Controlled Acceleration of Unstable Particles in Laser-Plasma Wakefields Using Structured Light

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Motivation

Conventional accelerating techniques are not fast enough to accelerate short-lived particles efficiently, what are we excluding?

Muons (μ)**:** difficult to accelerate with conventional techniques ($\tau_\mu = 2.2\ \mu s$) even if there is a huge interest in the high-energy physics community in building a muon collider [1].

Pions (π): impossible to accelerate with conventional accelerating machine (τ_π = 18 ns). So far, only studied from secondary decay. If first accelerated, they become a better source of muons.

What about a plasma based accelerator [2,3]?

In this work, we propose an acceleration method for these heavier, short-lived sub-relativistic particles, which are naturally generated at lower velocities.

While our focus remains on muons and pions, the same technique applies to heavier species, e.g., kaons and protons.

Slower Wakes Using Subluminal Drivers

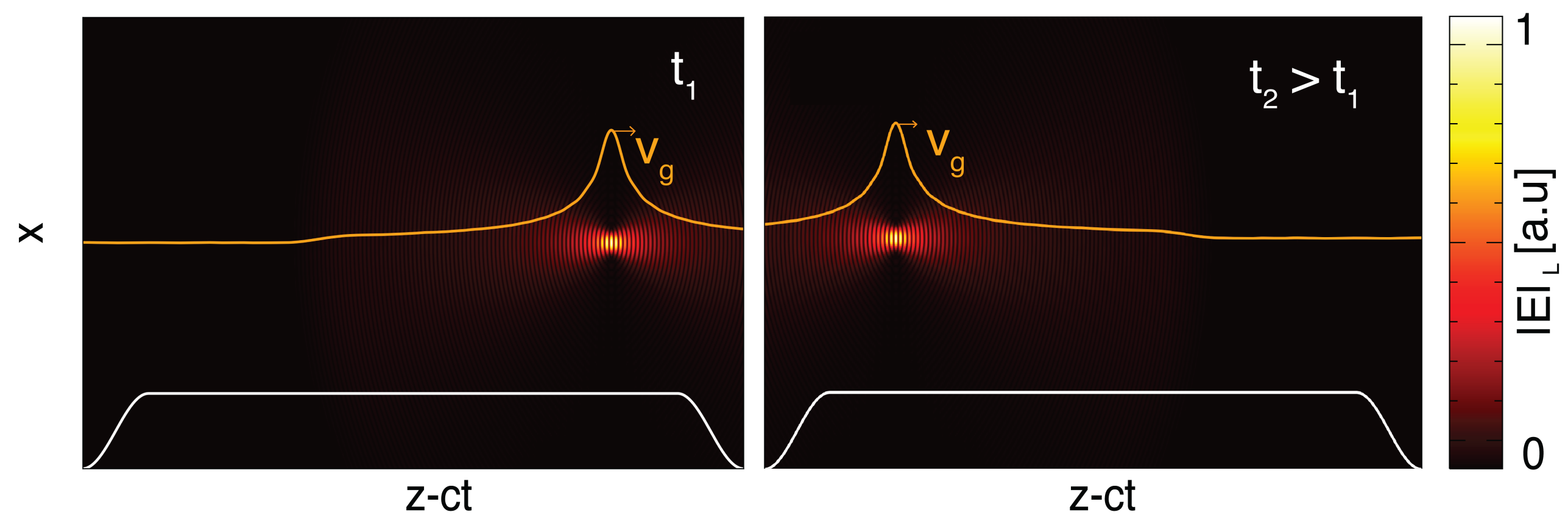
The first step toward a plasma-based acceleration method suitable for particles with non-relativistic velocities is, for example, trying to have **subluminal driver** ($v_g < \mathrm{c}$).

We use **optical pulses** whose intensity peaks move **slower than c**, allowing them to remain in sync with subrelativistic particles. Such **subluminal pulses** emerge when we constrain the pulse's frequencies ω and k_z (z is propagation direction) to lie at the intersection of the light cone with a tilted plane [5]:

$$\omega = \omega_0 + \left(k_z - \frac{\omega_0}{c}\right) v_g$$

This allows us to have pulses propagating with a group velocity $v_g \neq c$:

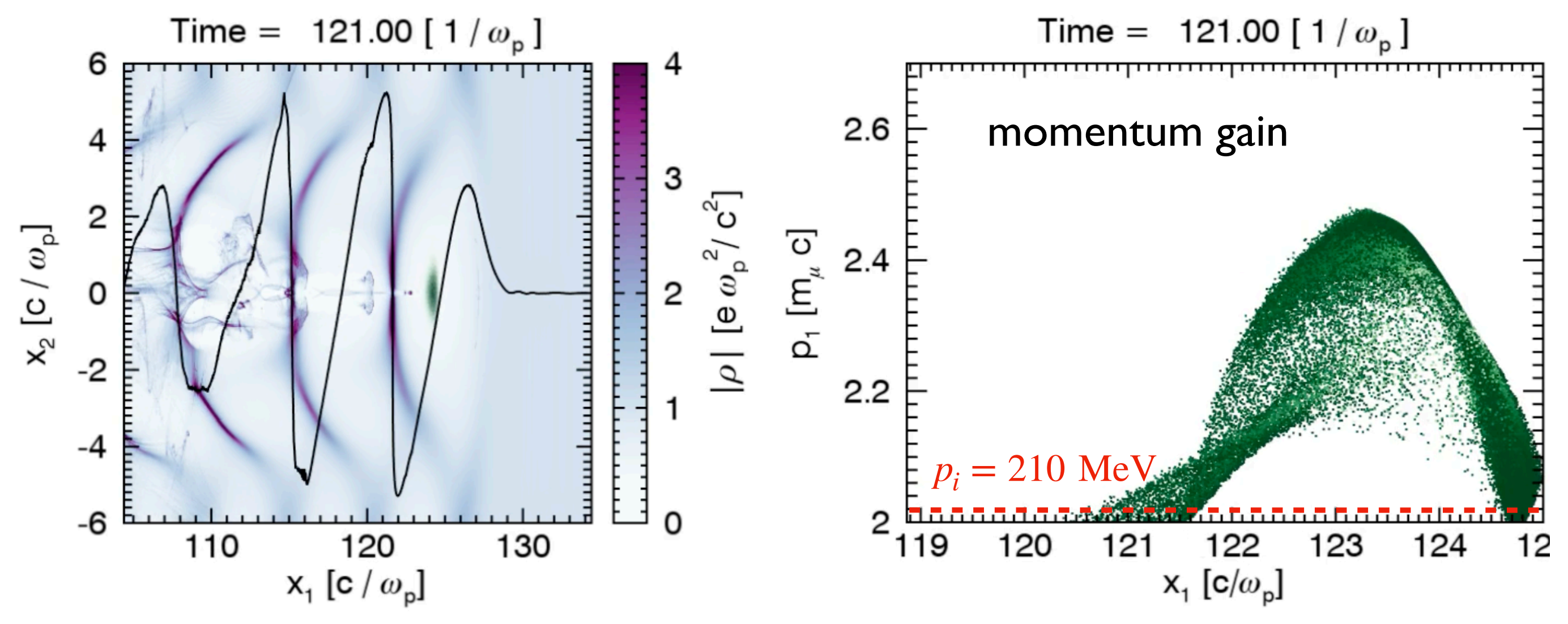
$$\frac{\partial\omega}{\partial k} = v_g$$



These laser's envelope (white) travels at c, but the **intensity peak** (orange) remains at a fixed velocity $v_g < c$.

Having a Subluminal Driver is not Enough: Dephasing

Is a subluminal driver enough to accelerate the muons to relativistic energies?
→ Let us consider a case with $v_d = 0.9c$ and $v_\mu^0 = 0.9c$



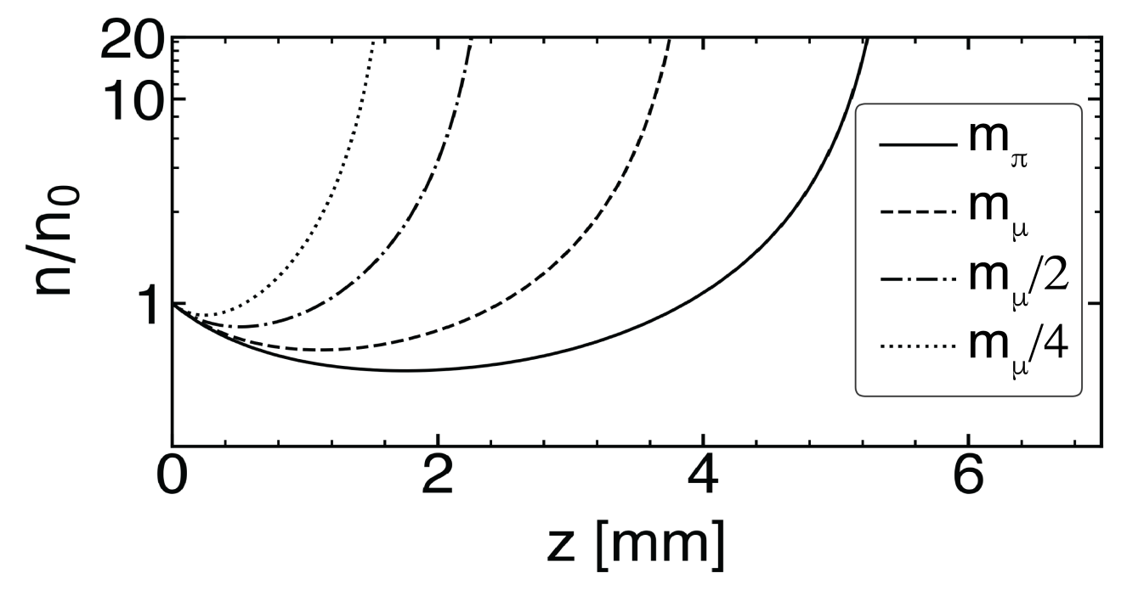
Quickly, the muons become faster than the wake, overtaking it and losing the good position to be accelerated (only up to 0.92c)!

A subluminal driver alone is insufficient for boosting subrelativistic beams to relativistic speeds, because **dephasing** quickly arises when particles overtake the wake.

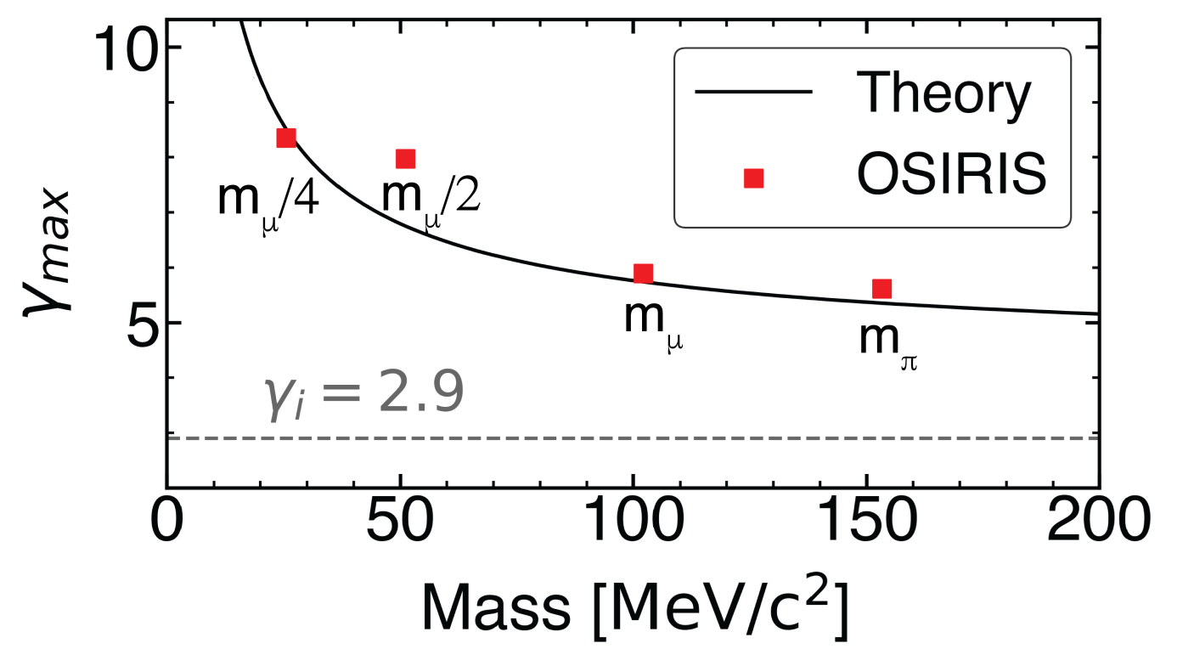
Varying the Plasma Density Allows Wake Speed Control

To **lock** subrelativistic beams into the accelerating phase, we **tailor** the plasma density so the wake's accelerating region continuously matches the beam velocity. In our approach, this condition emerges from the coupled system:

$$\begin{cases} v_w(t) = v_g - n_w \dfrac{d\lambda_p(x(t))}{dt} \\ \dfrac{dv(z)\gamma(z)}{dz} = \dfrac{e\alpha_0 c^2}{mv_g}\sqrt{\dfrac{n(z)}{n_0}} \end{cases}$$



With $v(z)$ and $\gamma(z)$ being the velocity and Lorentz factor of the beam and $n(z)$ the local plasma density. Solving for $n(z)$ gives us the ideal density profile to sustain longer phase-locking.

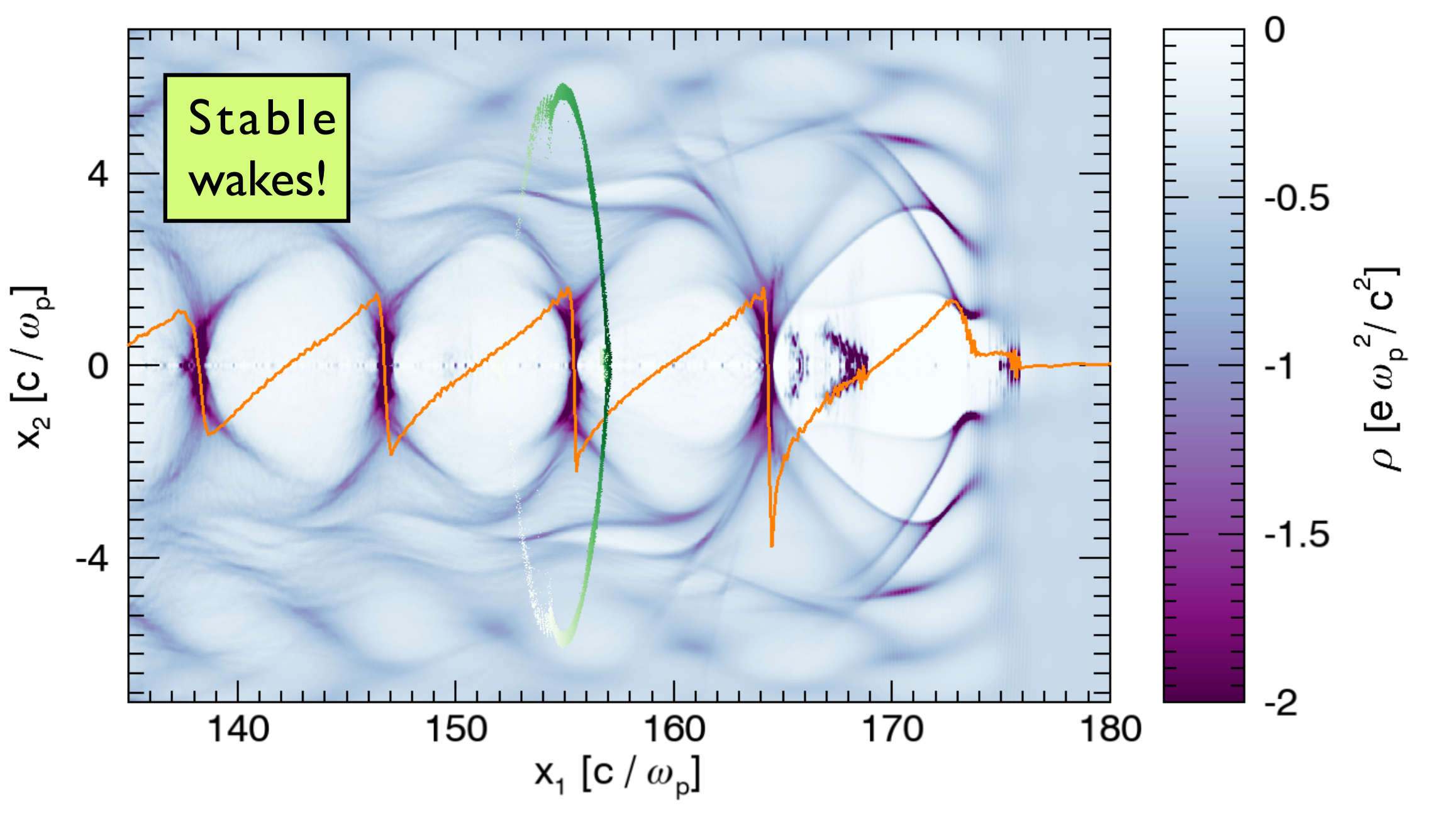


In quasi-3D OSIRIS [6] simulations we verified how muons and pions and artificially scaled masses beams with an initial velocity of $0.94c$ were brought to relativistic velocities using a subluminal driver ($v_g = 0.96c$) **combined** with a tailored density profile.

The maximum energy gain γ_{max} is in agreement with the theory.

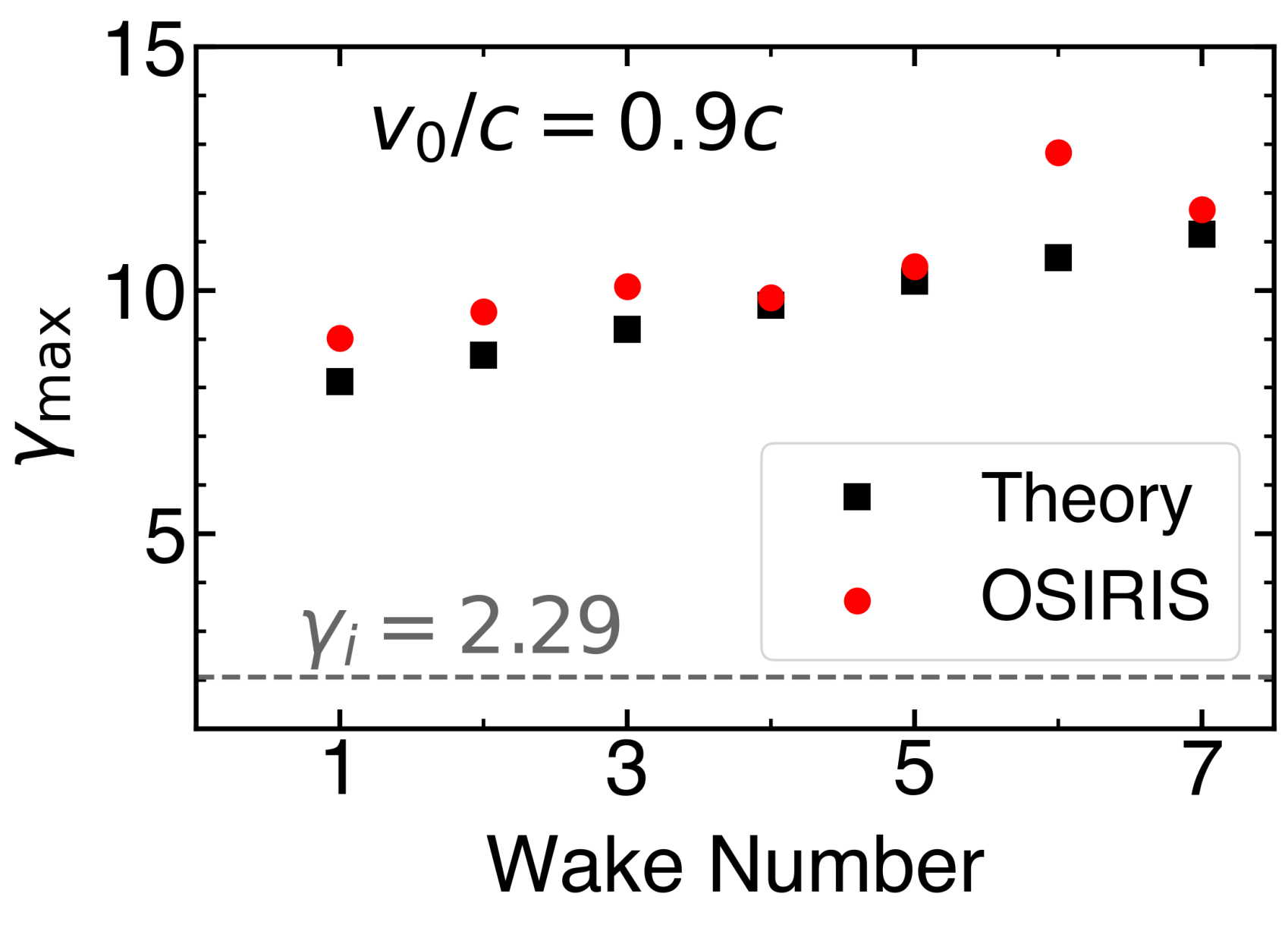
Simulations Results: Adaptability of our Theoretical Model

Quasi-3D simulations of the acceleration method proposed have been performed using OSIRIS [6] for different initial conditions.



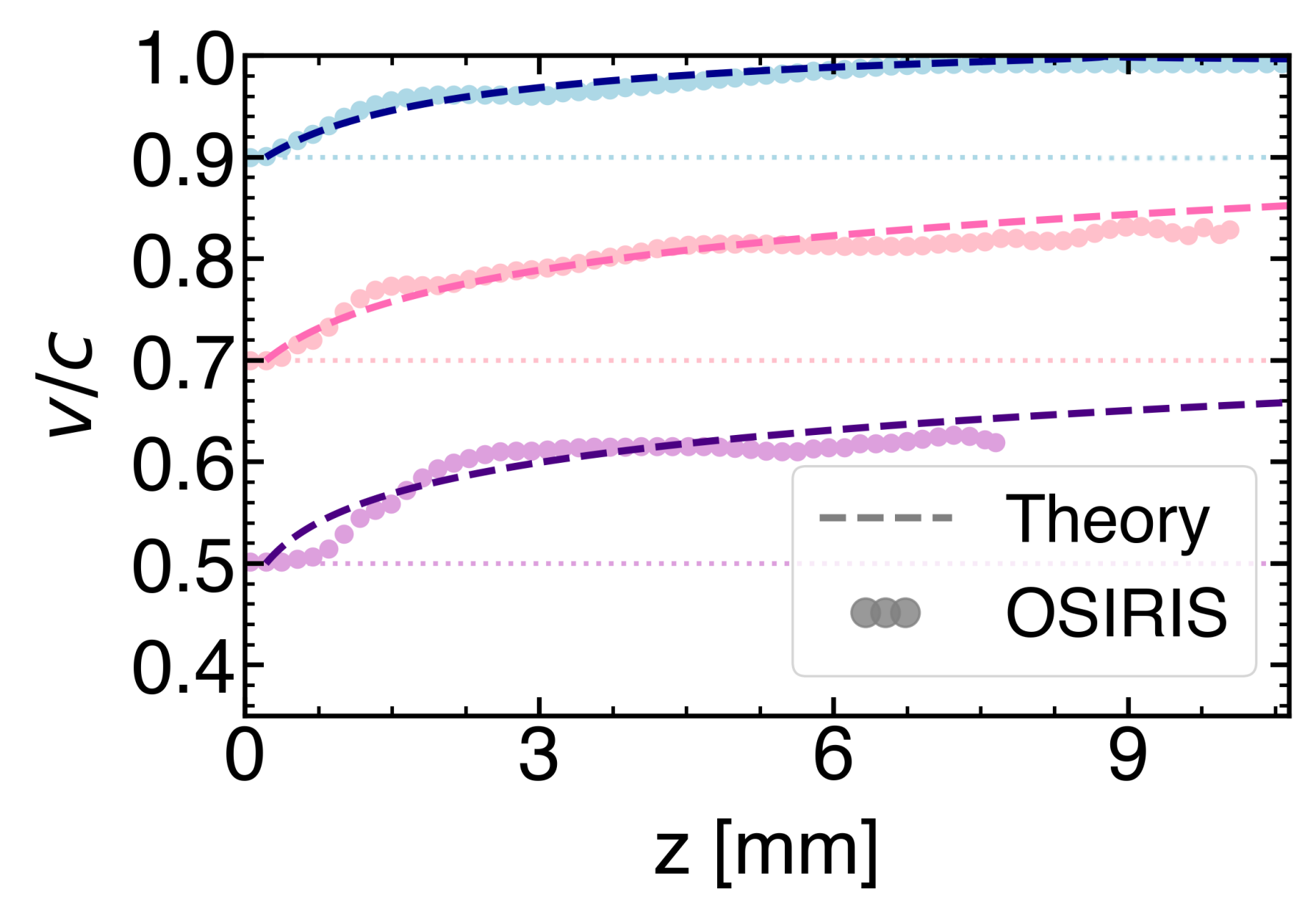
Example of wakefield structure formed using a driver with $v_d = 0.96c, a_0 = 3$ and $\omega_0 = 20$

Figure 1: Acceleration process illustration from the simulation of muons acceleration. The plasma density is in scale of blue to purple and the particles' density in scale of greens. The longitudinal electric field line out is in orange.



✓Good agreement between theory and simulations for different accelerating wakes.

Figure 2: Maximum energy γ_{max} reached by a $m_\mu/4$ beam initially at $0.9c$, accelerated in different wakes by a driver at $0.97c$.



✓The theory holds for different initial velocities of the accelerated particles.

Figure 3: Maximum velocity evolution v/c of three $m_\mu/4$ beams starting at $v/c = 0.5c$, $0.7c$, and $0.9c$. Each acceleration is driven with group velocities of $0.8c$, $0.7c$ and $0.9c$ respectively.

Conclusions and Future Work

- ⋆ Short-lived particles can not be accelerated with conventional accelerating techniques efficiently.
- ⋆ To fill this gap, we propose the possibility of accelerating non-relativistic particles using optical wave packets with a group velocity smaller than the speed of light in combination with a tailored density profile.
- ⋆ The acceleration proposed succeeded in bringing the muons and pions to relativistic velocities in one acceleration stage.
- ⋆ The theoretical model proposed proved to be robust over variations of the initial particle's mass, the acceleration wake used and the initial velocity of the particles.
- ⋆ The method presented extends naturally to heavier hadrons (e.g., kaons, protons) by adjusting the same procedure.

References

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