Electron acceleration in **beam-loaded and beam-dominated** laser wakefields

Andreas Döpp[1,2], Johannes Götzfried[1,2], Max Gilljohann[1,2], Hao Ding[1,2], Sabine Schindler[1,2], Laszlo Veisz[1,3], Stefan Karsch[1,2]

[1] *Faculty of Physics, LMU Munich*
[2] *Max-Planck Institute for Quantum Optics*
[3] *Department of Physics, Umea University, Umea, Sweden*

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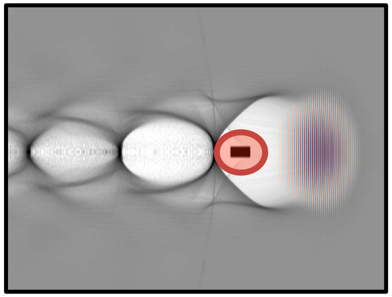
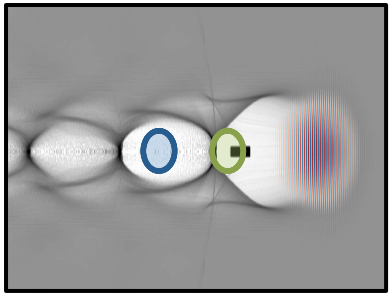
Outline

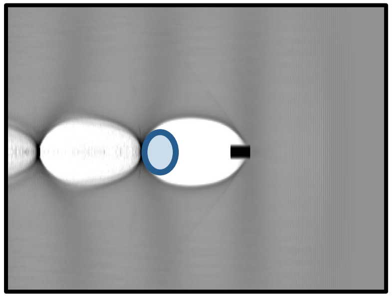
I. Influence of beam-loading on the electron **bunch itself**



II. Influence of beam-loading on **trailing bunches**

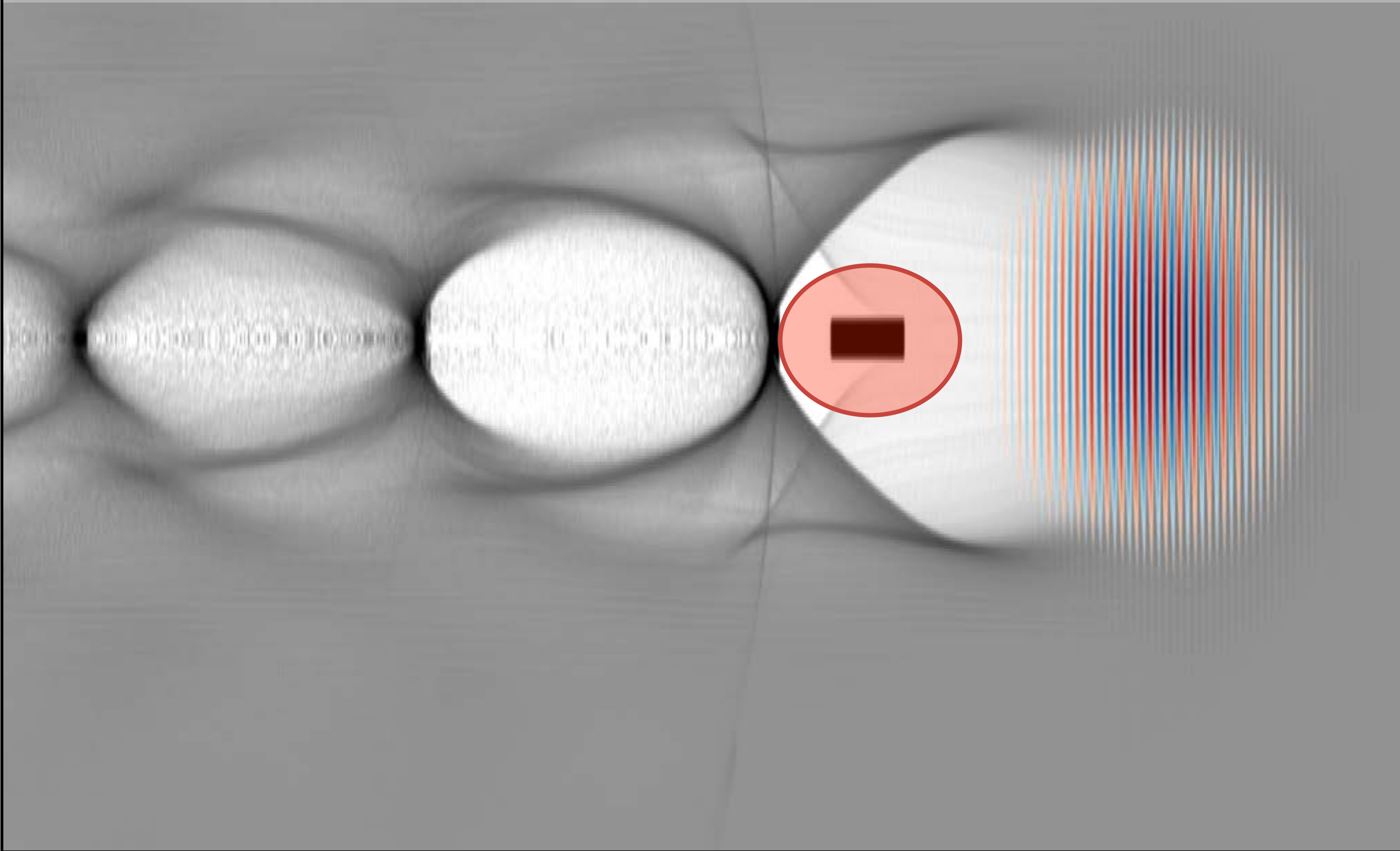


III. Evidence for a transition to the **beam-dominated regime**



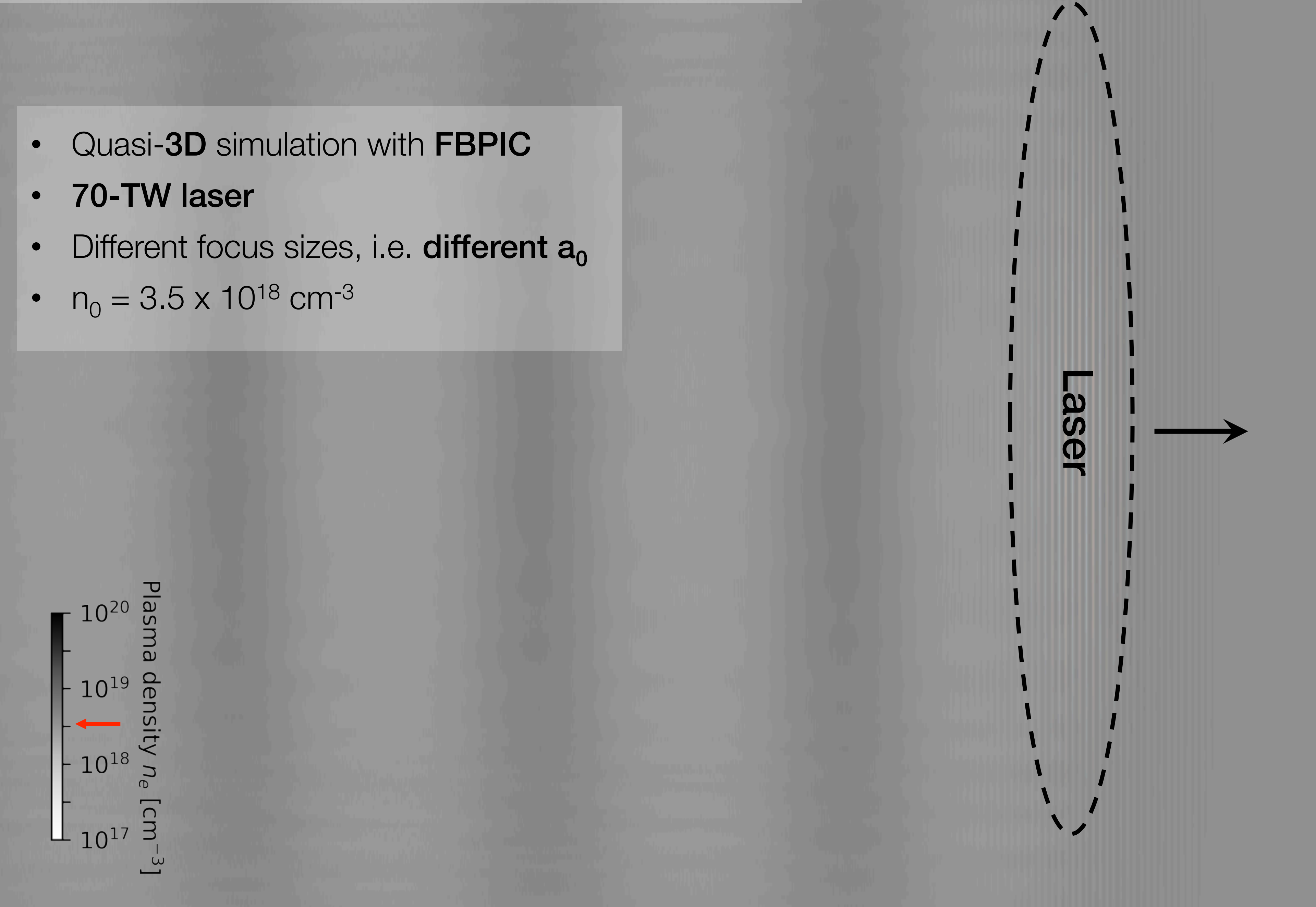
Part I

Influence of beam-loading on the electron **bunch itself**



Particle-in-Cell Simulations

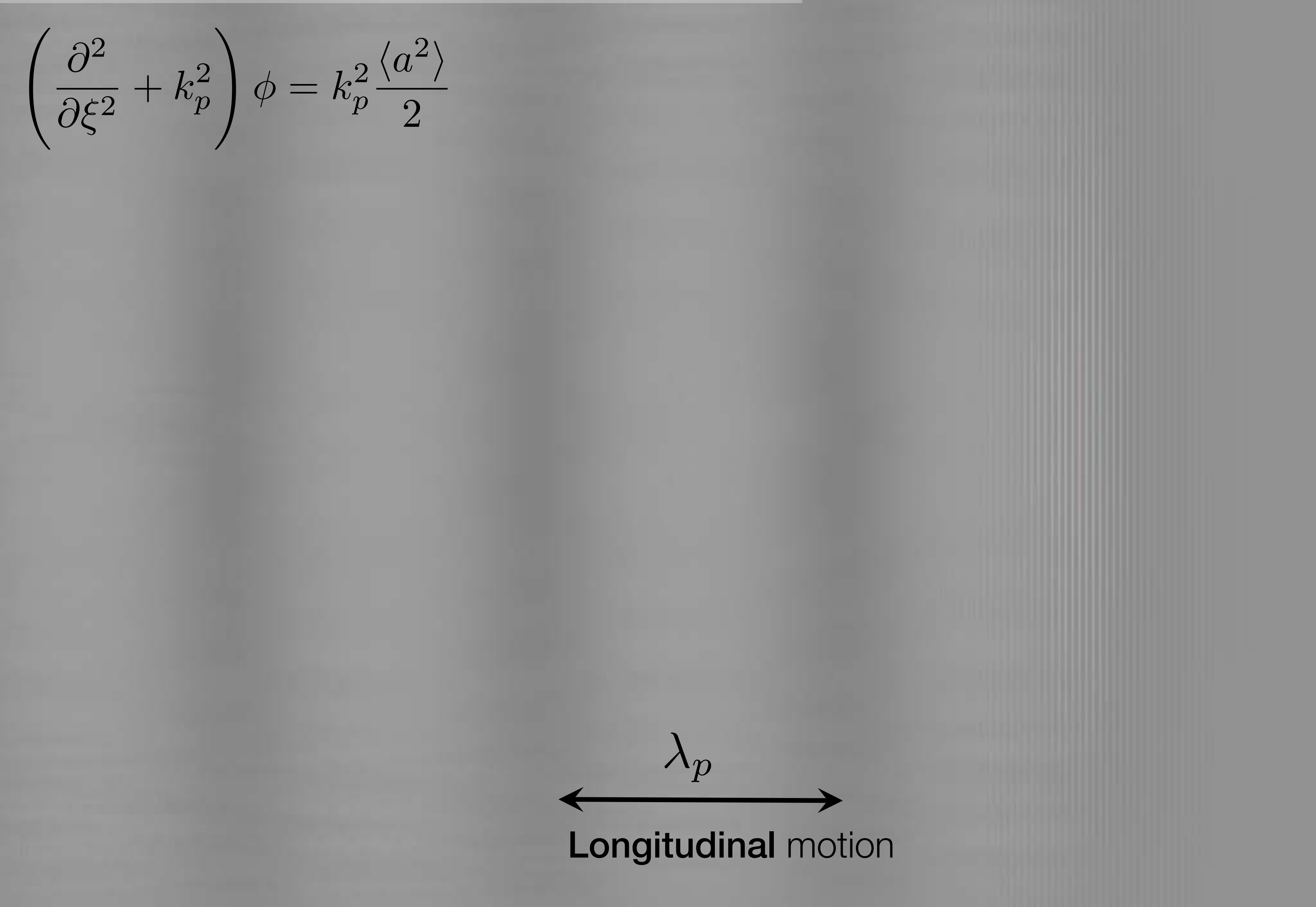
- Quasi-**3D** simulation with **FBPIC**
- **70-TW laser**
- Different focus sizes, i.e. **different a_0**
- $n_0 = 3.5 \times 10^{18}$ cm^{-3}



Linear laser wakefield

$a_0 = 1.0$

$$\left(\frac{\partial^2}{\partial\xi^2} + k_p^2\right)\phi = k_p^2\frac{\langle a^2\rangle}{2}$$



Weakly non-linear laser wakefield

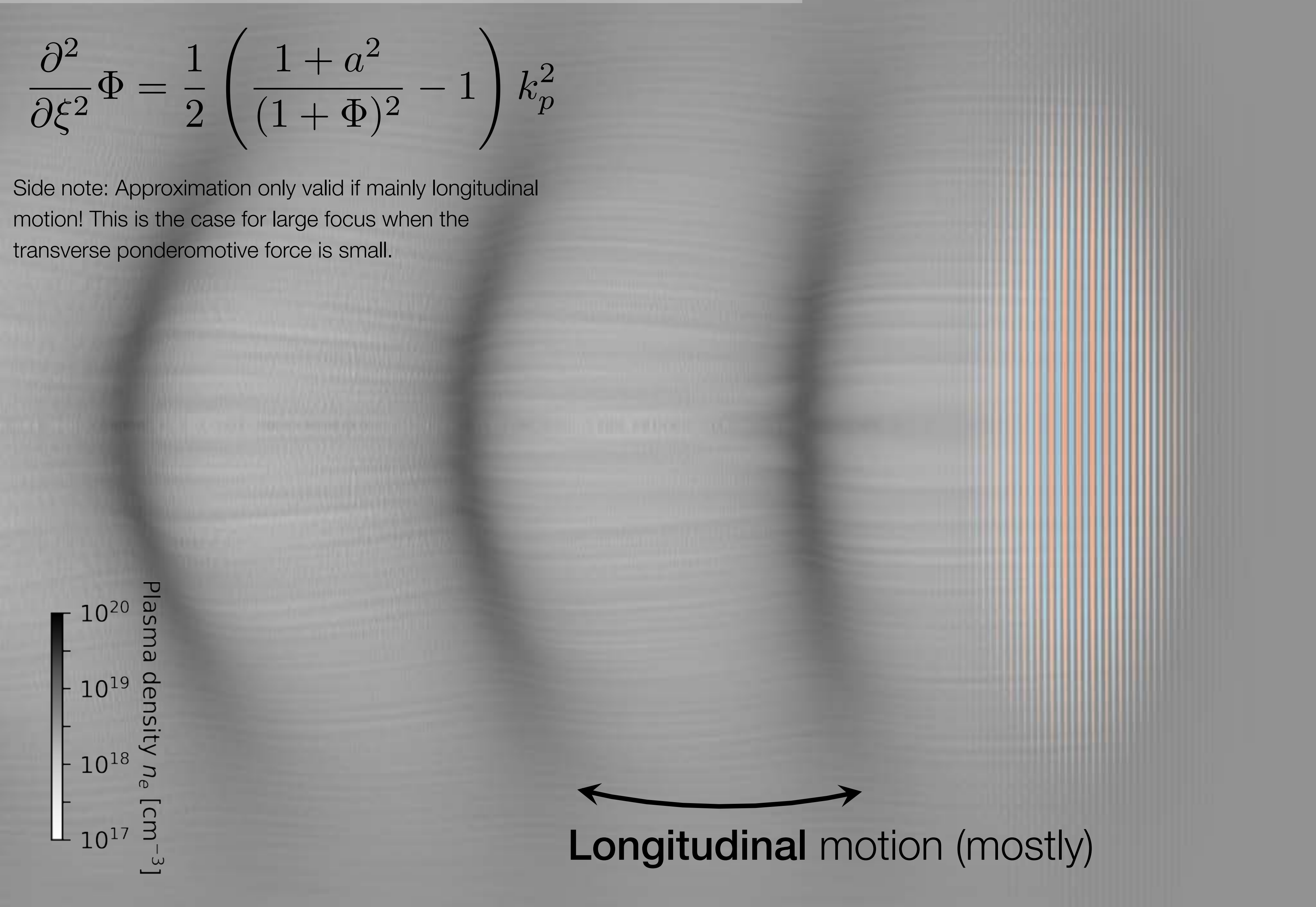
$a_0 = 1.5$

Non-linear laser wakefield

$a_0 = 2.0$

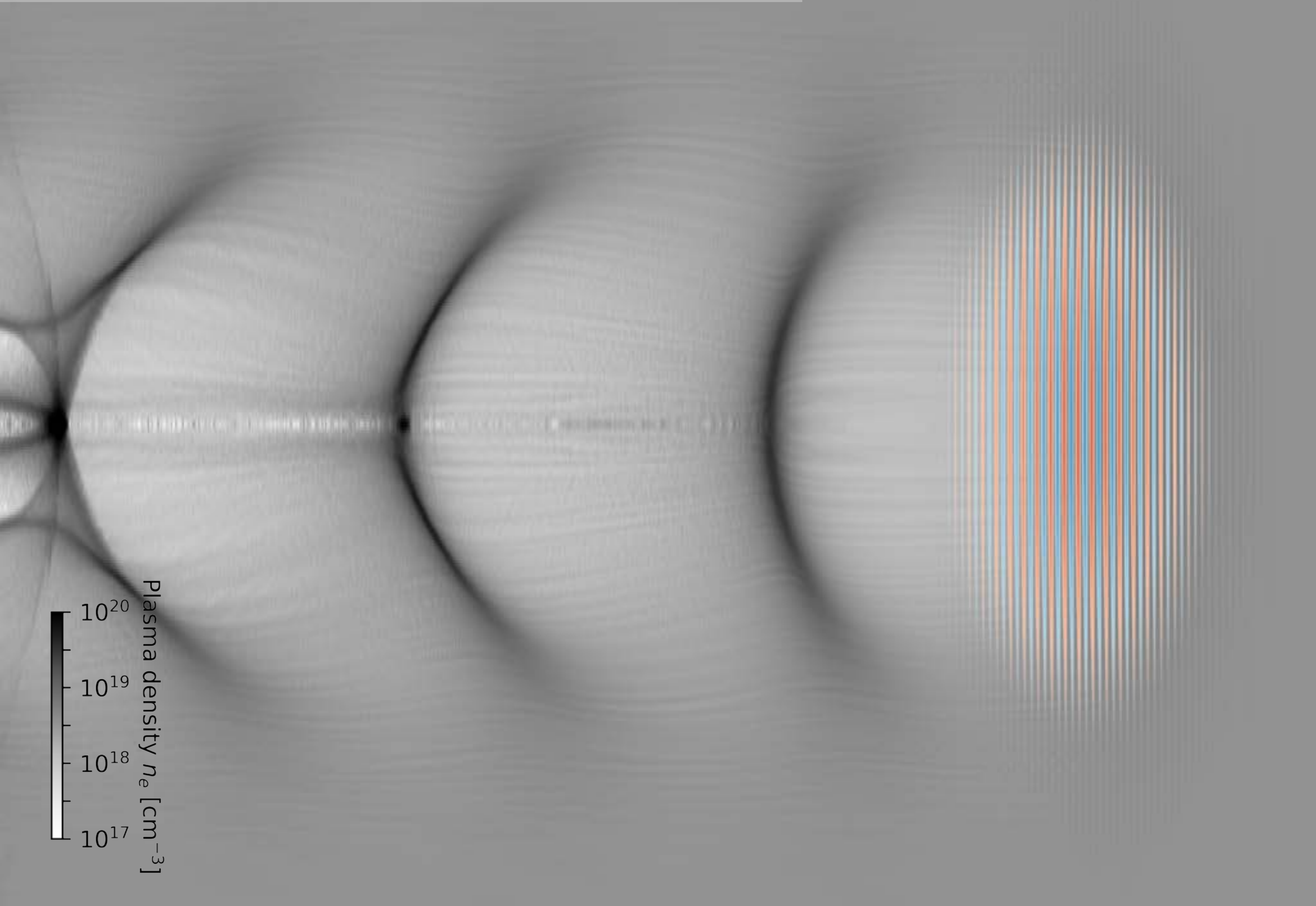
$$\frac{\partial^2}{\partial \xi^2}\Phi = \frac{1}{2}\left(\frac{1+a^2}{(1+\Phi)^2} - 1\right)k_p^2$$

Side note: Approximation only valid if mainly longitudinal motion! This is the case for large focus when the transverse ponderomotive force is small.



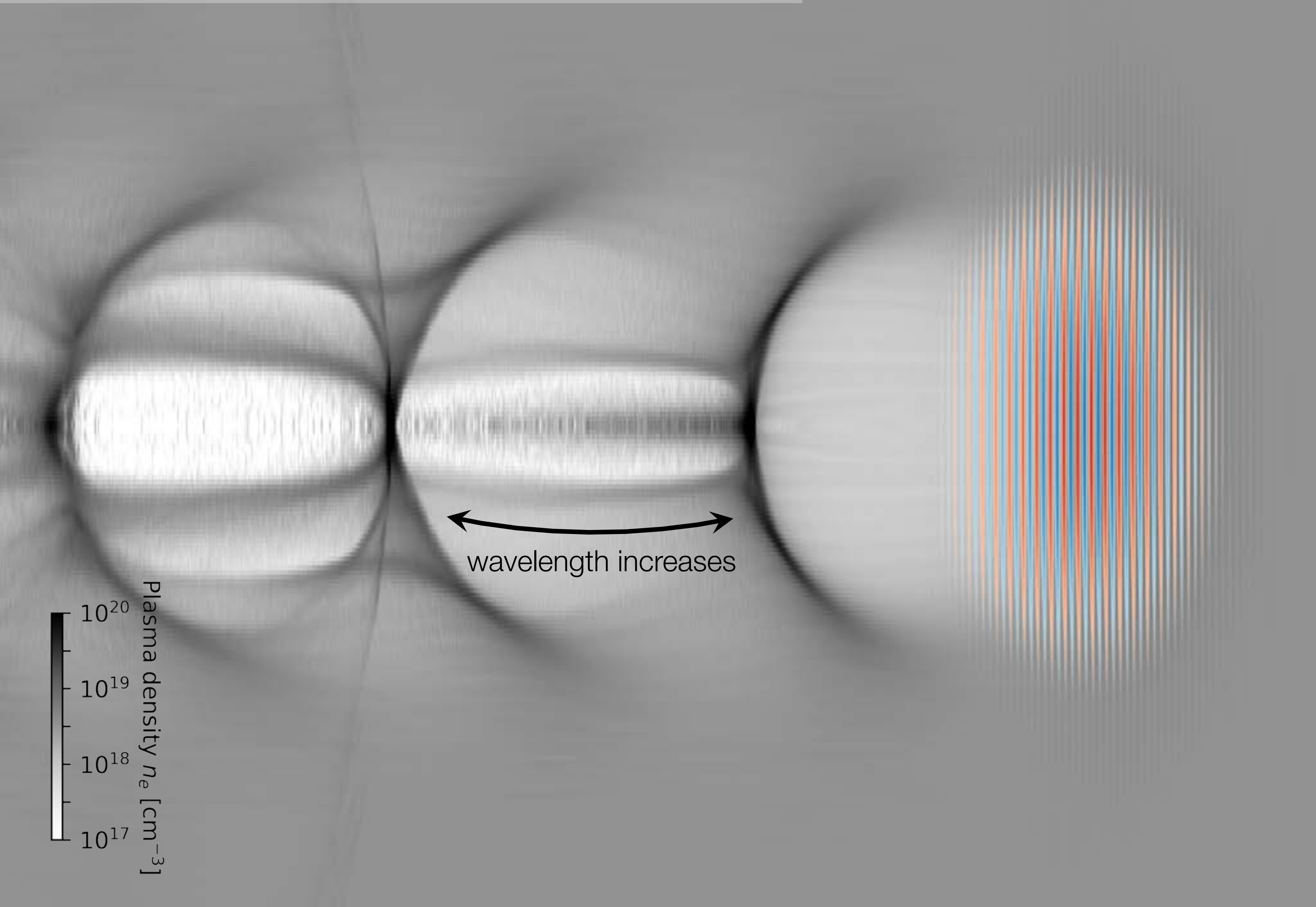
Non-linear laser wakefield

$a_0 = 2.5$



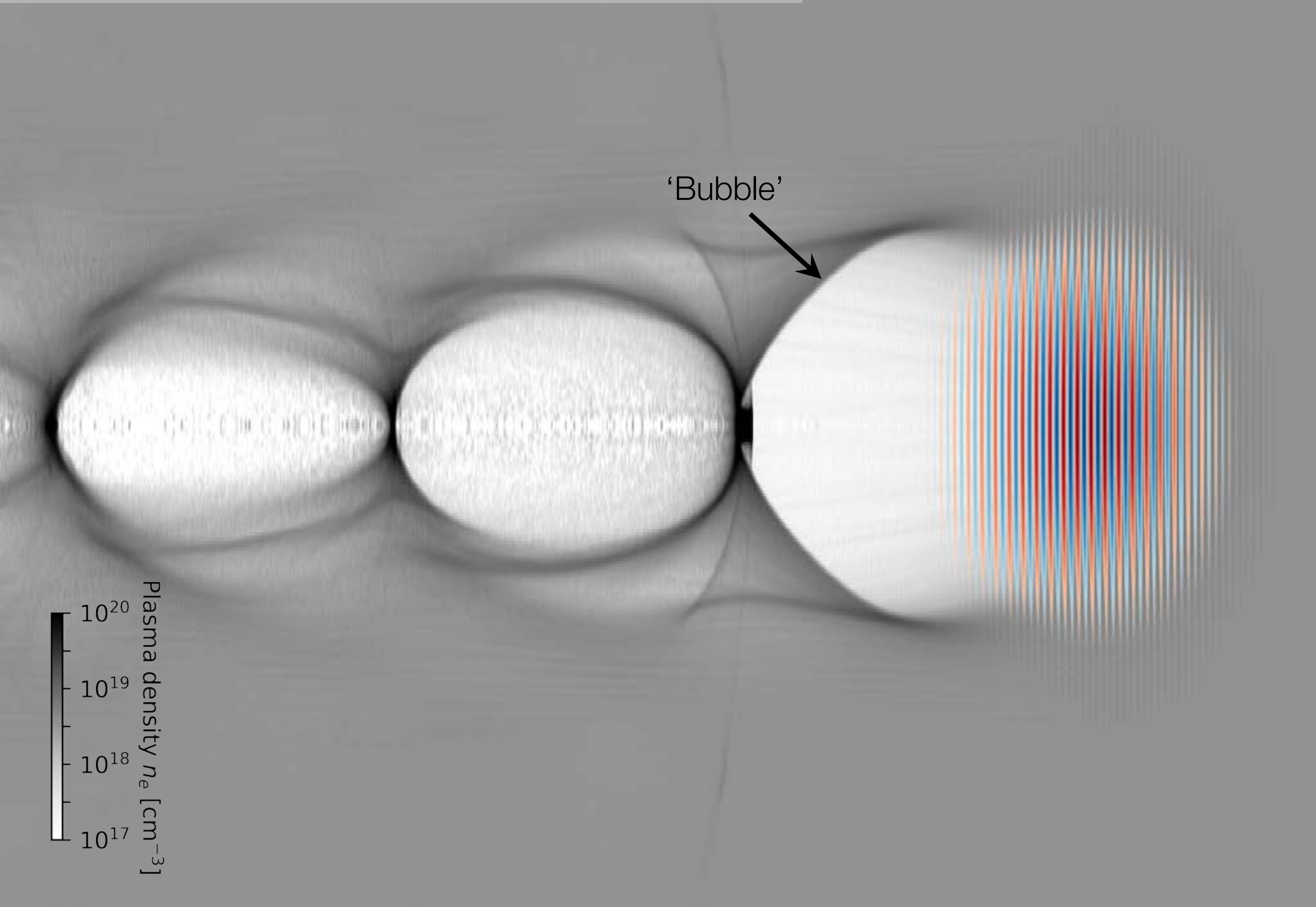
Non-linear laser wakefield

$a_0 = 3.2$

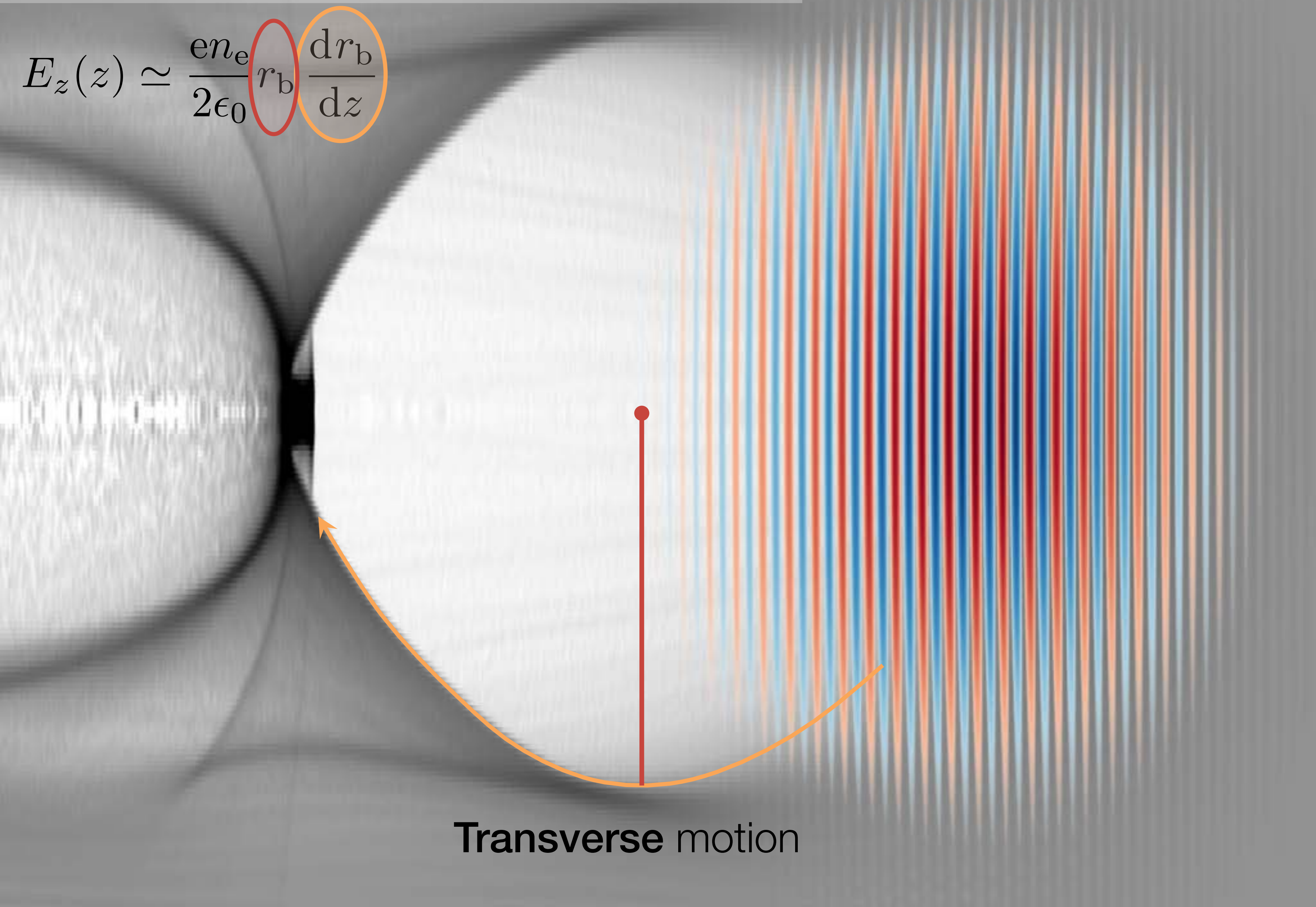


Blow-out laser wakefield

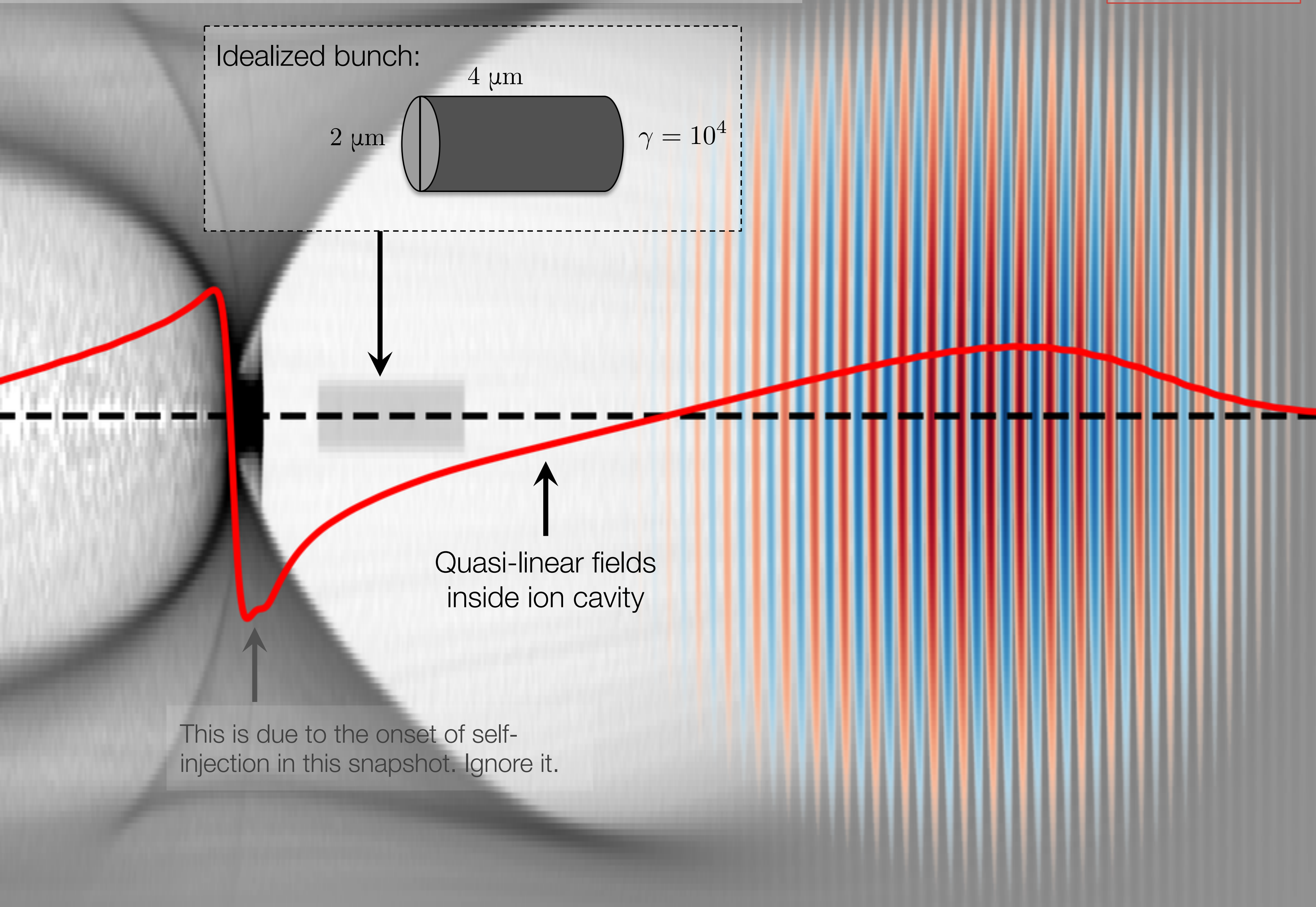
$a_0 = 4.0$



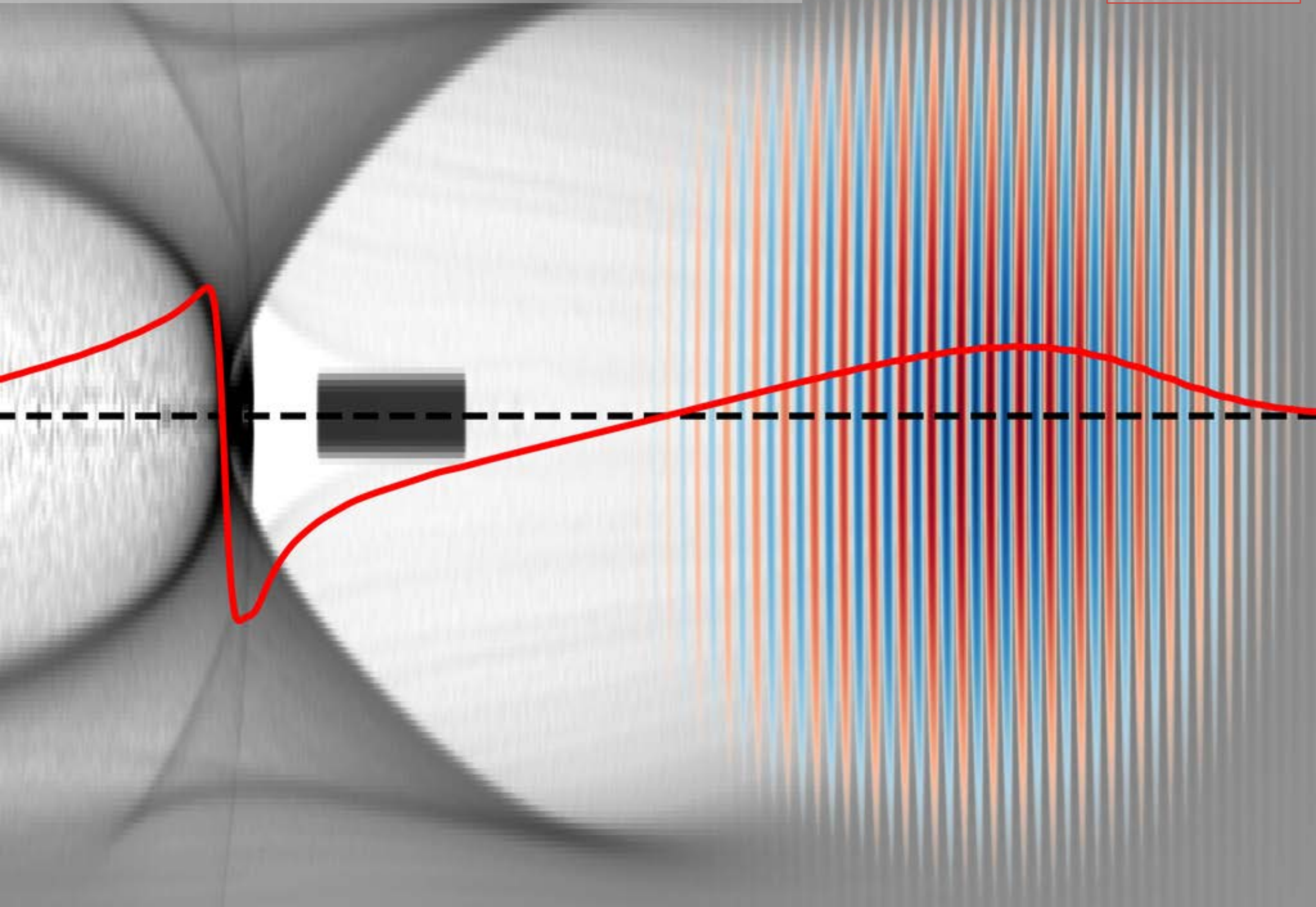
Blow-out laser wakefield



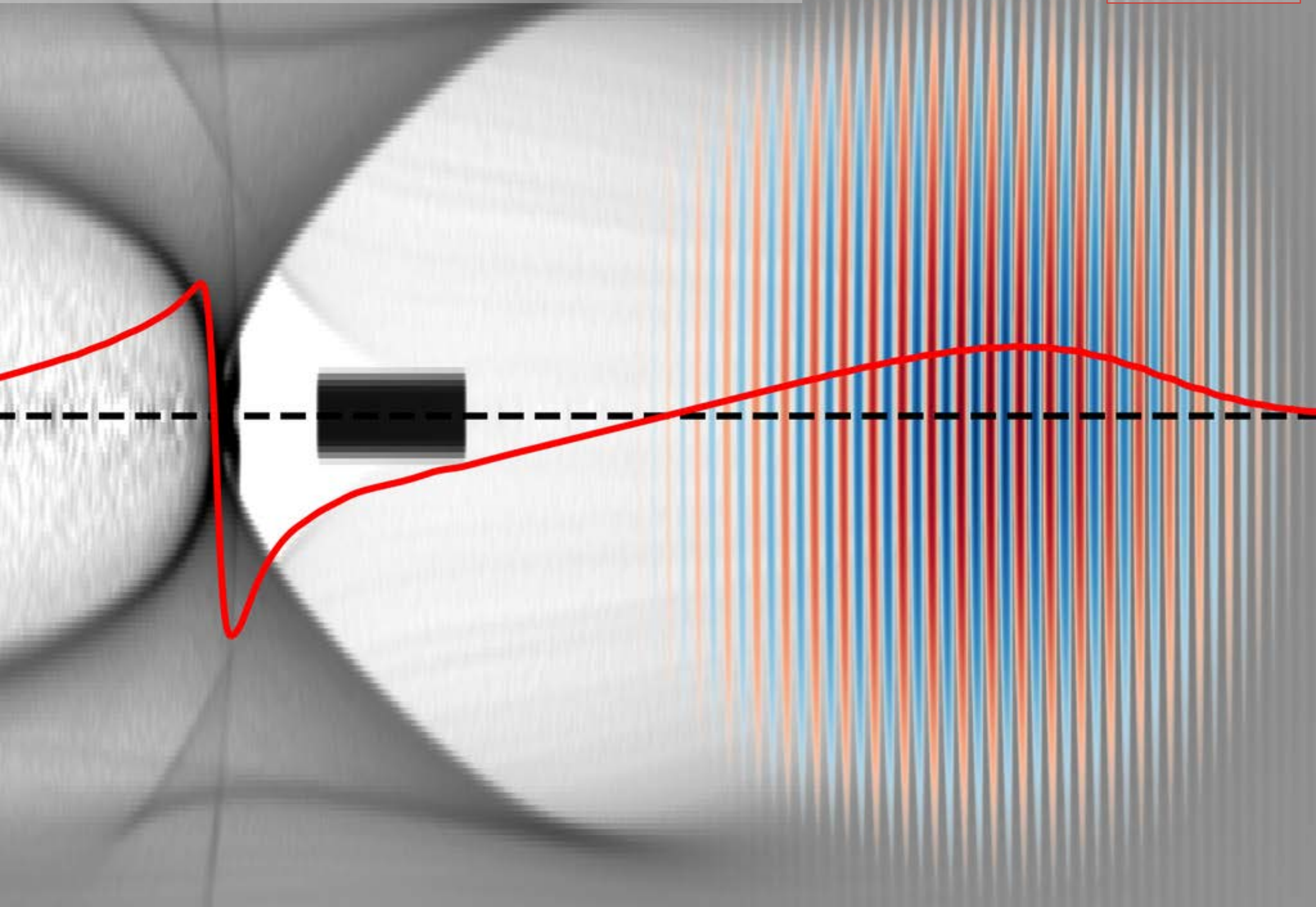
Beam-loaded laser wakefield



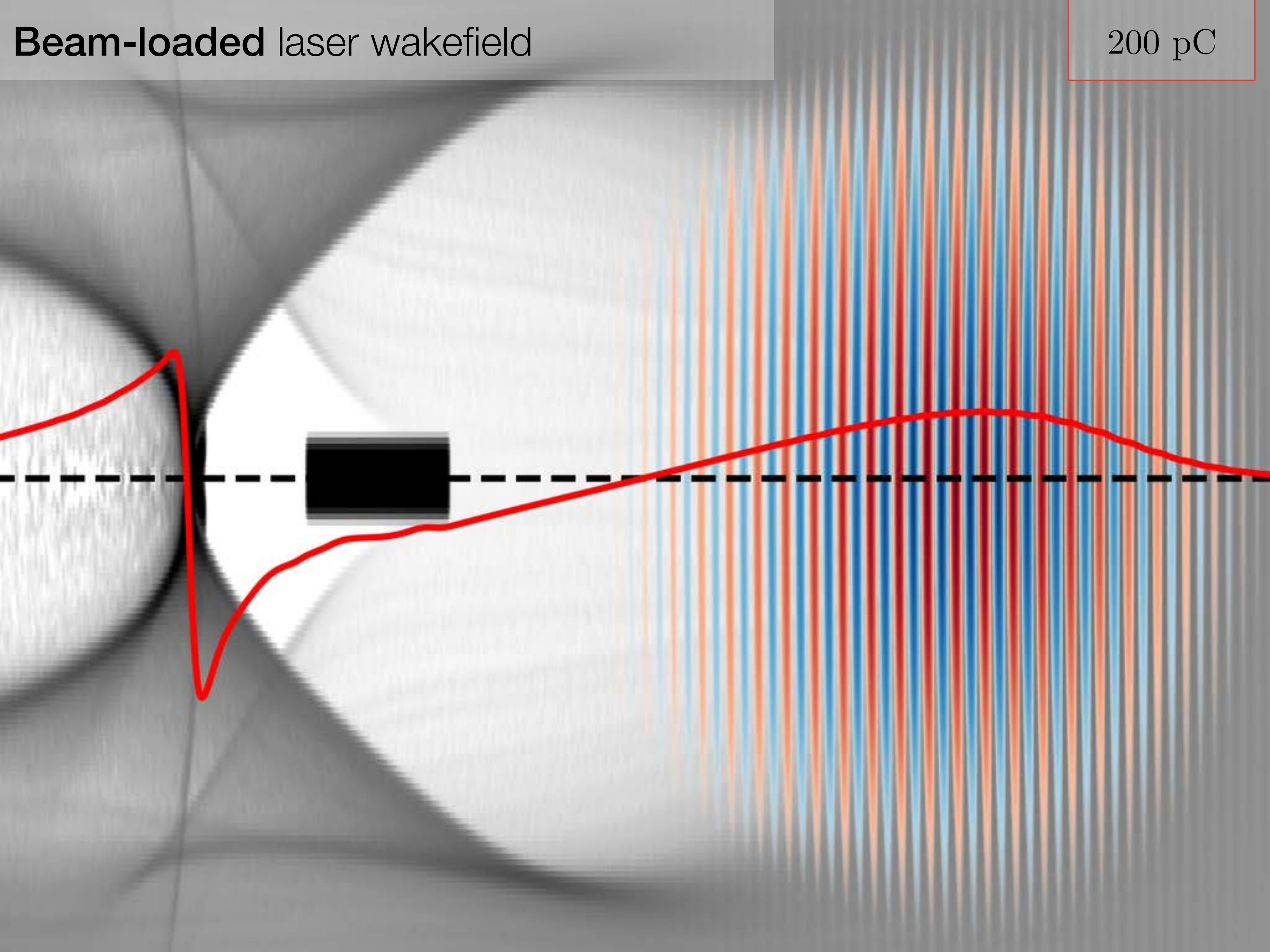
Beam-loaded laser wakefield



Beam-loaded laser wakefield

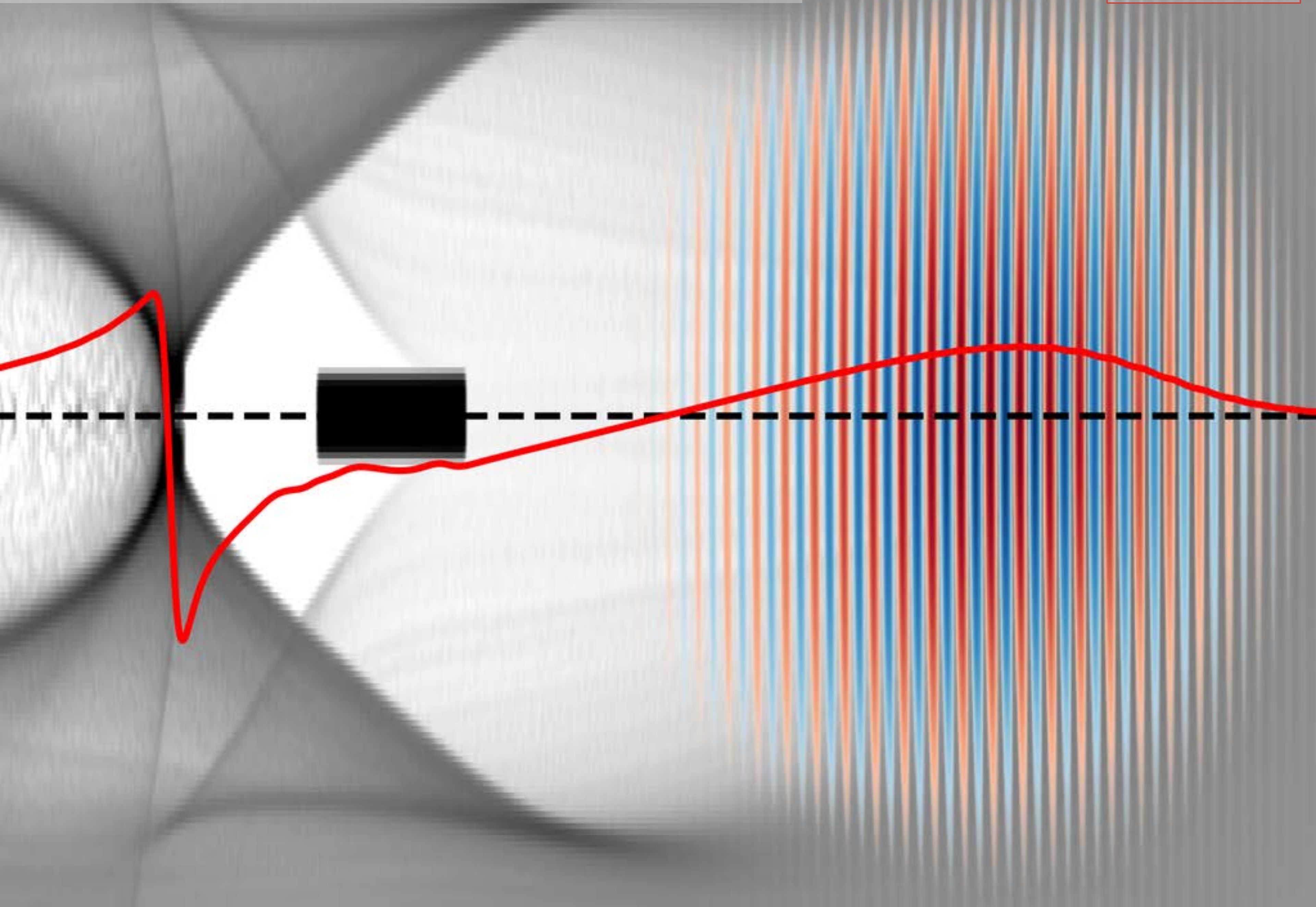


Beam-loaded laser wakefield

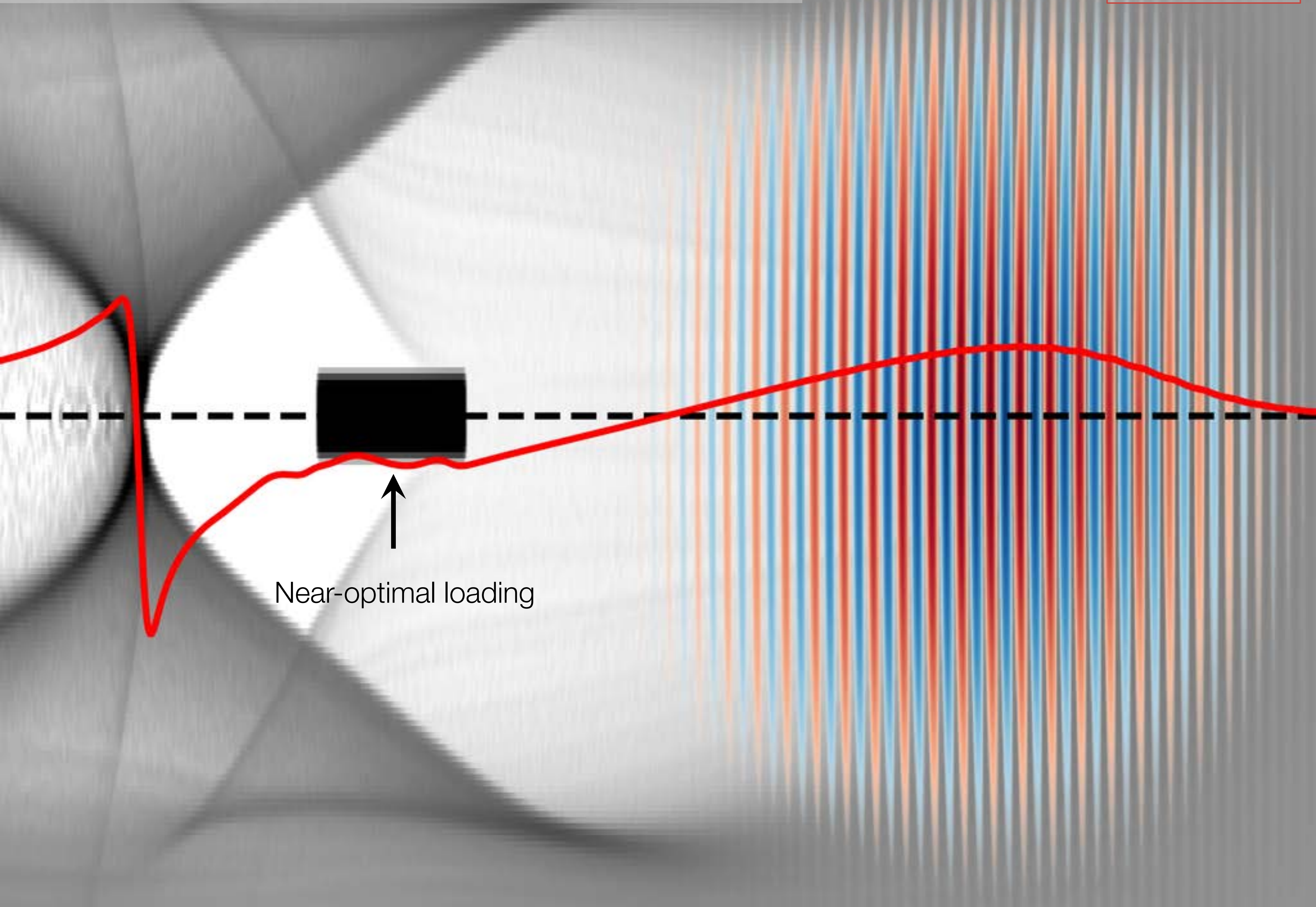


Beam-loaded laser wakefield

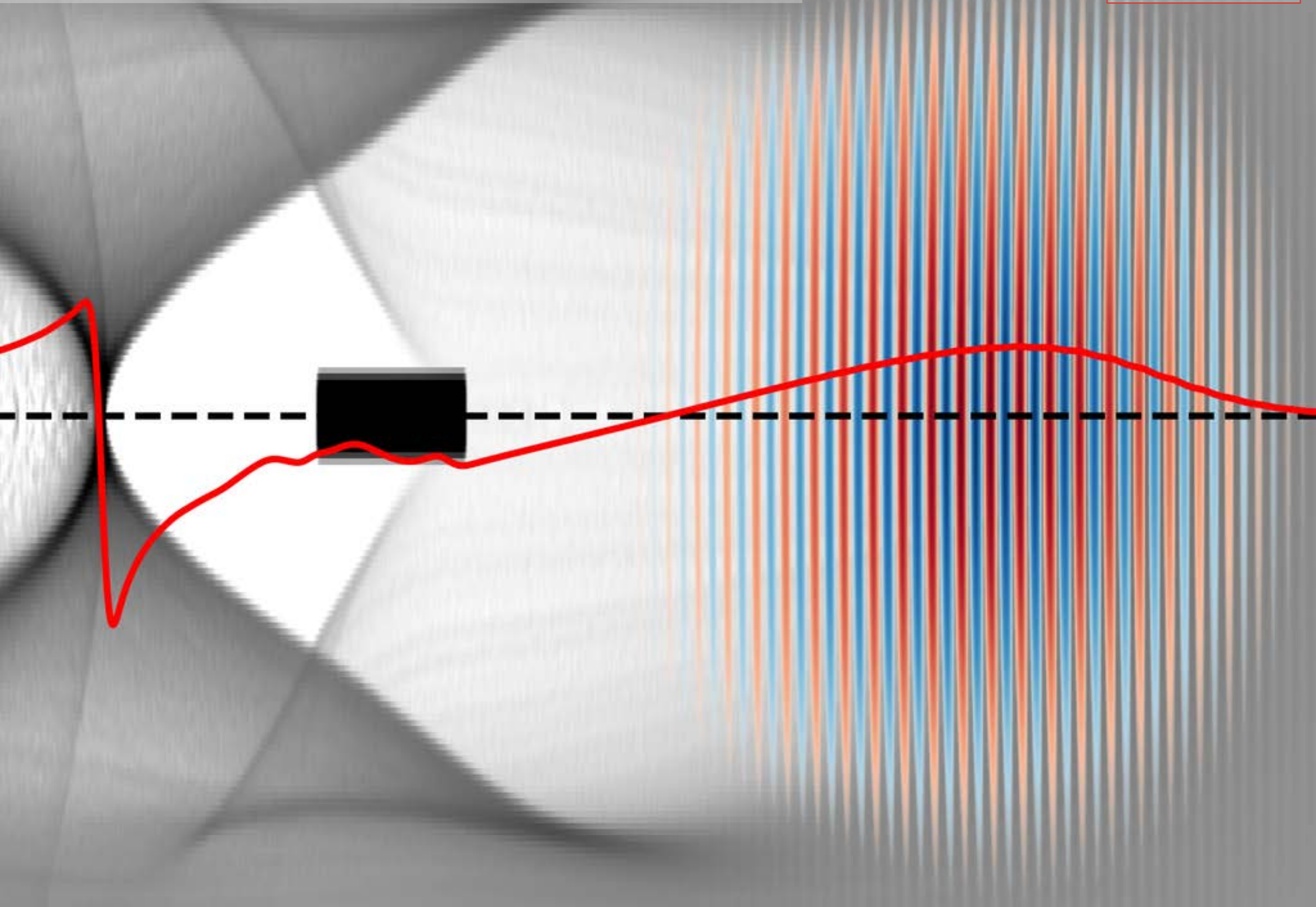
300 pC



Beam-loaded laser wakefield

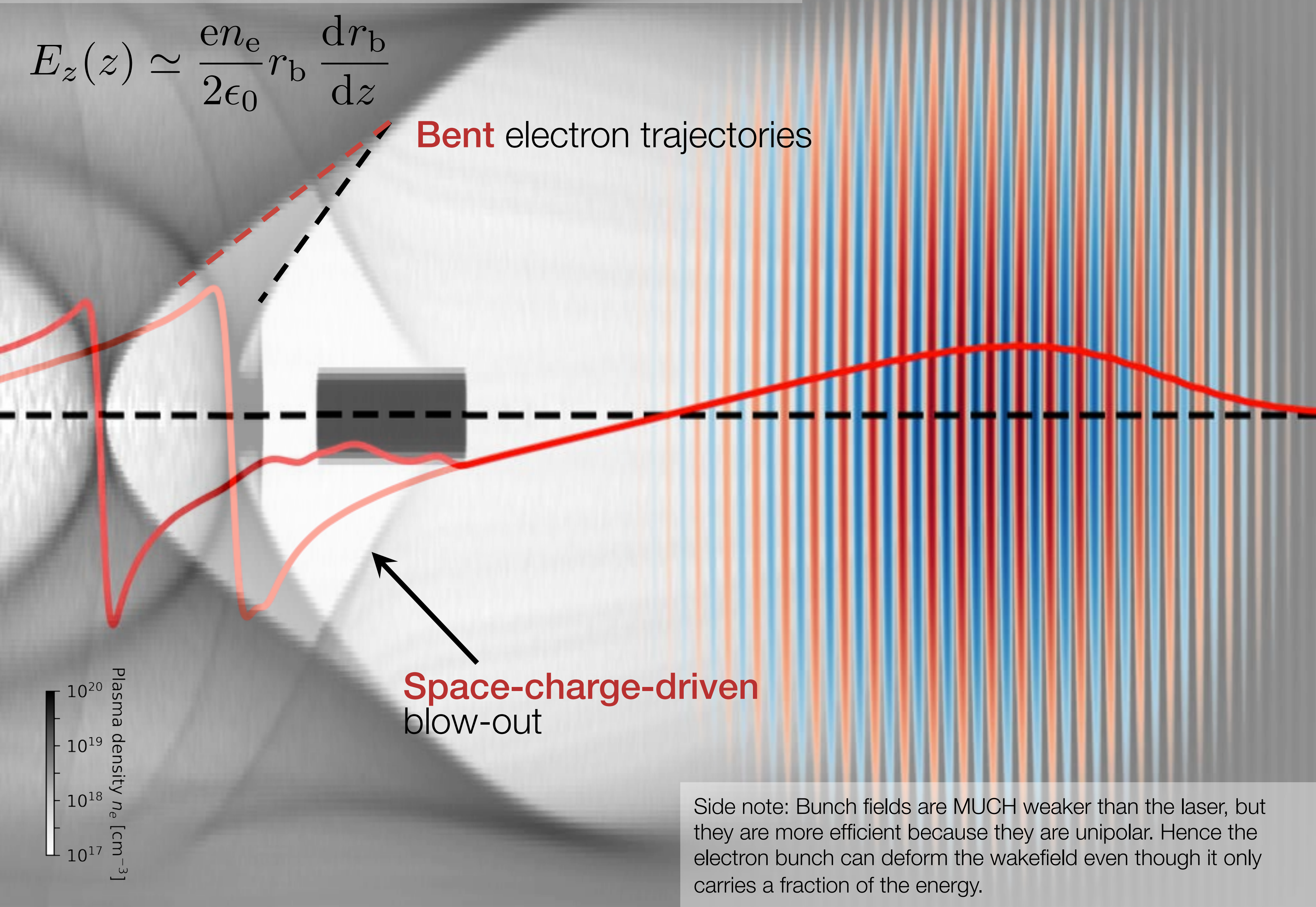


Beam-loaded laser wakefield



Beam-loaded laser wakefield

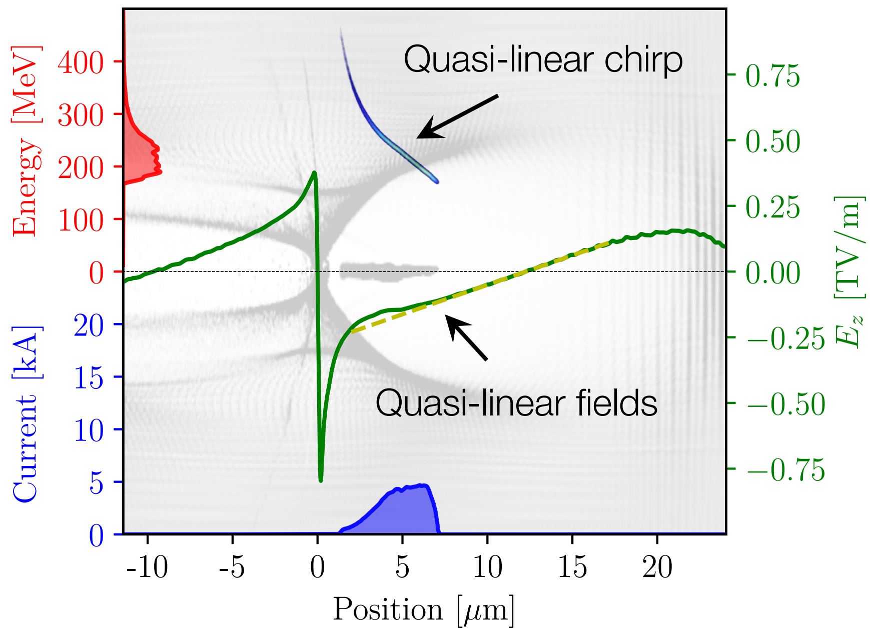
$$E_z(z) \simeq \frac{e n_\mathrm{e}}{2\epsilon_0} r_\mathrm{b} \frac{\mathrm{d}r_\mathrm{b}}{\mathrm{d}z}$$



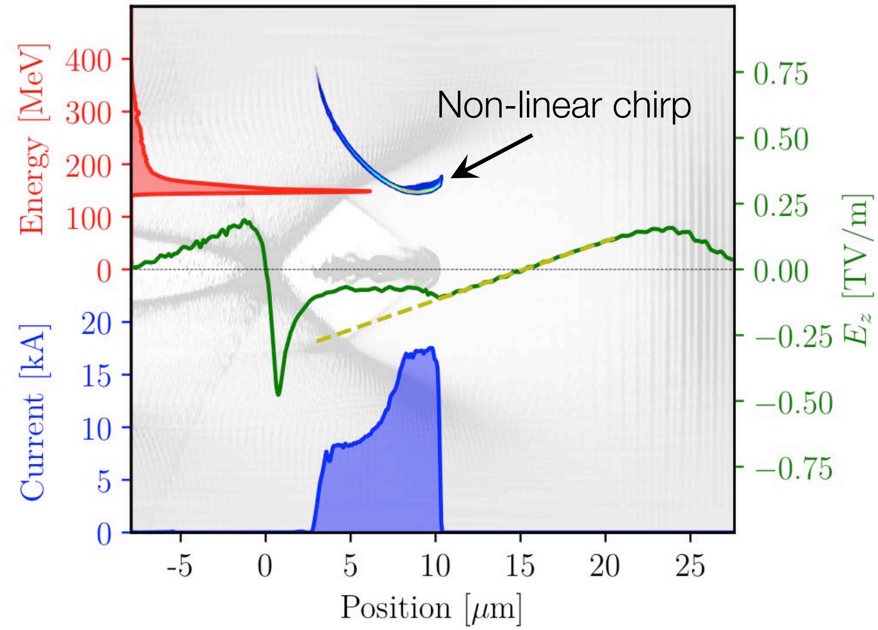
Side note: Bunch fields are MUCH weaker than the laser, but they are more efficient because they are unipolar. Hence the electron bunch can deform the wakefield even though it only carries a fraction of the energy.

Beam-loaded LWFA – Influence on energy spectrum

Weak beamloading



Strong beamloading

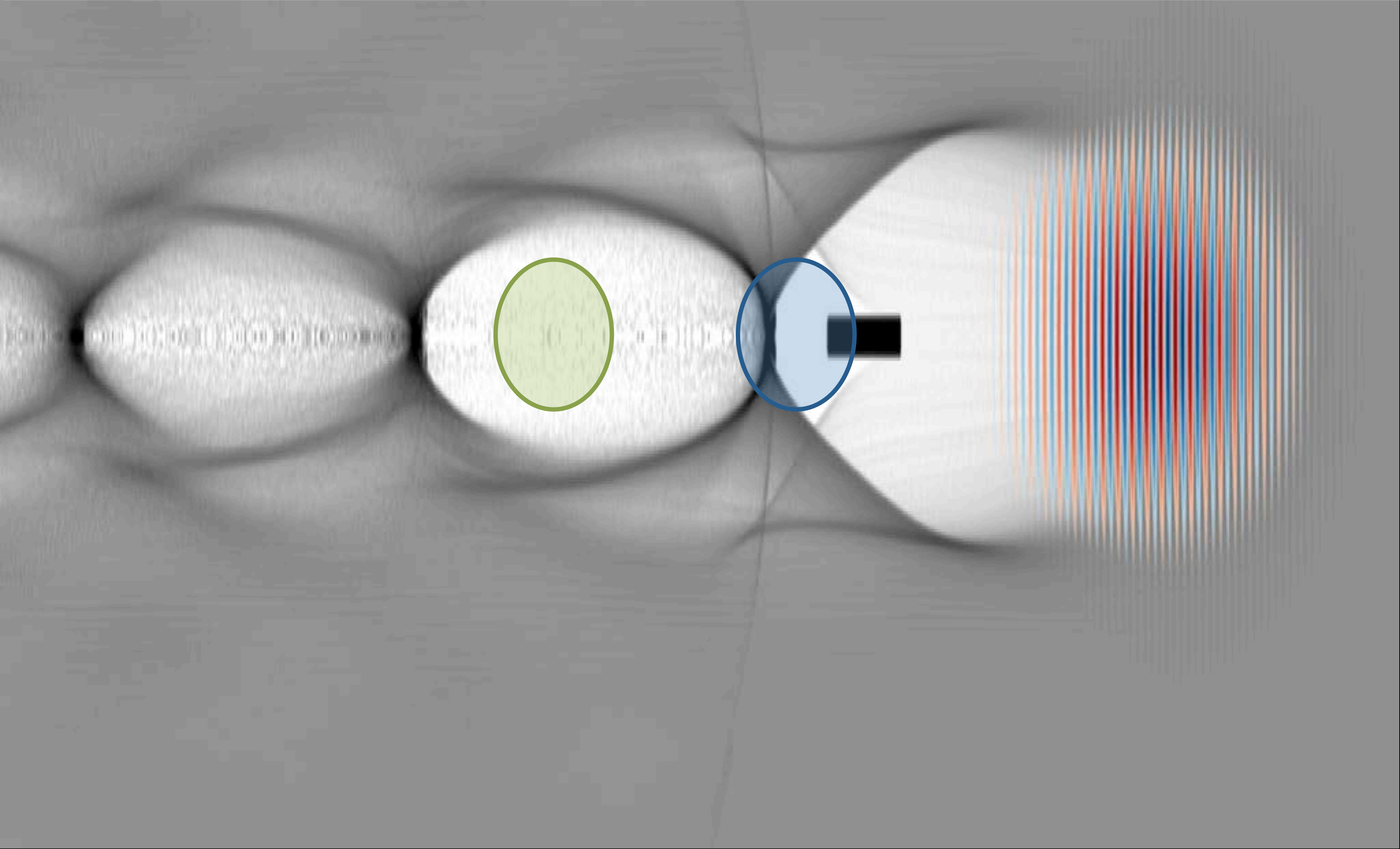


- Quasi-linear fields lead to quasi-linear chirp
- Electron spectrum dominated by current profile
- *Symmetric* spectrum (more or less) around mean energy

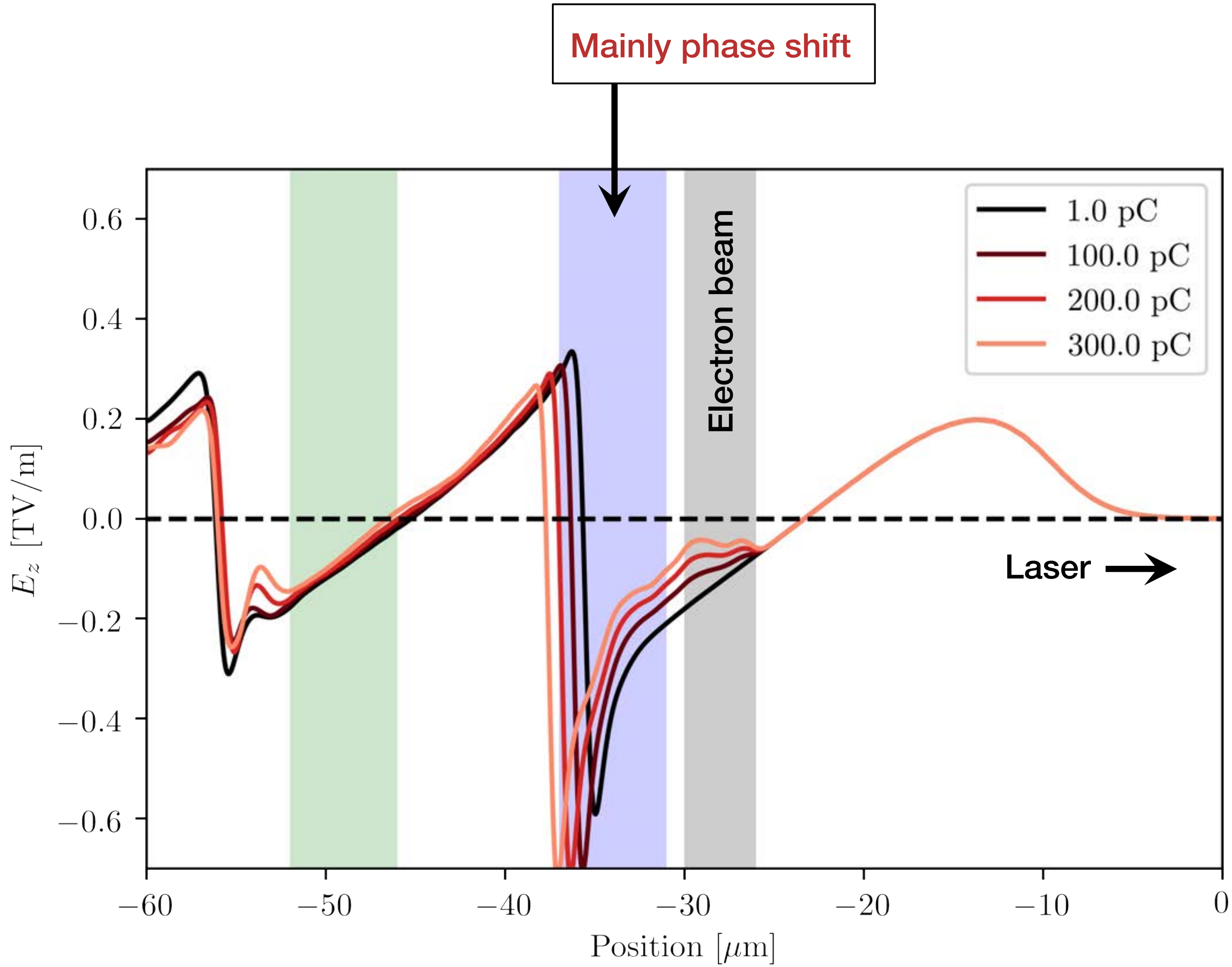
- Beam-loaded fields lead to non-linear chirp
- Electron spectrum dominated by chirp
- *Skewed* spectrum (Peak at low energy, high-energy tail)

Part II

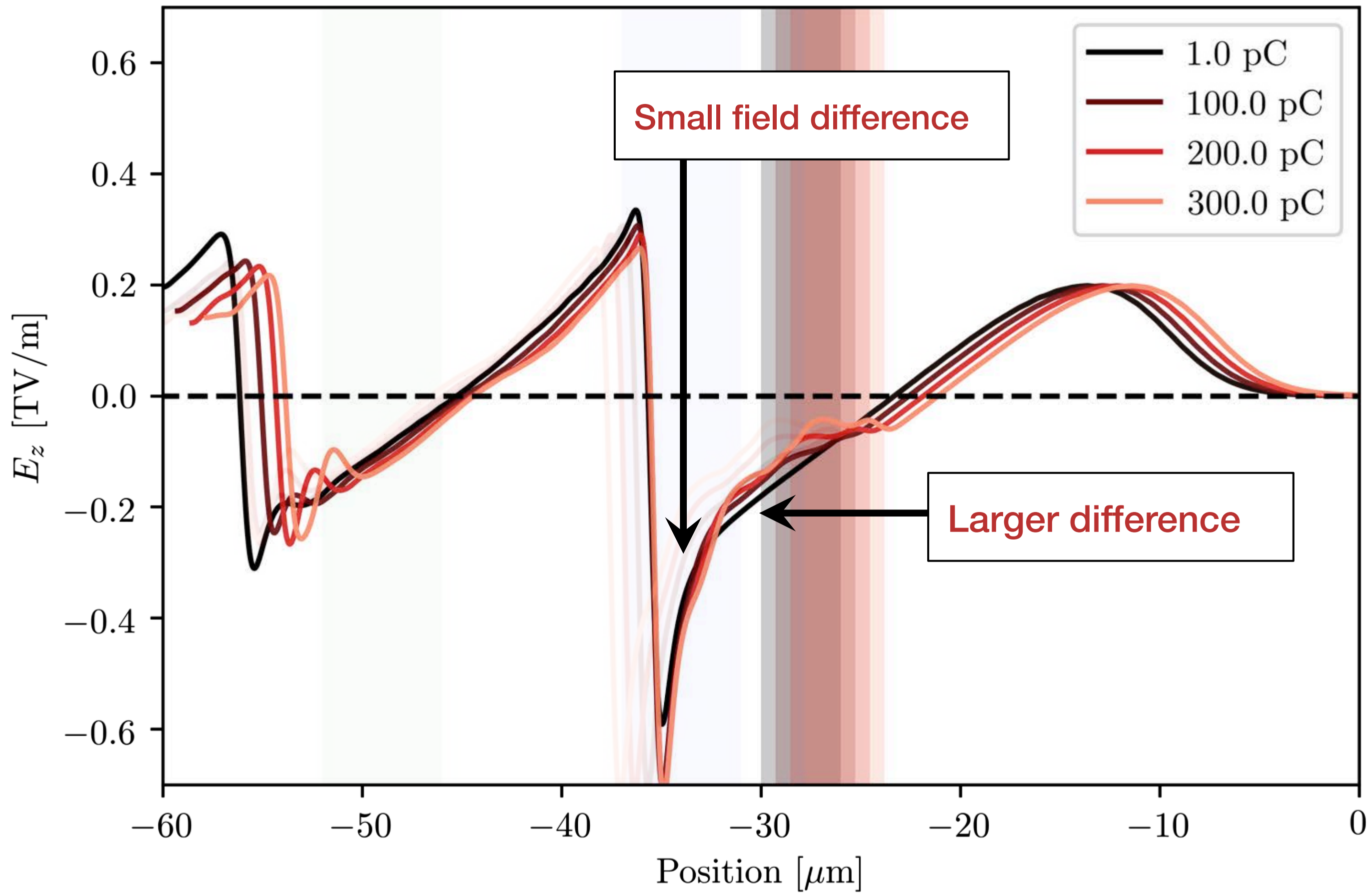
Influence of beam-loading on the electron **trailing bunches**



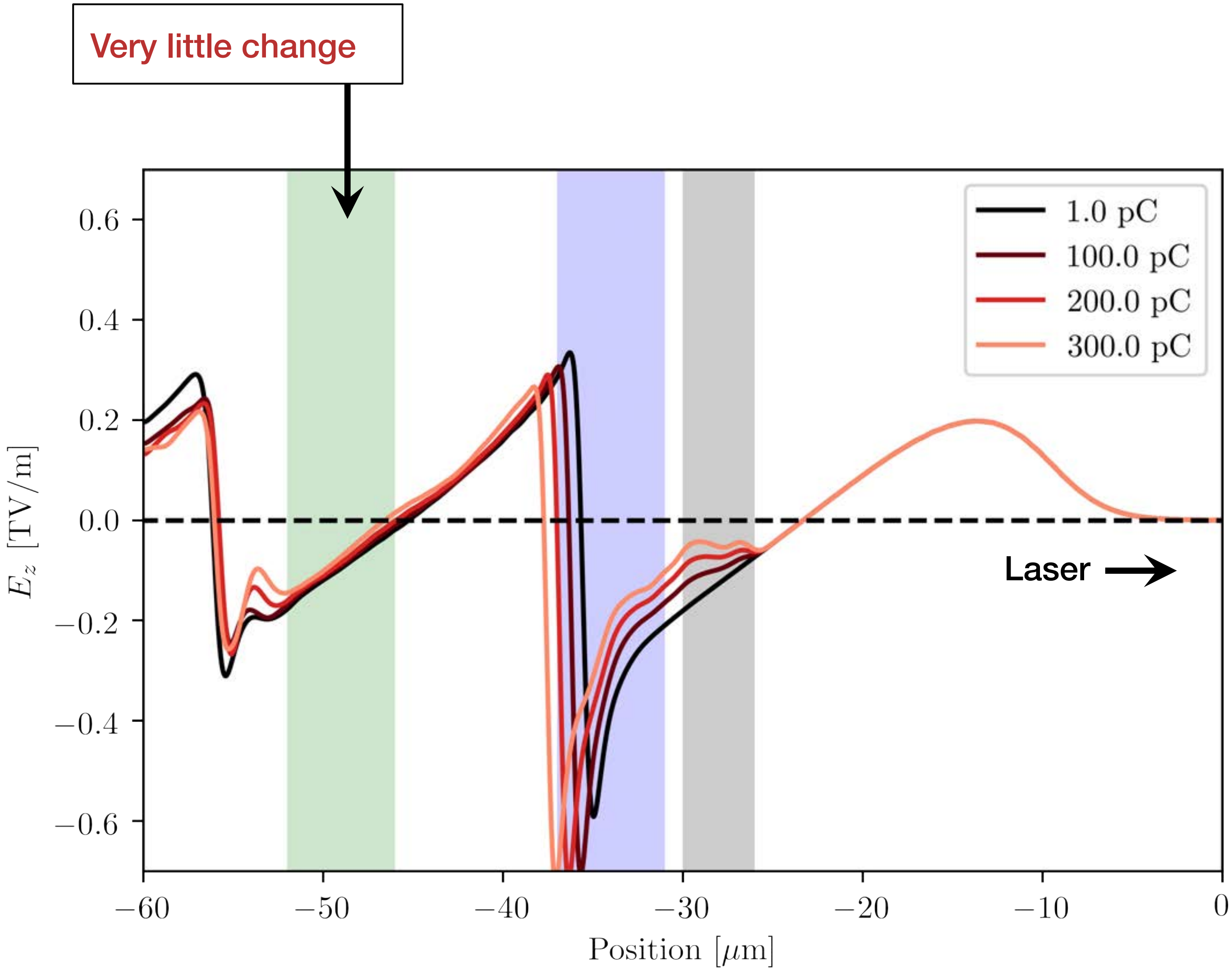
Influence on trailing wakefield Simulations



Influence on trailing wakefield Simulations



Influence on trailing wakefield Simulations

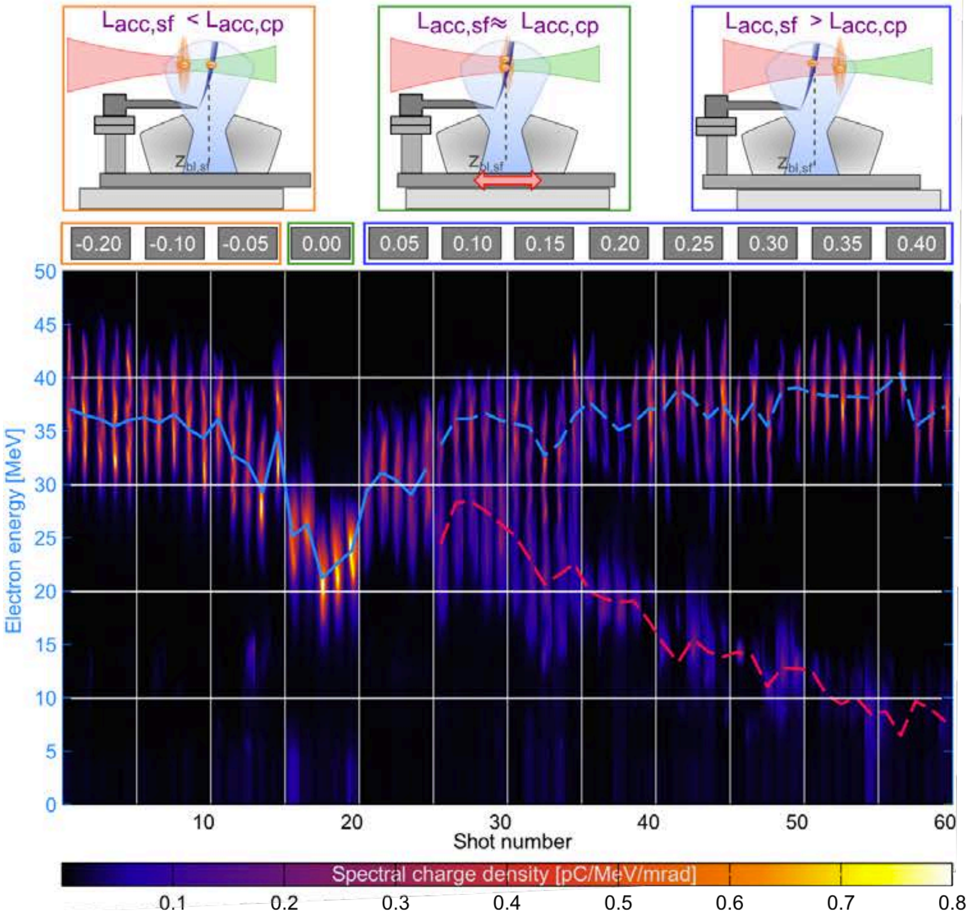


Influence on trailing wakefield Dual-energy beams

- First beam via shock-front injection
- Second beam from colliding pulse injection

Important:

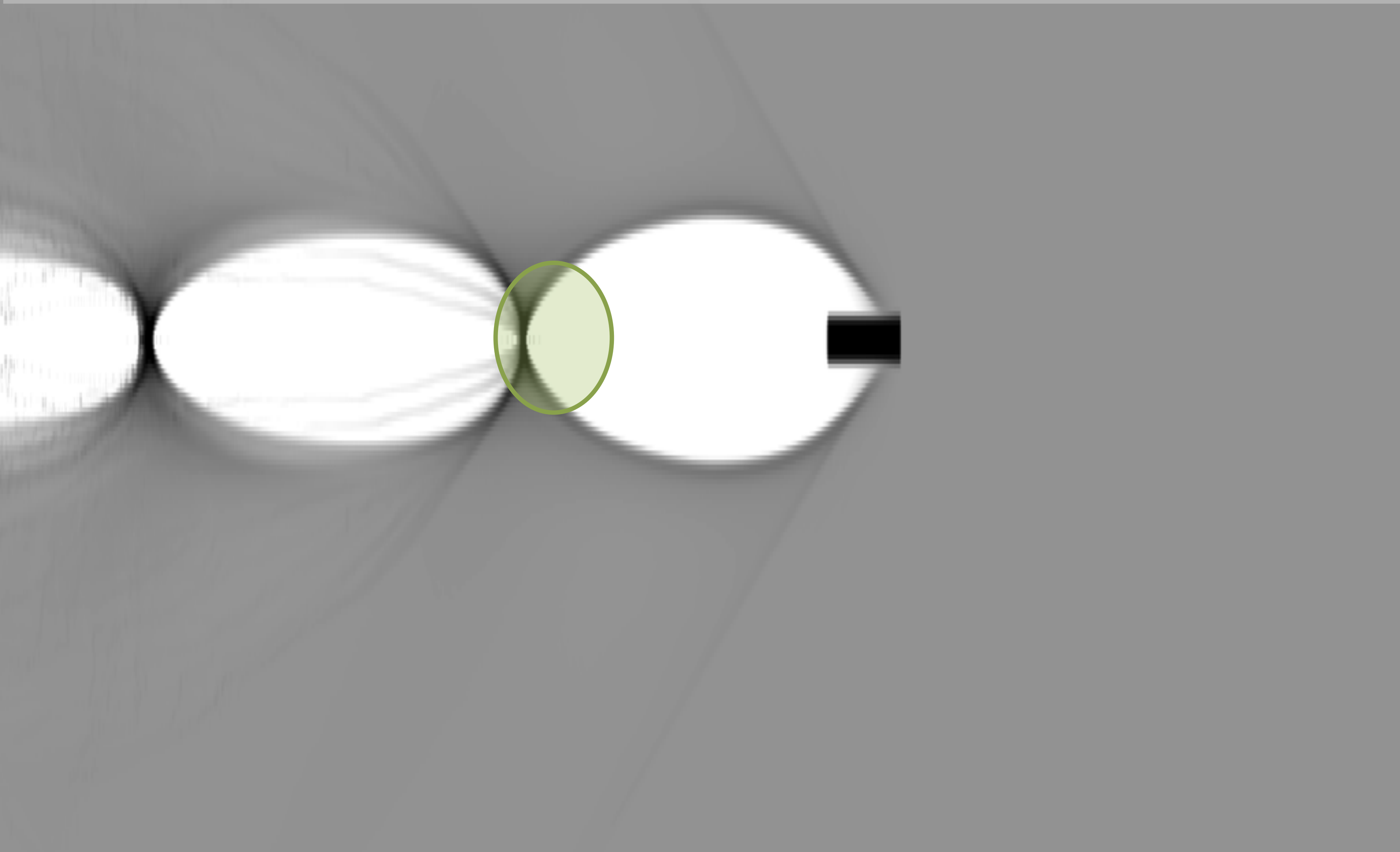
- Both injections occur in the first bubble
- Colliding pulse injected beam starts at the rear end of the bubble
- The larger the distance between shock and collision, the larger the bunch separation (due to dephasing)



- J. Wenz, A. Döpp et al. Dual-energy electron beams from a compact laser-driven accelerator. Nature Photonics (2019)

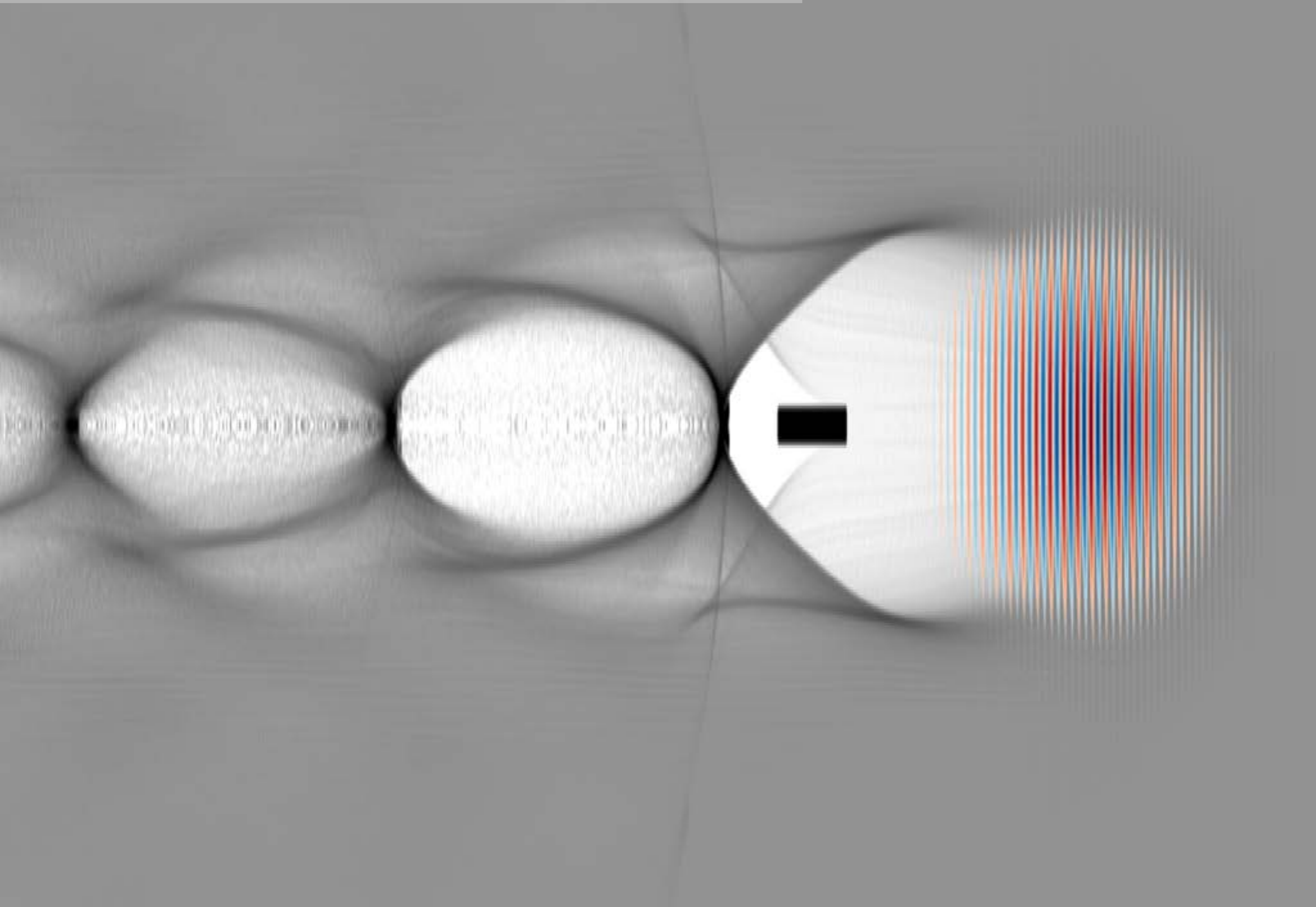
Part III

Evidence for a transition to the **beam-dominated regime**



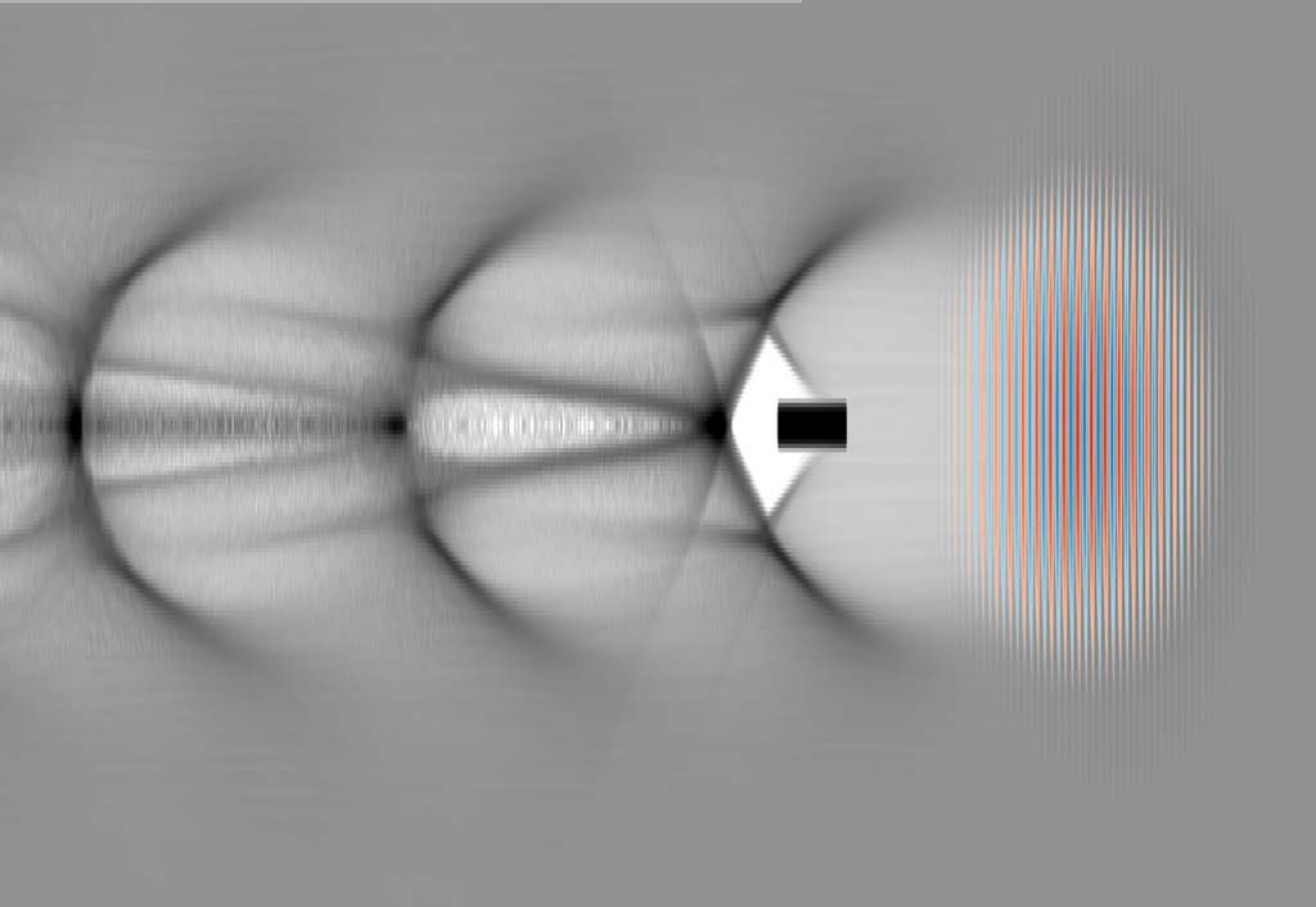
Beam-loaded laser wakefield

$a_0 = 4.0$



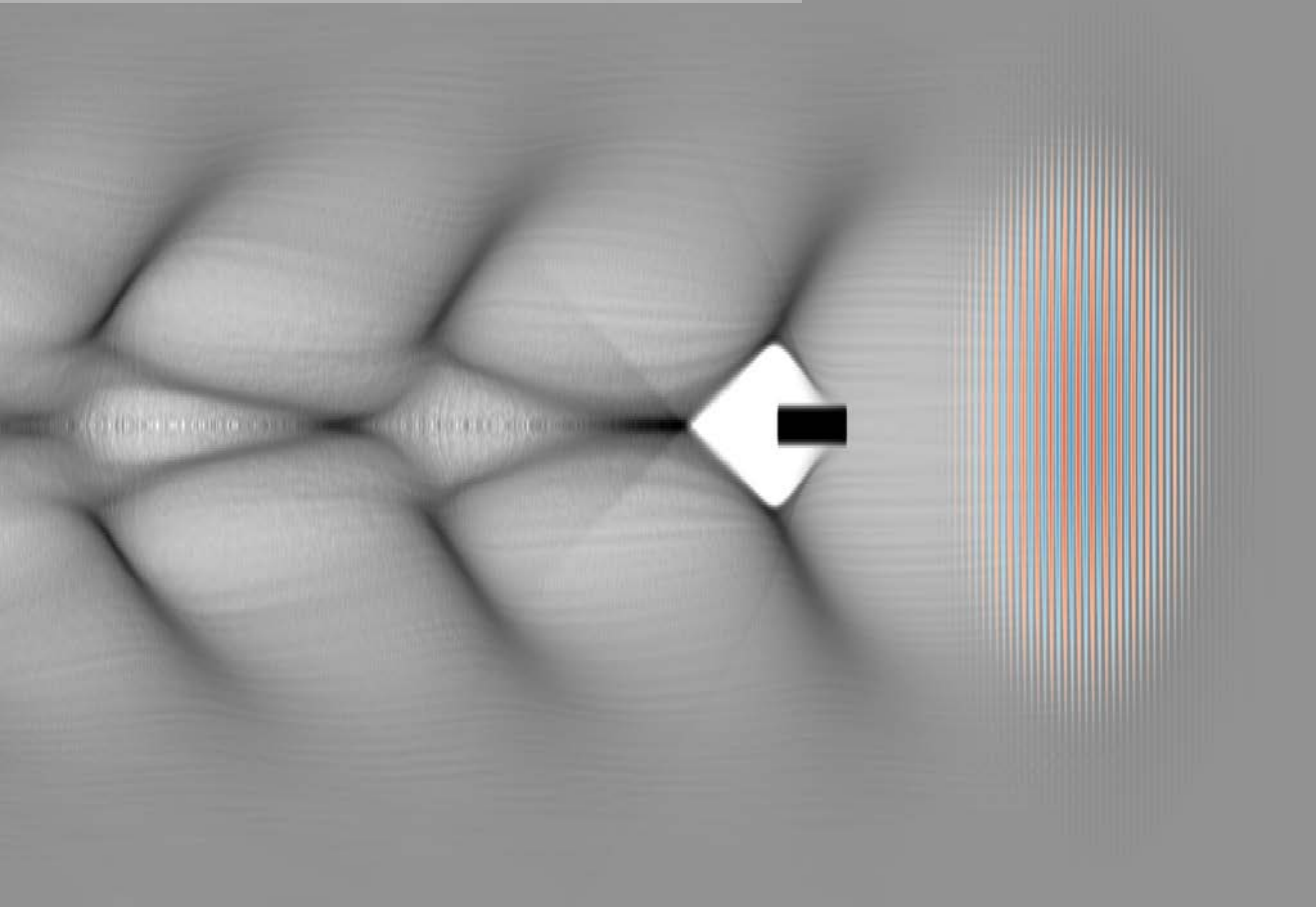
Beam-loaded laser wakefield

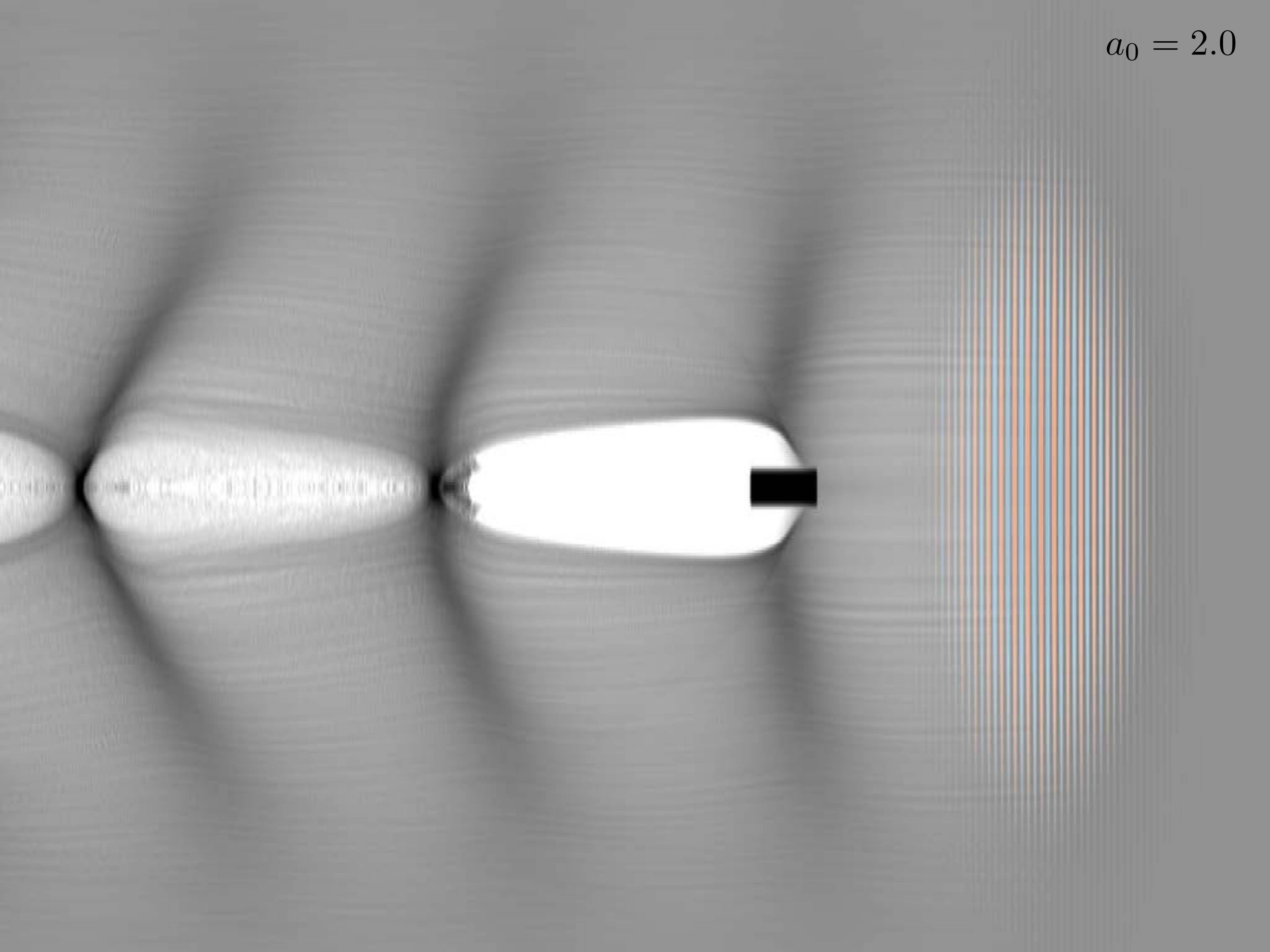
$a_0 = 3.2$



Beam-loaded laser wakefield

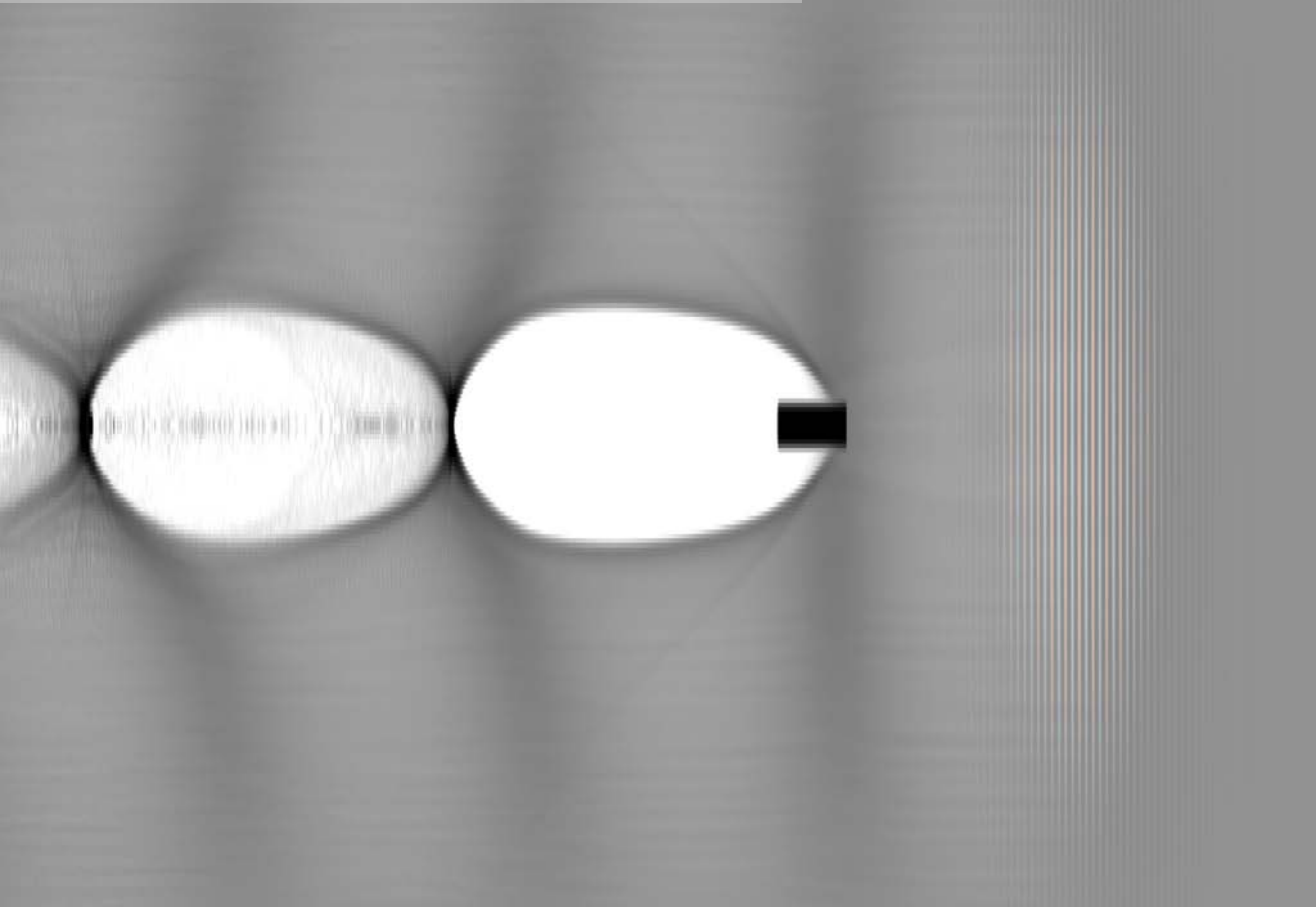
$a_0 = 2.5$



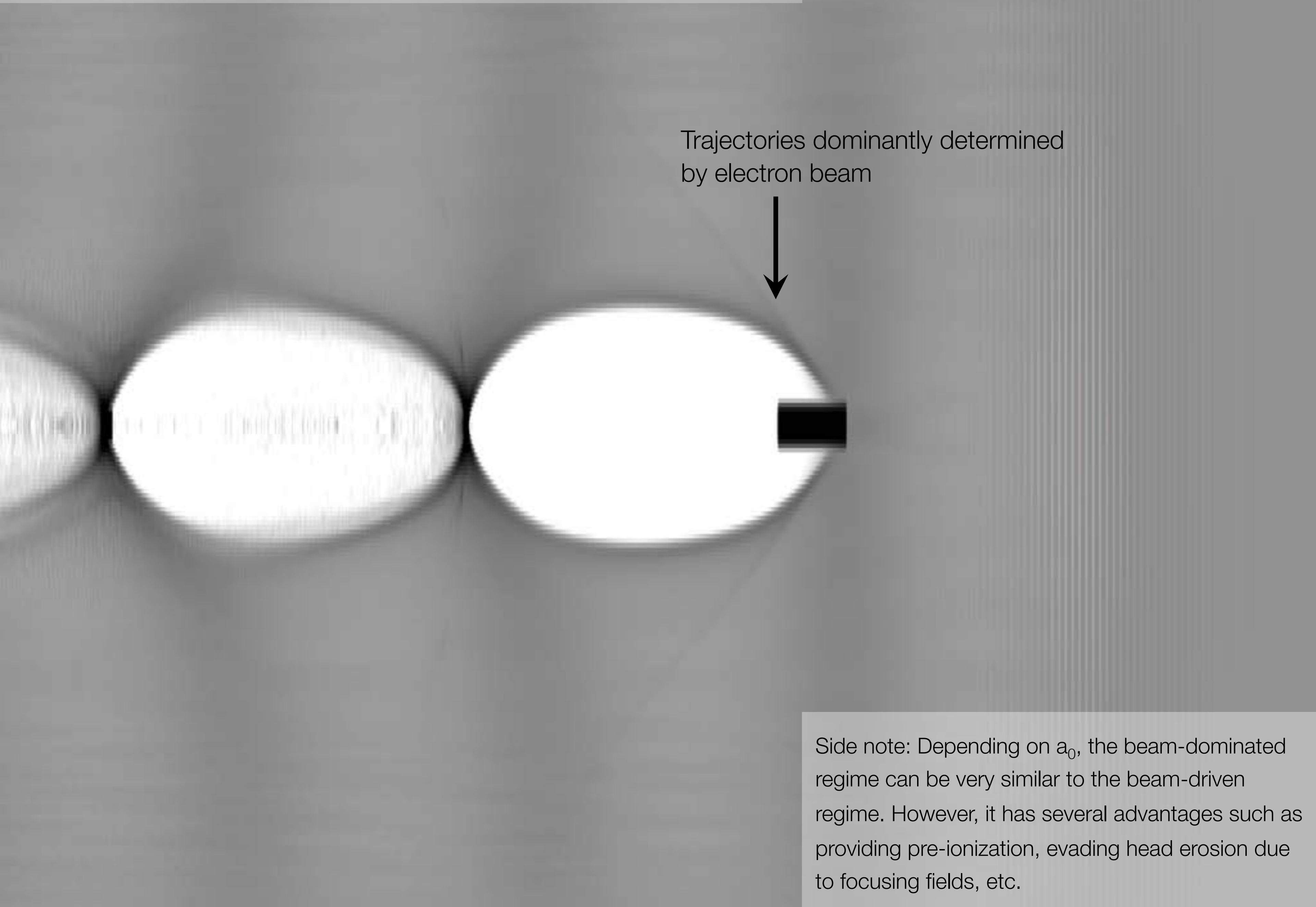

$a_0 = 2.0$

Beam-dominated laser wakefield

$a_0 = 1.5$



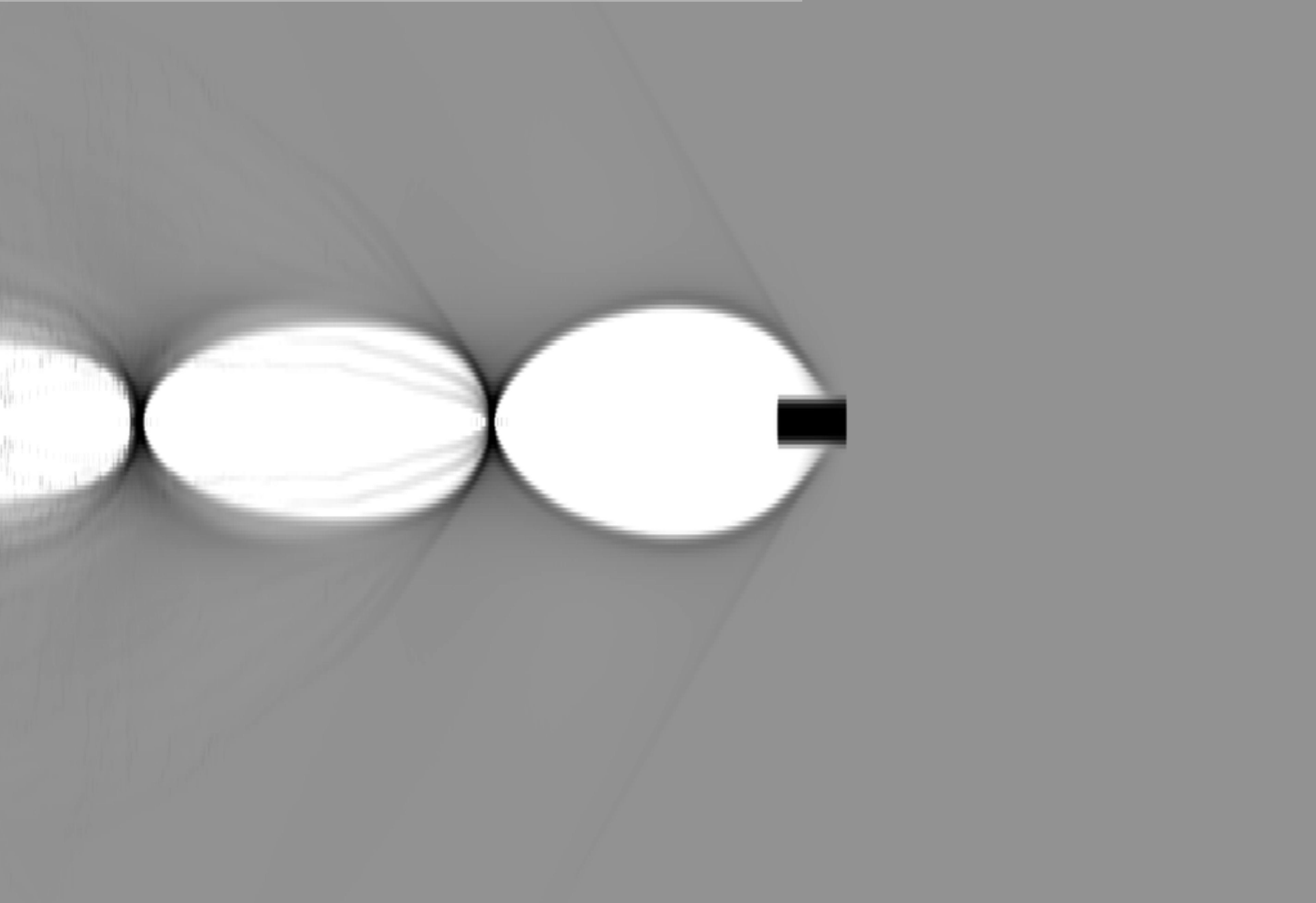
Beam-dominated laser wakefield



Side note: Depending on a_0, the beam-dominated regime can be very similar to the beam-driven regime. However, it has several advantages such as providing pre-ionization, evading head erosion due to focusing fields, etc.

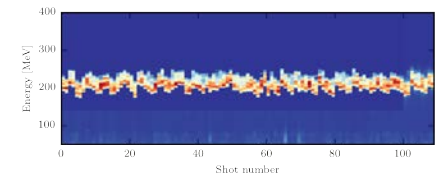
Beam-driven plasma wakefield

No laser

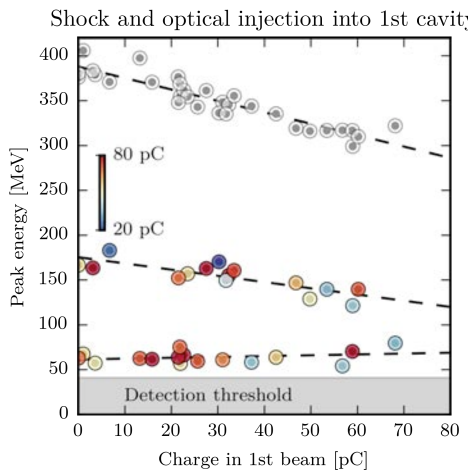


Conclusions

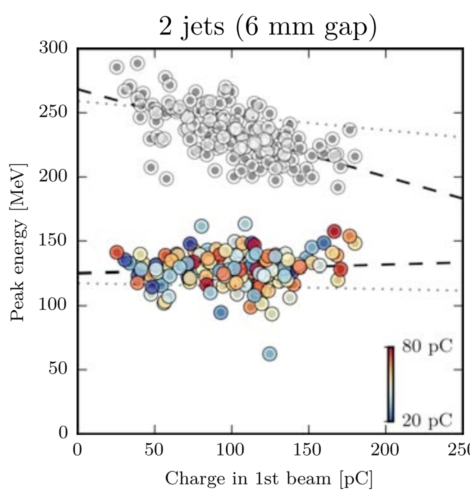
I. Demonstrated high-charge-density beams (>10 pC/MeV) and the **spectral influence of beam-loading**



II. Measured the **influence of beam-loading on trailing electron bunches** in dual-energy configurations



III. **Observed energy gain and PWFA-like behavior** in a beam-dominated scenario



Thank you for your attention!

If you liked this talk, **you might also be interested in:**

- S. Karsch et al. Dual energy electron beams from two independent injection events, **Wednesday 18:00 WG1**
- T. Heinemann et al. Demonstration of a millimeter-scale electron-beam driven plasma wakefield accelerator based on hybrid staging, **Thursday 18:00 WG1**
- A. Irman et al. Hybrid LWFA-PWFA staging: from concept to proof-of-principle experiments, **Friday 10:10 Plenary**

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