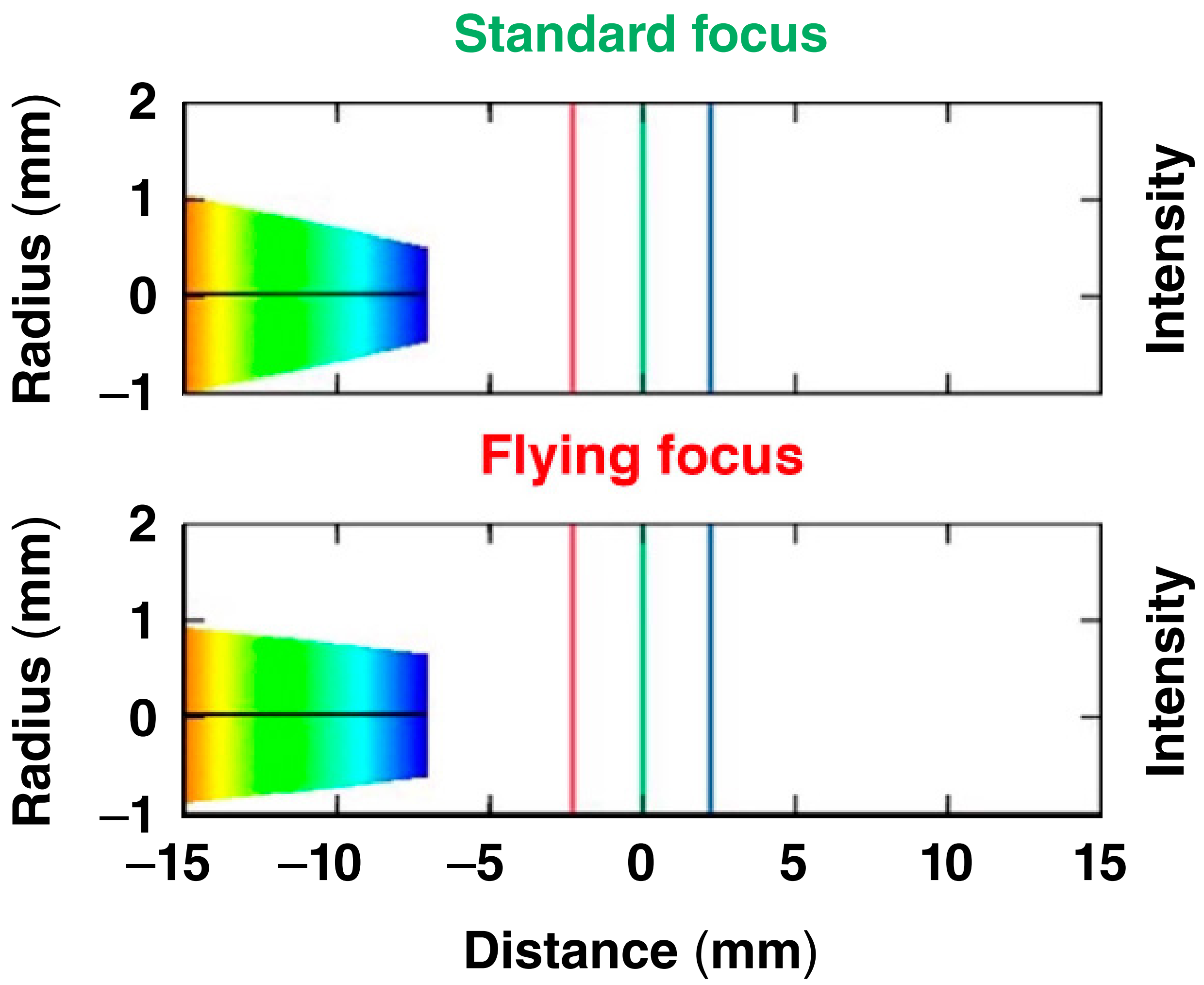
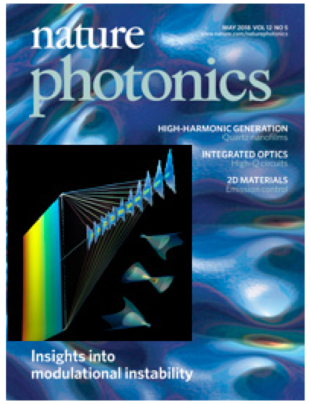
# Flying Focus: Spatiotemporal Control of Intensity for Laser-Based Applications



**D. H. Froula**
**Associate Professor, Physics Department**
**Plasma Physics Group Leader, Laboratory for Laser Energetics**
**University of Rochester**

**60th Annual Meeting of the**
**American Physical Society**
**Division of Plasma Physics**
**Portland, OR**
**5–9 November 2018**



**Summary**

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

- The flying focus provides unprecedented spatiotemporal control over laser–plasma interactions by decoupling
  - the spot size of the pulse from the focal range
  - the velocity of the peak intensity from the group velocity
- Experiments have demonstrated the flying focus and the ability to generate ionization waves at any velocity (IWAV)
- Flying focus was applied to several applications
  - photon accelerator: IWAV's can shift visible laser light to the XUV
  - Raman amplification: flying focus could overcome several challenges of laser-plasma amplifiers
  - Cherenkov radiation: flying focus allows new radiation sources
  - vacuum electron acceleration: flying focus enables vacuum acceleration

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*D. H. Froula *et al.*, Nat. Photonics 12, 262 (2018);
A. Sainte-Marie, O. Gobert, and F. Quéré, Optica 4, 1298 (2017).
XUV: extreme ultraviolet

# We have an outstanding research team working on the flying focus and its applications

**J. P. Palastro, D. Turnbull, T. J. Kessler, A. Davies, P. Franke, A. Howard, L. Nguyen, D. Ramsey, G. W. Jenkins, S.-W. Bahk, I. A. Begishev, R. Boni, J. Bromage, S. Bucht, R. K. Follett, D. Haberberger, J. Katz, and J. L. Shaw**

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University of Alberta

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Stoney Brook University

**J. Vieira**

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**F. Quéré**

CEA

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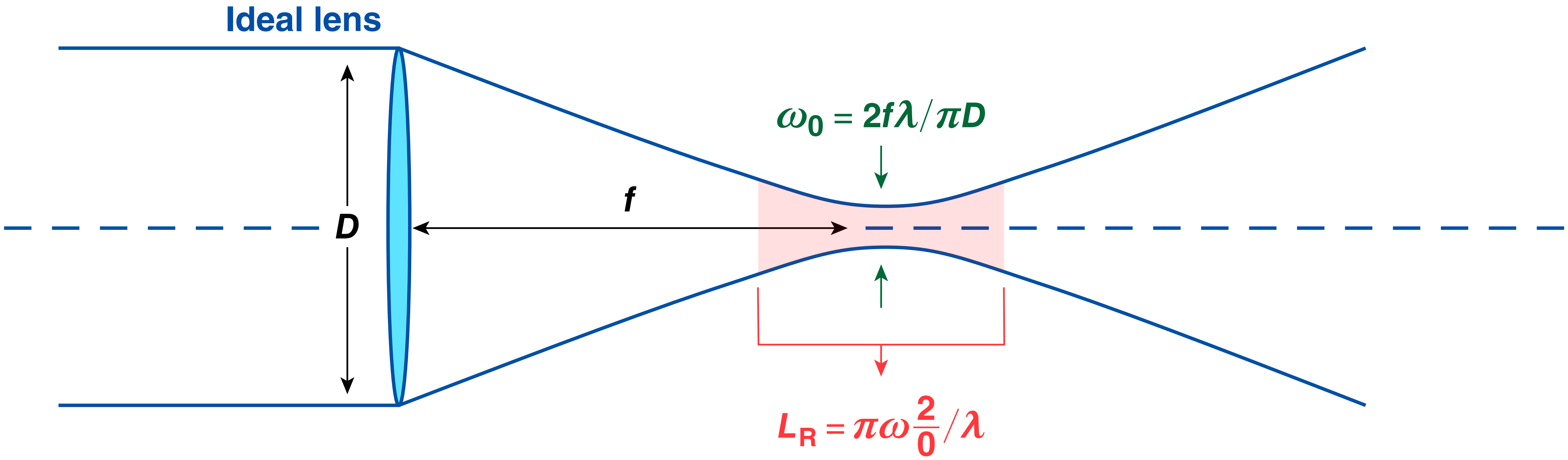
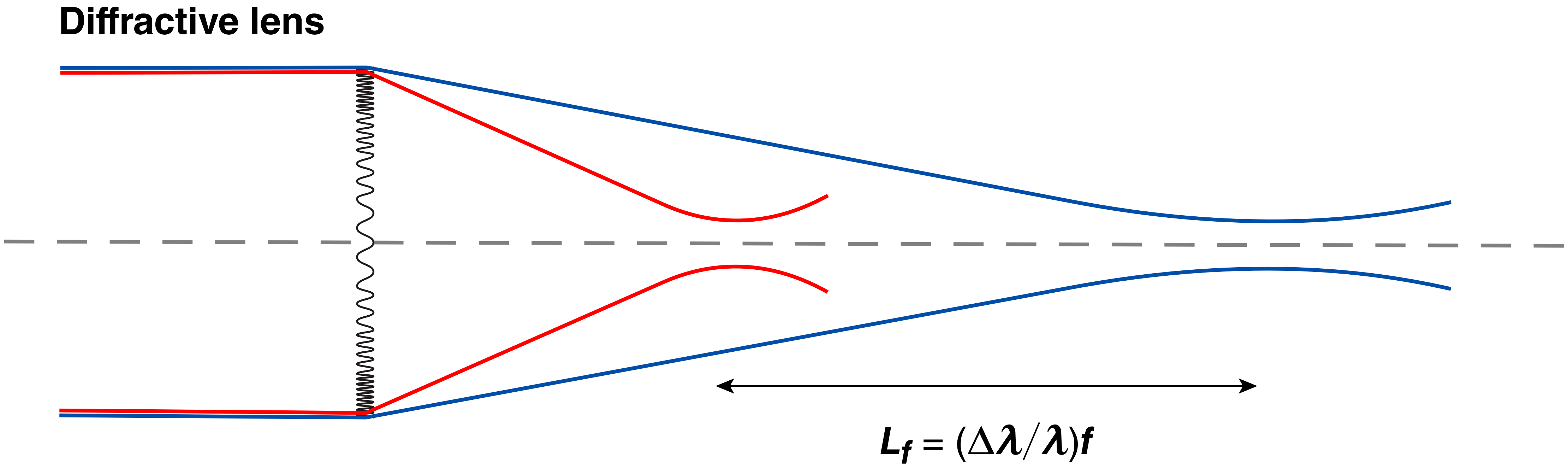
# Ideal lenses limit the region of high intensity to the Rayleigh range



**For fixed pulse power ($P$), increasing the Rayleigh range necessarily *decreases* the intensity, $I \sim P/\omega_0^2 \sim P/L_R$.**

TC14126b

# A diffractive lens has a different focal length for each color

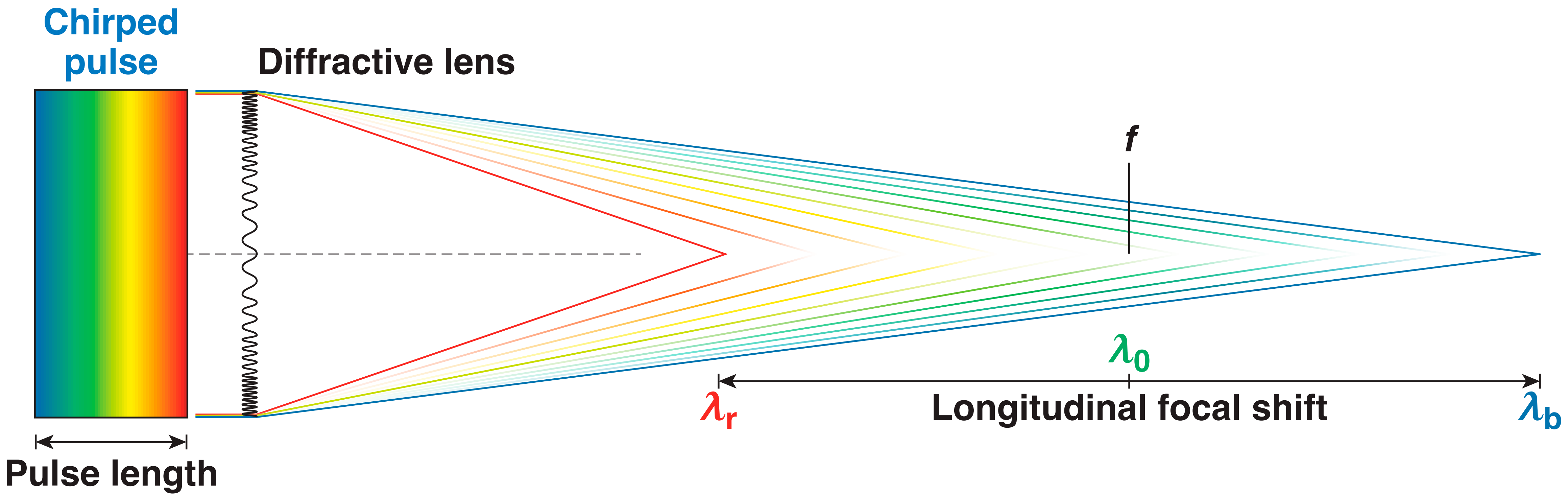


$L_f = (\Delta\lambda/\lambda)f$

**With only 10 nm of bandwidth, the distance separating focused colors can be ~100× greater than the Rayleigh length, *extending the range of high intensity*.**

TC14128c

# Combining a diffractive lens with a chirped laser pulse provides spatiotemporal control over the focus

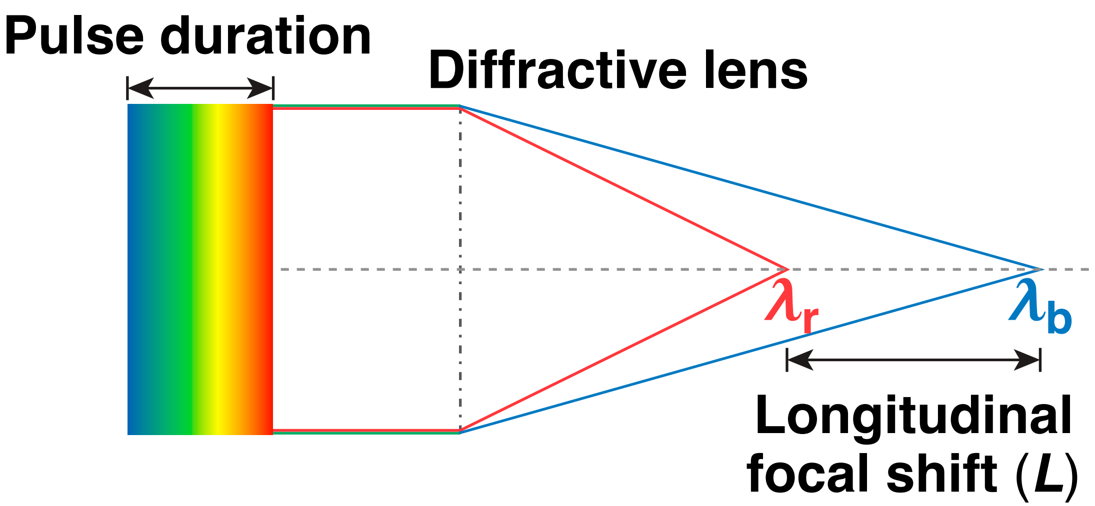


**The spectral phase of the pulse determines the time at which color reaches focus, resulting in a peak intensity with a dynamic trajectory.**

E26376b

Funded by DE-SC0016253 (PI Froula)

# The dynamic focus can propagate over 100× the Rayleigh length of the system

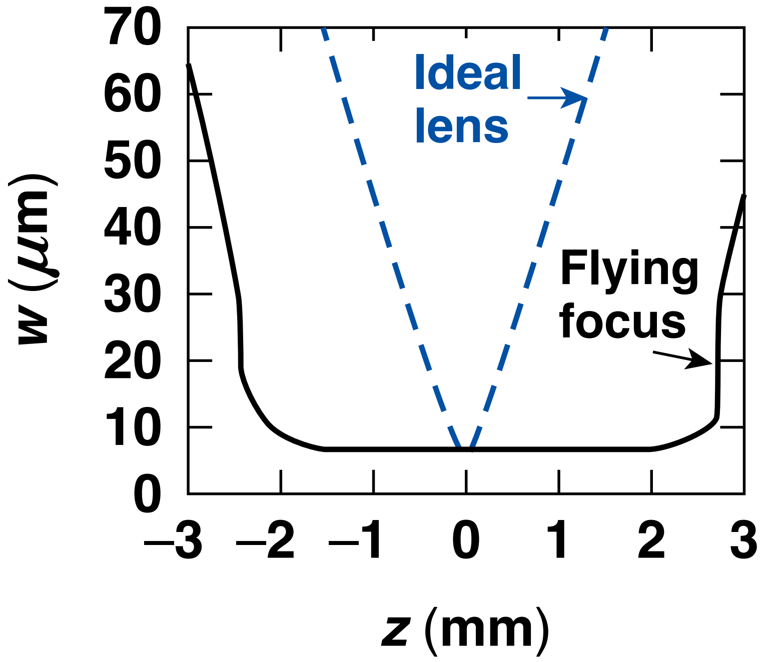


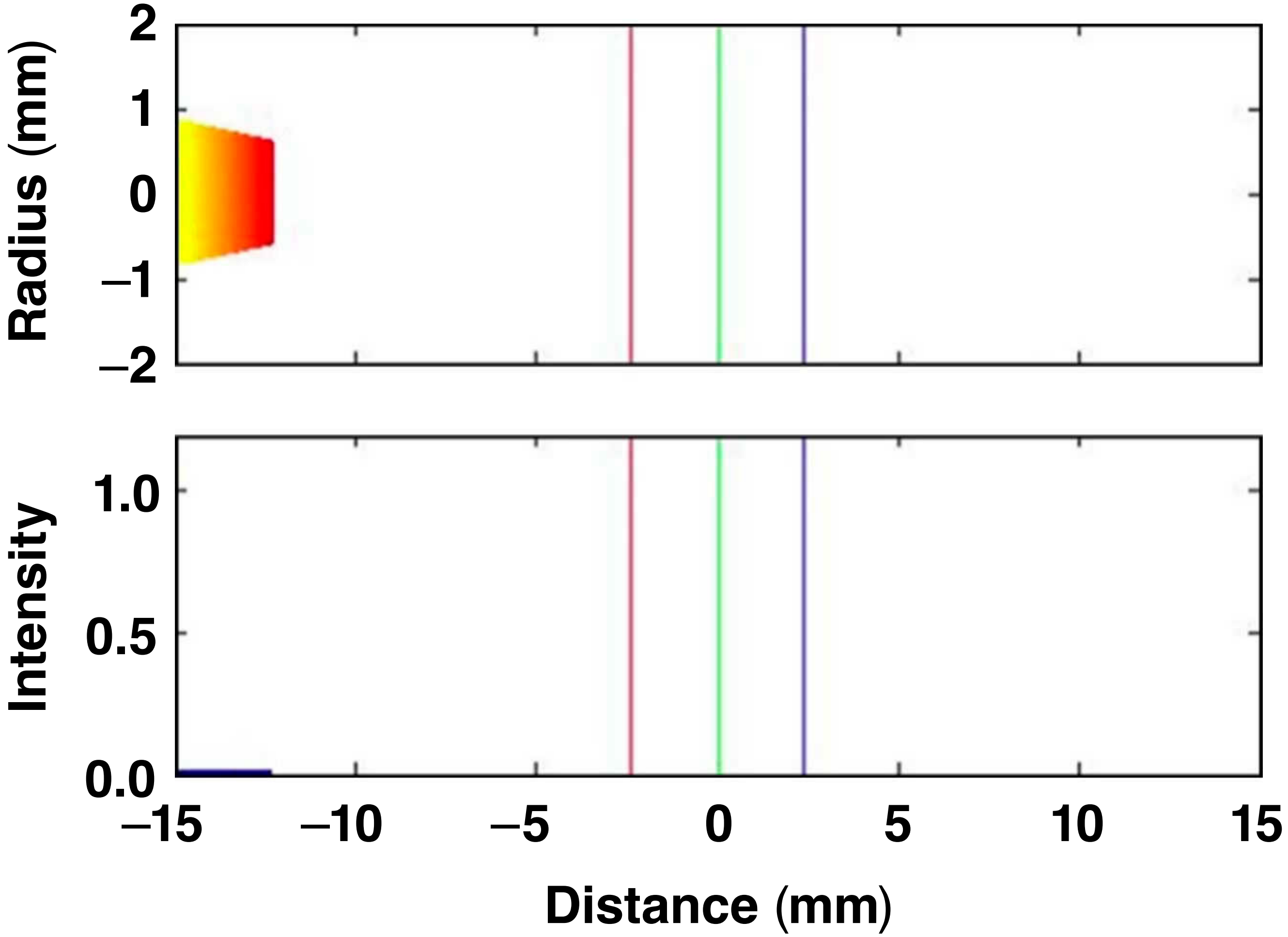
$$L = \frac{\Delta\lambda}{\lambda} f_0 \cong 4.5\ \text{mm}$$

$\lambda_0 = 1054\ \text{nm}$

$\Delta\lambda = 9.2\ \text{nm}$

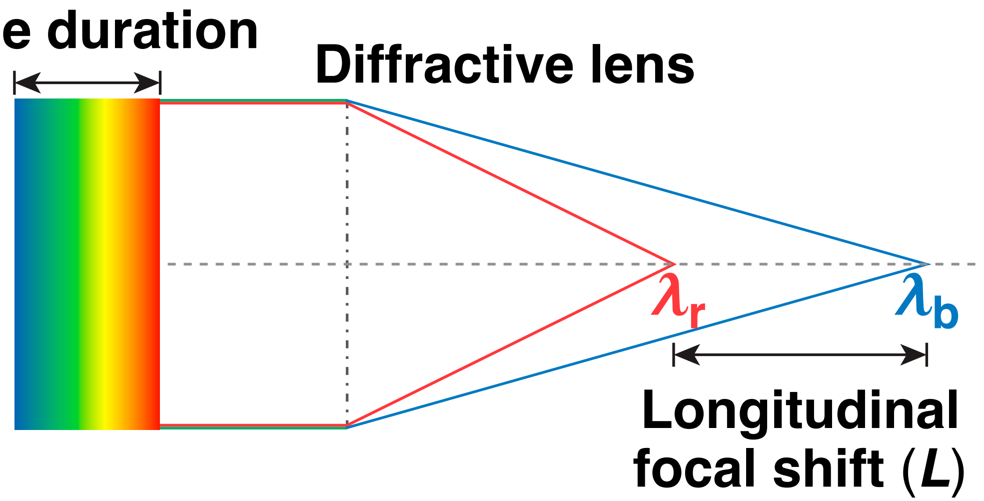
$f_0 = 511\ \text{mm}$





**The time between red and blue colors (i.e., pulse duration) determines the time to move from the first focus to the last (velocity).**

# The dynamic focus can propagate over 100× the Rayleigh length of the system



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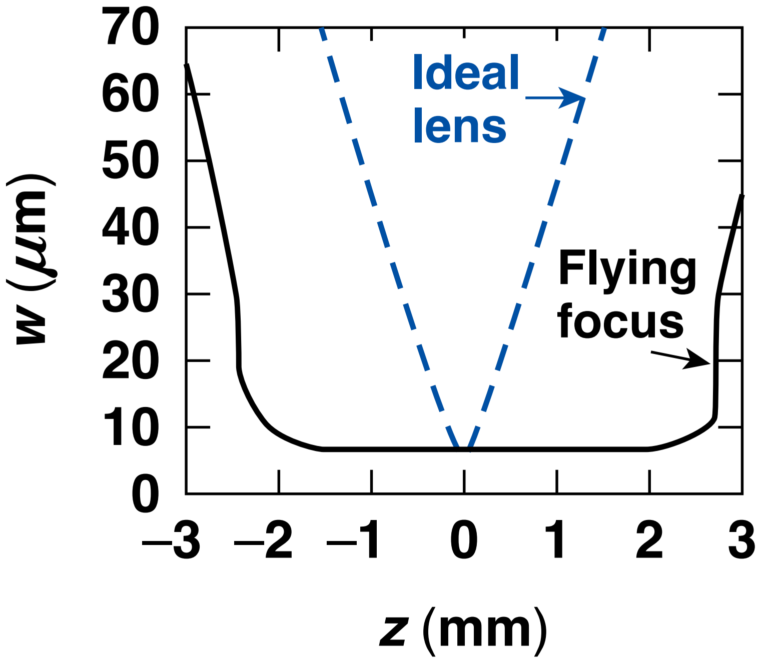

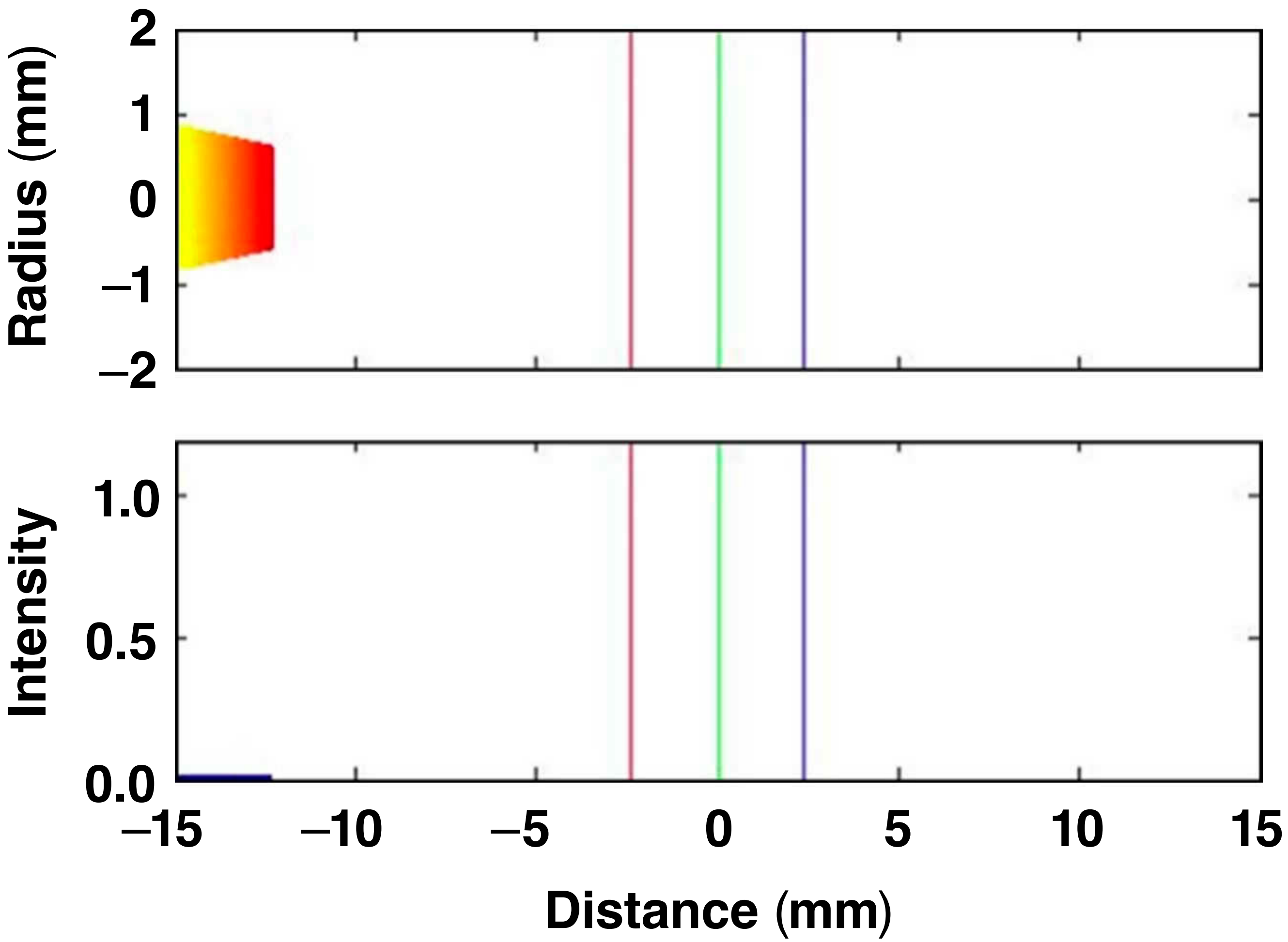

**The time between red and blue colors (i.e., pulse duration) determines the time to move from the first focus to the last (velocity).**

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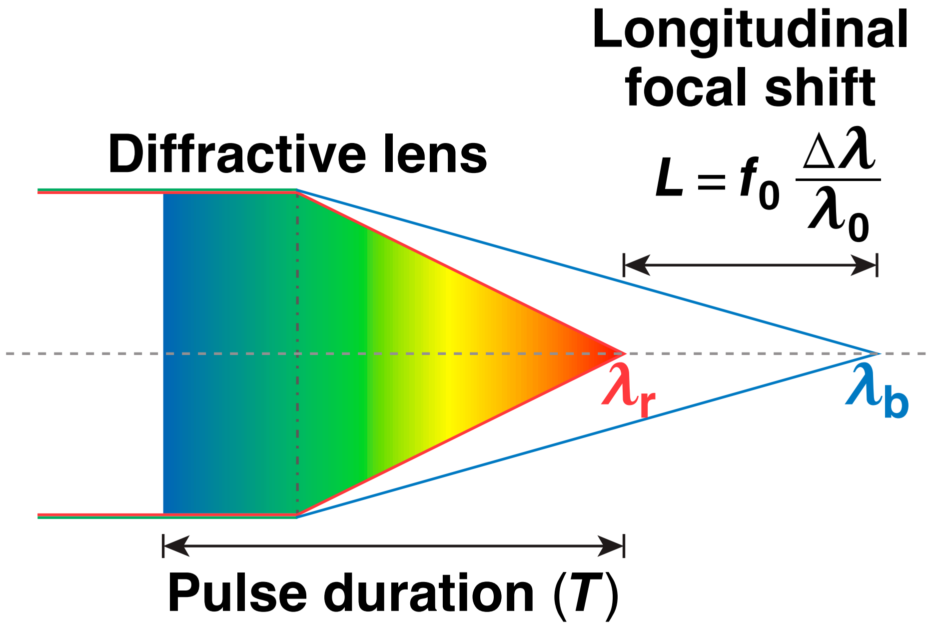
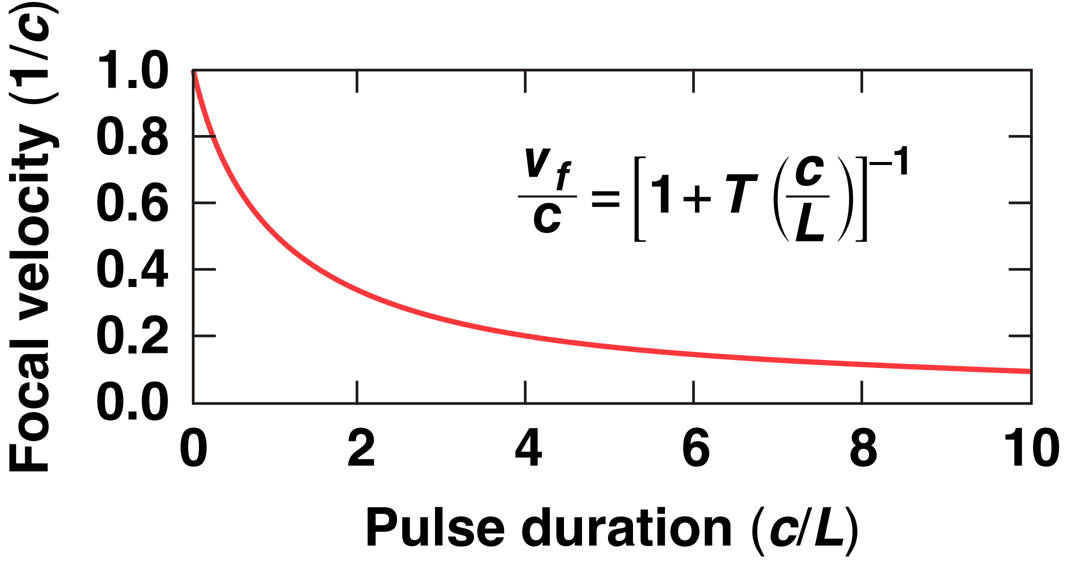
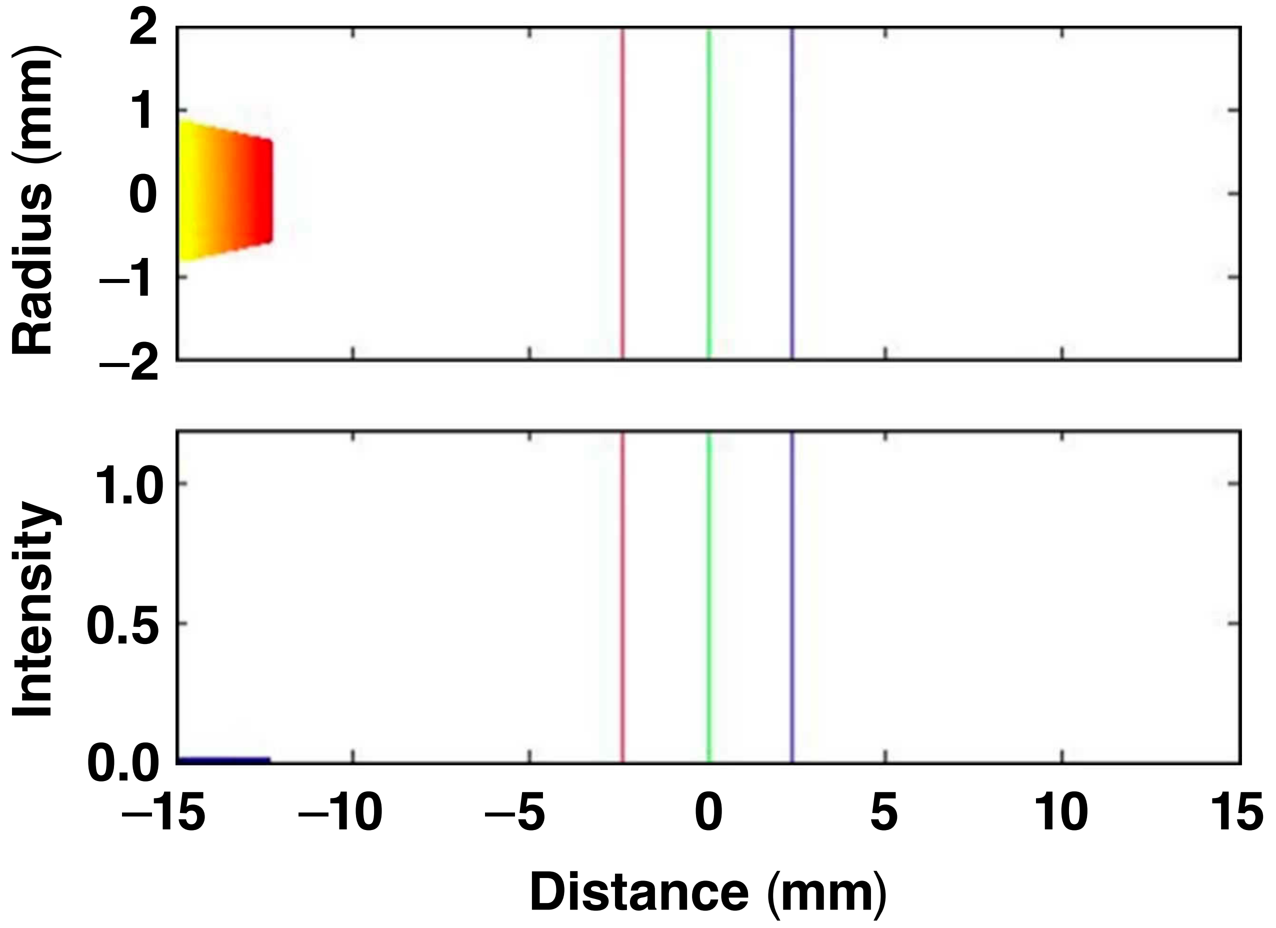
# By varying the pulse duration (chirp) of the laser (*T*), the velocity of the focus can be controlled

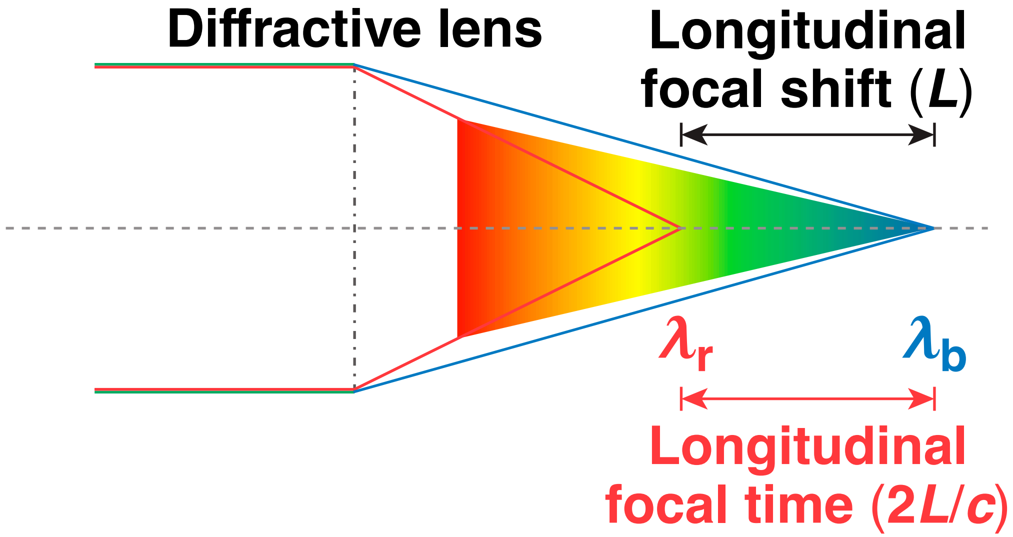


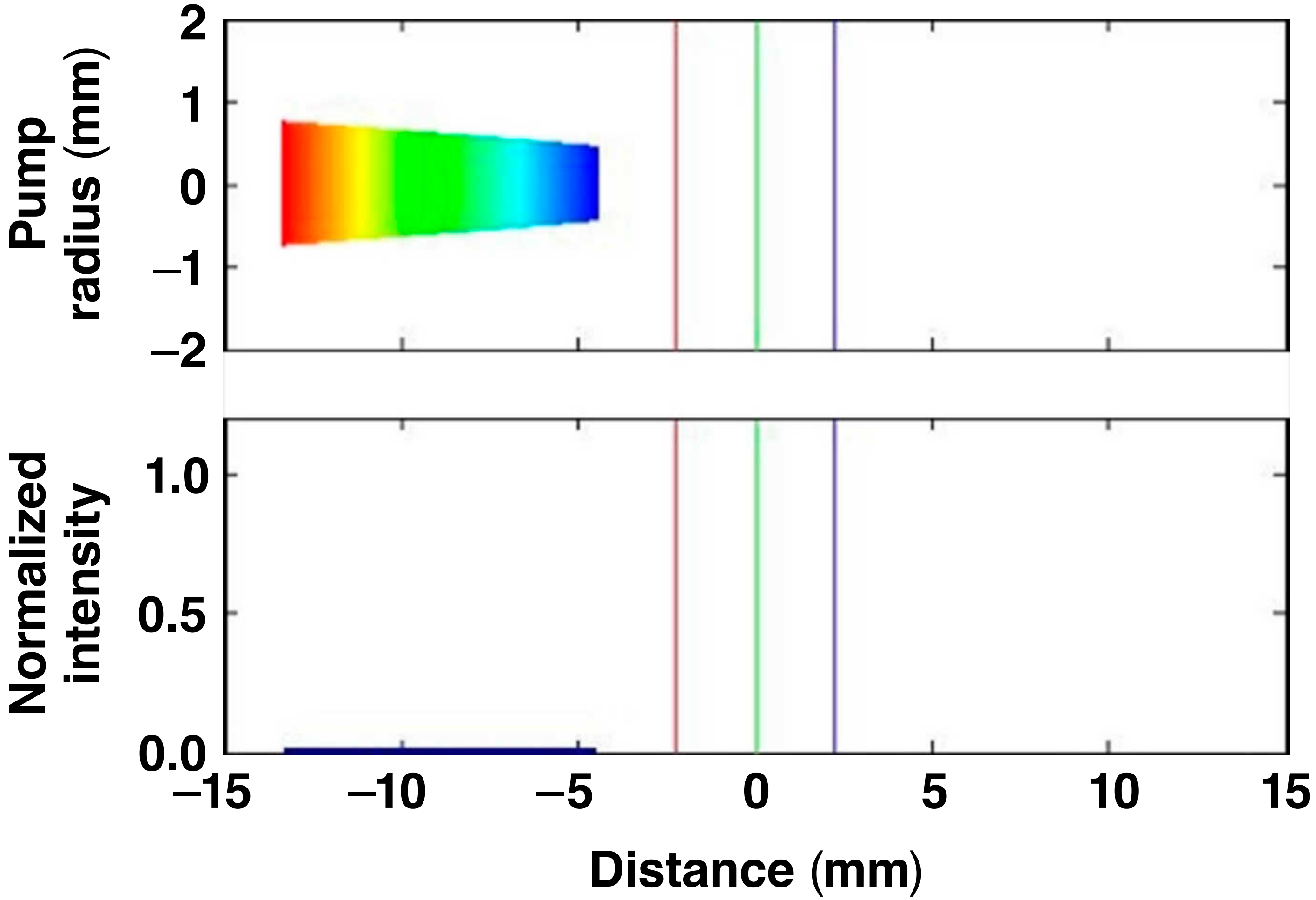




**The time between red and blue colors (i.e., pulse duration) determines the time to move from the first focus to the last (velocity).**

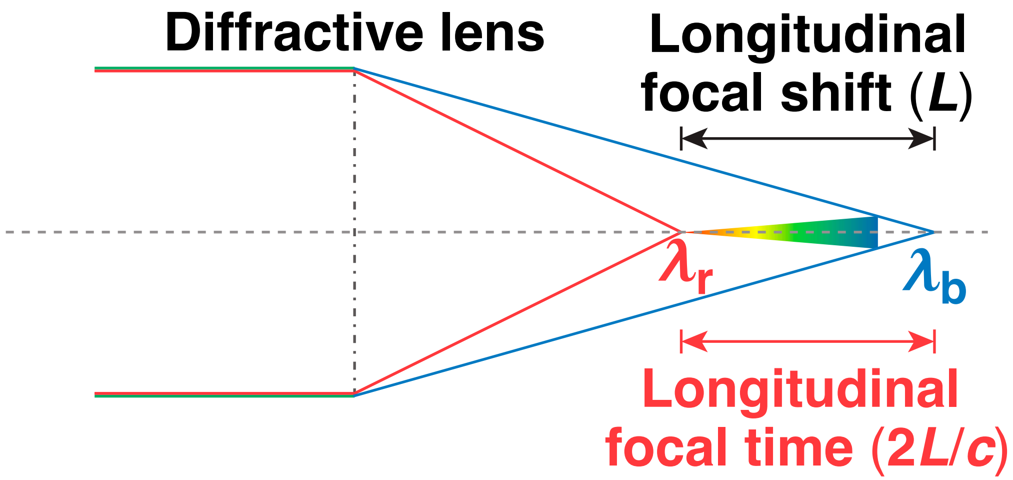
# By changing the direction of the chirp (blue to red) the focus can be made to counter-propagate

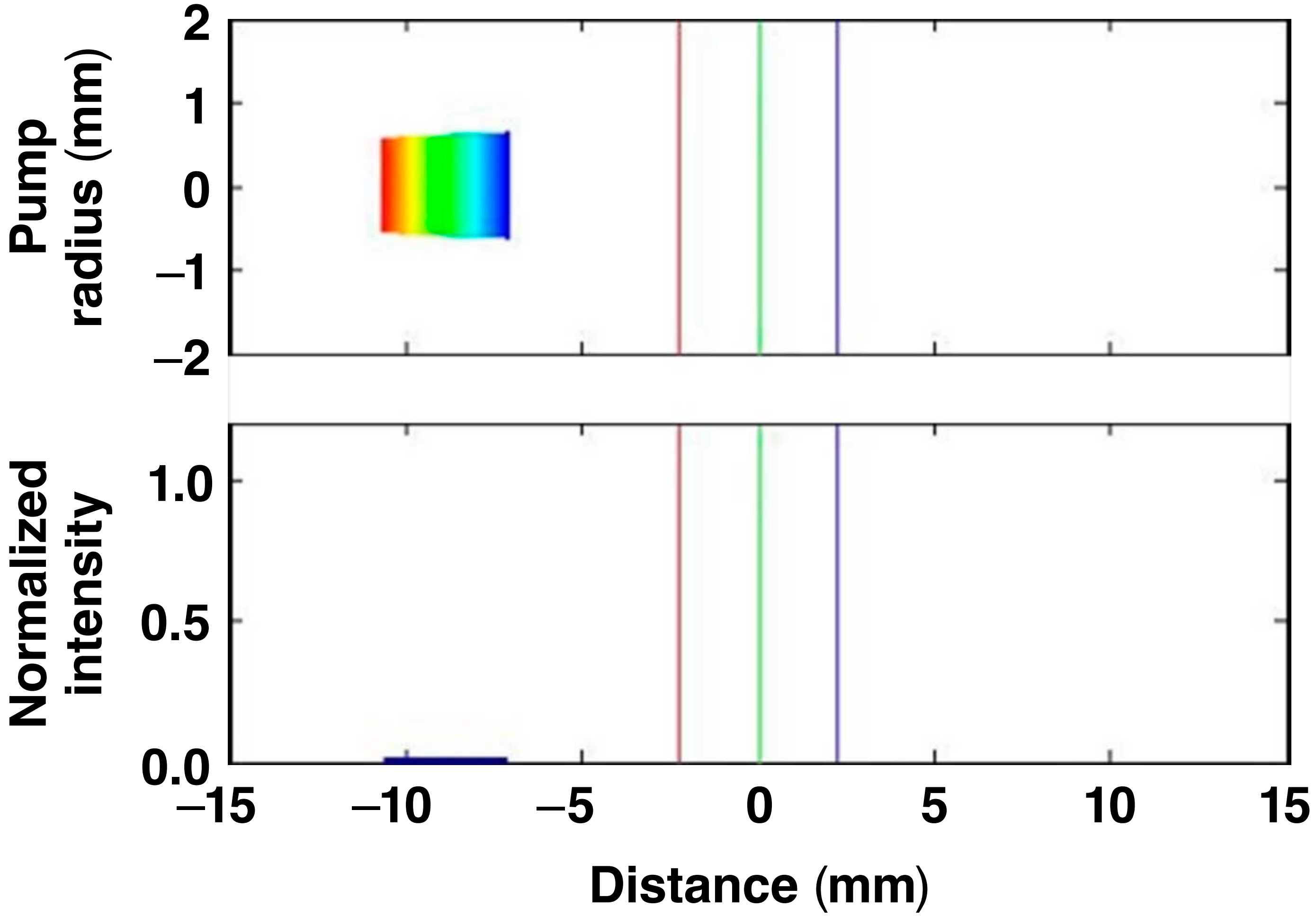




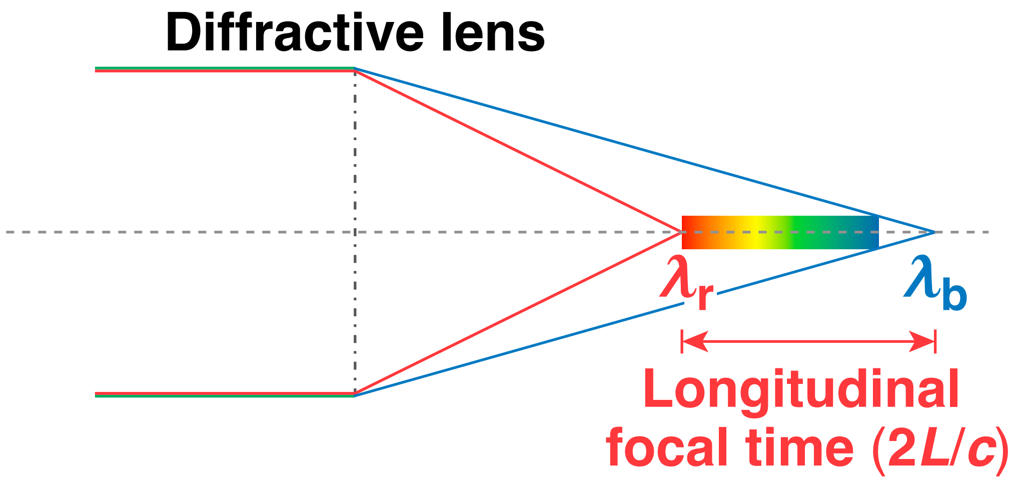
E26385d

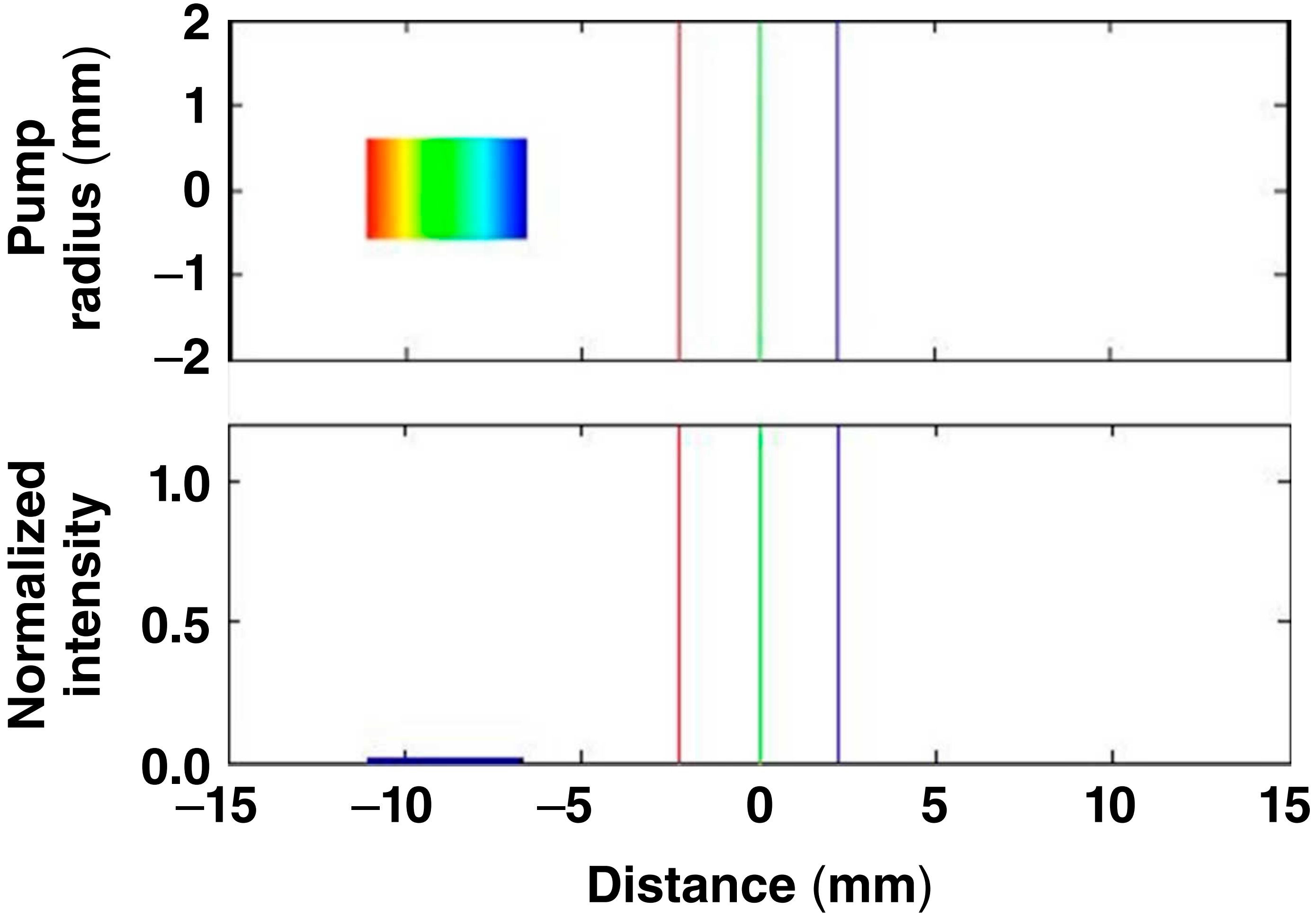
# Reducing the pulse duration of the negatively chirped beam (blue to red) produces a focal velocity faster than the speed of light





# Setting the pulse duration equal to the focal range ($L/c$) results in an "infinitely" fast focal velocity (line focus)





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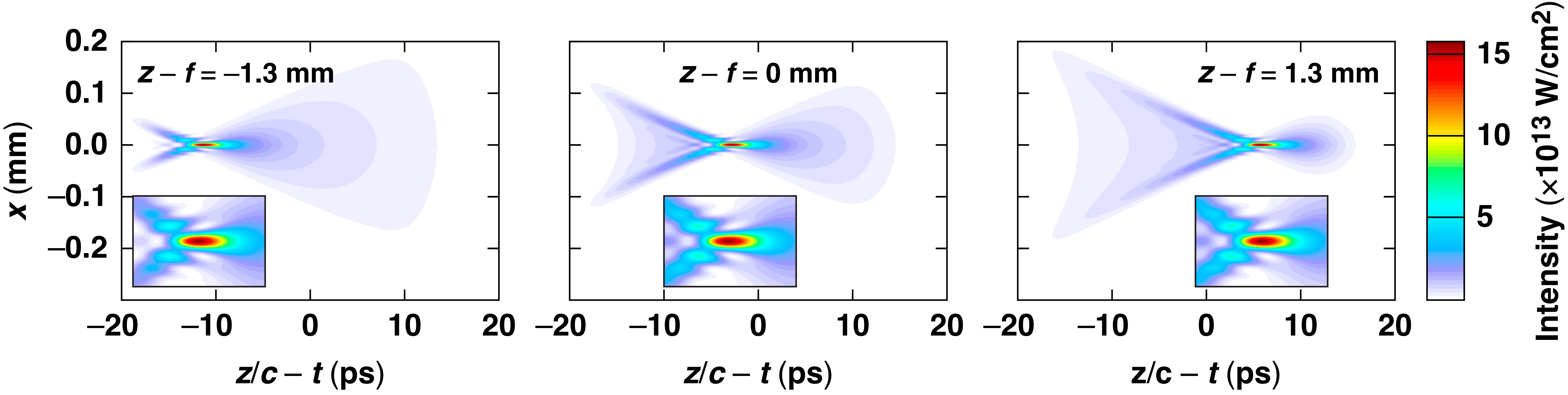
# A simulation of the focal region shows that the peak intensity of the flying focus propagates with a self-similar form



**The longitudinal profile of the intensity peak depends only on space and time in the combination**

$$\boxed{\left[1 - \frac{\Delta\lambda(z - ct)}{\lambda c T}\right]^{-1} z}$$

TC14131a

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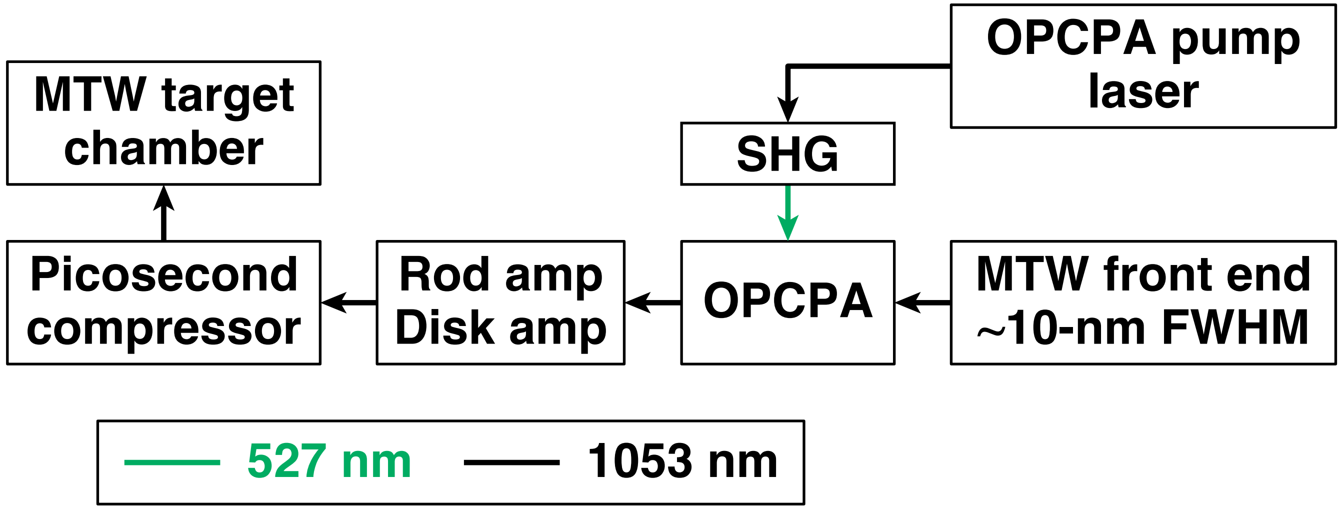
J. P. Palastro *et al.*, Phys. Rev. A 97, 033835 (2018).

# Outline

- Description of the flying focus
- **Experimental demonstration of the flying focus**
- Ionization waves of arbitrary velocity (IWAV’s)
- Applications of the flying focus

# The Multi-Terawatt (MTW) laser at the University of Rochester's Laboratory for Laser Energetics (LLE) was used to demonstrate the flying focus

- OPCPA front end and Nd:glass amplifiers (1053-nm, 10-nm bandwidth)
- 0.7 ps to 300 ps up to 50 J


OPCPA pump laser

SHG

MTW target chamber

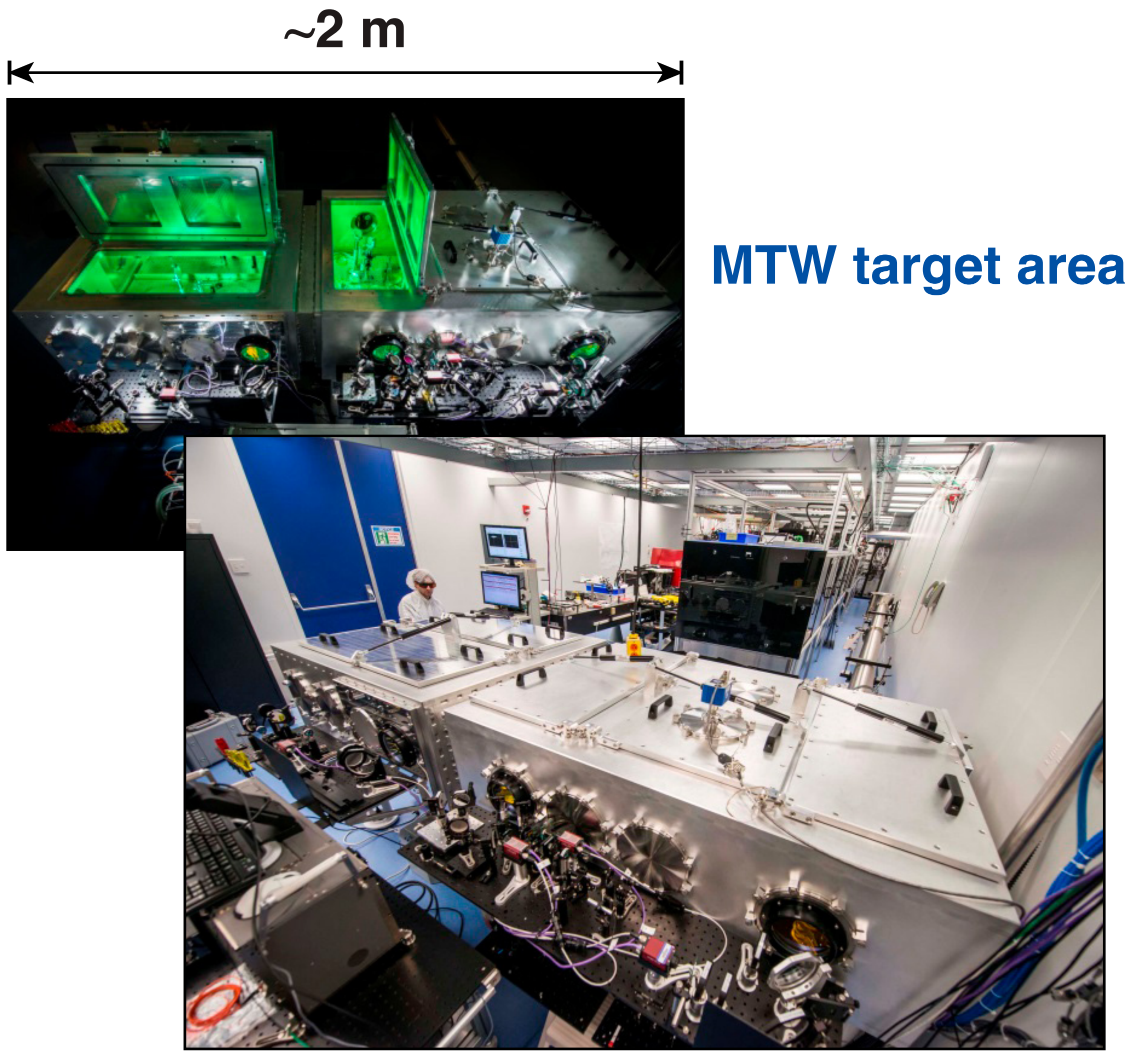
Picosecond compressor

Rod amp
Disk amp

OPCPA

MTW front end
~10-nm FWHM

🟩 527 nm
■ 1053 nm



MTW target area

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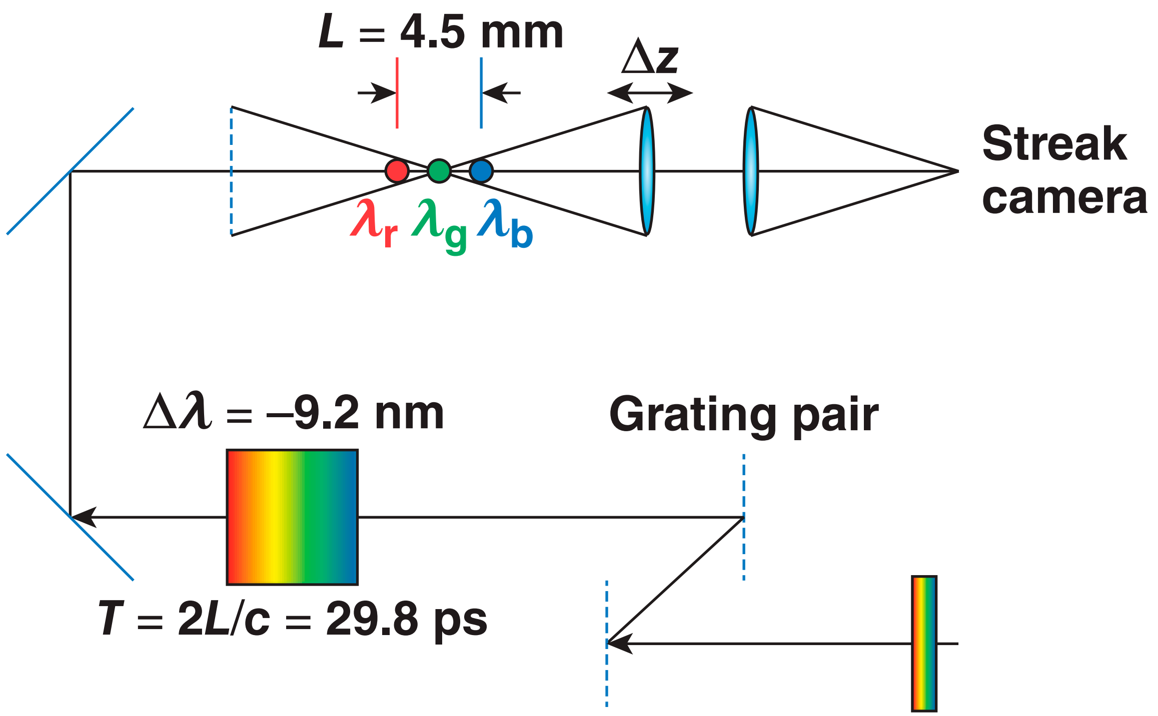
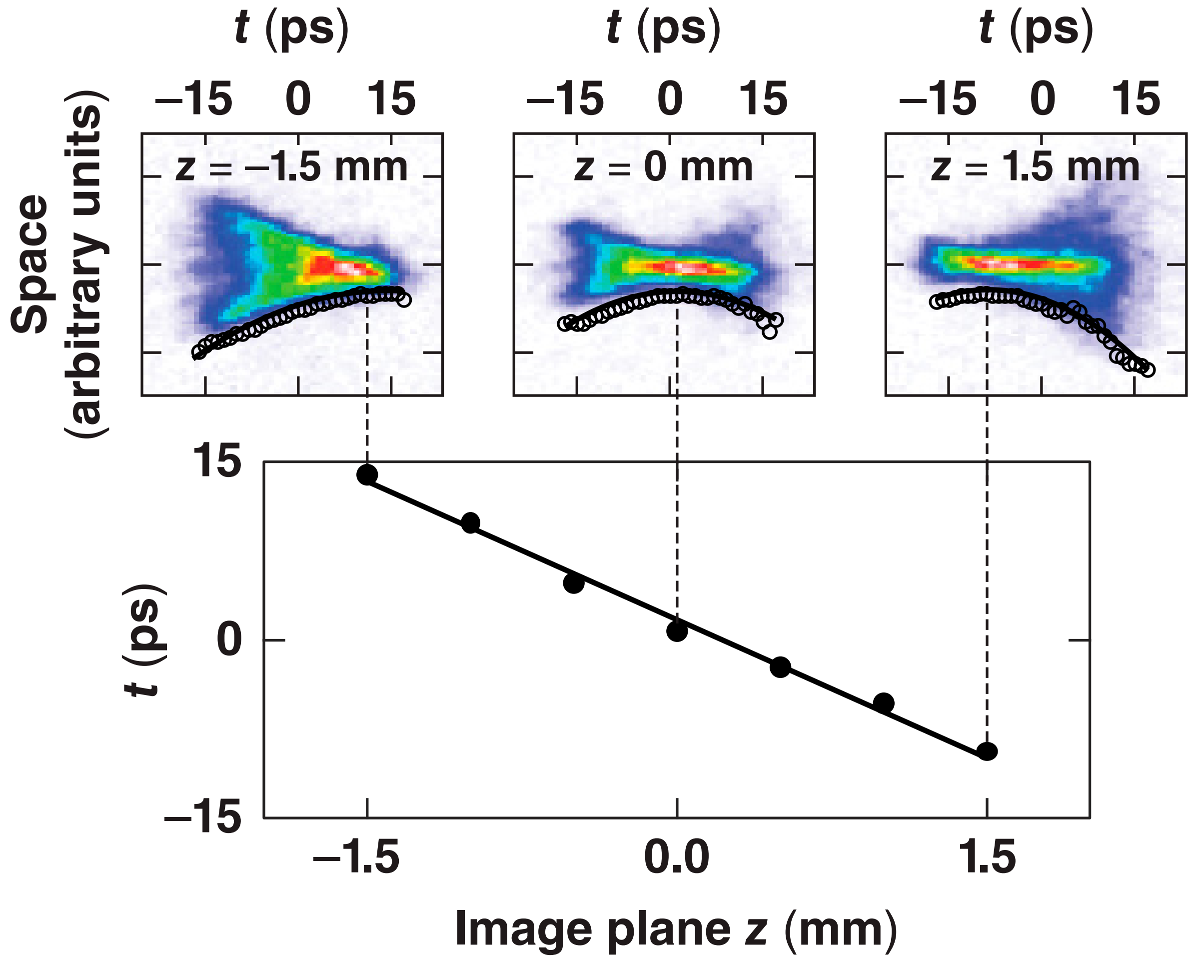
OPCPA: optical parametric chirped-pulse amplifier
SHG: second-harmonic generation

# A picosecond optical streak camera imaged the intensity profile of the flying focus



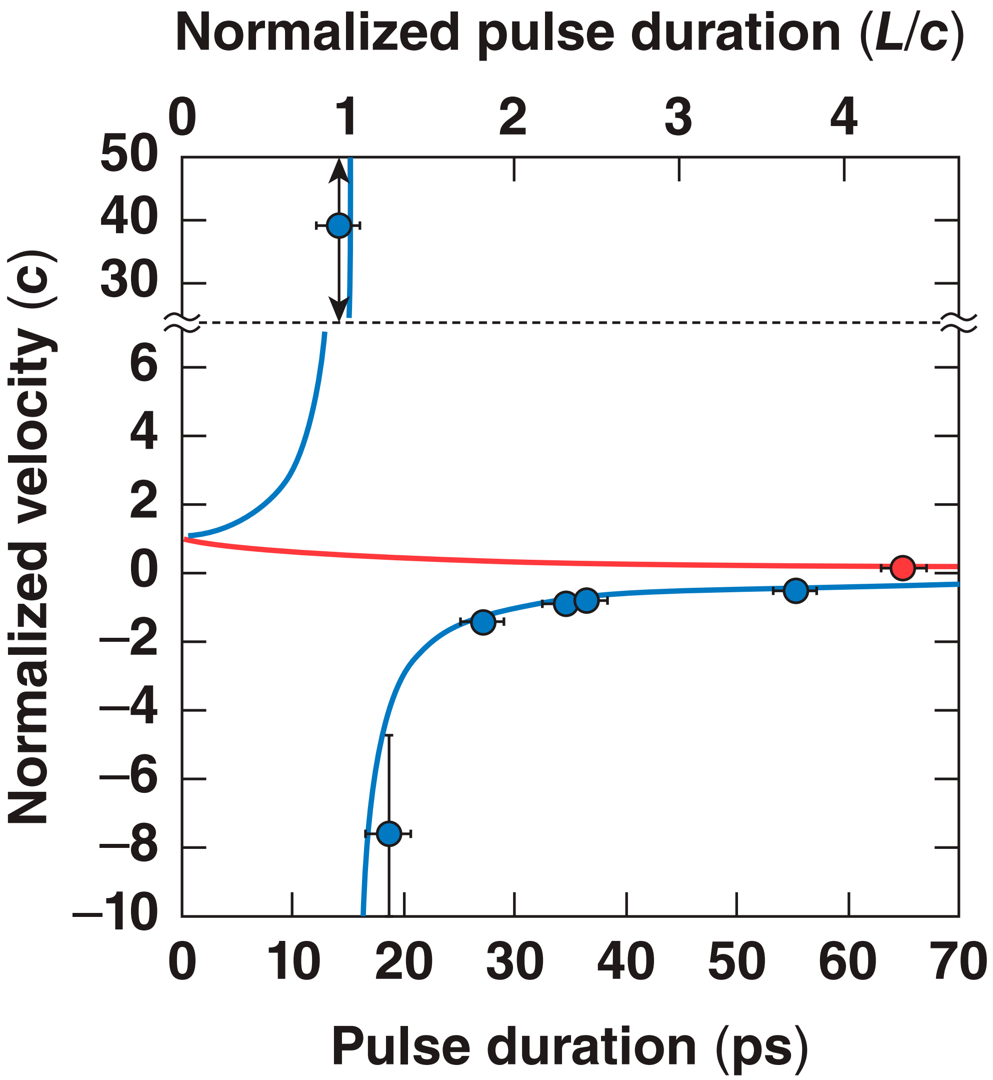


**Several locations in the focal region were imaged onto a streak camera, providing the spatiotemporal profile of the flying focus pulse.**

# The measurements show excellent agreement with the analytic calculations

**Focal velocity:**

$$\frac{v_f}{c} = \left(1 \pm \frac{cT}{L}\right)^{-1}$$



*T*: stretched pulse duration

$$L = f_0 \frac{\Delta\lambda}{\lambda_0} \cong 4.5\ \text{mm}$$

$$\lambda_0 = 1054\ \text{nm}$$

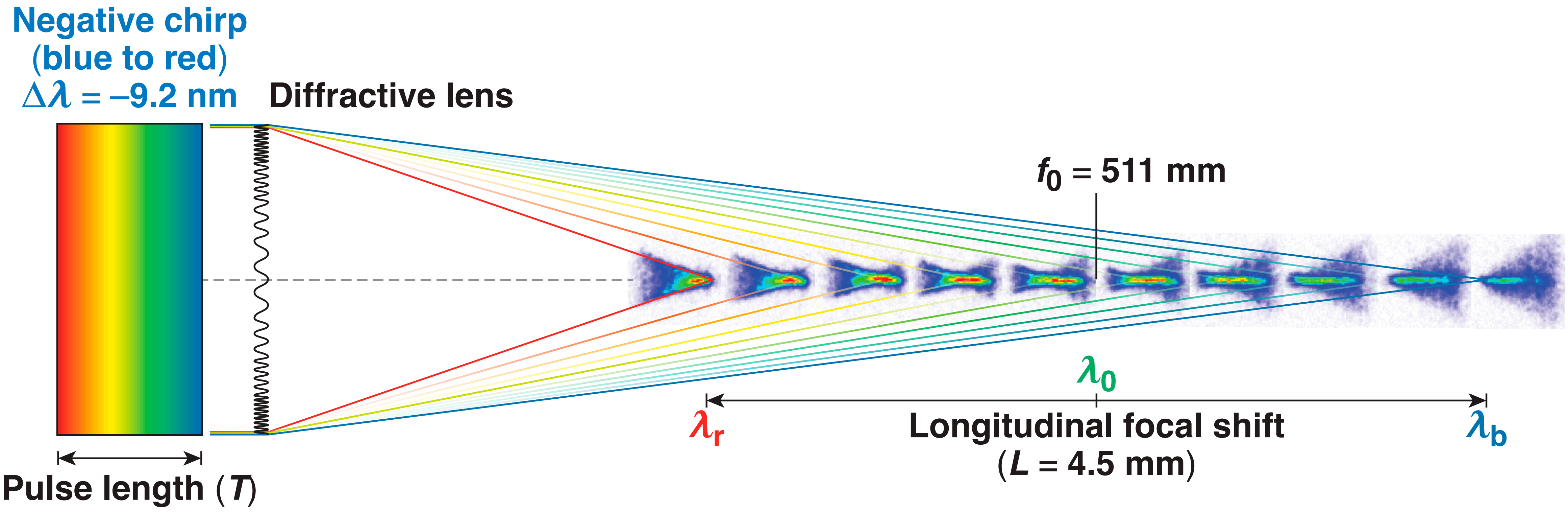
$$\Delta\lambda = 9.2\ \text{nm}$$

$$f_0 = 511\ \text{mm}$$

I2700a

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

# The measured images provided space and time information that were reconstructed to generate the focal intensity in space



**Negative chirp**
**(blue to red)**
**$\Delta\lambda = -9.2$ nm**

**Diffractive lens**

**$f_0 = 511$ mm**

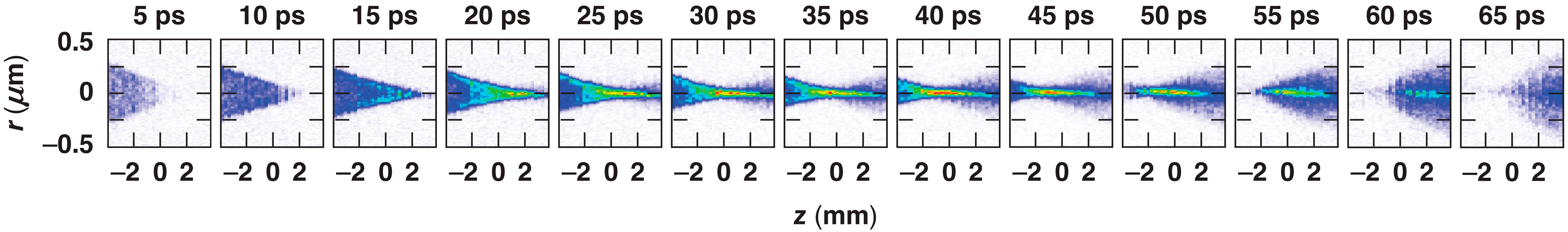
$\lambda_0$

$\lambda_r$

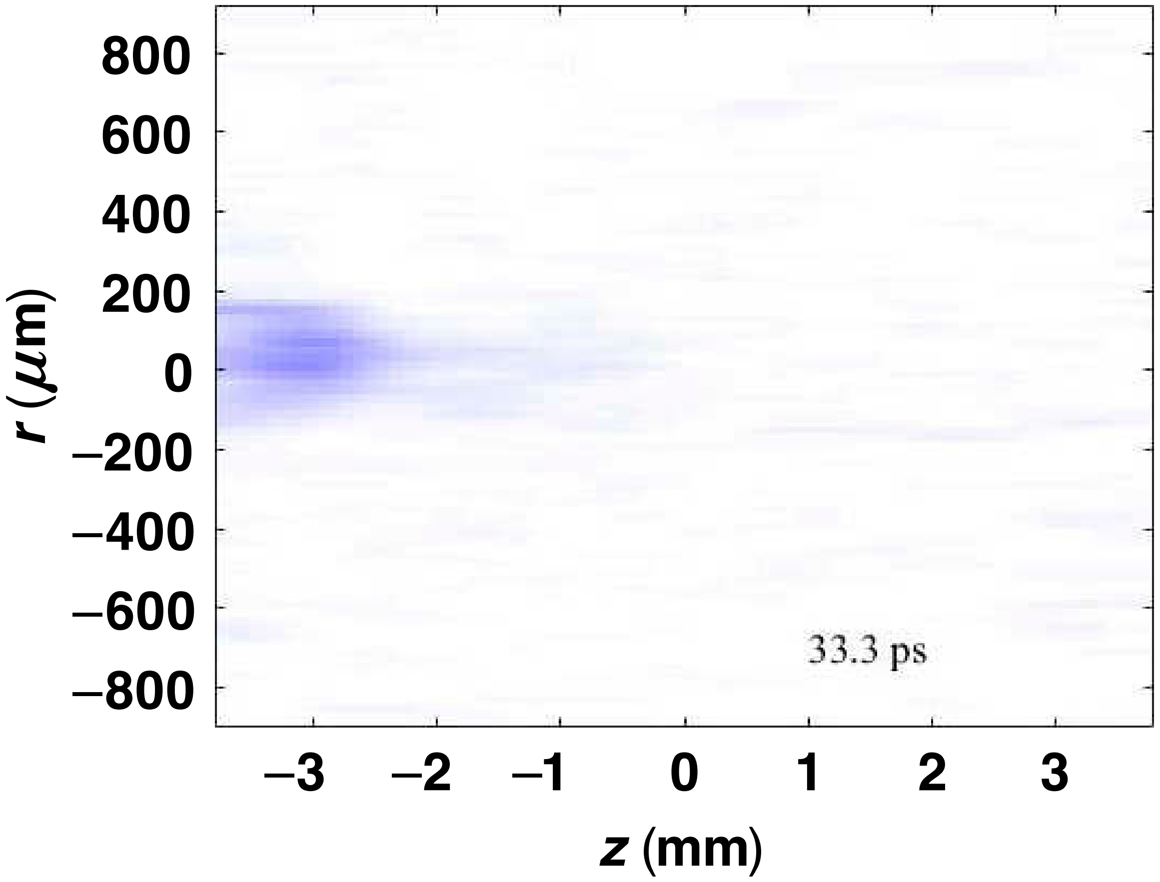
**Longitudinal focal shift**
**($L = 4.5$ mm)**

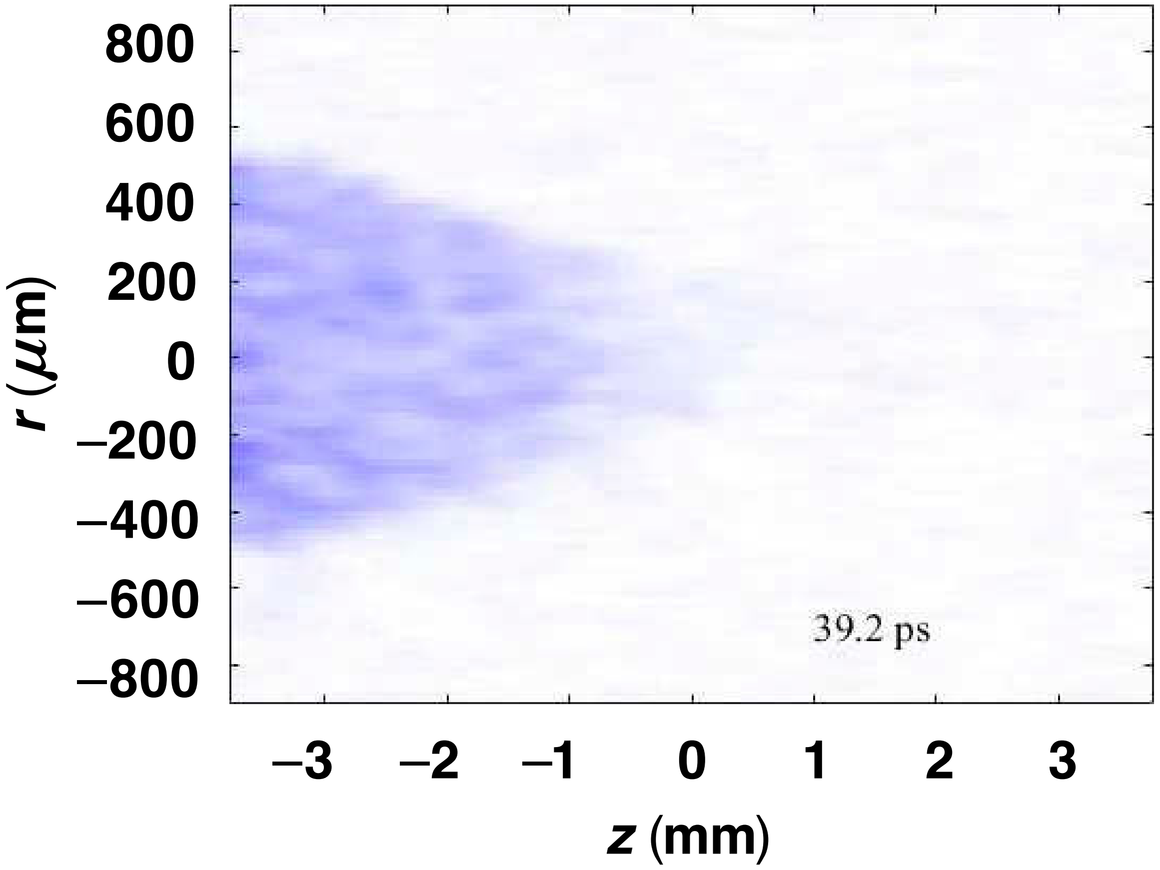
$\lambda_b$

**Pulse length ($T$)**

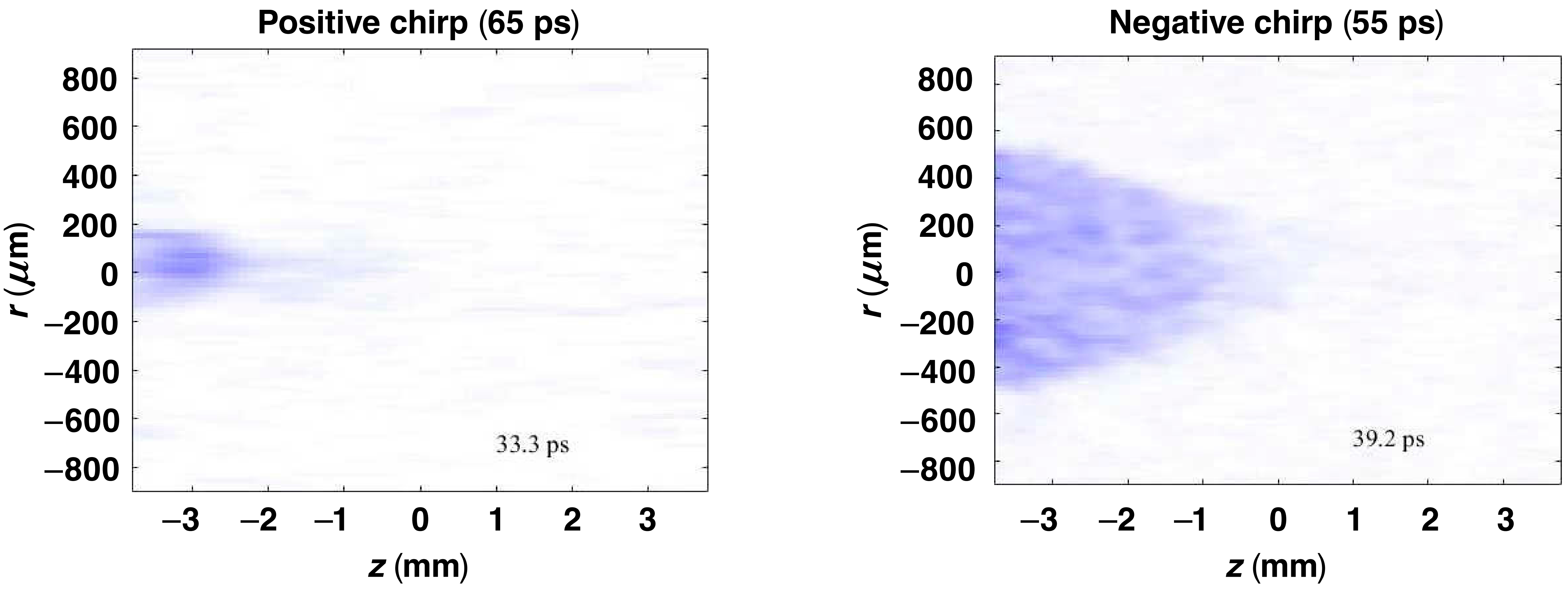


# The images form a movie of the flying focus (~3 ps/frame)


Positive chirp (65 ps)


Negative chirp (55 ps)

# The images form a movie of the flying focus (~3 ps/frame)

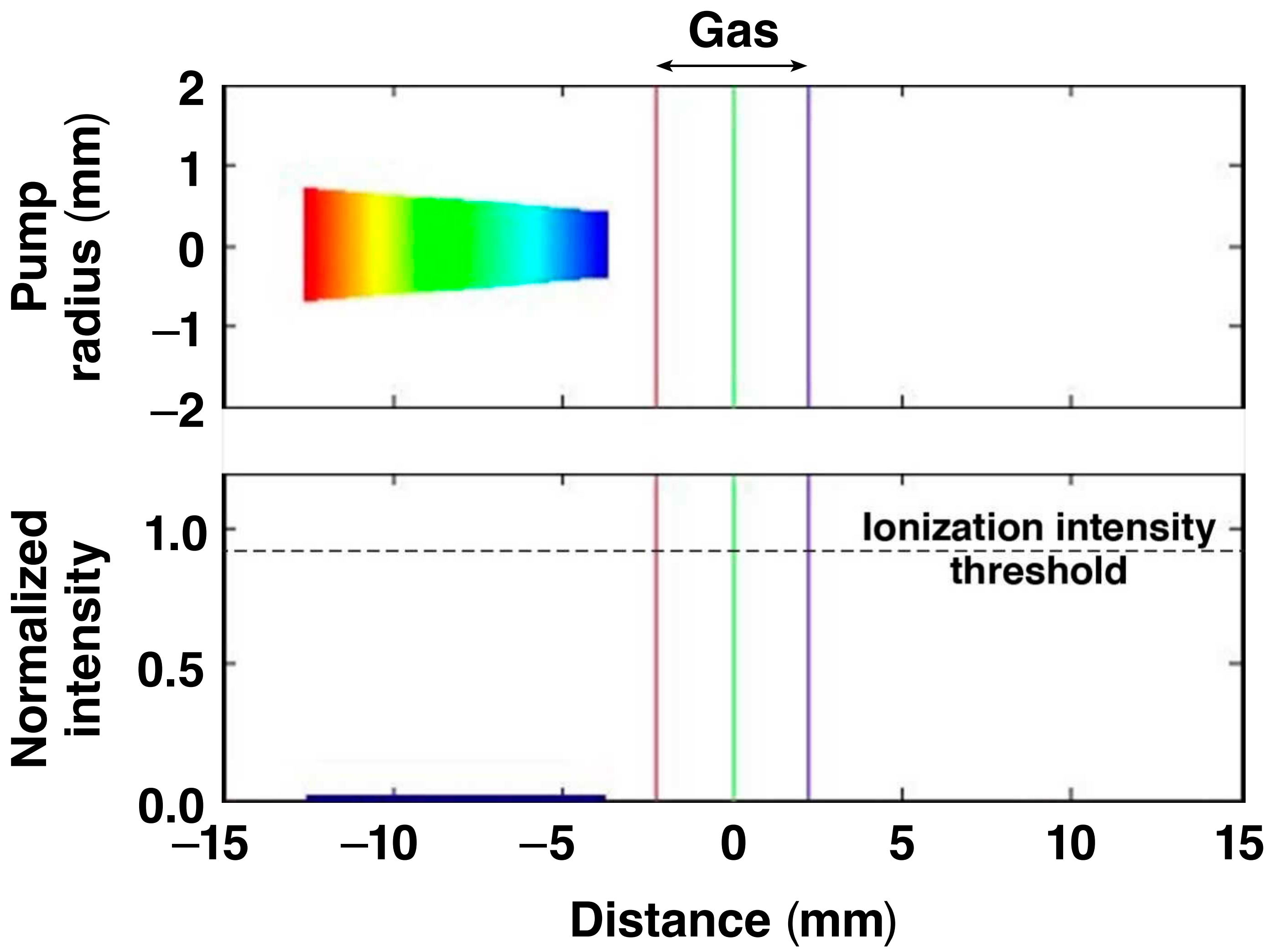


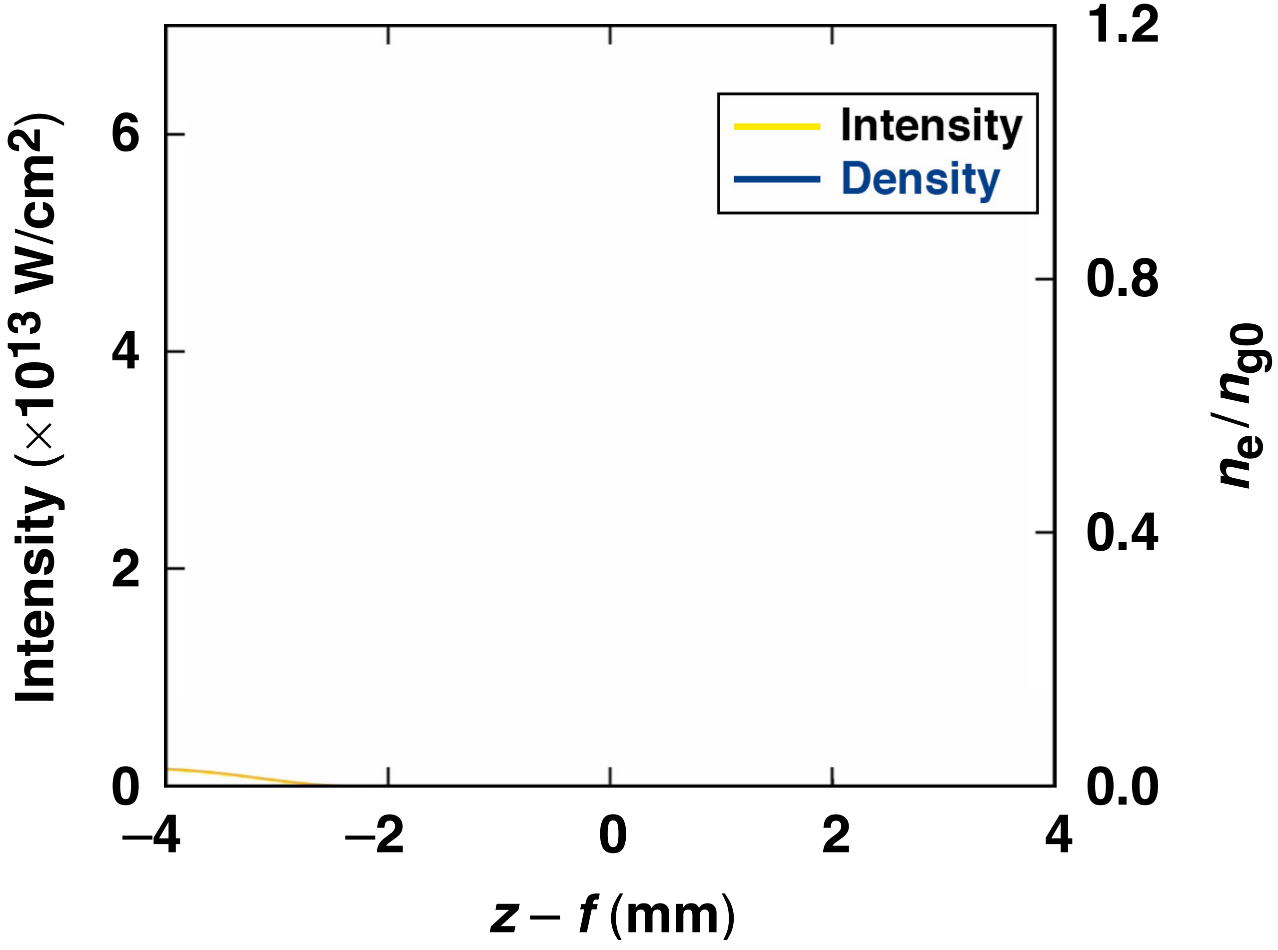
E26389d

# Outline

- Description of the flying focus
- Experimental demonstration of the flying focus
- **Ionization waves of arbitrary velocity (IWAV’s)**
- Applications of the flying focus

# The flying focus pulse can be used to generate an ionization wave of arbitrary velocity (IWAV)





**Counter-propagating flying focus mitigates ionization-induced refraction.**

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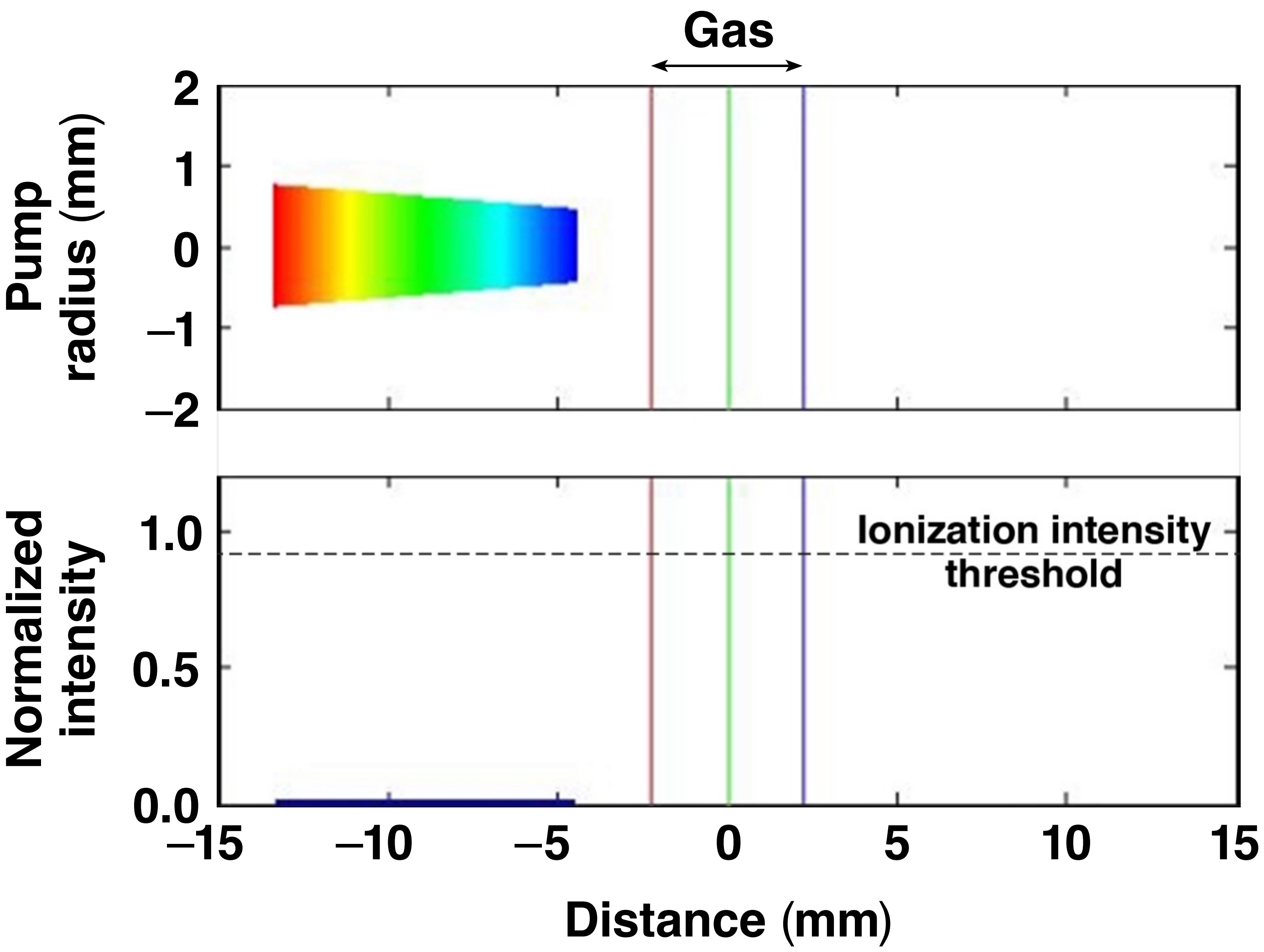
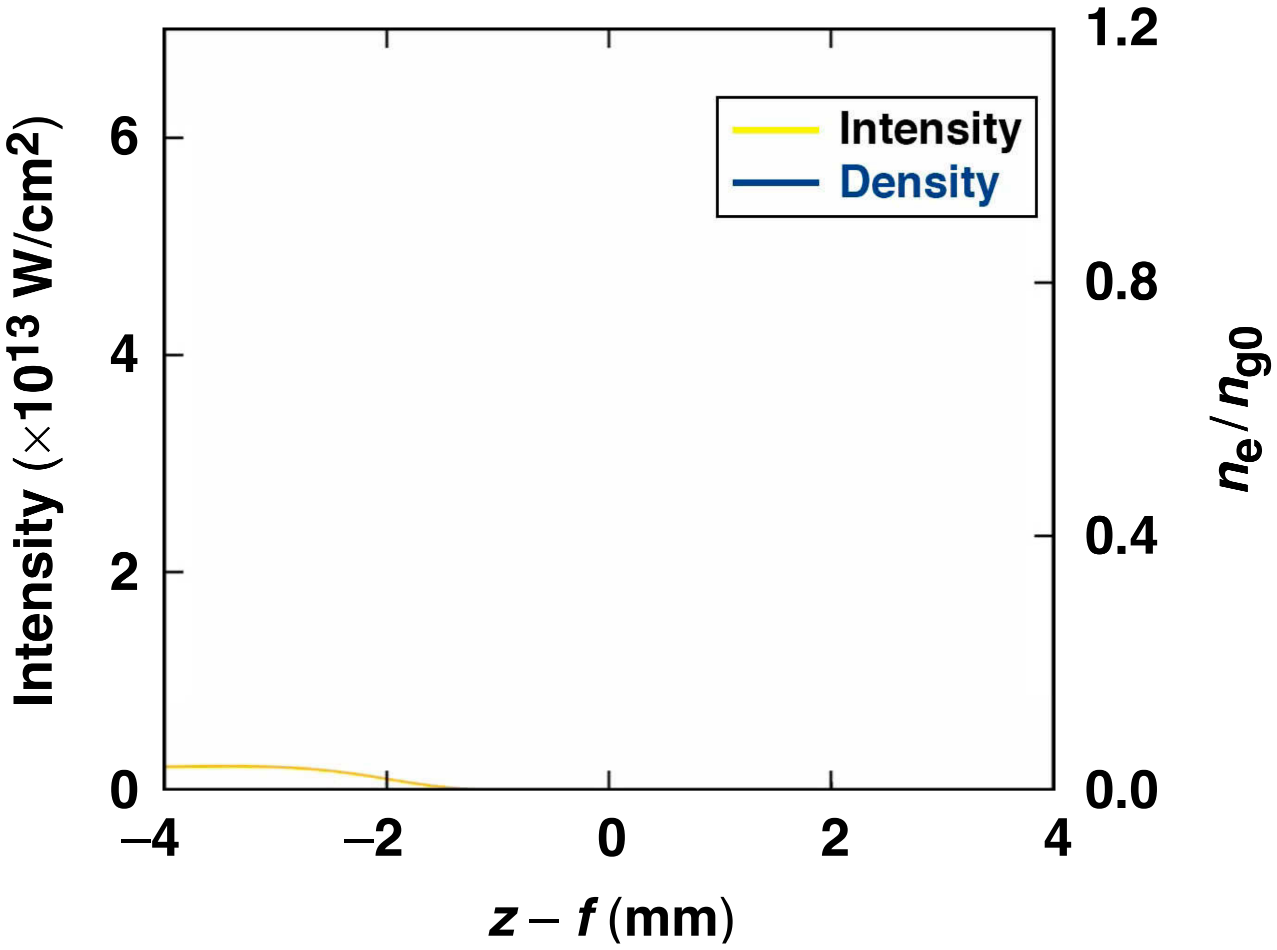
J. P. Palastro *et al.*, Phys. Rev. A 97, 033835 (2018).

E27813

# The flying focus pulse can be used to generate an IWAV

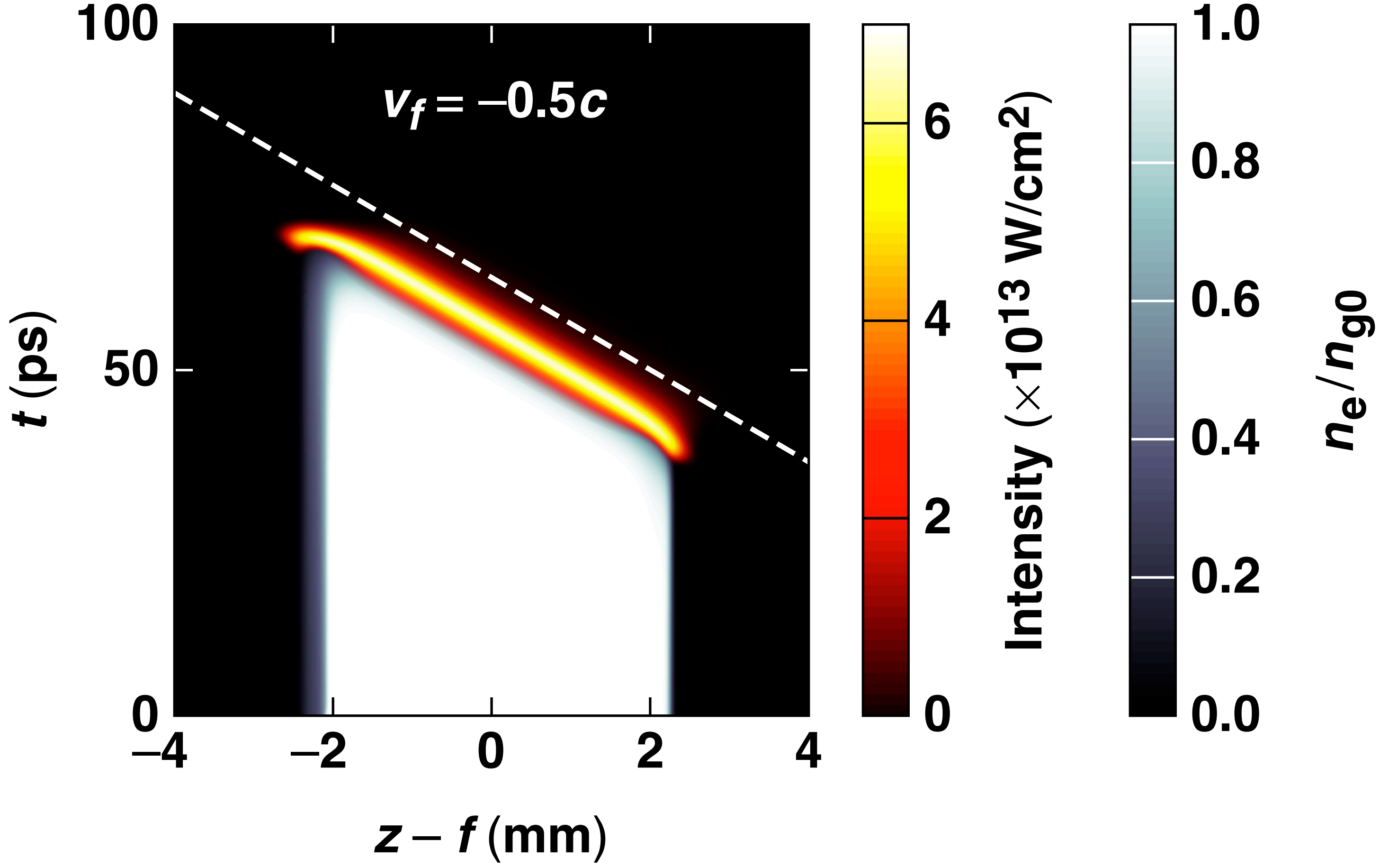


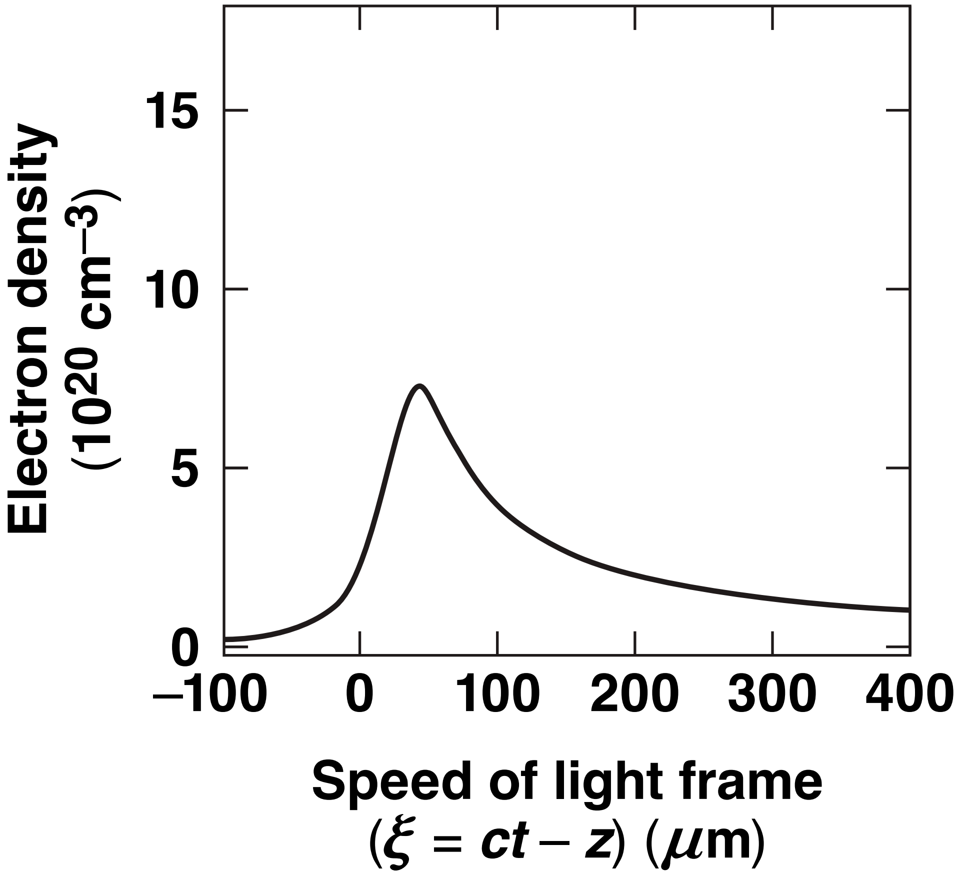


E27813a

J. P. Palastro *et al.*, Phys. Rev. A 97, 033835 (2018).

# A counter-propagating flying focus mitigates plasma refraction and produces a sharp ionization front



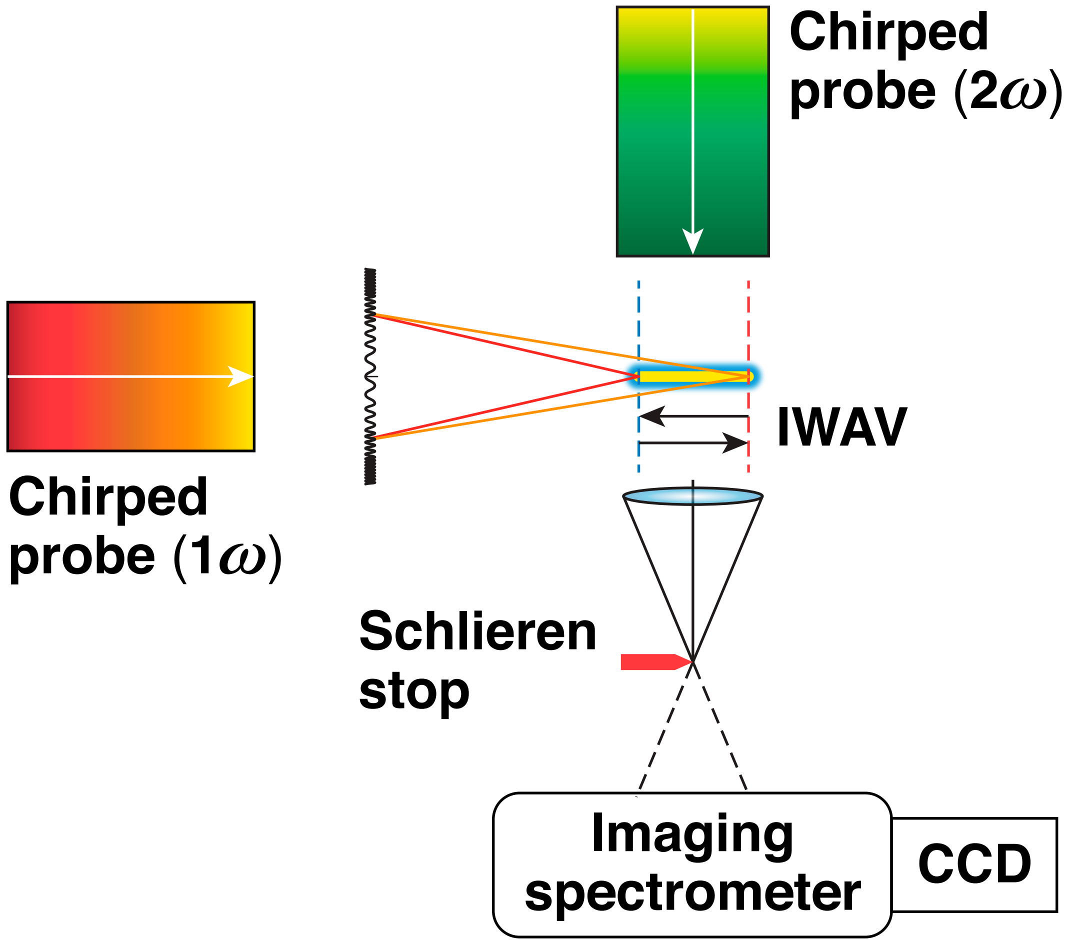


TC14137c

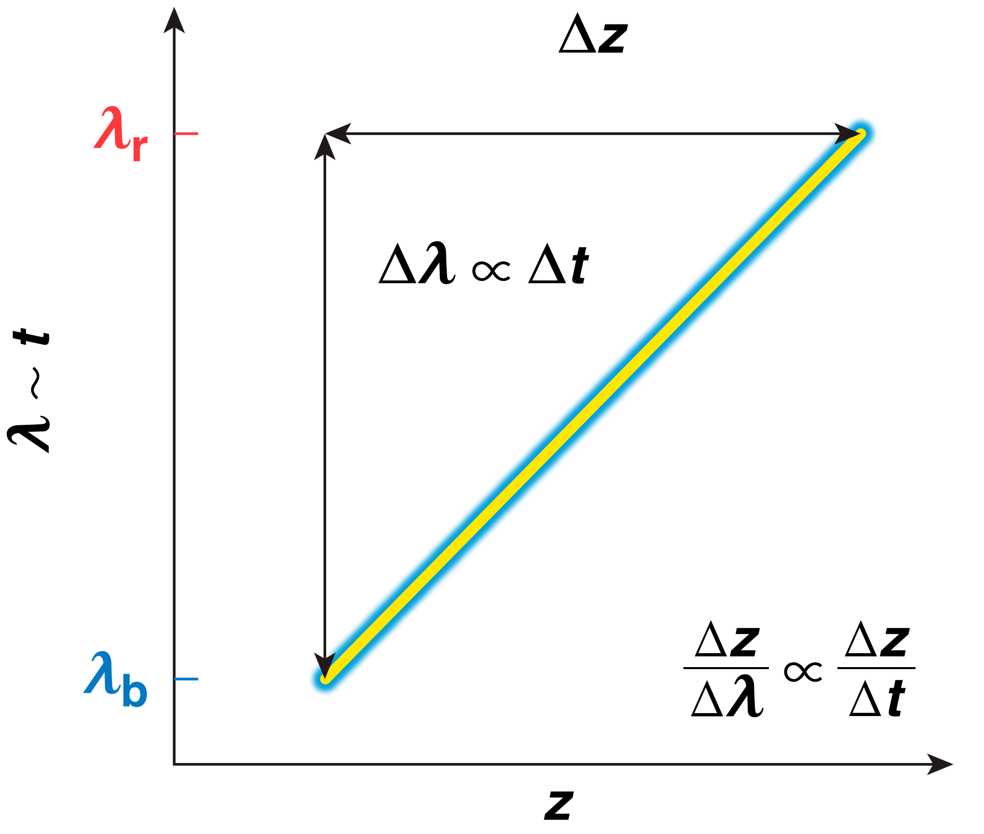
**Phil Franke**

PAS
Grad student

# To study IWAV’s in the laboratory, a spectrally resolved schlieren diagnostic was used



Spectrally (time) resolved schlieren



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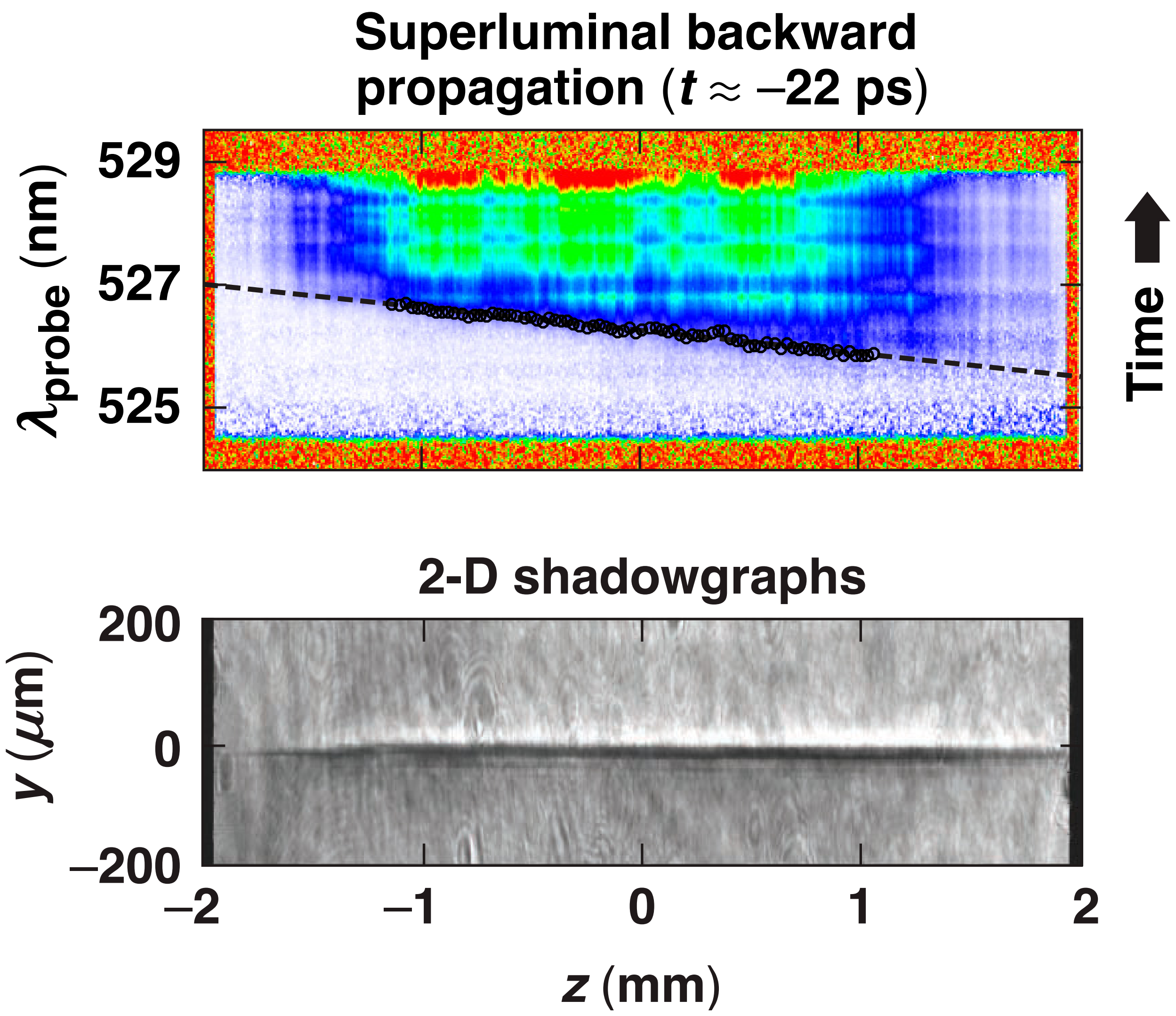
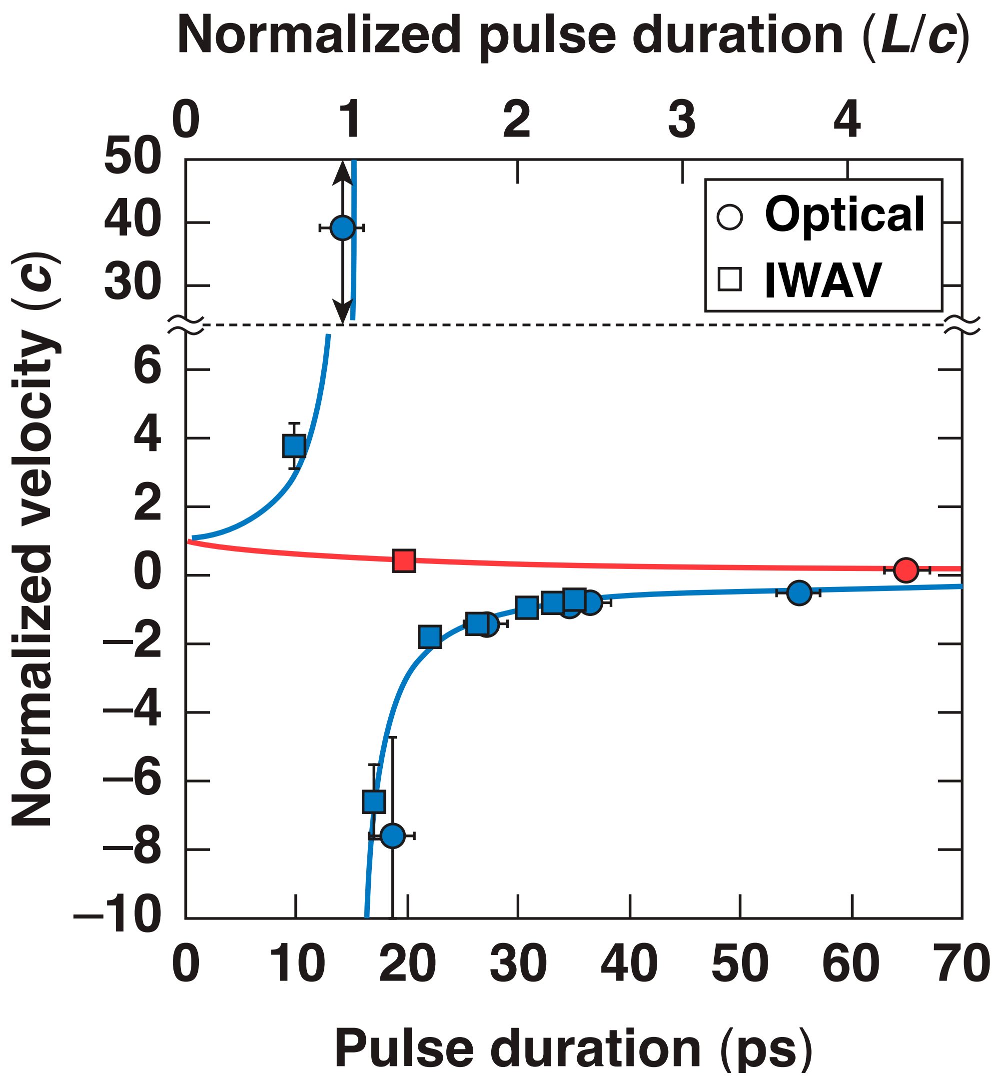
P. Franke, UP11.00093 this conference.
CCD: charge-coupled device

E27812

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


Superluminal backward propagation ($t \approx -22$ ps)

2-D shadowgraphs


Normalized pulse duration ($L/c$)

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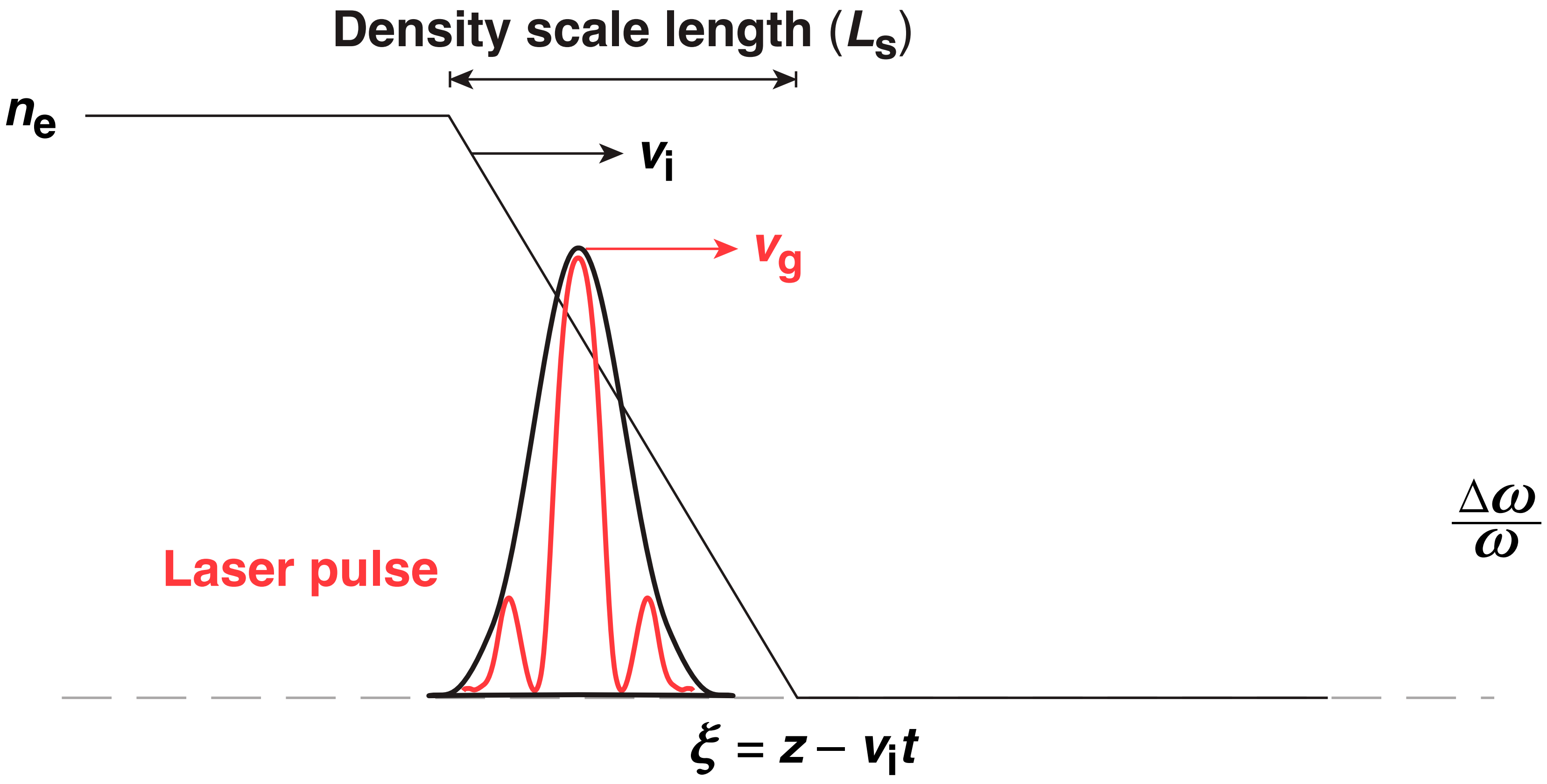
D. Turnbull *et al.*, Phys. Rev. Lett. 120, 024801 (2018);
D. Turnbull *et al.*, CO8.00012 this conference.

# Outline

- Description of the flying focus
- Experimental demonstration of the flying focus
- Ionization waves of arbitrary velocity (IWAV's)
- **Applications of the flying focus**

# The flying focus could be used extend the interaction length in a photon accelerator

**A photon accelerator uses a time-varying refractive index to increase the group velocity of light**



**Index of refraction**

$$n = \sqrt{1 - \left(\frac{\omega_p}{\omega}\right)^2} \qquad \omega_p \propto \sqrt{n_e}$$

**Frequency shift**

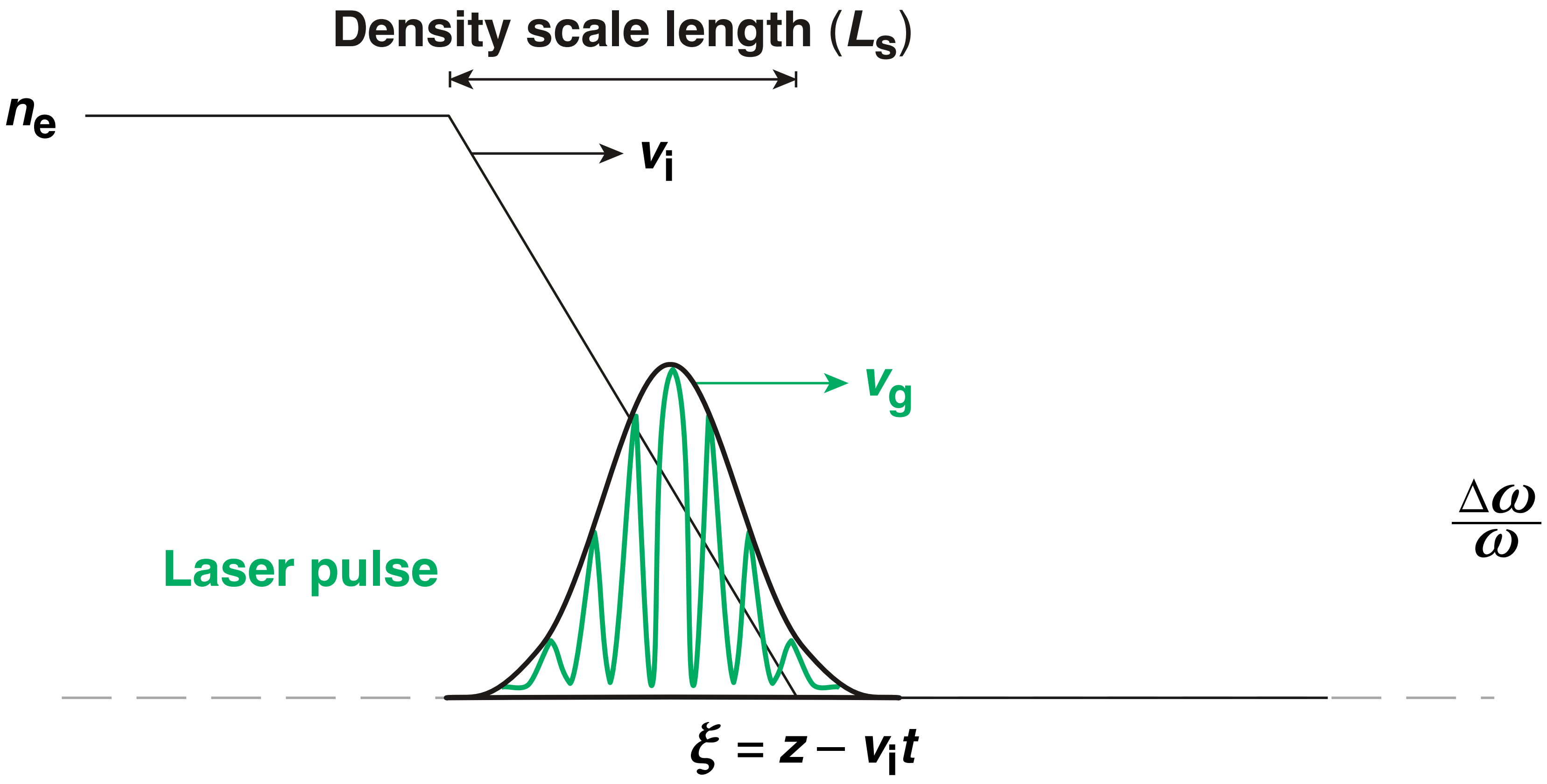
$$\frac{\Delta\omega}{\omega} = \sqrt{1 - \left(\frac{\omega_p}{\omega}\right)^2} \frac{Z_{\text{effective}}}{L_s}$$

E27972

Funded by DE-SC0019135 (PI Turnbull)

# The flying focus could be used extend the interaction length in a photon accelerator

**A photon accelerator uses a time-varying refractive index to increase the group velocity of light**



**Index of refraction**

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E27972a

Funded by DE-SC0019135 (PI Turnbull)

# The flying focus could be used extend the interaction length in a photon accelerator

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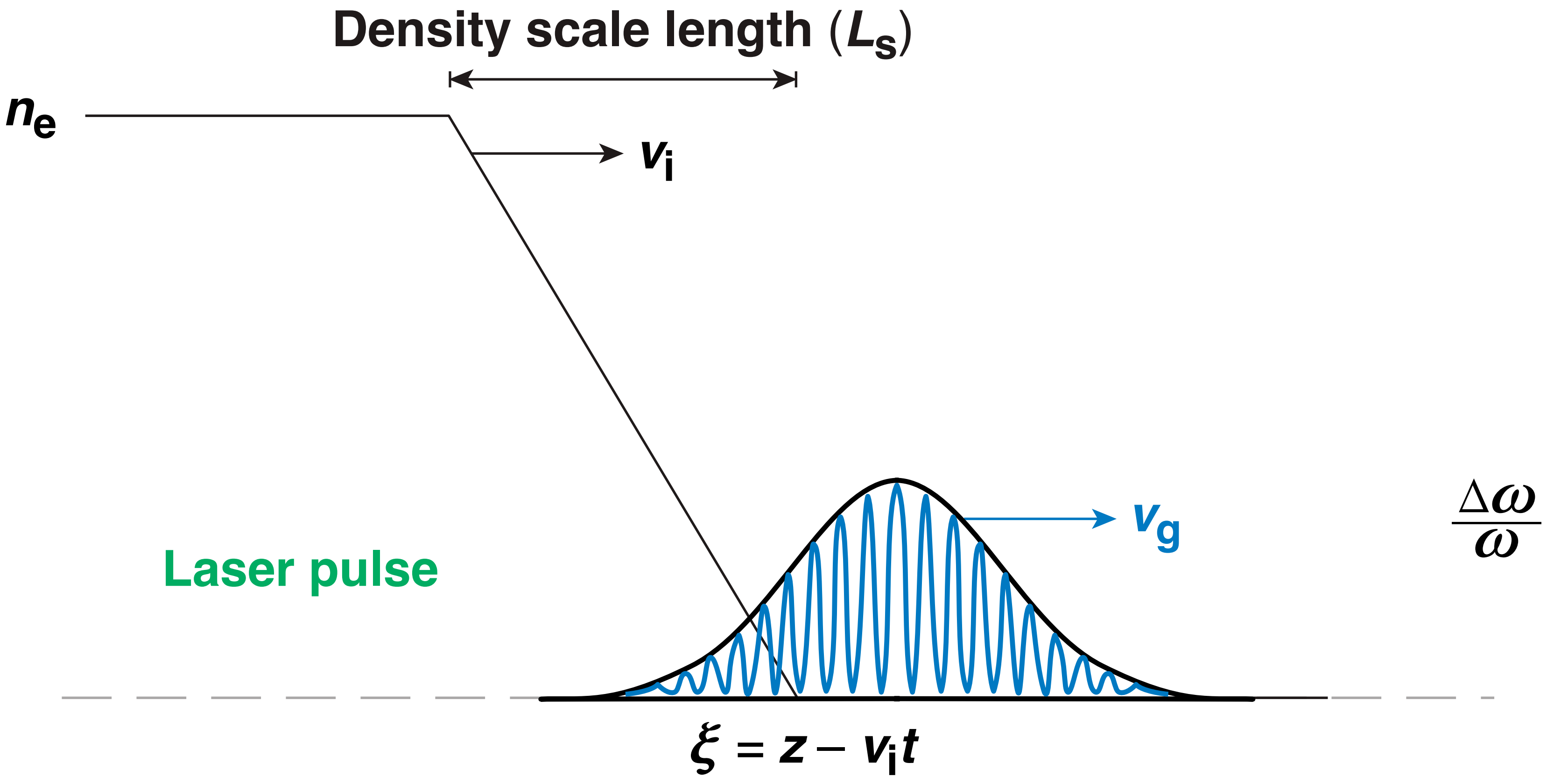

**Index of refraction**

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**Frequency shift**

$$\frac{\Delta\omega}{\omega} = \sqrt{1 - \left(\frac{\omega_p}{\omega}\right)^2} \frac{Z_{\text{effective}}}{L_s}$$

**As the photons accelerate they eventually outrun the ionization front in a "conventional" photon accelerator.**

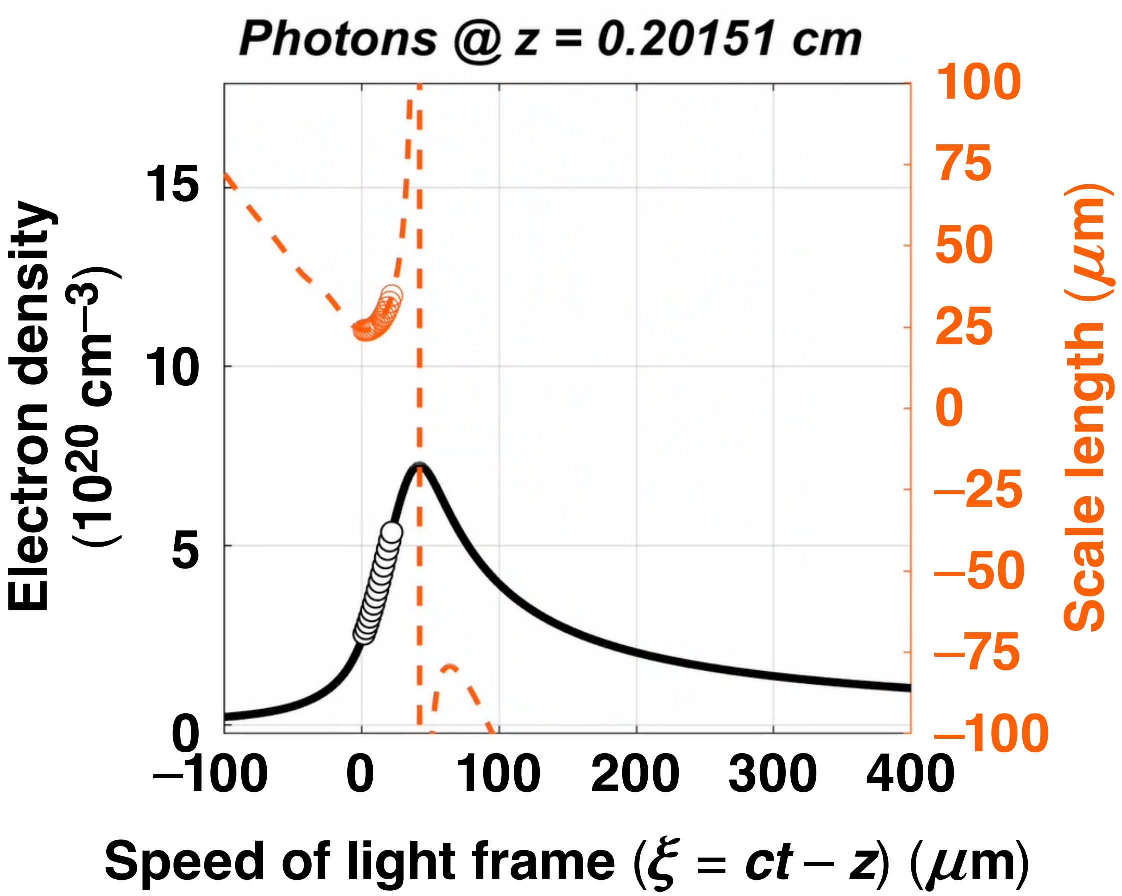
E27972b

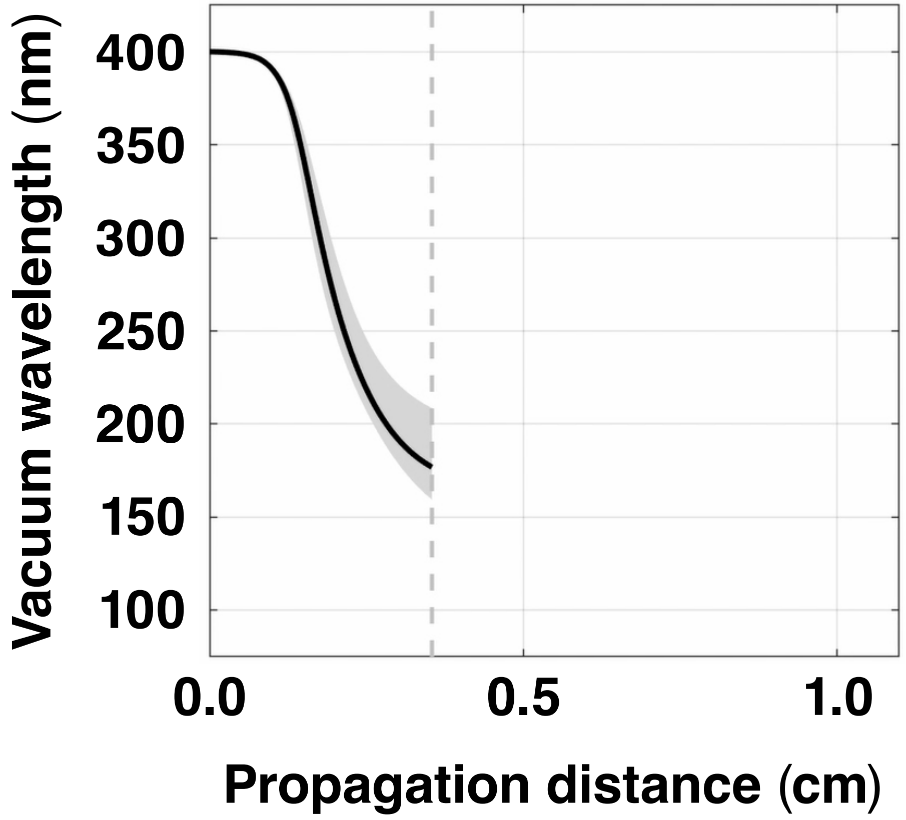
Funded by DE-SC0019135 (PI Turnbull)

**Andy Howard**

**PAS Undergraduate**

# By using the flying focus to generate ionization waves propagating at the speed of light, optical light can be frequency converted to the extreme ultraviolet





**The photon accelerator driven by a flying focus could convert optical light to the extreme ultraviolet (100 nm).**

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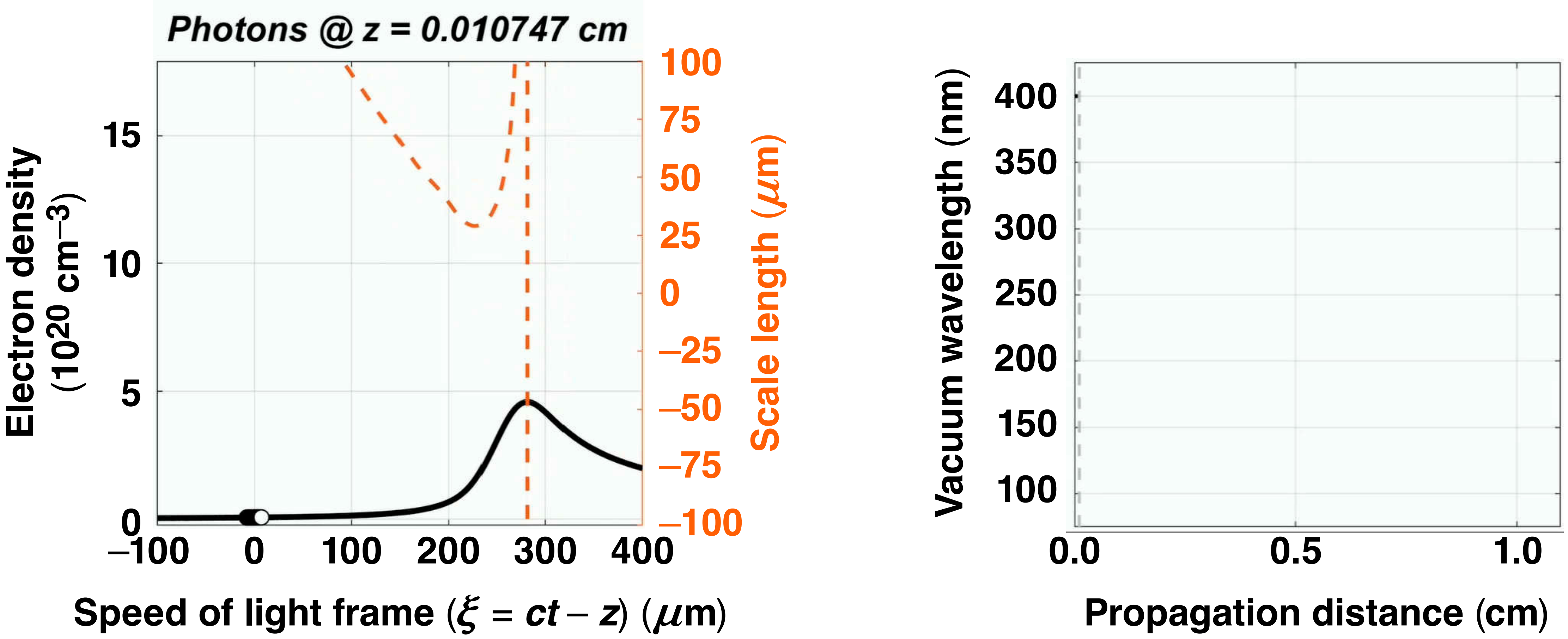
A. Howard *et al.*, in preparation for Phys. Rev. Lett.;
A. Howard *et al.*, PP11.00006, this conference.

Funded by DE-SC0019135 (PI Turnbull)

**Andy Howard**

**PAS Undergraduate**

# By using the flying focus to generate ionization waves propagating at the speed of light, optical light can be frequency converted to the extreme ultraviolet



**The photon accelerator driven by a flying focus could convert optical light to the extreme ultraviolet (100 nm).**

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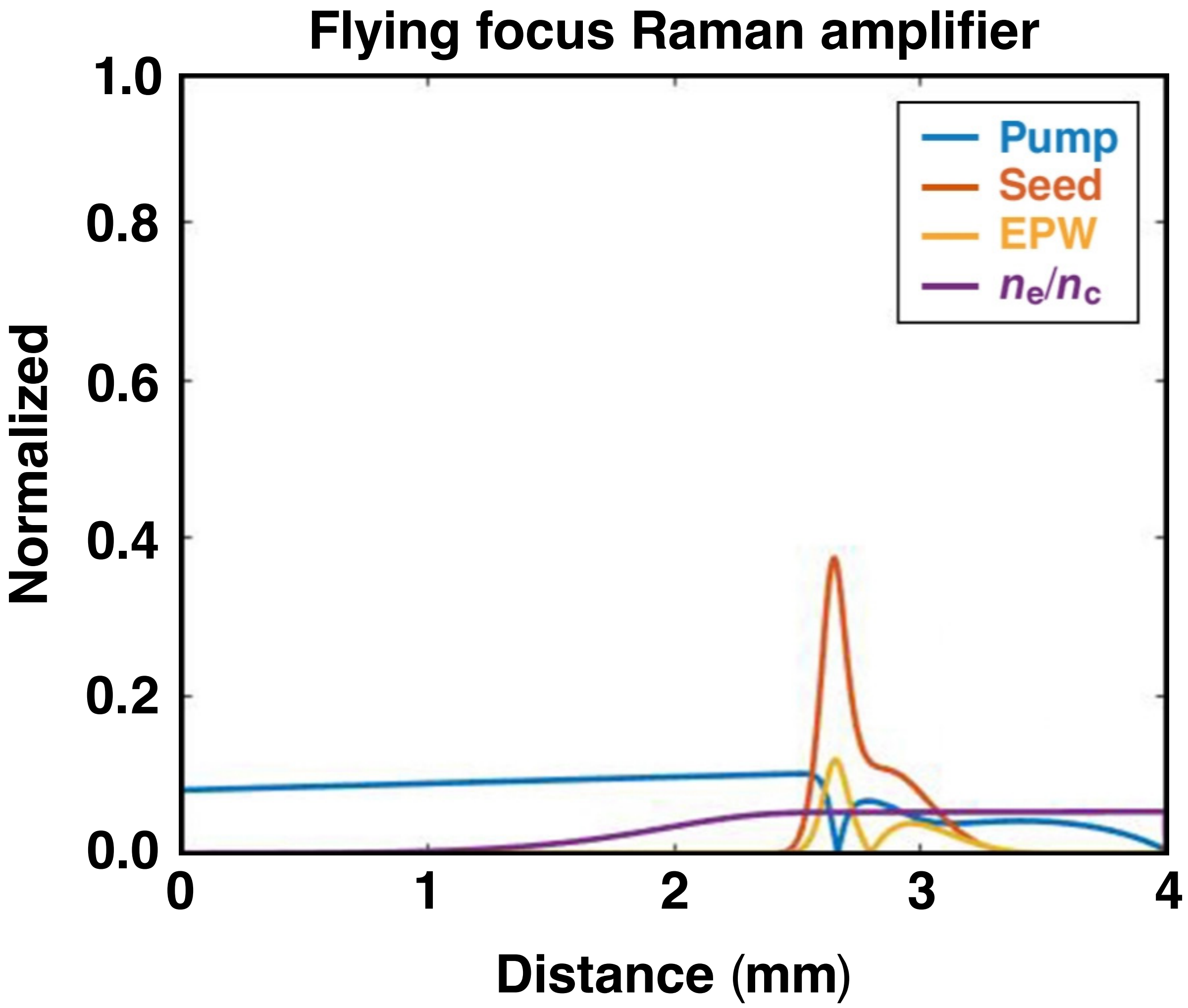
A. Howard *et al.*, in preparation for Phys. Rev. Lett.;
A. Howard *et al.*, PP11.00006, this conference.

E27815a

Funded by DE-SC0019135 (PI Turnbull)

# A counter-propagating ionization wave could overcome several challenges of Raman amplification

- **Constant longitudinal intensity:** the seed pulse experiences a constant pump intensity over the entire amplifier length
- **Counter-propagating ionization wave:** the pump will propagate through gas-eliminating parasitic instabilities
- **Plasma conditions:** the plasma conditions observed by the seed will be constant and controllable



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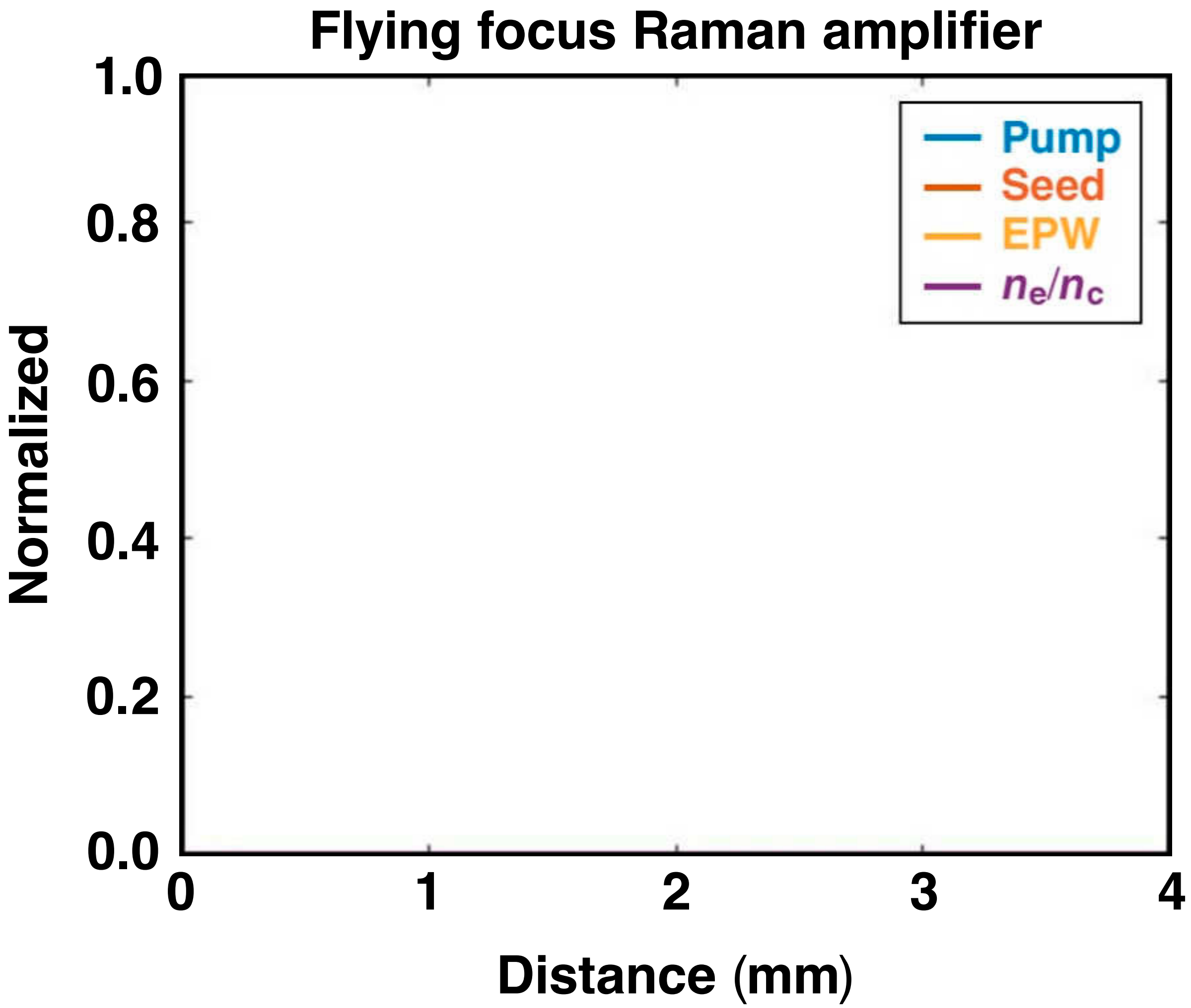
D. Turnbull *et al.*, Phys. Rev. Lett. 120, 024801 (2018).
EPW: electron plasma wave

E26271d

# A counter-propagating ionization wave could overcome several challenges of Raman amplification

- **Constant longitudinal intensity:** the seed pulse experiences a constant pump intensity over the entire amplifier length
- **Counter-propagating ionization wave:** the pump will propagate through gas-eliminating parasitic instabilities
- **Plasma conditions:** the plasma conditions observed by the seed will be constant and controllable



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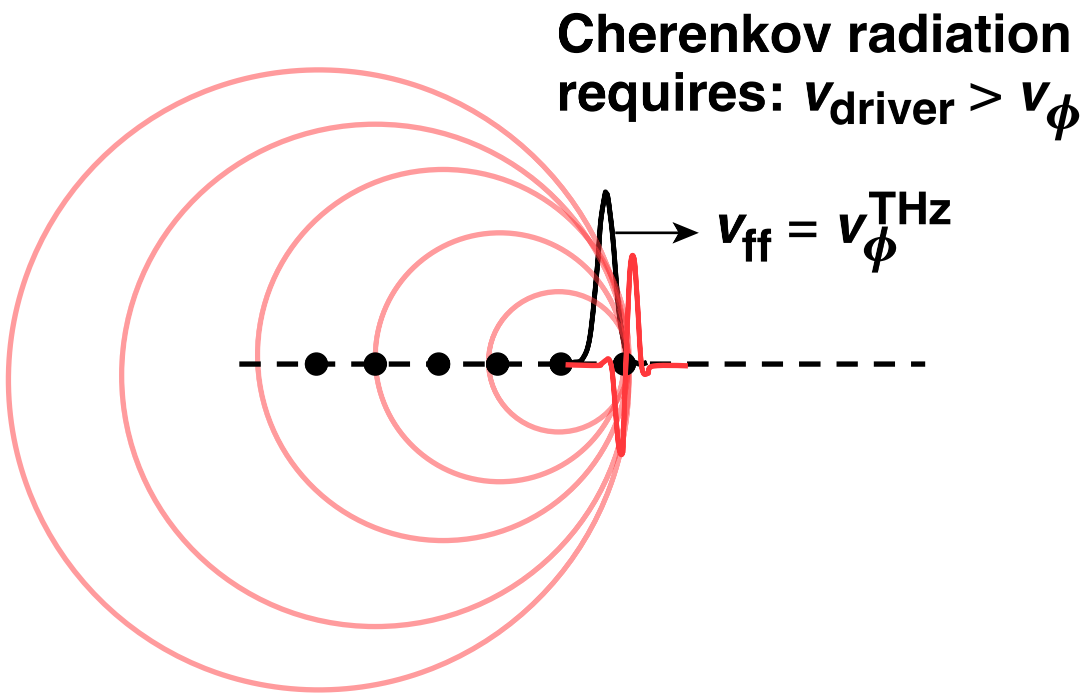
D. Turnbull *et al.*, Phys. Rev. Lett. 120, 024801 (2018).

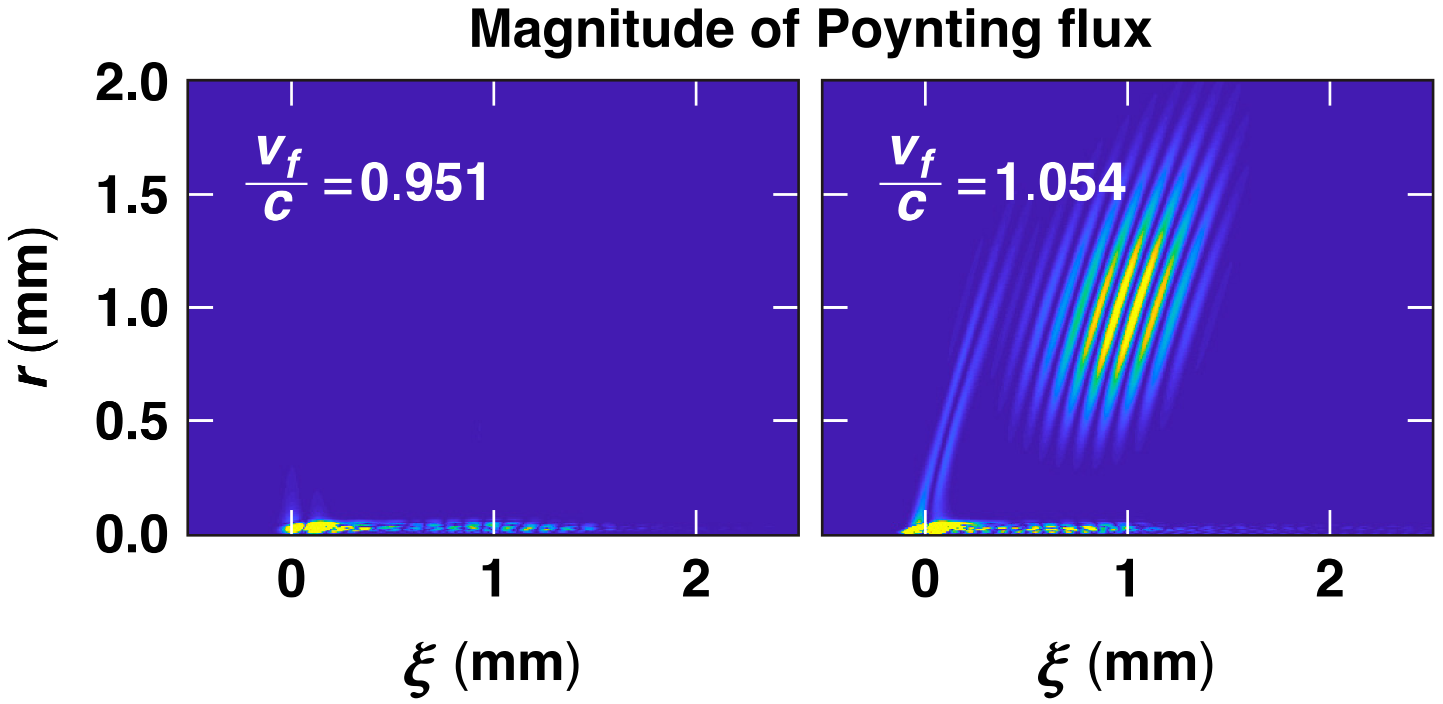
# The flying focus could enable new sources by decoupling the group velocity of light from the driver velocity

Cherenkov radiation
(THz source*)



**Cherenkov radiation is typically prohibited in a non-magnitized plasma ($v_{\text{gr}} < v_\phi$).**

The flying focus can generate Cherenkov radiation in a plasma



**The flying focus enables Cherenkov radiation in a plasma by propagating the driver faster than the phase velocity of the radiation.**

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*J. Palastro *et al.*, in preparation Phys. Rev. Lett.;
J. Palastro *et al.*, JO8.00008, this conference.

TC14148a

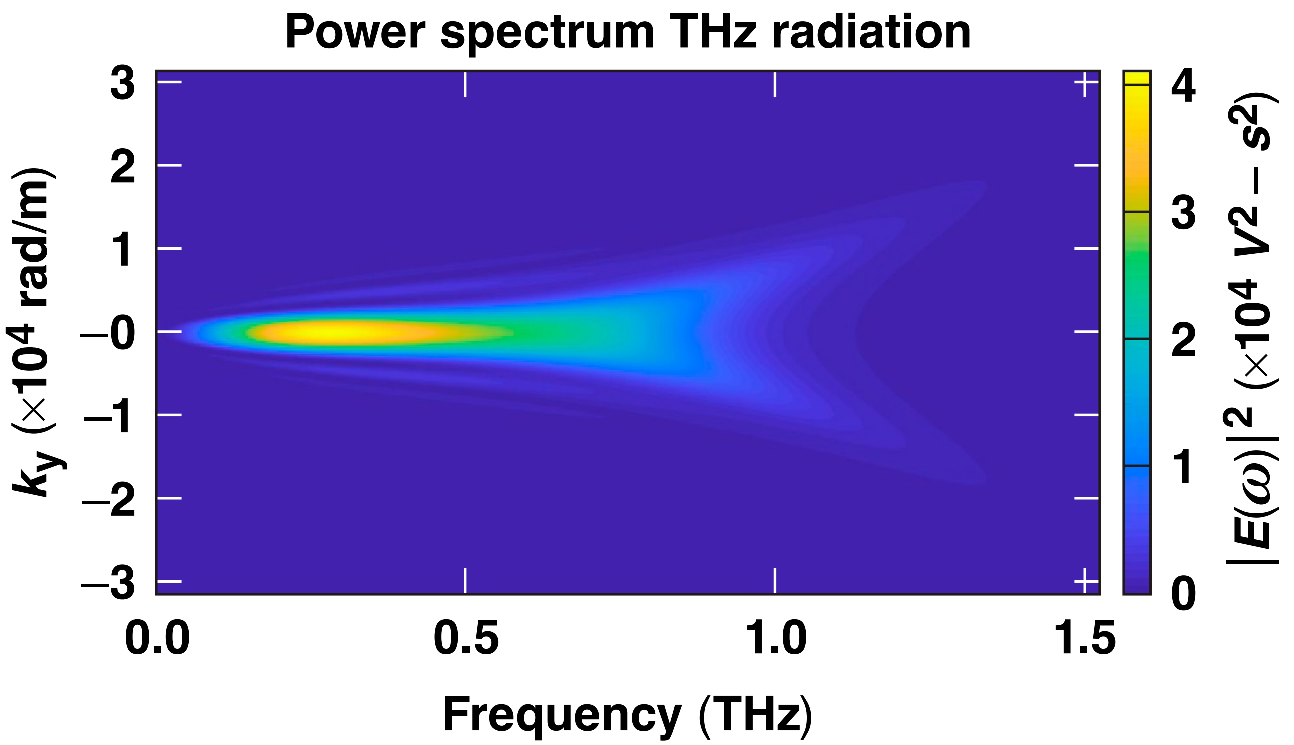
**Linh Nguyen**

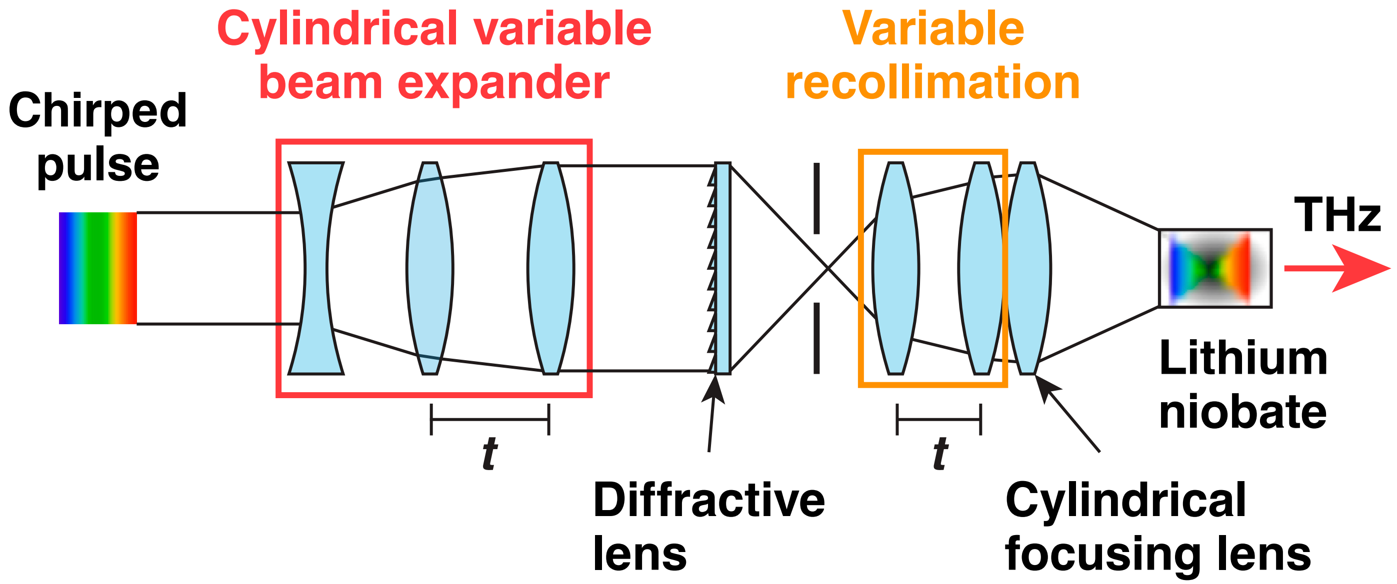
PAS
Grad student

# The flying focus can be used to phase match THz radiation in a crystal and extend the frequency-conversion process by orders of magnitude

**Greg Jenkins**

Inst. Optics
Grad student





**Simulations show on-axis phase matching in crystals over 1 cm,* otherwise constrained to off-axis phase matching.**

**A zoom lens system enables the flying focus velocity to be tuned for a given chrip.**

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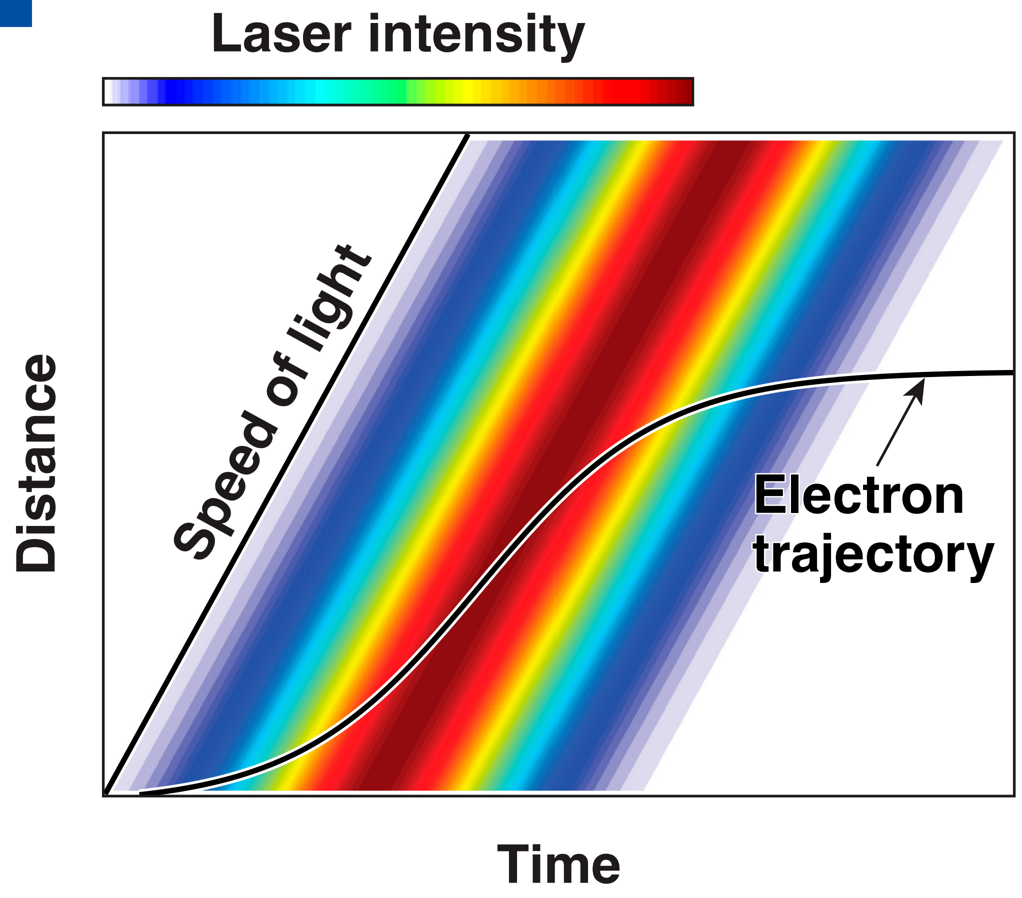
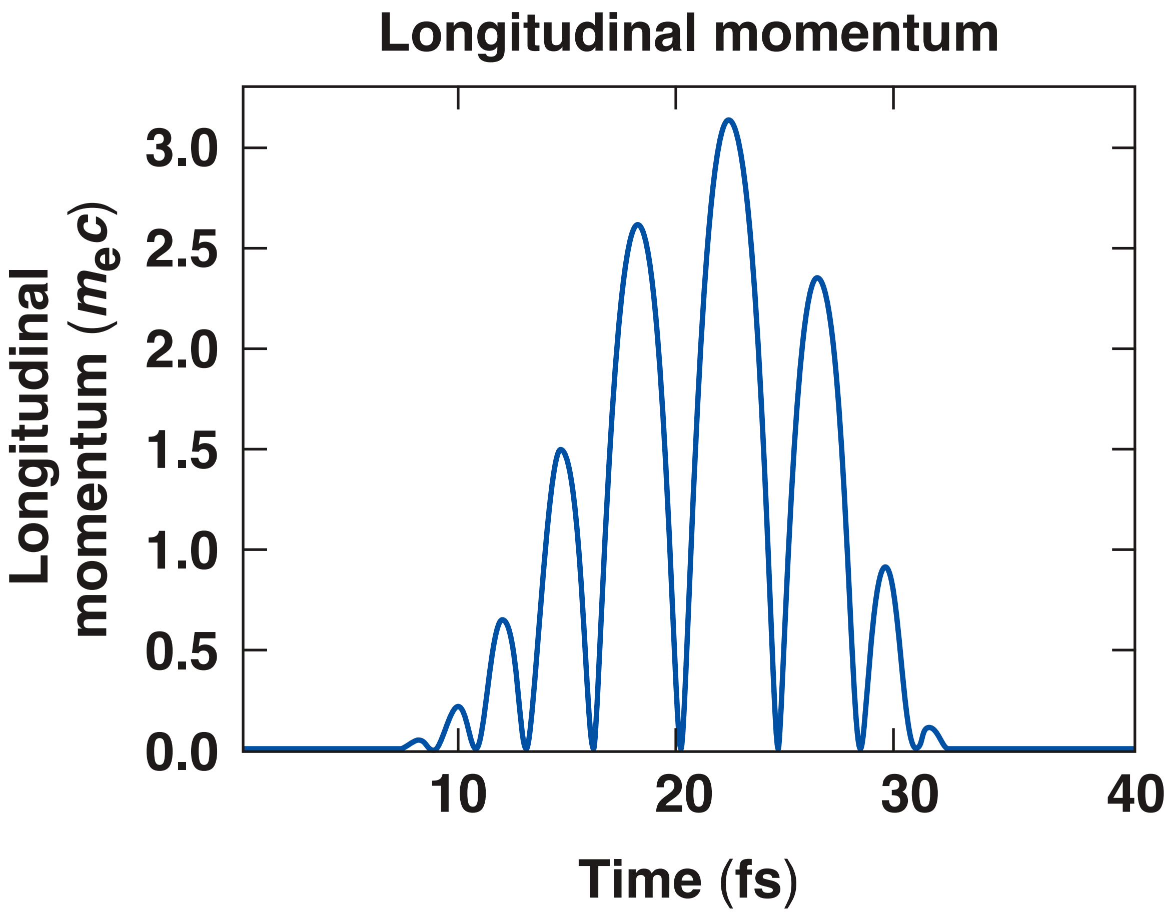
*K. L. Nguyen in preparation Phys. Rev. Lett.

**Dillon Ramsey**

PAS
Grad student

# The flying focus enables a novel mechanism for direct vacuum electron acceleration*





**Lawson–Woodward Theorem: the net energy gain for an electron in a laser pulse is zero.**

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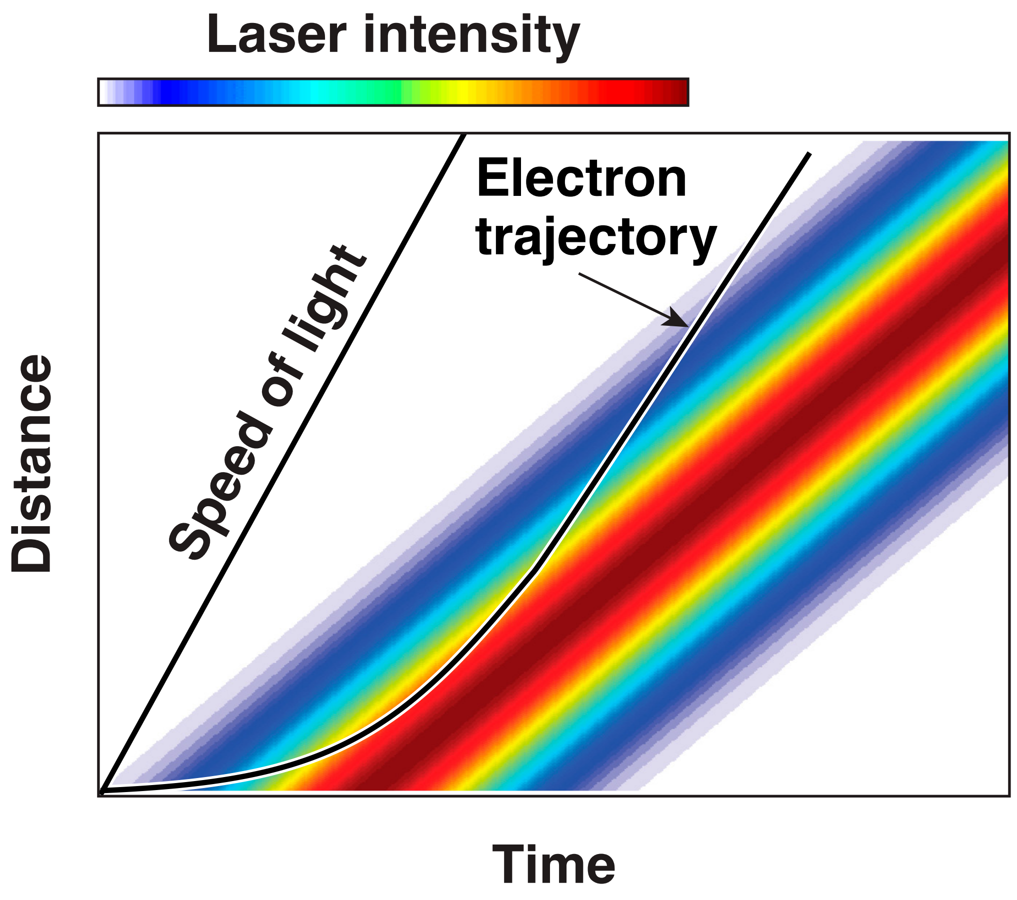
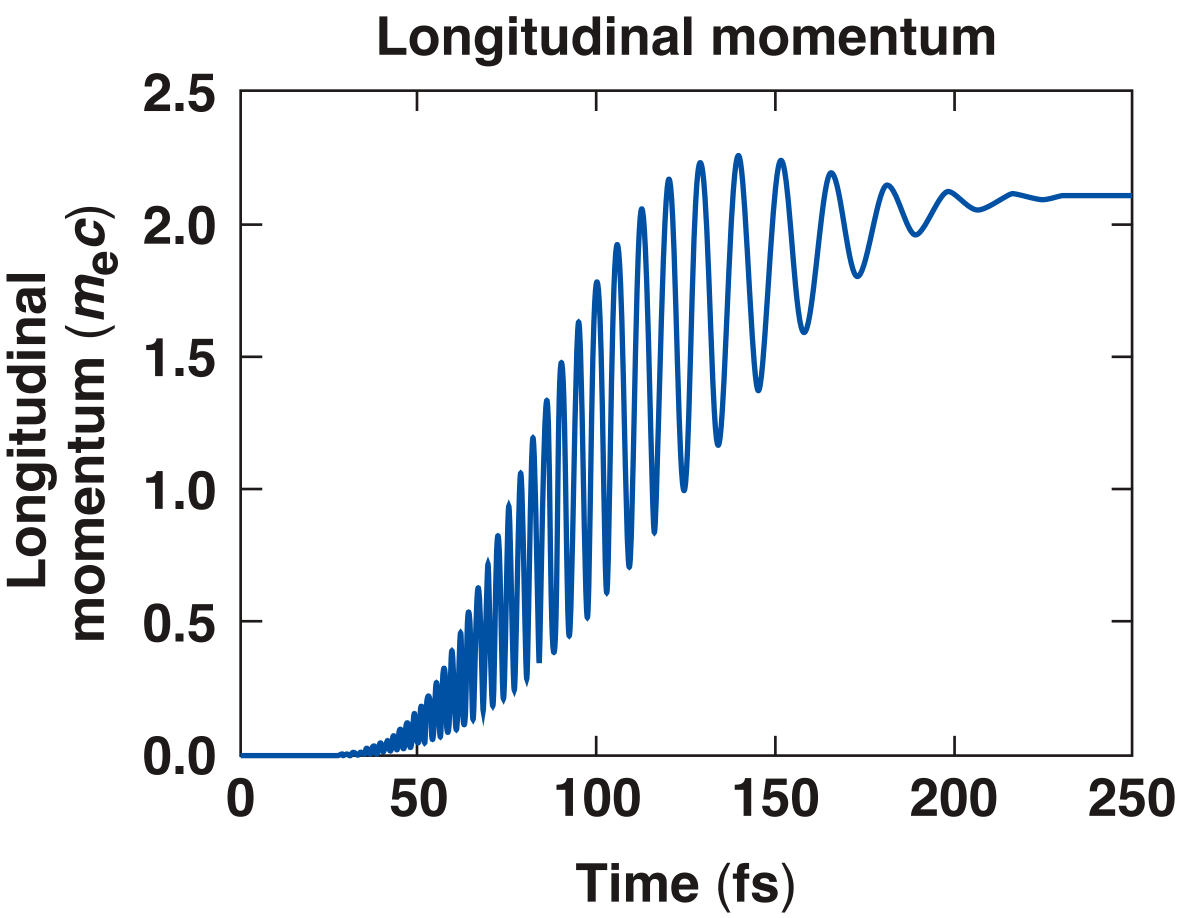
* D. Ramsey *et al.*, in preparation Phys. Rev. Lett.

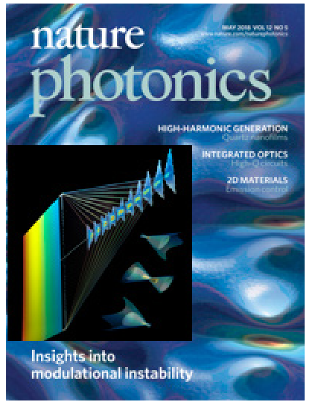
# In a flying focus pulse, electrons that overtake the laser pulse will exit with a longitudinal momentum





**Flying focus overcomes the Lawson–Woodward Theorem: electrons can extract energy from the laser pulse.**

E27804



**Summary/Conclusions**

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

- **The flying focus provides unprecedented spatiotemporal control over laser–plasma interactions by decoupling**
  - **the spot size of the pulse from the focal range**
  - **the velocity of the peak intensity from the group velocity**
- **Experiments have demonstrated the flying focus and the ability to generate ionization waves at any velocity (IWAV)**
- **Flying focus was applied to several applications**
  - **photon accelerator: IWAV's can shift visible laser light to the XUV**
  - **Raman amplification: flying focus could overcome several challenges of laser-plasma amplifiers**
  - **Cherenkov radiation: flying focus allows new radiation sources**
  - **vacuum electron acceleration: flying focus enables vacuum acceleration**

**This decoupling has the potential to enable or improve several laser-based applications.**

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*D. H. Froula *et al.*, Nat. Photonics 12, 262 (2018).
A. Sainte-Marie, O. Gobert, and F. Quéré, Optica 4, 1298 (2017).

# Thank you for your attention

3-D calculations
(counter-propagating flying focus)

| | |
|---|---|
| D. Turnbull<br>CO8.00012 | Ionization Waves of Arbitrary Velocity<br>4:12 pm, Monday, Nov. 5 |
| J. Palastro<br>JO8.00008 | Cherenkov Radiation from a Plasma<br>3:24 pm, Tuesday, Nov. 6 |
| A. Howard<br>JO8.00015 | Photon Acceleration in the Ionization Front of a Flying Focus<br>4:48 pm, Tuesday, Nov. 6 |
| P. Franke<br>UP11.00093 | Ionization Waves of Arbitrary Velocity<br>2:00 pm, Thursday, Nov. 8 |