Exploring the current filamentation or Weibel instability in laboratory scenarios with relativistic beams

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- **N. Shukla,** K. Schoeffler, J. Vieira, **T. Silva**, R.A. Fonseca
- Work in collaboration with:
  - P. Muggli (MPP), G. Sarri (QUB), **C. Arrowsmith (Oxford)**, G. Gregori (Oxford), R. Bingham (RAL)
- Simulation results obtained at **Accelerates (IST)** and **MareNostrum 2 (BSC, Spain)**

Advanced Grants "Accelerates" (2010) and InPairs (2015)

Plan for today

Motivation for exploring the current filamentation or the Weibel instability (shocks + dark matter models)

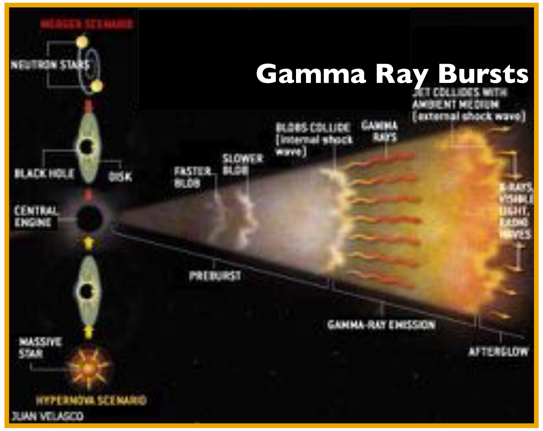
Our approach: particle-in-cell simulations + theory

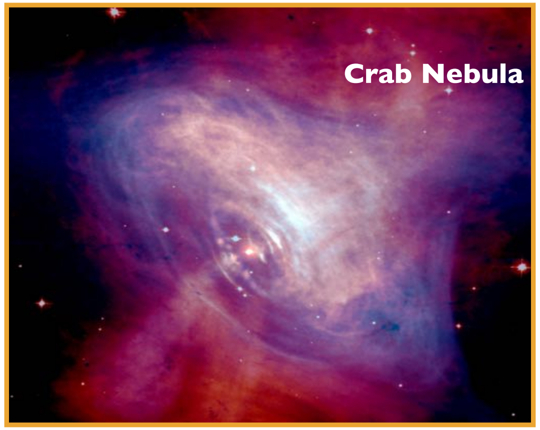
Generating fireball beams

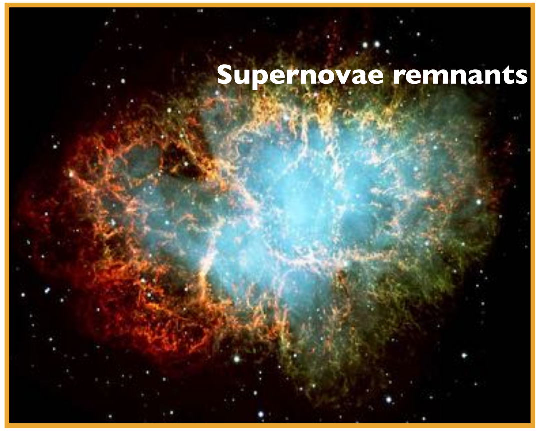
Onset of the current filamentation in the laboratory

Summary

Magnetic fields are ubiquitous in astrophysics and laboratory plasmas


Gamma Ray Bursts


Crab Nebula


Supernovae remnants

Turbulent dynamo

Seed magnetic fields are required

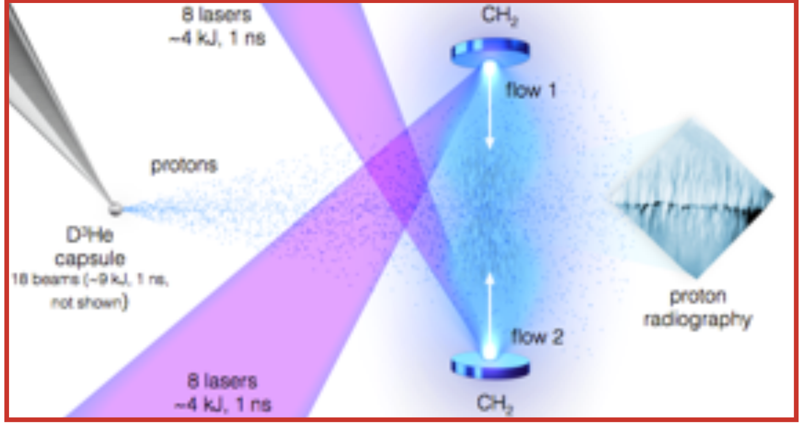
Seed magnetic field can be generated by

Biermann battery

Plasma micro instabilities e.g. Weibel/CFI Instability

https://www.futurity.org/turbulent-dynamo-1677482/

Experiments*



*G. Gregori's talk

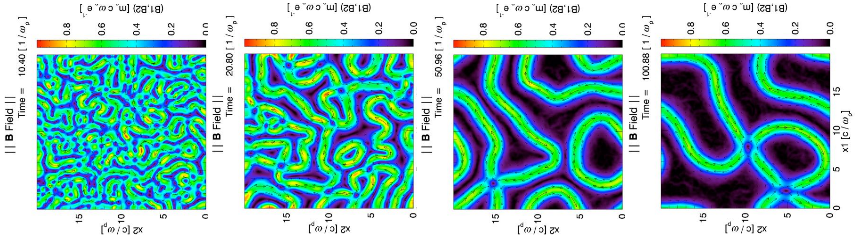
N. L. Kugland, et al., Nature Physics (2012); C. M. Huntington, et al., Nature Physics (2015)

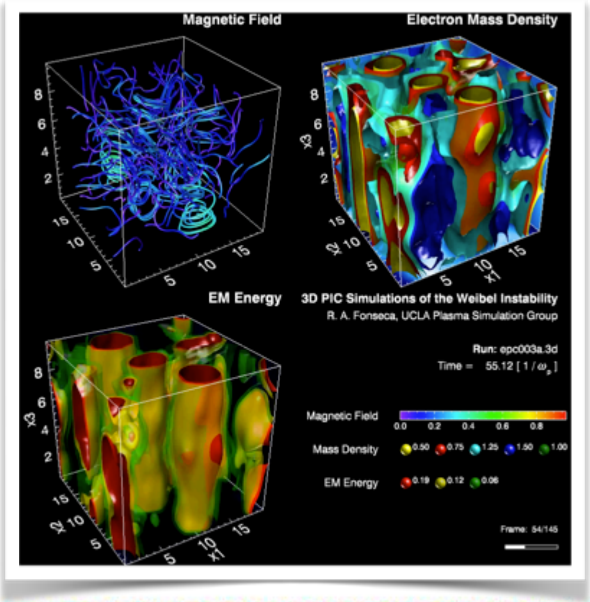
F. Fiuza et al,, Nature Physics (2020)

Plasma microinstabilities critical to shock formation and field structure in all these scenarios

- **B-fields generated by current filamentation/Weibel in GRBs**

  [Medvedev & Loeb, Gruzinov & Waxman, 99, Silva et al., 03]

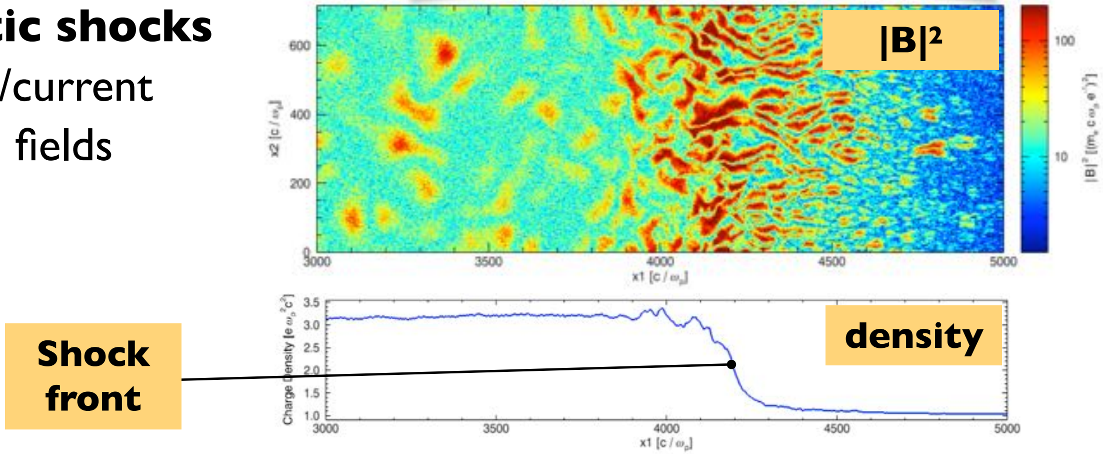




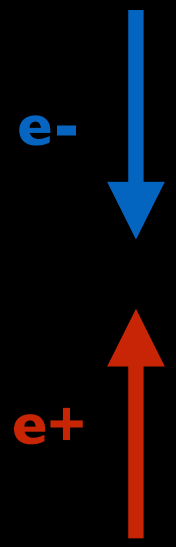
- **Fields in relativistic shocks**

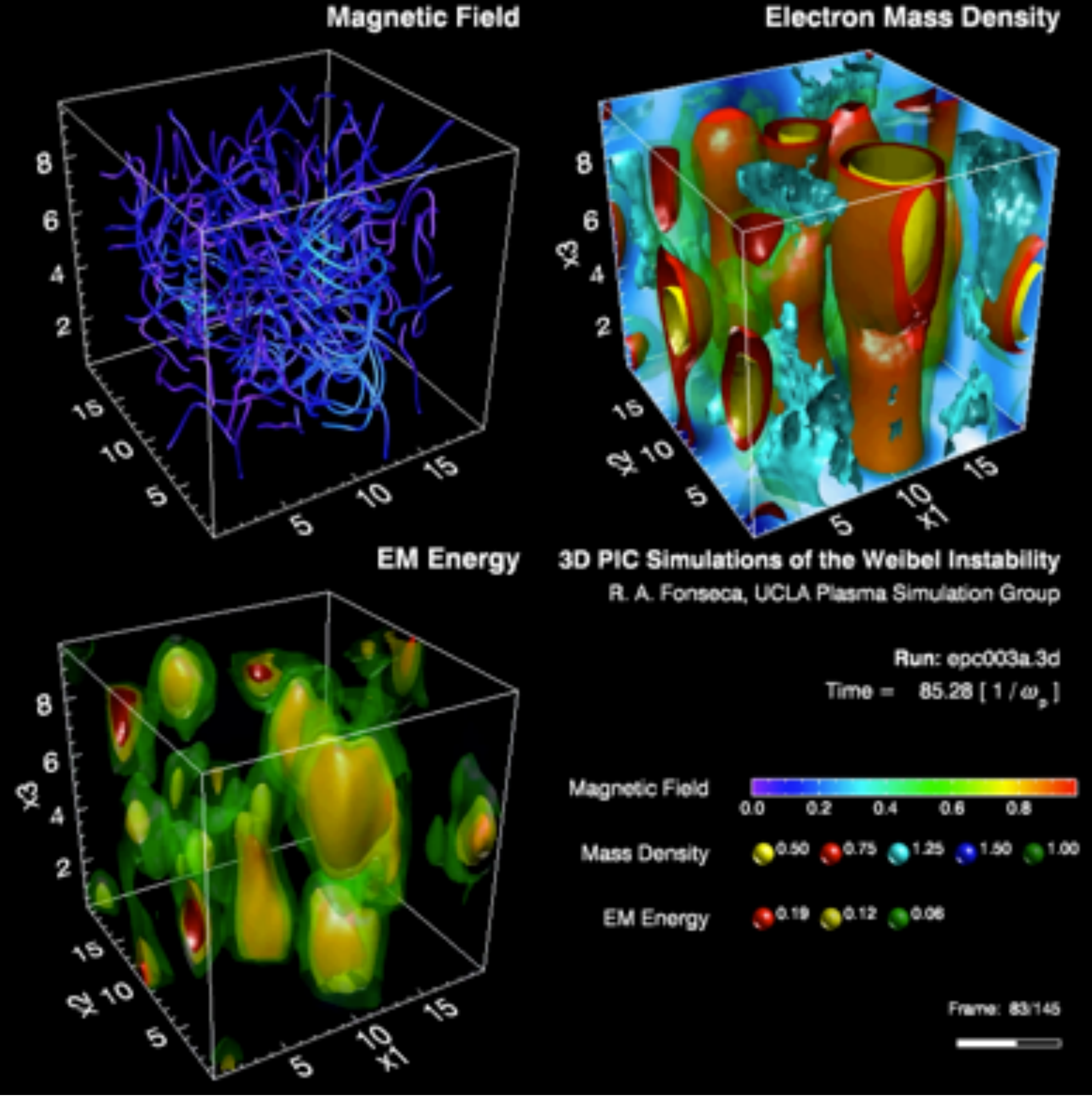
  are mediated by Weibel/current filamentation generated fields

  [Spiktovsky 08, Martins et al., 09]



Current filamentation (or Weibel instability)





Fields in shock ⇒ Fermi acceleration ⇒ B-field generation/amplification + radiation

- ***Ab initio* Fermi acceleration**

  determined by structure of the fields in the shock front

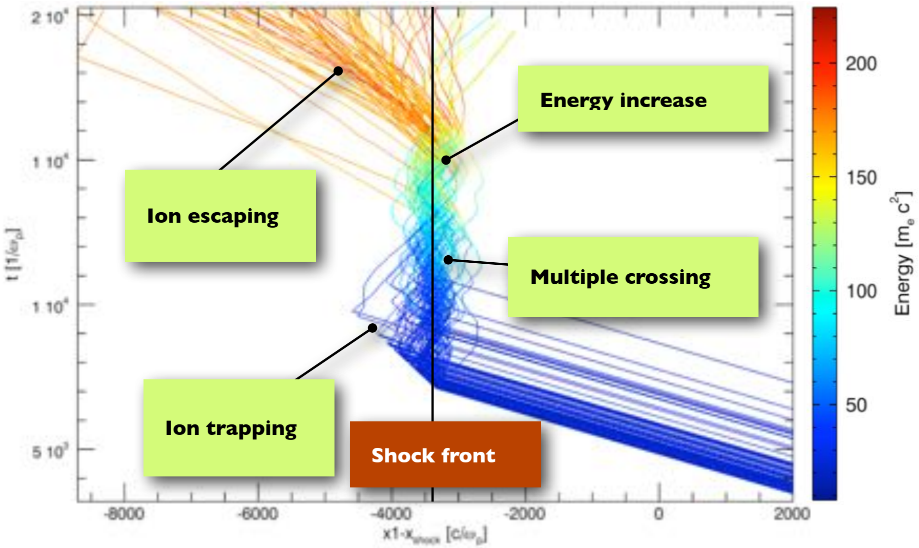
  [Spitkovsky 08, Martins et al., 09]

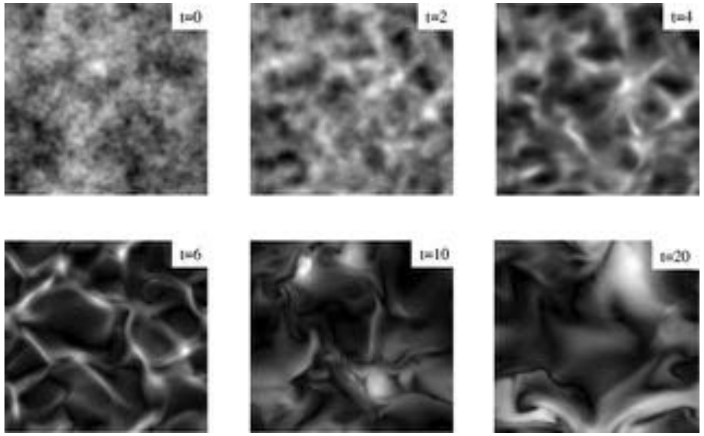
- **Synchrotron radiation affected by field structure**

  [Sironi, Spitkovsky 09, Sinha et al., JPP 20]

- **B-field amplification in upstream region via non-resonant “Bell” instability**

  [Bell 04]

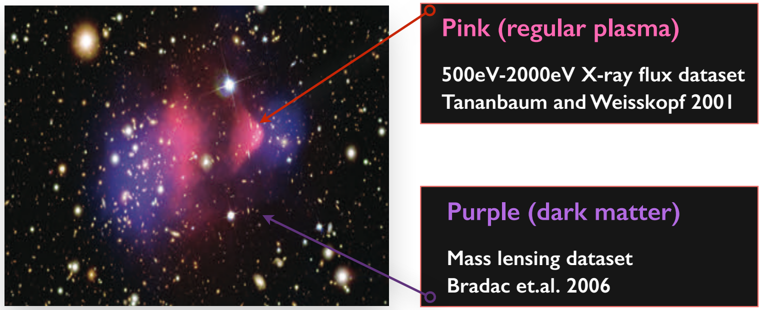




Can dark matter be charged under its own dark electromagnetism?

Bullet cluster: Chandra and Magellan AO

Two colliding clusters of galaxies



Pink (regular plasma)

500eV-2000eV X-ray flux dataset
Tananbaum and Weisskopf 2001

Purple (dark matter)

Mass lensing dataset
Bradac et.al. 2006

Two colliding components

Baryonic component undergoes significant interaction (slowing down)

Dark matter component passes through with no observable slowdown

Properties of dark electromagnetism*

Particle physics point of view

$$\alpha = \frac{e^2}{\hbar c} \longrightarrow \alpha_D = \frac{q_D^2}{\hbar c}$$

Plasma physics point of view

$$\omega_{pD} = \sqrt{\frac{4\pi q_D^2 n_D}{m_D}} = \sqrt{\frac{4\pi\alpha_D \hbar c \rho}{m_D^2}}$$

We know this

Scales we know

ρ : Dark matter mass density 0.01 GeV/cm^3

L : Length scale of dark matter cluster 100 kpc

α_D : Dark matter coupling strength ~1×10^{-3}

m_D : Dark matter mass ~1TeV

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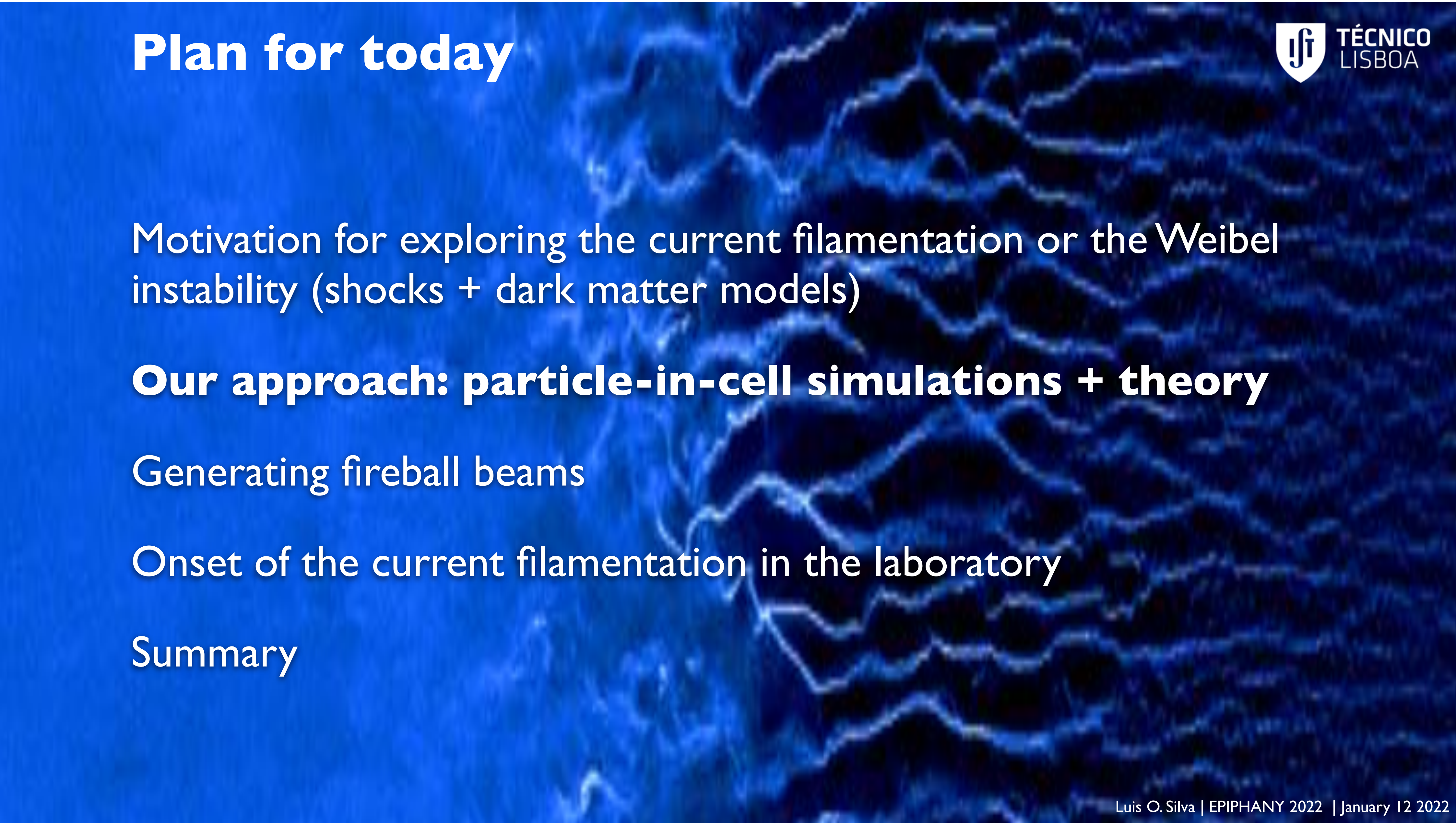
* L. Ackerman, et. al, Phys. Rev. D 79 (2009); J. L. Feng et al., JCP (2009)

Plan for today



Motivation for exploring the current filamentation or the Weibel instability (shocks + dark matter models)

Our approach: particle-in-cell simulations + theory

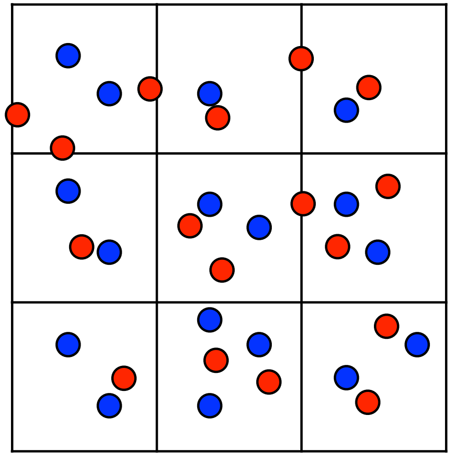
Generating fireball beams

Onset of the current filamentation in the laboratory

Summary

Towards exascale particle-in-cell simulations

Solving Maxwell's equations on a grid with self-consistent charges and currents due to charged particle dynamics



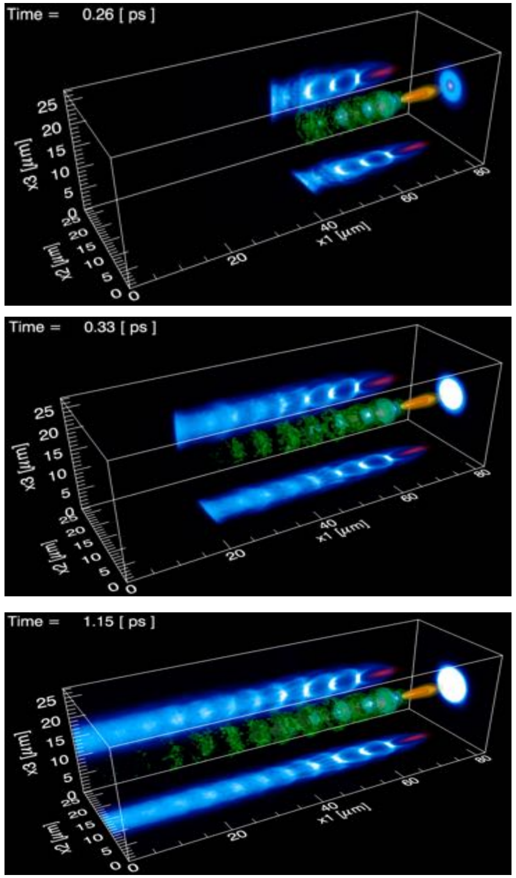
State-of-the-art

~ 10^{12} particles

~ $(12000)^3$ cells

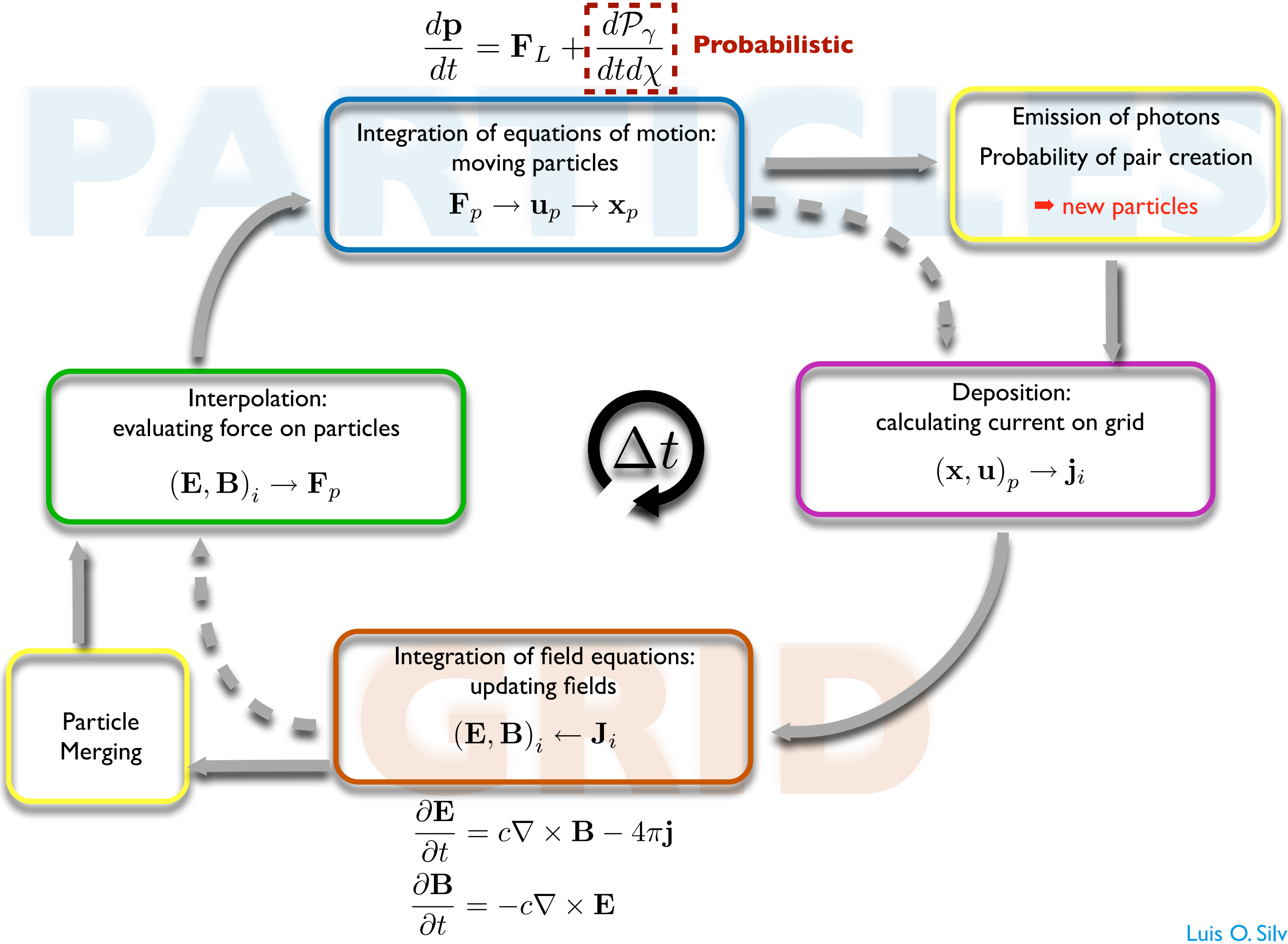
RAM ~ 1 Gbyte - 100 TByte
Run time: hours to months
Data/run ~ few MB - 100s TByte

One-to-one simulations of plasma based accelerators & cluster dynamics
Weibel/two stream instability in astrophysics, relativistic shocks, fast igniton/inertial fusion energy, low temperature plasmas



Particle-in-cell (PIC) - (Dawson, Buneman, 1960's)
Maxwell's equation solved on simulation grid
Particles pushed with Lorentz force

Particle-in-cell loop (e.g. including QED effects)



$$\frac{d\mathbf{p}}{dt} = \mathbf{F}_L + \boxed{\frac{d\mathcal{P}_\gamma}{dtd\chi}}$$

Probabilistic

Integration of equations of motion:
moving particles

$\mathbf{F}_p \rightarrow \mathbf{u}_p \rightarrow \mathbf{x}_p$

Emission of photons

Probability of pair creation

➡ new particles

Deposition:
calculating current on grid

$(\mathbf{x}, \mathbf{u})_p \rightarrow \mathbf{j}_i$

Δt

Integration of field equations:
updating fields

$(\mathbf{E}, \mathbf{B})_i \leftarrow \mathbf{J}_i$

$$\frac{\partial \mathbf{E}}{\partial t} = c\nabla \times \mathbf{B} - 4\pi \mathbf{j}$$

$$\frac{\partial \mathbf{B}}{\partial t} = -c\nabla \times \mathbf{E}$$

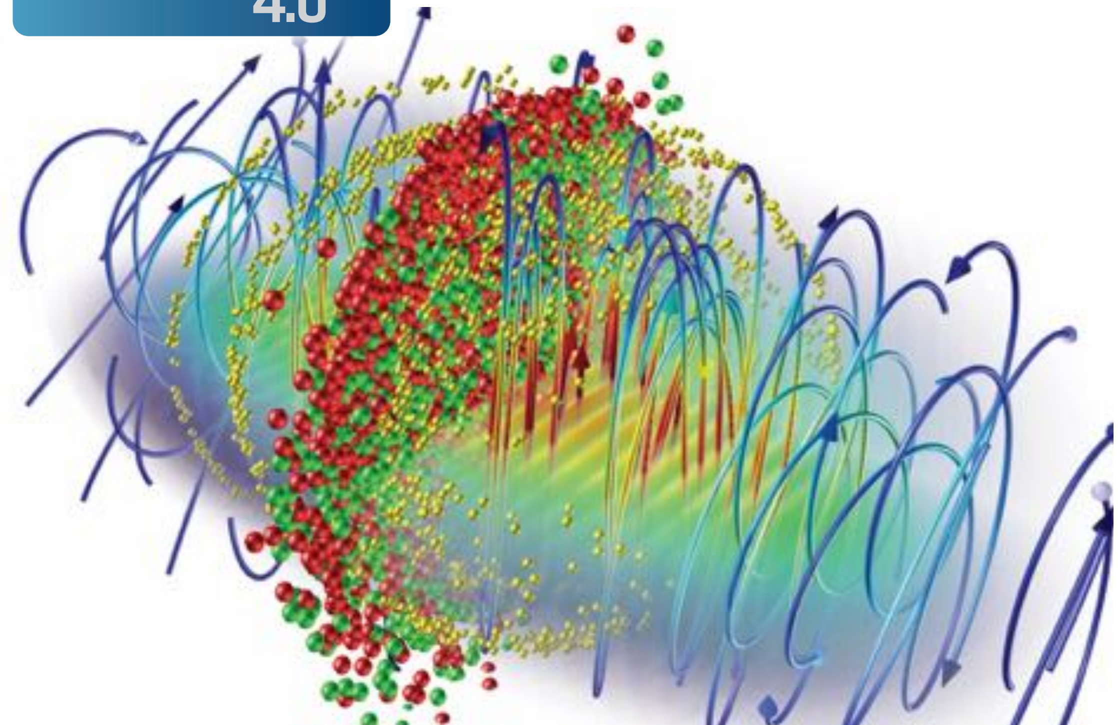
Particle Merging

Interpolation:
evaluating force on particles

$(\mathbf{E}, \mathbf{B})_i \rightarrow \mathbf{F}_p$

Osiris 4.0

Committed to open science



OSIRIS framework

- Massively Parallel, Fully Relativistic Particle-in-Cell Code
- Parallel scalability to 2 M cores
- Explicit SSE / AVX / QPX / Xeon Phi / CUDA support
- Extended simulation/physics models

Open-access model

- 40+ research groups worldwide are using OSIRIS
- 250+ publications in leading scientific journals
- Large developer and user community
- Detailed documentation and sample inputs files available

Using OSIRIS 4.0

- The code can be used freely by research institutions after signing an MoU
- Find out more at:

http://epp.tecnico.ulisboa.pt/osiris

UCLA TÉCNICO LISBOA

Ricardo Fonseca: ricardo.fonseca@tecnico.ulisboa.pt

Dark EM can be studied using PIC simulations

DM interactions can be modelled by electron-positron like-plasma

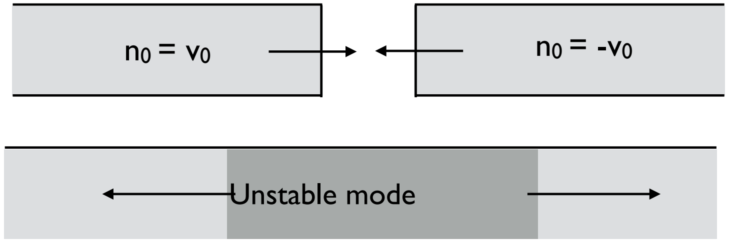
DM self-interactions is identical to that of a collisionless e^- e^+ plasma*

⇩

Can be subjected to several microinstabilities; generates E and B fields

⇩

Well understood analytically and numerically in the linear regime**



$n_0 = v_0$

$n_0 = -v_0$

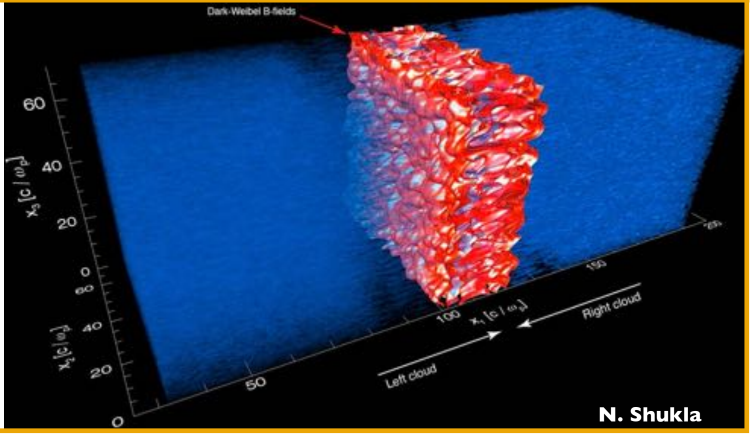
Unstable mode

Complexity of the system can be fully captured only by particle-in-cell simulations

We are interested in the bulk slowdown of dark plasma slabs

⇩

Underlying physics is highly nonlinear and involves a wide difference of spatial and temporal scales



N. Shukla

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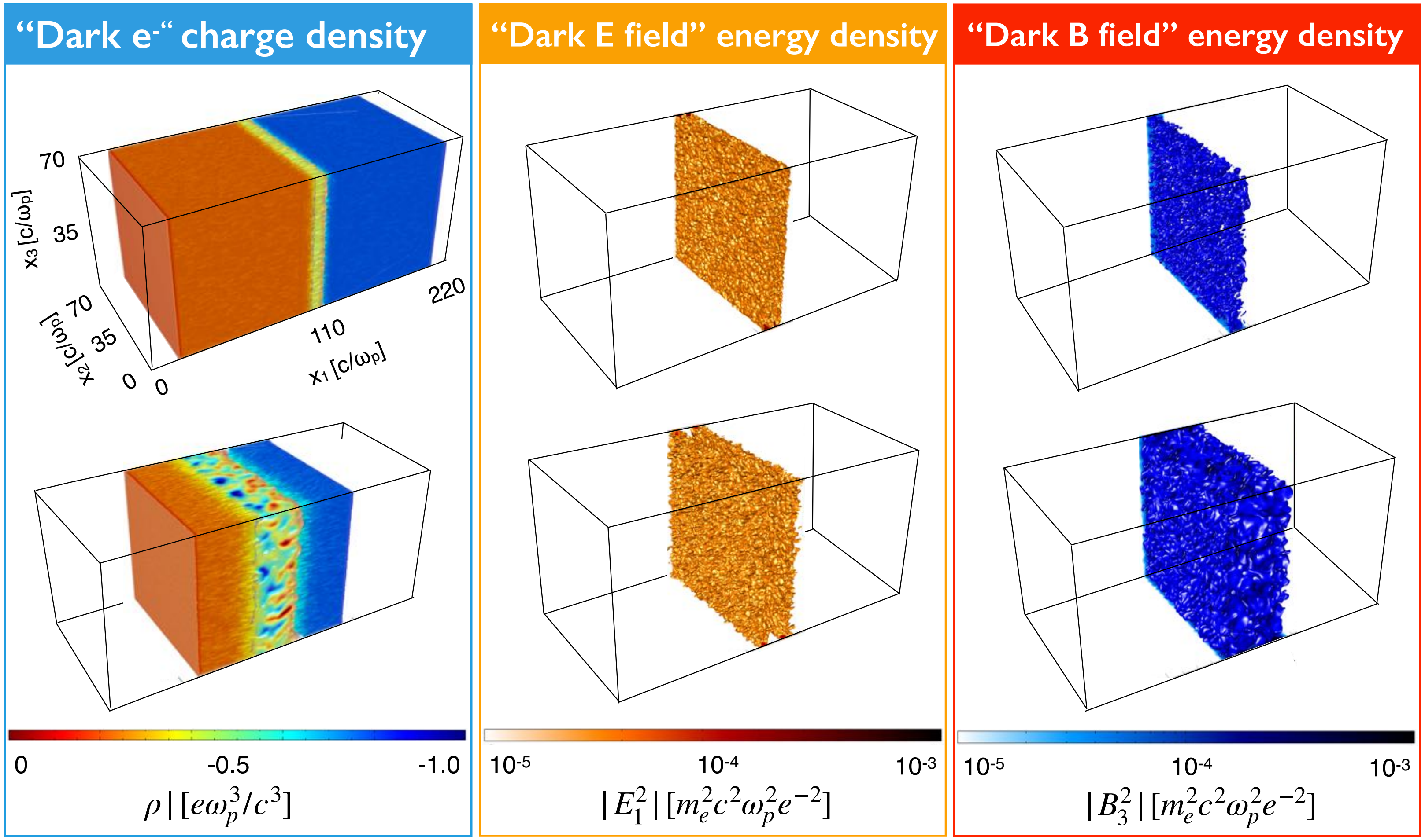
* L. Ackerman, et. al, Phys. Rev. D 79 (2009), P. Agrawal, et. al, J Cosmol Astropart P, 022 (2017).

** A. Bret, et. al, Phys. Plasmas, (2010); L. O. Silva, et. al, Astrophys. J. (2003).

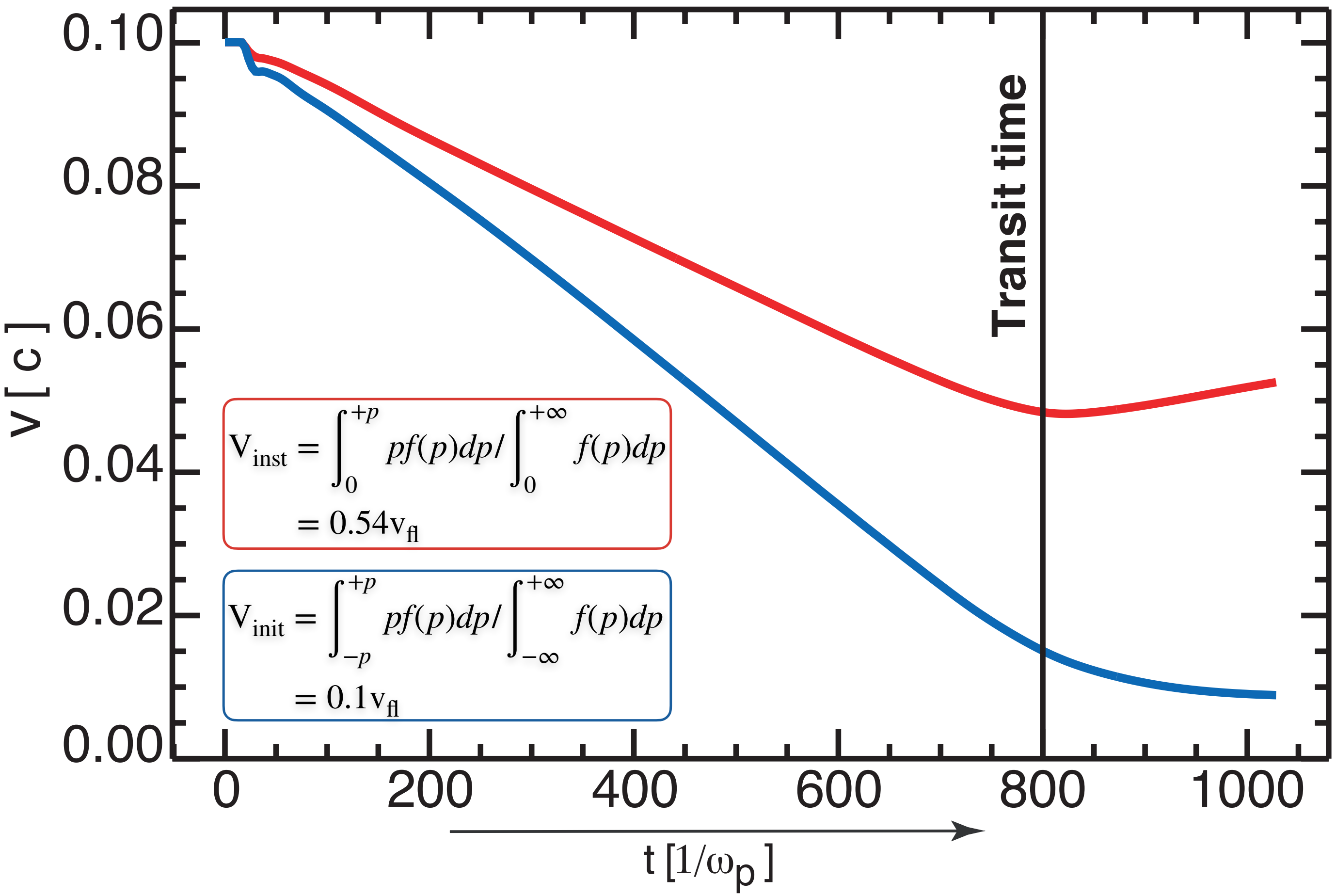
Electromagnetic instabilities generated for wide range of conditions



N. Shukla et al. arXiv:2109.00023 (2021)

Can these instabilities lead to slowdown?

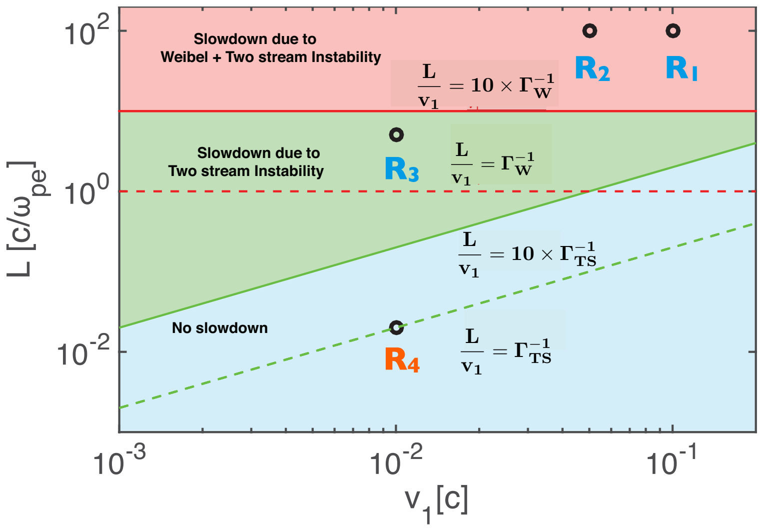
Temporal evolution of the velocity of right moving dark e$^-$



N. Shukla et al. arXiv:2109.00023 (2021)

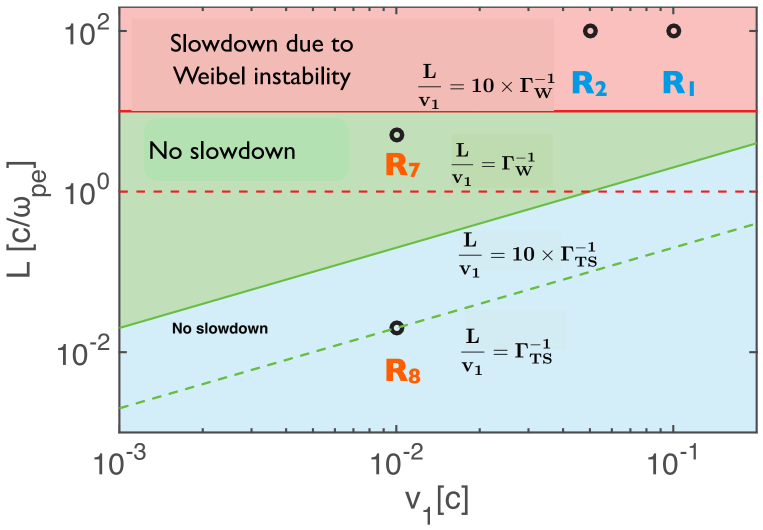
Significant slow-down for all temperatures ($L > 10\ c/\omega_p$)

Cold dark plasma slab



Slowdown occurs due to electromagnetic fields generated by two-stream and Weibel instabilities

Warm dark plasma slab



Slowdown occurs due to Weibel generated magnetic fields

N. Shukla et al. arXiv:2109.00023 (2021)

Significant constraint on dark-matter interaction due to slowdown

TÉCNICO LISBOA

Estimate of bounds on dark matter

Significant slowdown occurs unless :

$$L < 10\,\Gamma_W^{-1}\,v_1$$

Particle physics point of view equivalent to :

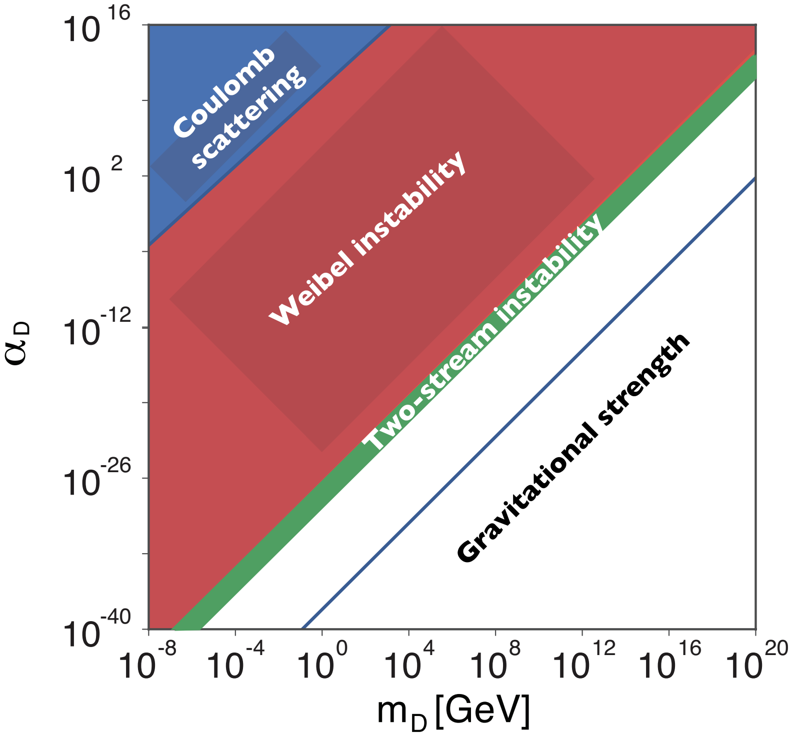
Limit on L for the Weibel instability

$$\alpha_D < 4.2 \times 10^{-25} \left(\frac{L}{100kpc}\right)^{-2} \left(\frac{\rho_D}{0.01GeV/cm^3}\right)^{-1} \times \left(\frac{m_D}{1TeV}\right)^{2}$$

Limit on L for the Two-stream instability

$$\alpha_D < 4.2 \times 10^{-27} \left(\frac{L}{100kpc}\right)^{-2} \left(\frac{\rho_D}{0.01GeV/cm^3}\right)^{-1} \times \left(\frac{m_D}{1TeV}\right)^{2} \left(\frac{v_{fl}}{0.1c}\right)^{2}$$

Allowed region of α_D vs m_D



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Summary

Relativistic fireballs in the laboratory

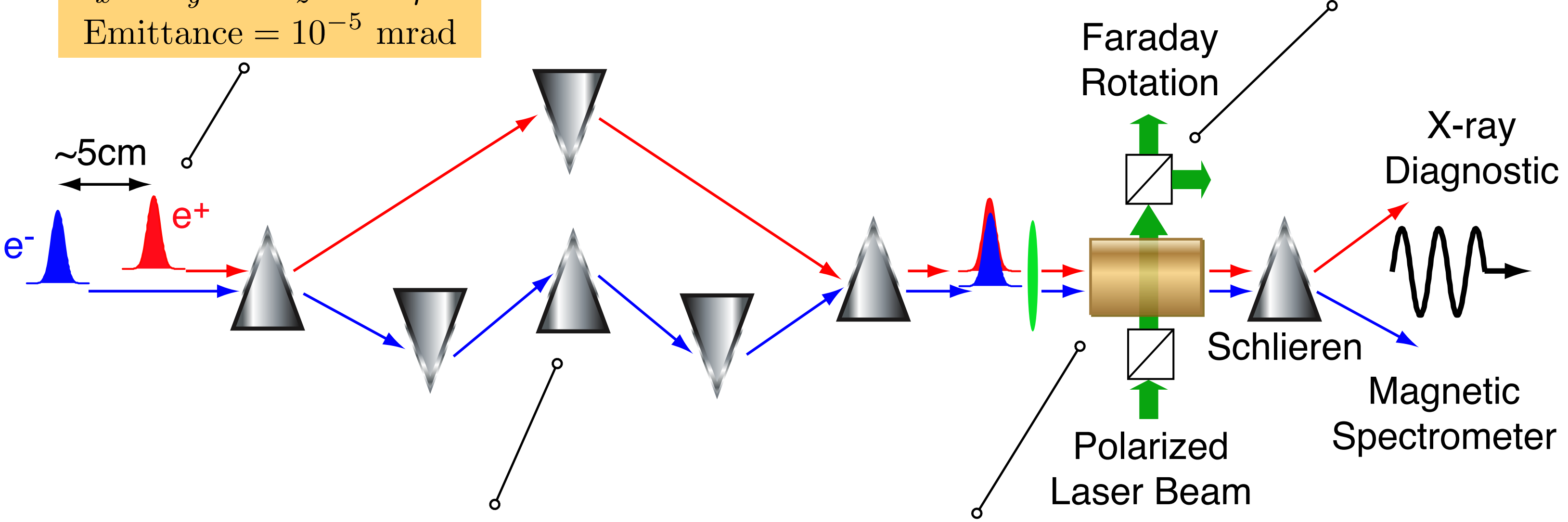
Configuration for e-e+overlap and fireball generation

29 GeV electron and positron bunches

$\sigma_x = \sigma_y = 2\sigma_z = 20\ \mu\mathrm{m}$

$\mathrm{Emittance} = 10^{-5}\ \mathrm{mrad}$

Probing magnetic fields



Dephasing technique to overlap beams

Typically used in PWFA to reduce bunch distance to ~100 microns

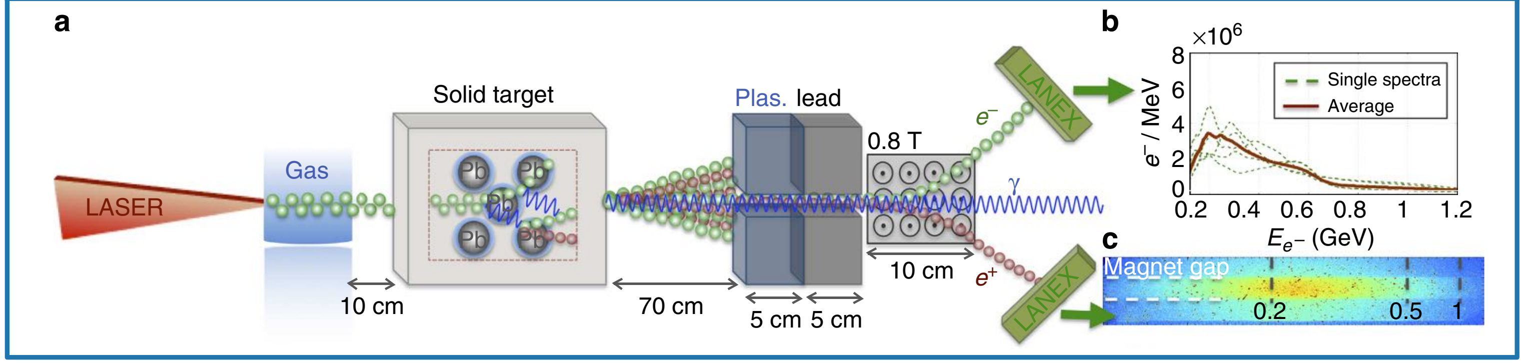
20 cm plasma

$n_e = 2.7 \times 10^{17}\ \mathrm{cm}^{-3}$

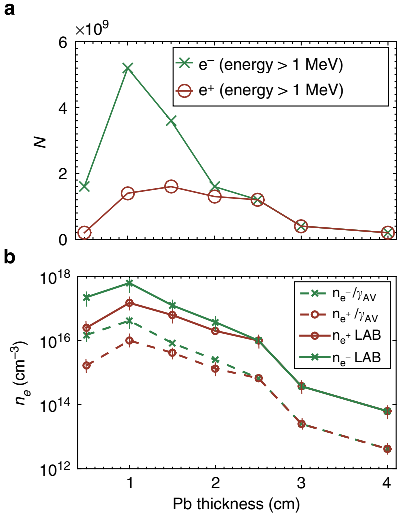
P. Muggli, S. F. Martins, J. Vieira, L. O. Silva, arXiv:1306.4380
N. Shukla et al, New Journal of Physics (2020)

e-e+ fireballs from laser generated beams in solids

Experimental results demonstrate formation of e-e+ fireball



e-e+ fireball is neutral

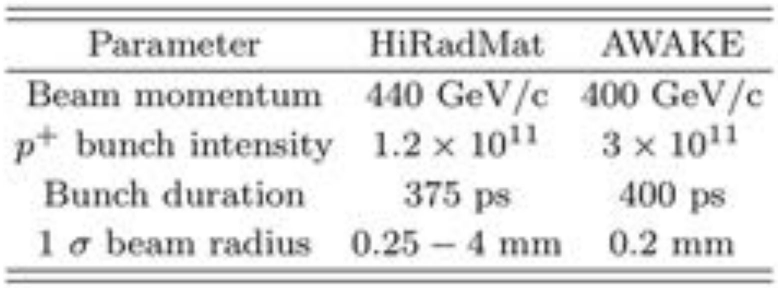


G. Sarri *et al.*, Nature Communications (2015)

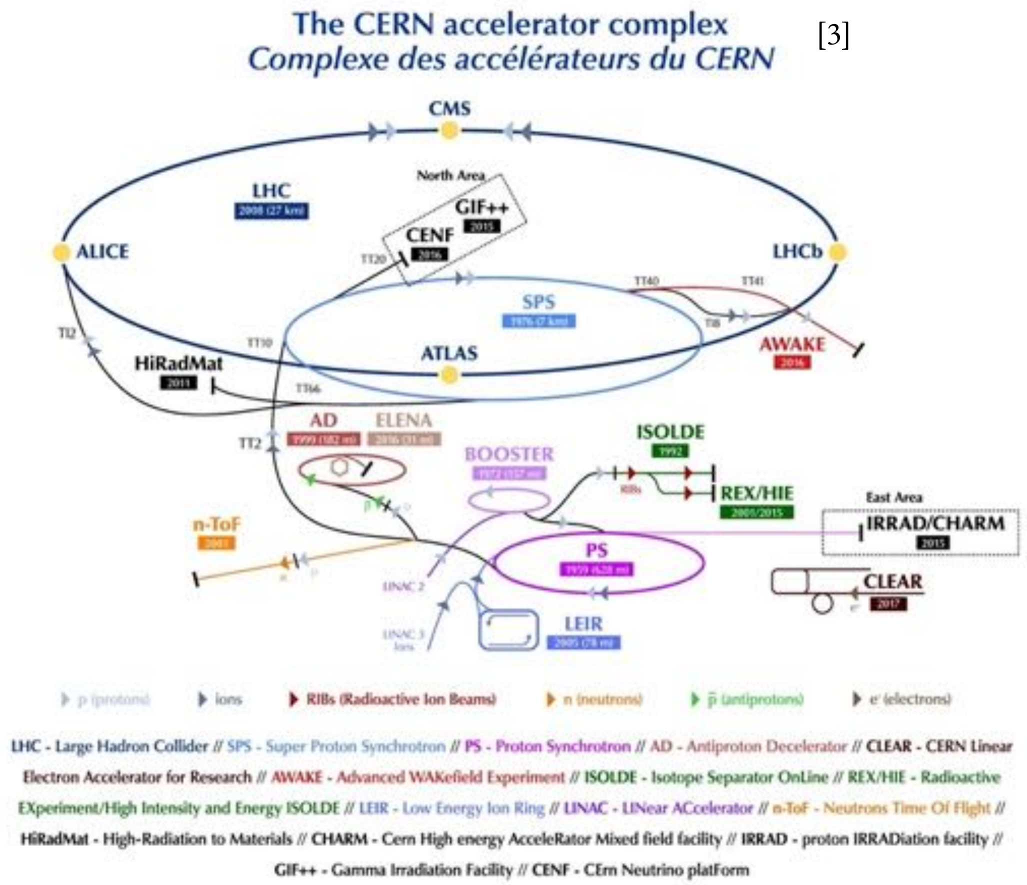
Idea for experiment at CERN

We present an unexplored proton-based approach to generating ultra-dense pair beams using 400 GeV/c protons available at CERN facilities such as HiRadMat[1] (High-Radiation to Materials) and AWAKE[2] (Advanced Proton Driven Plasma Wakefield Acceleration Experiment). These facilities can provide 400 ps pulses containing more than 10^{11} protons.

Beam parameters:



Parameter	HiRadMat	AWAKE
Beam momentum	440 GeV/c	400 GeV/c
p^+ bunch intensity	1.2×10^{11}	3×10^{11}
Bunch duration	375 ps	400 ps
$1\ \sigma$ beam radius	0.25 – 4 mm	0.2 mm



[3]

C. Arrowsmith et al., Physical Review Research (2021)

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[1] I. Efthymiopoulos, et al., Tech. Rep. (2011).
[2] E. Gschwendtner, et al., Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment 829, 76 (2016).
[3] Mobs E.,ERN-GRAPHICS-2019-002 (2019).

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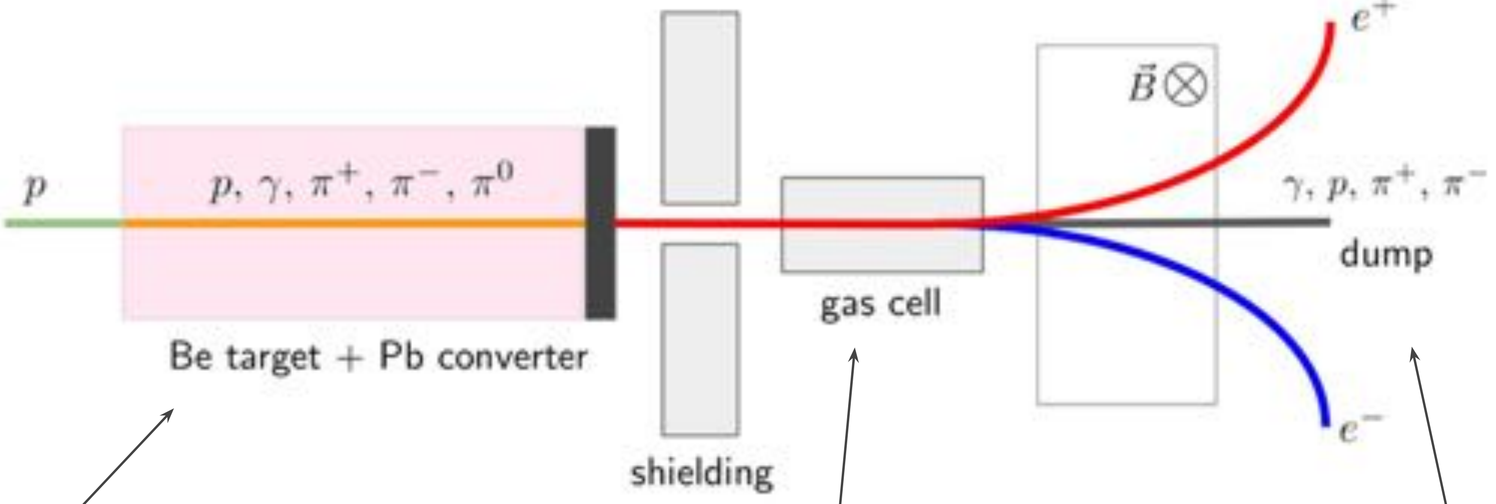
Idea for experiment at CERN



Beams composed of electrons, positrons, photons, protons and other hadrons are generated using a beryllium target followed by a lead converter…

…Driving the beam into a gas cell will ionize the gas, forming a background plasma where the beam-plasma interaction can be studied…

…Since the bulk of the electrons and positrons in the beam have much smaller momentum than the hadrons, dipole magnets can be used to deflect e+/e– out of the beam to study their energy spectra, while the hadrons are deflected less and are absorbed by the beam dump.

C. Arrowsmith et al., Physical Review Research (2021)

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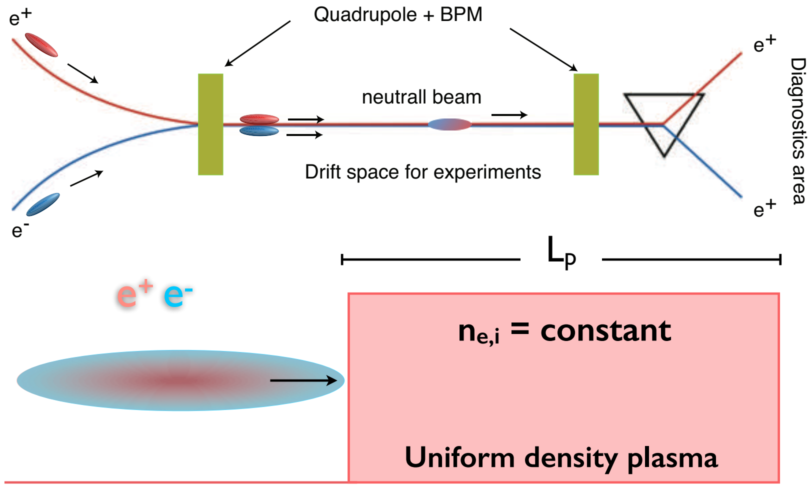
Beam filamentation & B-field generation with 29 GeV fireballs @ SLAC

Fireball beams in the lab

Dephasing technique to overlap beams typically used in PWFA to reduce bunch distance to ~100 µm



Beam focused at plasma entrance

Beam parameters*

- Gaussian profiles: $n_{b0}\, e^{-\left(\frac{x^2}{\sigma_x^2}+\frac{y^2}{\sigma_y^2}+\frac{z^2}{\sigma_z^2}\right)}$
- $\sigma_x = 10.2$ µm ; $\sigma_y = \sigma_z = 20.4$ µm
- Energy = 29 GeV
- Density ($n_{e,p}$) = 2.7×10^{17} cm^{-3}
- Emittance (mm-mrad) = 1 to 2

Plasma parameters

- Plasma density ($n_{e,i}$) = 2.7×10^{17} cm^{-3}

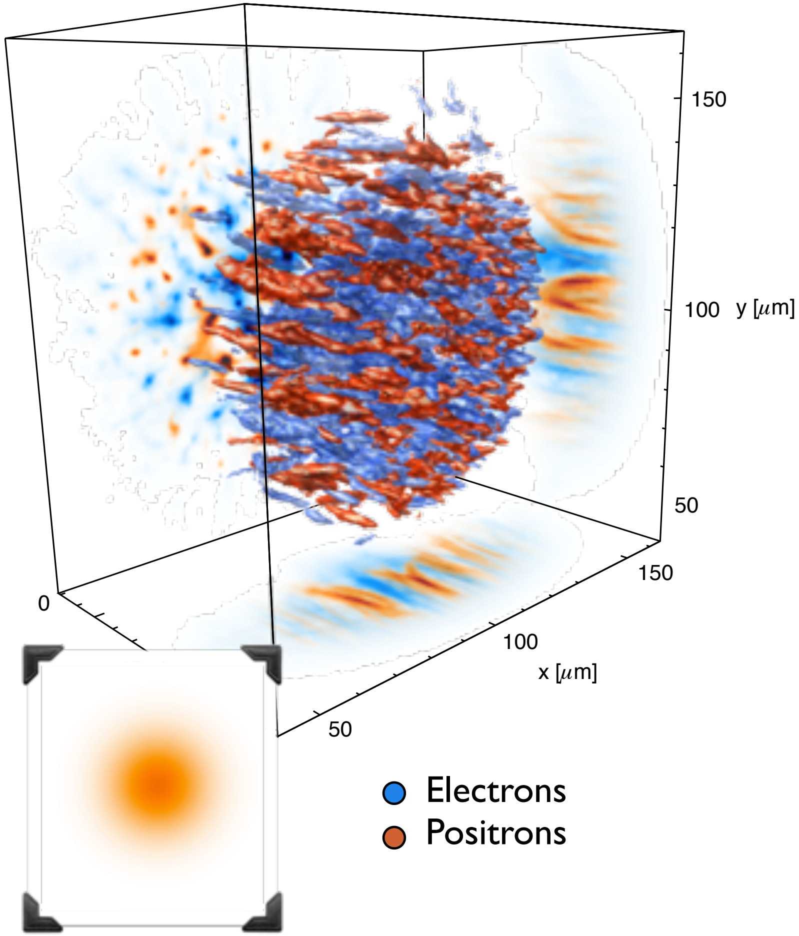
* Kimura et al., AIP Conference Proceedings Volume 877, 534

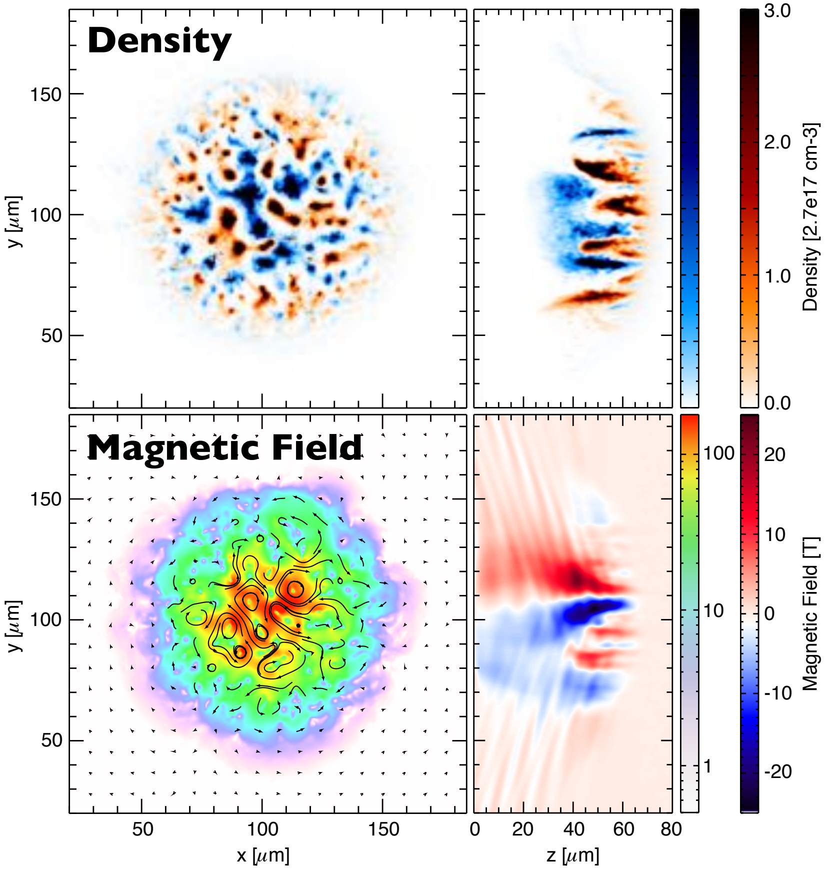
e-e+ fireballs: astrophysics in the laboratory

Beam filamentation & B-field generation with 29GeV fireballs @ SLAC

P. Muggli, S. F. Martins, J. Vieira, L. O. Silva, arXiv:1306.4380

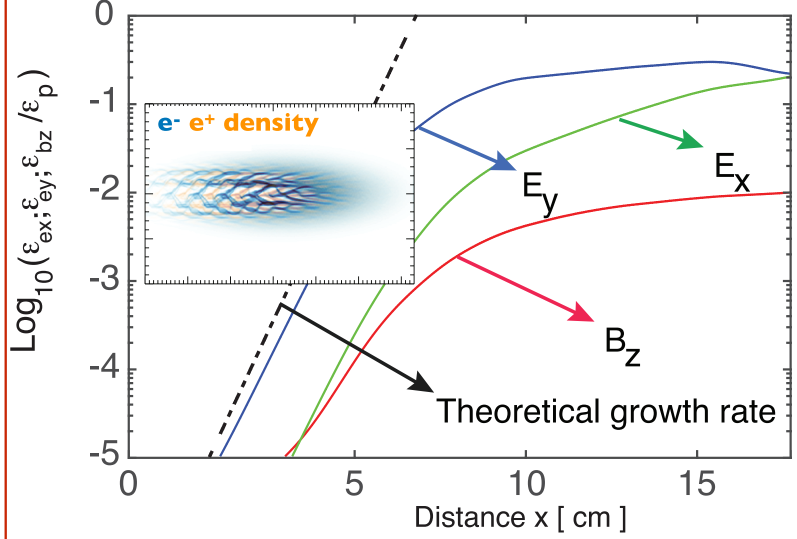
N. Shukla et al., New Journal of Physics (2020)





Filamentation in the lab: avoid competing mechanisms

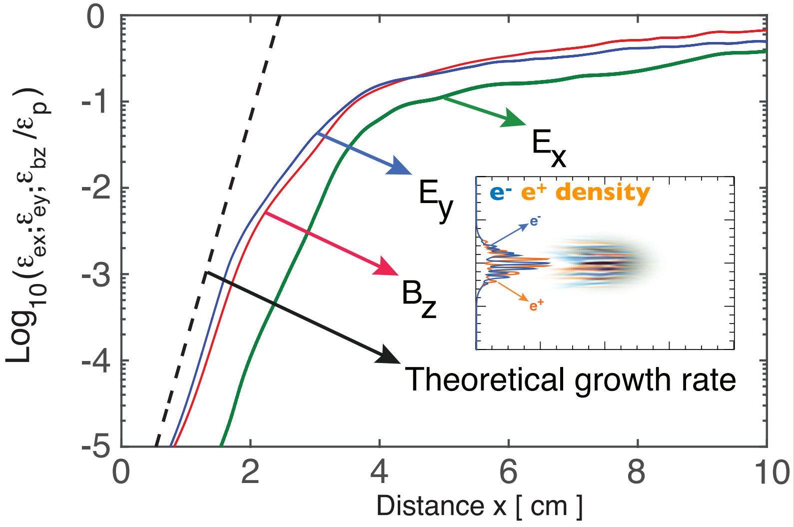
Longer beam $\sigma_x \sim 12\ [c/\omega_p]$



Oblique instability dominates for $n_b/n_0 \ll 1$

$$\frac{\Gamma_{\text{Oblique}}}{\Gamma_{\text{CFI}}} = \frac{\sqrt{3}}{2^{4/3}}\frac{1}{\beta_b}\left(\gamma_b \frac{n_0}{n_b}\right)^{1/6}$$

Short beam



Fireball beam saturates 10 cm after propagating inside the plasma

$\sigma_x \sim 1\ [c/\omega_p]$; $\sigma_y \sim 2\ [c/\omega_p]$

$n_b/n_0 = 1$

P. Muggli, S. F. Martins, J. Vieira, L. O. Silva, arXiv:1306.4380; N. Shukla et al, JPP 84 (3) (2018)
N. Shukla et al., New Journal of Physics (2020)

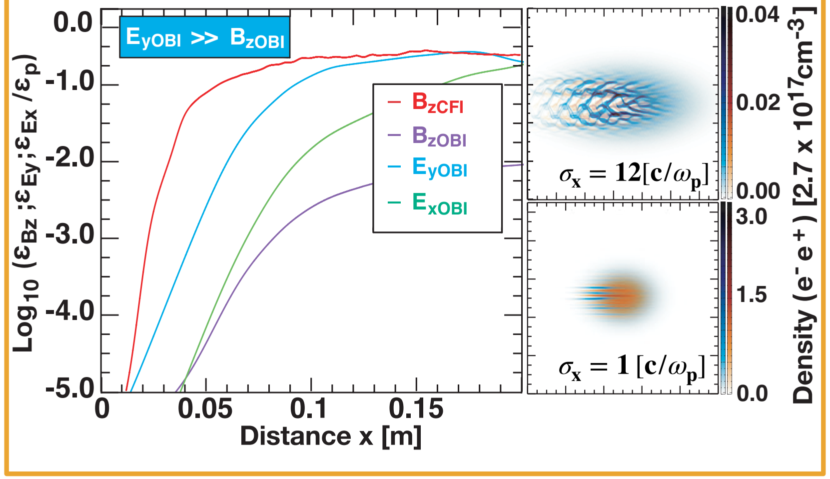
Filamentation in the lab: avoid competing mechanisms

Role of electrostatic instabilities

Oblique instability dominates for $n_b/n_0 \ll 1$

$$\frac{\Gamma_{\text{Oblique}}}{\Gamma_{\text{CFI}}} = \frac{\sqrt{3}}{2^{4/3}}\frac{1}{\beta_b}\left(\gamma_b\frac{n_0}{n_b}\right)^{1/6}$$

(filamentation vs oblique instability competition)

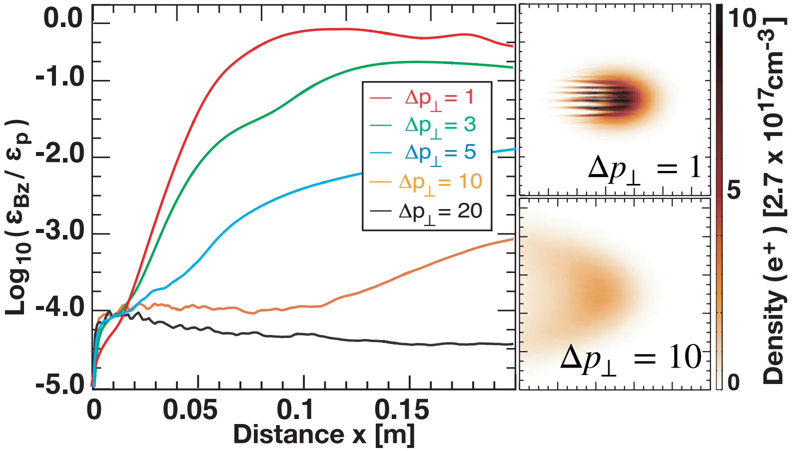


Thermal spread suppresses CFI

filamentation dominates if thermal beam spread is sufficiently small

$$p_{\perp\text{th}} \ll \gamma_b\left(\frac{c\Gamma_{\text{CF1}}\sigma_\perp^2}{L_{\text{growth}}}\right)^{1/2} \propto \gamma_b^{3/4}$$

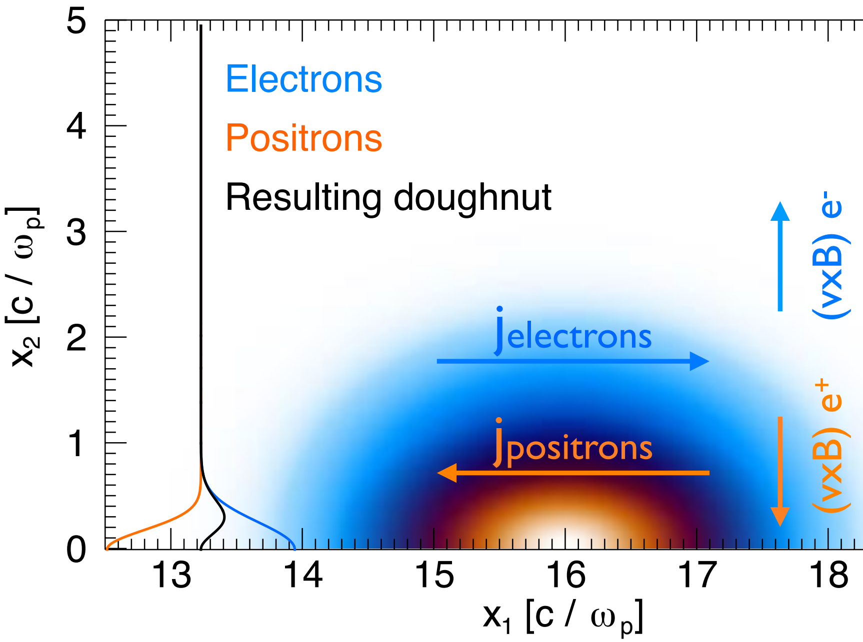
(expansion rate smaller than growth rate)



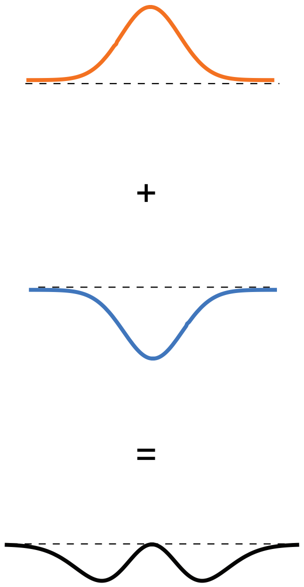
N. Shukla et al., JPP 84 (3) (2018)

Non-neutral fireball beams:
from wakefield acceleration to current filamentation

Non-neutral fireball setup



Density profile



- **Fireball:** co-propagating non-neutral e-e+ beam

  In laboratory astrophysics: filamentation instability appears for $\sigma_r \gg c/\omega_p$

  In plasma acceleration: new instability leads to wakefield excitation for $\sigma_r \lesssim c/\omega_p$

- **Fireball non-neutrality** acts as seed to trigger instabilities

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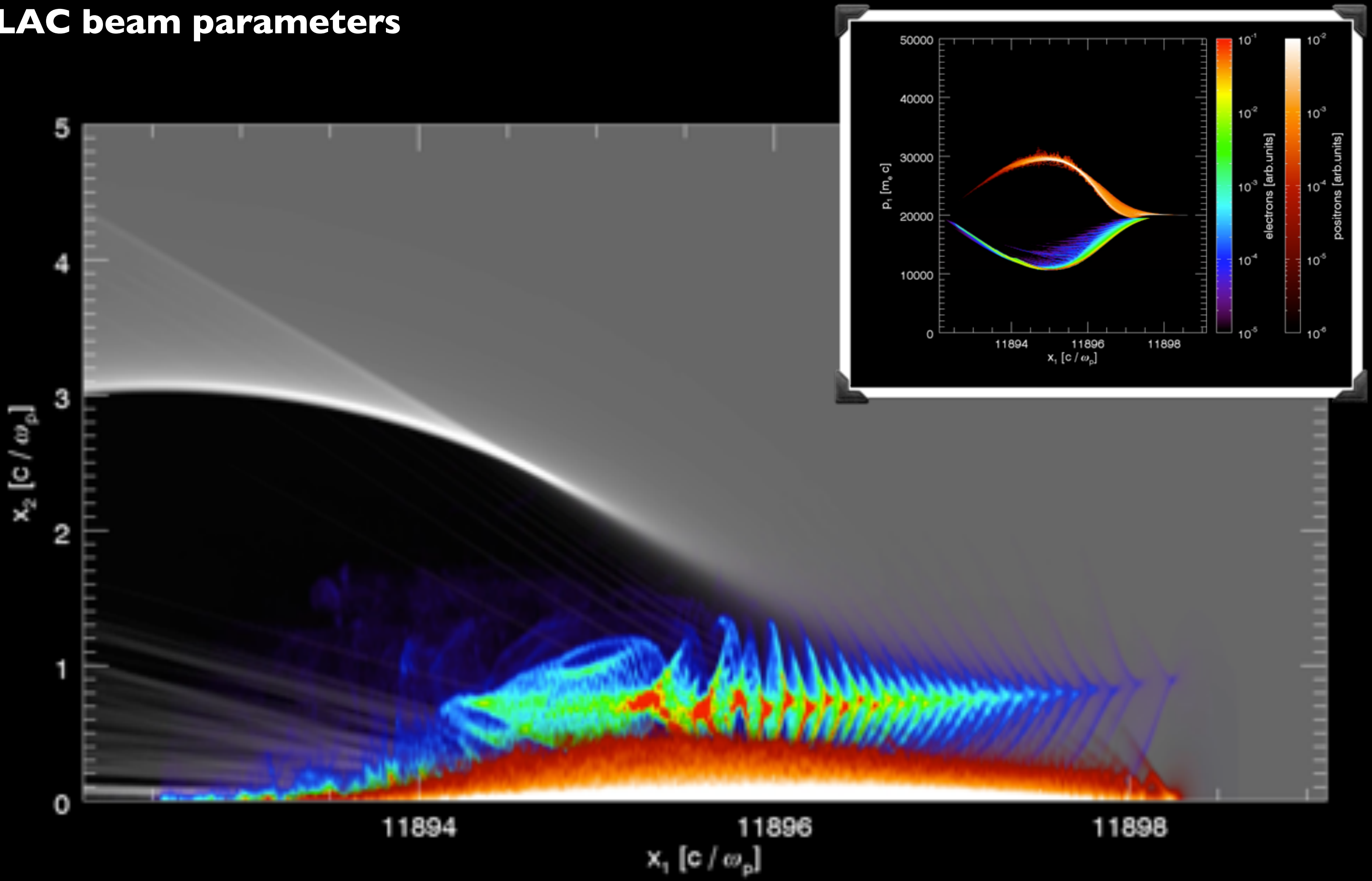
Positron acceleration by non-neutral fireballs

SLAC beam parameters



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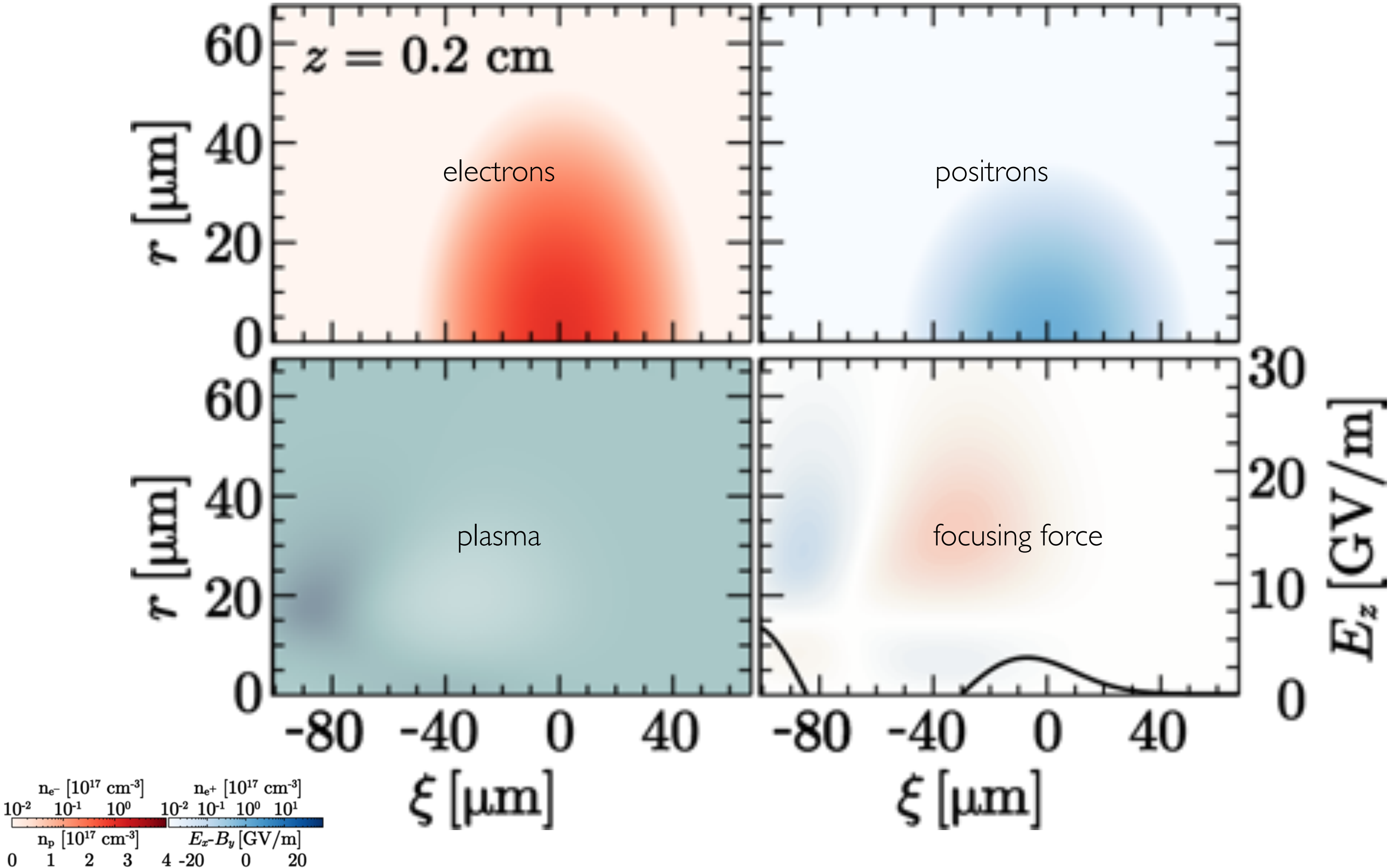
Single-filament instability of non-neutral fireballs

SLAC beam parameters



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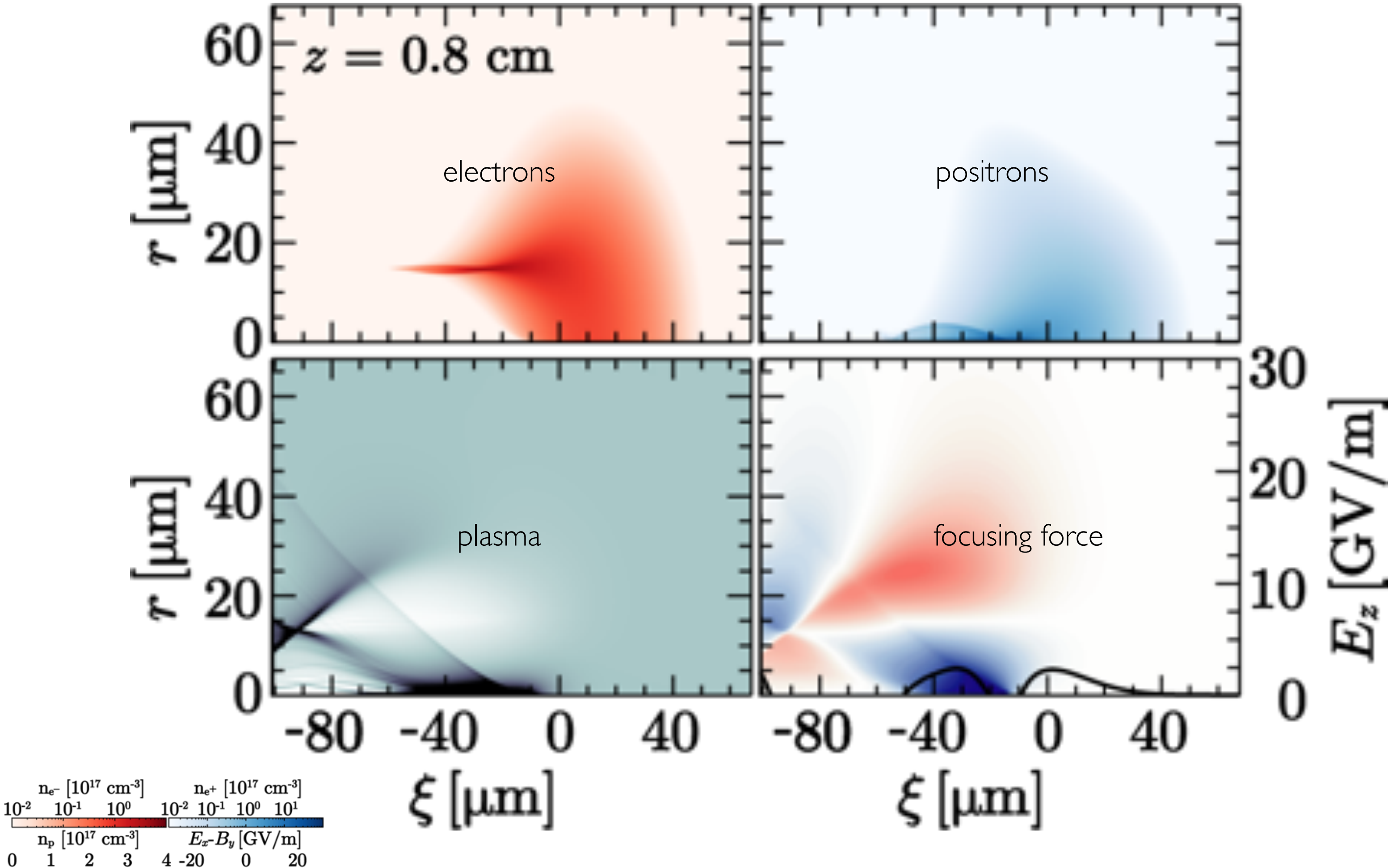
Single-filament instability of non-neutral fireballs

1. Unstable feedback loop leads to spatial separation of the beam



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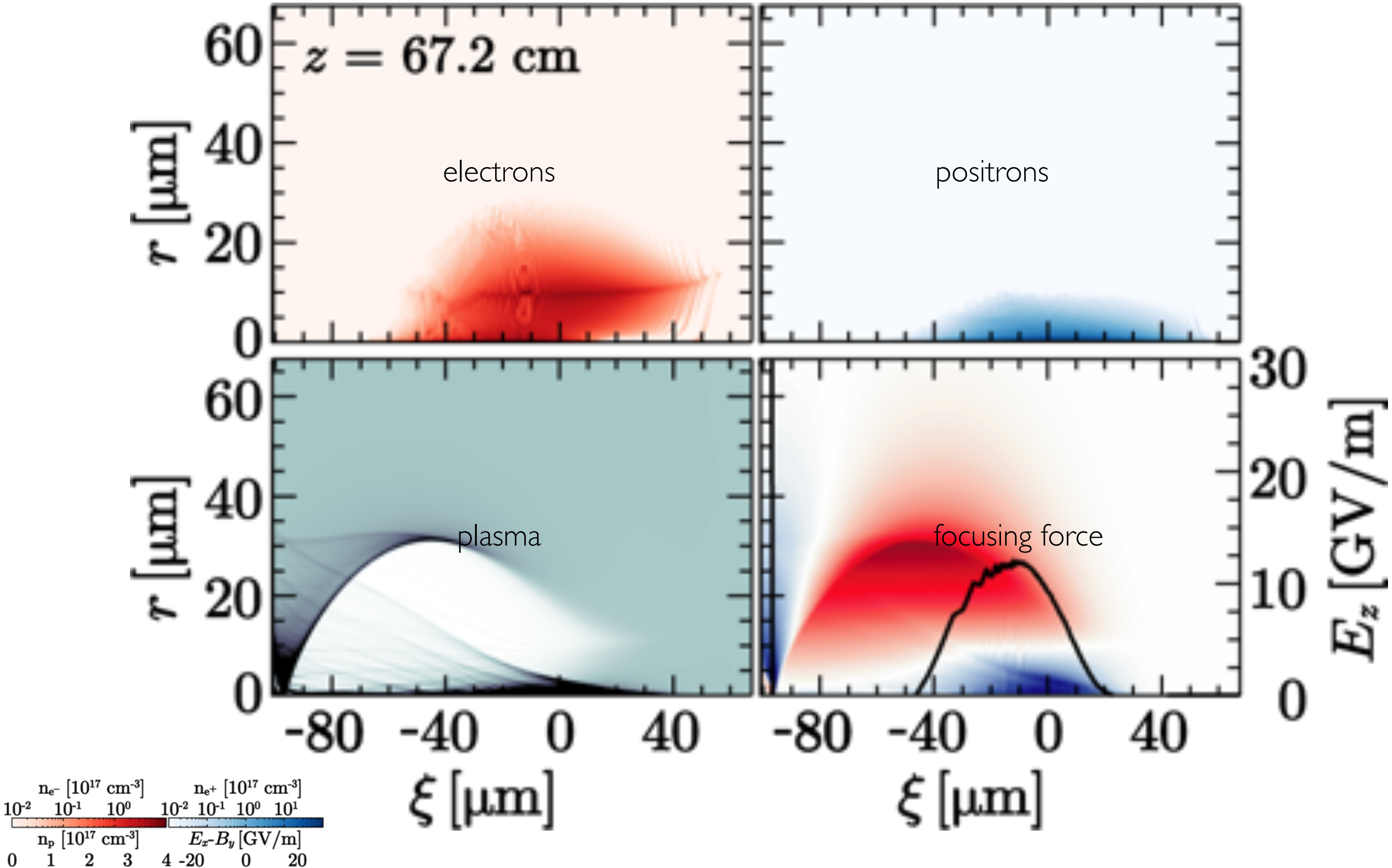
Single-filament instability of non-neutral fireballs

2. Formation of dense plasma electron filament on-axis



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Summary

Plasma microphysics is important to understand properties of B-fields + their evolution + radiation + particle acceleration in a wide variety of astrophysical scenarios

Relativistic particle beams can probe some of the relevant microphysics

Numerical simulations and theoretical estimates show that lab experiments (e.g. SLAC, laser-driven beams, CERN) can now explore the onset and saturation of the current filamentation/ Weibel instability

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