

Effects of Chromatic Aberration in a Dephasingless Laser Wakefield Accelerator

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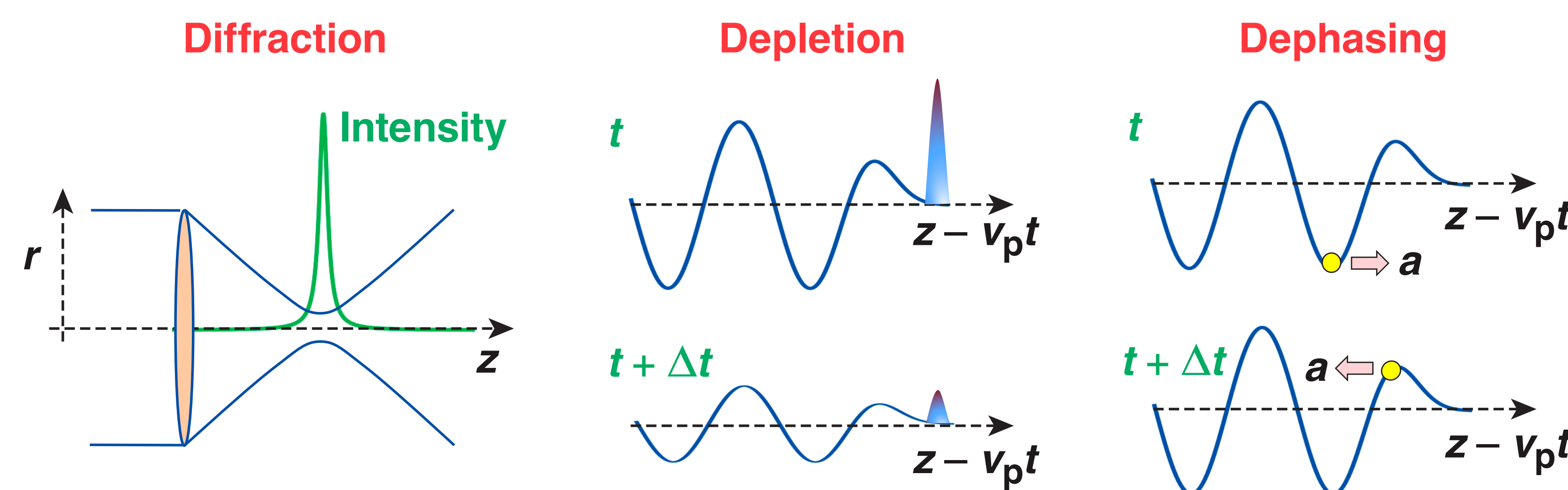
University of Rochester, Laboratory for Laser Energetics

Introduction

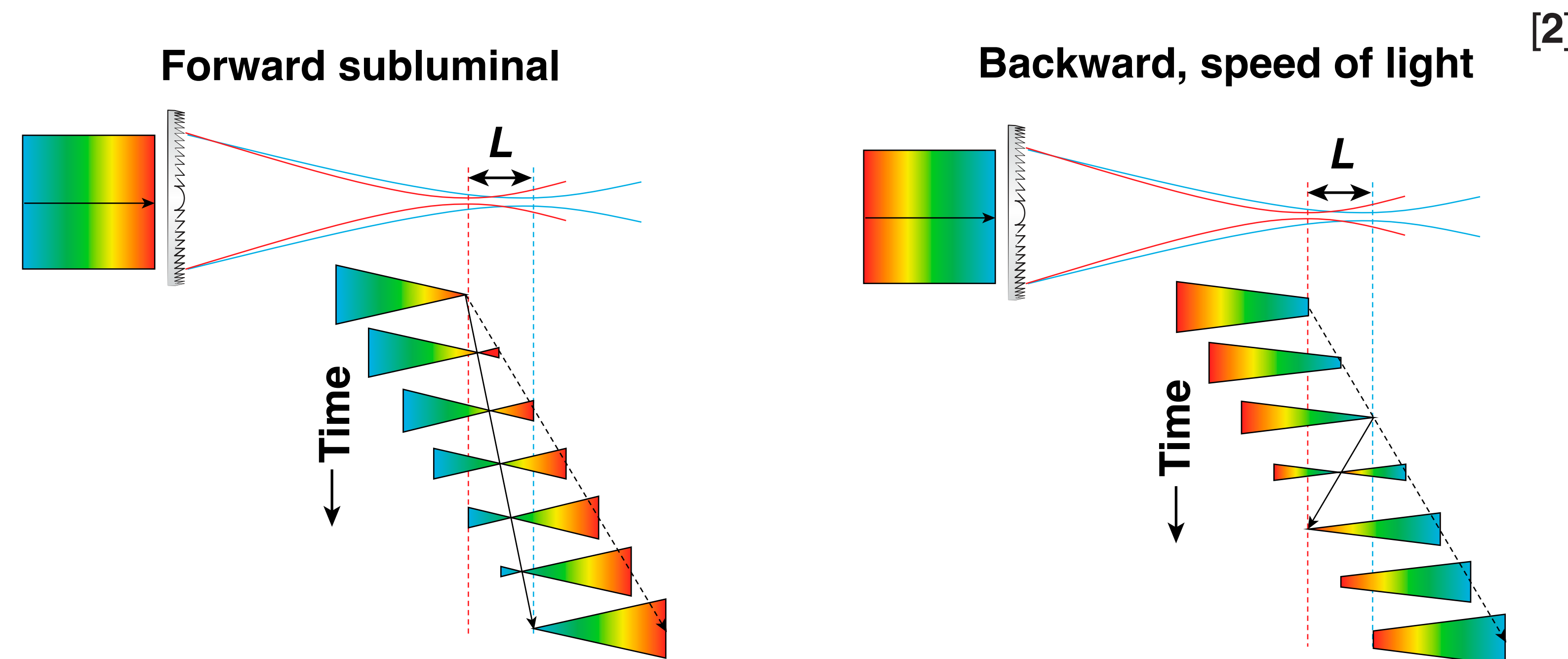
In a laser-wakefield accelerator (LWFA), the ponderomotive force of an intense laser pulse propagating through a plasma excites a large-amplitude plasma wakefield that can trap and accelerate electrons [1].

Three fundamental challenges limiting LWFA performance are

- Diffraction: the laser pulse diffracts as it propagates, decreasing its intensity and thus its ability to drive a wake
- Depletion: the laser pulse loses energy to the wakefield, decreasing its intensity
- Dephasing: electrons ($v_z \sim c$) outrun the accelerating phase of the wakefield and are no longer accelerated



Chromatic Flying Focus

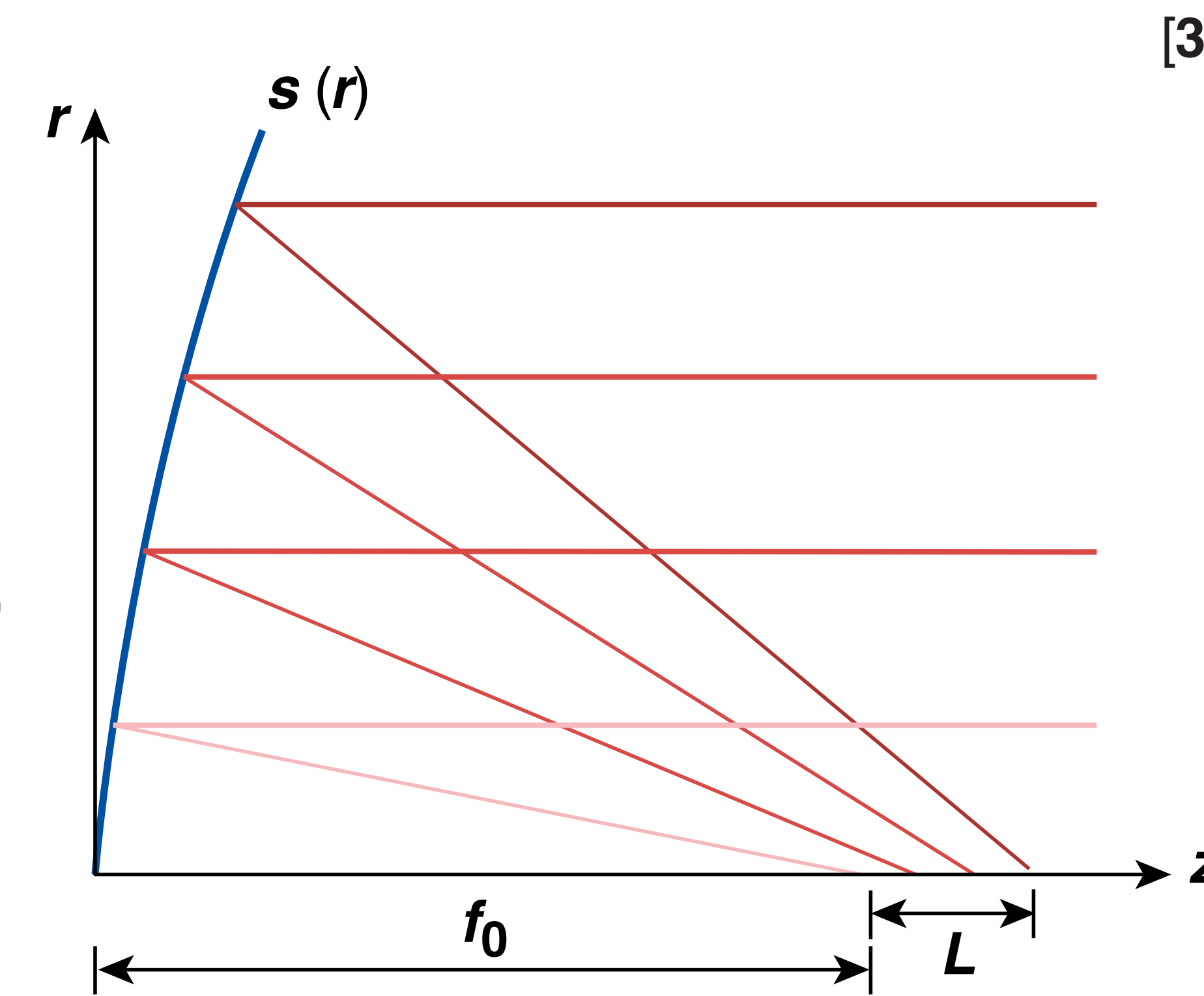


- The original flying focus uses a highly chromatic diffractive focusing optic to focus different colors in a pulse to different axial locations in the far field [2]
- By controlling the chirp of the input pulse, the arrival time of each color to its respective focus can be controlled
- However, since the pulse's bandwidth is spread out over the focal region, the ultrashort pulse duration is lost

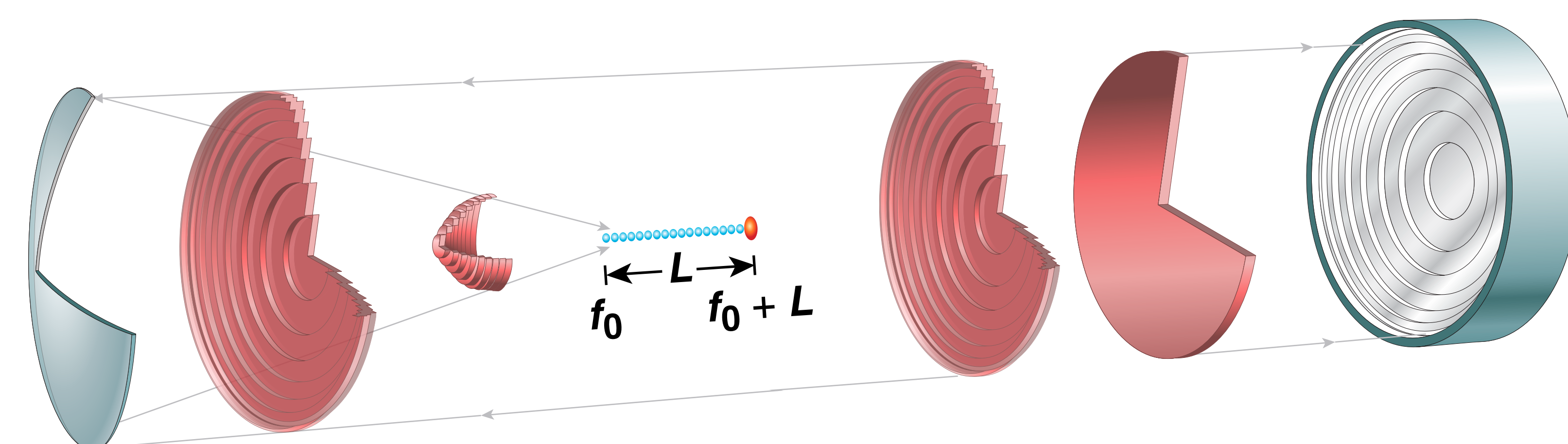
Axiparabola and Radial Group Delay

- An axiparabola is a reflective optic that focuses light rays at different radial locations in the near field to different axial locations in the far field [3]
- By controlling the arrival time of each radius at the axiparabola with a tailored radial group delay, an intensity peak can be driven at a desired velocity

r – radial coordinate
 z – longitudinal coordinate
 $s(r)$ – axiparabola sag function
 f_0 – focal length offset
 L – focal depth



Axiparabola and Reflective Echelon

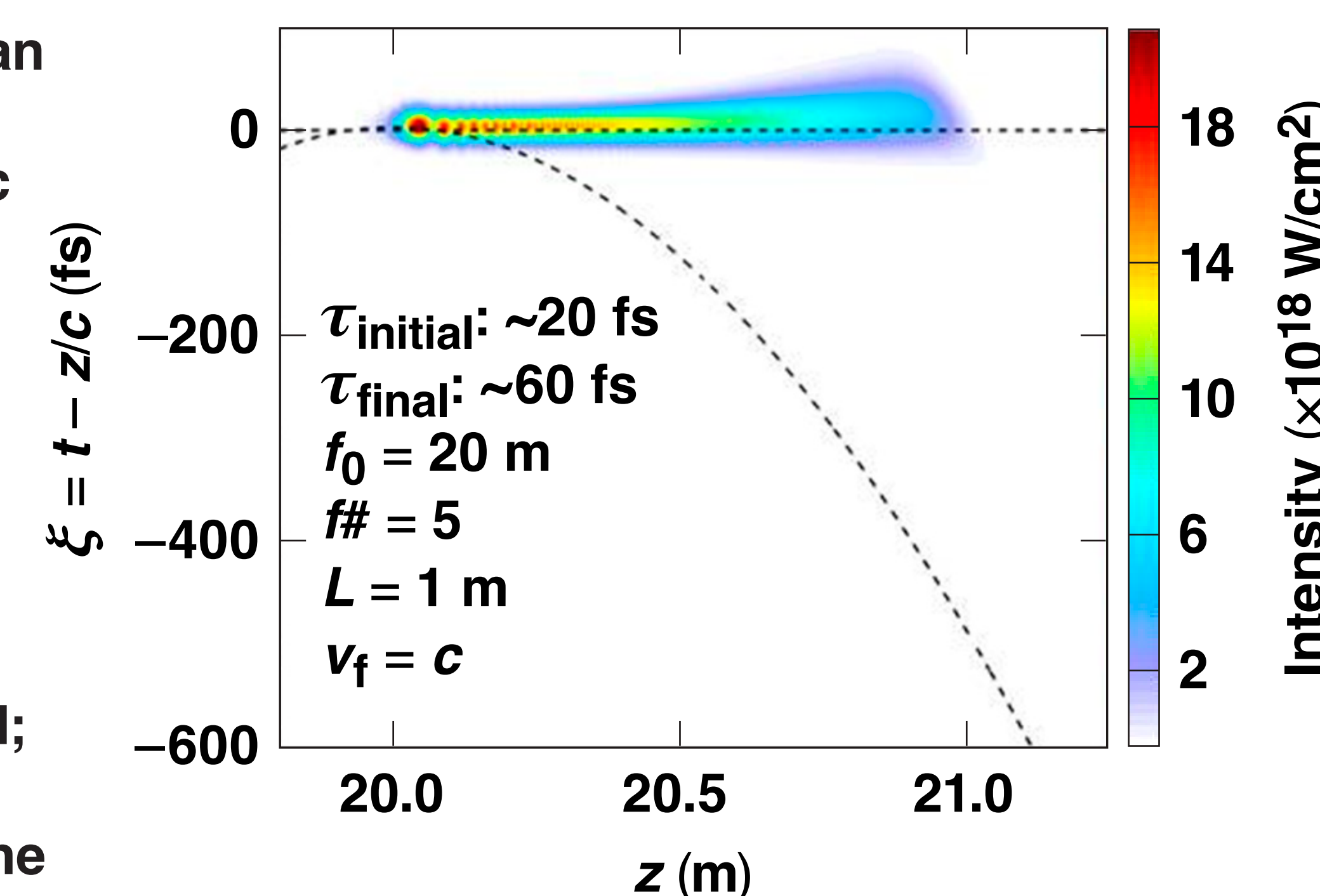


- A reflective echelon (1) separates a pulse into concentric rings, (2) imparts a stepped radial group delay to the pulse to control the arrival time of each ring to the axiparabola, and (3) circumvents chromatic aberration inherent in refractive optics [4]

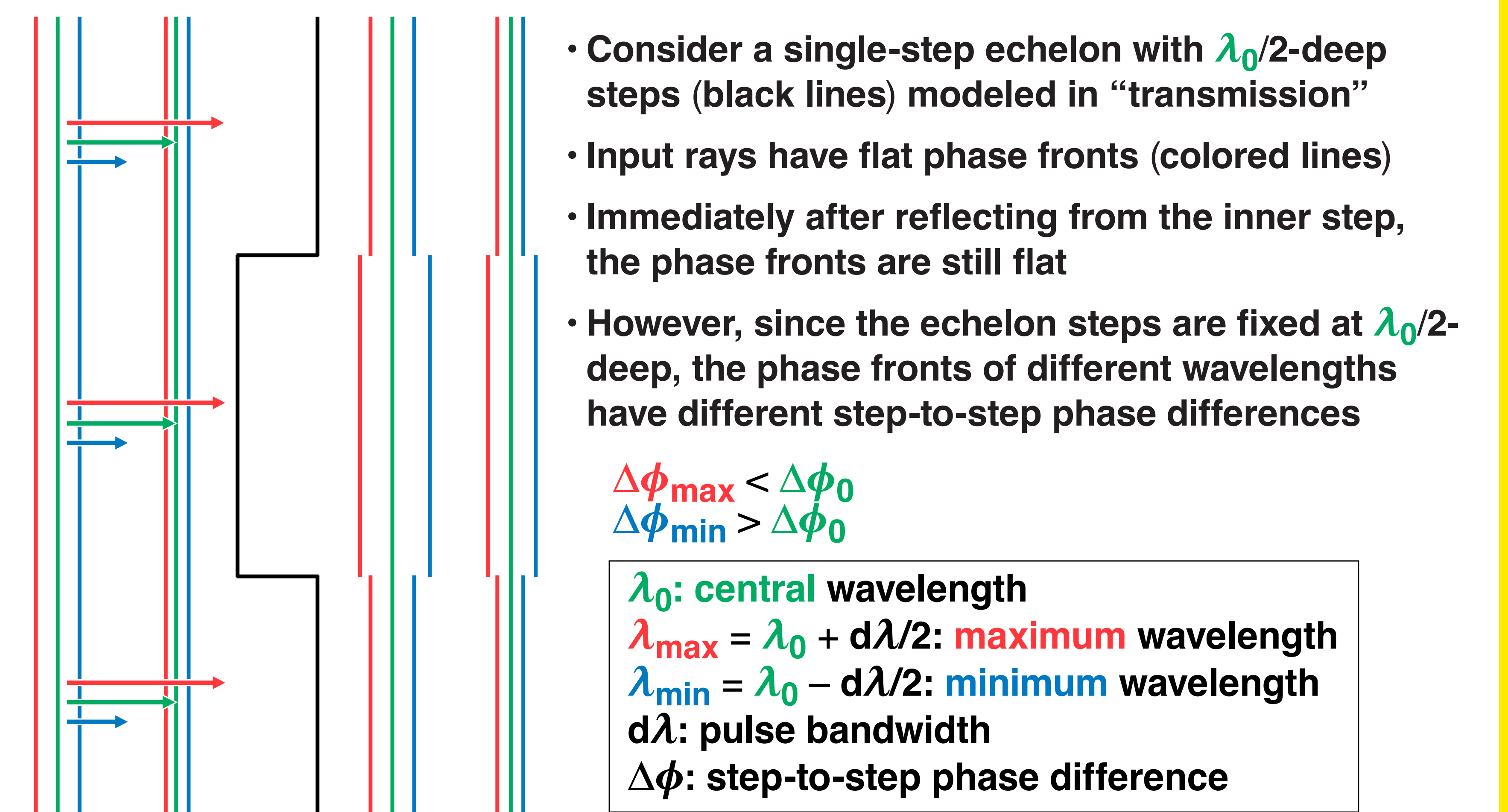
- Within each echelon step, the pulse front (surface coinciding with the peak intensity of the pulse) and phase front (surface of constant phase) are flat

- Despite using reflective optics, simulations suggest an increase in pulse duration in the far field akin to chromatic aberration; this is shown in the figure to the right by the broadening of the pulse in ξ as the pulse propagates

- The dashed horizontal line shows a constant focal velocity of the intensity peak when the echelon is included; the dashed curve shows an increasing focal velocity of the intensity peak without the echelon



Quasi-Chromatic Aberration in the Reflective Echelon



- This leads to longitudinal chromatism and thus pulse broadening in the far field

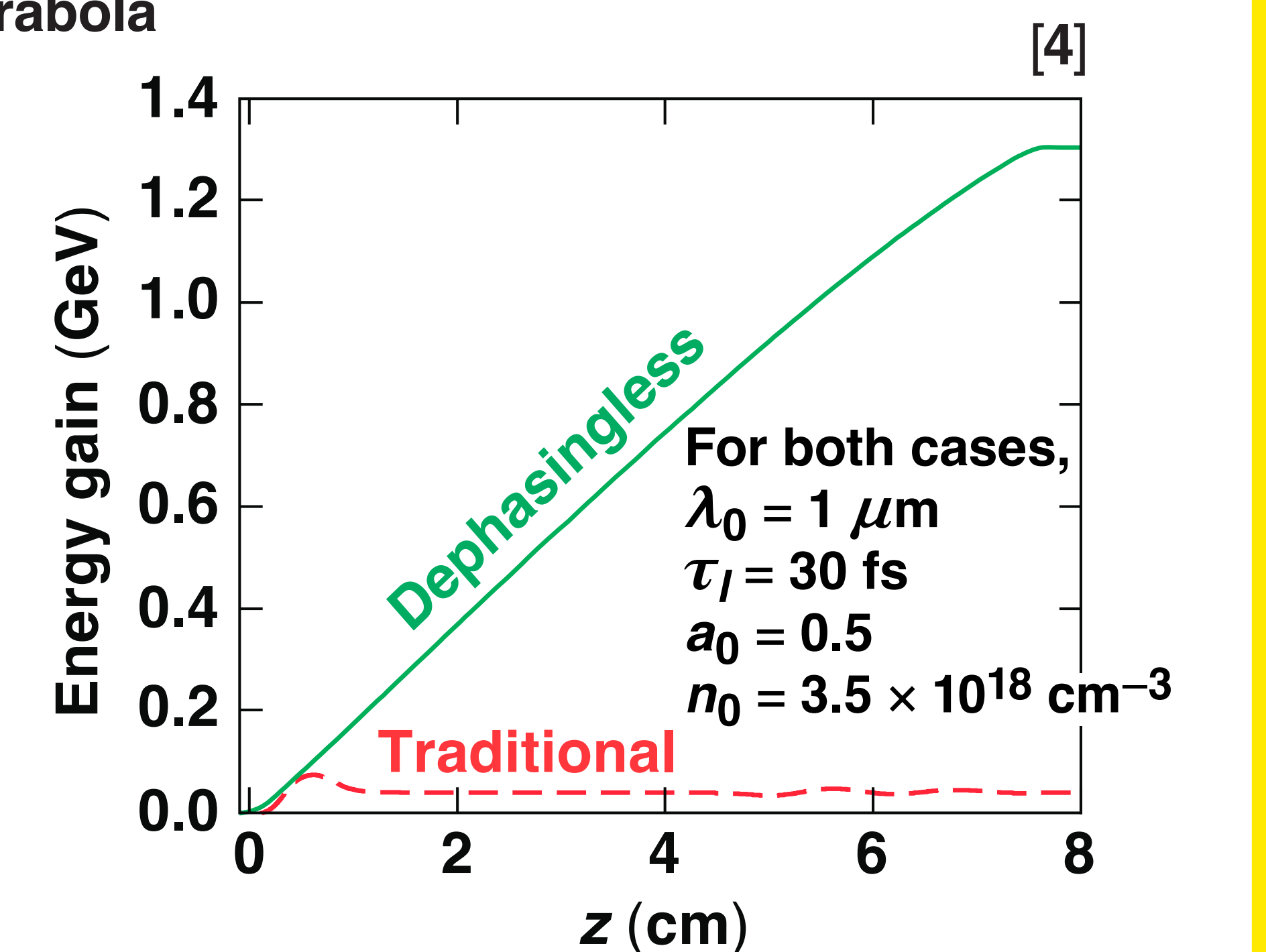
Conclusions

- A reflective echelon can impart a stepped radial group delay to a pulse prior to its creation of a flying focus with an axiparabola

- Far-field chromatic-like aberrations arise because the echelon steps are fixed at a depth defined by the central wavelength, therefore other wavelengths in the pulse no longer maintain the same fixed-phase relation from step to step

- Simulations suggest this quasi-chromatic aberration is noticeable for long axiparabola focal lengths (~ 1 m) but insignificant for lengths relevant for dephasingless laser wakefield acceleration (~ 10 cm)

- In the DLWFA, the electron gains 1.3 GeV over 16 dephasing lengths, while in the traditional LWFA, the electron outruns the laser pulse and only gains a maximum of 75 MeV energy over a single dephasing length [4]



References

- [1] T. Tajima and J. M. Dawson, Phys. Rev. Lett. 43, 267 (1979).
- [2] D. H. Froula *et al.*, Phys. Plasmas 26, 032109 (2019).
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Acknowledgements

The author thanks members of the Plasma and Ultrafast Laser Science and Engineering (PULSE) Division for scientific discussions and support of this project. Additionally, many thanks go to the Illustrations Department at the Laboratory for Laser Energetics for assistance in preparing this poster. This material is based upon work supported by the Department of Energy National Nuclear Security Administration under Award Number DE-NA0003856 and the Department of Energy Office of Fusion Energy under Award Number DE-SC00215057.

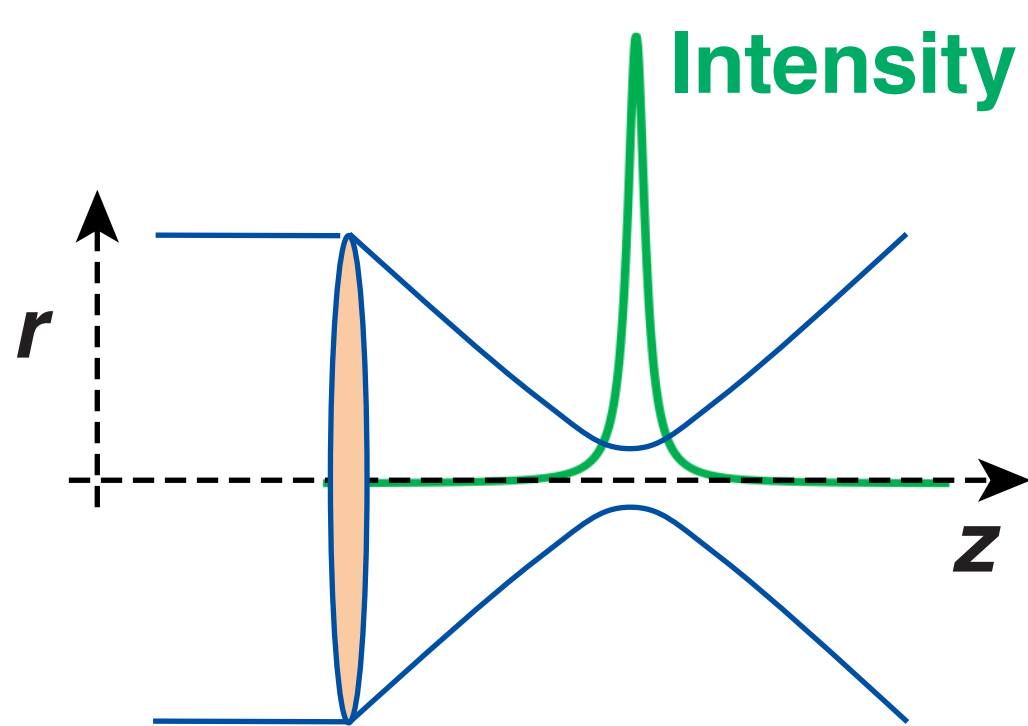
Introduction

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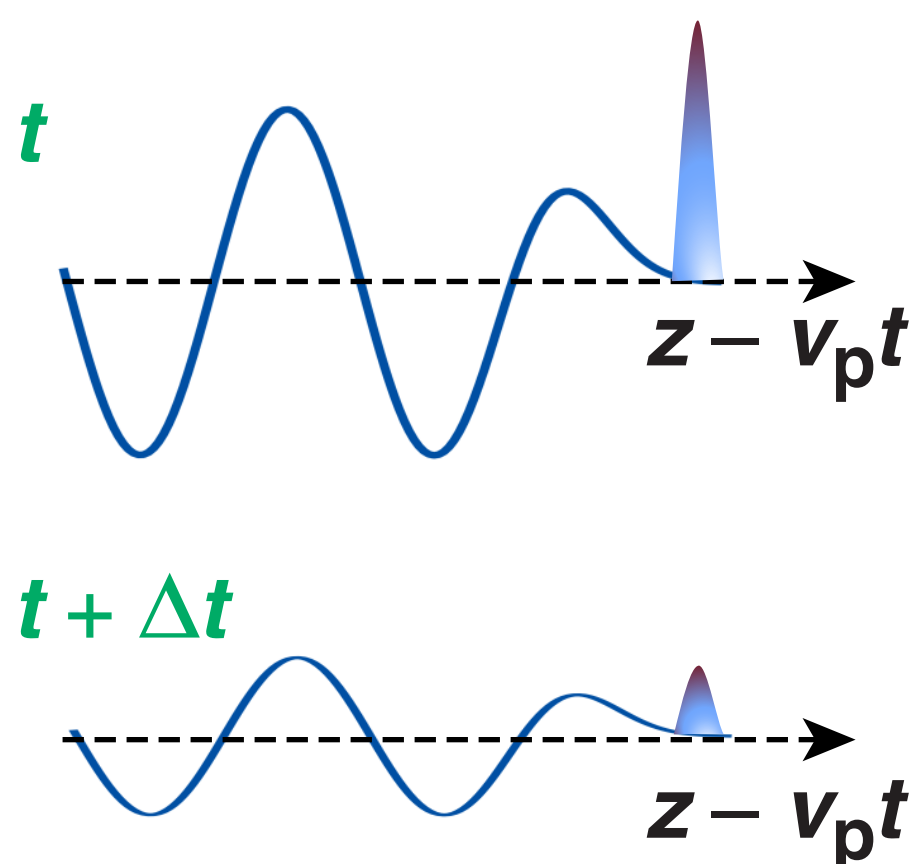
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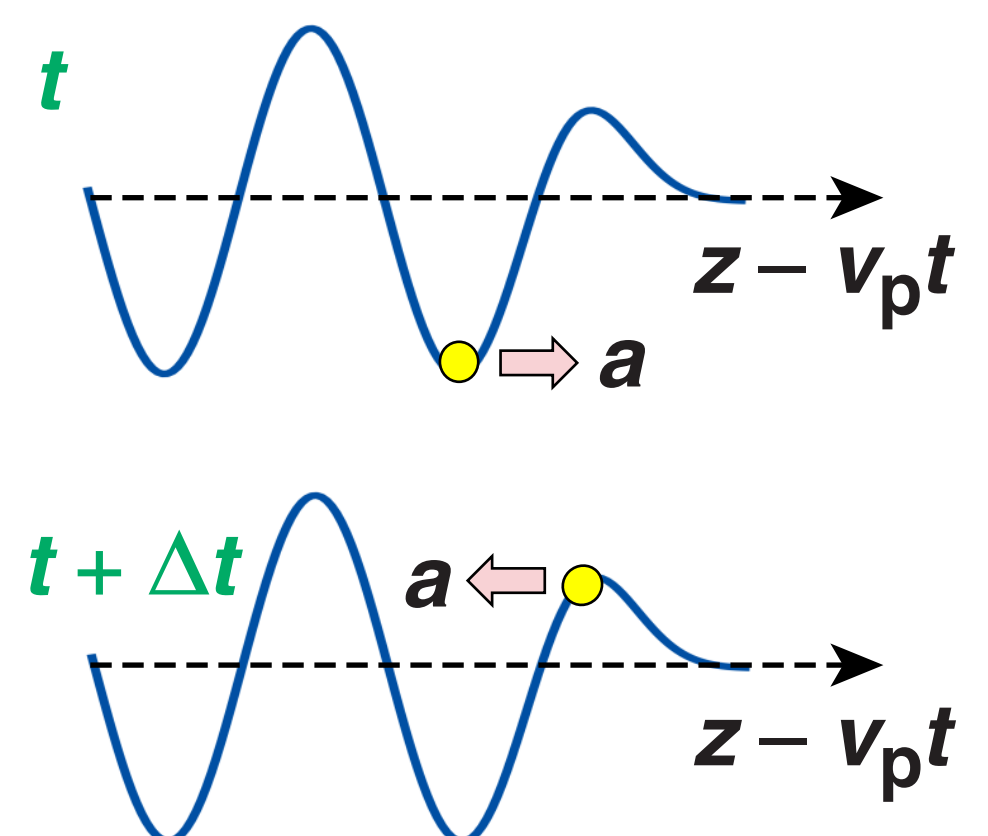
Diffraction



Depletion

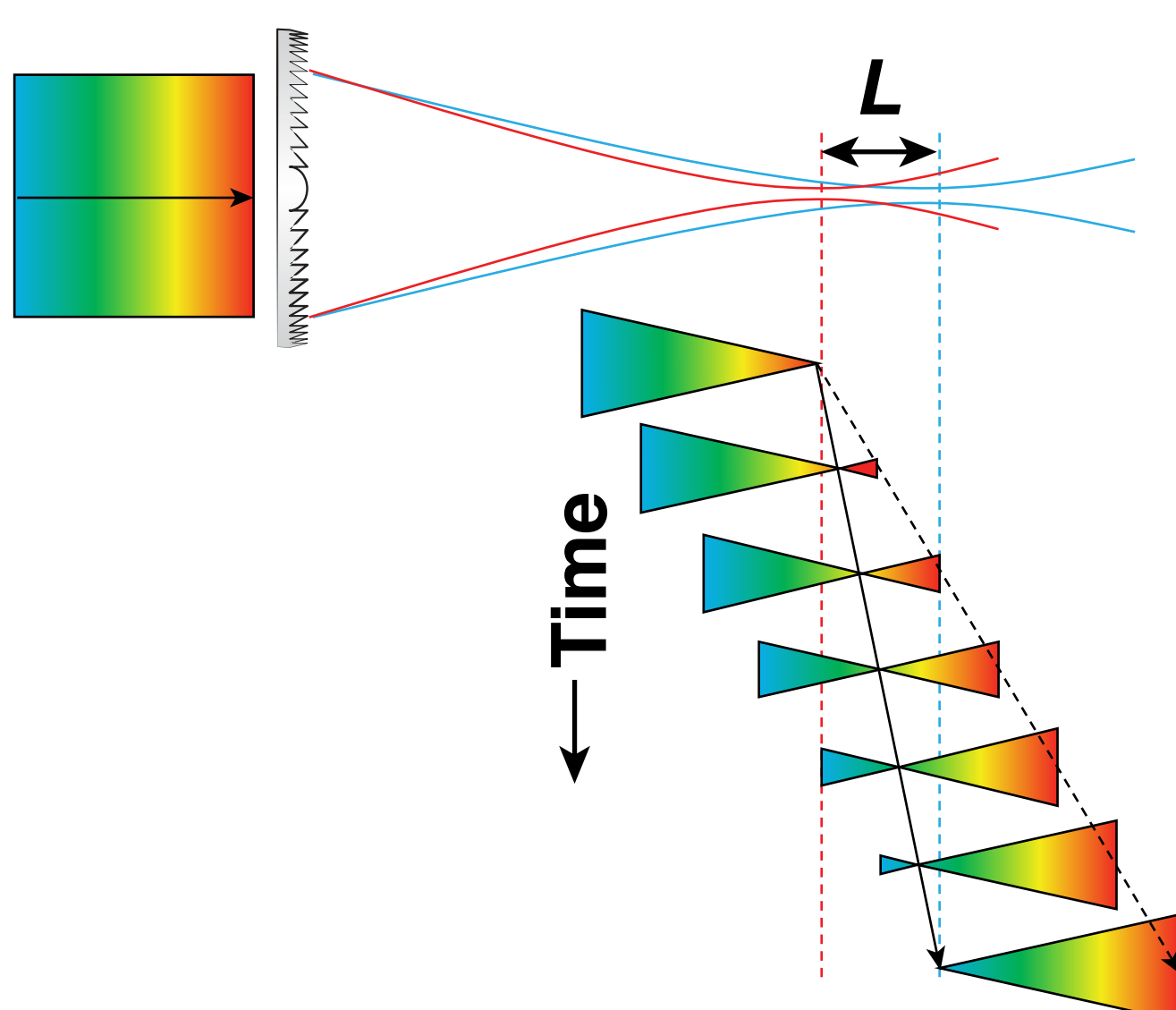


Dephasing

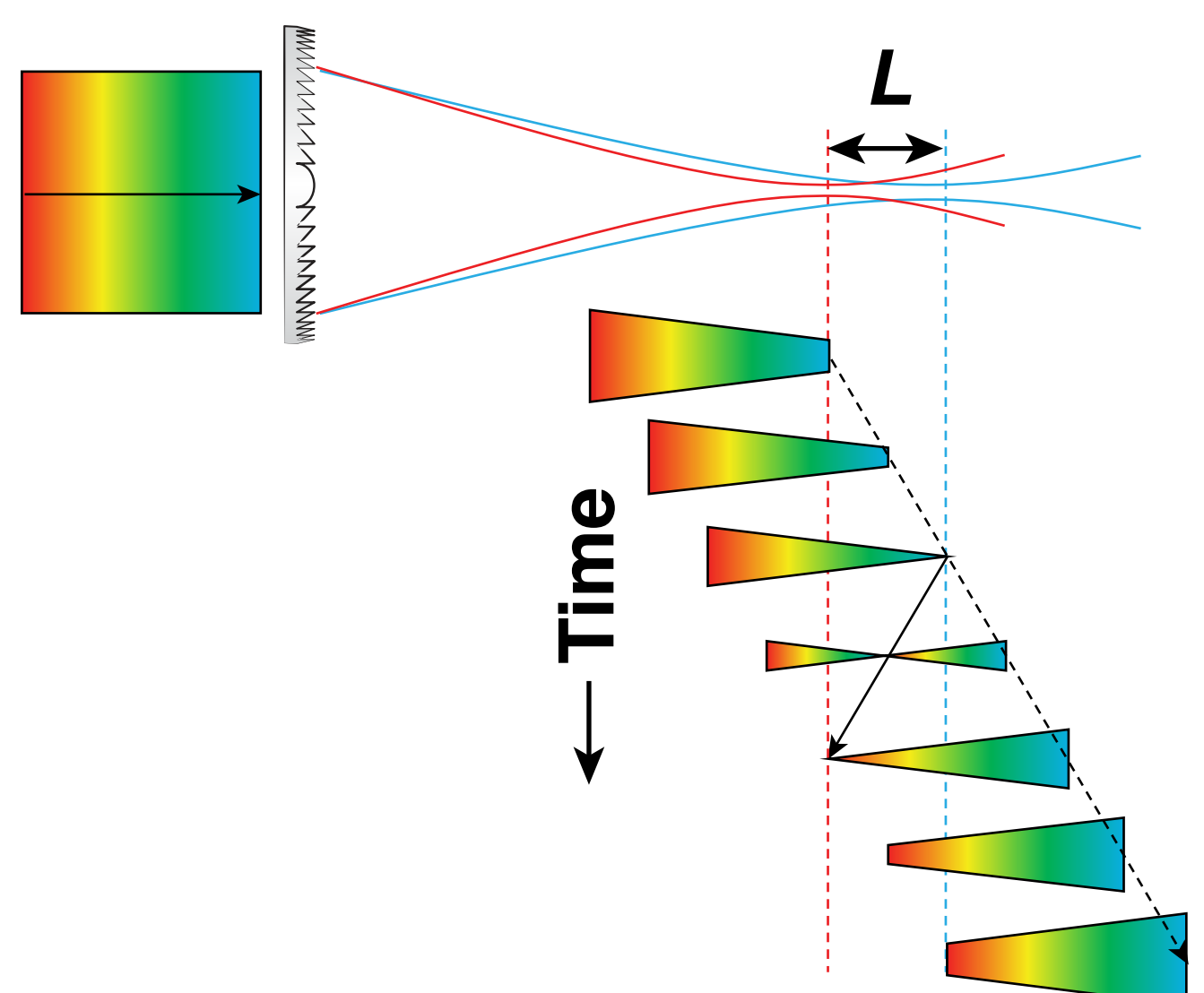


Chromatic Flying Focus

Forward subluminal



Backward, speed of light



[2]

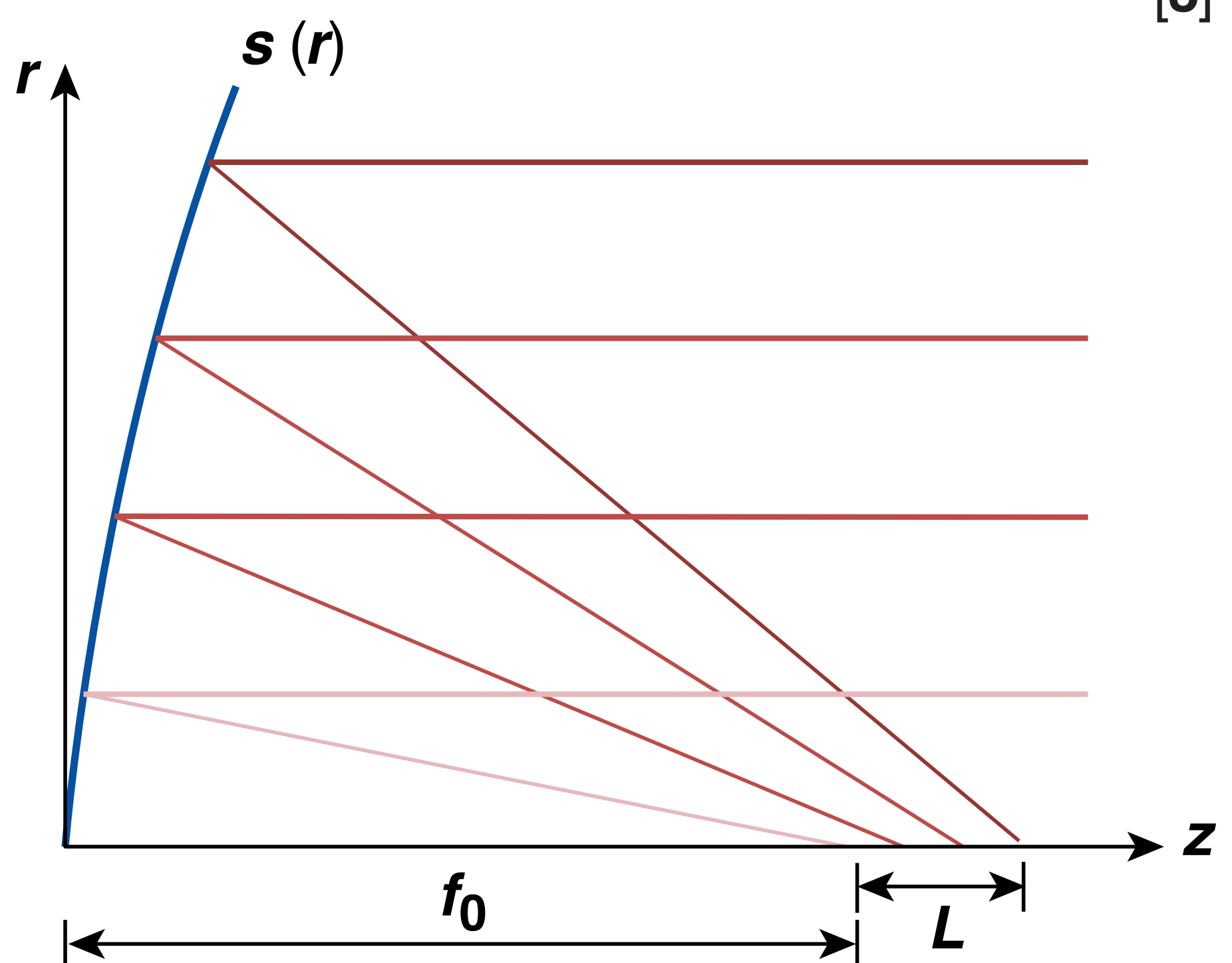
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Axiparabola and Radial Group Delay

[3]

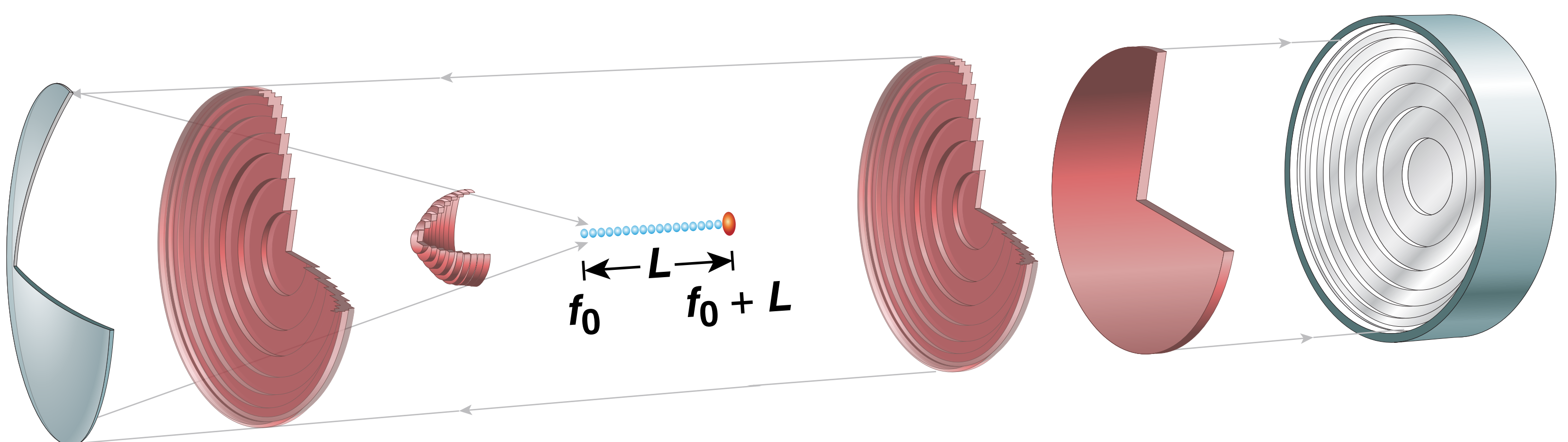
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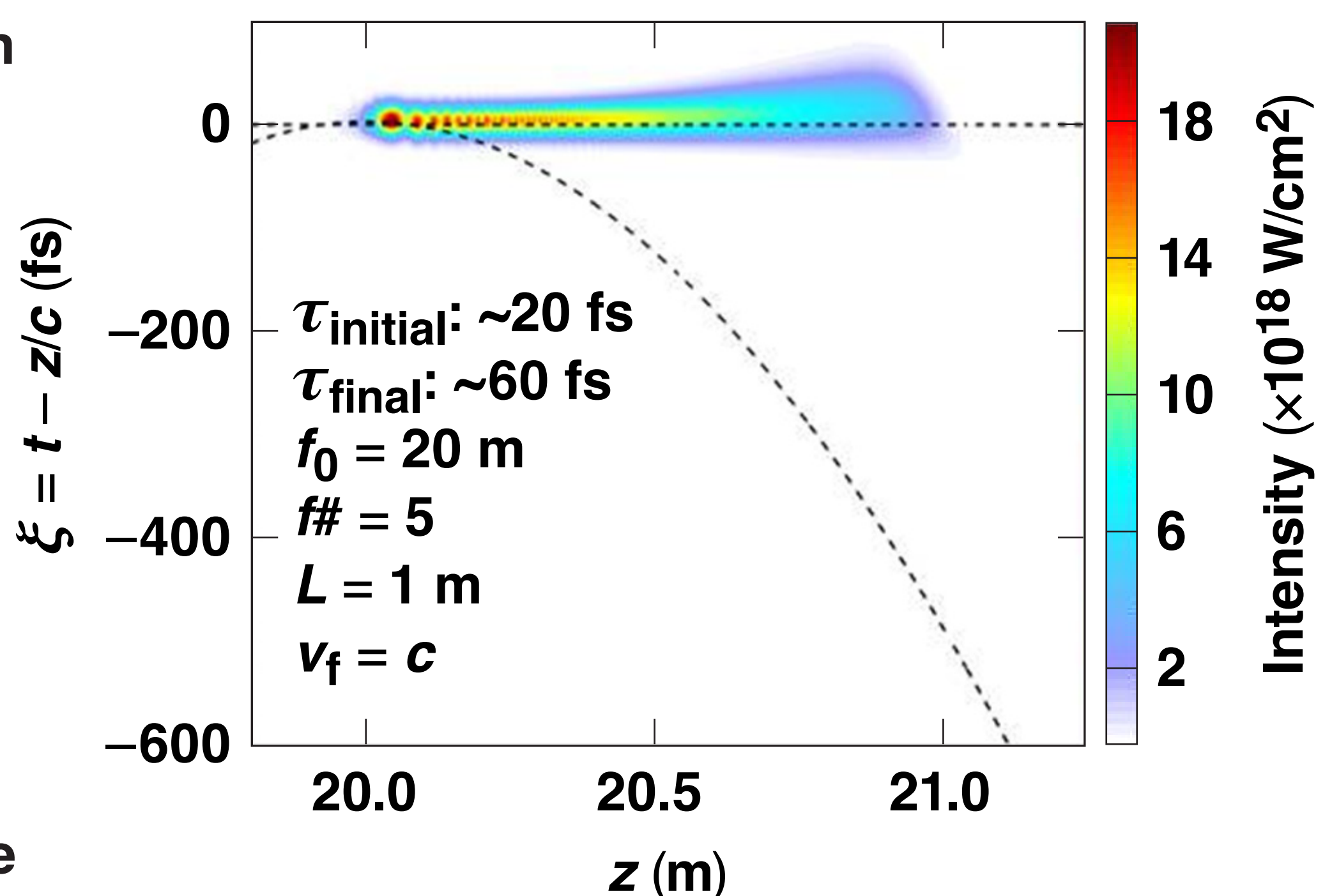


Axiparabola and Reflective Echelon

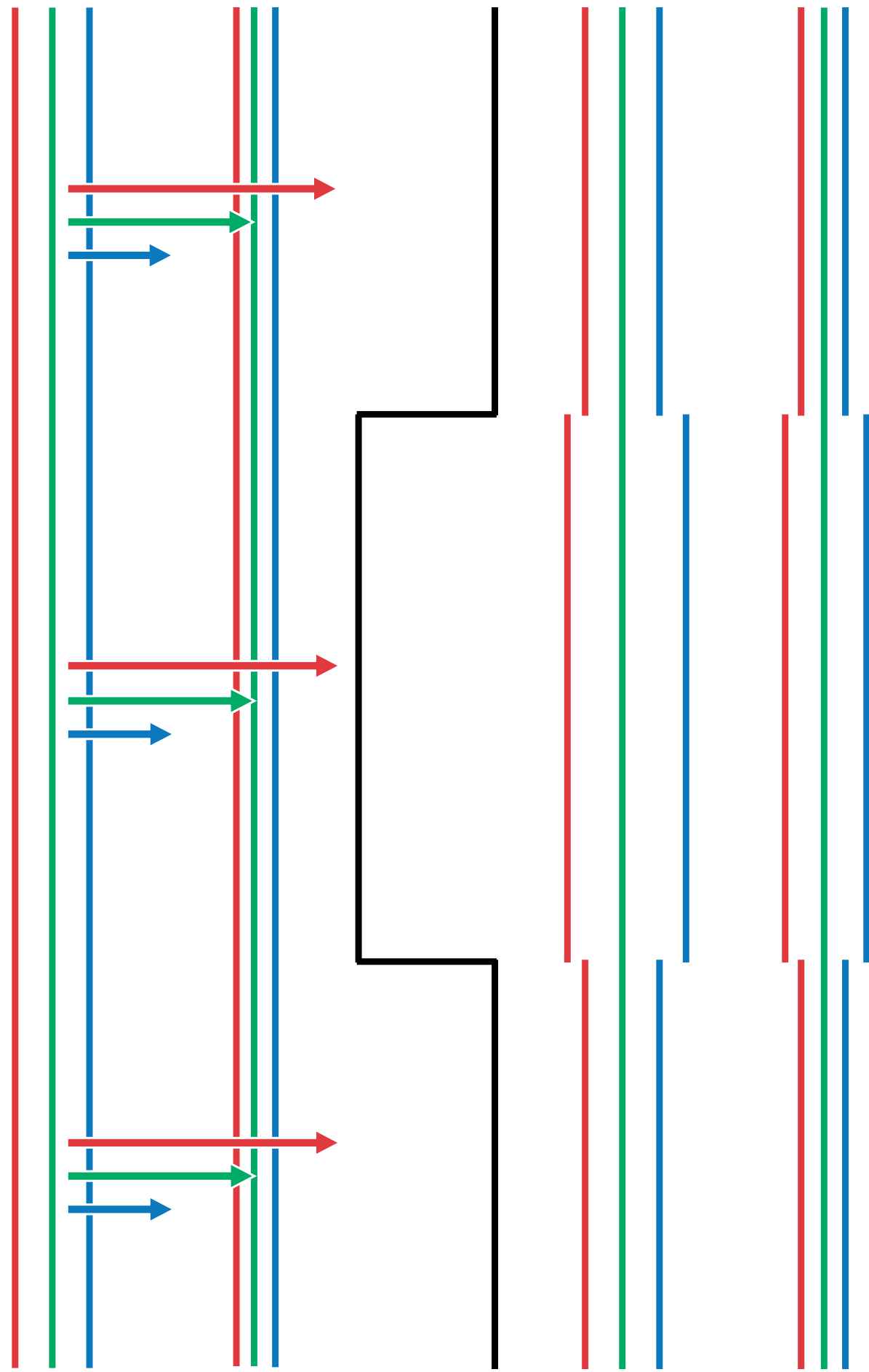
[4]



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Quasi-Chromatic Aberration in the Reflective Echelon



- Consider a single-step echelon with $\lambda_0/2$ -deep steps (black lines) modeled in “transmission”
- Input rays have flat phase fronts (colored lines)
- Immediately after reflecting from the inner step, the phase fronts are still flat
- However, since the echelon steps are fixed at $\lambda_0/2$ -deep, the phase fronts of different wavelengths have different step-to-step phase differences

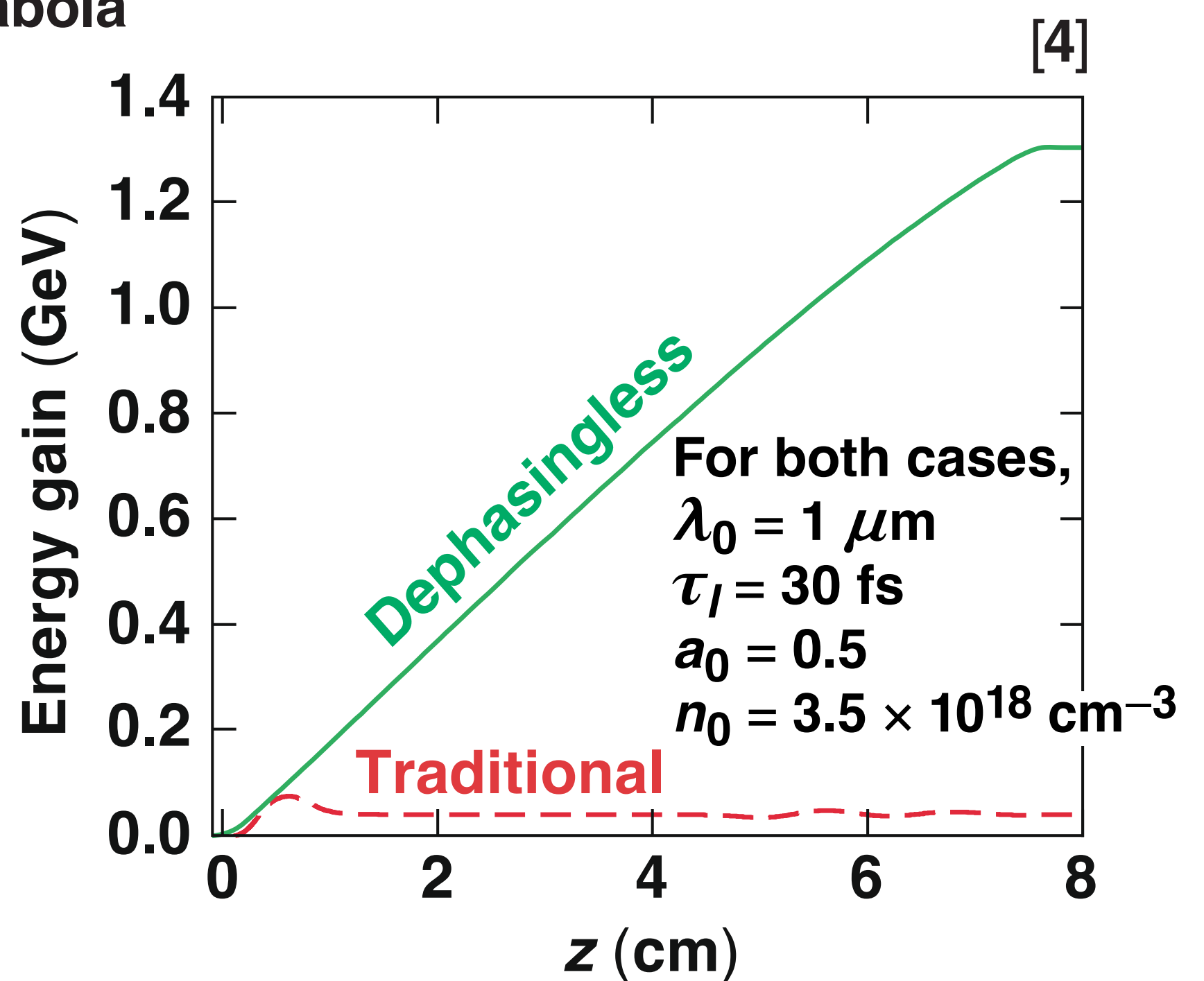
$$\begin{aligned}\Delta\phi_{\text{max}} &< \Delta\phi_0 \\ \Delta\phi_{\text{min}} &> \Delta\phi_0\end{aligned}$$

λ_0 : central wavelength
 $\lambda_{\text{max}} = \lambda_0 + d\lambda/2$: maximum wavelength
 $\lambda_{\text{min}} = \lambda_0 - d\lambda/2$: minimum wavelength
 $d\lambda$: pulse bandwidth
 $\Delta\phi$: step-to-step phase difference

- This leads to longitudinal chromatism and thus pulse broadening in the far field

Conclusions

- A reflective echelon can impart a stepped radial group delay to a pulse prior to its creation of a flying focus with an axiparabola
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