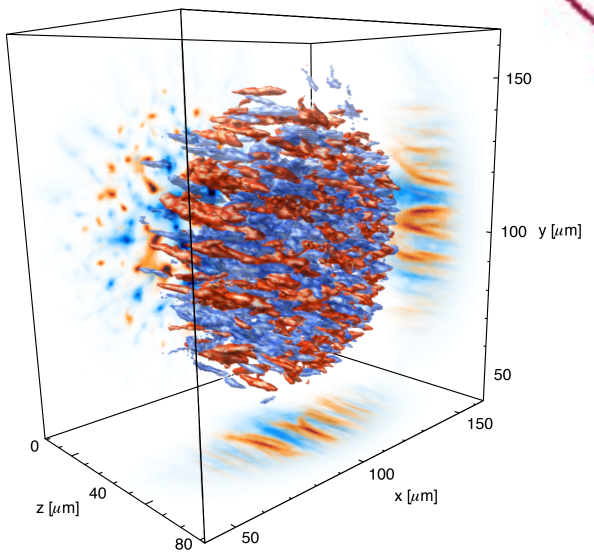
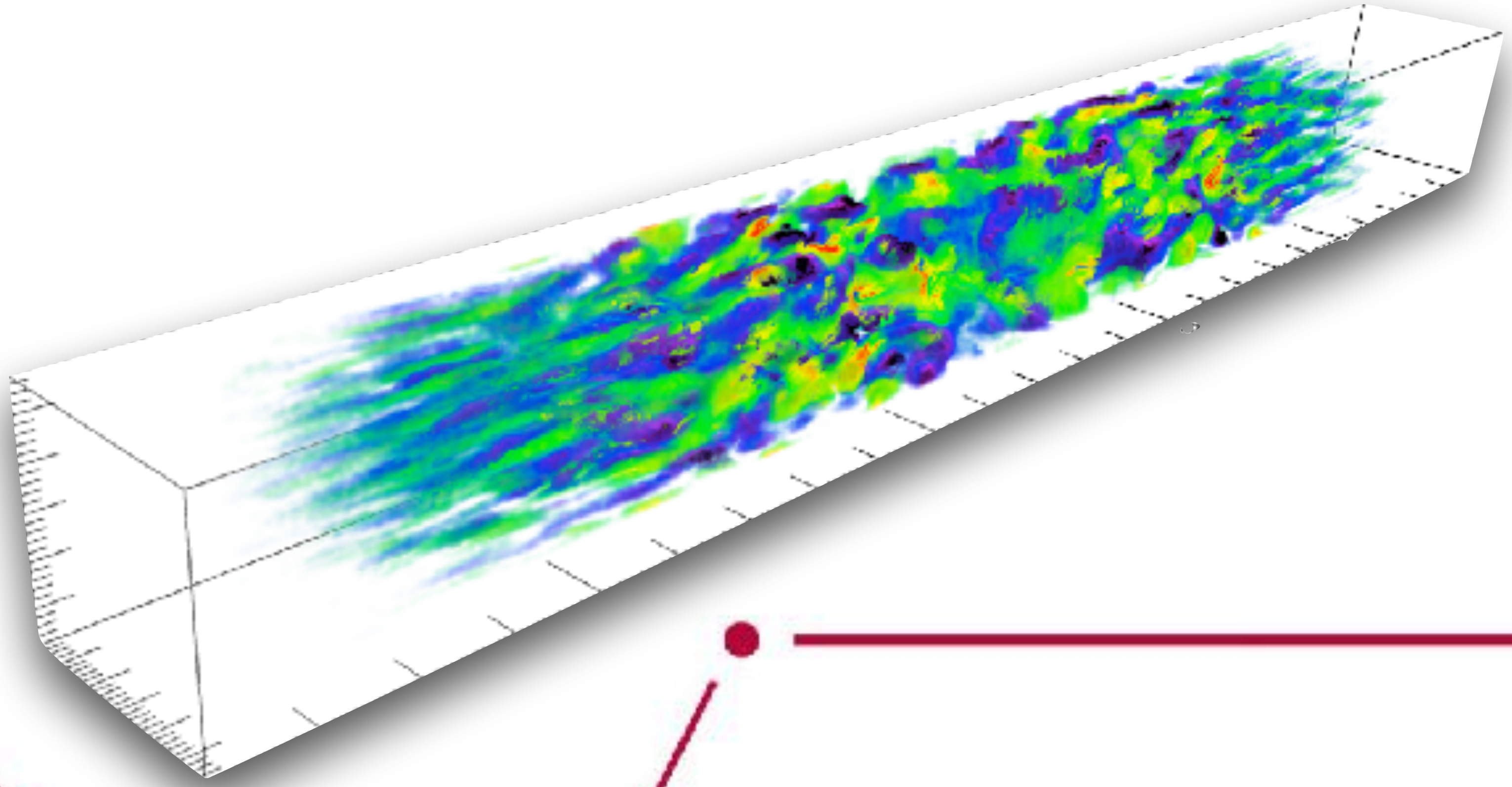
Laboratory astrophysics with electron-positron beams at FACET-II

Frederico Fiúza

fiuza@slac.stanford.edu





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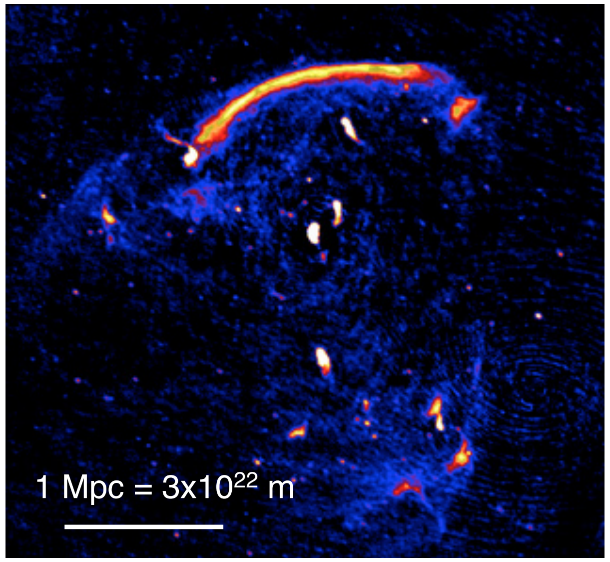
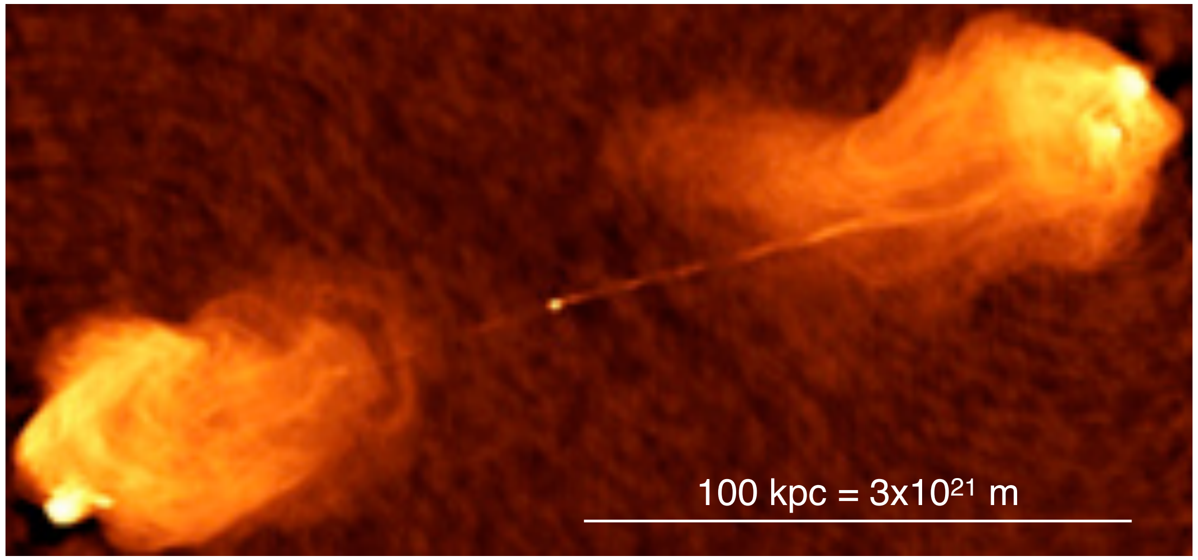
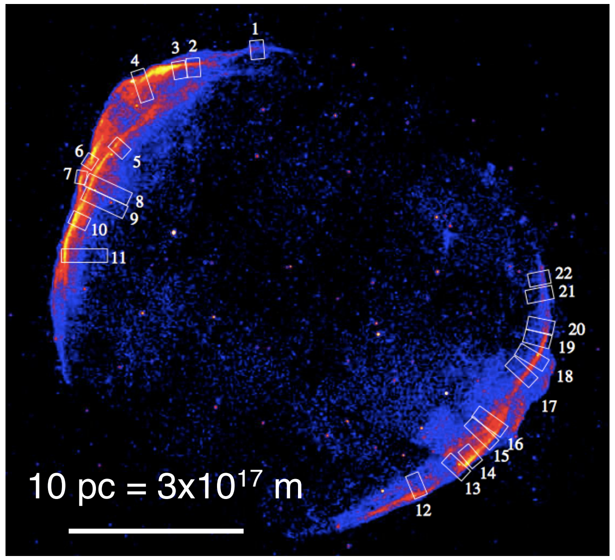
Outline

- Introduction: the role of relativistic micro-instabilities in astrophysical plasmas
- Interaction of fireball beam with plasma: transition from oblique and Weibel instabilities
- Current-driven magnetic field amplification
- Conclusions

Plasma processes shape high-energy astrophysical environments

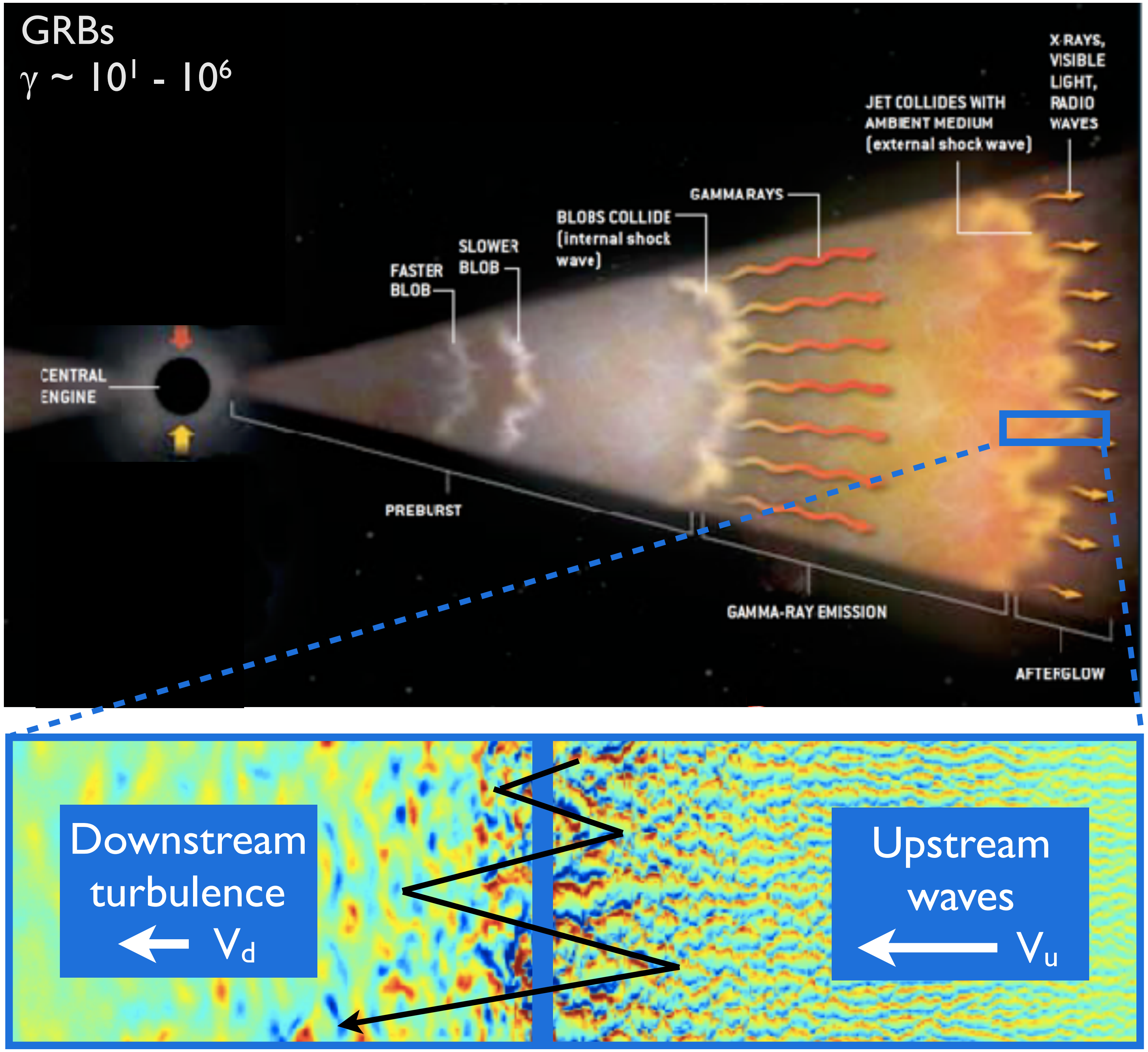

Galaxy Clusters


AGN jets / Blazars

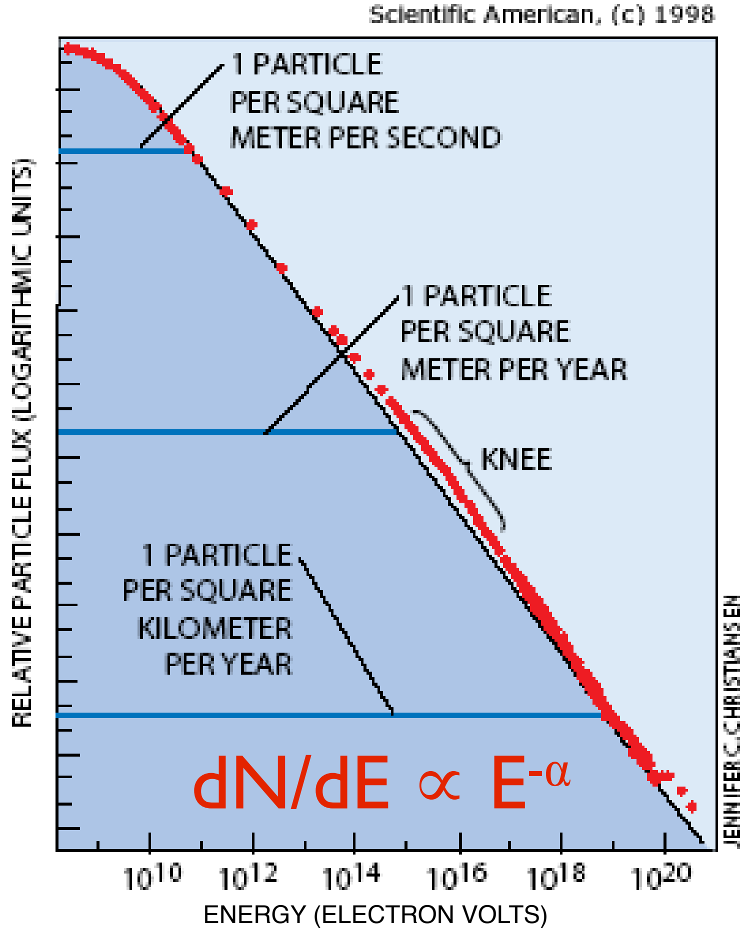

Supernovae remnants

- Span a wide range of scales and plasma conditions:
  - non-relativistic ($v = 100 - 1000$ km/s) to highly relativistic ($\gamma = 10^6$)
  - weakly magnetized to highly magnetized
- Can amplify magnetic fields and accelerate particles to very high energies: up to 10^{21} eV
- Emit radiation across entire EM spectrum: radio to γ-rays
- Significant progress in understanding of non-relativistic systems from solar system, but studies of highly relativistic environments are limited

The relativistic fireball model for GRBs



CR spectrum

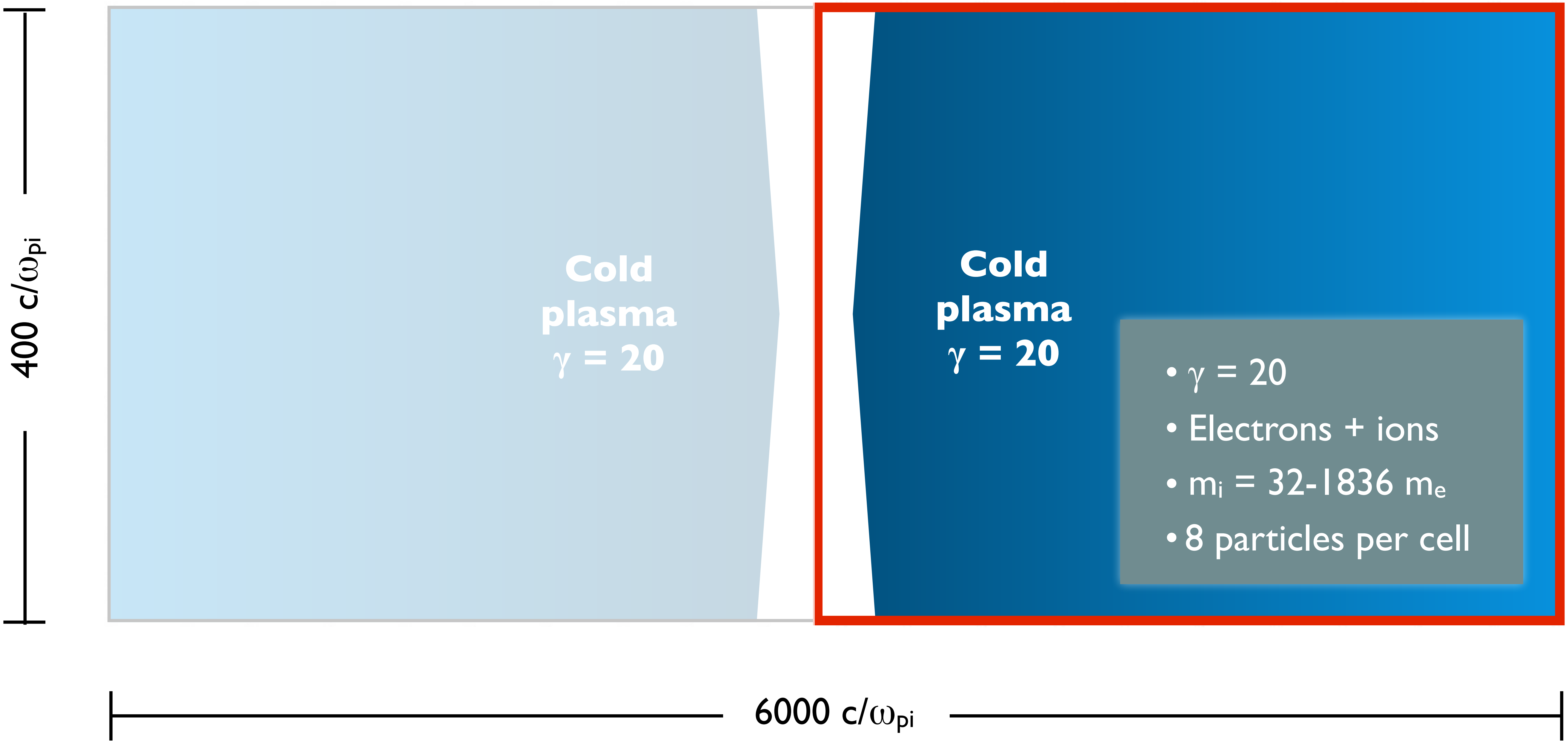


Which collisionless processes (plasma instabilities) mediate the slow down of energetic flows, amplification of B-fields, and the acceleration of particles?

N. Gehrels, L. Piro, and P.J.T. Leonard, Scientific American (2002)
R. Blandford & D. Eichler, Physics Reports 154, 1 (1987)

We want to understand interaction of relativistic collisionless plasma flows

Simulation setup for interaction of two semi-infinite plasmas



$400\ c/\omega_{pi}$

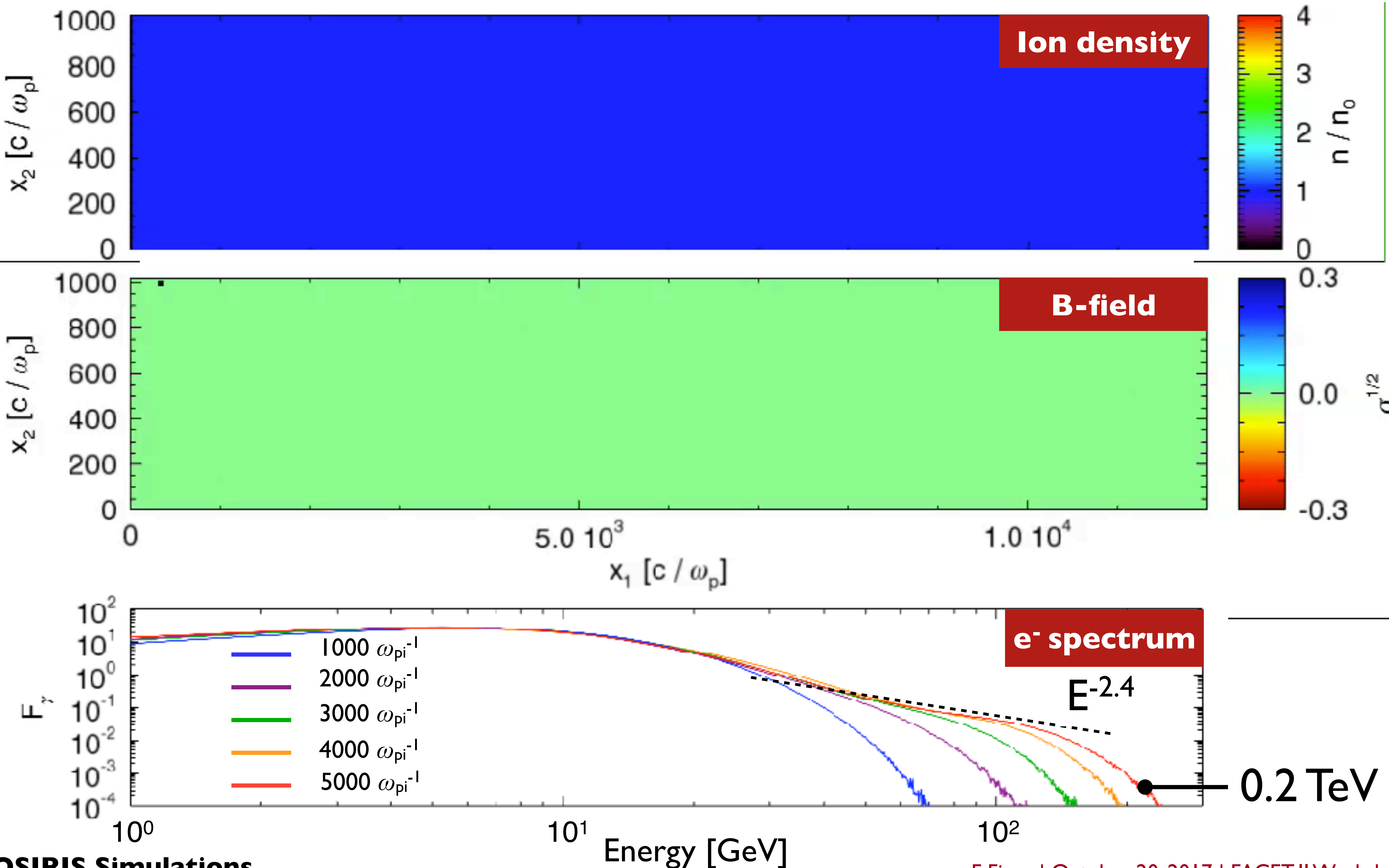
Cold plasma $\gamma = 20$

Cold plasma $\gamma = 20$

- $\gamma = 20$
- Electrons + ions
- $m_i = 32\text{-}1836\ m_e$
- 8 particles per cell

$6000\ c/\omega_{pi}$

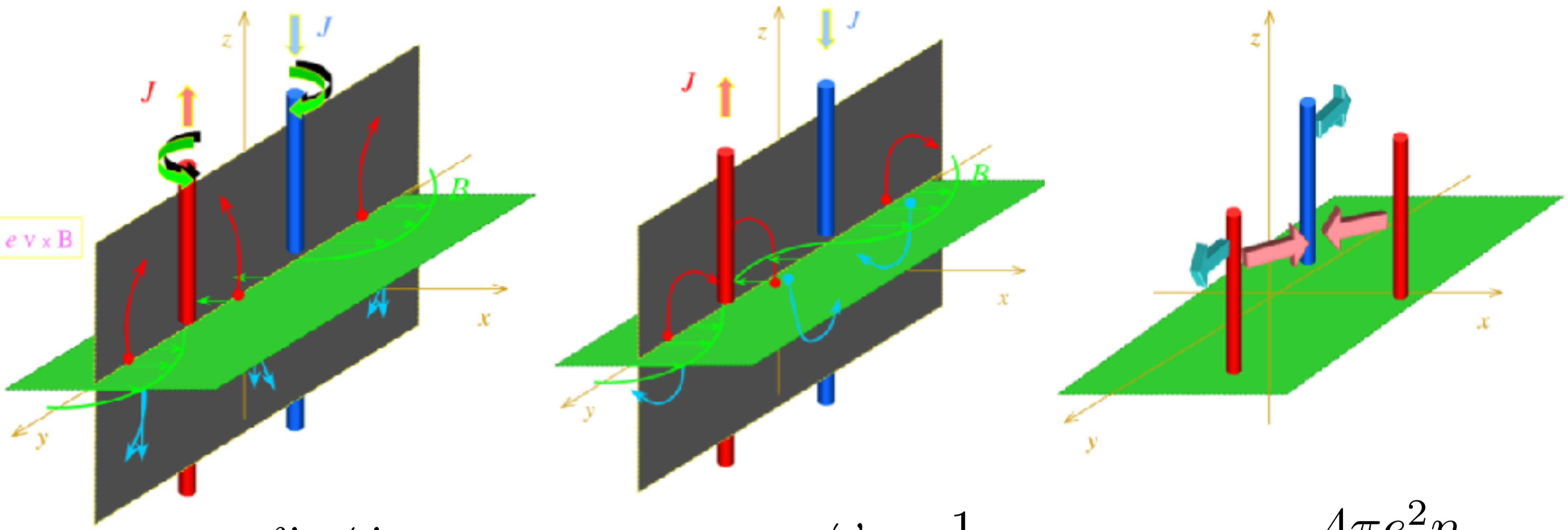
Relativistic collisionless shocks are good particle accelerators



0.2 TeV

OSIRIS Simulations

Weibel instability (CFI) dominates in unmagnetized relativistic plasmas



Linear regime

$$\Gamma_W = \frac{v_0}{c}\frac{\omega_p}{\gamma_0^{1/2}}$$

Saturation

$$k_{max} = \frac{\omega_p}{c}\frac{1}{\gamma_0^{1/2}}$$

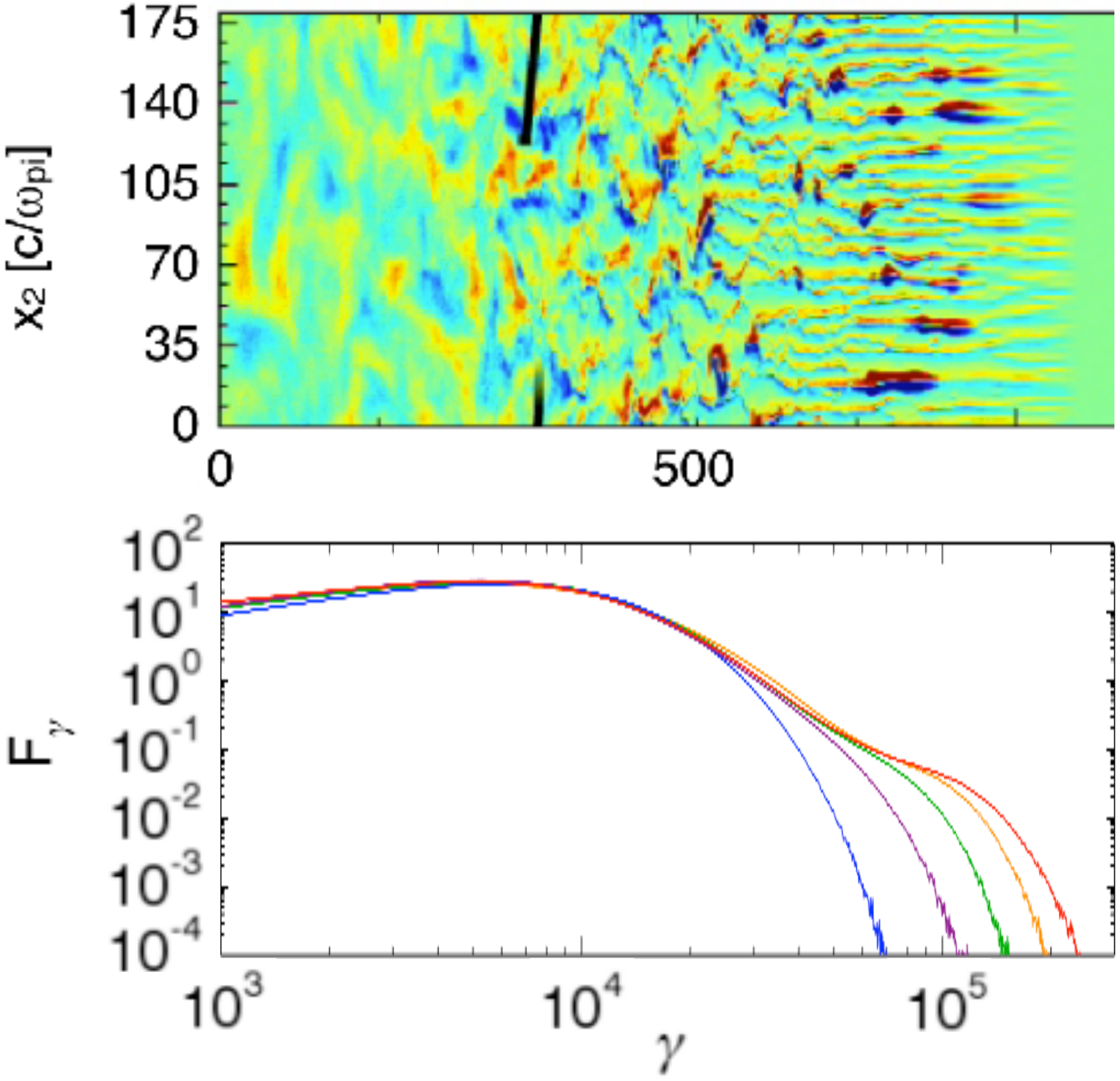
Merging

$$\omega_p^2 = \frac{4\pi e^2 n}{m}$$

Instability can transfer significant fraction (1-10%) of kinetic energy of plasma flows into magnetic energy

E. S. Weibel, PRL 2, 83 (1959); B. D. Fried, Phys. Fluids 2, 337 (1959)
A. Gruzinov & E. Waxman, APJ 511, 852 (1999); M. Medvedev & A. Loeb, ApJ 526, 697 (1999)
L. O. Silva et al., ApJ 596, L121 (2003)
A. Spitkovsky ApJ 673, L39 (2008)

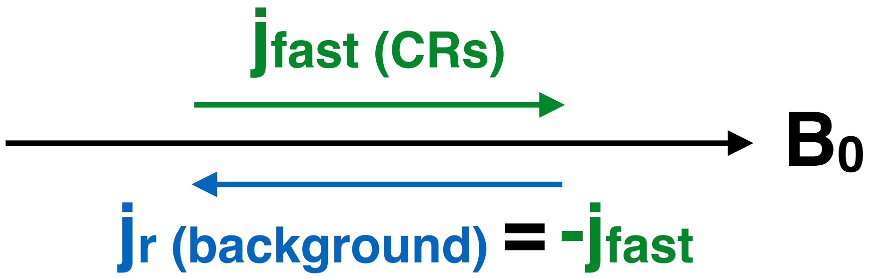
Long-term evolution is not yet well understood



- **How do current filaments break and lead to onset of turbulence?**
- **What is the long-term fate of Weibel-driven B-fields?**
- **How do CRs amplify ambient field at large scales?**

A. Spitkovsky ApJ 673, L39 (2008)
S. F. Martins ApJ 695, L189 (2009)
U. Keshet et al., ApJ 693, L127 (2009)
F. Fiuza et al., PRL 108, 235004 (2012)

CRs current-driven magnetic field amplification (Bell instability)



j_{fast} (CRs)

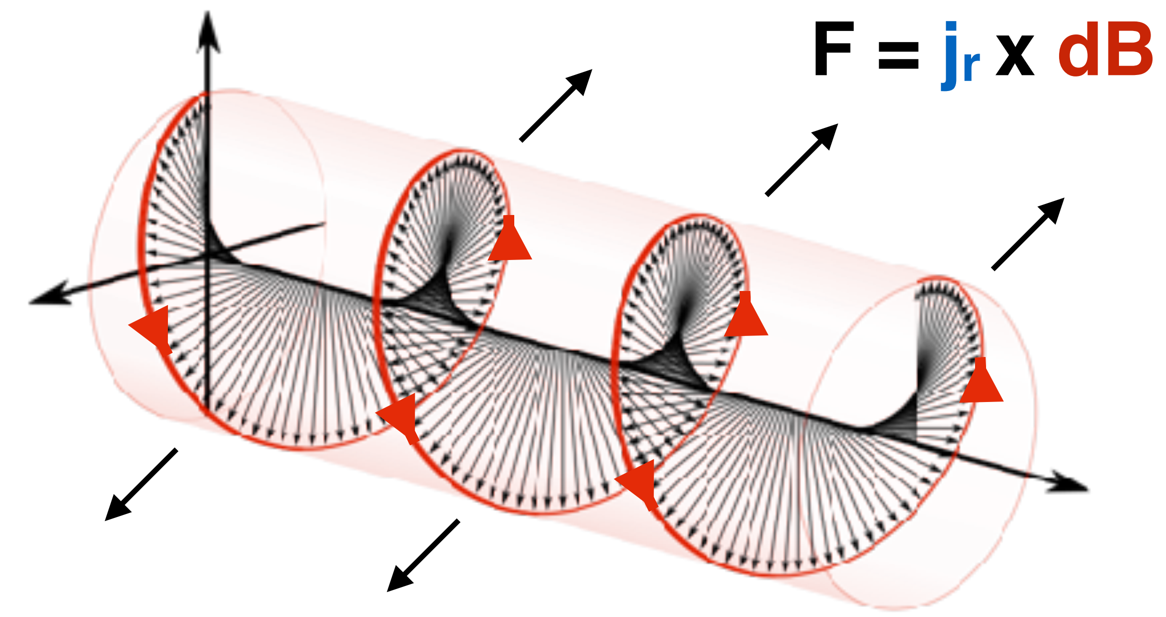
B_0

j_r (background) = $-j_{fast}$

Fast particles are unmagnetized

Background is magnetized

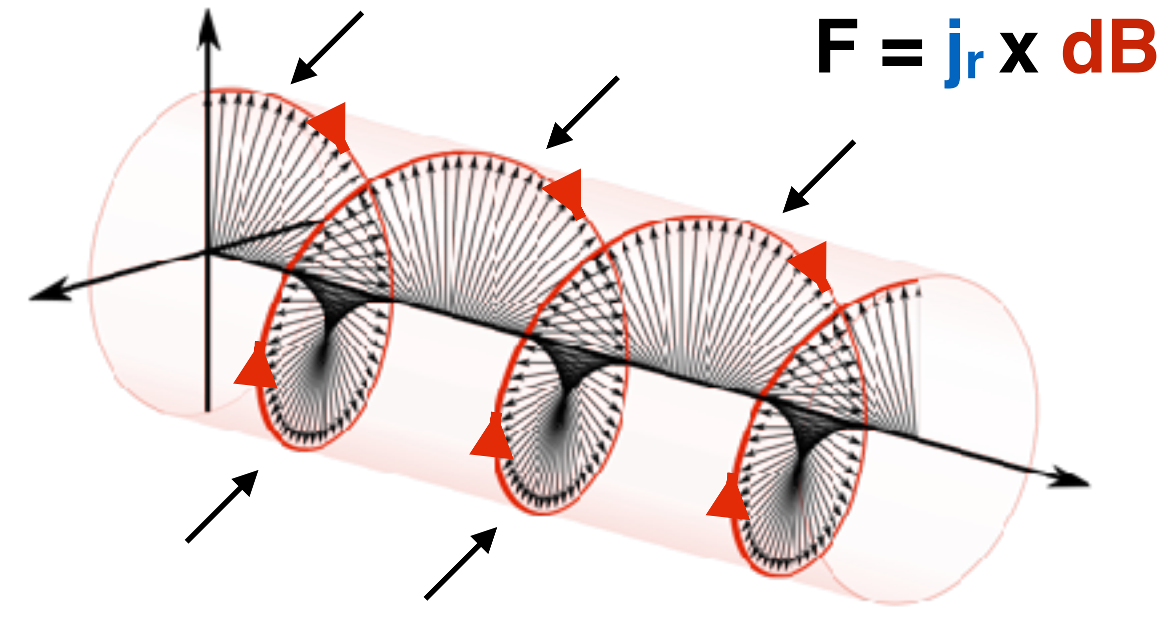
Right-hand circular polarization



F = j_r x dB

B-field amplification

Left-hand circular polarization



F = j_r x dB

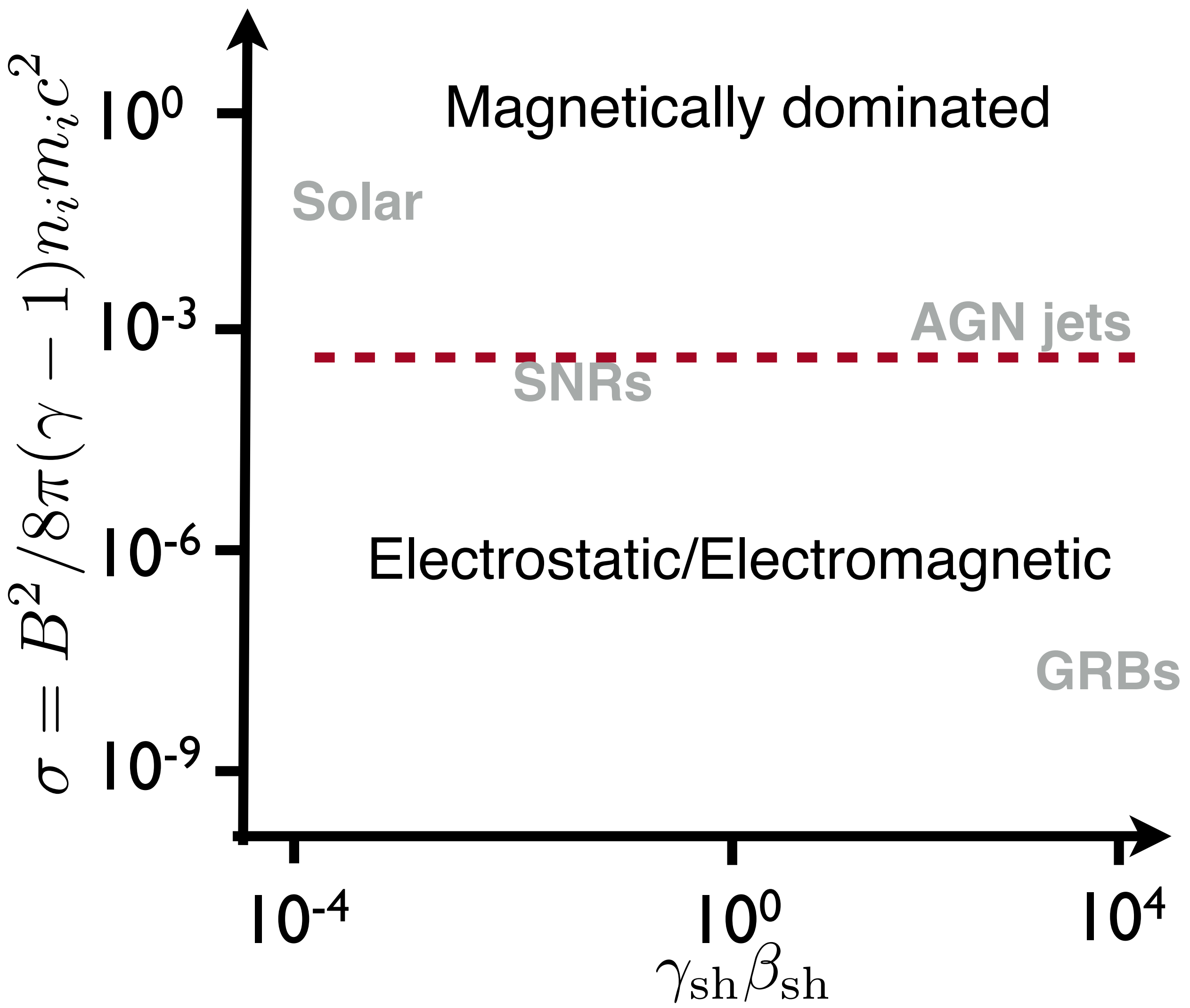
No amplification

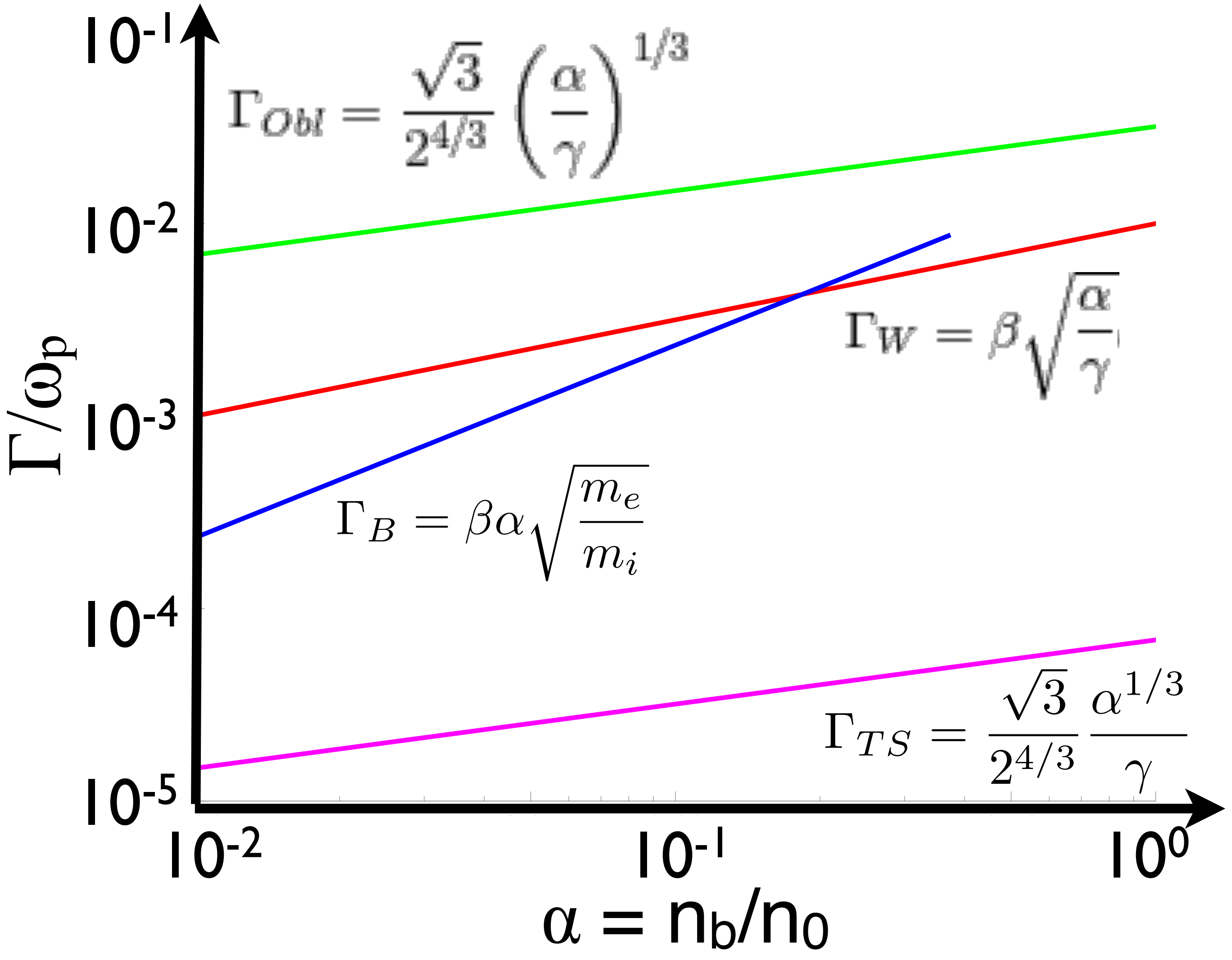
$$\Gamma_B = \frac{v_b}{c}\frac{n_b}{n_0}\sqrt{\frac{m_e}{m_i}}\omega_p \qquad k_{max} = \frac{1}{2}\frac{v_b}{v_A}\frac{n_b}{n_0}\sqrt{\frac{m_e}{m_i}}\frac{\omega_p}{c} \qquad v_{A,sat} \approx v_b$$

Bell instability leads to non-resonant amplification of circularly polarized waves

S. G. Lucek, A. R. Bell, MNRAS 314, 65 (2000); A. R. Bell, MNRAS 353, 550 (2004)

Beam-plasma interaction depends on the plasma conditions

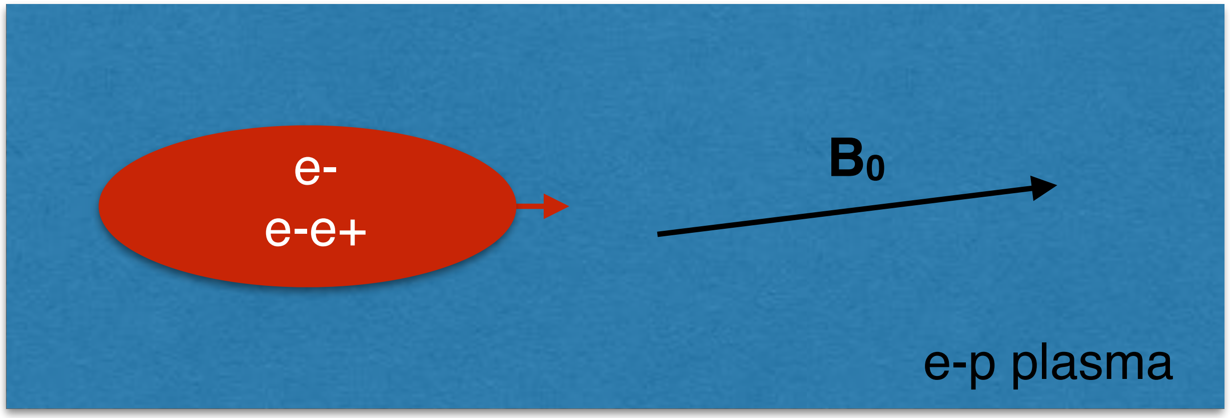

Astrophysical objects


Growth rates for beam with $\gamma = 10^4$ (5 GeV)

We want to understand the plasma physics that governs these different regimes

A. Bret, L. Gremillet, M. Dieckmann, Phys. Plasmas 17, 120501 (2010)
L. Sironi, A. Spitkovsky, J. Arons, ApJ 711, 22 (2013)
A. Stockem, F. Fiuza et al., Sci. Reports 4, 3934 (2014)

FACET-II experiments could probe interplay between different instabilities in the relativistic regime for the first time



Range of parameters:

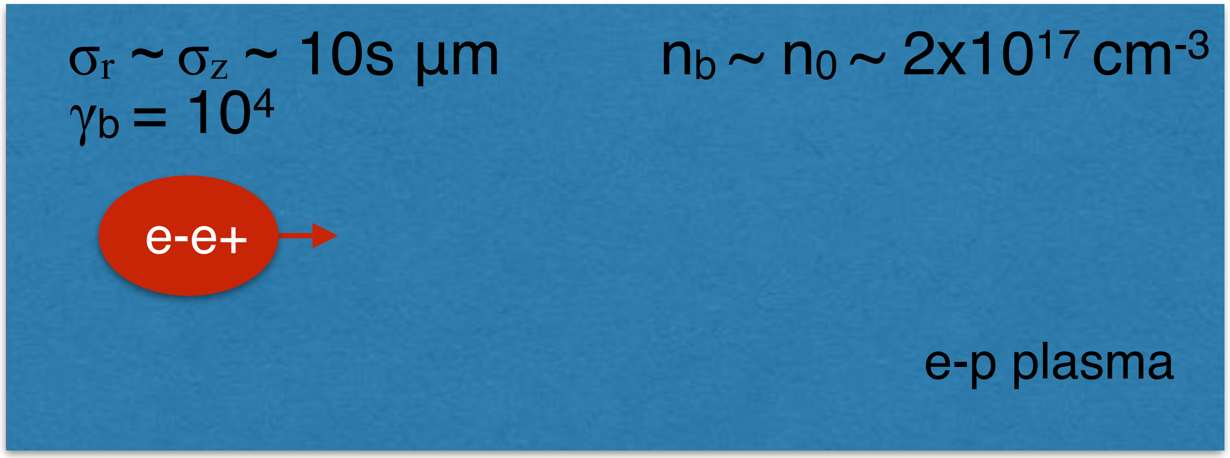
$n_b/n_0 = 0.01 - 1$

$\gamma_b = 10^3 - 10^4$

$B_0 = 1\text{-}10$ T

- **First experimental demonstration of these instabilities in relativistic regime**
- **Explore competition of modes in linear regime and non-linear stage for a wide range of parameters**
- **Identify dominant radiation mechanisms**
- **Provide careful benchmark for numerical and theoretical models**

Fireball beams in the lab



$\sigma_r \sim \sigma_z \sim$ 10s μm

$\gamma_b = 10^4$

$n_b \sim n_0 \sim 2\text{x}10^{17}\ \text{cm}^{-3}$

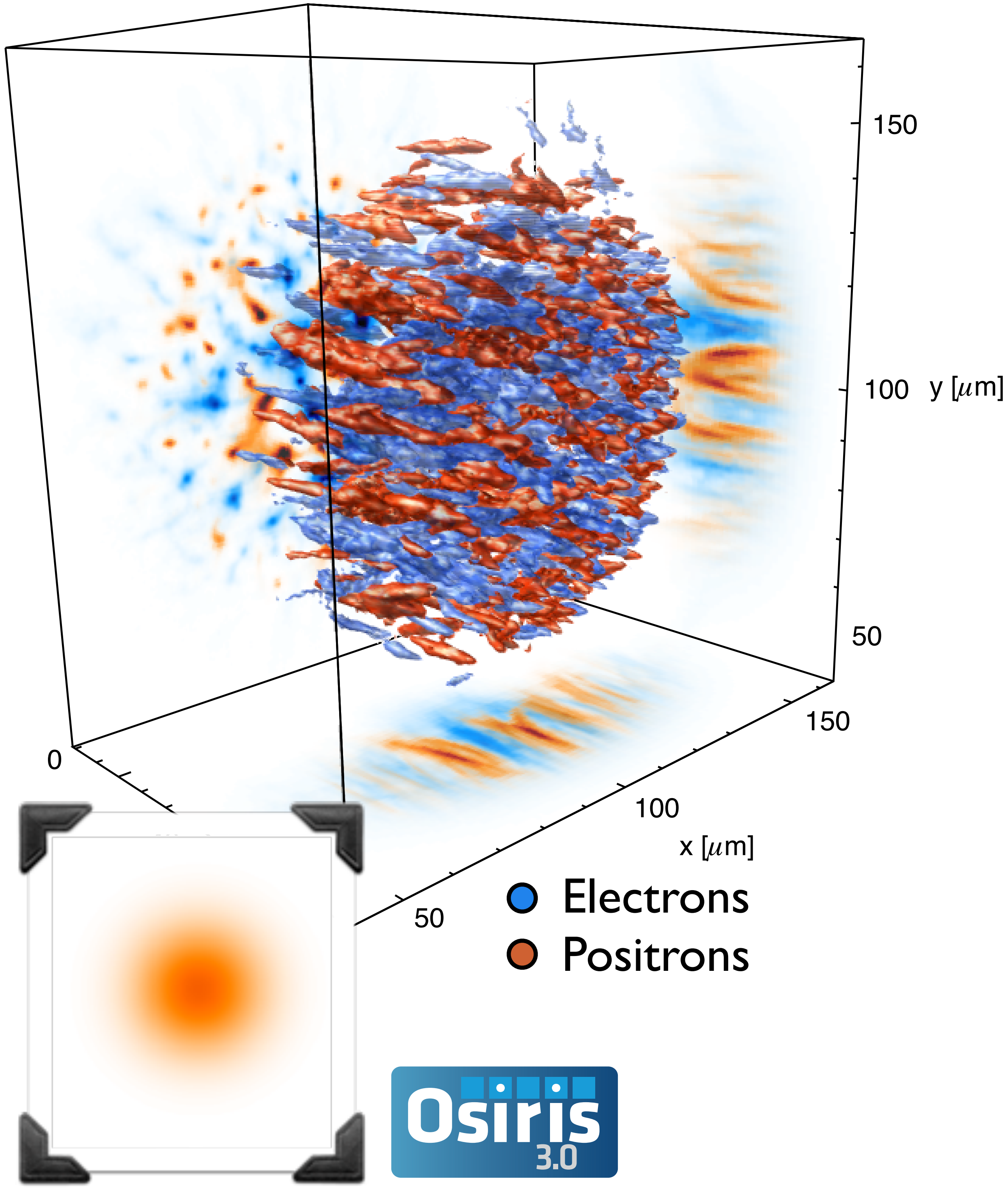
e-e+

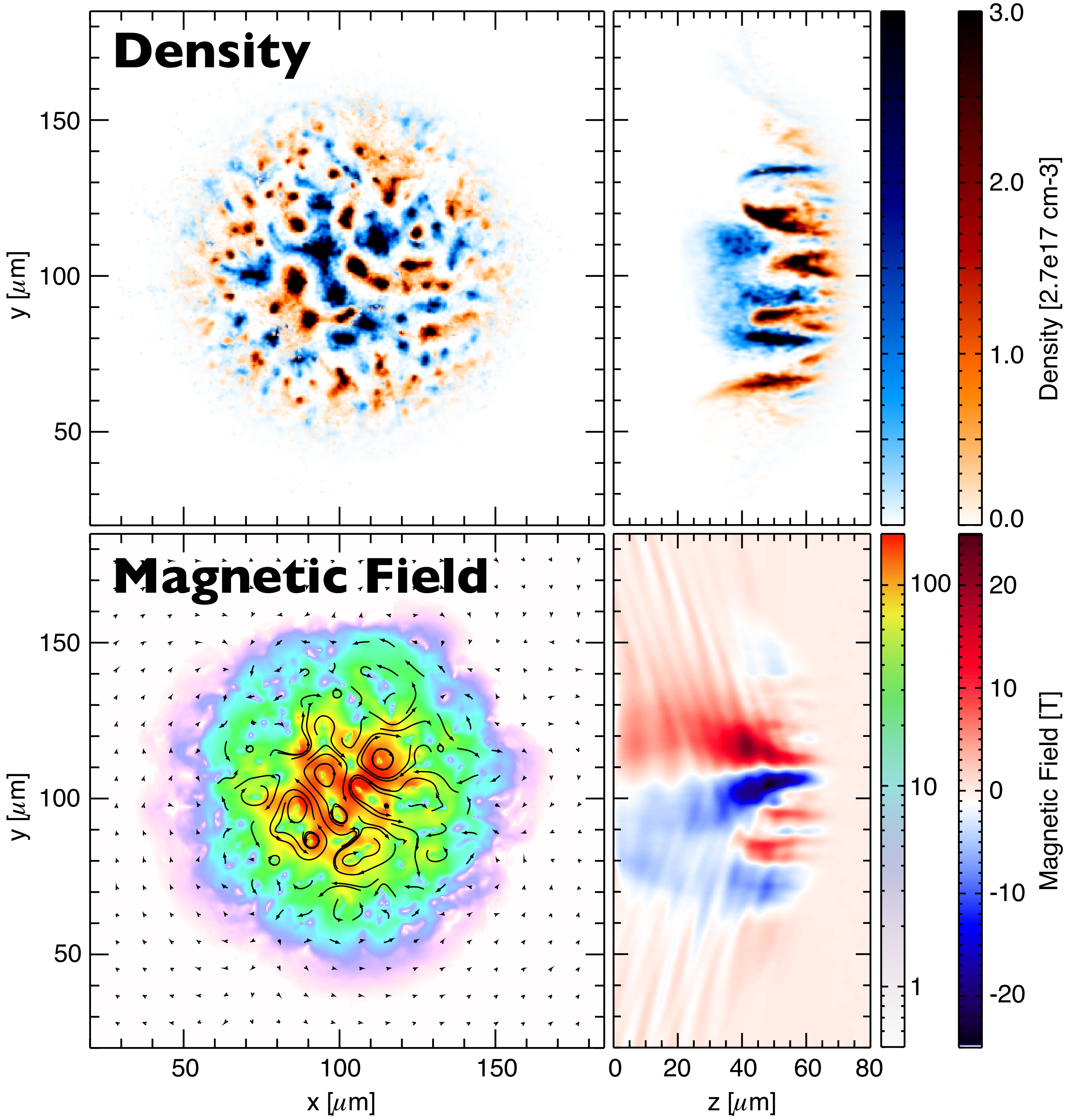
e-p plasma

e-e+ fireballs: astrophysics in the laboratory

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

* P. Muggli, S. F. Martins, N. Shukla, J. Vieira and L. O. Silva, arXiv:1306.4380 (2013)





Osiris 3.0

Filamentation in the lab: avoid competing mechanisms

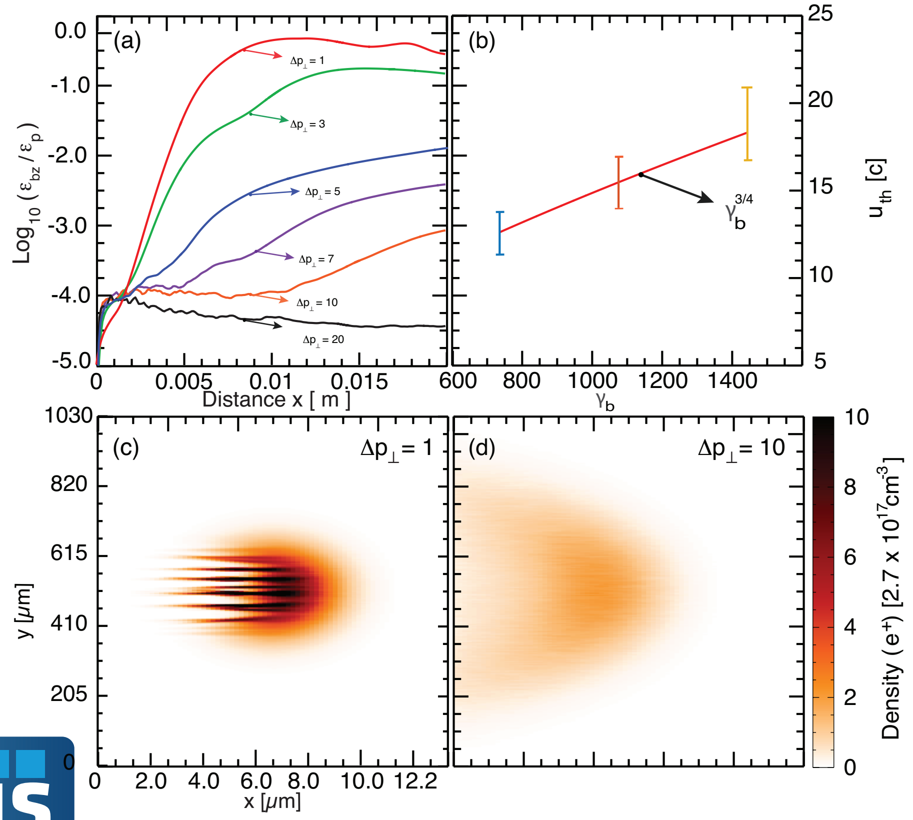
simulations performed considering fireball bunches with < 1 GeV

Thermal spread suppresses CFI

filamentation dominates if thermal beam spread is sufficiently small

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

(expansion rate smaller than growth rate)



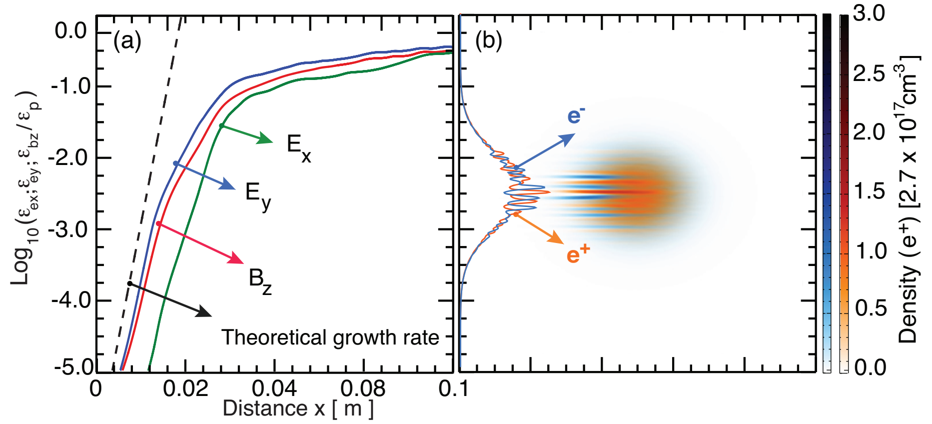
Role of electrostatic instabilities

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

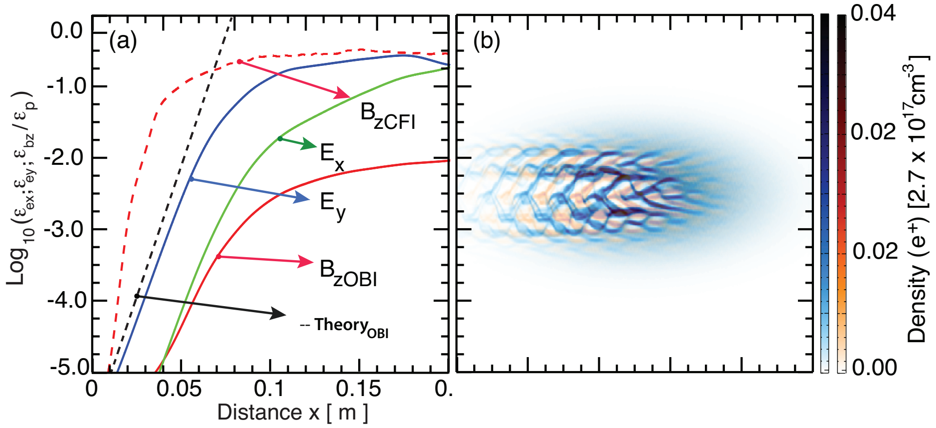
$$\frac{\Gamma_{\mathrm{Oblique}}}{\Gamma_{\mathrm{CFI}}} = \frac{\sqrt{3}}{2^{4/3}} \frac{1}{\beta_b} \left(\gamma_b \frac{n_0}{n_b} \right)^{1/6}$$

(filamentation vs oblique instability competition)

filamentation



oblique

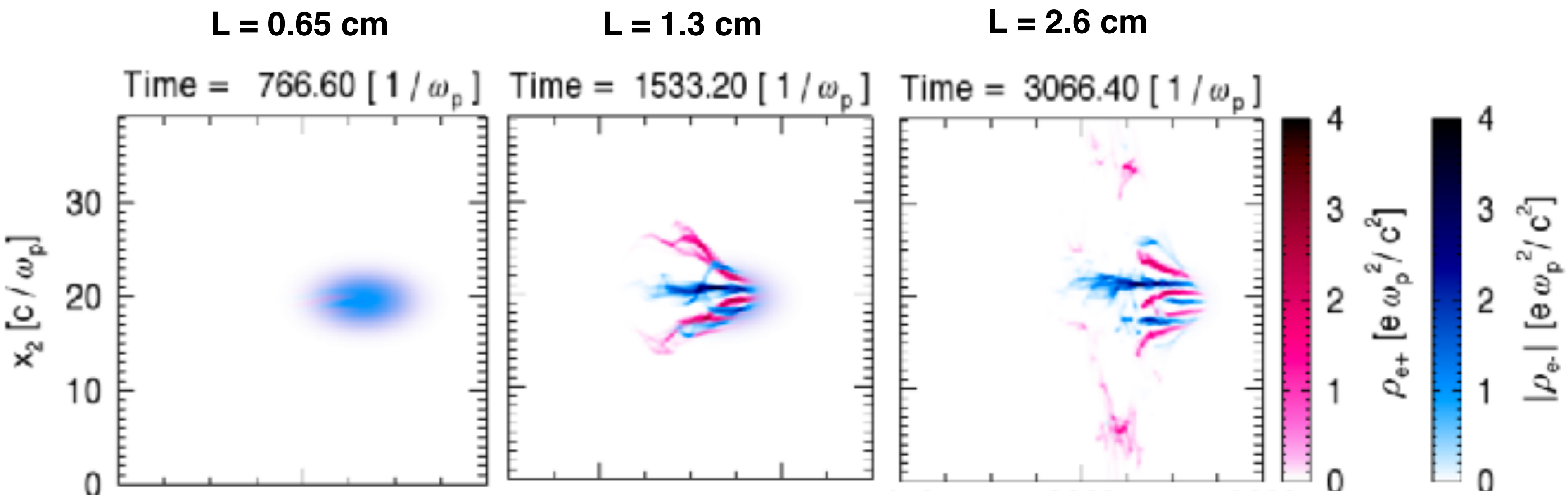


Osiris 3.0

N. Shukla *et al.* submitted to JPP (2017)

Current filamentation leads to excitation of nonlinear wake

Current filamentation/ separation between e+ and e-



Background plasma cannot fully compensate short beam current

For short beams (few c/ω_p) strong wakefield is excited at late times

- **Direct imaging of Weibel B-fields and their decay can be challenging (fields dominated by wake for c/ω_p scale beams)**
- **Transition radiation from beams at exit of the plasma would allow characterization of instability as a function of background plasma length/density**

Polarisation as a diagnostic for the filamentation instability

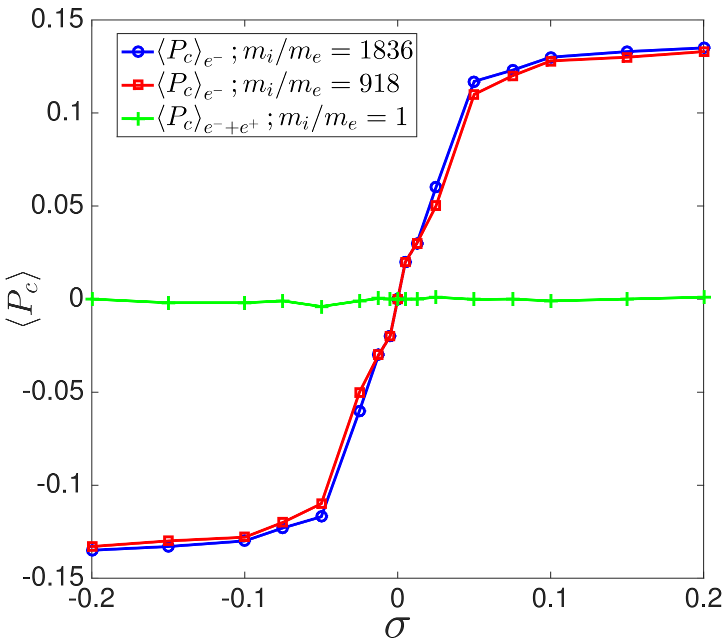
2D simulations, periodic boundaries, 10 MeV fireball

Circularly polarised astro bursts

recent observation of circularly polarised x-ray bursts [Weirsema *et al.*, Nature, **509**, 201 (2014)]

filamentation instabilities consistent with observations for:

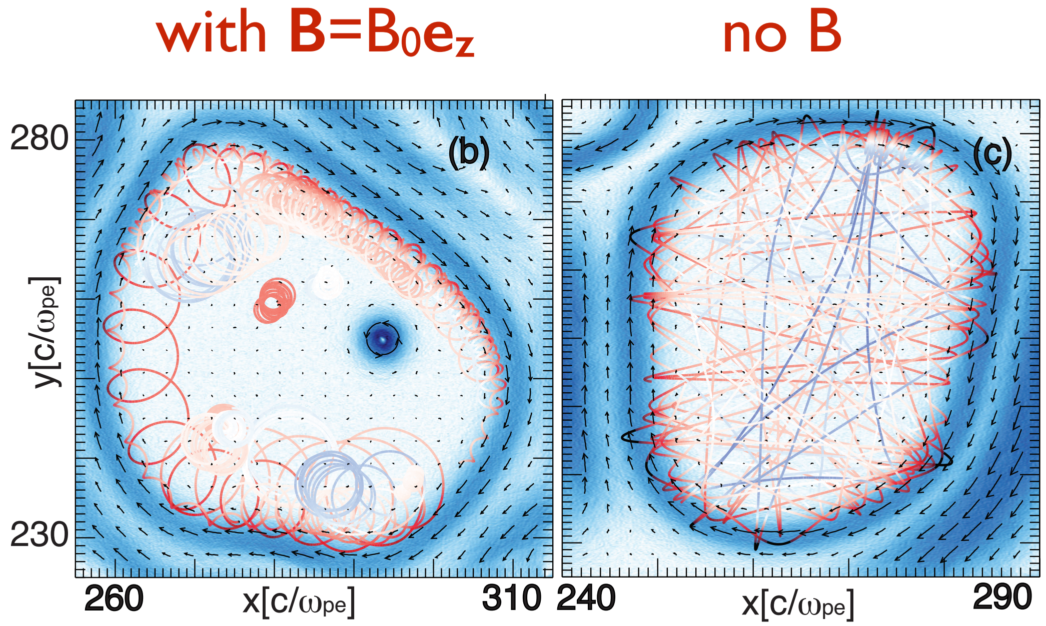
- large mass ratios
- magnetised configurations



jRad simulations for radiation emission (J. L. Martins *et al.* Proc. SPIE (2009))

Physical mechanisms

- large mass ratios required for stable filaments at the electron scale
- external B fields induce overall electron rotation along filament

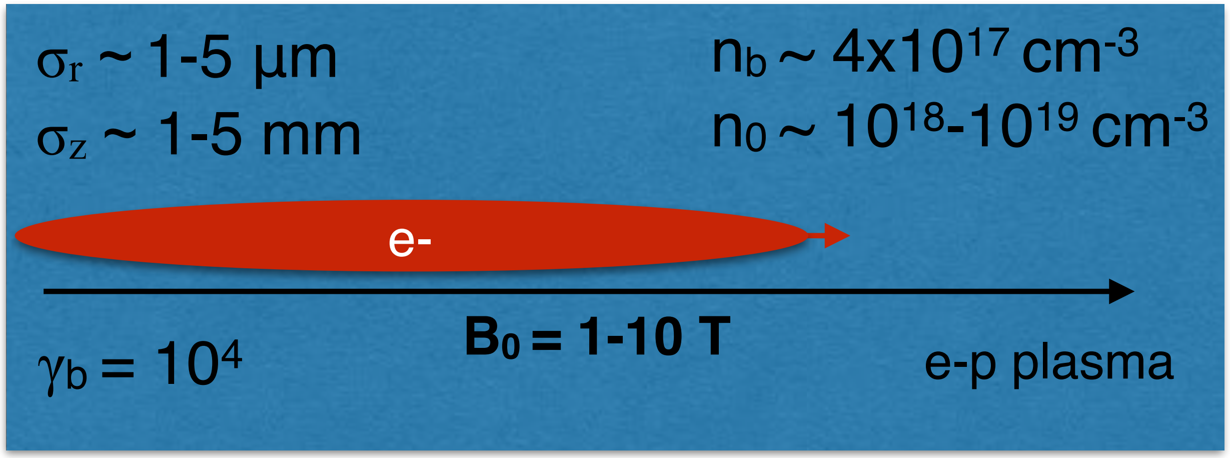

with B=$B_0 e_z$ no B

$$\sigma = B_z^2/(4\pi\gamma_0 m_e n_0 c^2)$$

<Pc> is average polarisation level

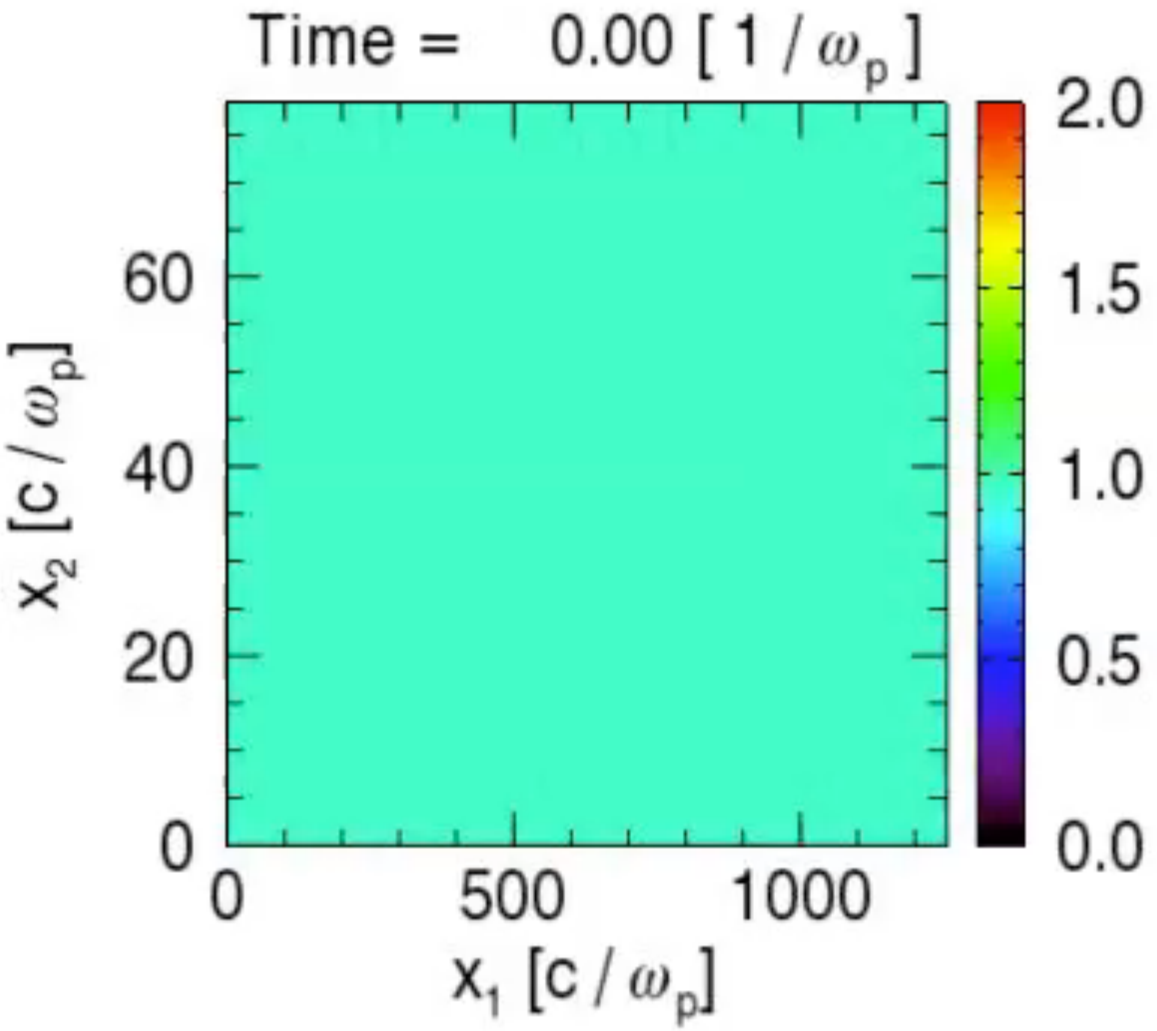
U. Sinha *et al.* to be submitted to PRL (2017)

Bell instability driven by e-beam in the lab

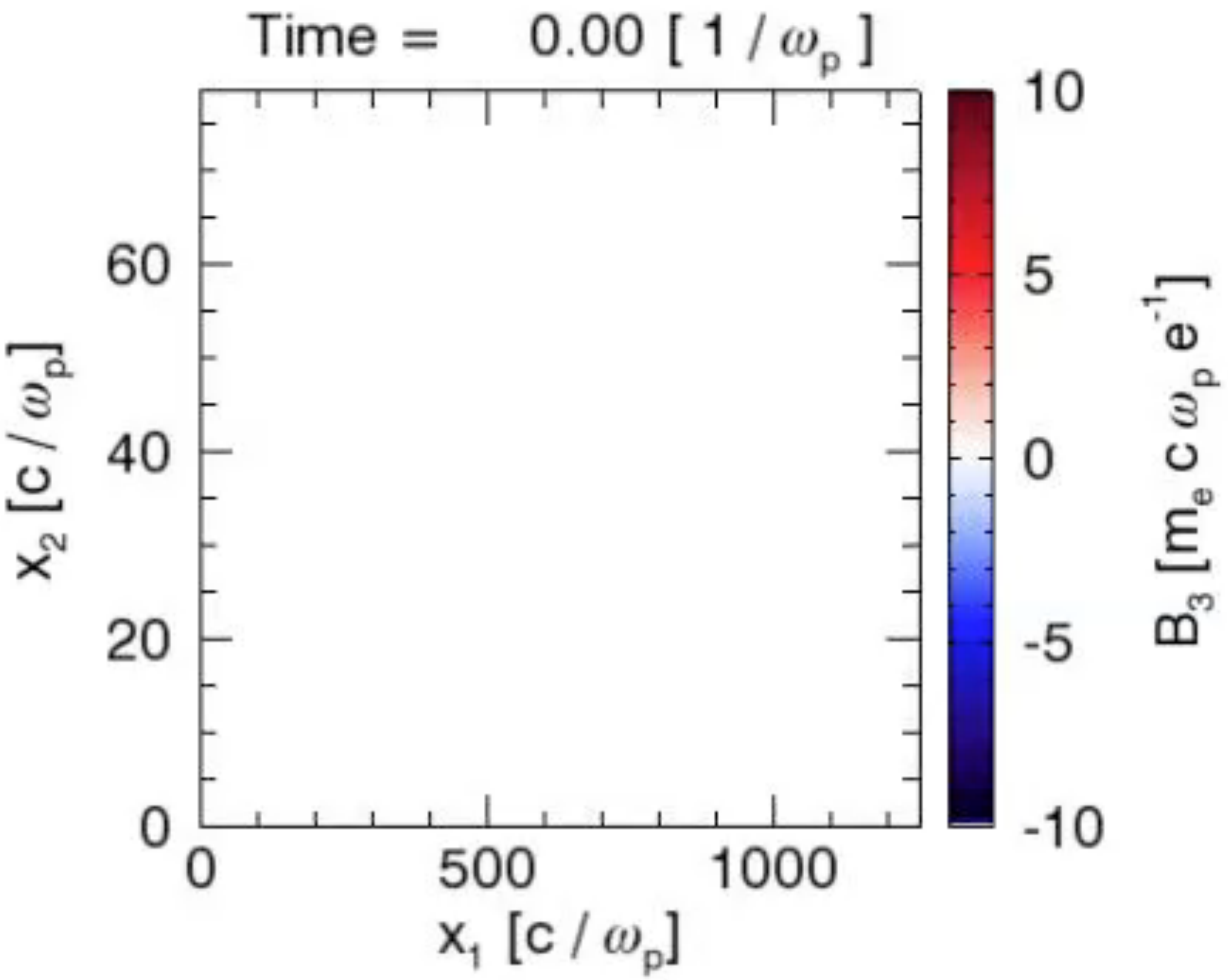


Bell instability dominates long-term interaction for $n_b/n_0 \sim 0.01 - 0.4$ and $v_A/c \sim 10^{-3} - 10^{-1}$

Background density (n/n_0)



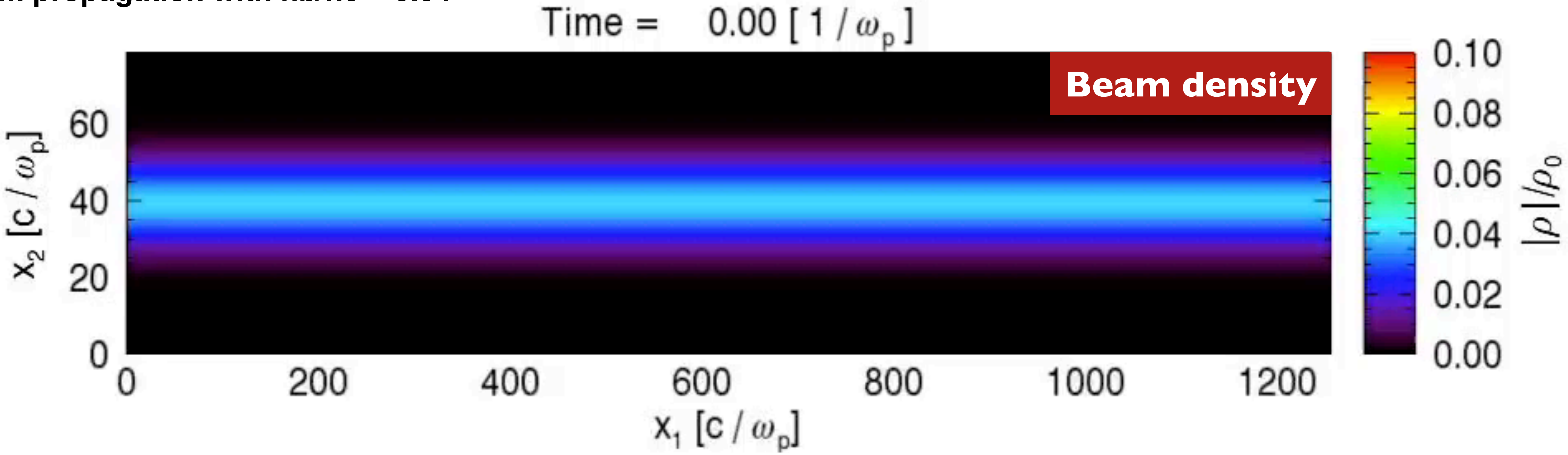
Perpendicular B-field



B-field amplification by Bell (non-resonant) instability

Non-resonant B-field amplification by FACET-II beam

cm propagation with nb/n0 ~ 0.04



- First results indicate possibility to amplify B-field to δB ~ B_0
- Role of competing processes for finite size beam need to be addressed carefully (e.g. self-modulation and hosing instabilities)

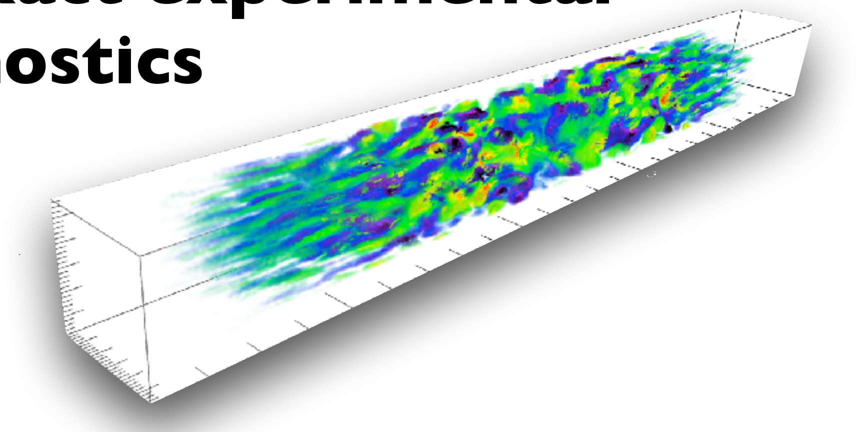
Conclusions

- **Relativistic beam-plasmas can support a wide range of instabilities which are relevant for astrophysical environments but their long-term evolution is not yet well understood**

- **FACET-II experiments can probe for the first time some of these processes: e.g. competition between oblique, Weibel, Bell instability**

- **PIC simulations illustrate the ability to excite and probe these instabilities for idealized FACET-II parameters**

- **More detailed studies are needed to address exact experimental conditions and identify most appropriate diagnostics**



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