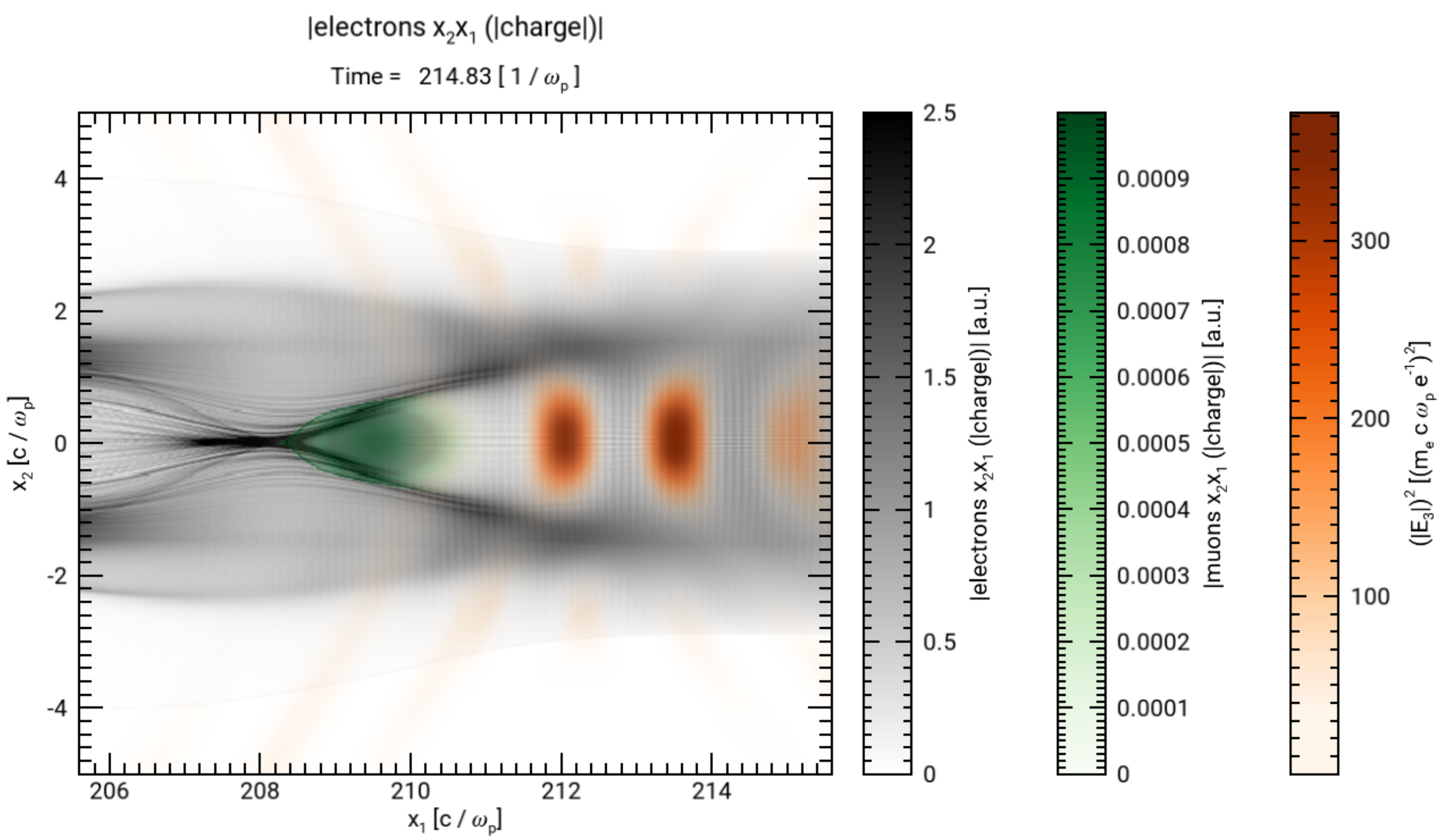
Muon acceleration in plasma-based accelerators

Chiara Badiali

Jorge Vieira et al.

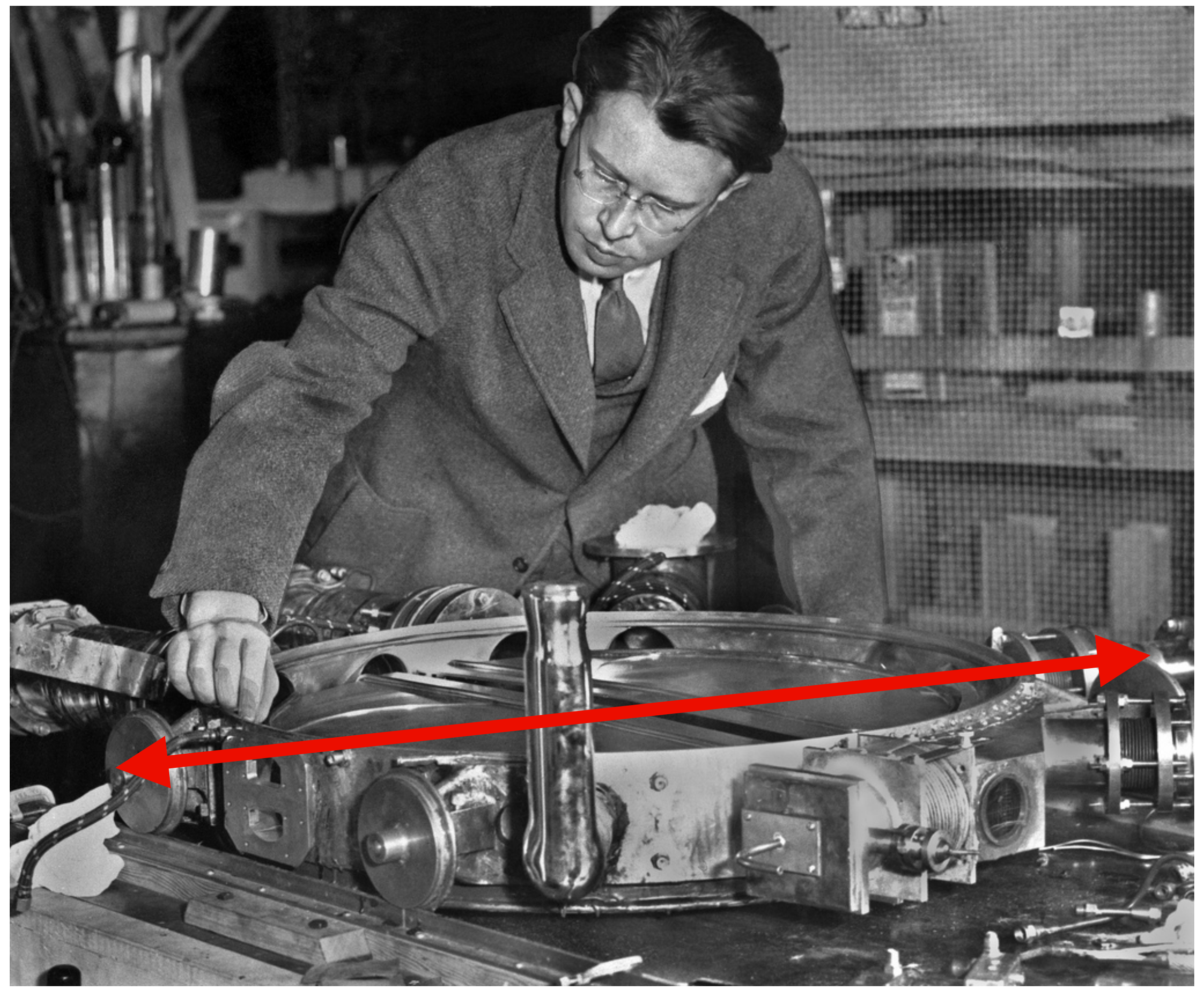
[1] GoLP / Instituto de Plasmas e Fusão Nuclear
Instituto Superior Técnico, Lisbon, Portugal

epp.tecnico.ulisboa.pt || **golp**.tecnico.ulisboa.pt



Historical evolution of particle accelerators

Do we want to continue to go for bigger and bigger accelerators?

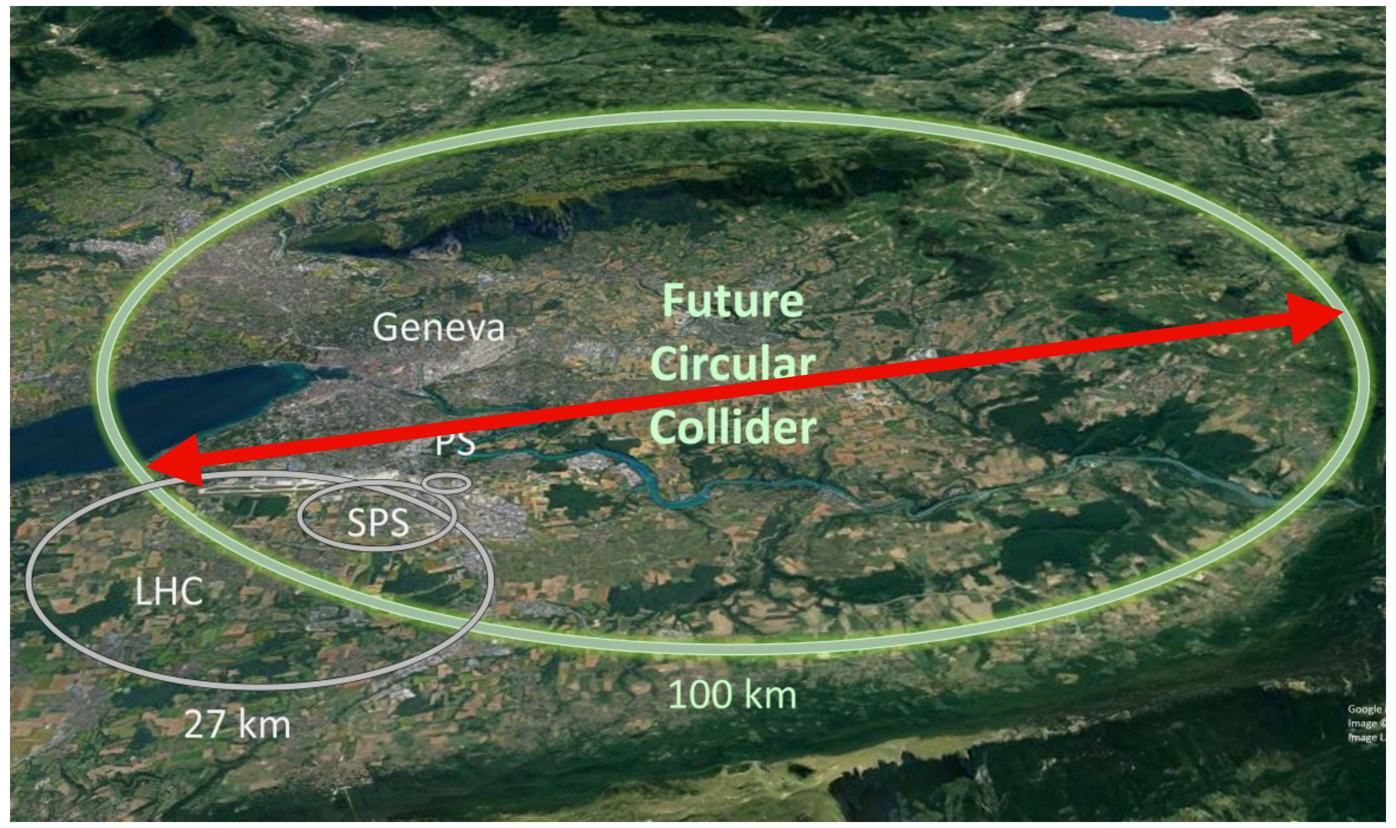


~ 1.5 m

Ernest Lawrence  with the first circular accelerator, the **cyclotron**

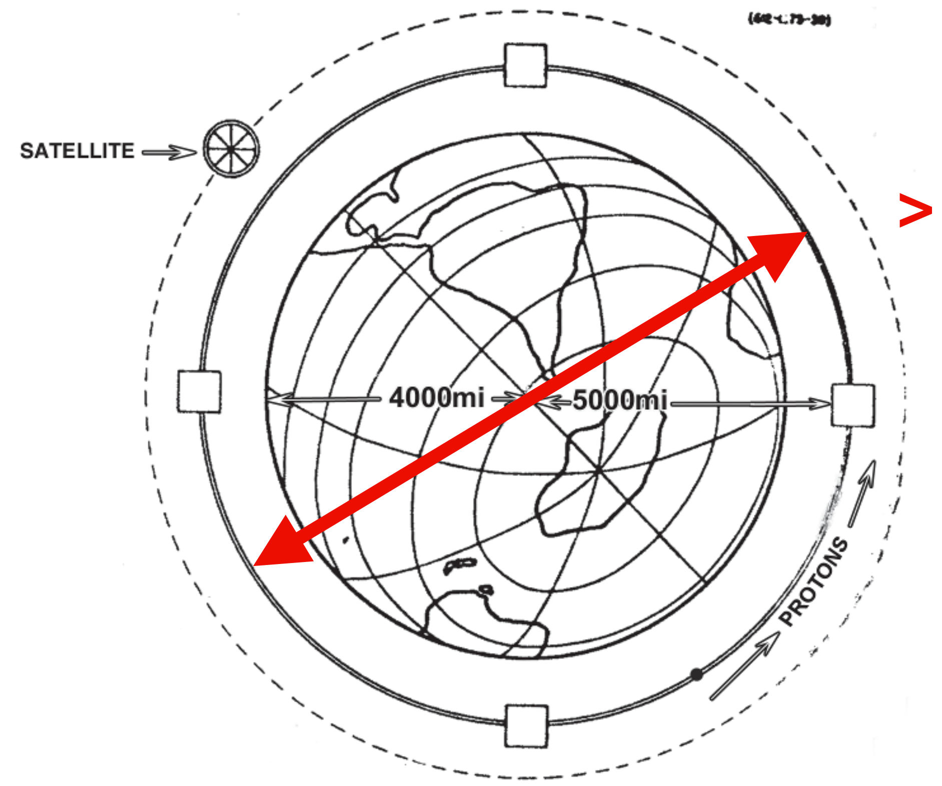
~ 8.6 km

LHC, currently the most powerful particle accelerator in the world (13 TeV)



~ 32 km

FCC: 100 TeV of expected energy for hadrons



>12.742 km

Fermi's idea of a circular collider around the world

Historical evolution of particle accelerators

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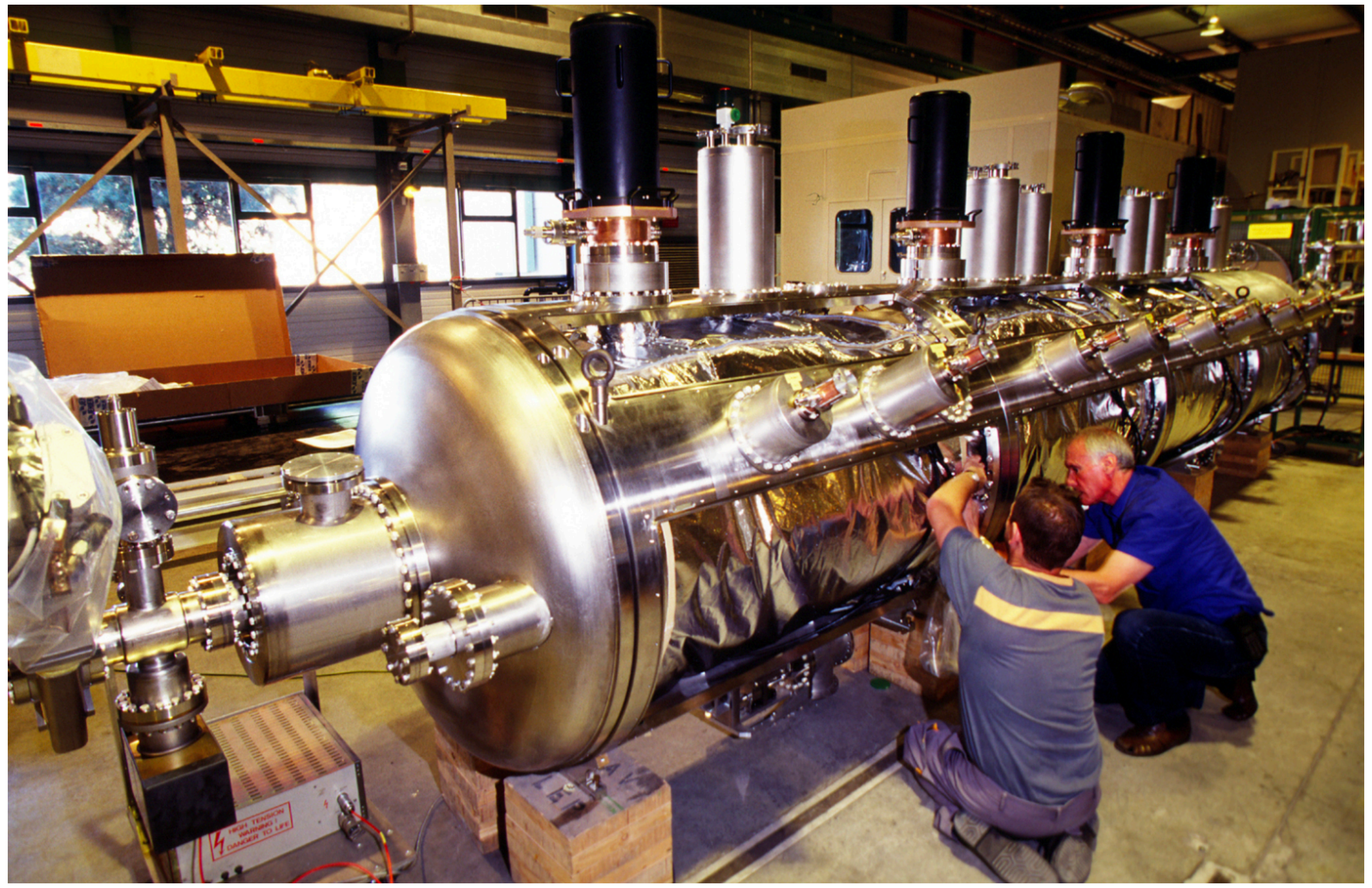
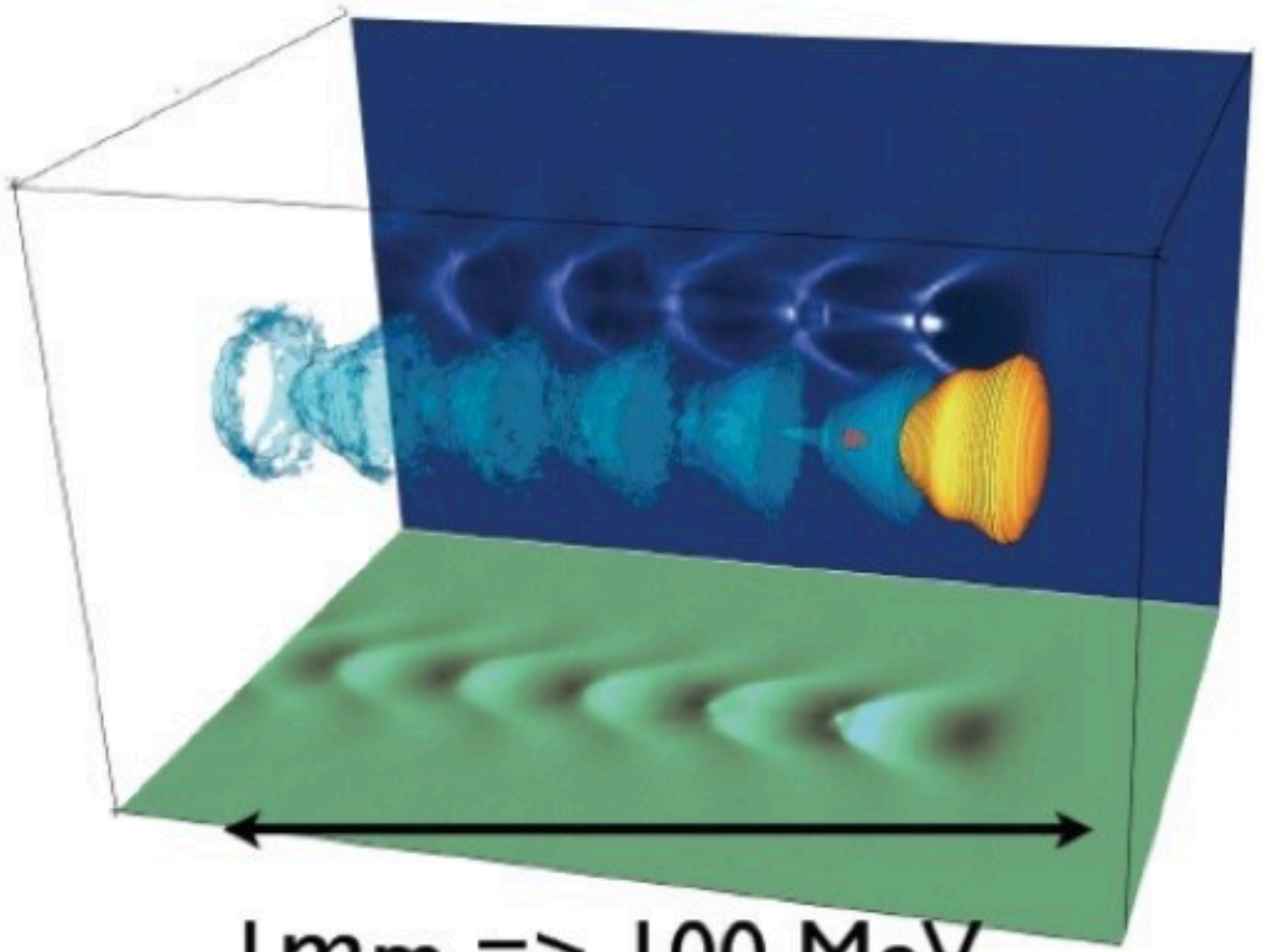
Conventional accelerators



Electric field < 100 MV/m

Limitation set by the **material breakdown**

Plasma accelerators



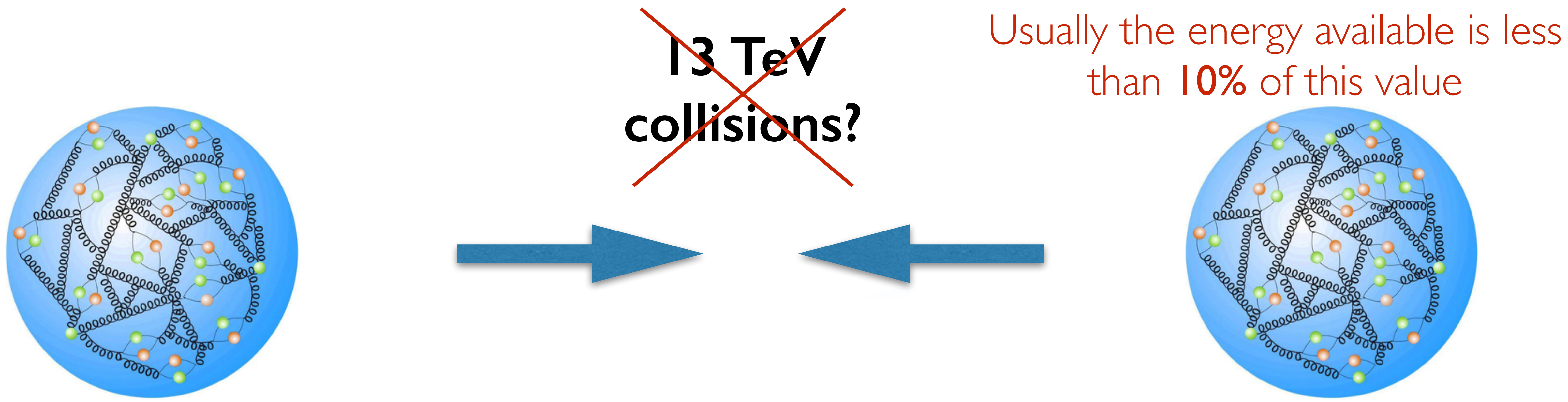
Electric field > 100 GV/m

Plasmas, unlike any other medium are **naturally broken** → able to achieve **ultra-high gradient acceleration.**

V. Malka, Proceedings, CAS - CERN Accelerator School: Plasma Wake Acceleration , 1-28 (2016)

Why a muon collider?

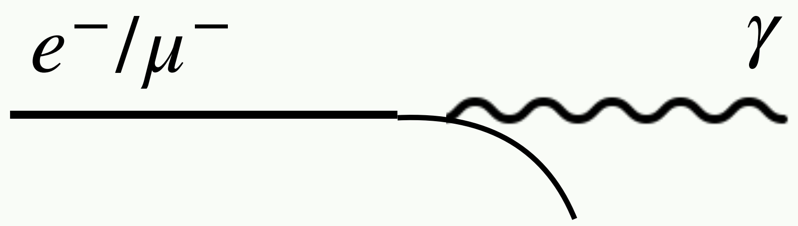
What are the best particles to collide?



Muons, like electrons, are **fundamental particles**, for this reason their full energy is available in collisions

→ a **14 TeV** muon collider with sufficient enough luminosity would provide similar discovery reach as a **100 TeV** proton-proton collider.

Furthermore, $m_\mu = 200\ m_e$ so that:



$$\frac{\Delta E_\mu}{\Delta E_e} = \left(\frac{m_e}{m_\mu}\right)^4 \sim 10^{-12}$$

Muons have a finite life-time ($2.2\ \mu$s) → We have to accelerate them quickly them before they decay, exploiting the time-life dilation in the lab reference frame given by the Lorentz boost ($\tau' = \gamma\tau$)
→ **advantage in using plasma based accelerators.**

K. R. Long et al., Nature Physics **17**, pages 289–292 (2021)

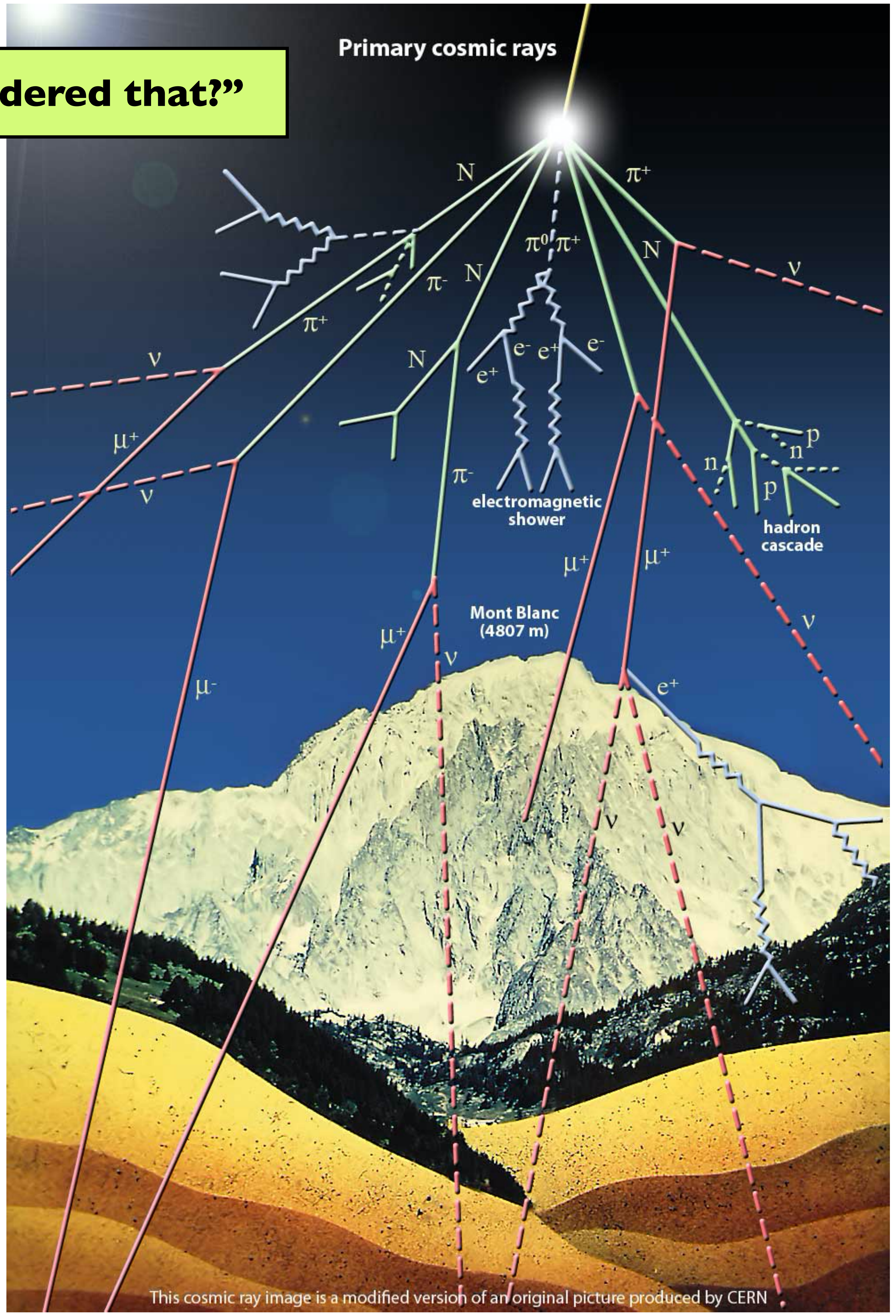
Muon production: proton beam against a dense target

GEANT4 A SIMULATION TOOLKIT

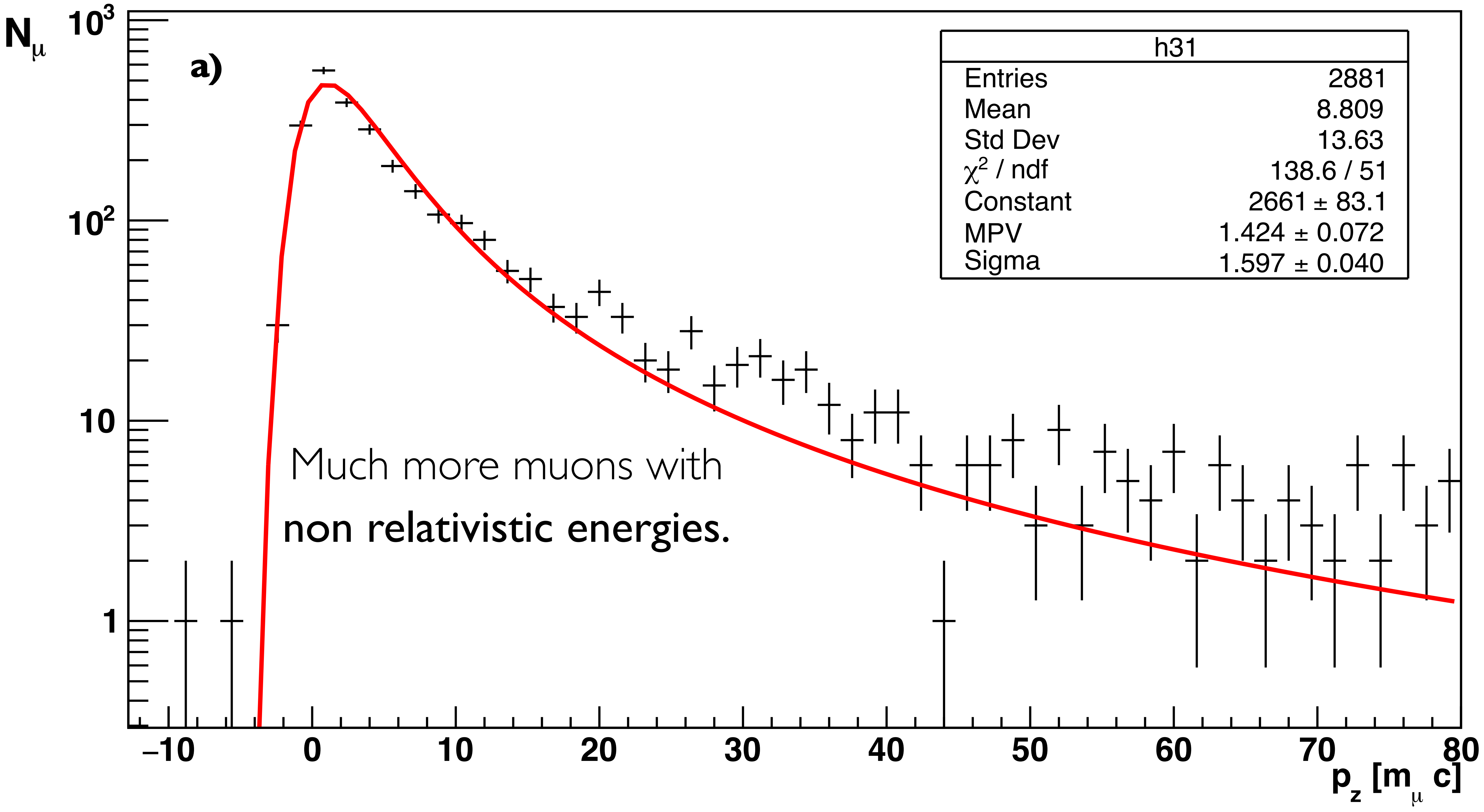
TÉCNICO LISBOA

μ^- production in the earth's atmosphere

"Who ordered that?"



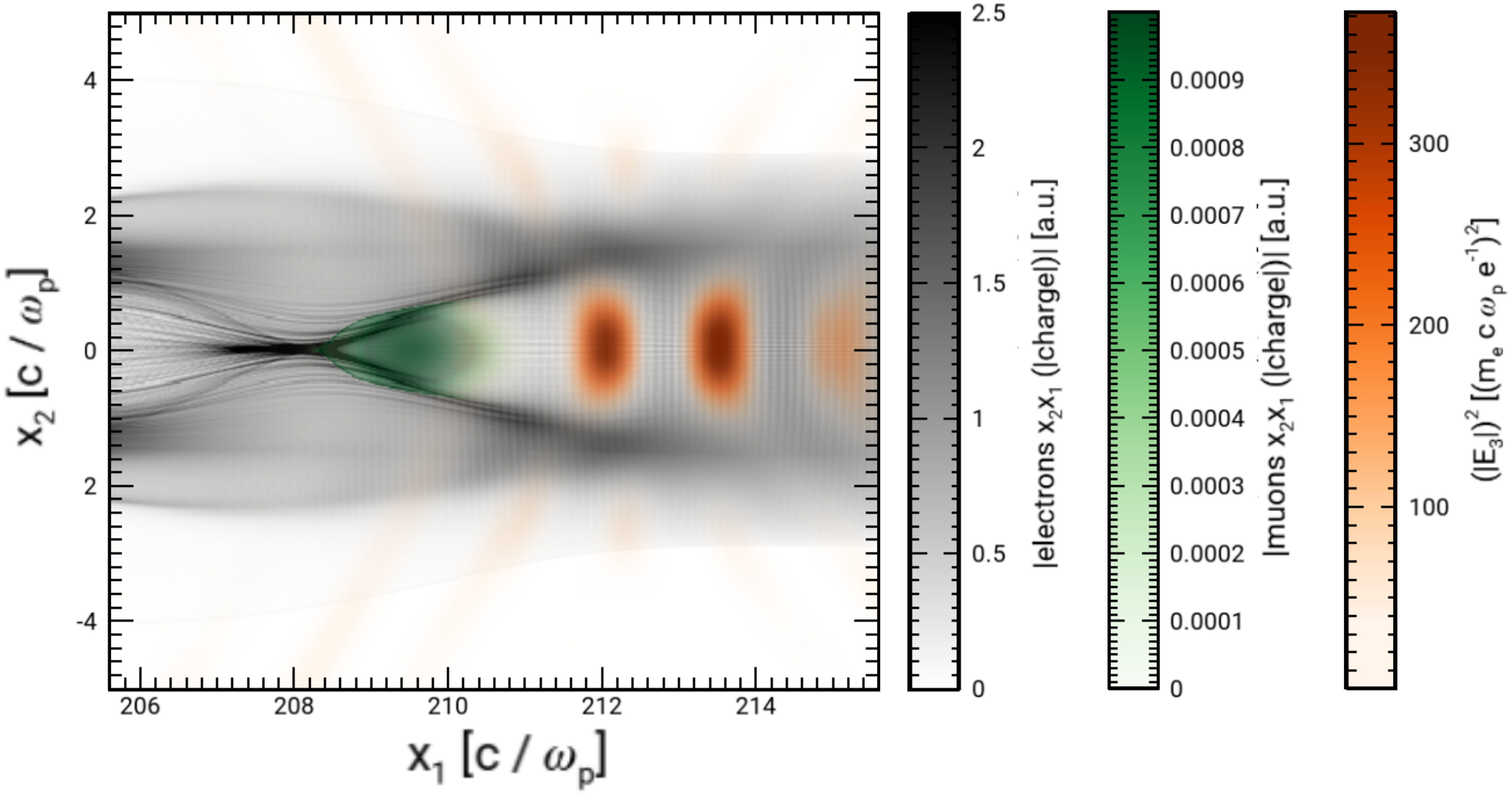
High energetic proton beam against a dense target



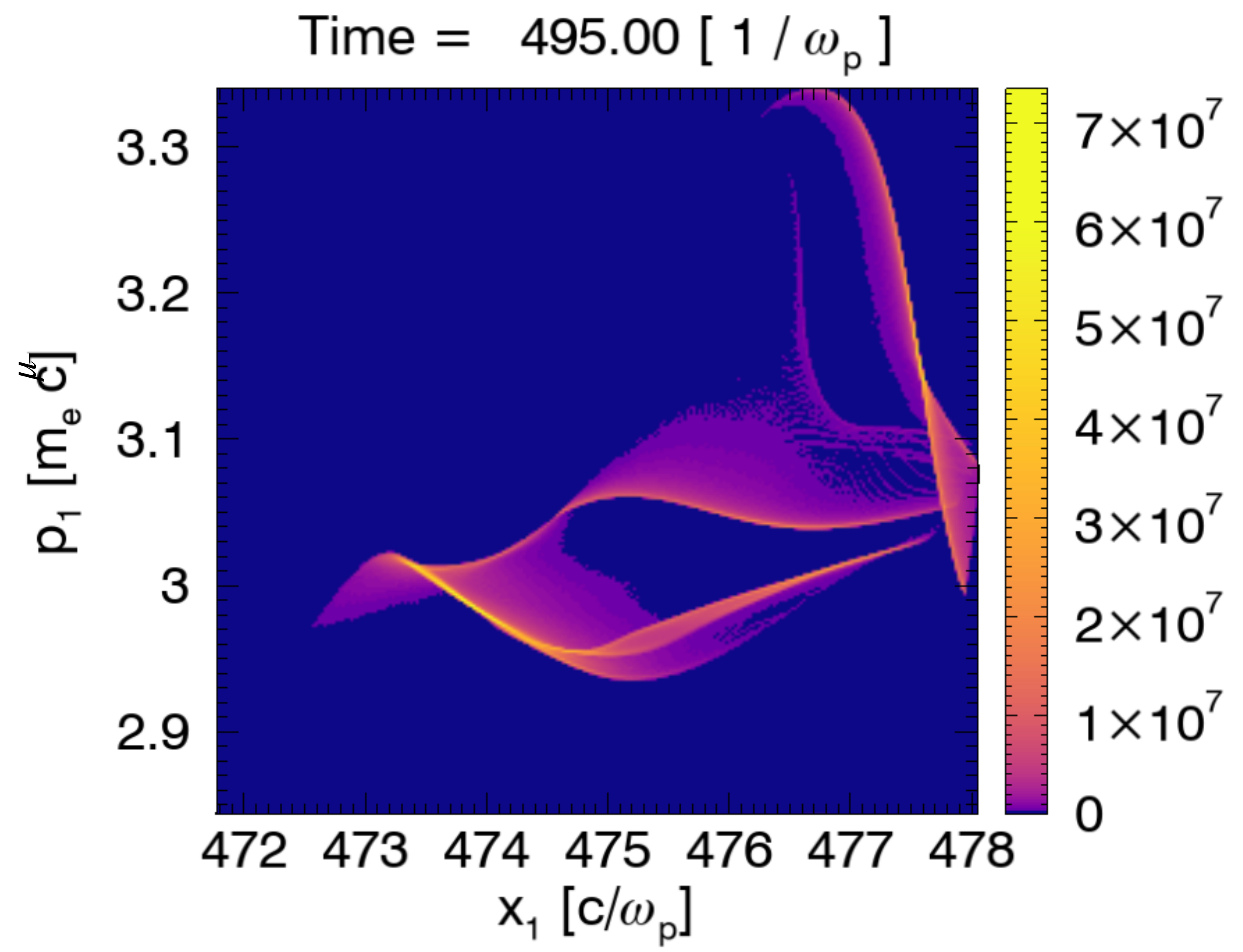
A **GEANT4*** simulation with a proton beam of $5 \cdot 10^6$ monoenergetic protons ($E_p = 450\ GeV$) was performed (in reality ~10^{12} protons).

* J.Allison et al., Nucl. Instrum. Meth.A 835 (2016) 186-225.

Current results in a nutshell



Increase up to the ~ 9.5 %
of their initial momentum



So, we were able to see already the muons being trapped and slightly accelerated, now we want to **improve the acceleration**!

Simulation results obtained with the **particle-in-cell code OSIRIS***

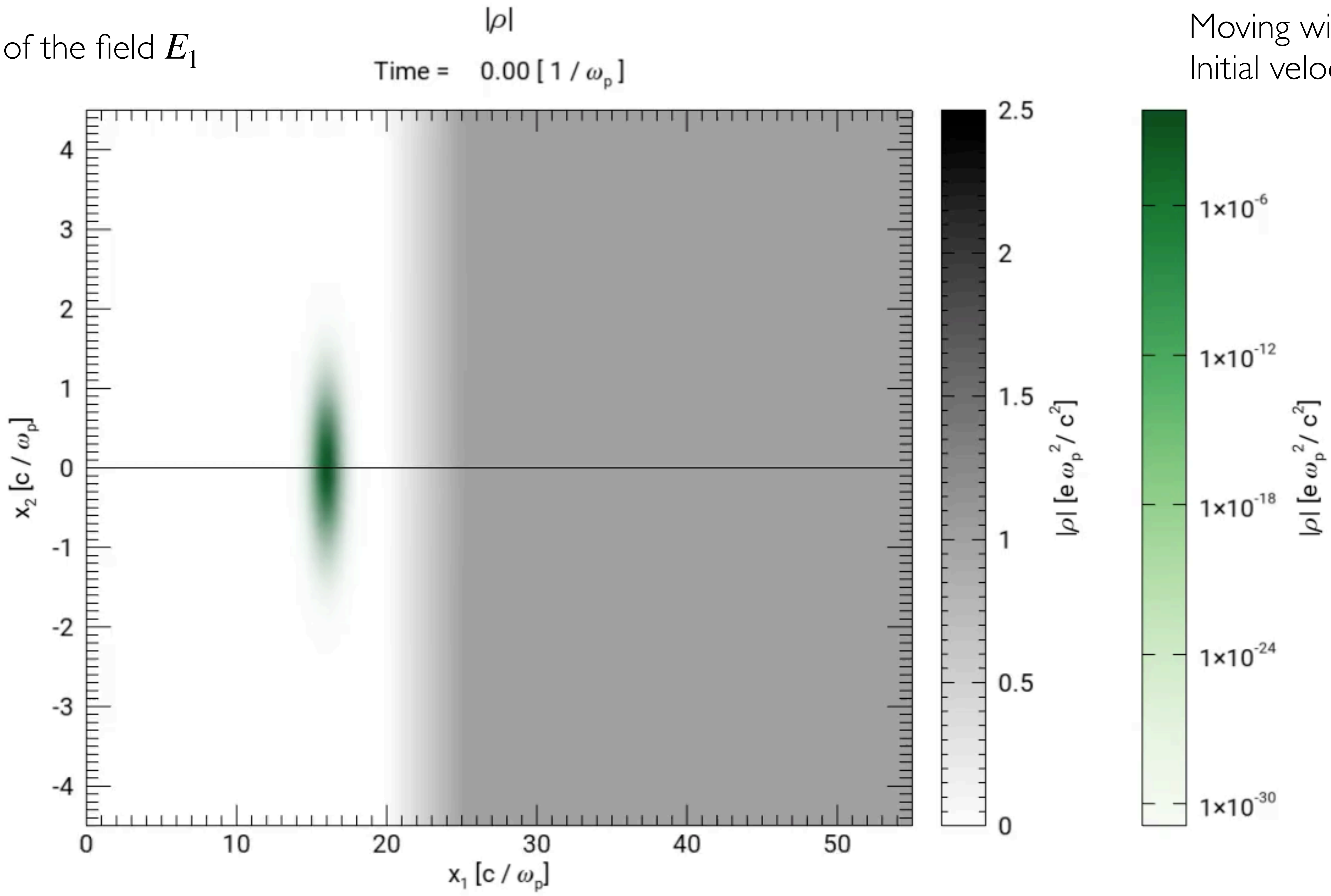
* R.A. Fonseca et al., Phys. Plasmas Control. Fusion 55, 124011 (2013).

BACK UP SLIDES

Testing of the analytical model in 2D using OSIRIS

In black, the line out of the field E_1

Moving window at **0.95c**
Initial velocity of the muons of **0.9c**



Optical space-time wave packets with arbitrary group velocities

The group velocity of an optical pulse can usually be modified in the propagation in a material.

In free space, we can sculpt optical pulses with a modulation of the spatial and temporal degrees of freedom.

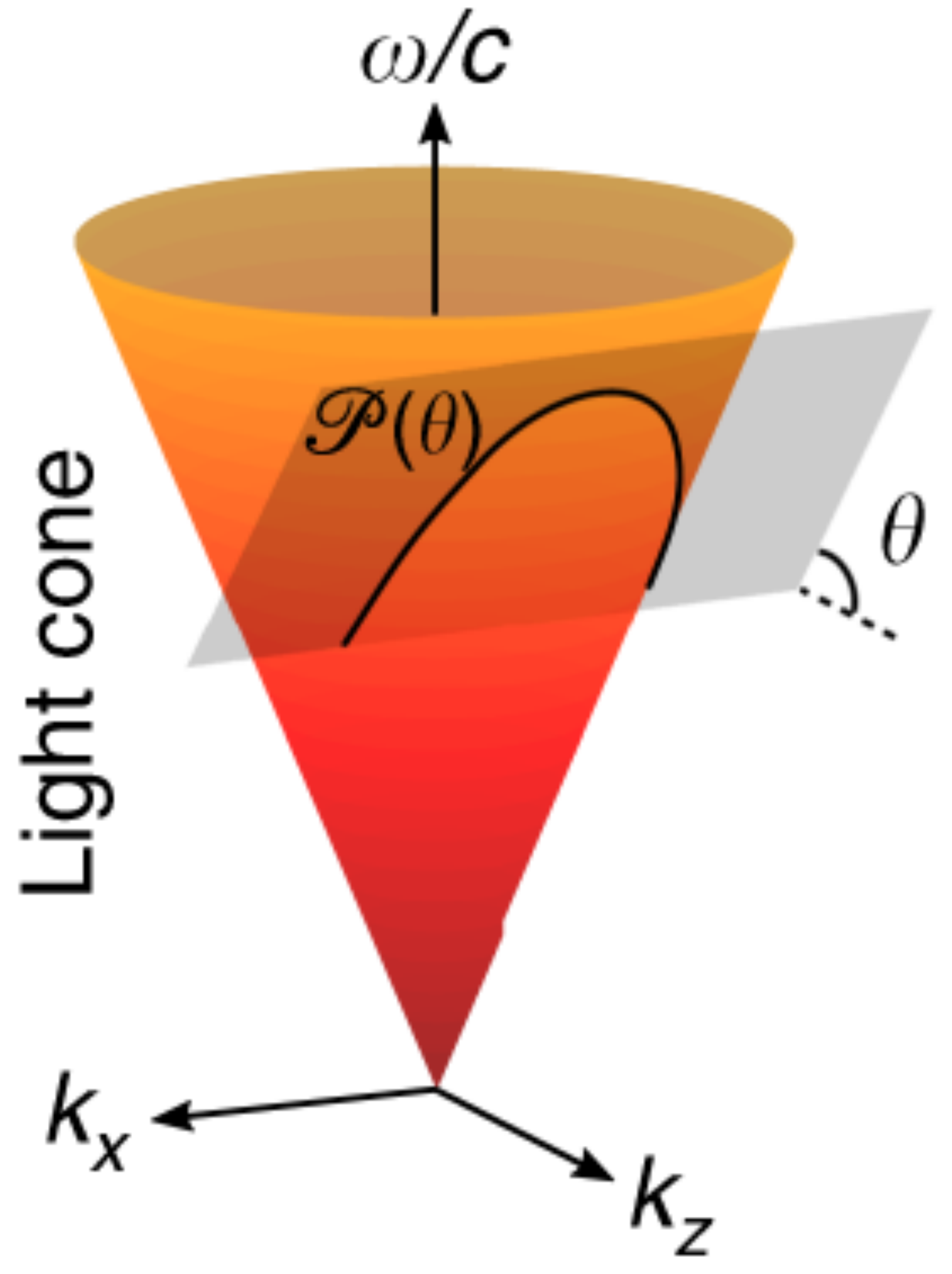
Spatio-temporal wave packets: each spatial frequency is uniquely associated with a specific temporal frequency (or wavelength)

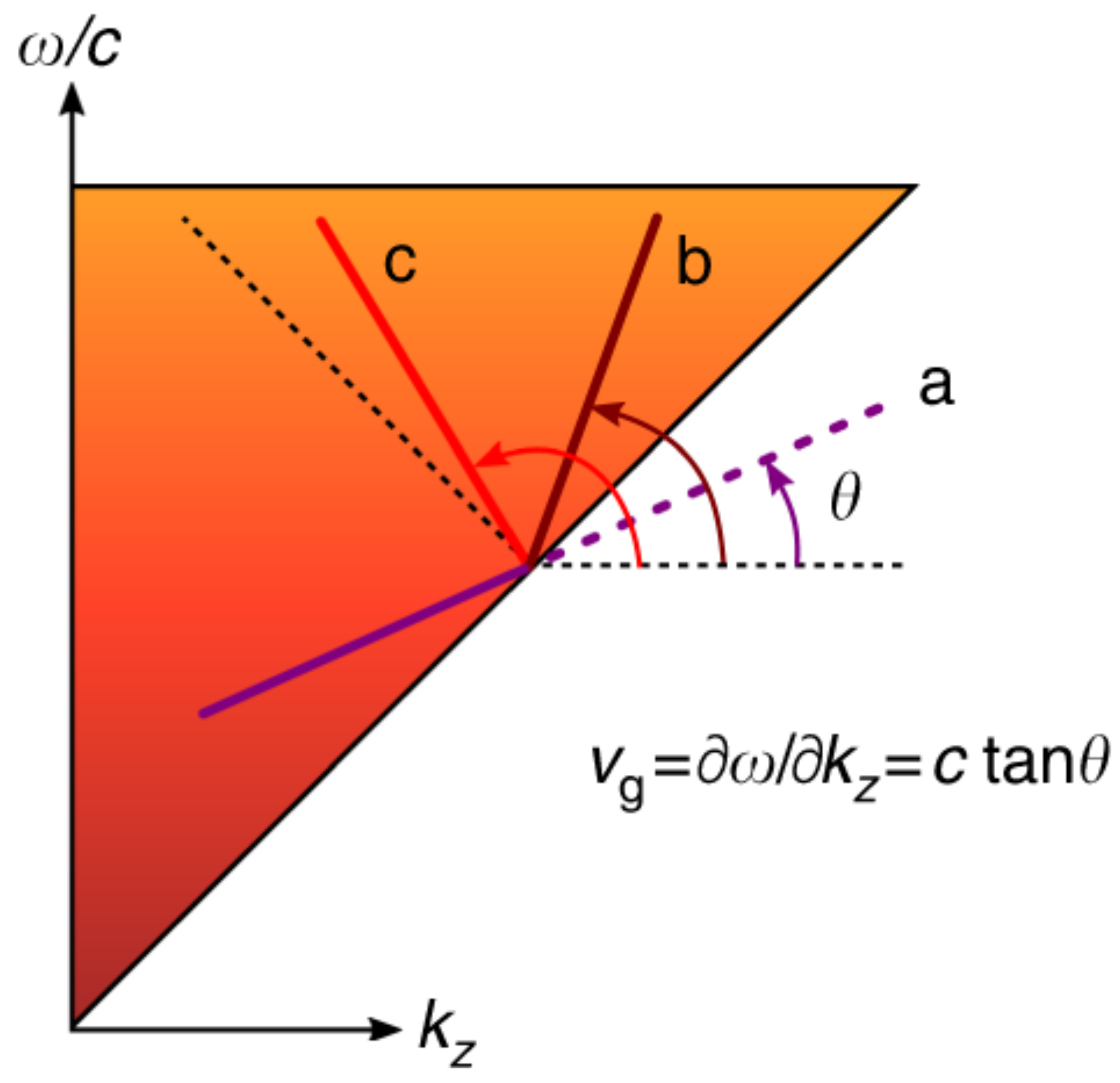
Light cone

$$k_x^2 + k_z^2 = (\omega/c)^2$$

Hyperplane

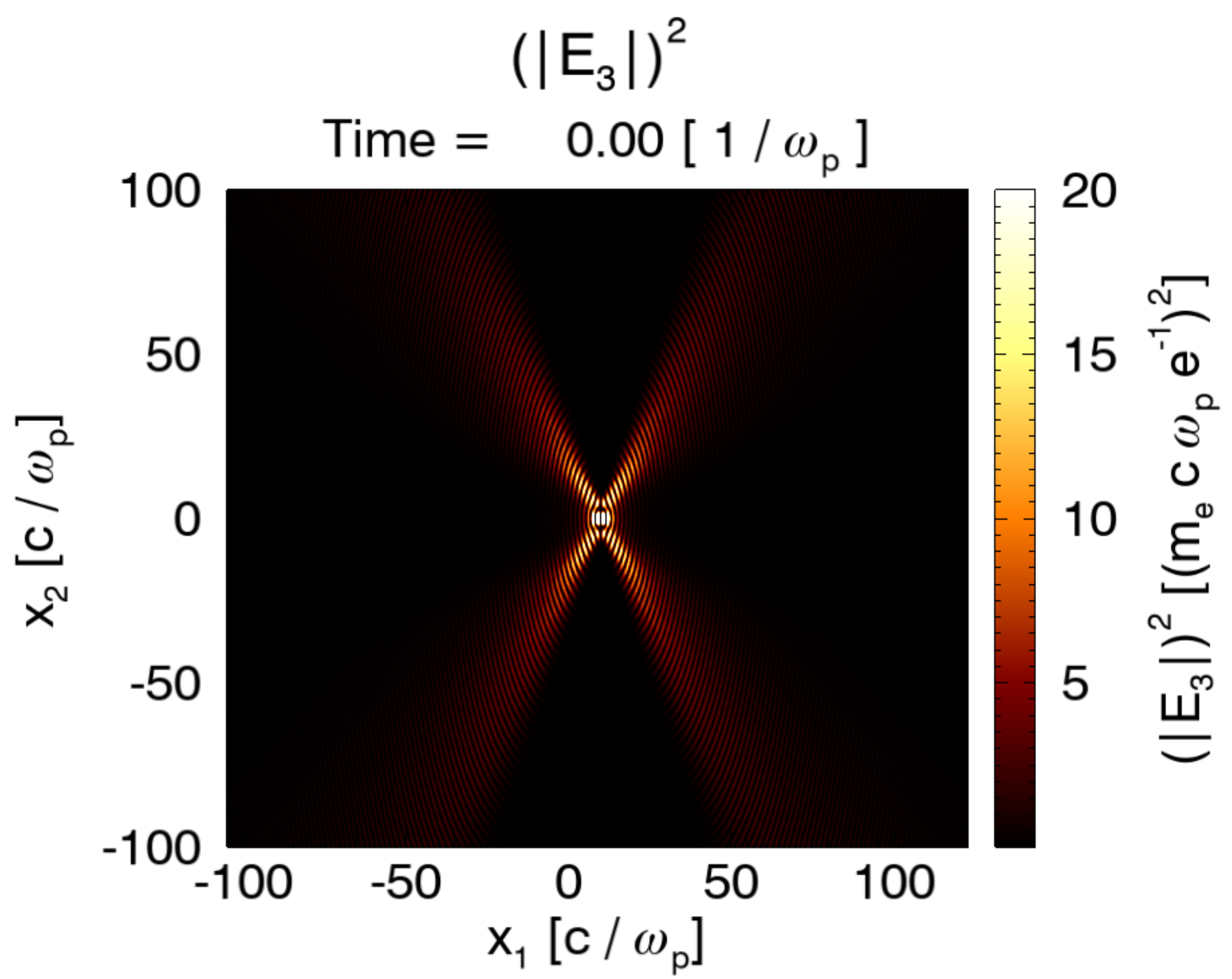
$$\omega/c = k_0 + (k_z - k_0)\tan\theta$$

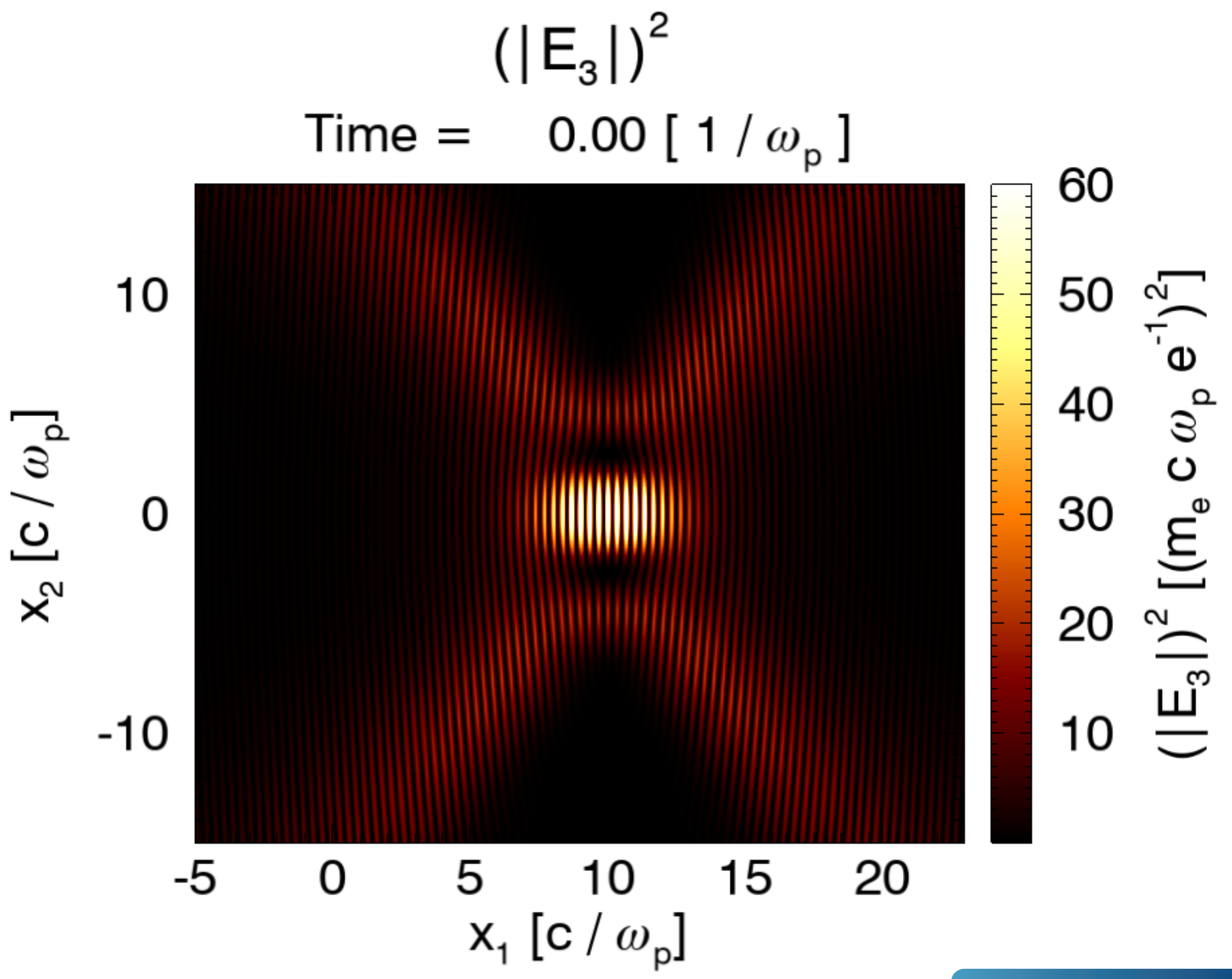




Kondakci, H. Esat; Abouraddy, Ayman F., Nature Communications, **10**, Article number: 929 (2019) https://doi.org/10.1038/s41467-019-08735-8

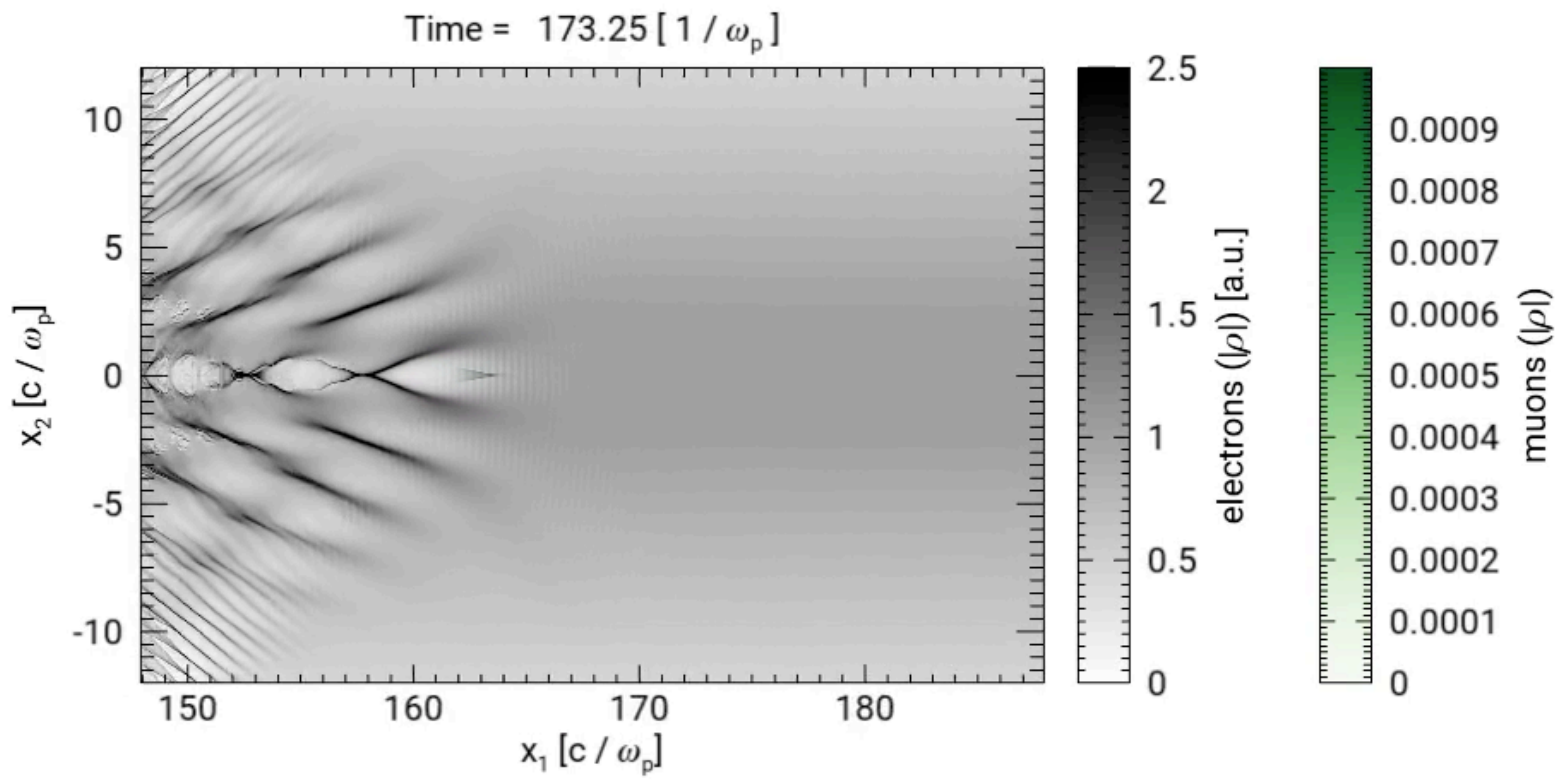
OSIRIS 2D simulations of subluminal space-time wake packets*



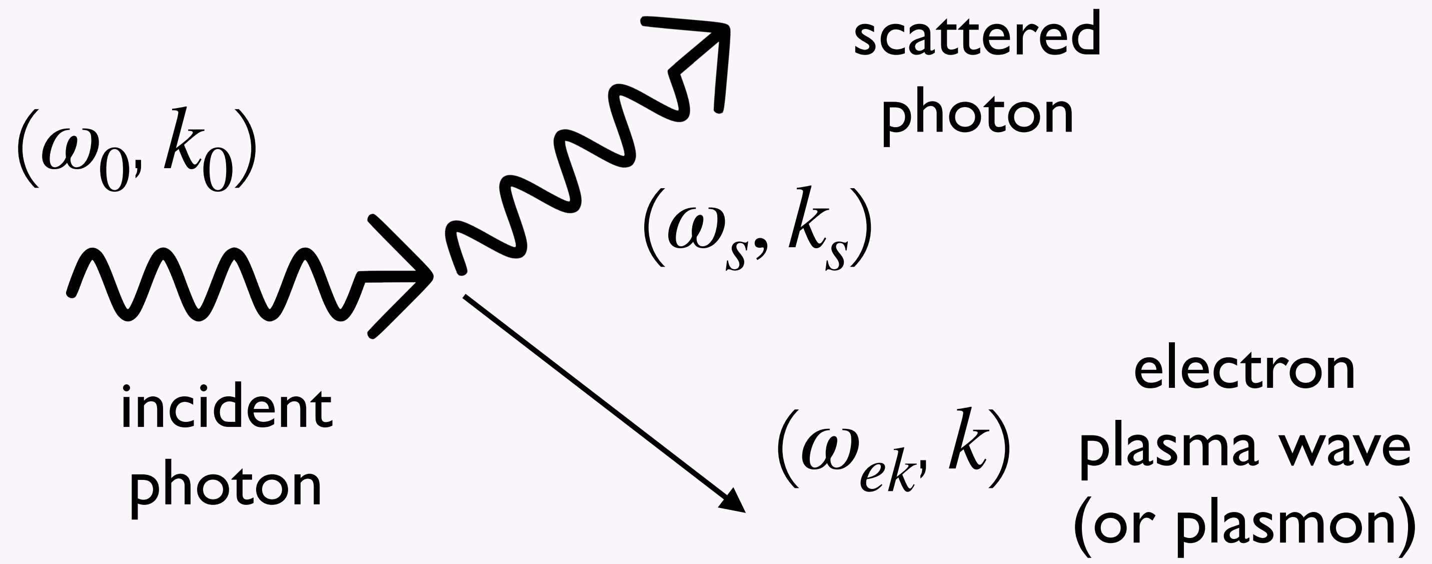


*B. Malaca et al., in preparation

Instabilities in the propagation of the pulses in a larger plasma



The Raman scattering can be characterised as the **resonant decay:**



Where, for energy conservation reasons:

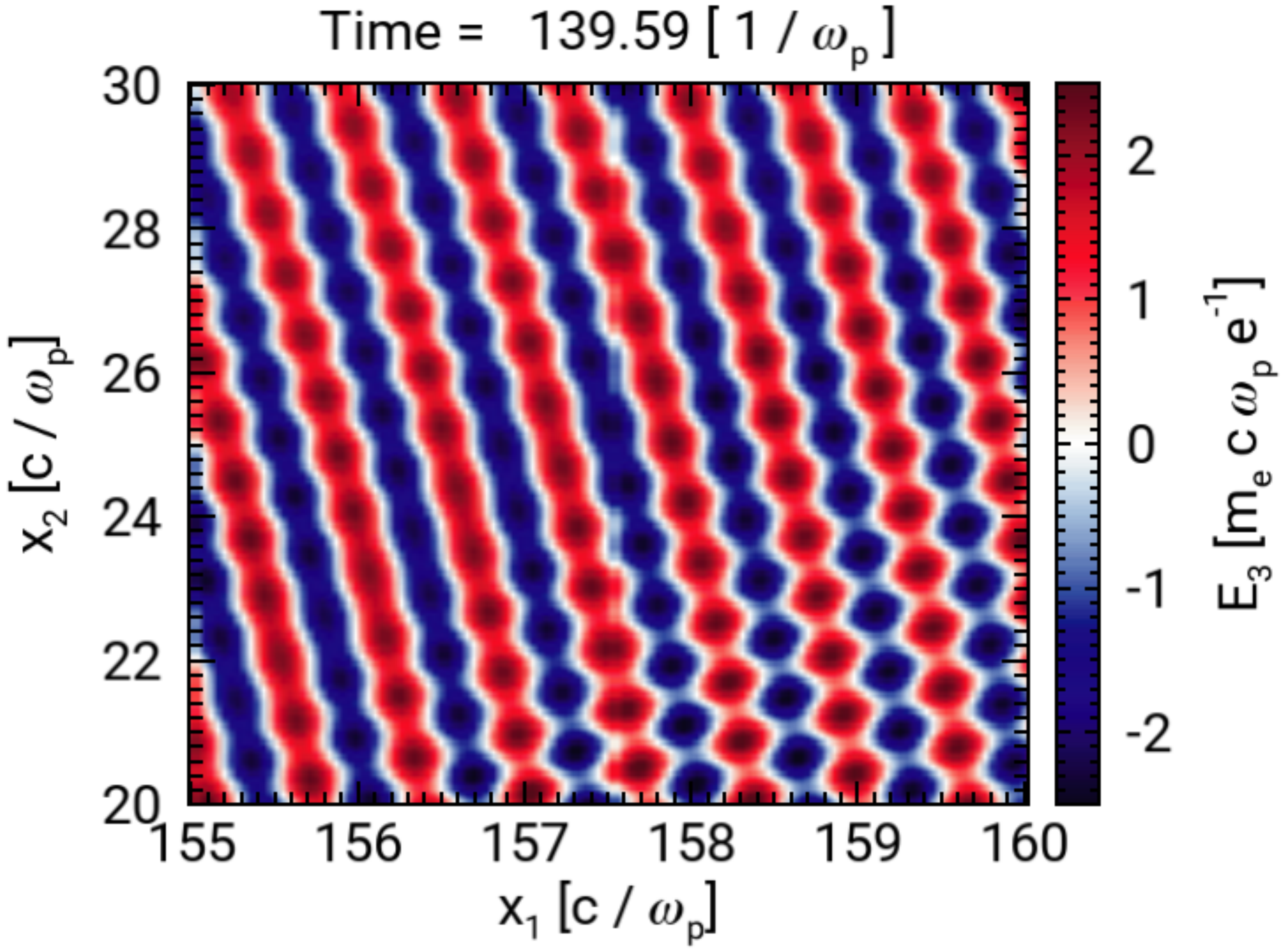
(1) $$\omega_0 = \omega_s + \omega_{ek}$$
$$\vec{k}_0 = \vec{k}_s + \vec{k}$$

$\omega_0 \gtrsim 2\omega_{pe}$
$(n \lesssim n_{cr}/4)$

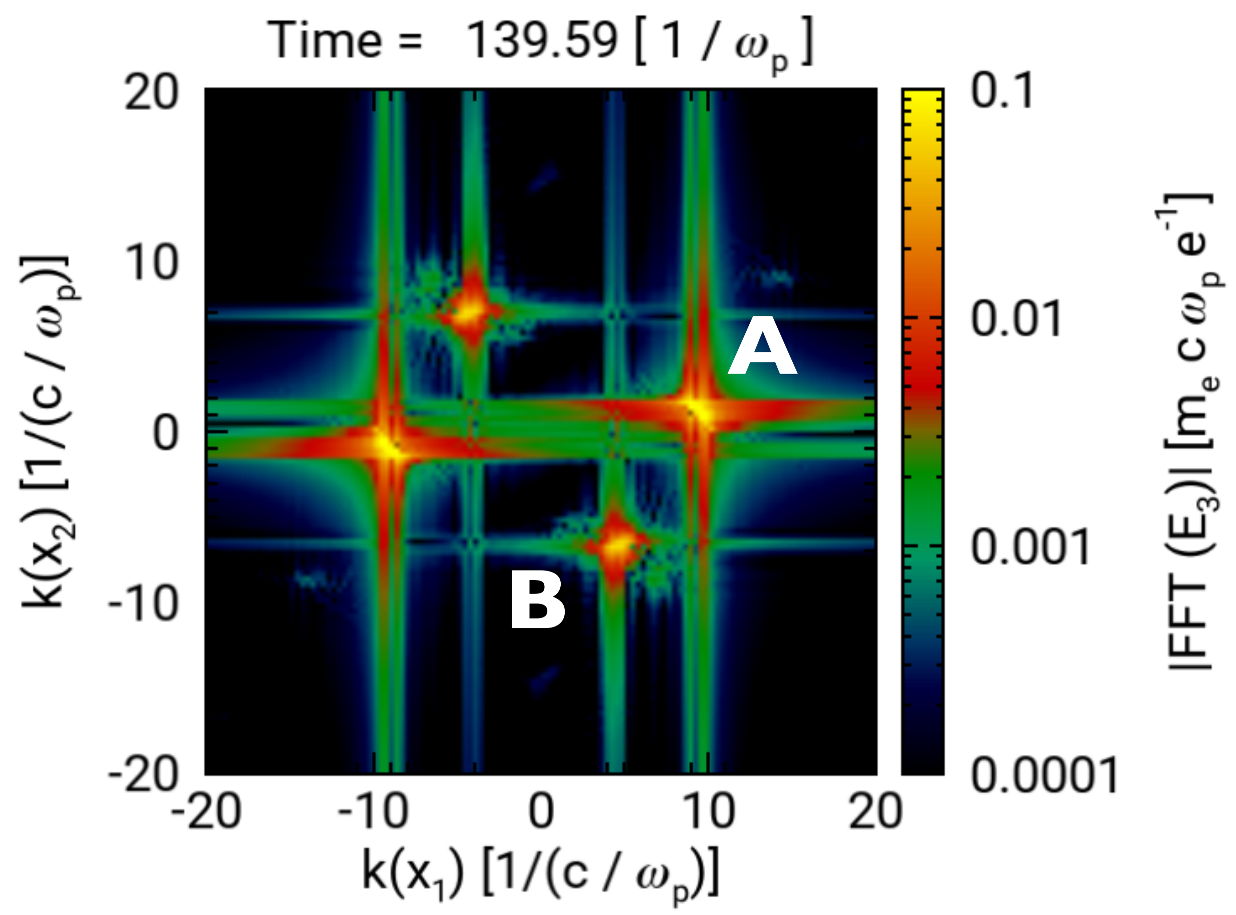
Could this be associated with Raman scattering?

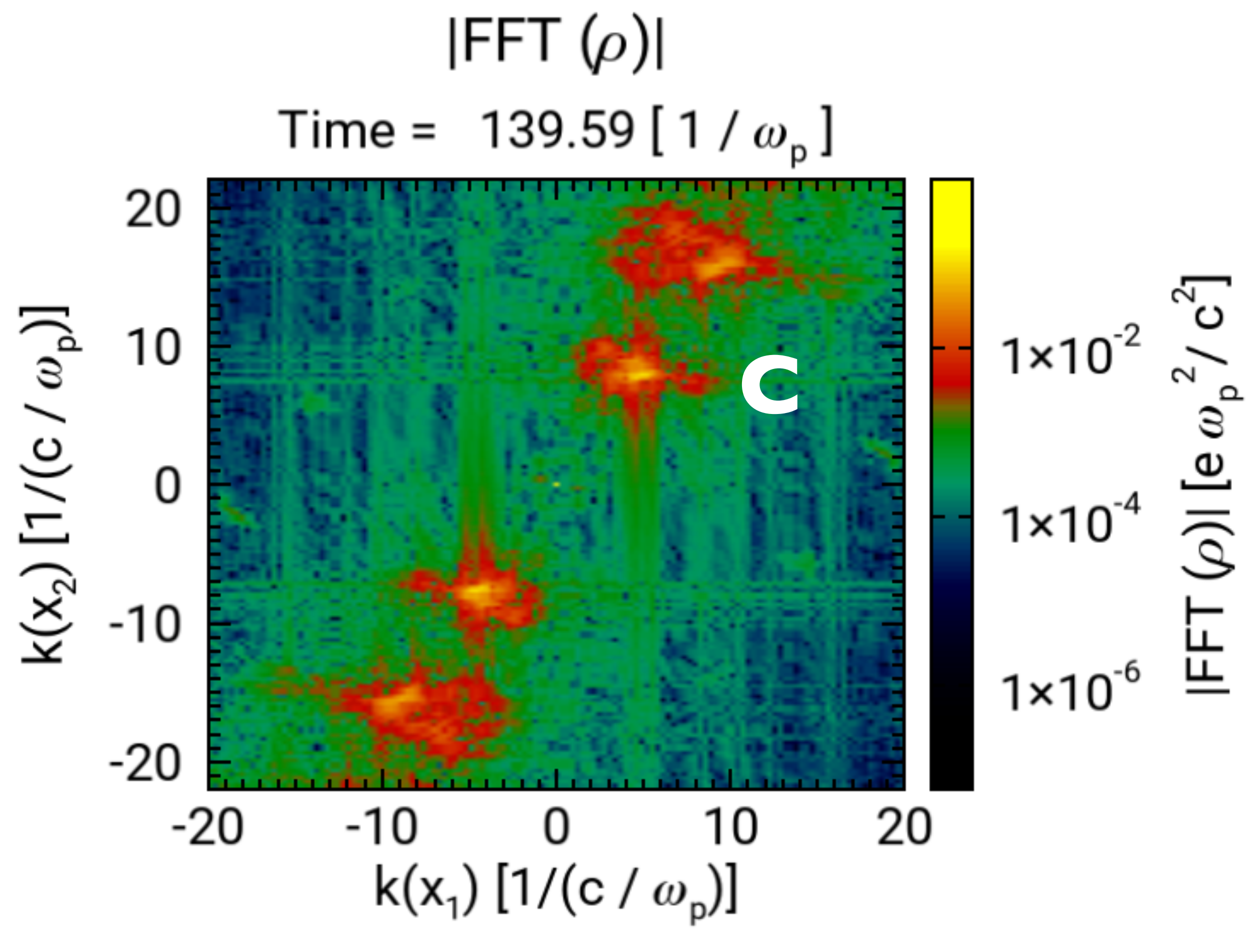
Let's investigate a regione of the pulse

Let's check the the matching conditions (1) in a region of one of the *wings* of the pulse:



Check on the matching conditions





For A: (k_x,k_y) = (9, 1.5)
For B: (k_x,k_y) = (4, -6.6)

For C: (k_x,k_y) = (4.5, 8.5)

$$\vec{k}_0 = \vec{k}_s + \vec{k}$$

Nonetheless, we still don't know the nature of this instability, it could be also **numerical** (it seems to disappear after a while).

Contents

Analytical model of acceleration of μ^- with accelerating drivers

Future video of muons not catching the wake for the acceleration

An acceleration method, using an external field with a time dependent phase velocity to accelerate non relativistic particles has been developed.

Imposing the phase-locking condition ($\beta_z(t) = \beta_\phi(t)$), we find:

$$\beta_z^2(t) = \frac{\left(\frac{qE_0 t}{mc} + \beta_0\right)^2}{1 + \left(\frac{qE_0 t}{mc} + \beta_0\right)^2}$$

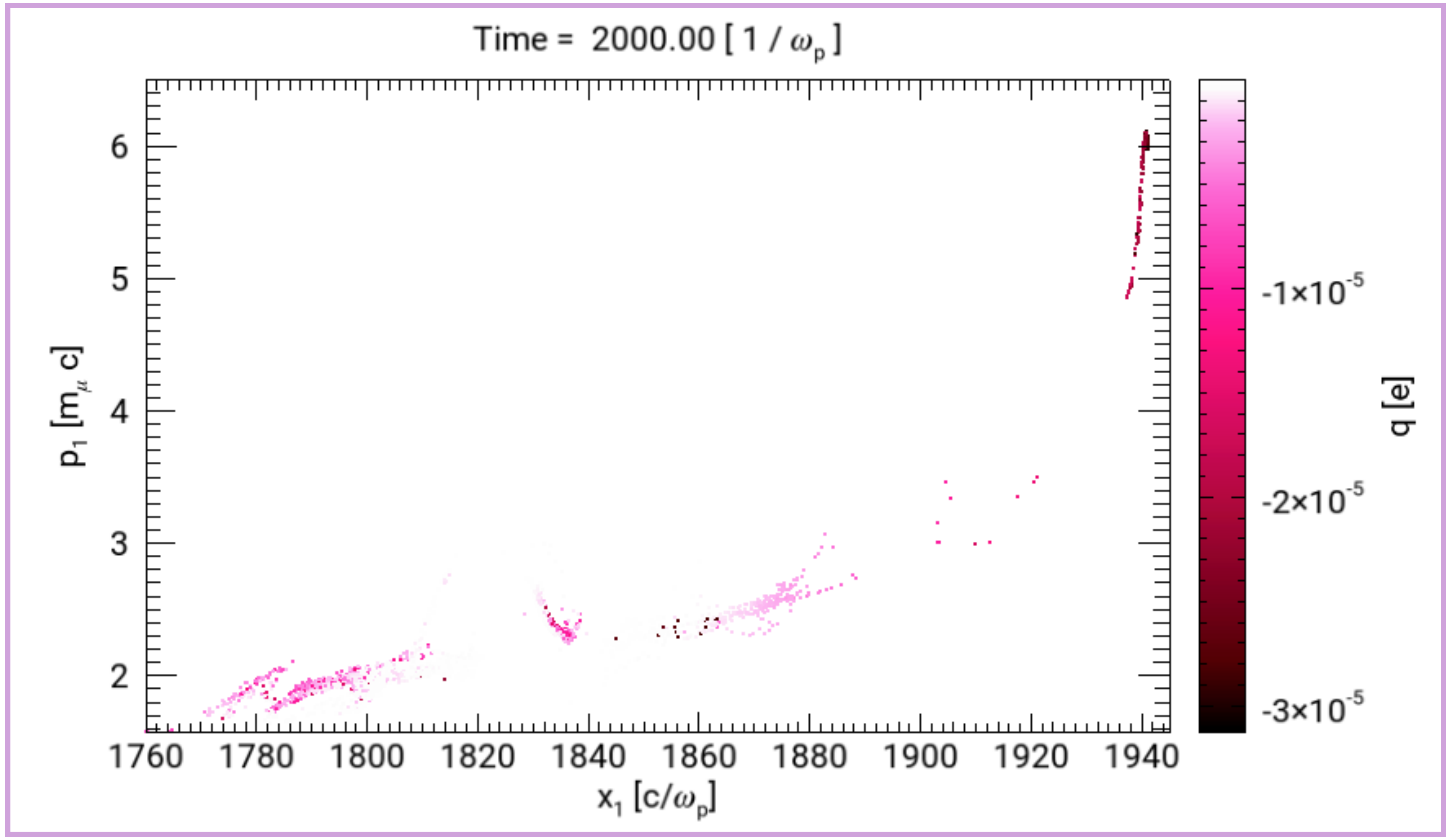
With $\beta_z \rightarrow 1$ for $t \rightarrow \infty$
and $\beta_z(t=0) = \beta_0$

This analytical model has first been tested in 1D using Mathematica, and then in 2D using the particle-in-cell code OSIRIS.

Energy gain in the analytical model

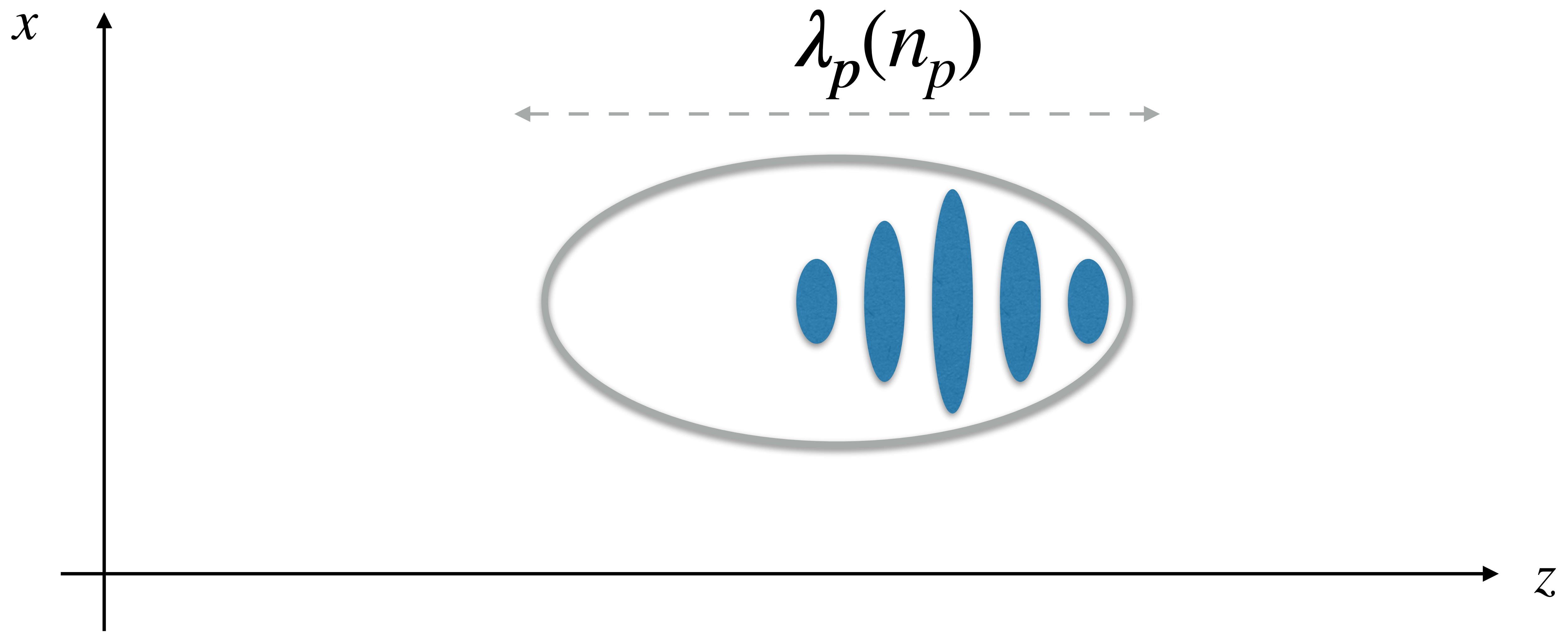
Expected energy gain:

```
In[3]:= β[2000] / Sqrt[1 - β[2000] ^2]
Out[3]= 6.03
```



~14% of the muons are accelerated by **300%** of their initial energy.

Plasma ramp for the "acceleration" of the plasma wake



S. Bulanov et al, Phys. Rev. E **58**, R5257(R) – Published 1 November (1998), https://doi.org/10.1103/PhysRevE.58.R5257

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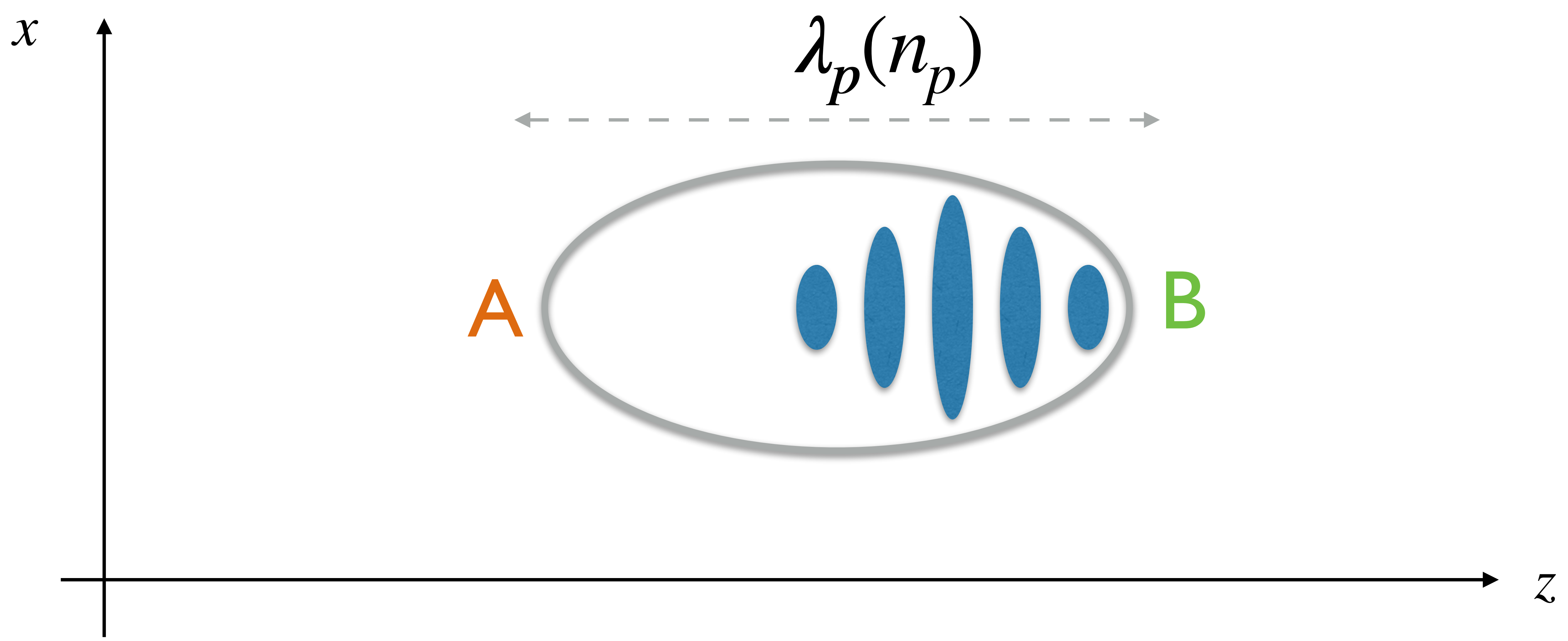

$$z_B = v_g t$$

$$v_B = v_g$$

$$z_A = v_g t - \lambda_p(n_p)$$

$$v_A = \frac{dz_A}{dt} = v_g - \frac{d\lambda_p(n_p)}{dt} = v_g - \frac{\partial \lambda_p}{\partial n_p}\frac{\partial n_p}{\partial t}$$

S. Bulanov et al, Phys. Rev. E **58**, R5257(R) – Published 1 November (1998), https://doi.org/10.1103/PhysRevE.58.R5257

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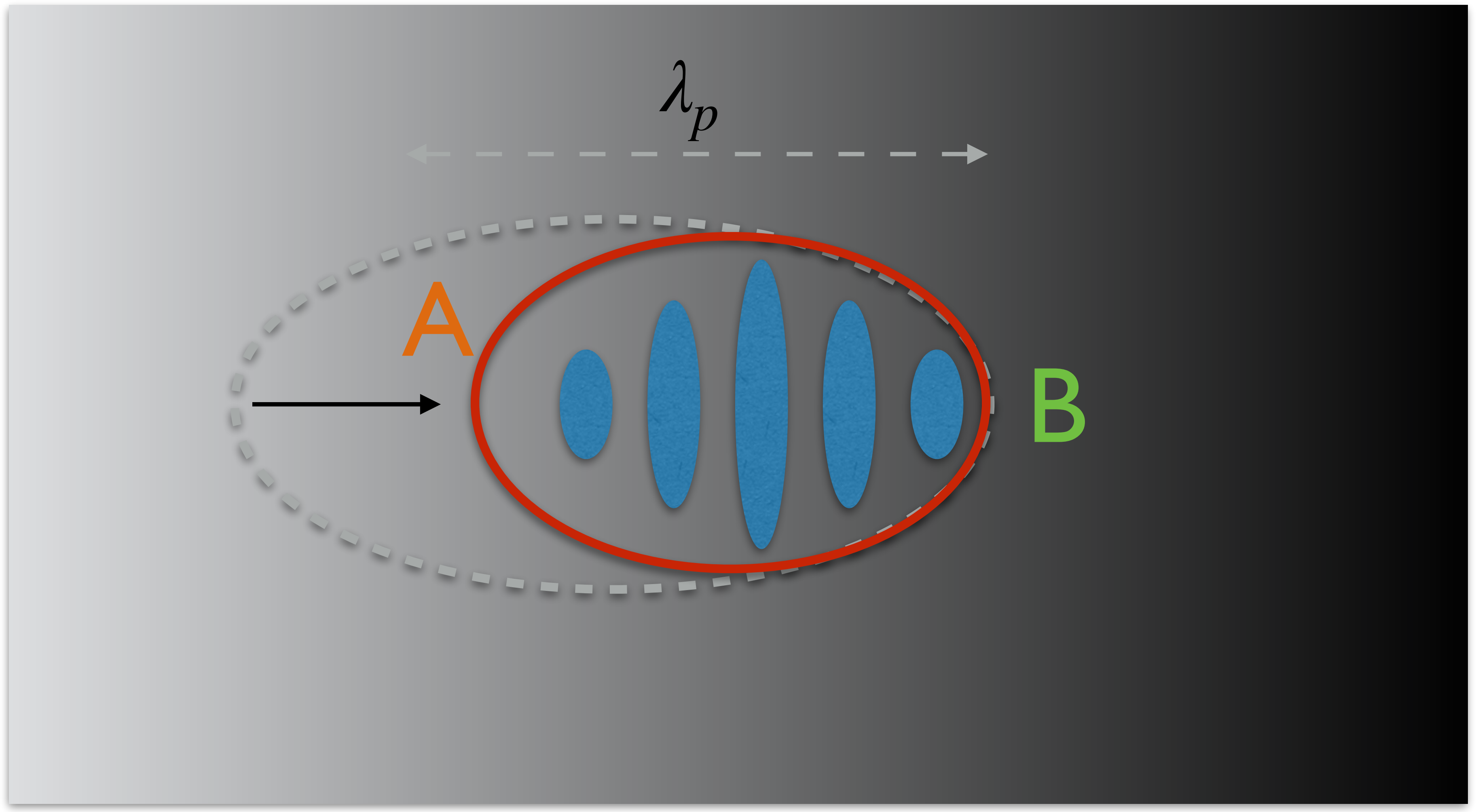

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$$v_A = \frac{dz_A}{dt} = v_g - \frac{d\lambda_p(n_p)}{dt} = v_g - \frac{\partial \lambda_p}{\partial n_p}\frac{\partial n_p}{\partial t}$$

This **accordion** effect results in an acceleration of the back of the plasma wake → it could help us to **extend the acceleration distance.**

S. Bulanov et al, Phys. Rev. E **58**, R5257(R) – Published 1 November (1998), https://doi.org/10.1103/PhysRevE.58.R5257

Conclusions & Future Work

Plasma accelerators could be substantial advantages in the acceleration of muons

➡ They could accelerate them before they decay, mitigating muon decay losses.

Plasma acceleration using subluminal drivers has been tested

➡ Using space-time optical wave packets, the acceleration of non-relativistic muons has been observed with 2D OSIRIS simulations

We show phase-locking for a realistic distribution of non-relativistic muons

➡ The method proposed has been first analytically developed and then tested using 2D OSIRIS simulations

➡ In the future, an implementation of a combination of optical wave packets in free space and plasma ramps will be invastigated to try to replicate the theoretical external field proposed.

3D OSIRIS simulations of the acceleration method proposed will be performed

Acknowledgments

TÉCNICO LISBOA

Simulation results obtained at MareNostrum (BSC).

Thank you for your attention

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