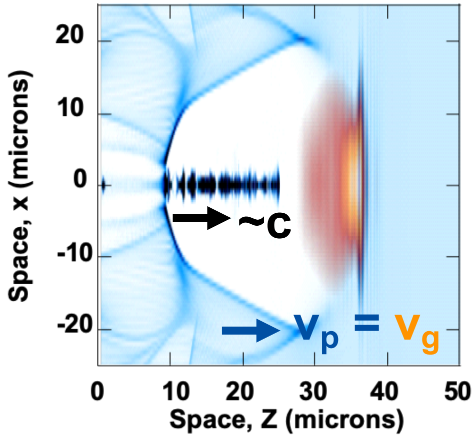

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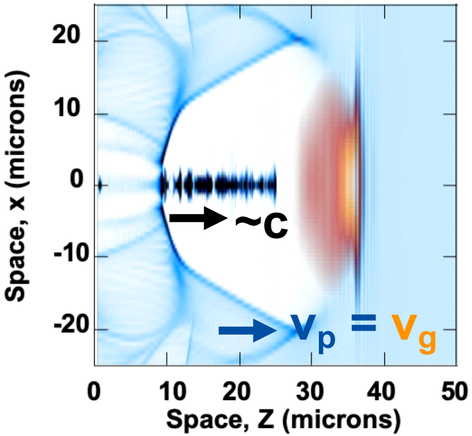

- A laser pulse travelling at v_g drives a plasma wave with phase velocity $v_p = v_g$
- Electrons injected and accelerated in the wave **can outrun the wave (c > v_g)**
- The laser pulse must maintain a high intensity during the acceleration

Conventional optics and laser pulses limit the efficacy of laser-based applications

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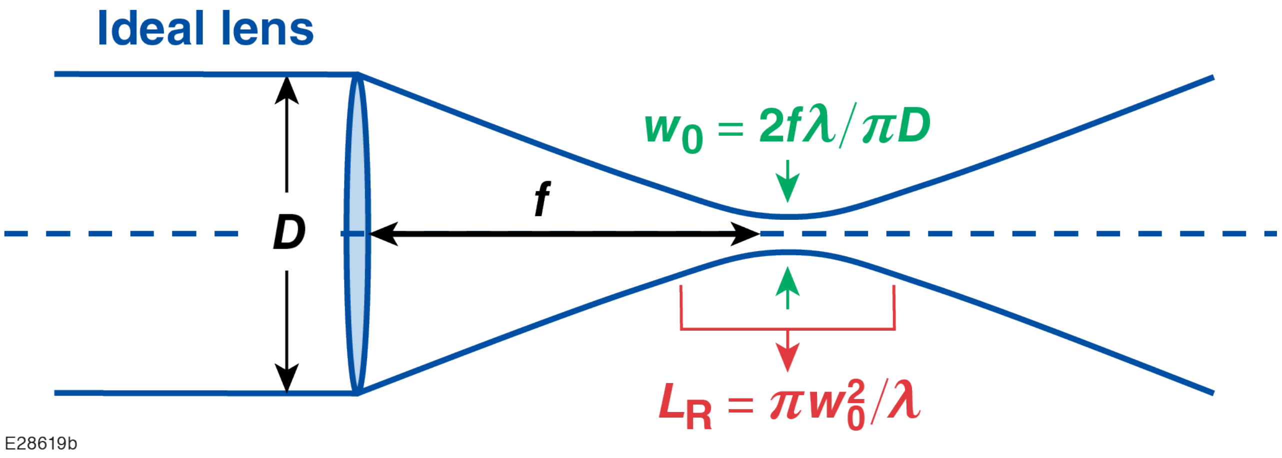
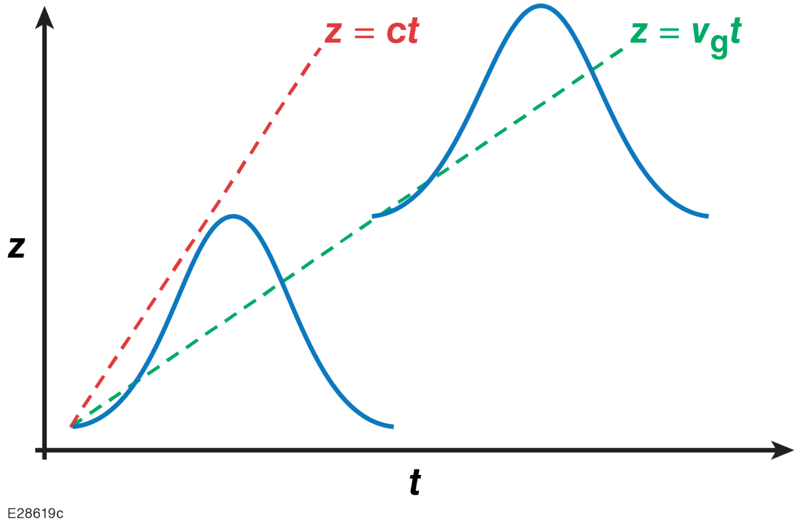


With conventional optics, diffraction limits the range of high intensity

Conventional optics and laser pulses limit the efficacy of laser-based applications

2. The velocity of the peak intensity must conform to some underlying process



Conventional laser pulses are constrained to travel at the group velocity

Spatiotemporal pulse shaping provides controllable velocity intensity peaks that can be sustained for long distances

- Spatiotemporal pulse shaping refers to structuring a laser pulse with advantageous space-time correlations that can be tailored to an application
- Experiments have demonstrated velocity control, the formation of ionization waves of arbitrary velocity, and "attosecond lighthouses"
- Simulations and theory predict that pulse shaping can be used in **many** more phenomena, including laser wakefield, photon, and Fermi acceleration

The flexibility offered by spatiotemporal pulse shaping can improve laser-based applications and enable fundamental physics studies

Contributors

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Institute of Laser Engineering, Osaka University — Z. Li

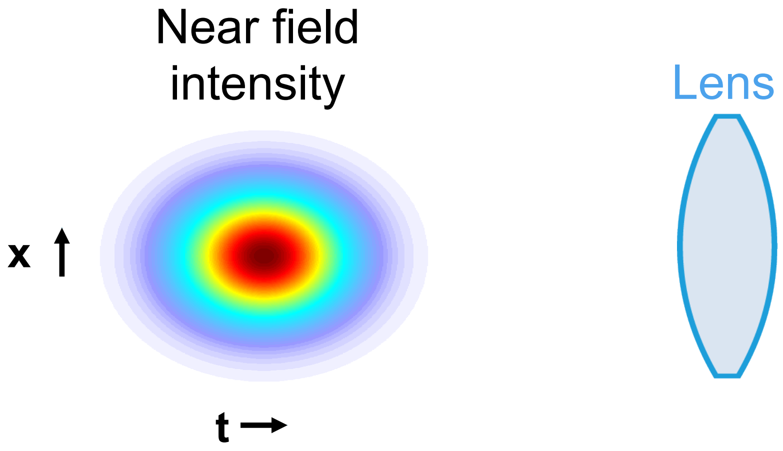
Outline

1. Spatiotemporal pulse shaping

2. Applications

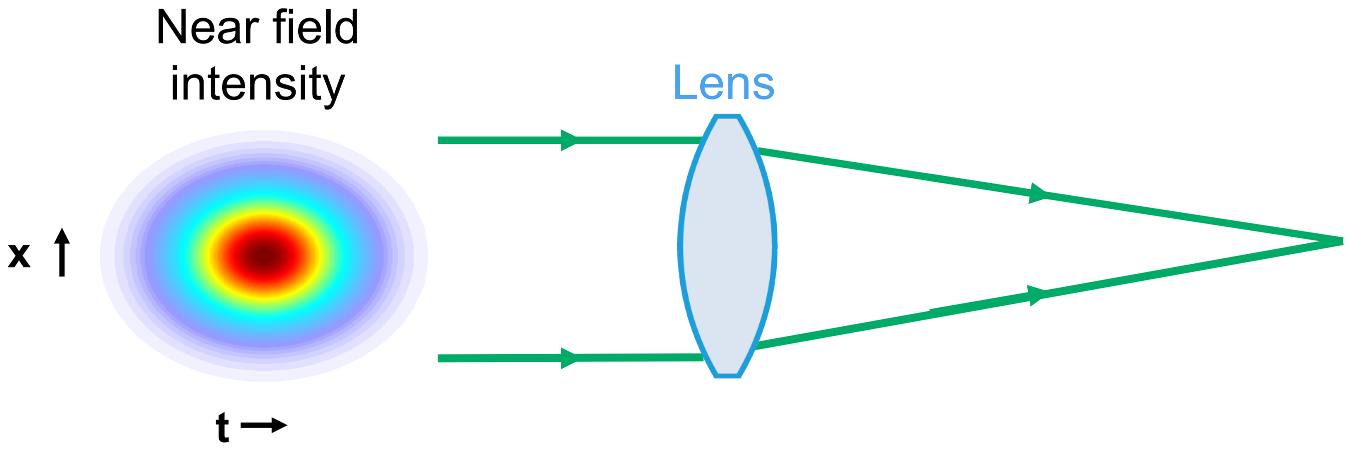
3. Basic plasma science

What is spatiotemporal pulse shaping?



Conventional laser pulses have separable (i.e. uncorrelated) space-time dependencies in the far field

What is spatiotemporal pulse shaping?



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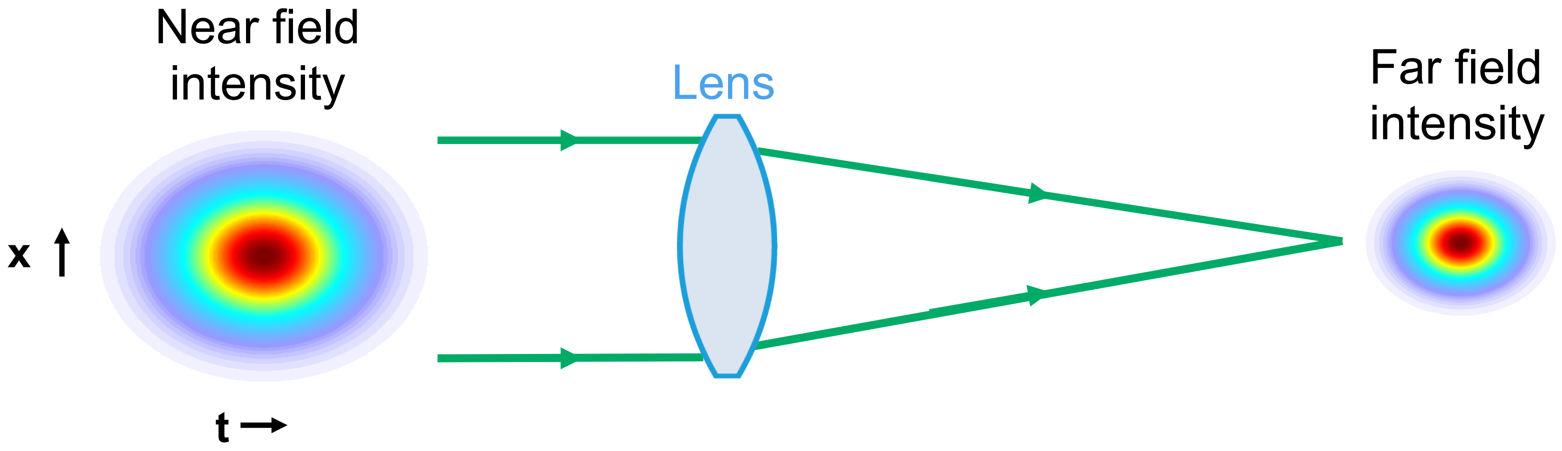

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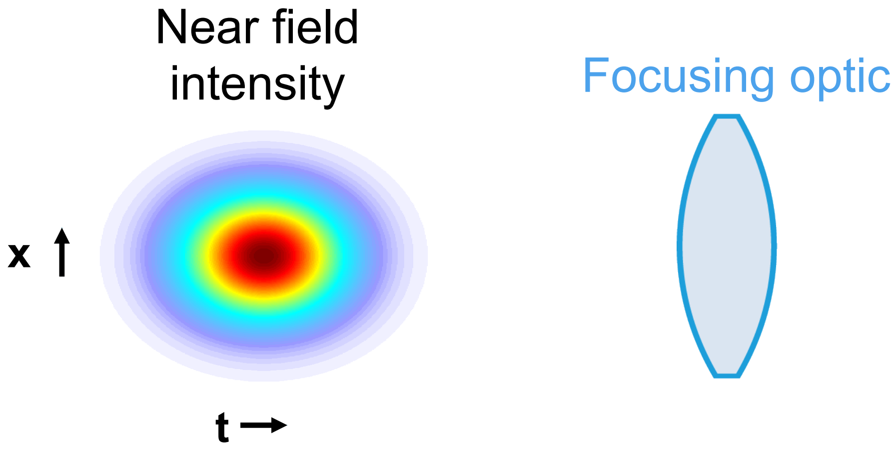

Answer: Structuring a laser pulse with advantageous space-time correlations that can be tailored to a particular application

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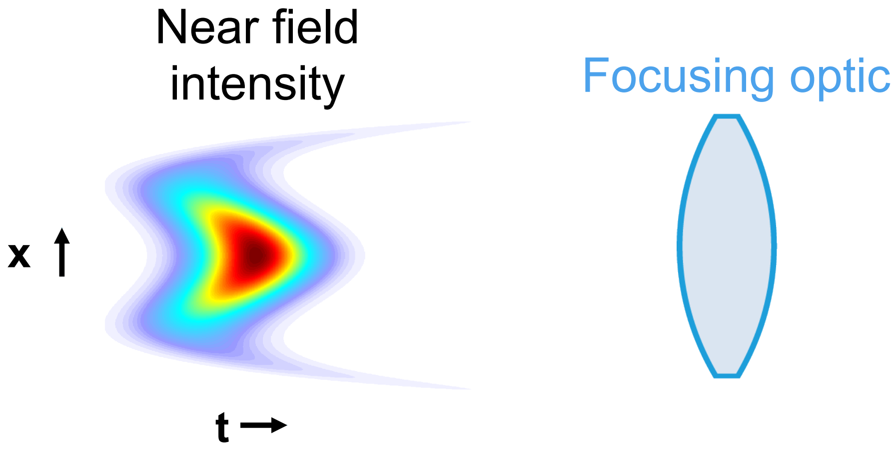

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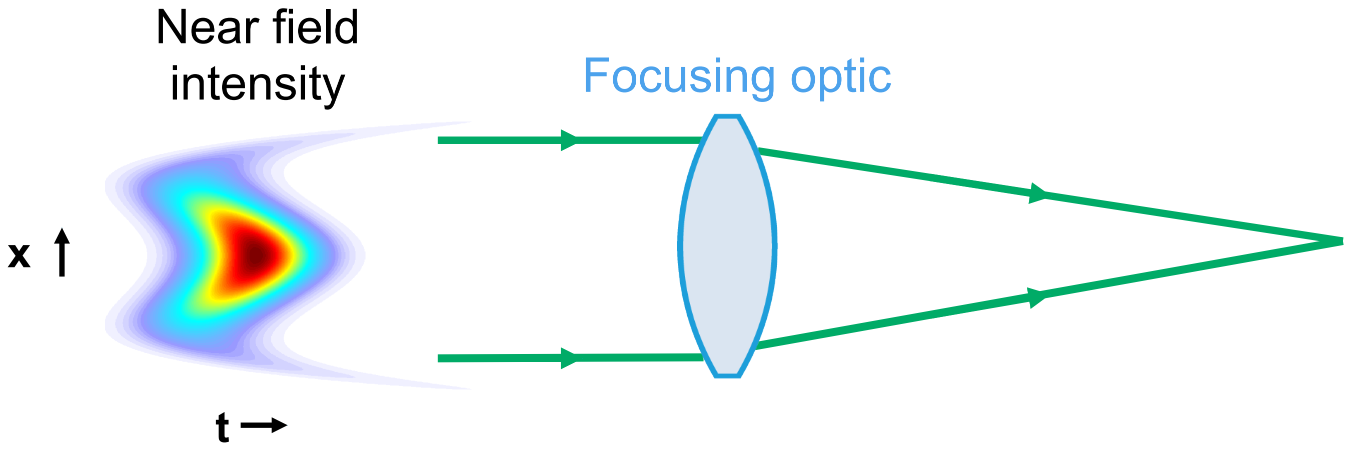

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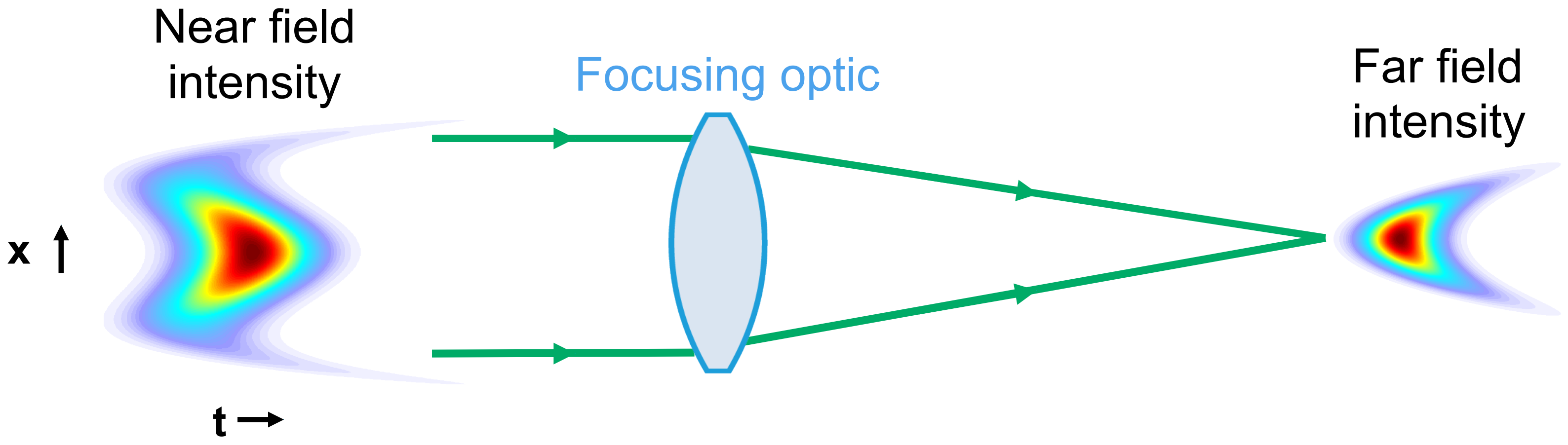

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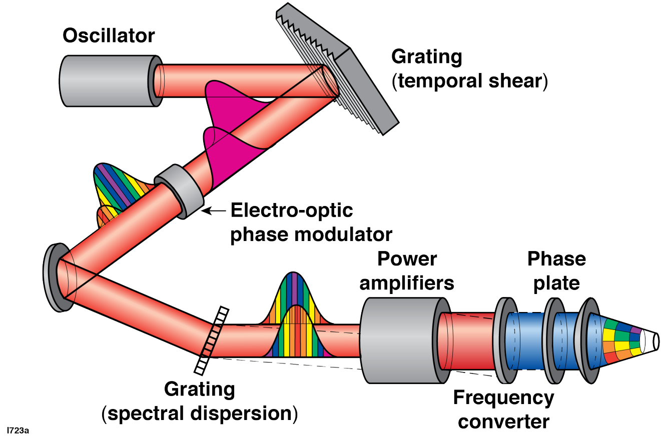
The idea that spatiotemporal pulse shaping can be used for laser-based applications is by no means new

Smoothing by spectral dispersion for ICF,1989*



Frequency shear in the near field dynamically disperses frequencies in the fair field, smoothing hot spots

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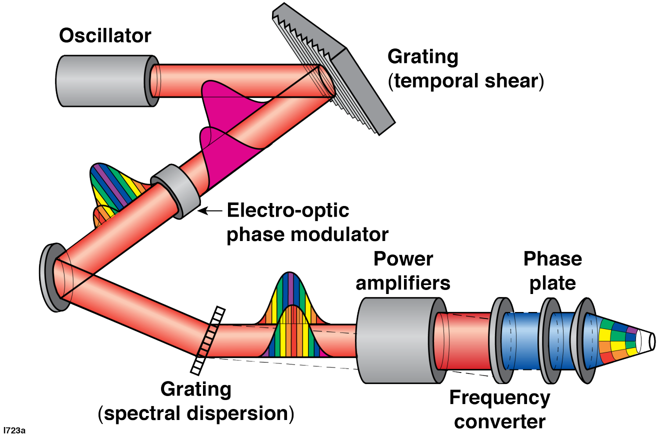

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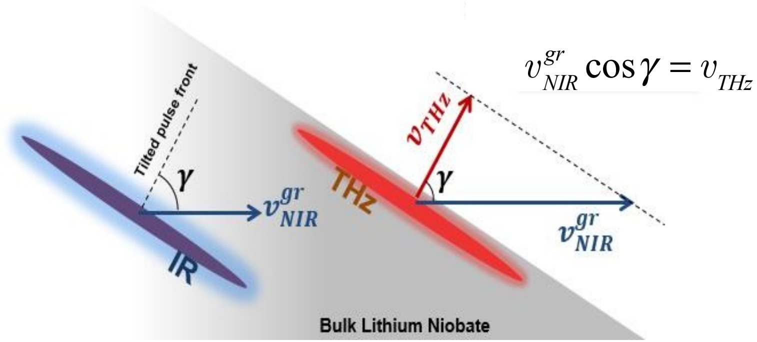
Tilted pulse-front phase-matching for THz generation, 2001**



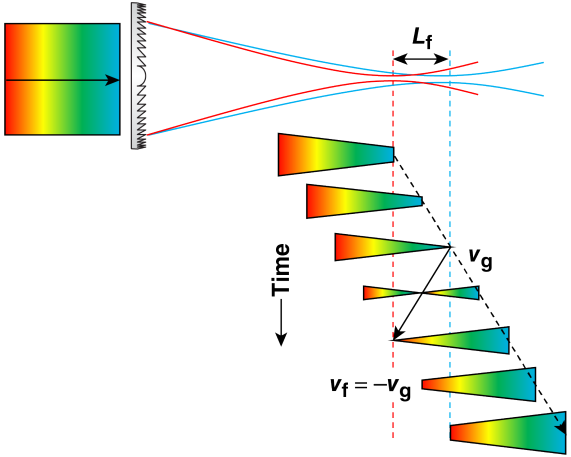
picture from F. Kärtner group website

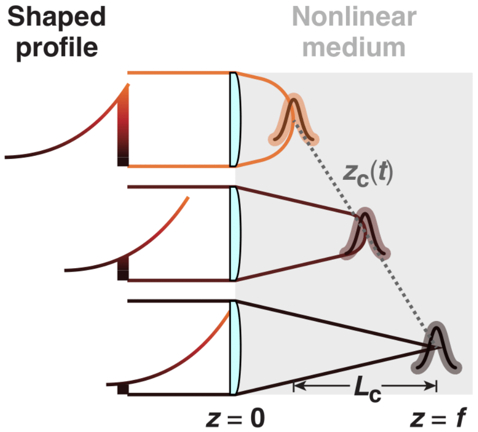
Projecting the group velocity onto the direction of the THz allows for phase matching in spite of dispersion

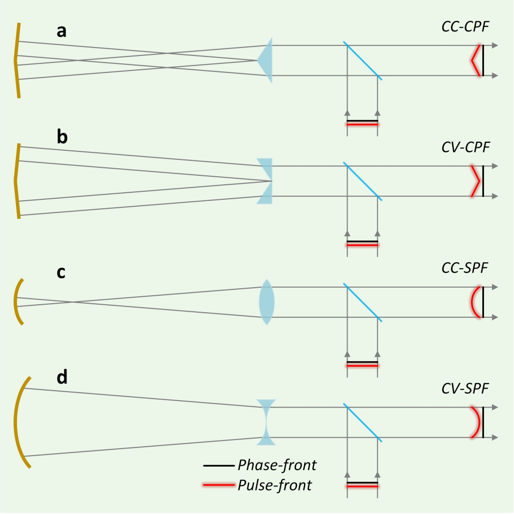
*S. Skupsky *et al.*, J. Appl. Phys. (1989)

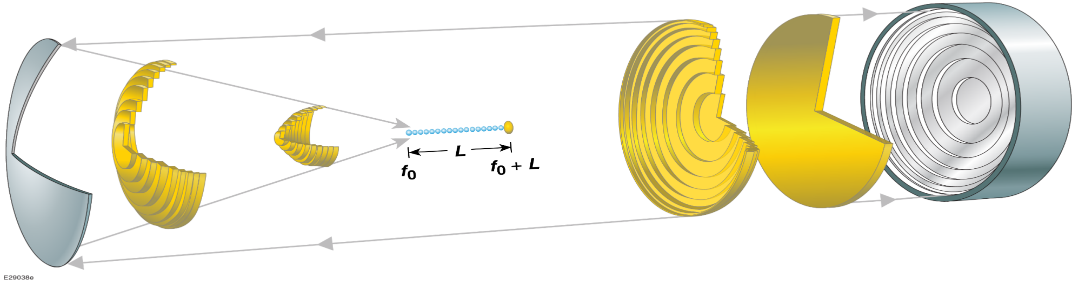
**R.M. Koehl and K.A. Nelson, Chem. Phys. (2001)

Modern techniques for spatiotemporal pulse shaping offer cylindrical symmetry, velocity control, and extended focal ranges



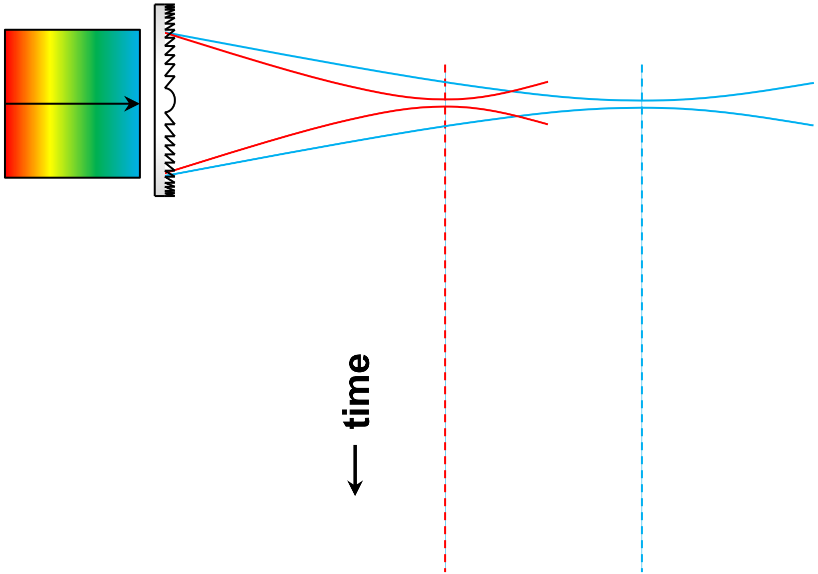






A. Sainte-Marie *et al.*, Optica (2018)
D. Froula *et al.*, Nat. Photonics (2018)
T. Simpson *et al.*, Submitted(2020)
Z. Li *et al.*, Nat. Sci. Reports (2020)
J. Palastro *et al.*, Phys. Rev. Lett. (2020)
C. Caizergues *et al.*, Nat. Photonics (2020)

A chirped laser pulse focused by a chromatic lens exhibits a dynamic, or "flying", focus



The chirp and chromatic focusing set the time and location at which each frequency comes to its focus, providing control over the velocity of the intensity peak

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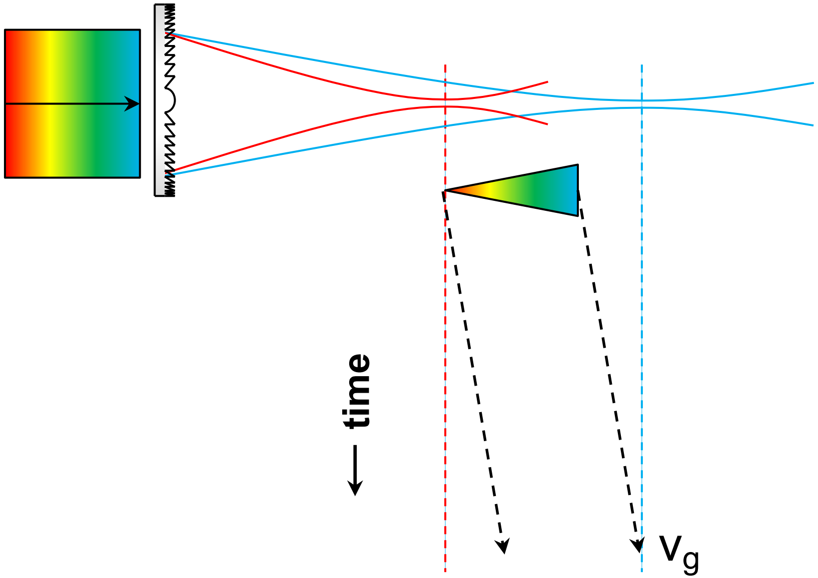

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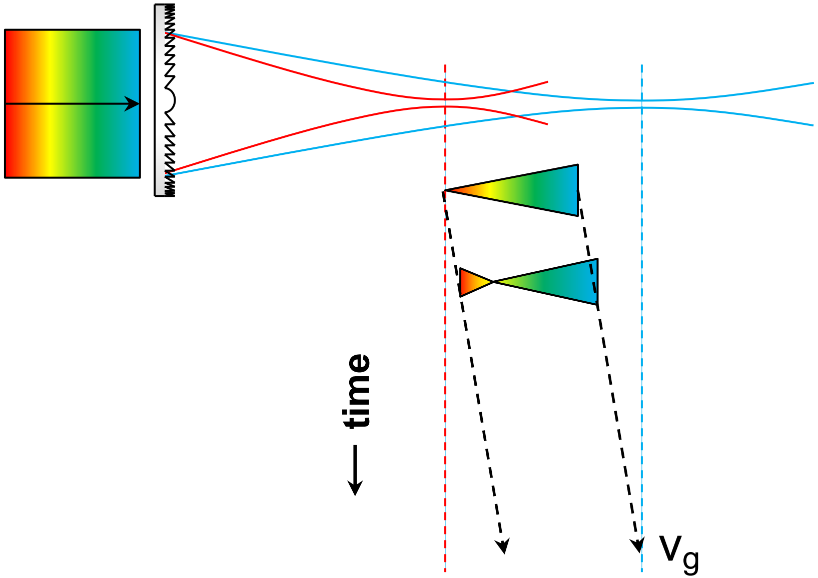

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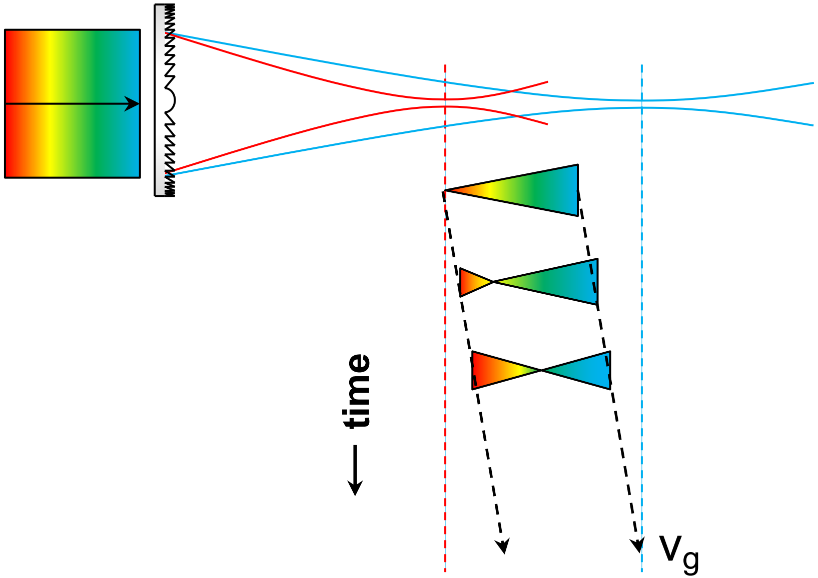

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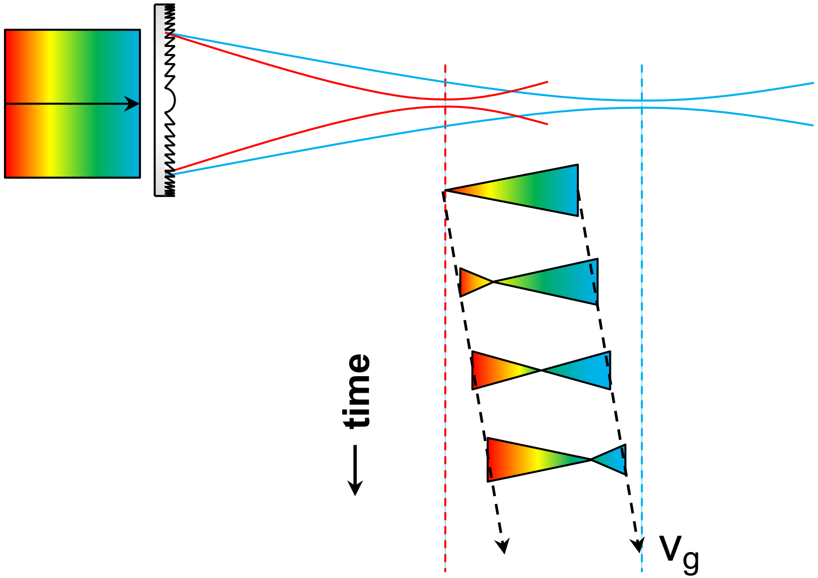

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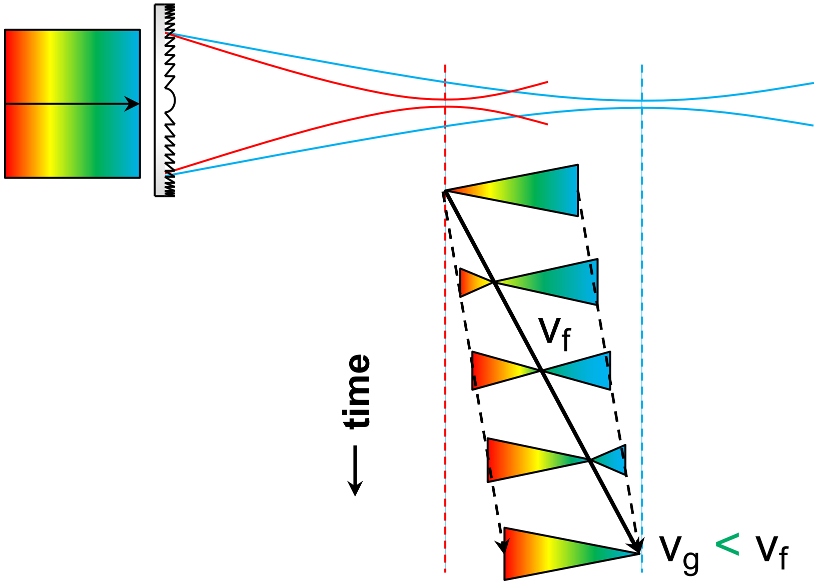

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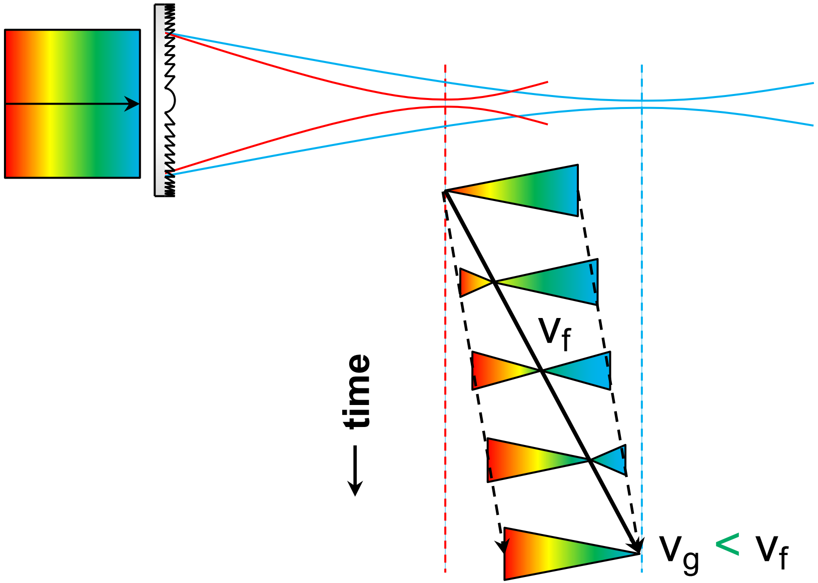

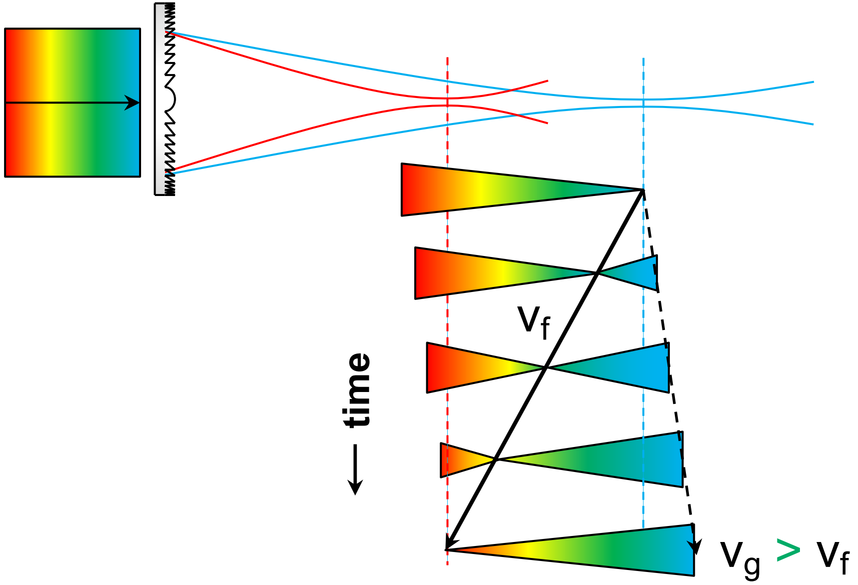

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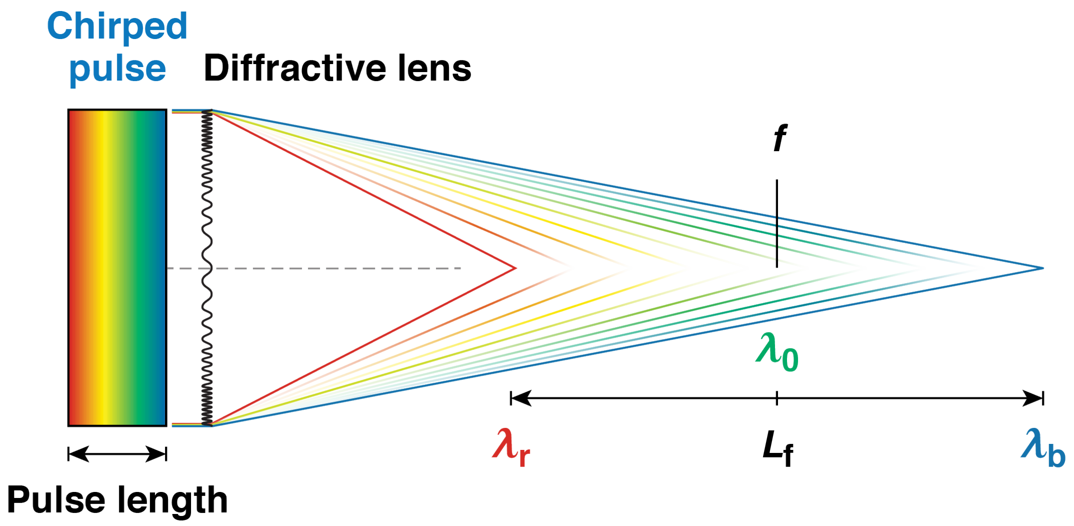
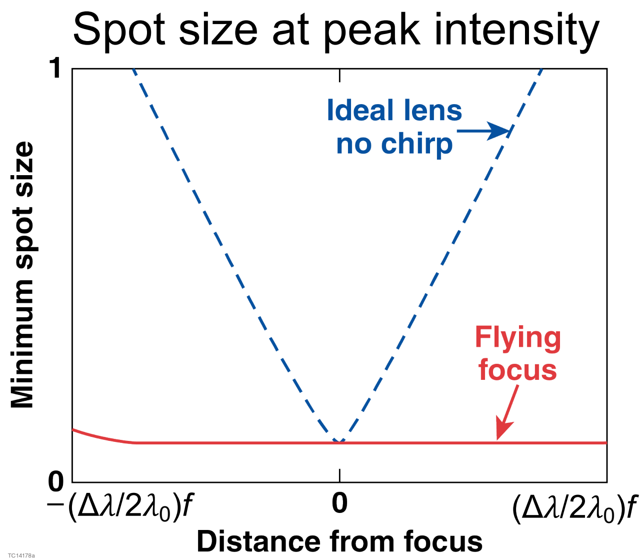
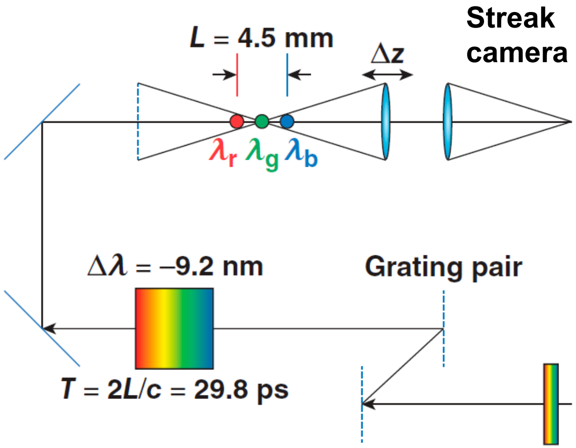
The "flying focus" delivers a diffraction limited spot over distances unconstrained by diffraction

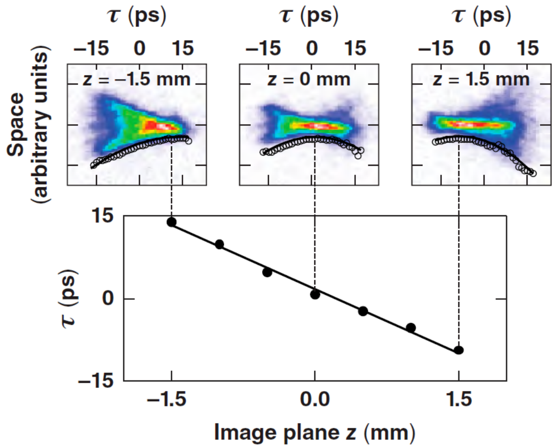


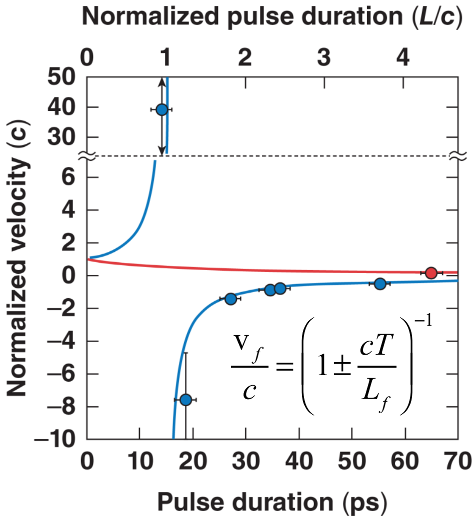


The bandwidth and focal length set the range of high intensity: $L_f = (\Delta\lambda/\lambda_0)f$

Experimental measurements of the flying focus are in excellent agreement with analytic calculations

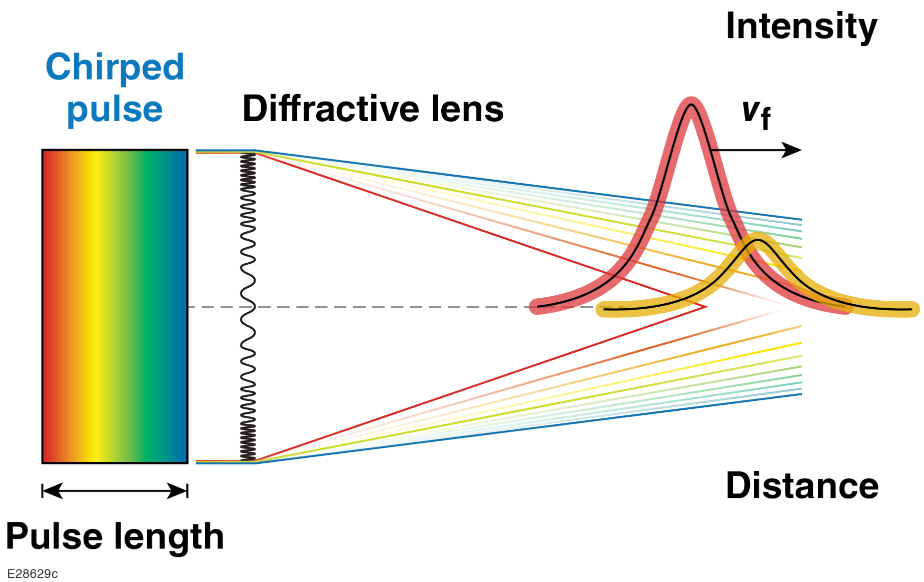






Several locations in the focal region were imaged onto a picosecond streak camera, providing the spatiotemporal profile of the flying focus pulse

The distance over which adjacent frequencies come in and out of focus determine the duration of the intensity peak



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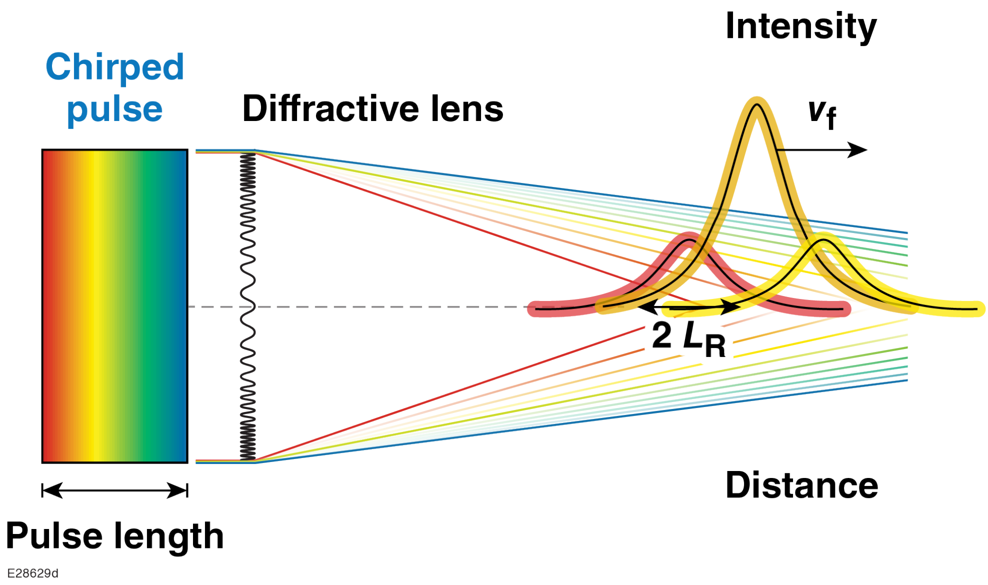

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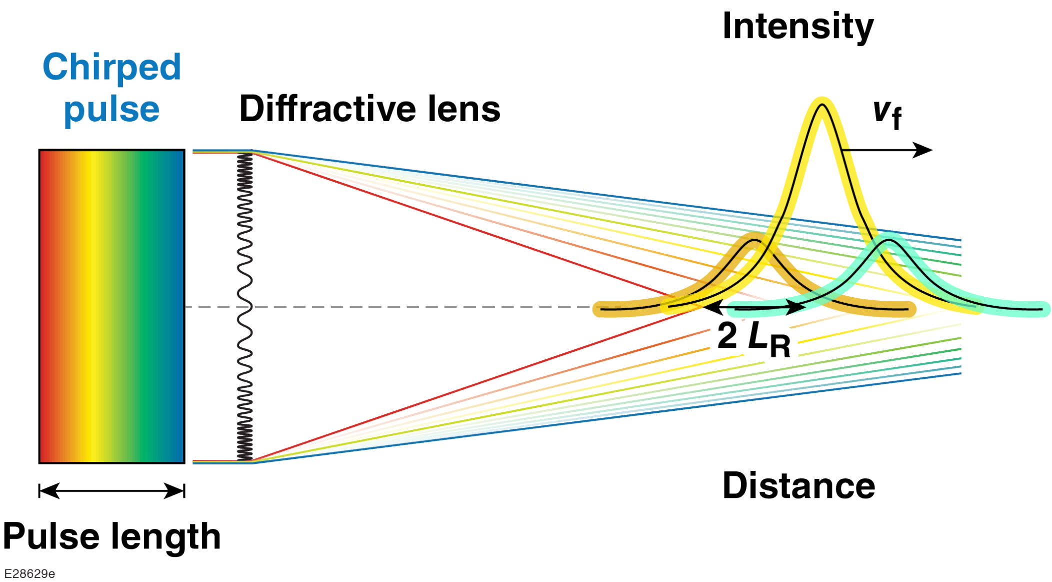

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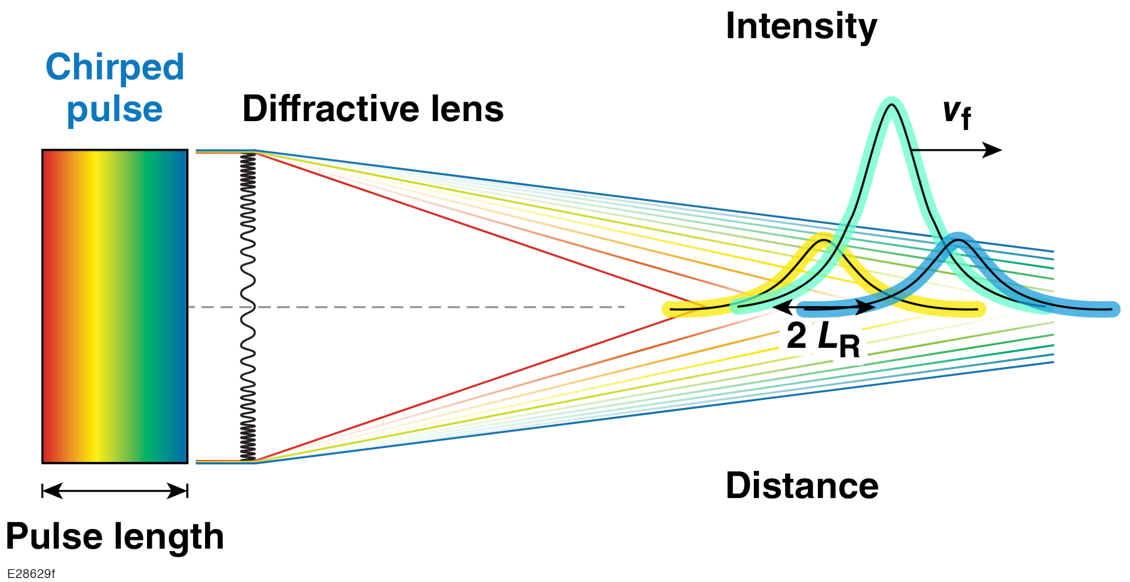


Effective duration set by the Rayleigh range

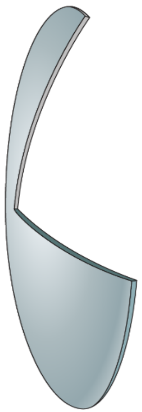
$$\Delta t \sim L_R / v_f$$

Many applications that could benefit from a tunable velocity require an ultrashort (< 1ps) intensity peak

J.P. Palastro *et al.*, Phys. Rev. A (2018)

For velocities near *c*, an axiparabola and a radial echelon can deliver ultrashort laser pulses to the far field

Axiparabola*



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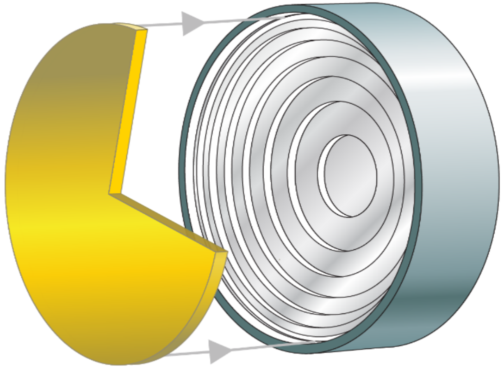
Radial Echelon**



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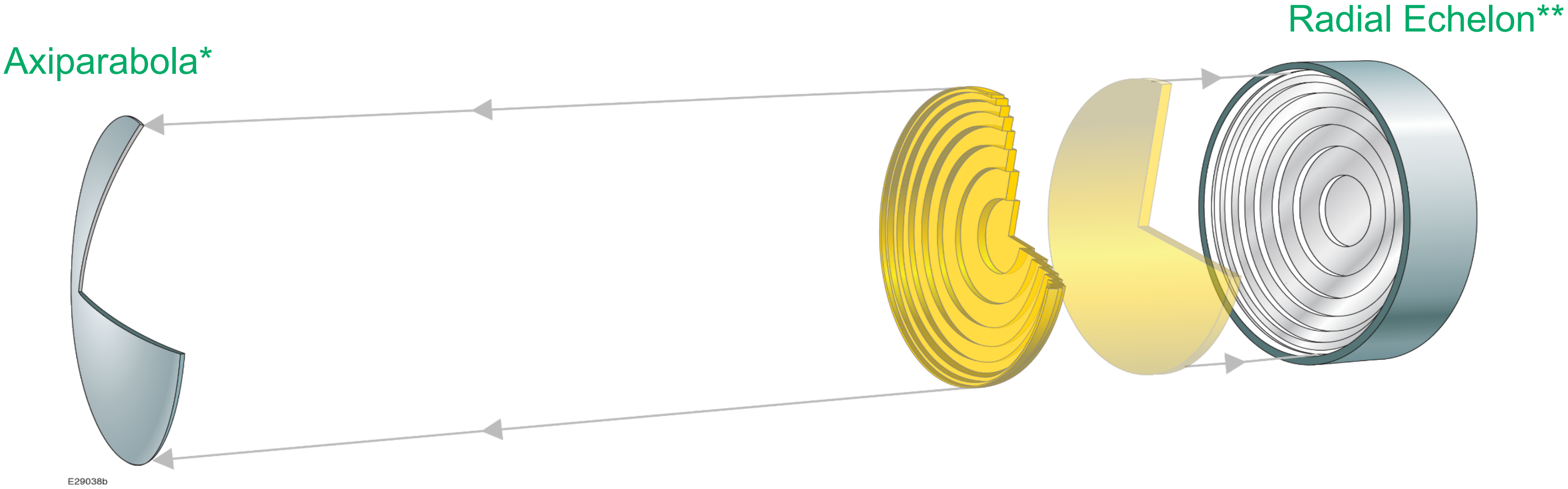

The radial echelon controls the time at which each annulus reaches its focus

**J.P. Palastro *et al.* Phys. Rev. Lett. (2020)

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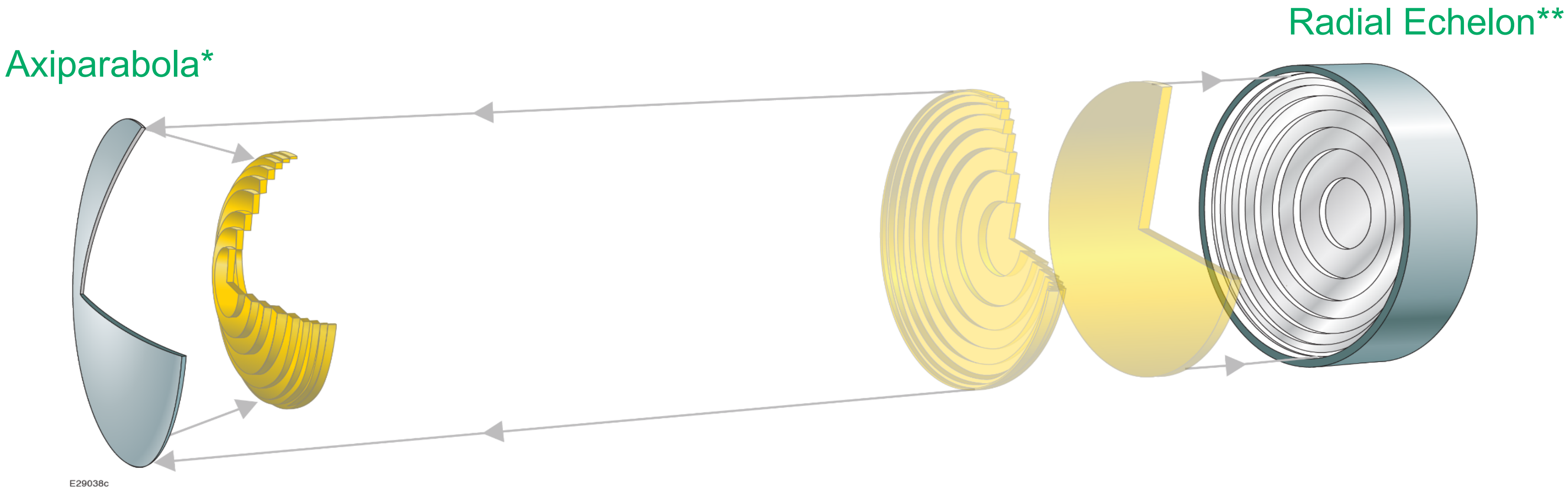

The axiparabola controls the focal length of each ring

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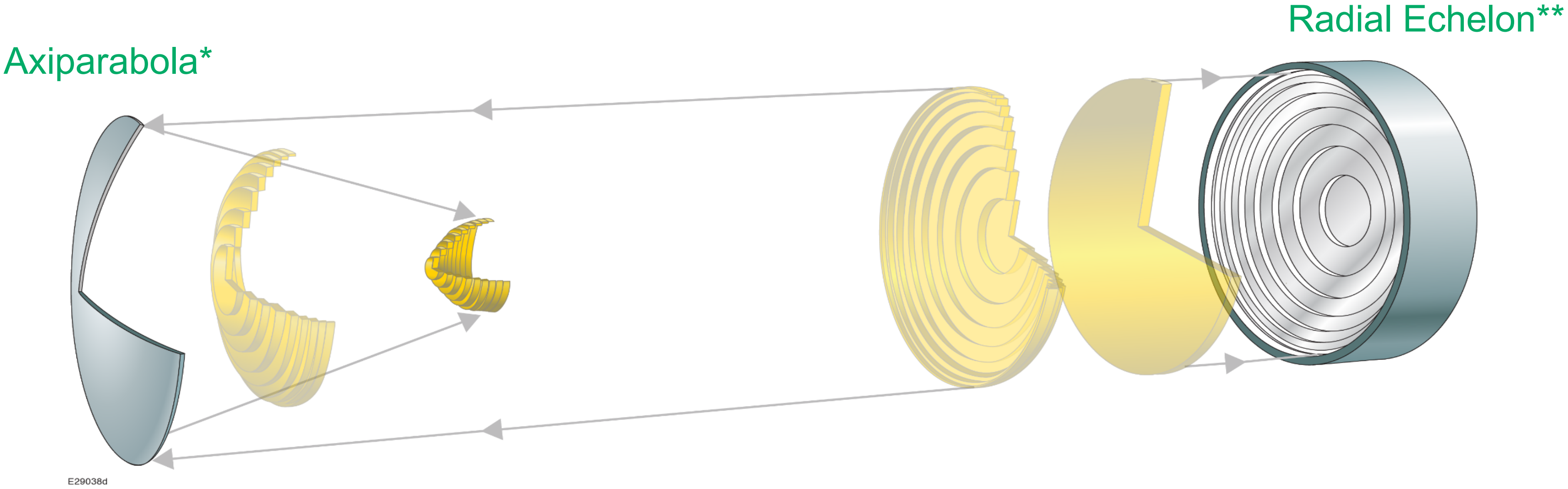

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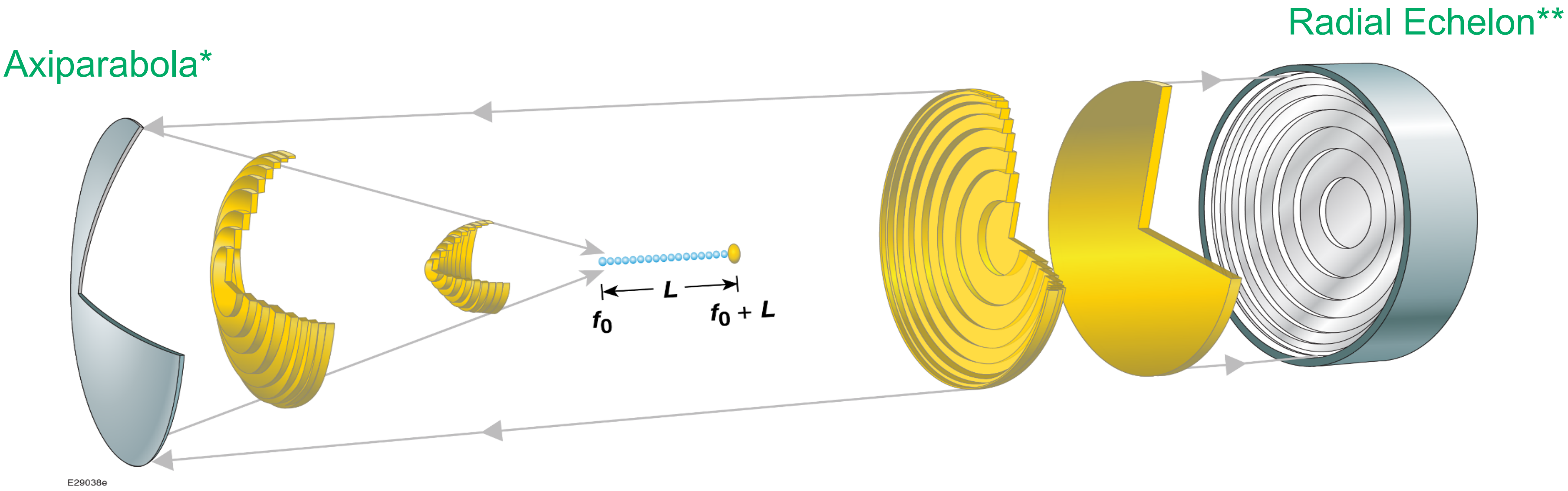
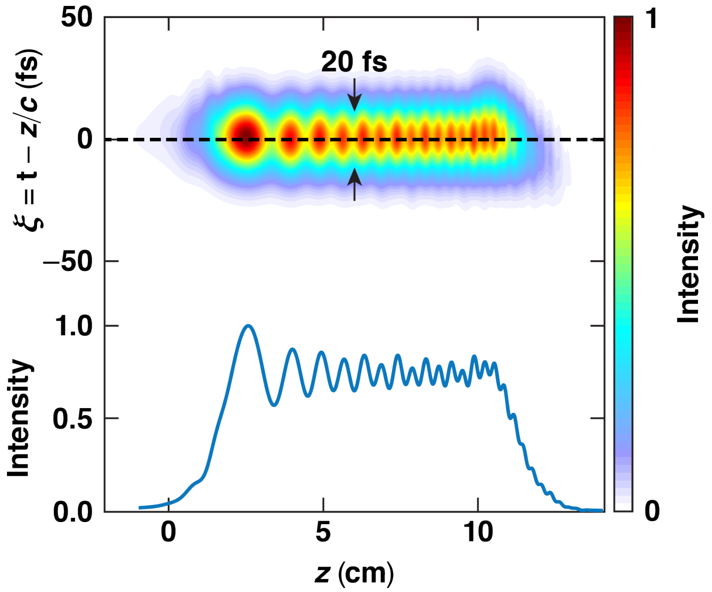


The shape of the echelon provides control over the velocity, while the spherical aberration of the axiparabola provides an extended focal range

**J.P. Palastro *et al.* Phys. Rev. Lett. (2020)

*S. Smartsev *et al.* Opt. Lett. **44**, 3414 (2019)

Wave propagation simulations demonstrate that the axiparabola and echelon can deliver a short pulse with a small spot over 10 cm



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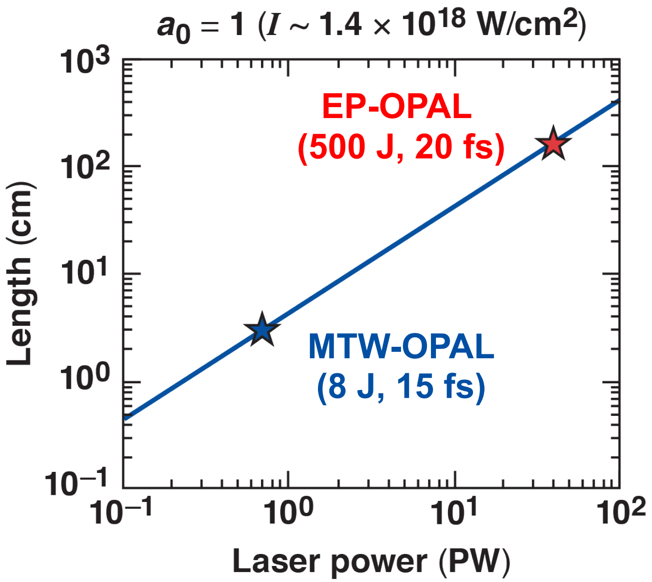

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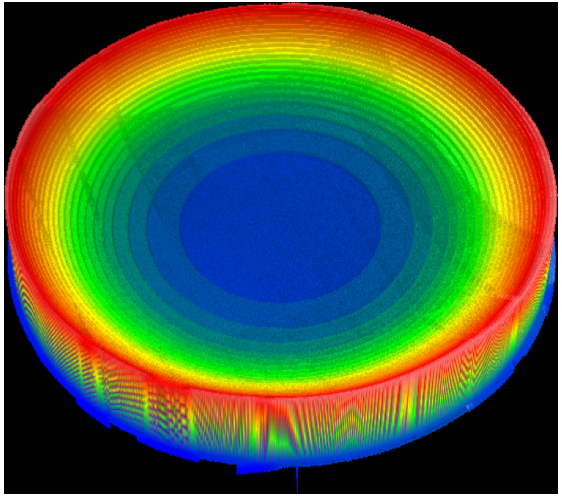
Emerging short-pulse laser systems provide the capability to produce relativistic intensities that propagate over centimeters to meters

LLE has developed an in-house capability to fabricate radial echelons using electron-beam evaporation



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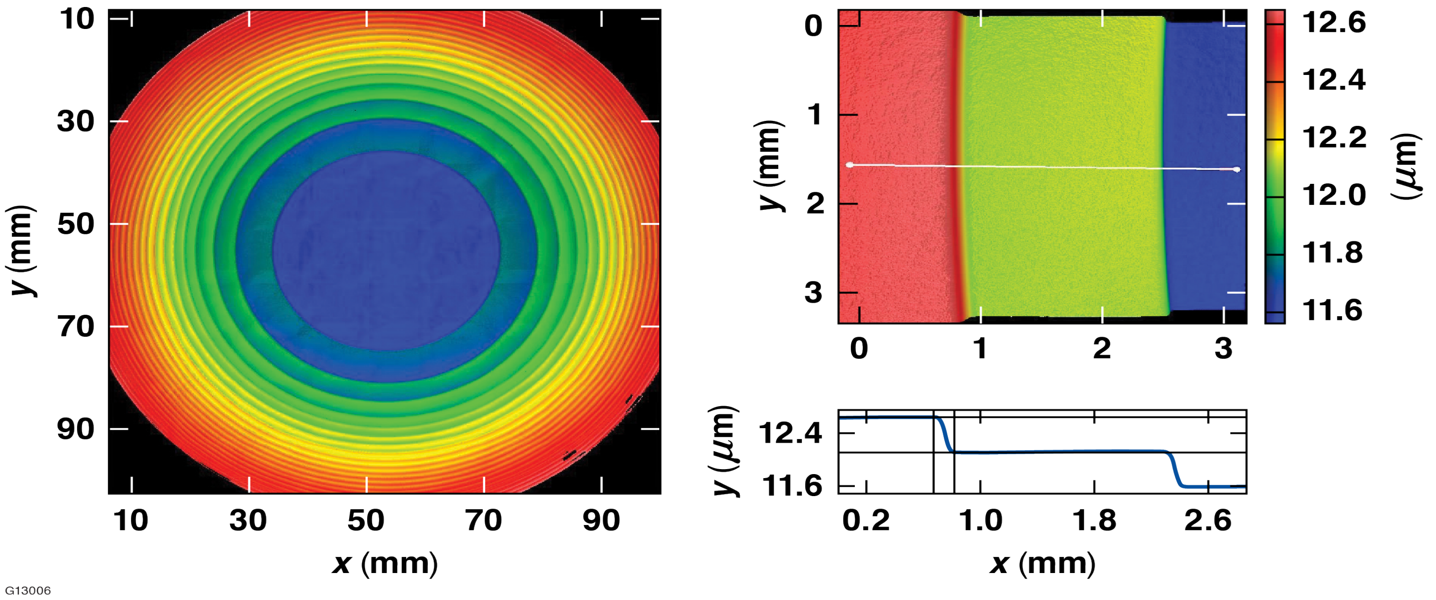
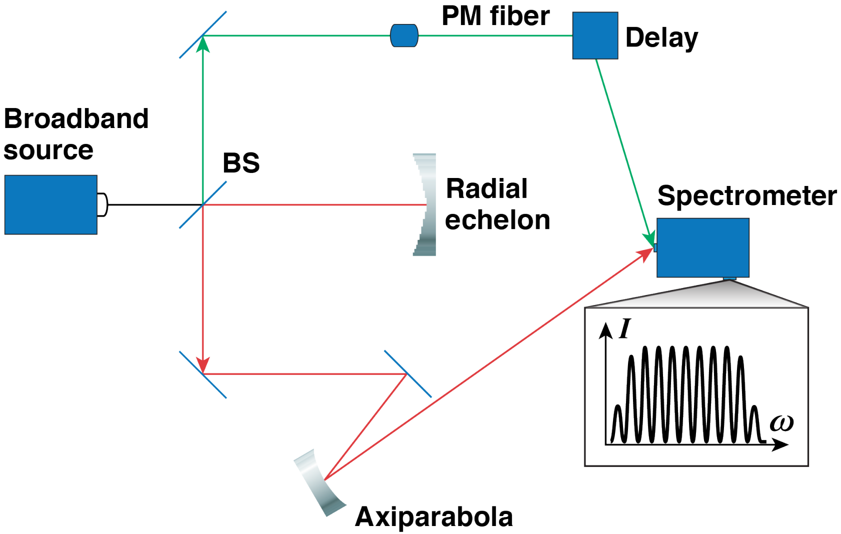
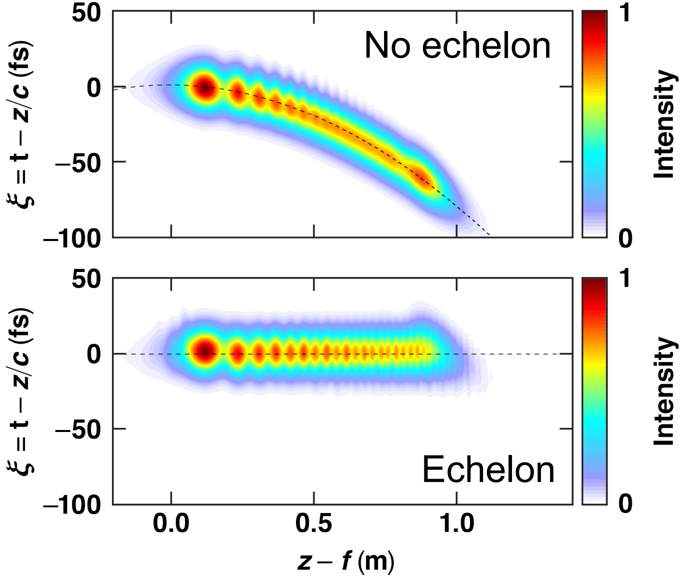


White light interferometry measurements have ensured that the manufactured echelons meet the specs for upcoming experiments

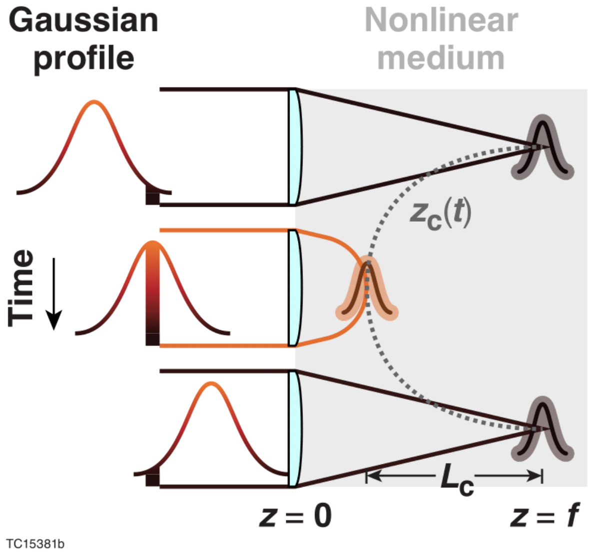
Upcoming experiments will demonstrate velocity control using the axiparabola-echelon pair





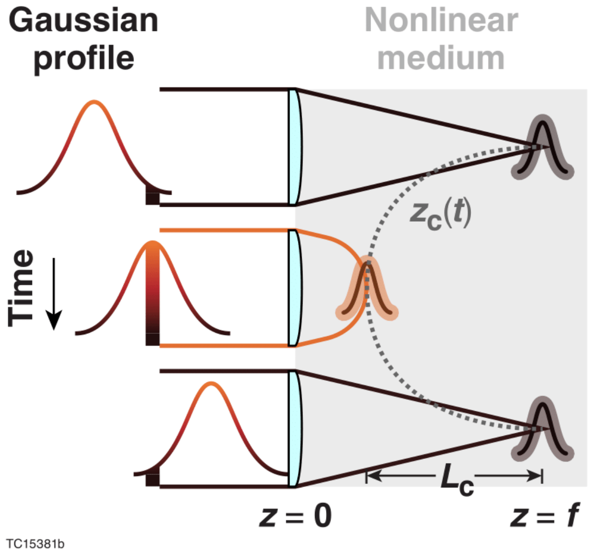
The spectral interference of a reference pulse with the imaged far-field of the axiparabola-echelon provides the relative delay and velocity

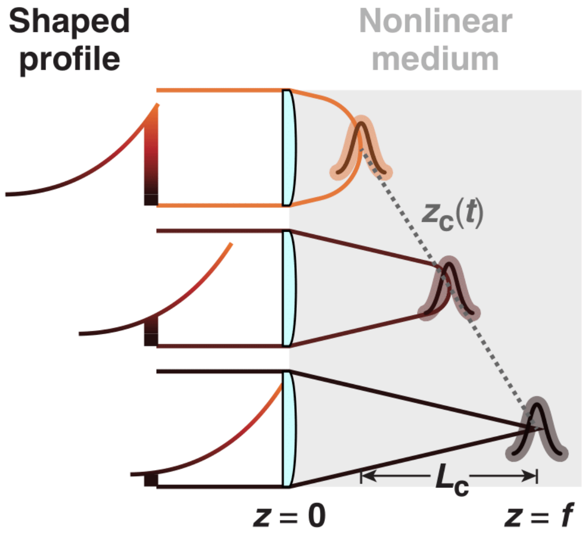
Existing techniques for spatiotemporal control rely on linear optical elements, but nonlinear optics can be used as well



In a nonlinear medium, each temporal slice within a laser pulse has a power-dependent focal length

Existing techniques for spatiotemporal control rely on linear optical elements, but nonlinear optics can be used as well





In a nonlinear medium, each temporal slice within a laser pulse has a power-dependent focal length

By shaping the temporal profile of the laser pulse, the peak intensity can move at any velocity

T. Simpson, submitted

Outline

1. Spatiotemporal pulse shaping

2. Applications

3. Basic plasma science

Outline

1. Spatiotemporal pulse shaping

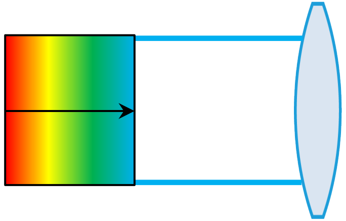
2. Applications

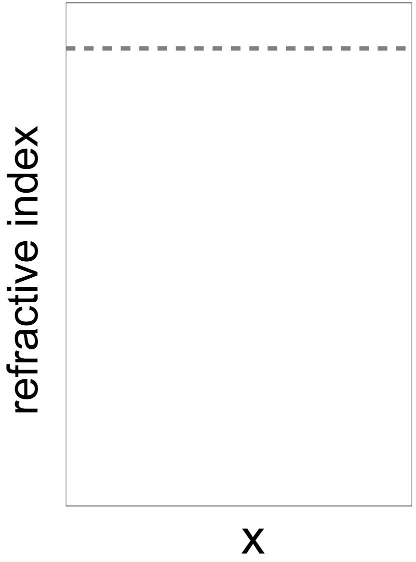
- Plasma channel formation
- Laser wakefield acceleration
- Vacuum laser acceleration
- Photon acceleration

3. Basic plasma science

Laser and beam driven advanced accelerators and directed energy applications require the formation of long plasma channels

Ionization refraction can inhibit the formation of long plasmas





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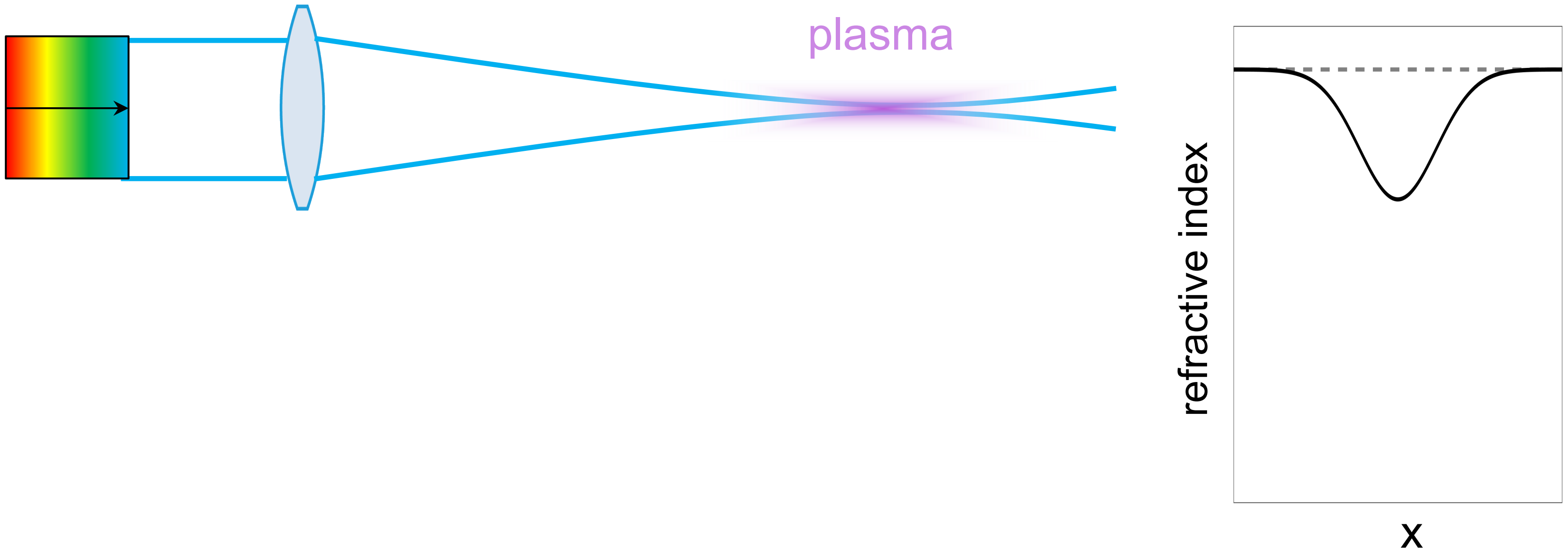

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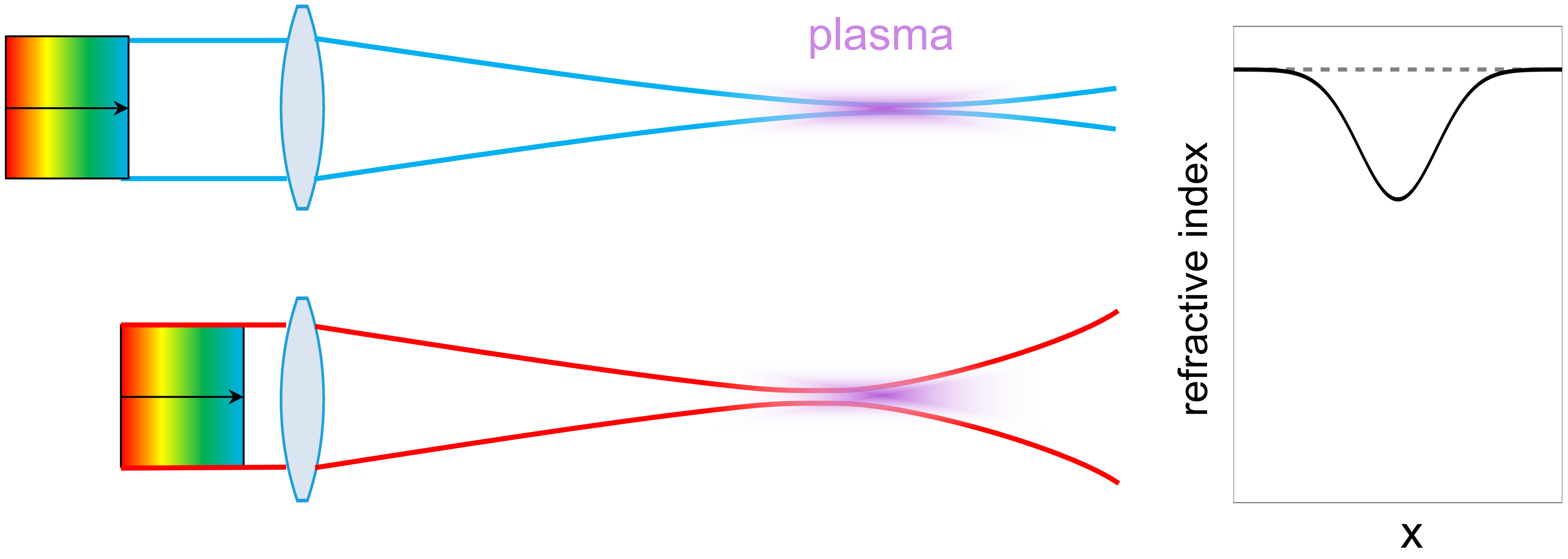

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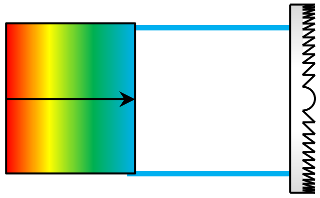

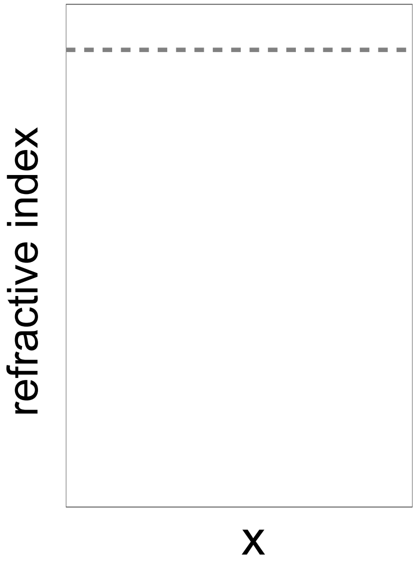

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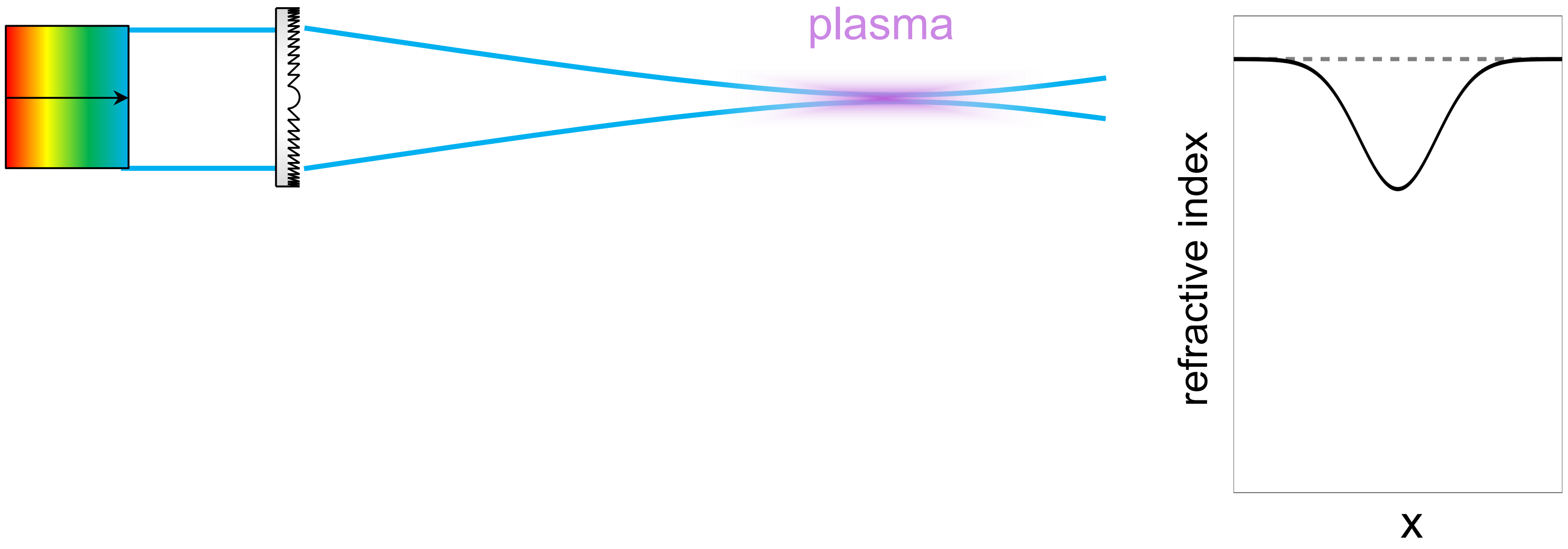

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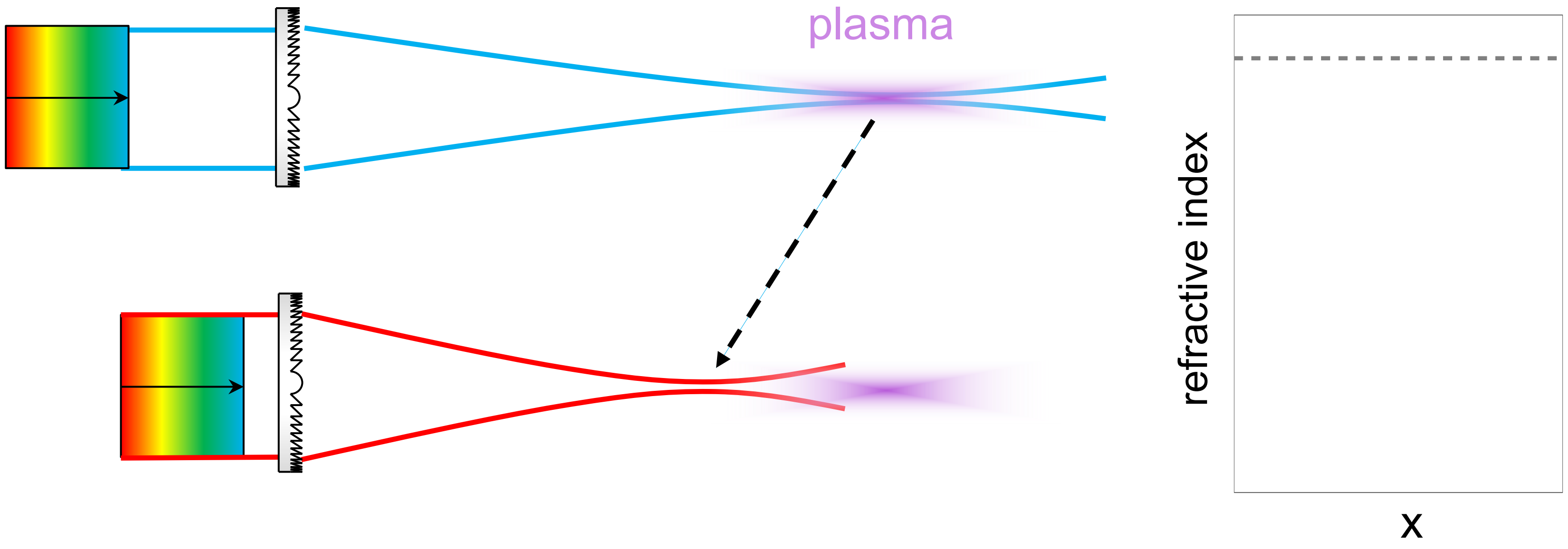

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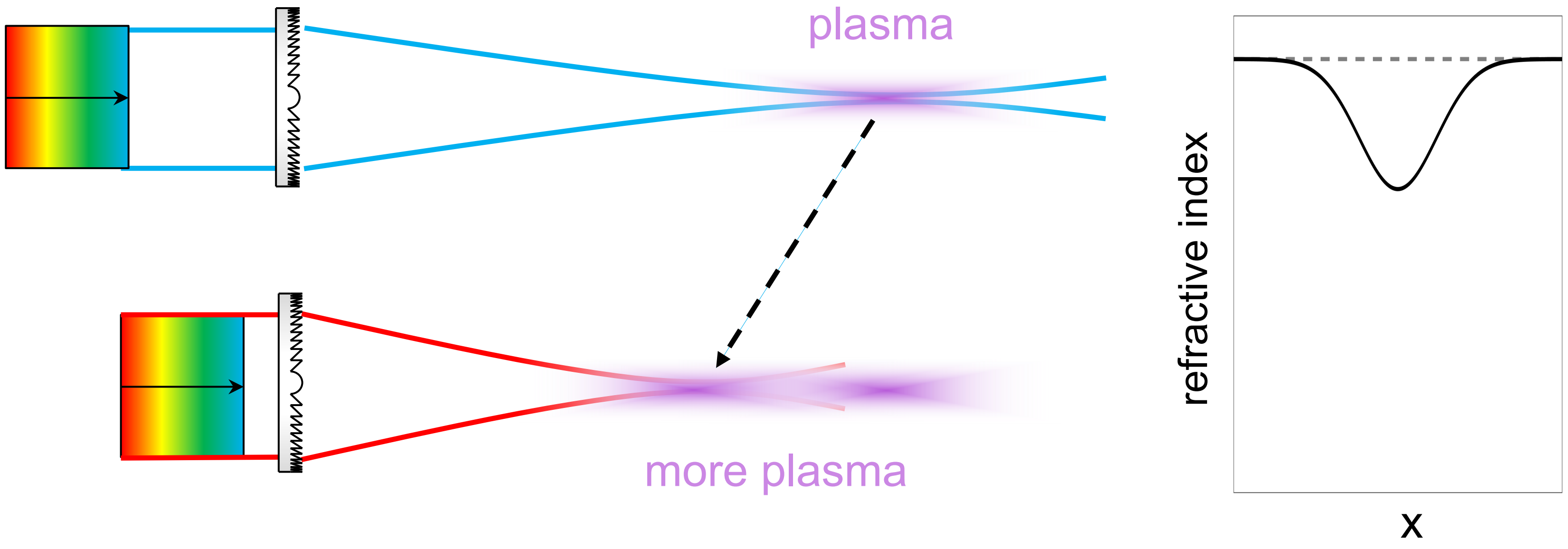
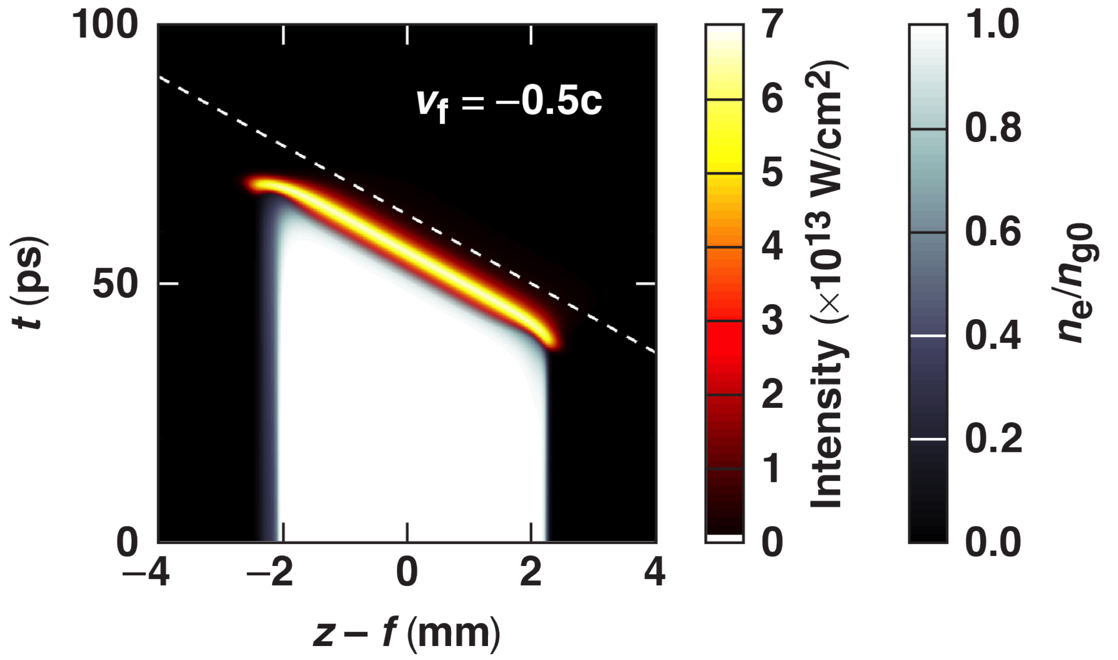
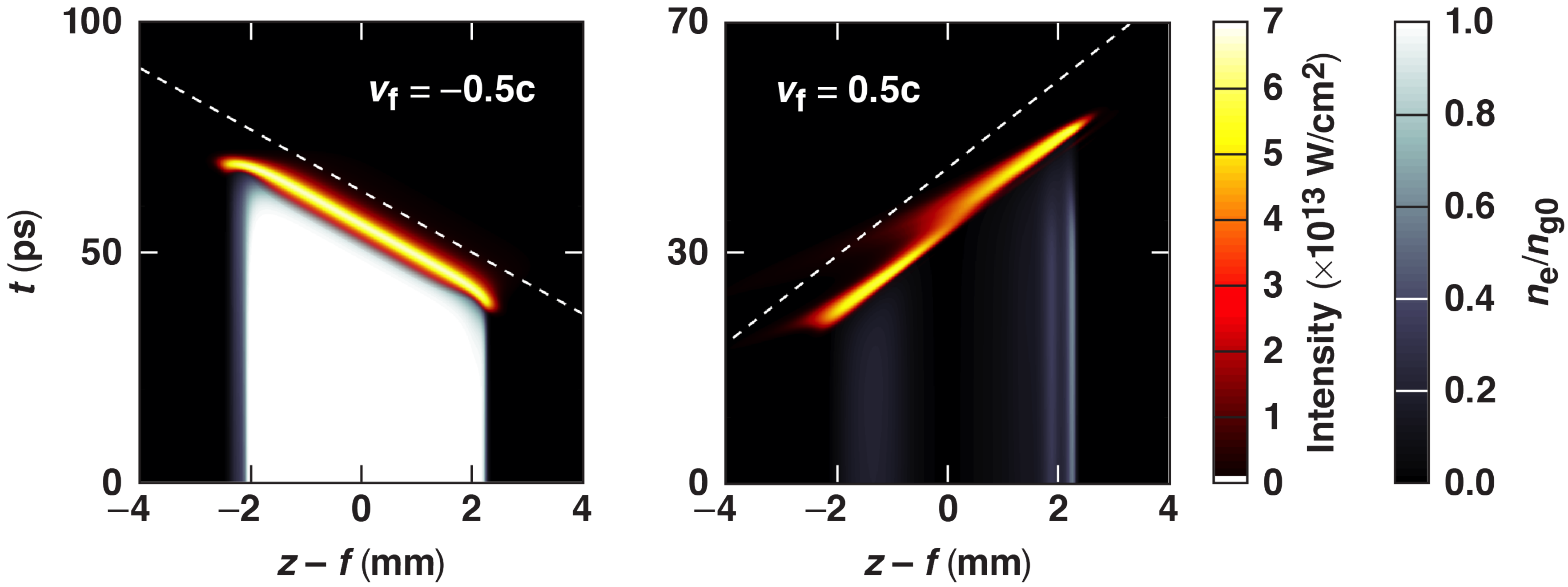


A counterpropagating flying focus mitigates plasma refraction and produces a sharp, clean ionization front



TC15505

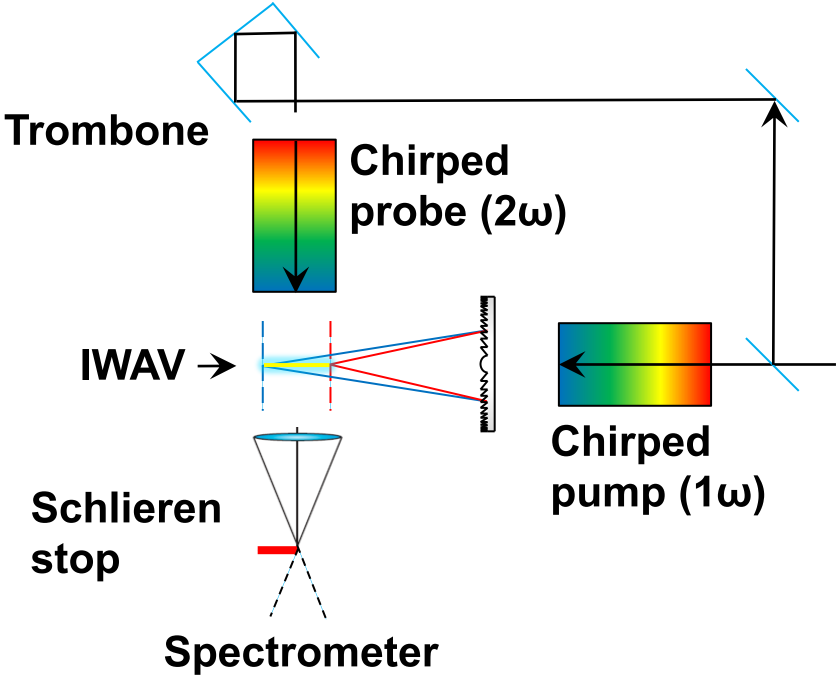
A counterpropagating flying focus mitigates plasma refraction and produces a sharp, clean ionization front

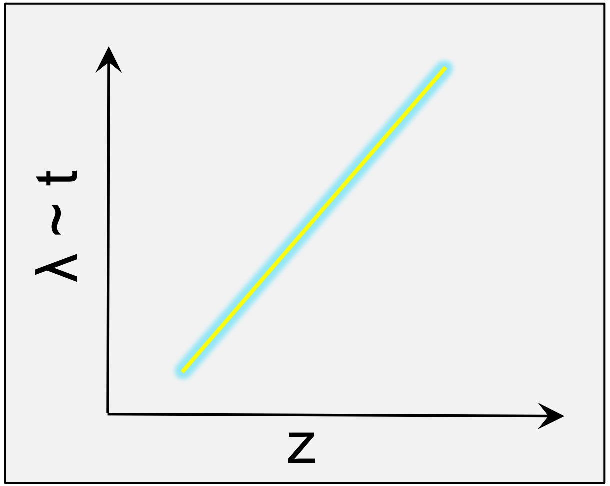


TC15504

- For $v_f = 0.5c$, plasma refracts the back of the pulse, limiting ionization

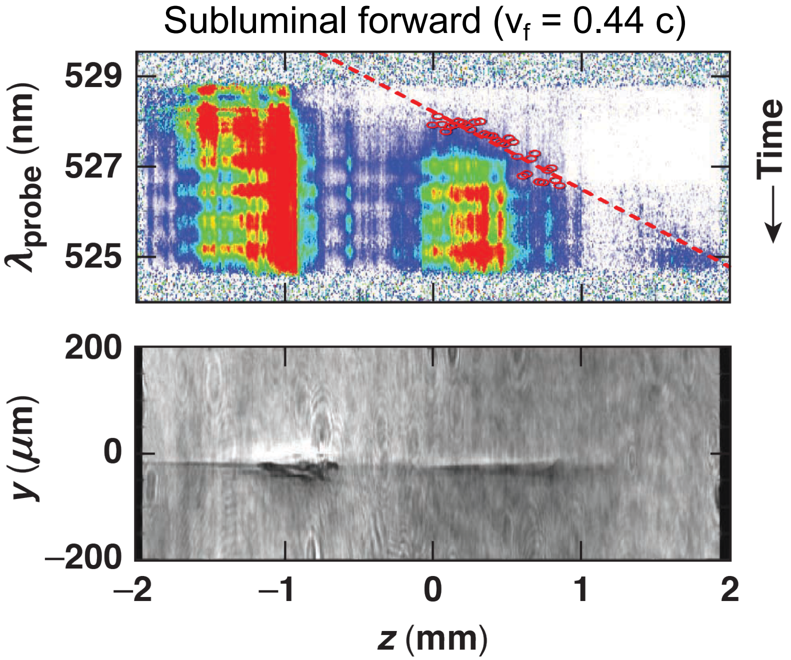
A novel time-resolved Schlieren diagnostic successfully demonstrated IWAV propagation

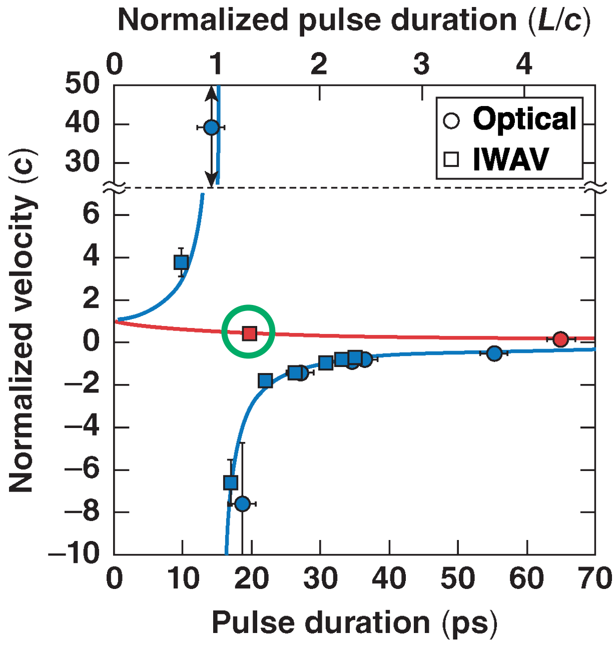




1D chirped Schlieren measures location of the ionization front in space and wavelength (~ time)

The analytic calculations and simulations are in excellent agreement with the measurements

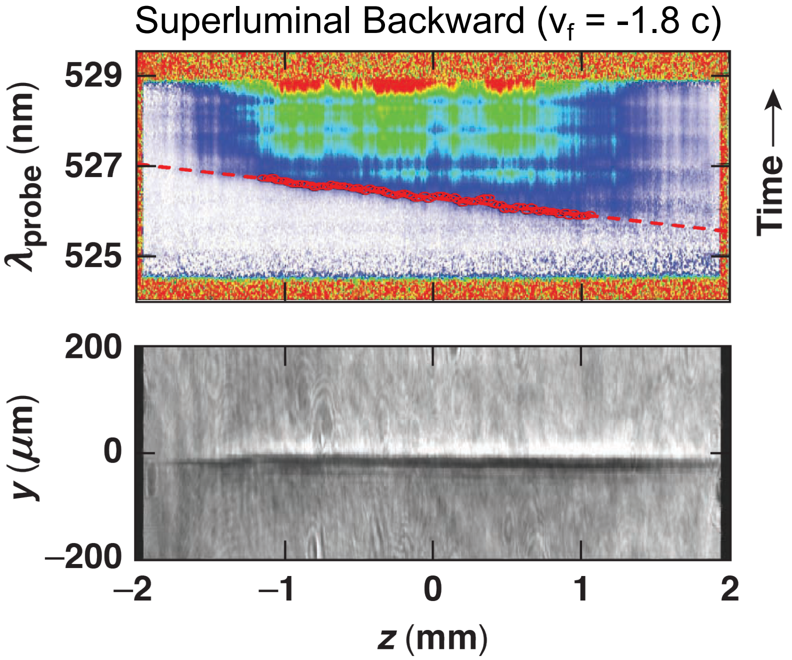


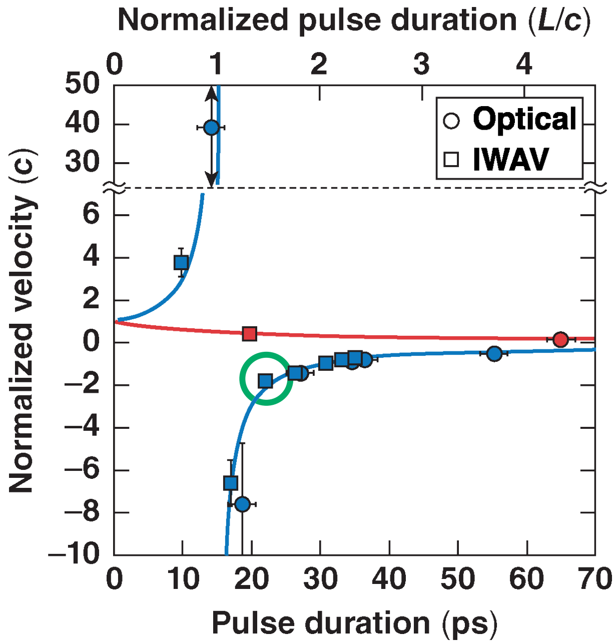


TC15494

Ionization refraction inhibited the formation of a continuous plasma channel

The analytic calculations and simulations are in excellent agreement with the measurements



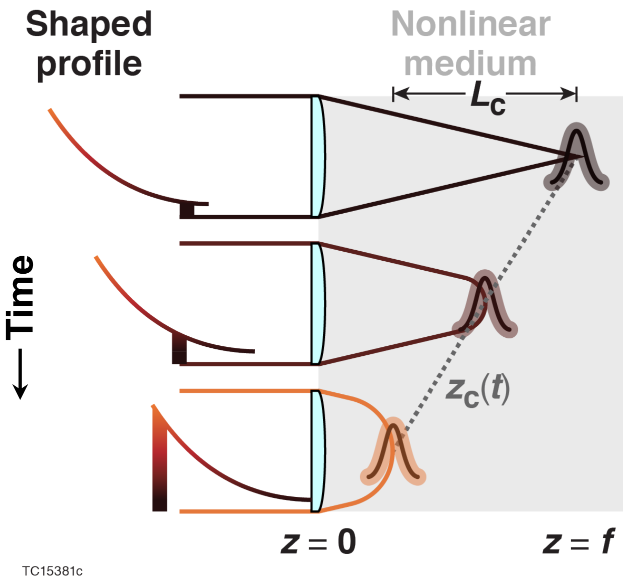


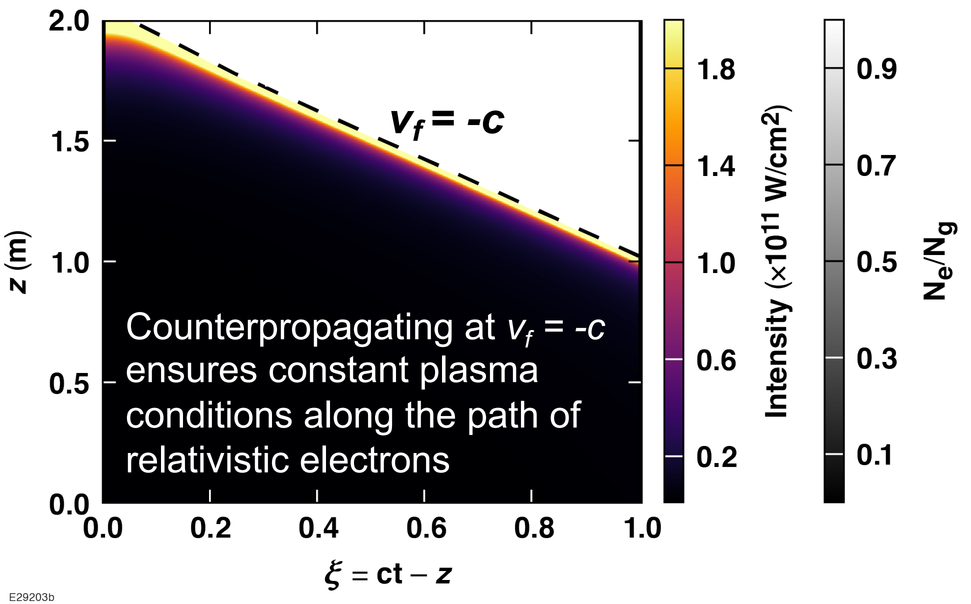
TC15495

Backwards propagation of the intensity peak eliminates ionization refraction

D. Turnbull *et al.*, Phys. Rev. Lett. **120**, 225001 (2018)

The "self-flying focus" could create the meter-scale plasma channels necessary for advanced accelerators





A laser wakefield accelerator driven by spatiotemporally shaped pulse could accelerate electrons to ~300 GeV over 1 meter

A high-intensity laser pulse can drive a plasma wave that accelerates electrons to relativistic energies over short distances

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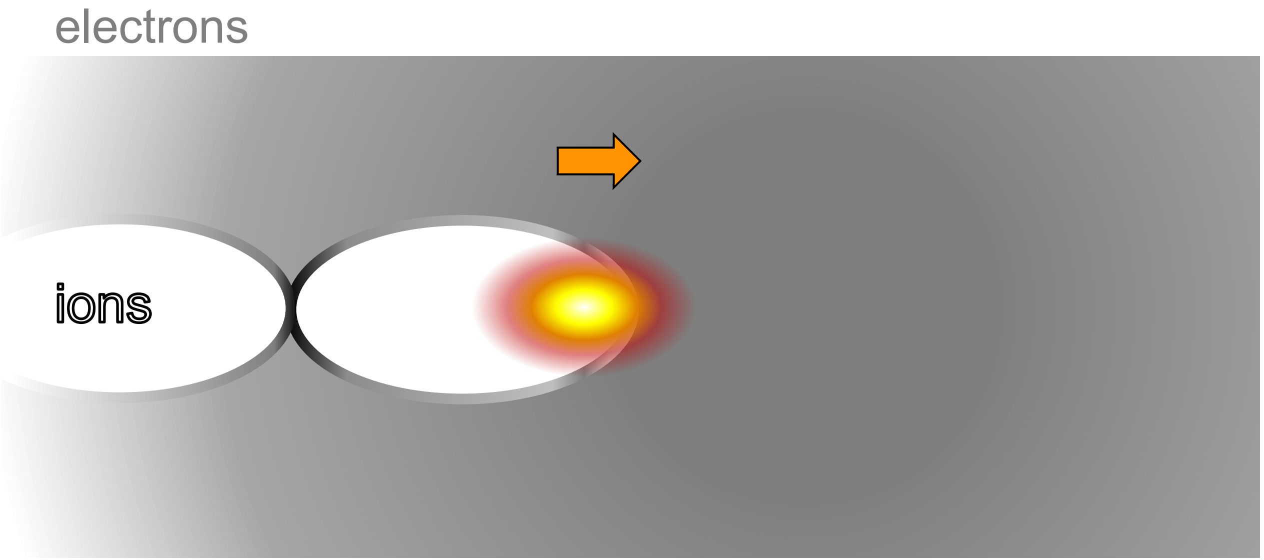

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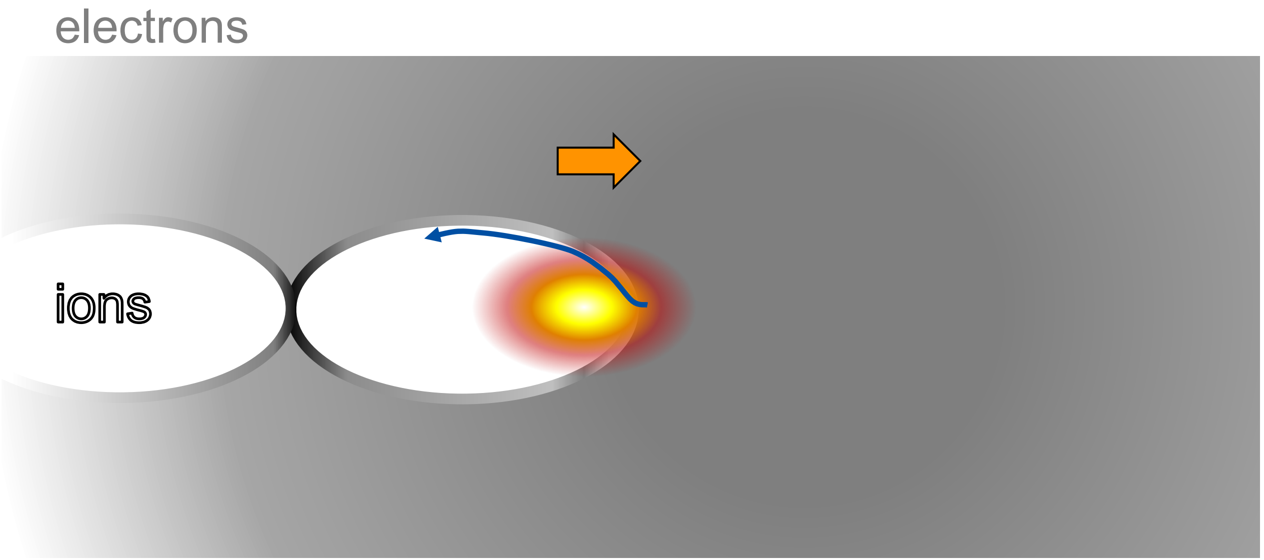

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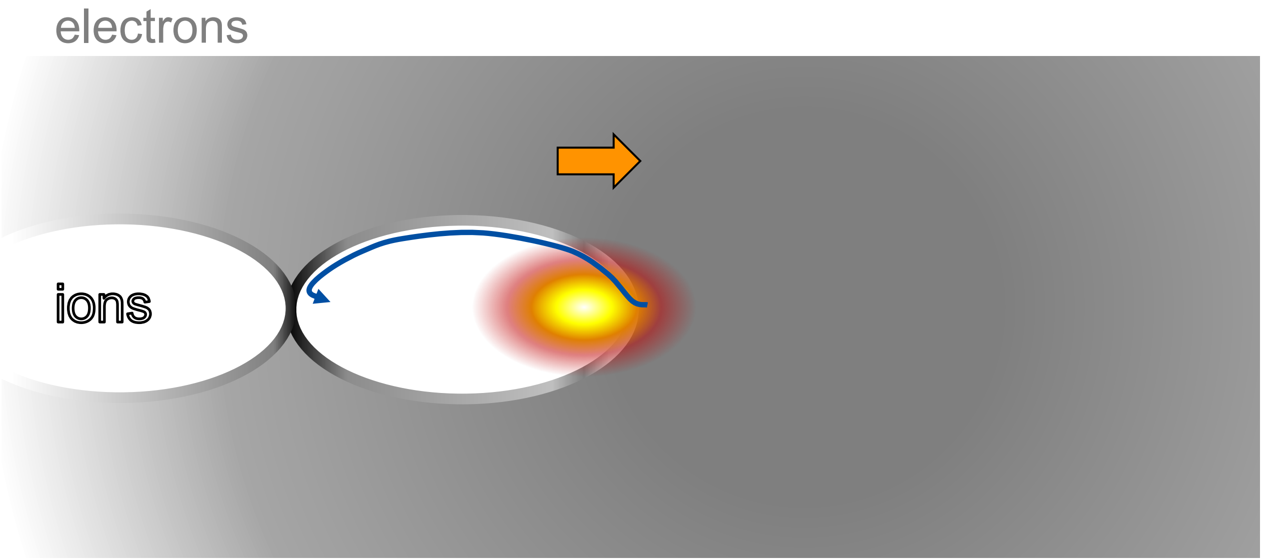

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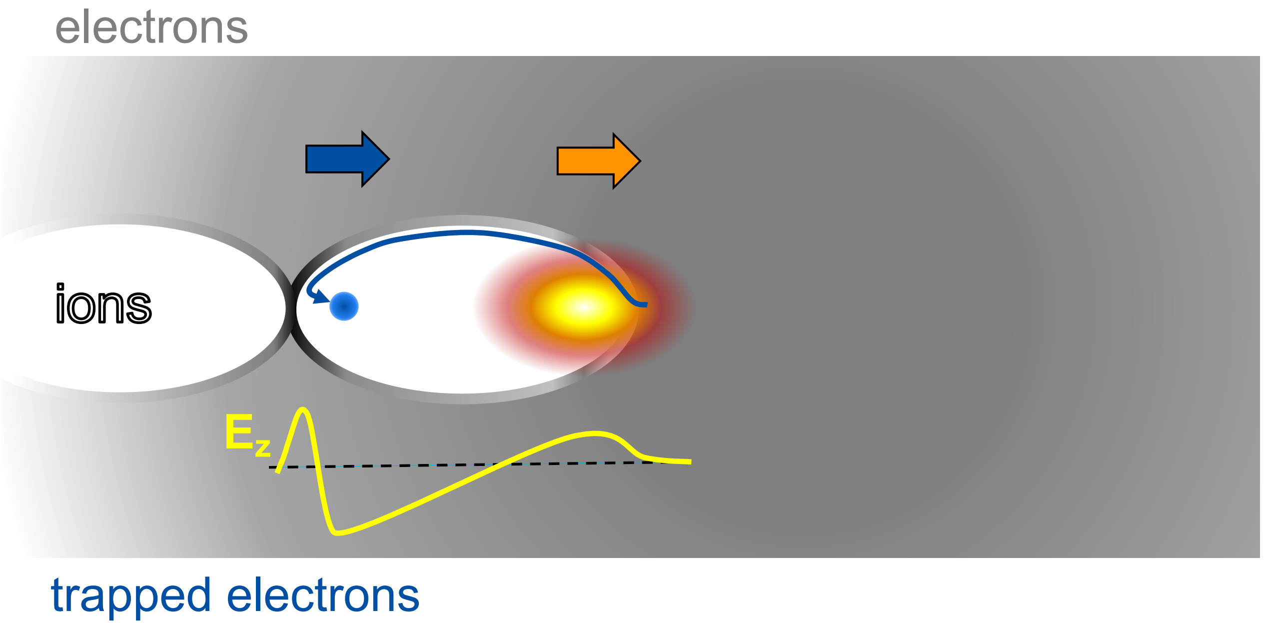

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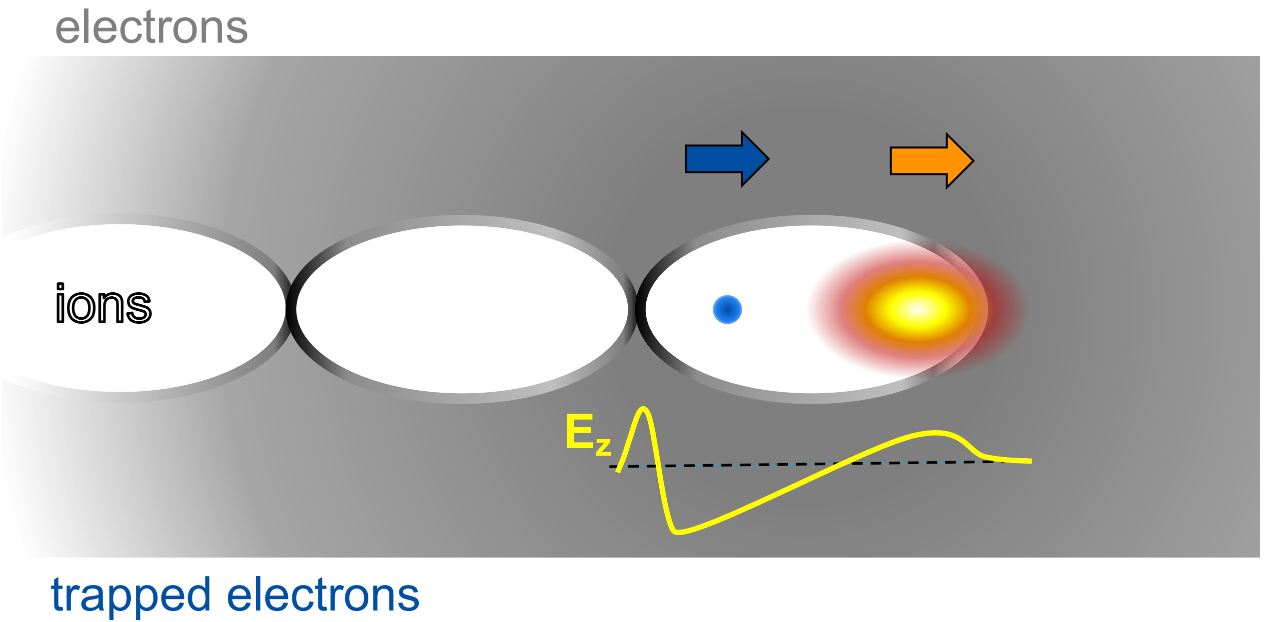
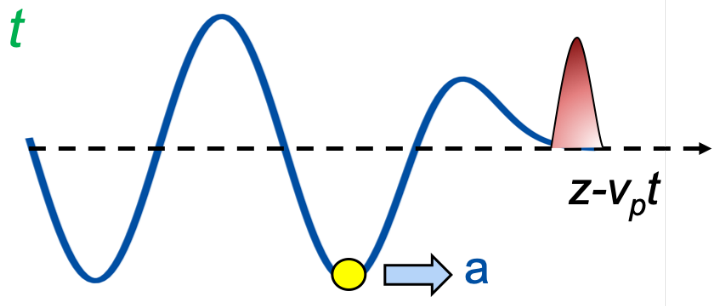


In traditional laser wakefield acceleration, relativistic electrons can outrun the accelerating phase of the wakefield, i.e., dephase

Dephasing



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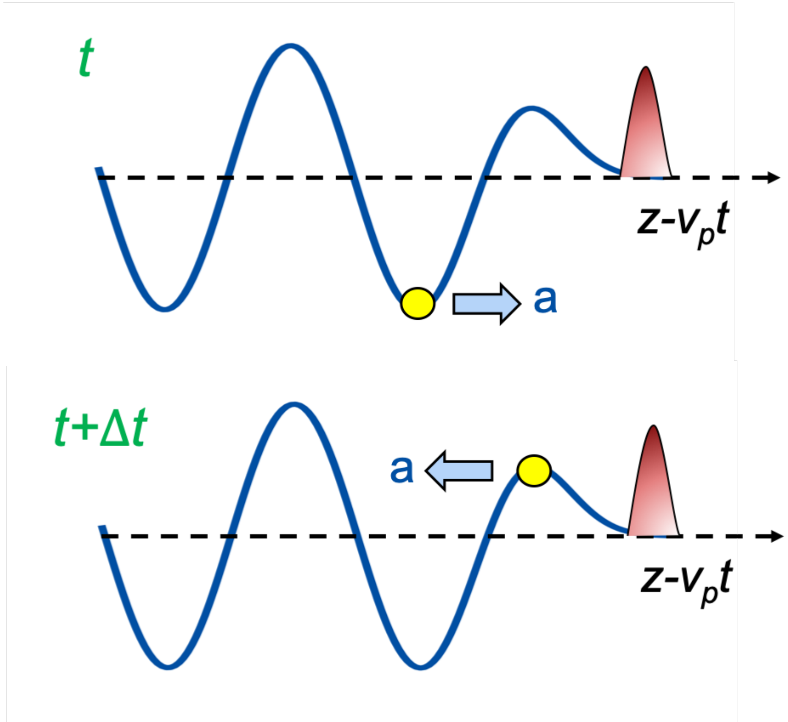

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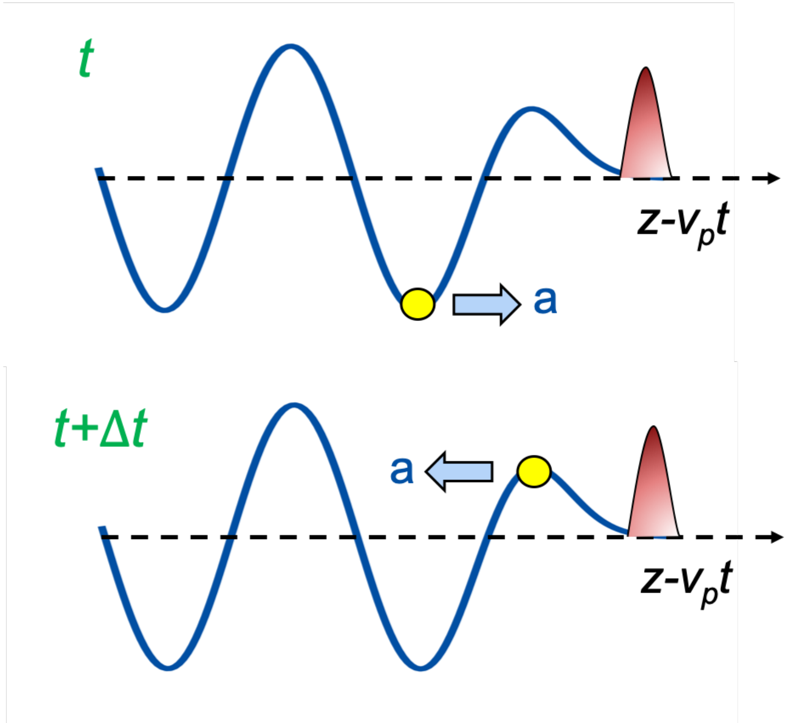


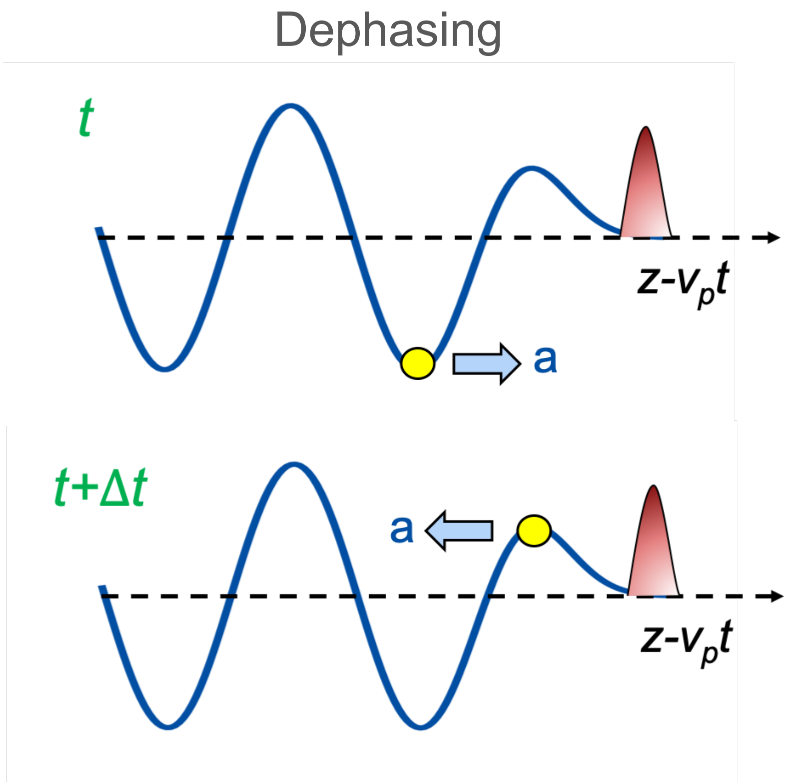
- The group velocity of the laser pulse sets the phase velocity of the plasma wave

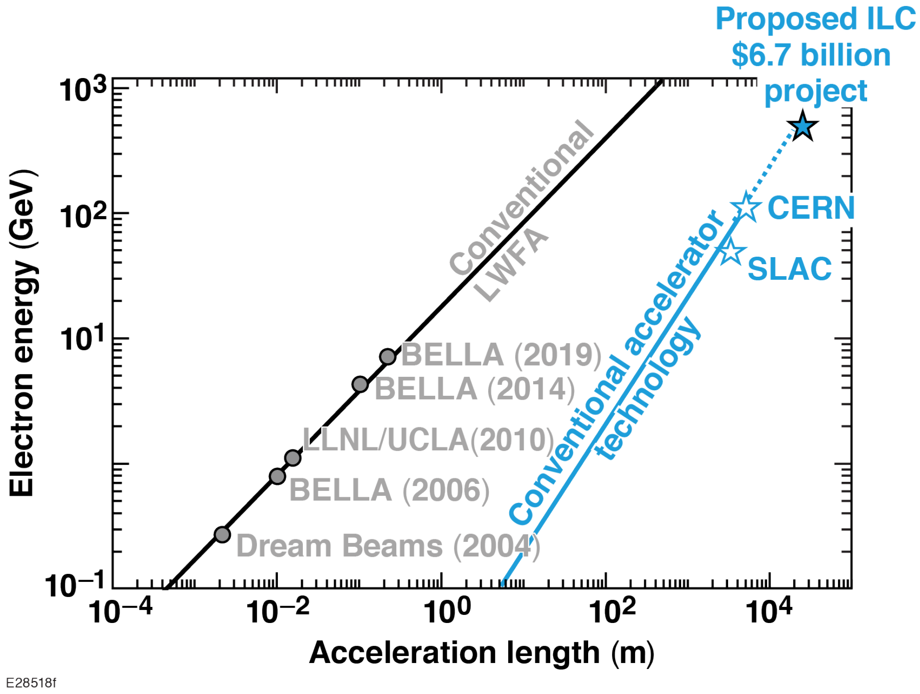
$$v_p = c\left(1 - \frac{\omega_p^2}{\omega^2}\right)^{1/2} < c$$

- Lowering the plasma density increases the group velocity and the distance over which the electron outruns the acceleration phase

$$L_d = 2\pi c \frac{\omega^2}{\omega_p^3}$$

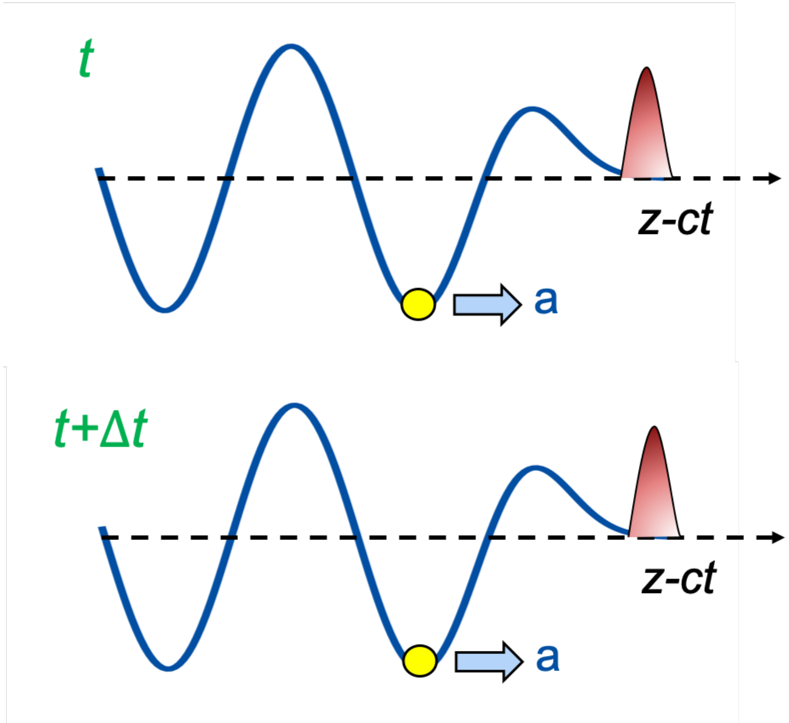
In traditional laser wakefield acceleration, relativistic electrons can outrun the accelerating phase of the wakefield, i.e., dephase

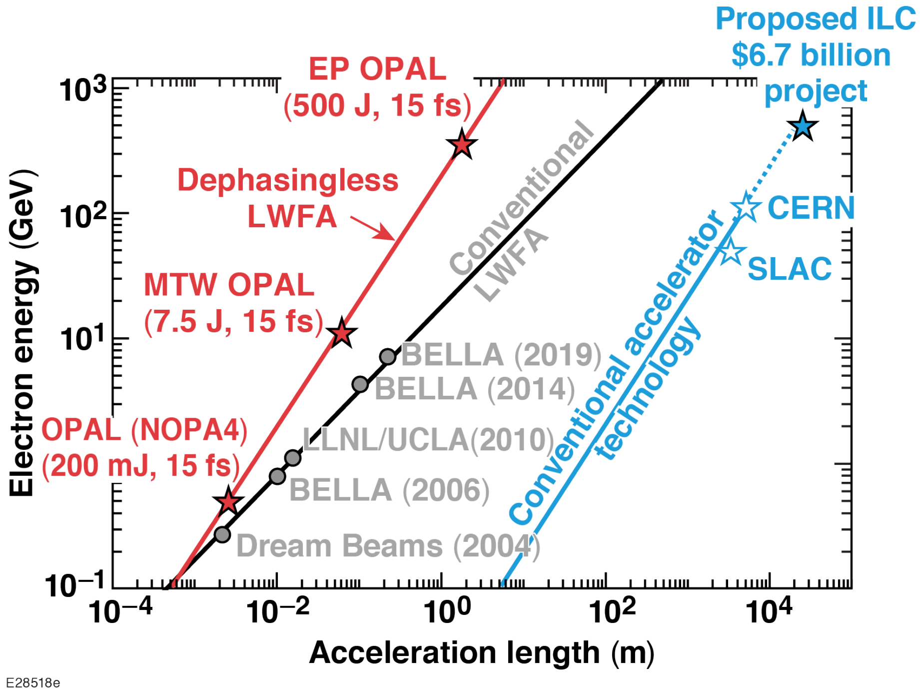




Spatiotemporal control provides an intensity peak that can move at the vacuum speed of light in plasma, eliminating dephasing*,**

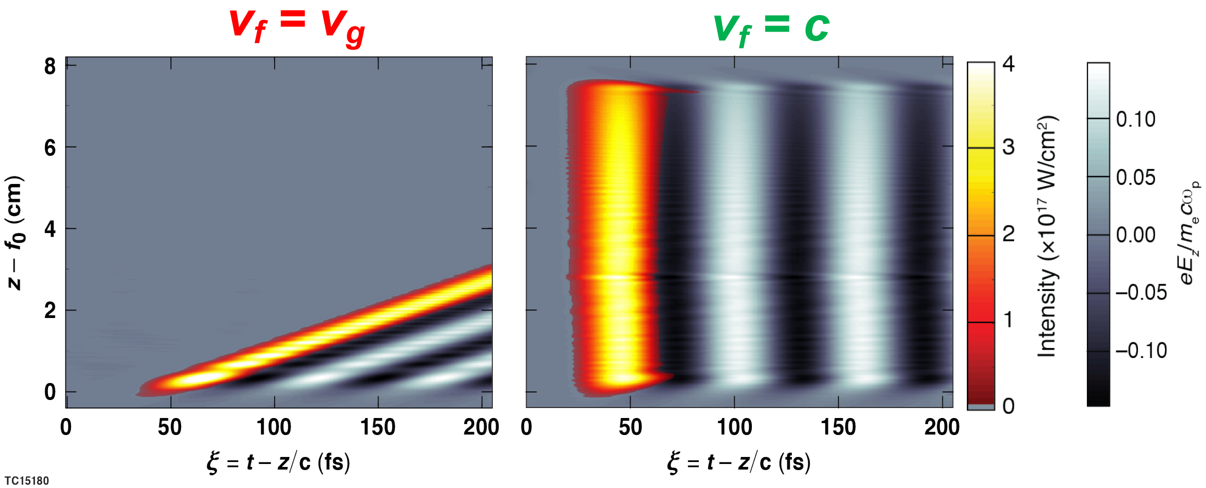
No Dephasing





*J.P. Palastro *et al.* Phys. Rev. Lett. (2020) **C. Caizergues *et al.*, Nat. Photonics (2020)

Simulations demonstrate that a dephasingless LWFA can accelerate electrons to much higher energies than a traditional LWFA



Propagation simulations show that a laser pulse prepared by an axiparabola-enchelon pair can drive a wake with a phase velocity = c

*J.P. Palastro *et al.* Phys. Rev. Lett. (2020)

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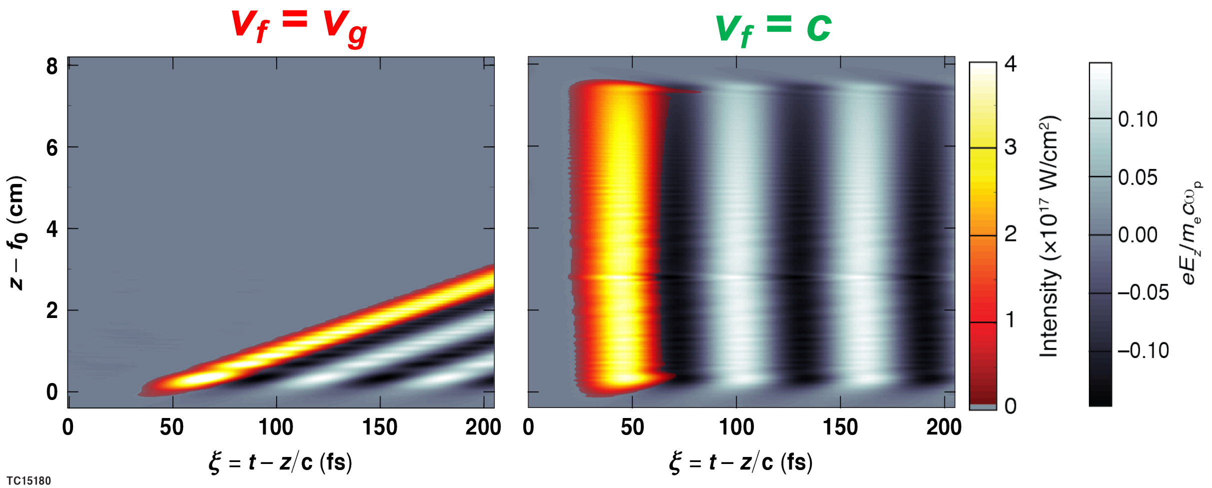
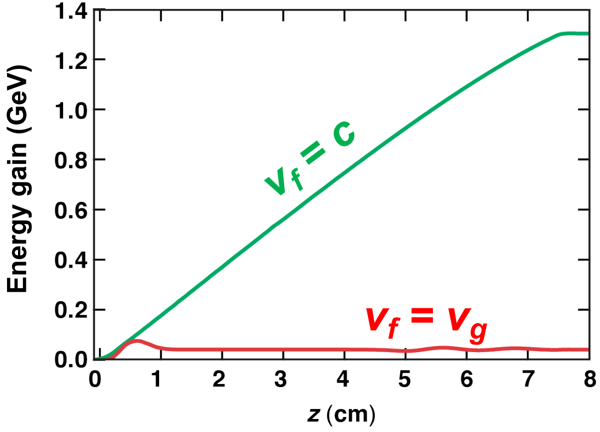


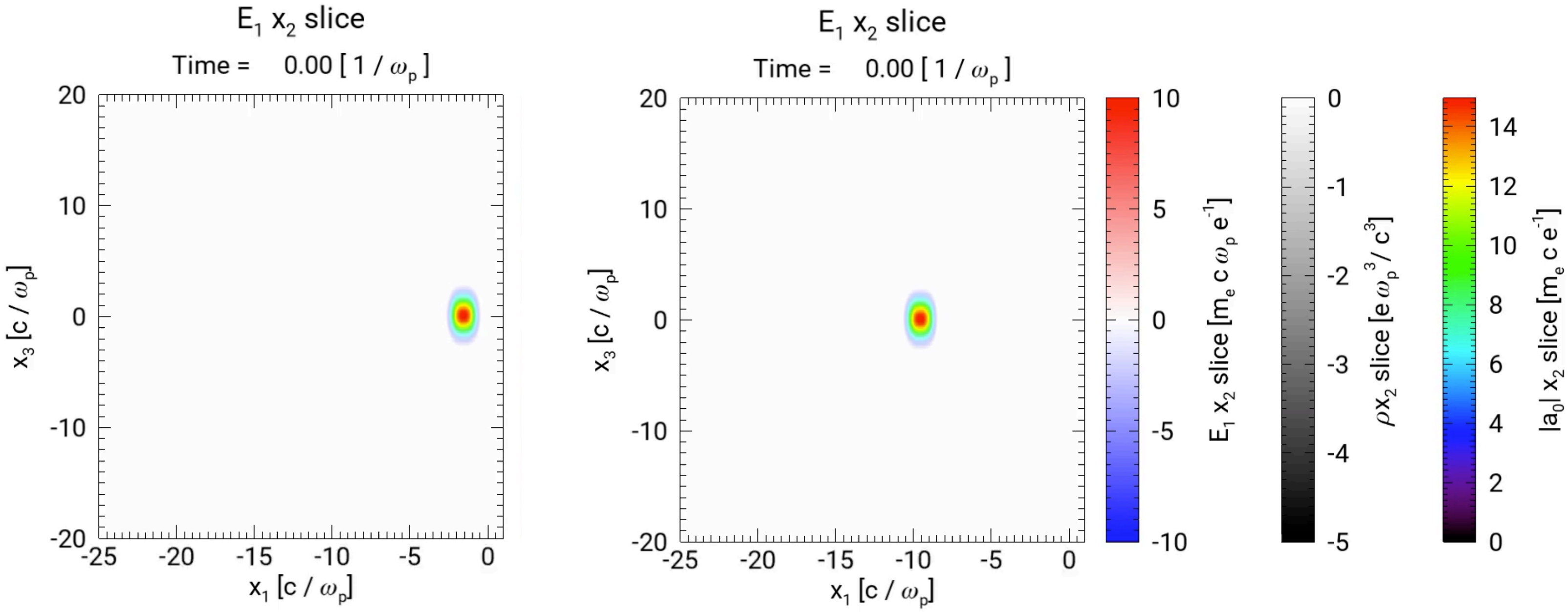


Propagation simulations show that a laser pulse prepared by an axiparabola-enchelon pair can drive a wake with a phase velocity = c

An electron cannot outrun a wakefield moving at the vacuum speed of light

*J.P. Palastro *et al.* Phys. Rev. Lett. (2020)

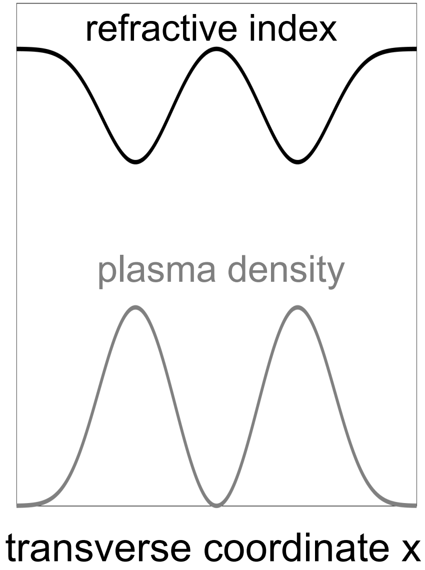
A superluminal wake cannot trap charged particles and is therefore immune to wavebreaking

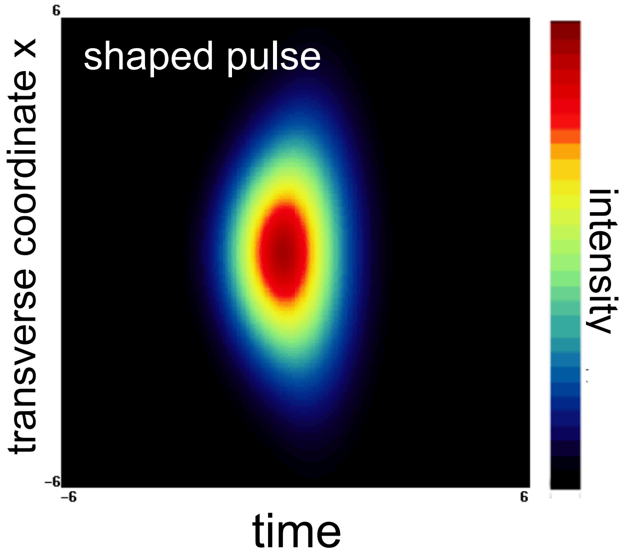


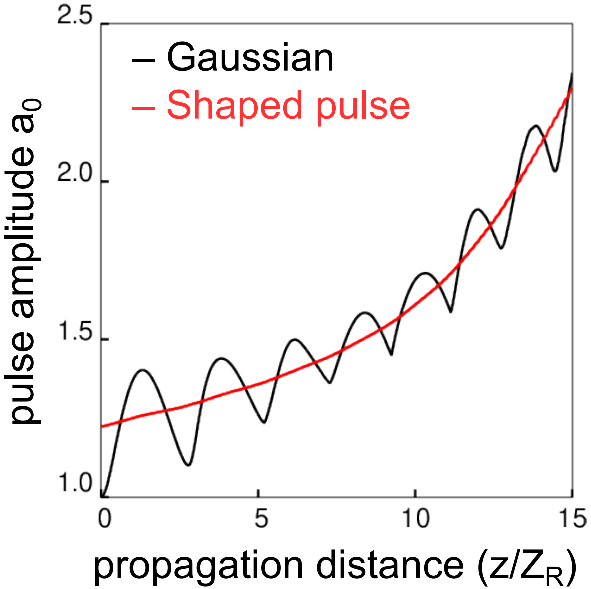
A superluminal wake can be driven with an arbitrarily large amplitude without unwanted electron trapping that can spoil the electron bunch quality

*J.P. Palastro *et al.* submitted (2020) **B. Malaca *et al.* In Progress (2020)

A shaped pulse can improve plasma channel guiding by eliminating spot size oscillations due to nonlinear focusing





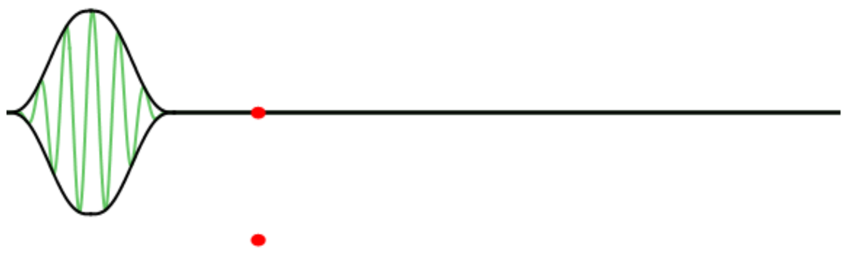


Pulse shaping allows for stable guiding at much higher laser powers

C. Benedetti *et al.*, Phys. Rev. E (2015) C. Benedetti *et al.*, Phys. Plasmas (2012)

Spatiotemporal pulse shaping enables a novel mechanism for vacuum acceleration, eliminating the complications of plasma

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



An electron gains axial momentum on the leading edge of the pulse, but loses all of this momentum on the falling edge

Spatiotemporal pulse shaping enables a novel mechanism for vacuum acceleration, eliminating the complications of plasma

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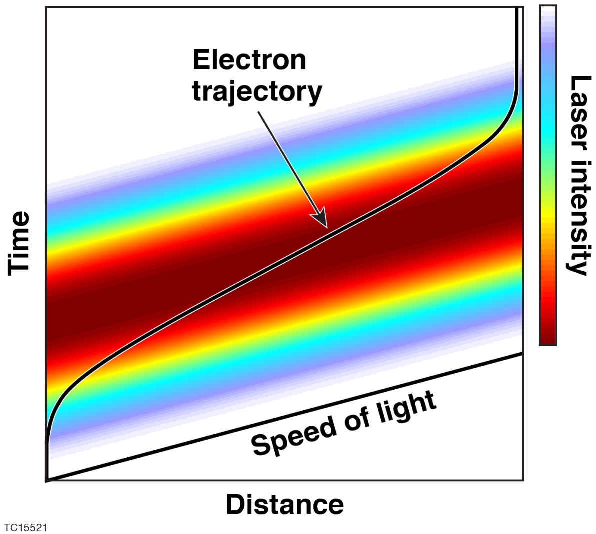
Standard Focus

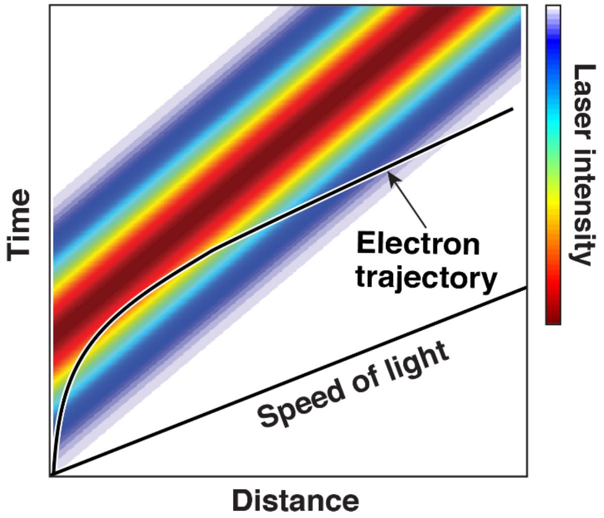


An electron gains axial momentum on the leading edge of the pulse, but loses all of this momentum on the falling edge

Spatiotemporal pulse shaping enables a novel mechanism for vacuum acceleration, eliminating the complications of plasma

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

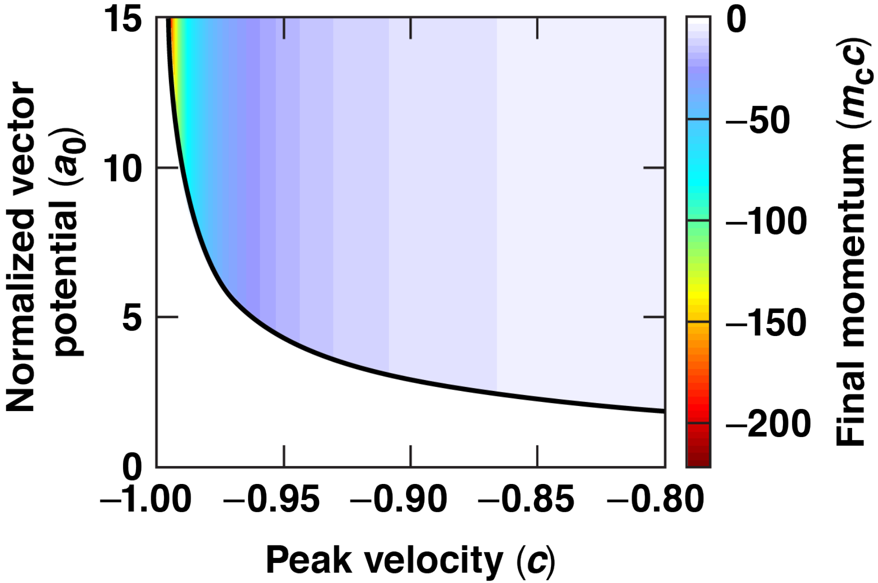
Flying Focus



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

D. Ramsey, accepted Phys. Rev. E

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



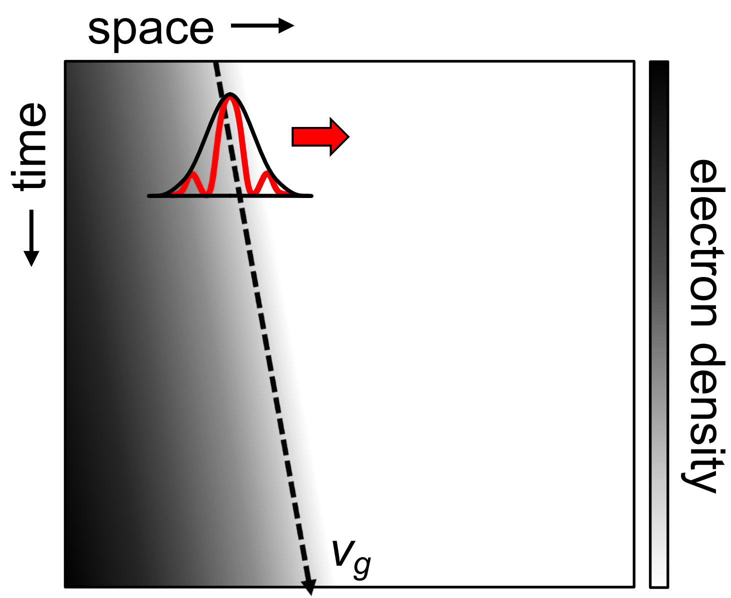
TC15520

The electron gains energy when the ponderomotive potential of the pulse (a_0^2) exceeds the kinetic energy of the electron in the flying focus Lorentz frame

D. Ramsey, accepted Phys. Rev. E

An ionization wave created by a flying focus pulse can accelerate optical photons to the XUV

A time-varying refractive index can accelerate (i.e., frequency upshift) photons



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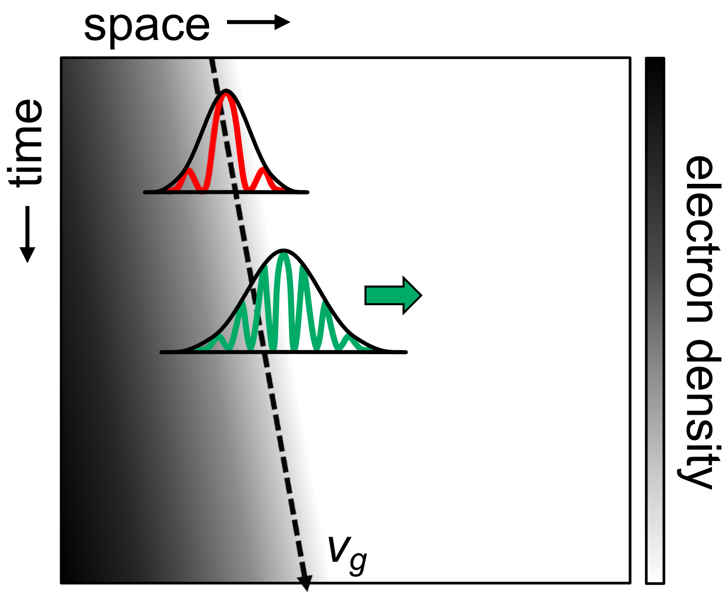

An ionization wave created by a flying focus pulse can accelerate optical photons to the XUV

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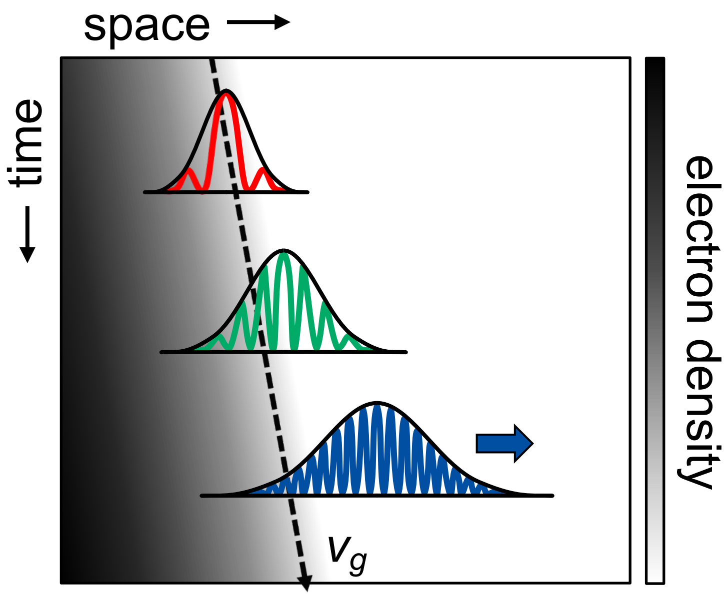
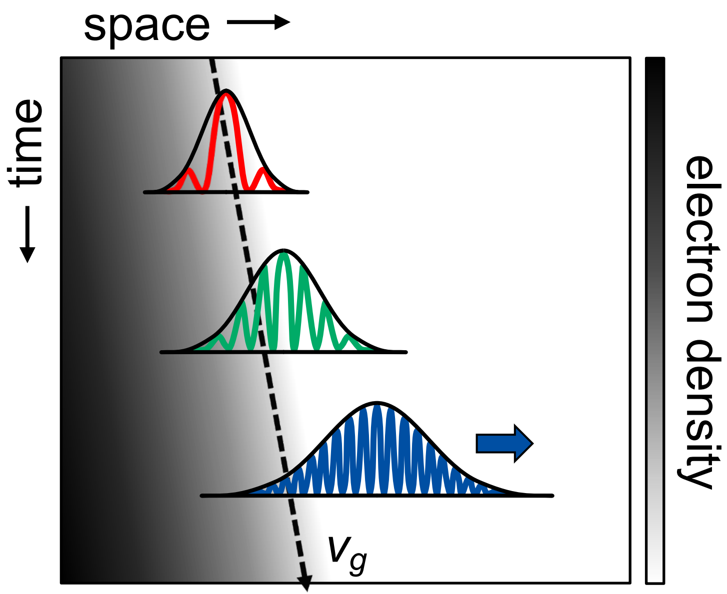


An ionization wave created by a flying focus pulse can accelerate optical photons to the XUV

A time-varying refractive index can accelerate (i.e., frequency upshift) photons



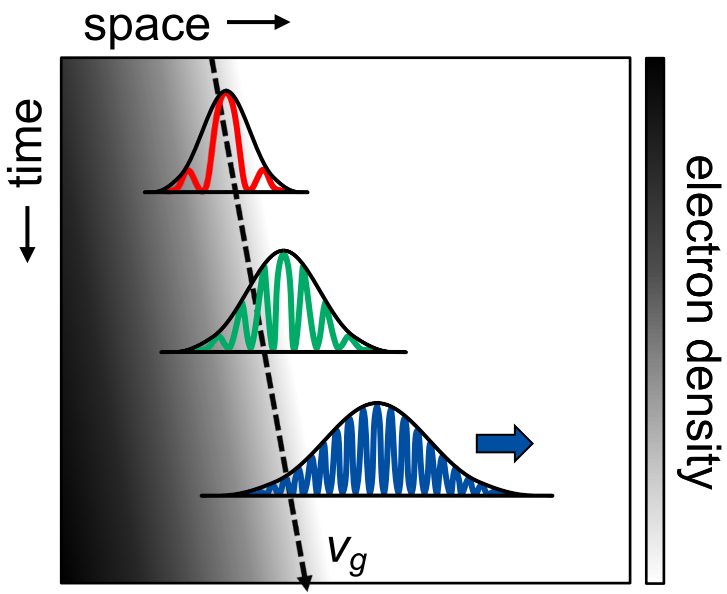
- A traditional photon accelerator has two limitations

  1. Ionization refraction

  2. Photons outrunning the gradient

An ionization wave created by a flying focus pulse can accelerate optical photons to the XUV

A time-varying refractive index can accelerate (i.e., frequency upshift) photons



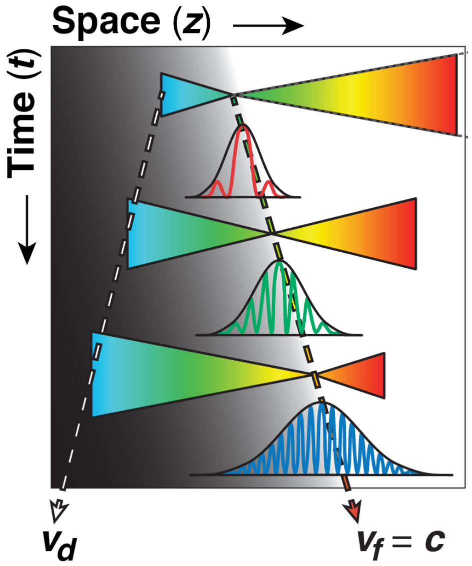
- A traditional photon accelerator has two limitations

  1. Ionization refraction

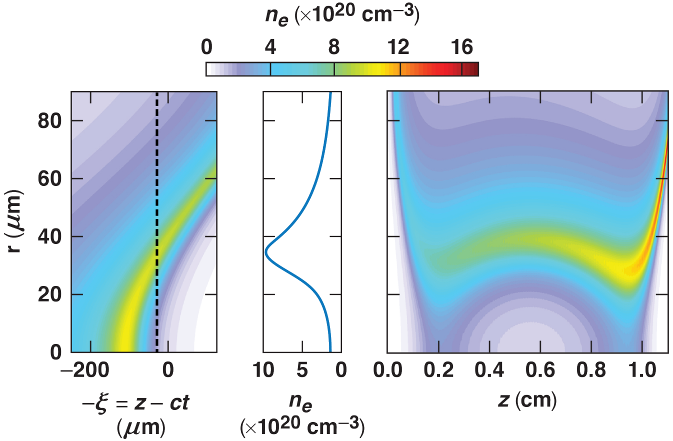
  2. Photons outrunning the gradient

Two schemes can be used to overcome these limitations

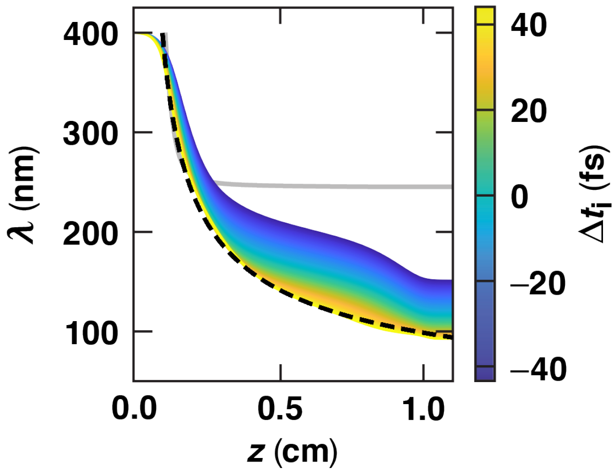
Scheme 1: The flying focus triggers an ionization front travelling at -*c* in a shaped gas target that accelerates a witness pulse



TC14718b



TC14924

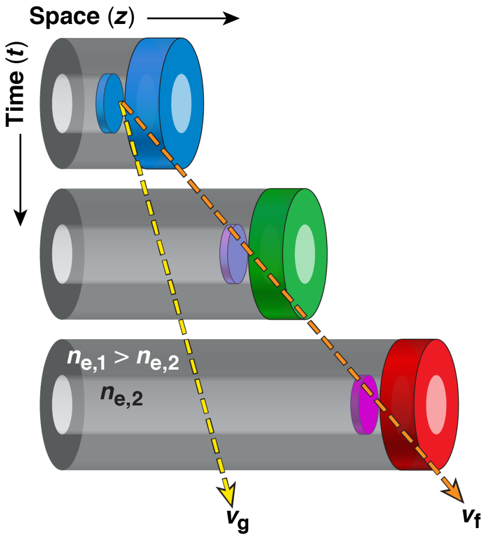


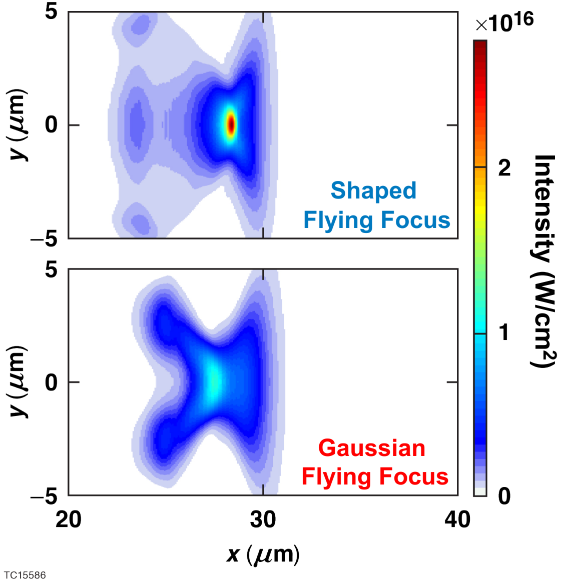
TC14720a

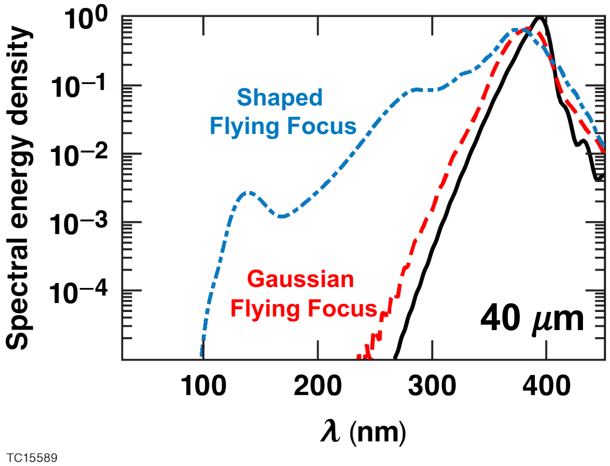
The ionization wave at -*c* avoids refraction of the drive pulse and prevents the witness pulse from outrunning the gradient; the shaped gas target eliminates refraction of the witness pulse

*A. Howard et al. PRL 2019

Scheme 2: A shaped flying focus pulse creates a plasma channel and self-accelerates in a dense target







The shaped flying focus pulse creates an ionization wave in the form of an optical fiber that prevents refraction as it upshifts in frequency

Outline

1. Spatiotemporal pulse shaping

2. Applications

3. Basic plasma science

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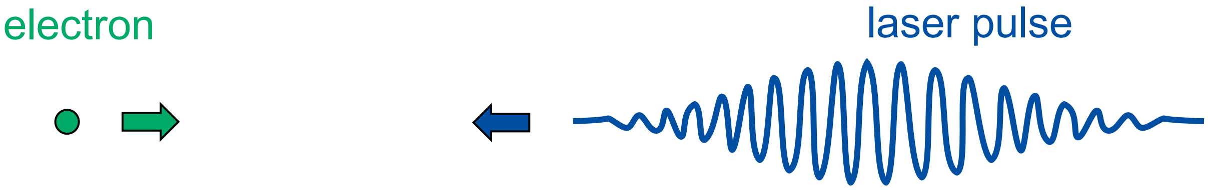
- Inverse Compton Scattering
- The attosecond “lighthouse”
- Fermi acceleration

The flying focus can amplify observable strong-field QED phenomena in Compton scattering

In nonlinear Compton scattering, an electron driven by an intense laser pulse emits a photon



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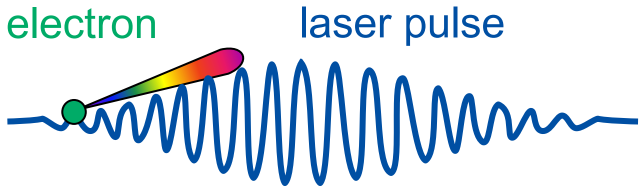

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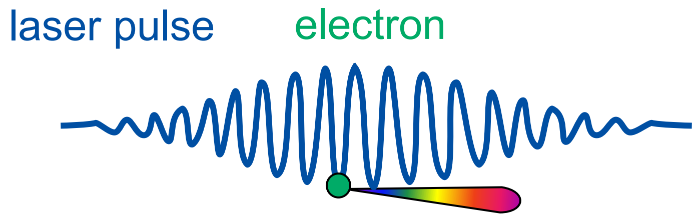

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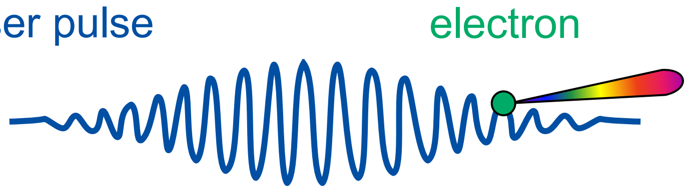

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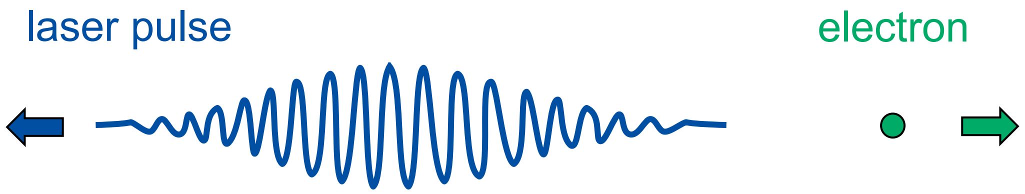

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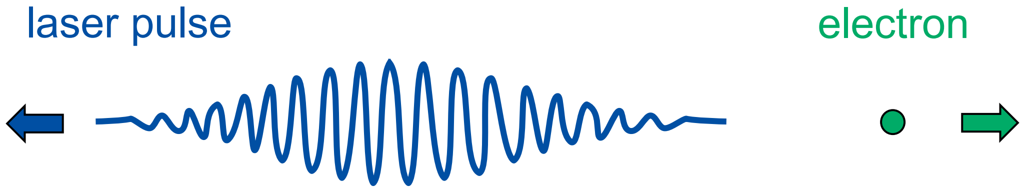
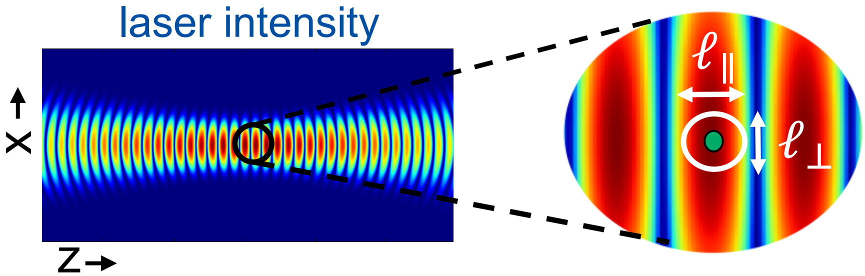


Radiation originating from a region around the electron, or formation volume, constructively interferes in the far-field



A. Di Piazza, submitted

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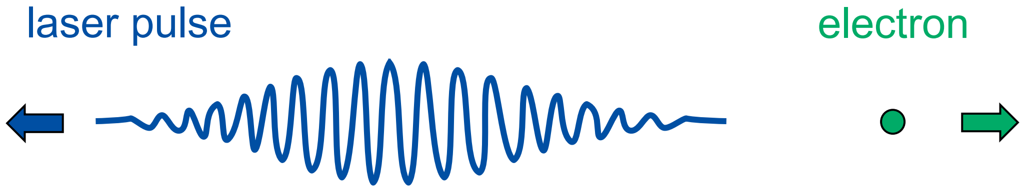

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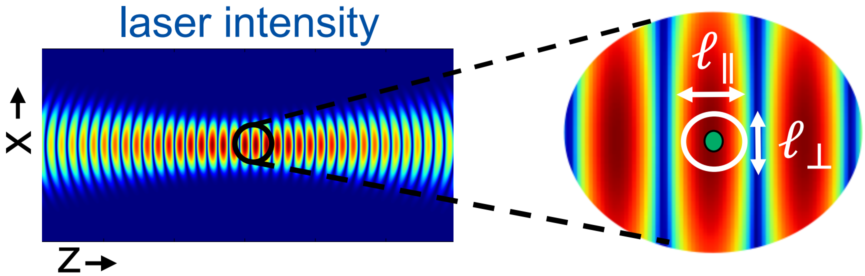

$\ell_{\parallel}$ is a classical quantity related to the emission angle and trajectory curvature

$\ell_{\perp}$ is a quantum quantity related to the delocalized nature of the electron

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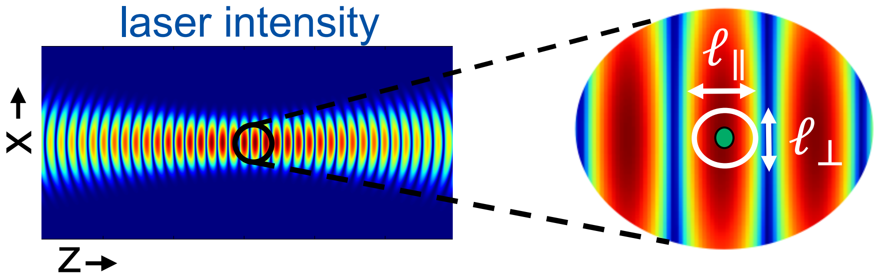
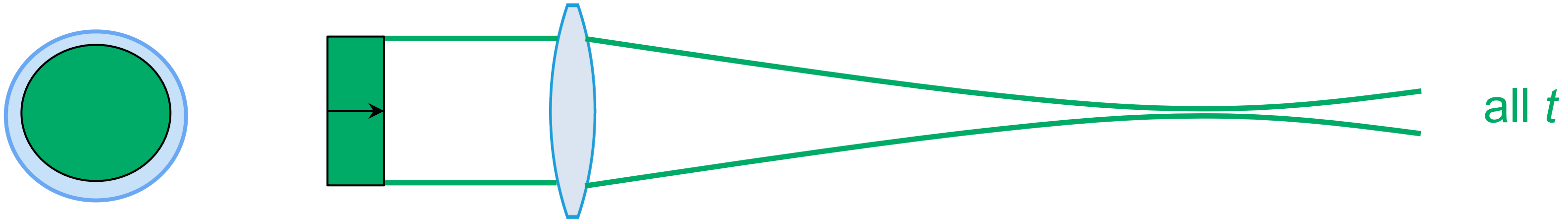


$\ell_{\perp}$ is a quantum quantity related to the delocalized nature of the electron

Typically the laser field does not vary significantly within the formation volume and it can be considered point-like

In a flying focus co-propagating with the electron, the effect of the transverse formation length can accumulate modifying the emission spectrum

A spatiotemporally shaped pulse with pulse-front tilt can be used to create an "attosecond lighthouse"*,**



Focusing a pulse with pulse-front tilt correlates time within the pulse to angle

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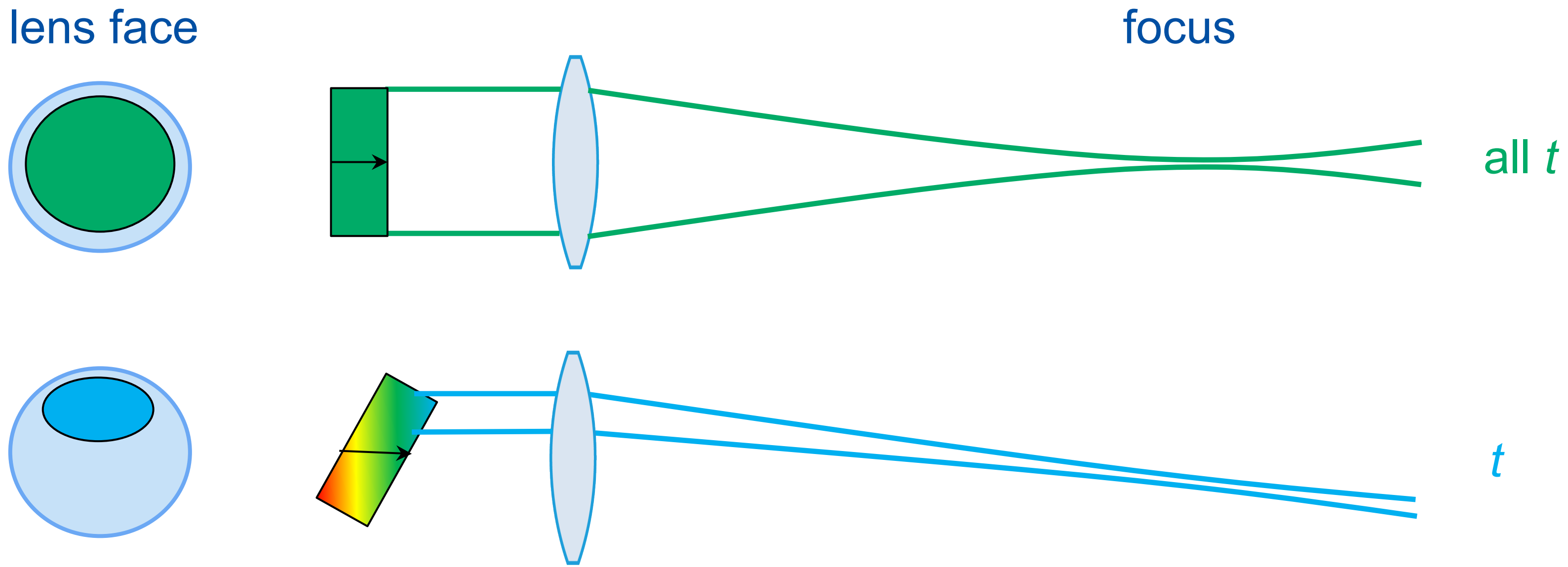

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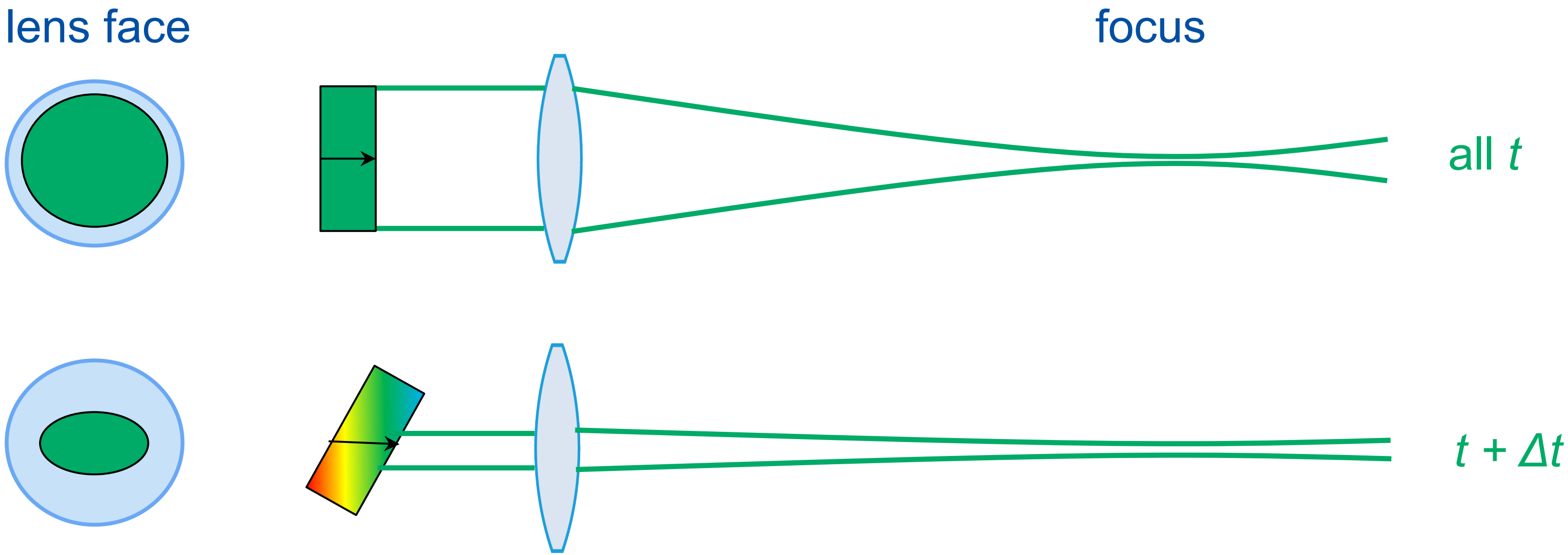

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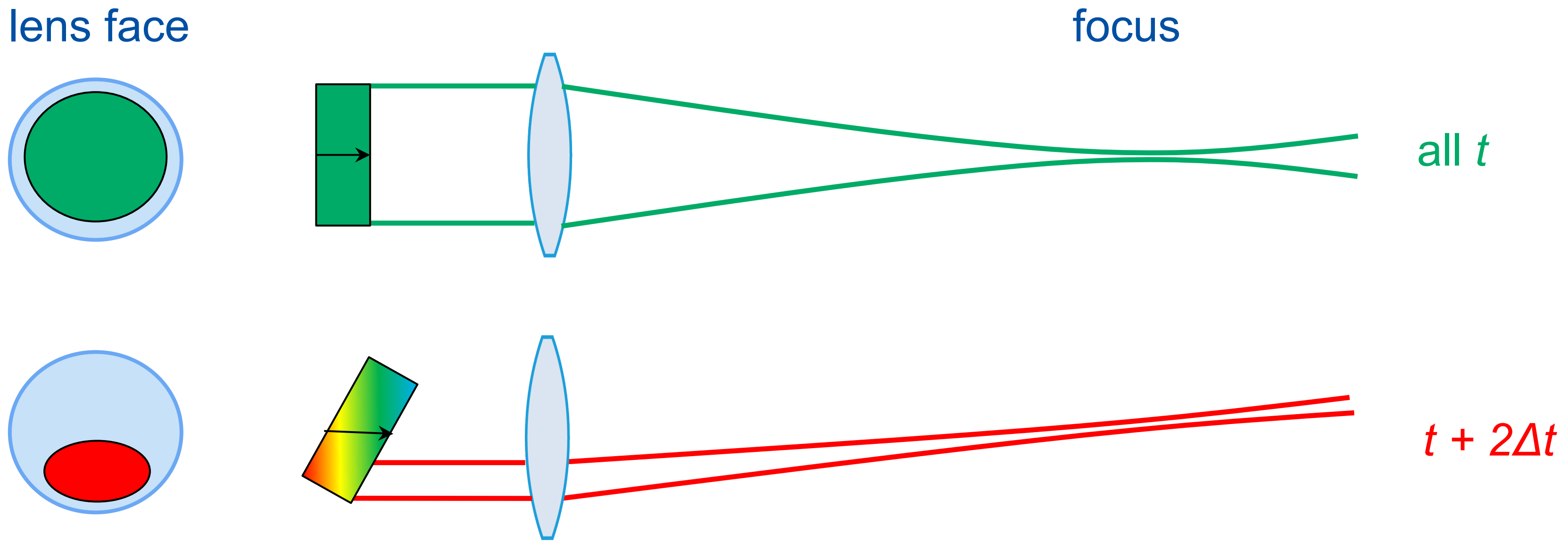

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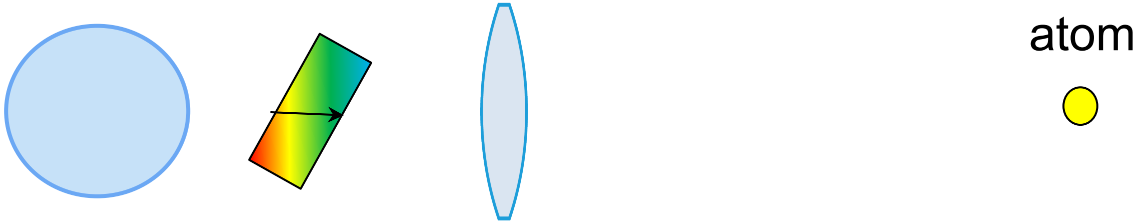

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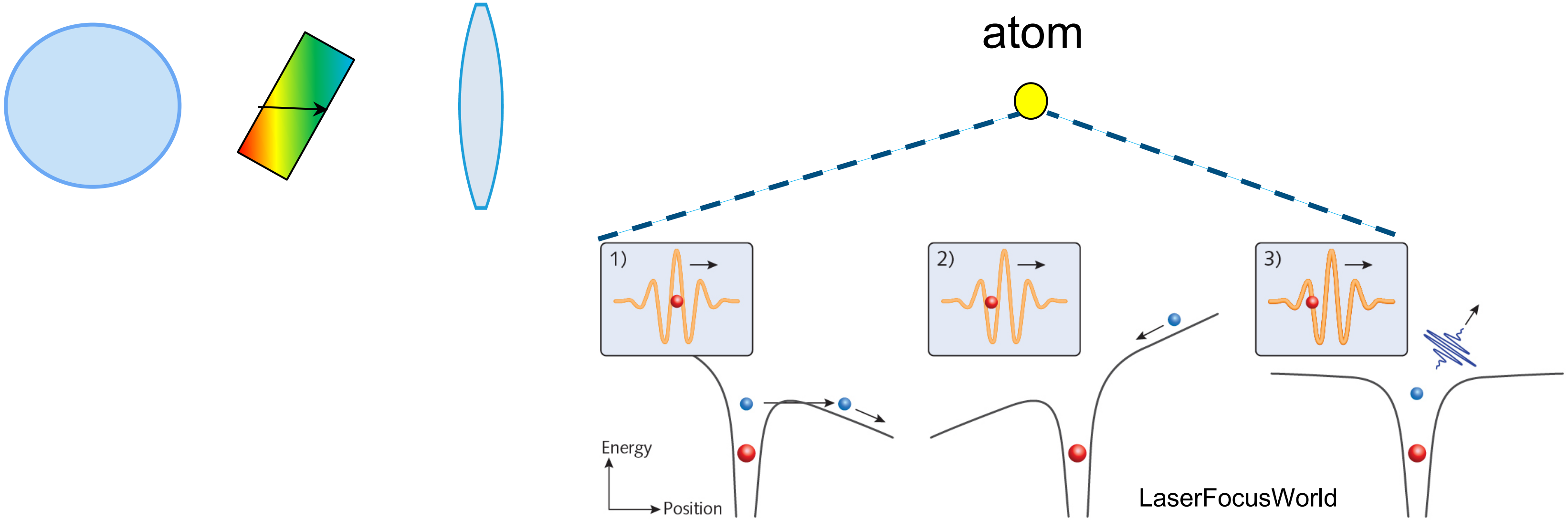

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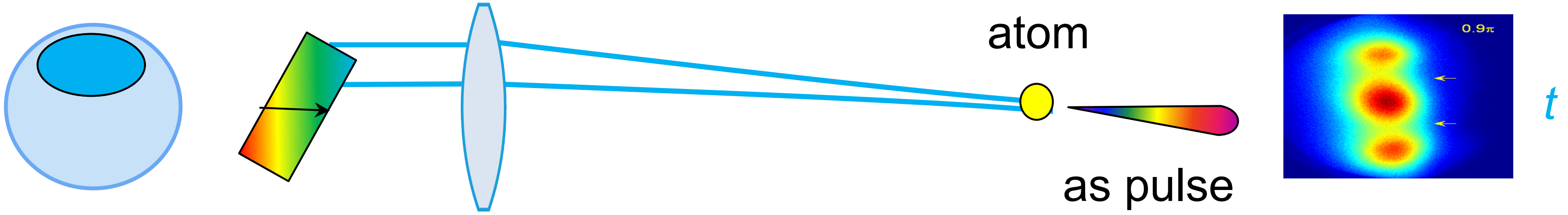

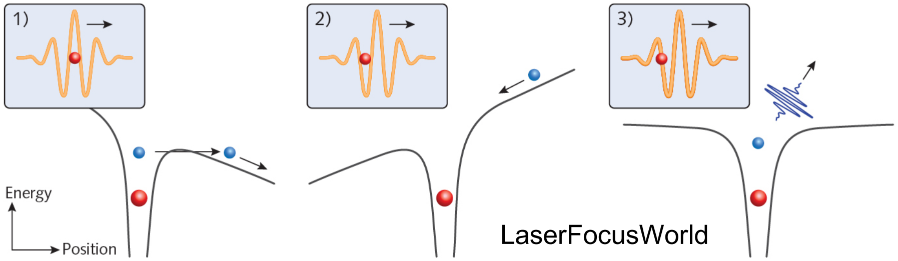

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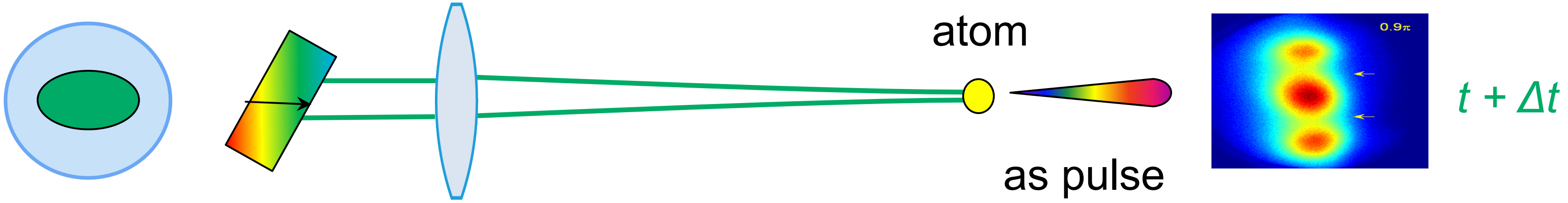

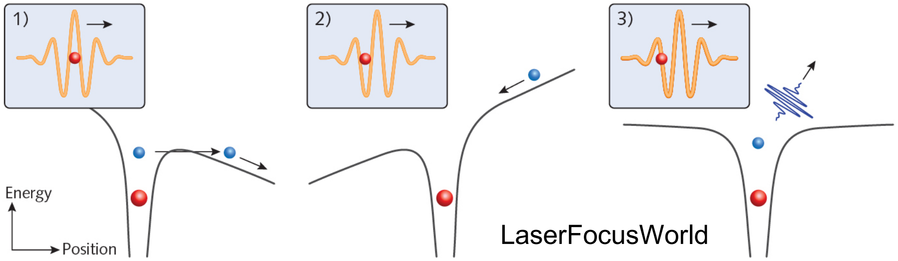

LaserFocusWorld

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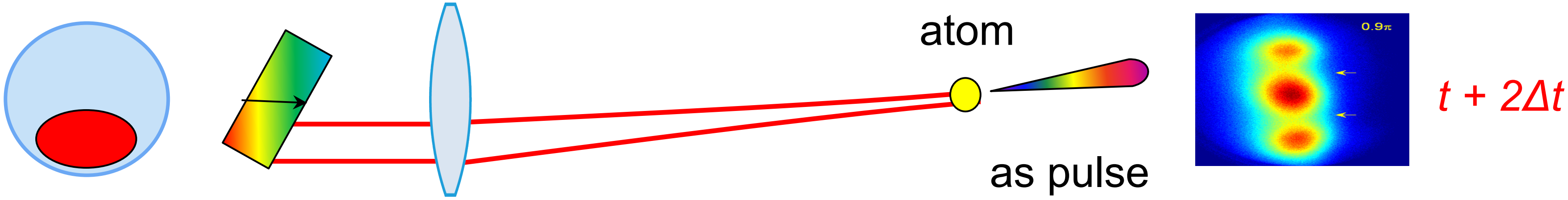

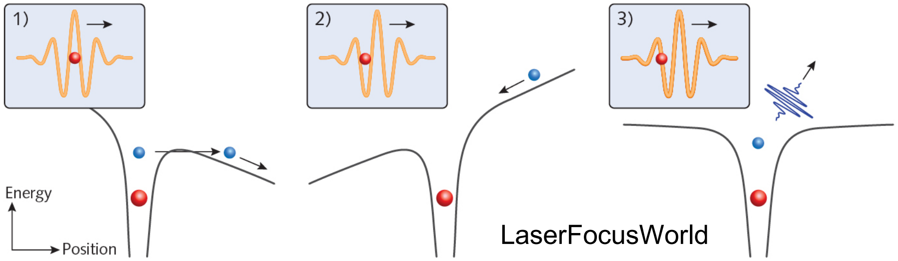

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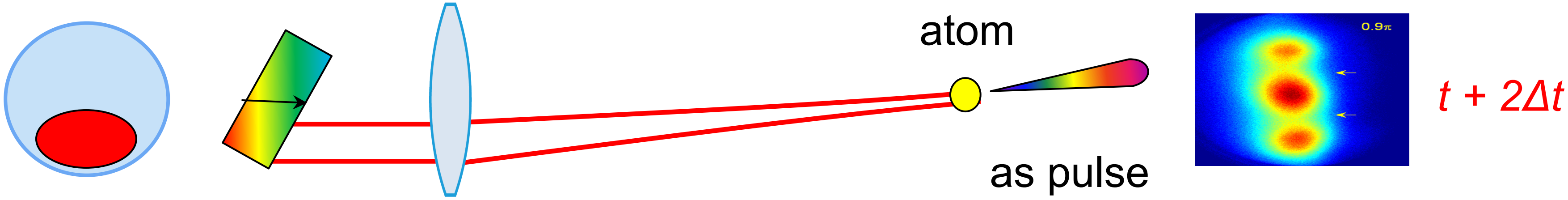
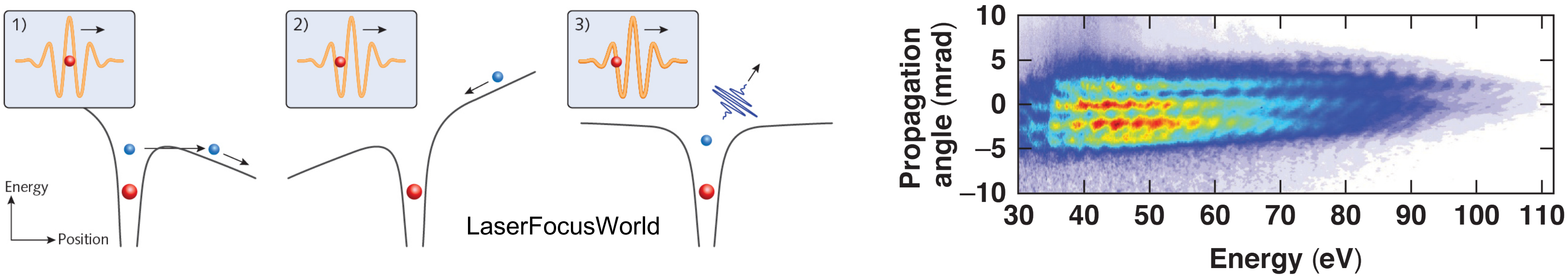




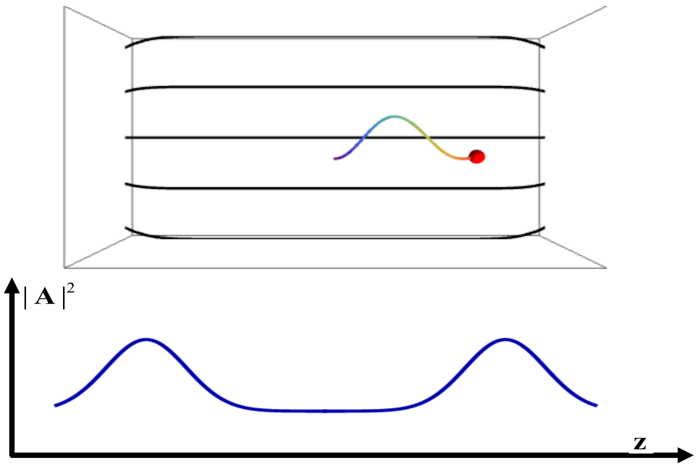
TC15528

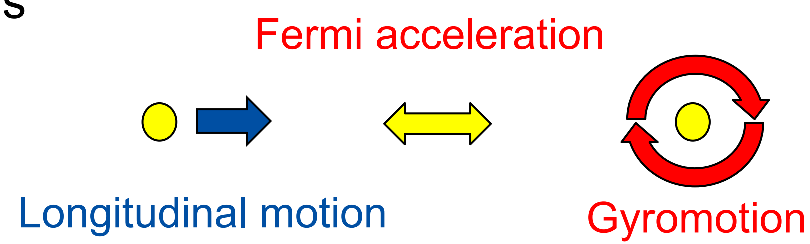
Pulse front tilt isolates the attosecond pulses from high harmonic generation providing a probe and source with unprecedented time resolution and duration

*J.A. Wheeler *et al.* Nat. Photonics. (2012) **K.T. Kim *et al.*, Nat. Photonics (2013)

The flying focus provides a laboratory scale surrogate to study Fermi acceleration

A charged particle will continually gain energy during repeated reflections from counter-traveling magnetic mirrors





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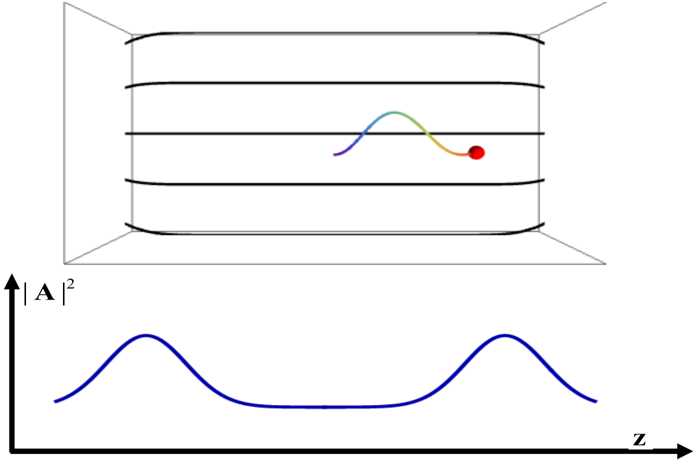
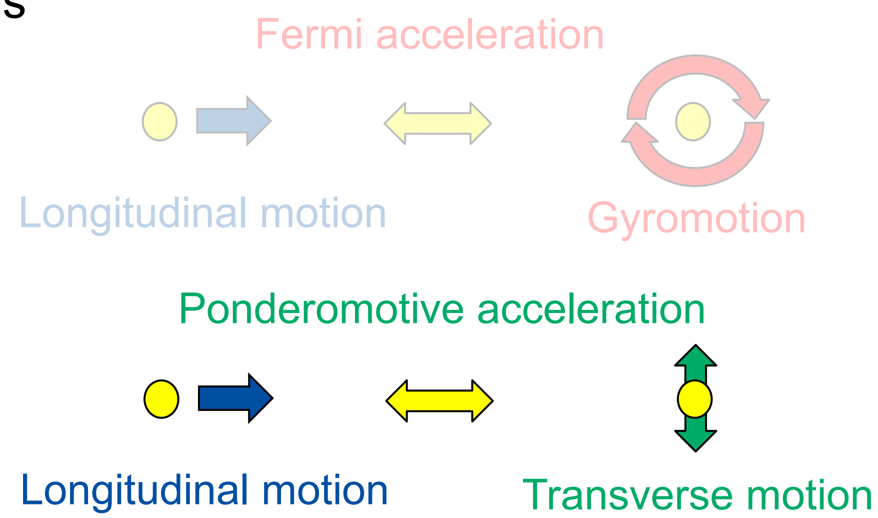


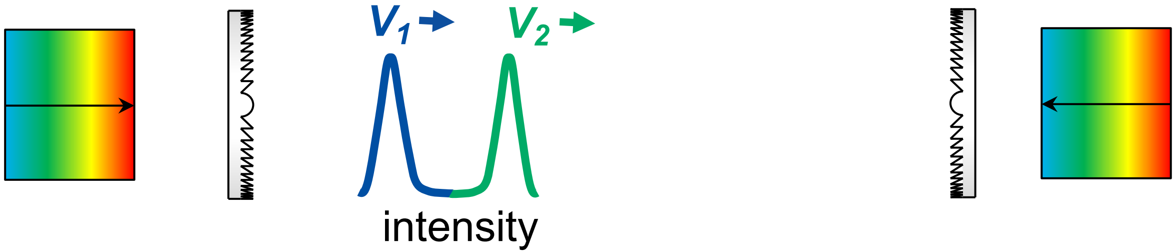


The dynamics of ponderomotive acceleration in subluminal intensity peaks is equivalent to Fermi acceleration in moving magnetic potentials

D. Ramsey, in preparation

The flying focus provides a laboratory scale surrogate to study Fermi acceleration

Two flying foci with different focal velocities can emulate magnetic mirrors



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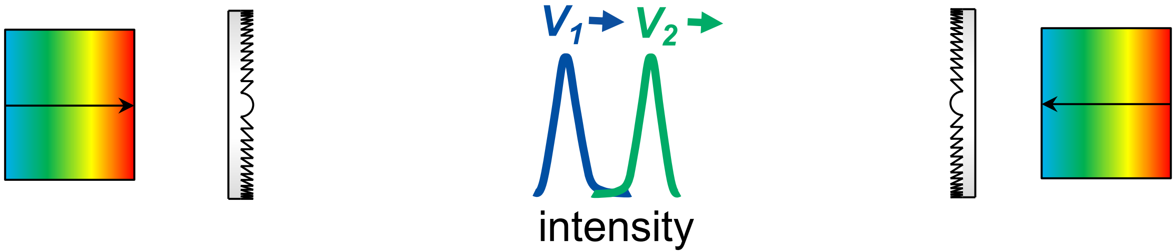

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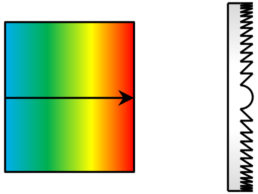

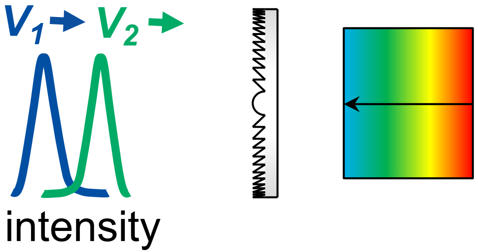

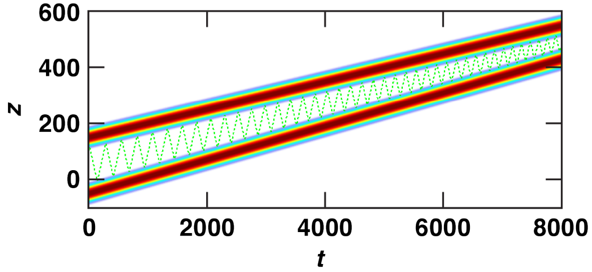

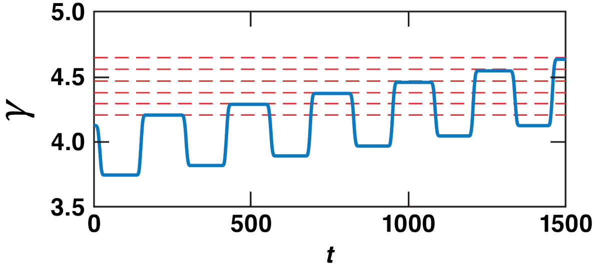

TC15532

Initial simulations show the expected discrete jumps in electron energy and produce energy spectra similar to those predicted by A. Bell*

*A.R. Bell, Mon. Not. R. astr. Soc. (1978)

D. Ramsey, in preparation

Spatiotemporal pulse shaping provides controllable velocity intensity peaks that can be sustained for long distances

- Spatiotemporal pulse shaping refers to structuring a laser pulse with advantageous space-time correlations that can be tailored to an application

- Experiments have demonstrated velocity control, the formation of ionization waves of arbitrary velocity, and “attosecond lighthouses”

- Simulations and theory predict that pulse shaping can be used in **many** more phenomena, including laser wakefield, photon, and Fermi acceleration

The flexibility offered by spatiotemporal pulse shaping can improve laser-based applications and enable fundamental physics studies