# Cosmic-Ray Driven Instabilities

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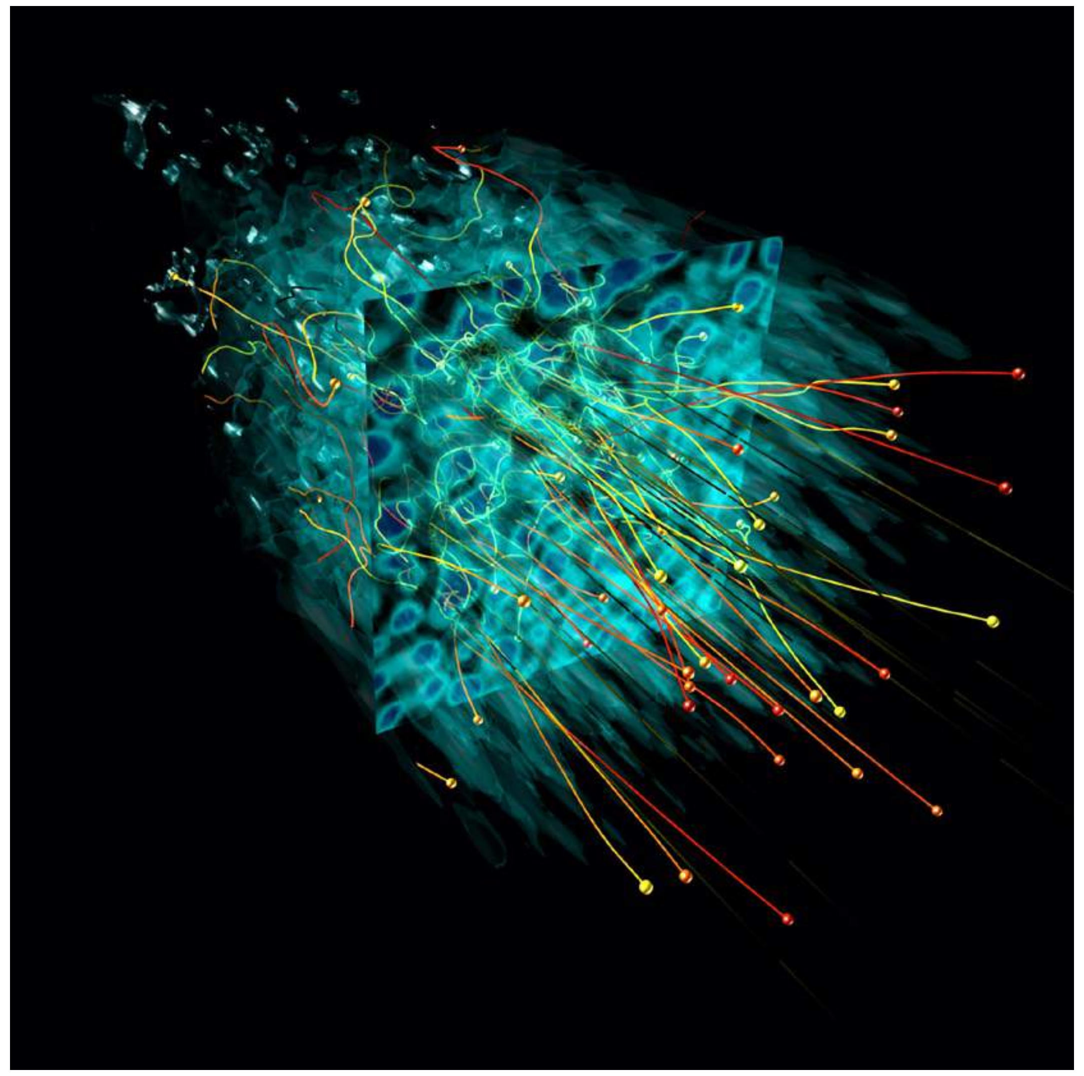
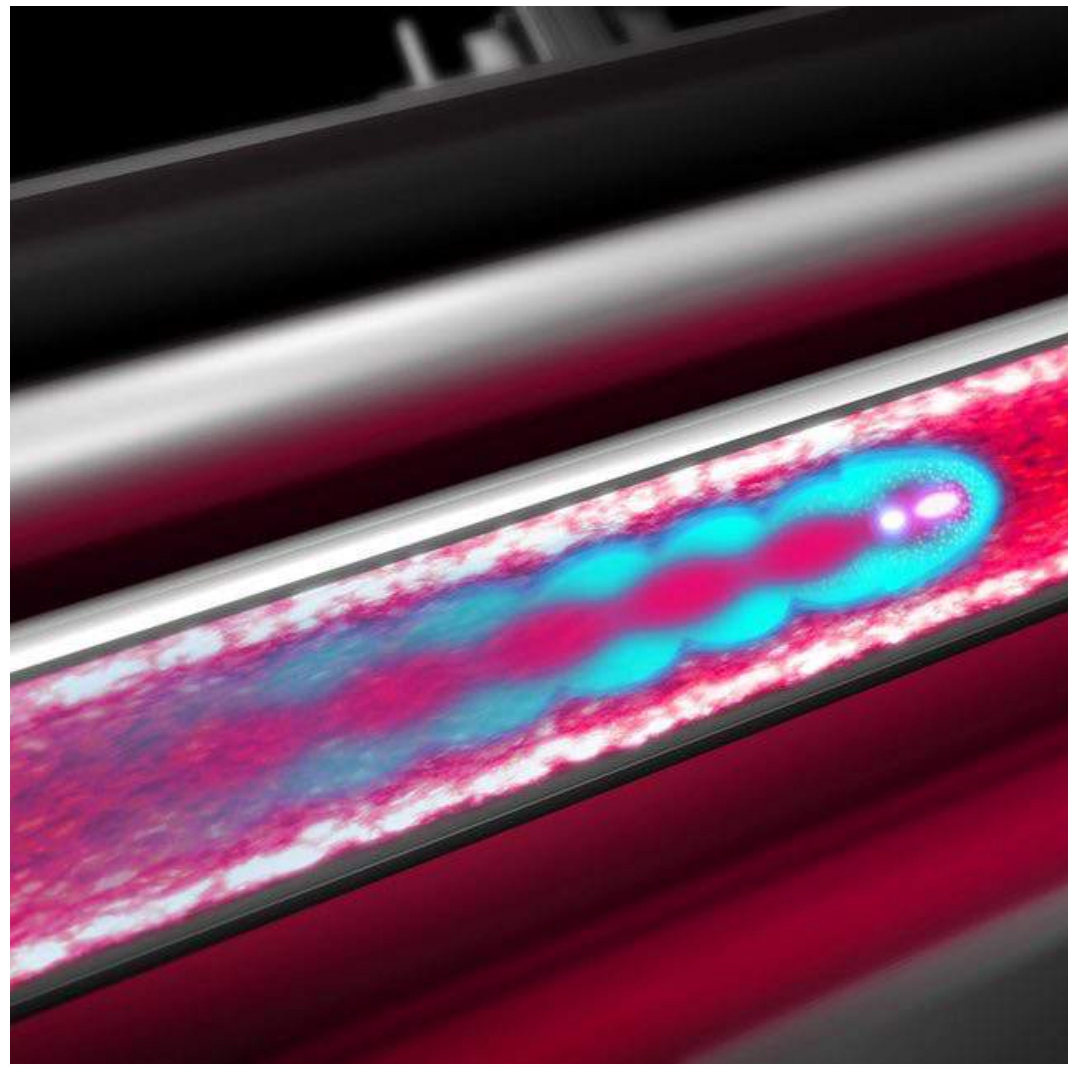
SLAC NATIONAL ACCELERATOR LABORATORY





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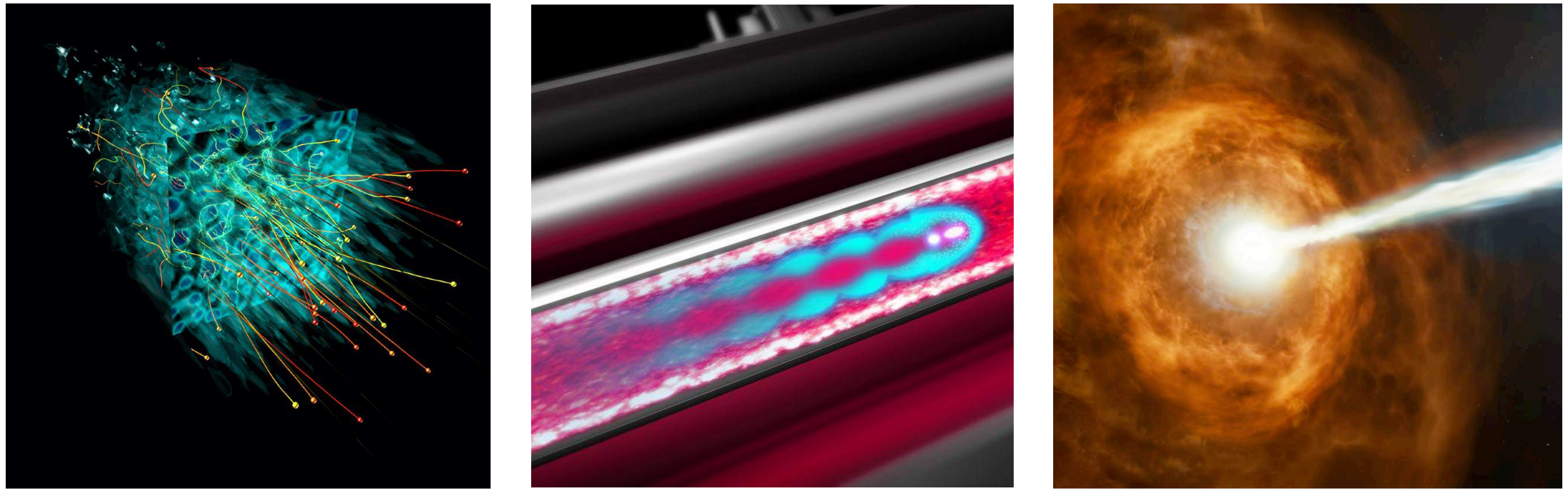

**Collaborators:**
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M. Tamburini (MPIK)

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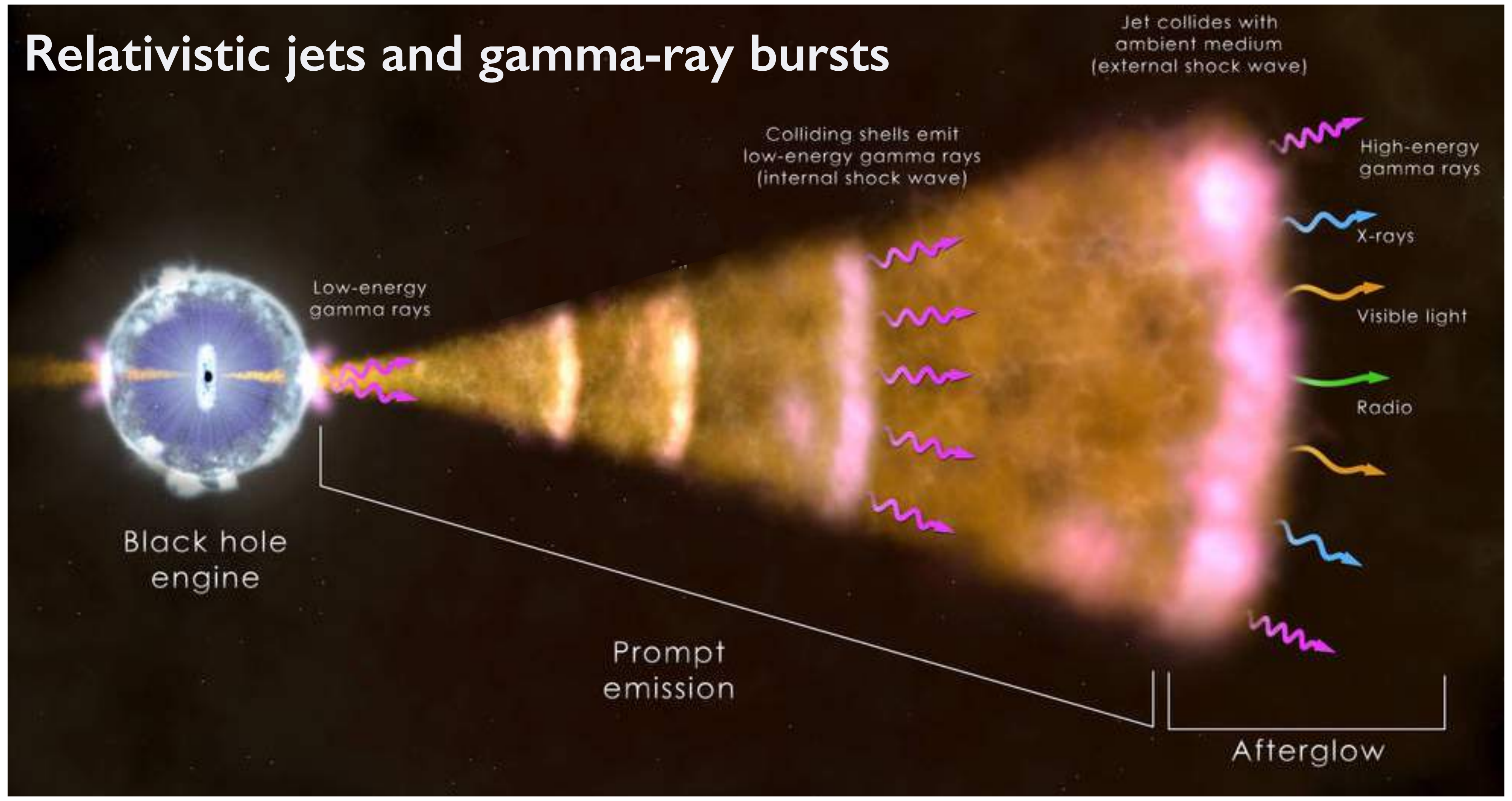
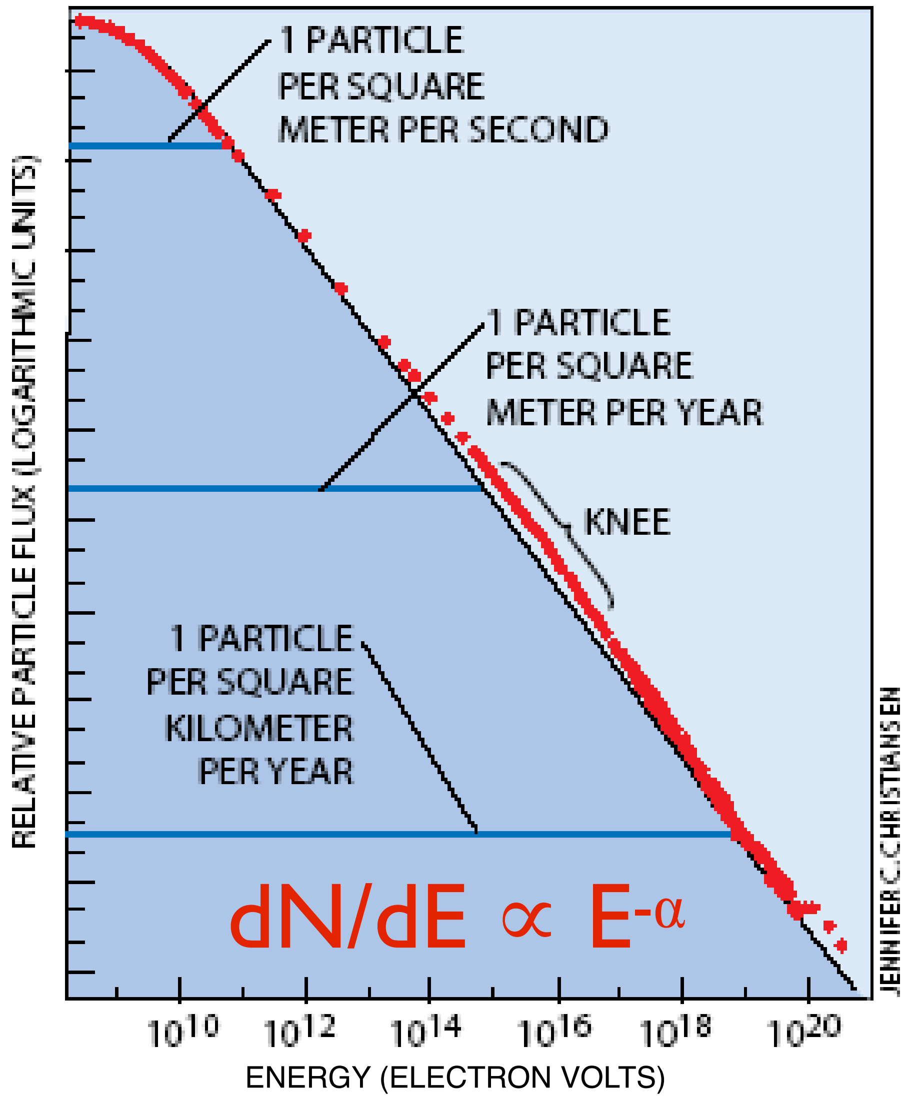
# Astrophysical plasmas are extraordinary particle accelerators


Relativistic jets and gamma-ray bursts


Supernova remnant shocks

Scientific American, (c) 1998

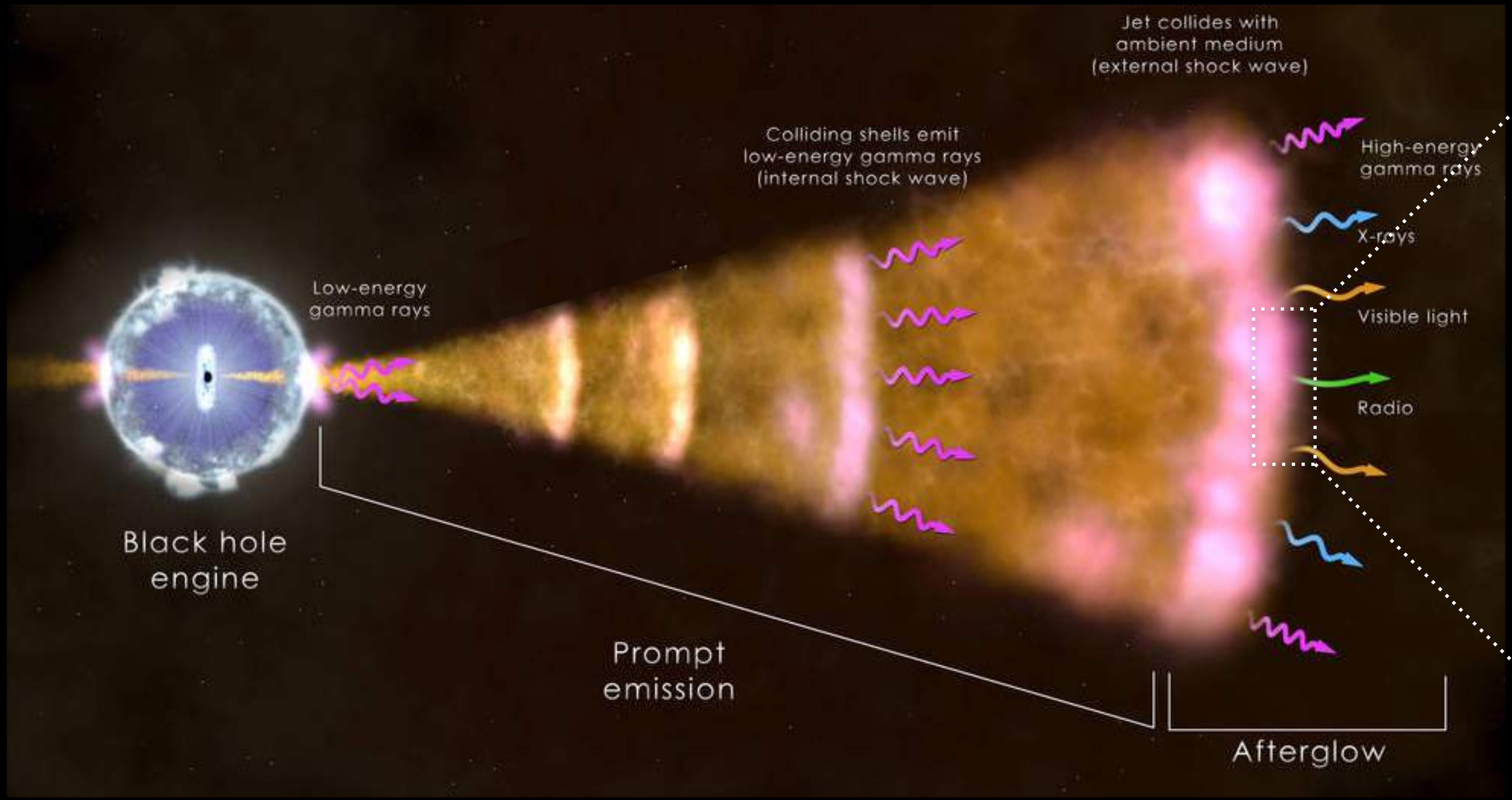


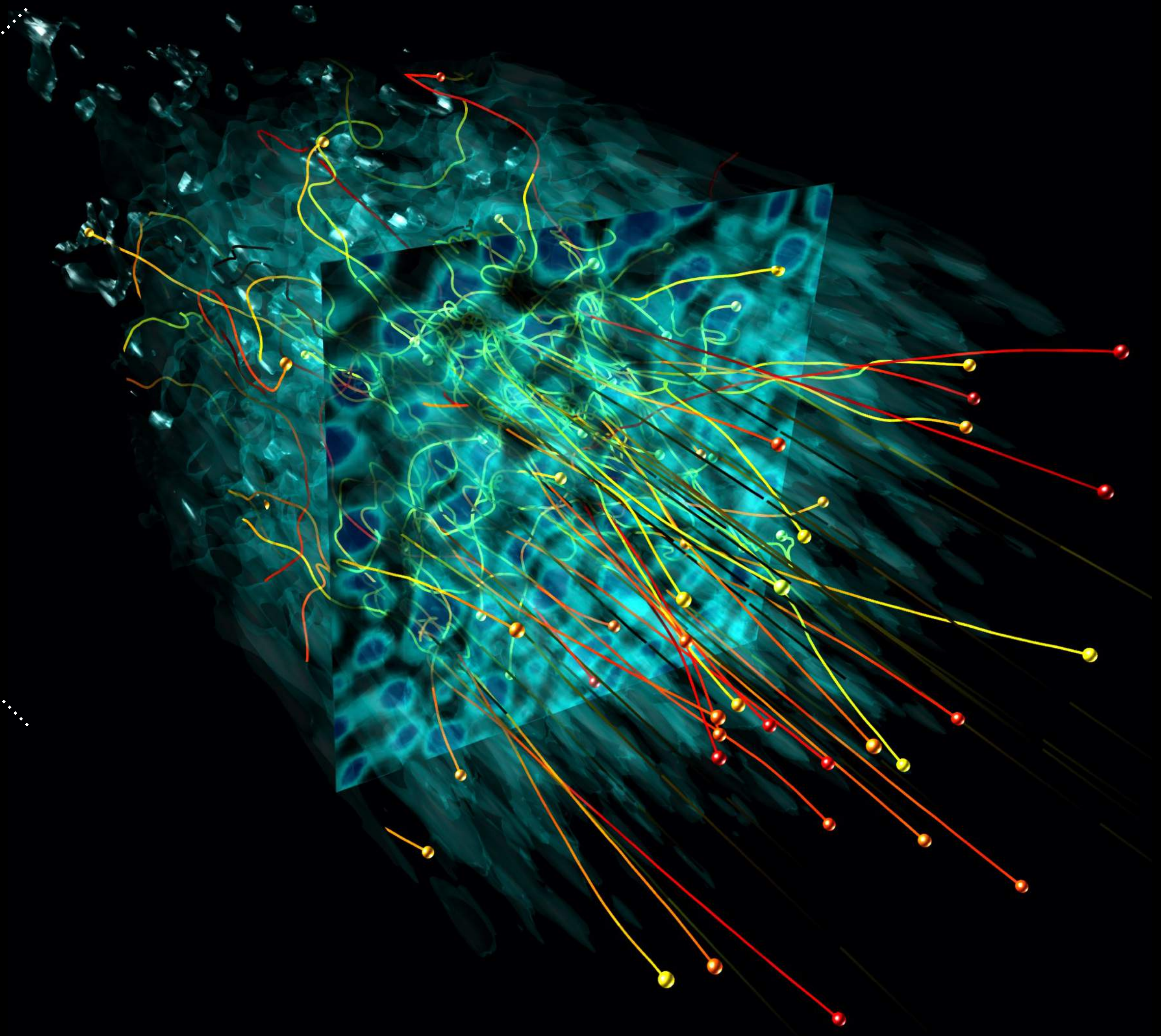
- What do astrophysical shocks manage to be such efficient accelerators?
- How are ultrahigh-energy cosmic rays (with up to $10^{20}$ eV!) accelerated?
- What controls the EM and particle signatures of compact objects and their mergers?
- Can we study these processes in the lab and harness them to produce more efficient accelerators and light sources?

The answers are tied to kinetic plasma processes that control energy partition in these extreme astrophysical environments

**Advances in numerical tools and accelerator facilities/ light sources are now enabling studies of relevant plasma processes to help unveil these mysteries**

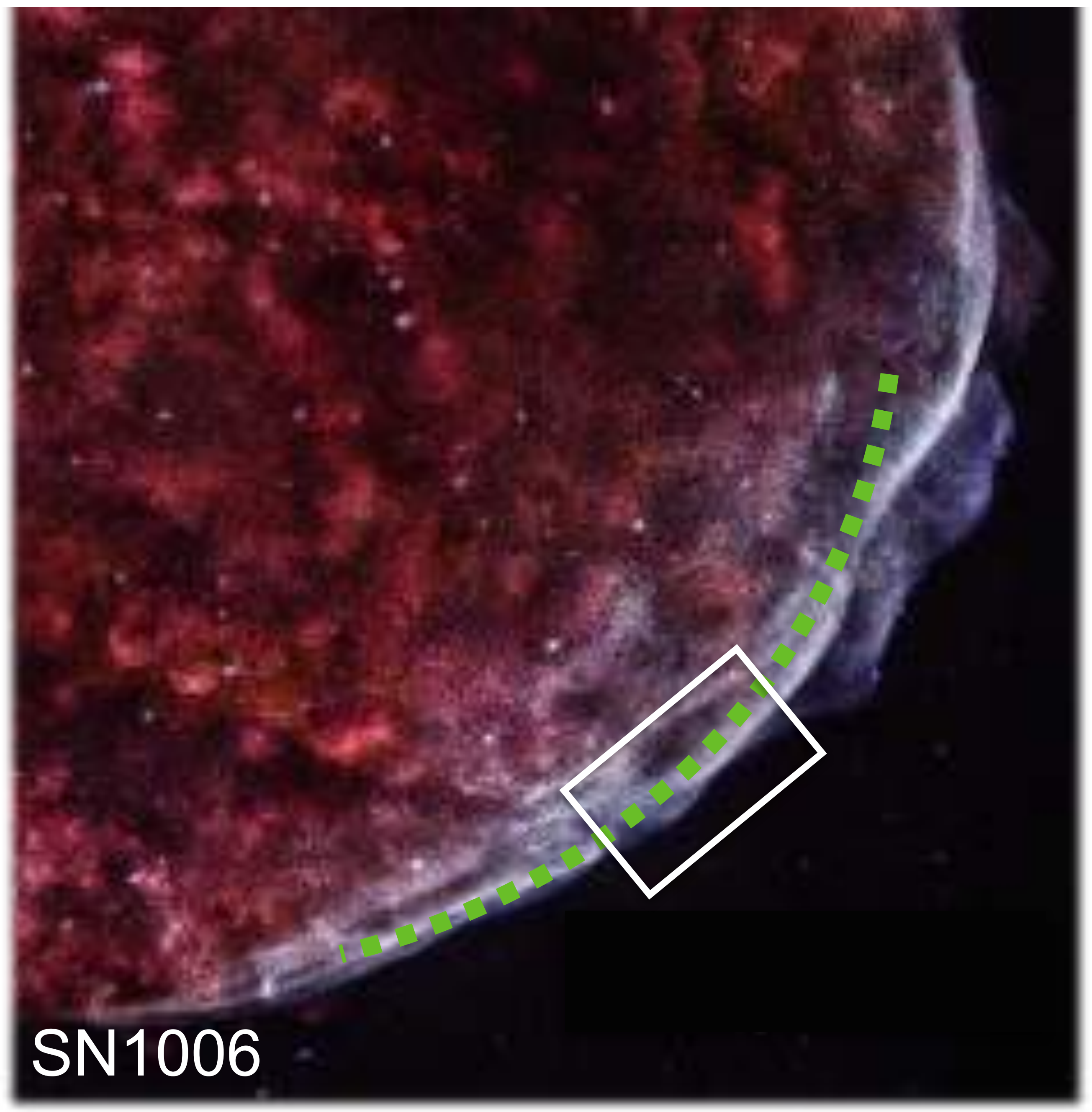
# Cosmic accelerators and the importance of CR-driven instabilities

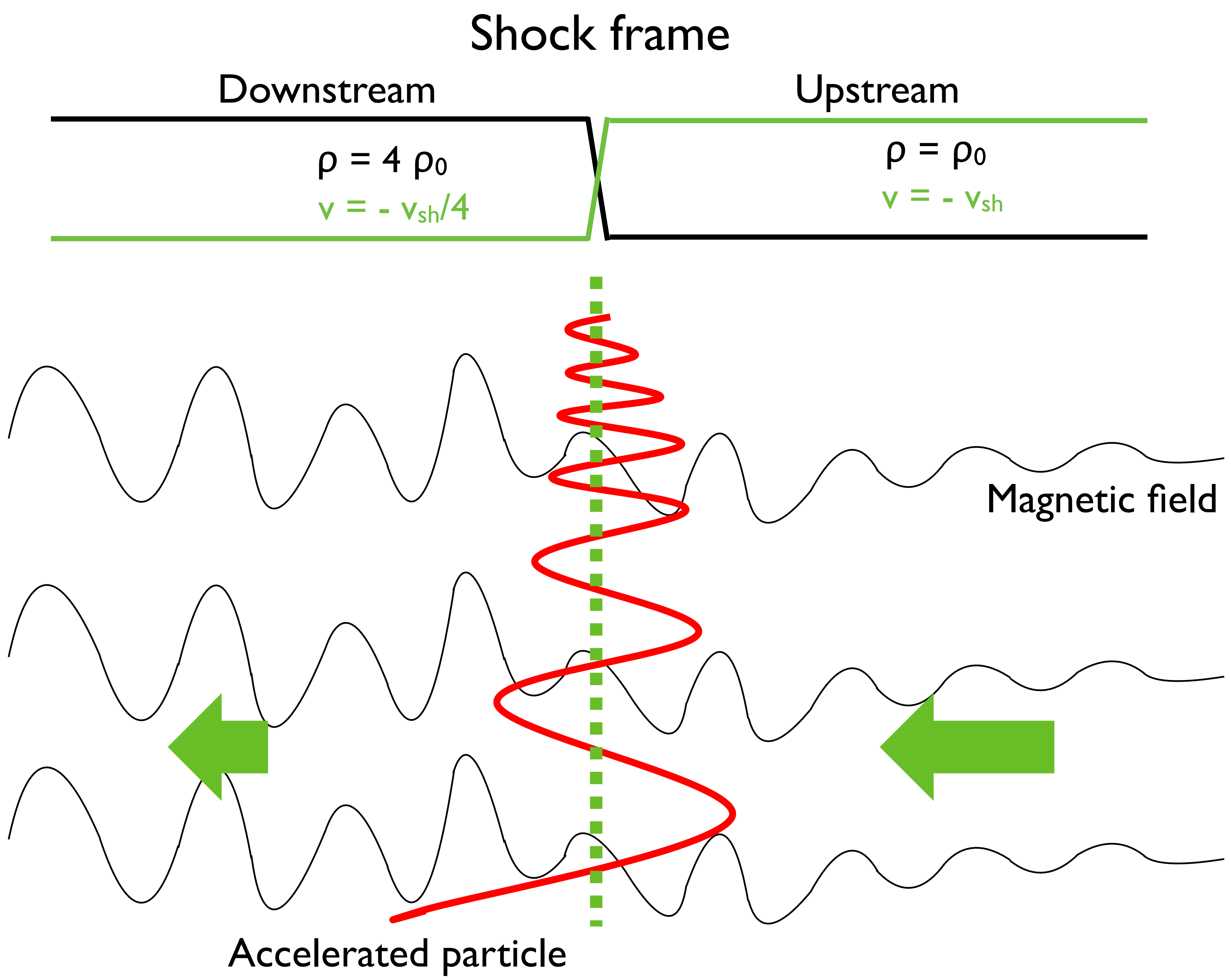




# Collisionless shocks are thought to be dominant source of energetic cosmic rays

SNR collisionless shock





**1st order Fermi mechanism in shocks***
(a.k.a. diffusive shock acceleration)

Fractional energy gain per shock crossing:

$$\frac{\Delta\epsilon}{\epsilon} = \frac{v_{sh}}{c}$$

Fractional particle loss per shock crossing:

$$\frac{dn}{n} = -\frac{v_{sh}}{c}$$

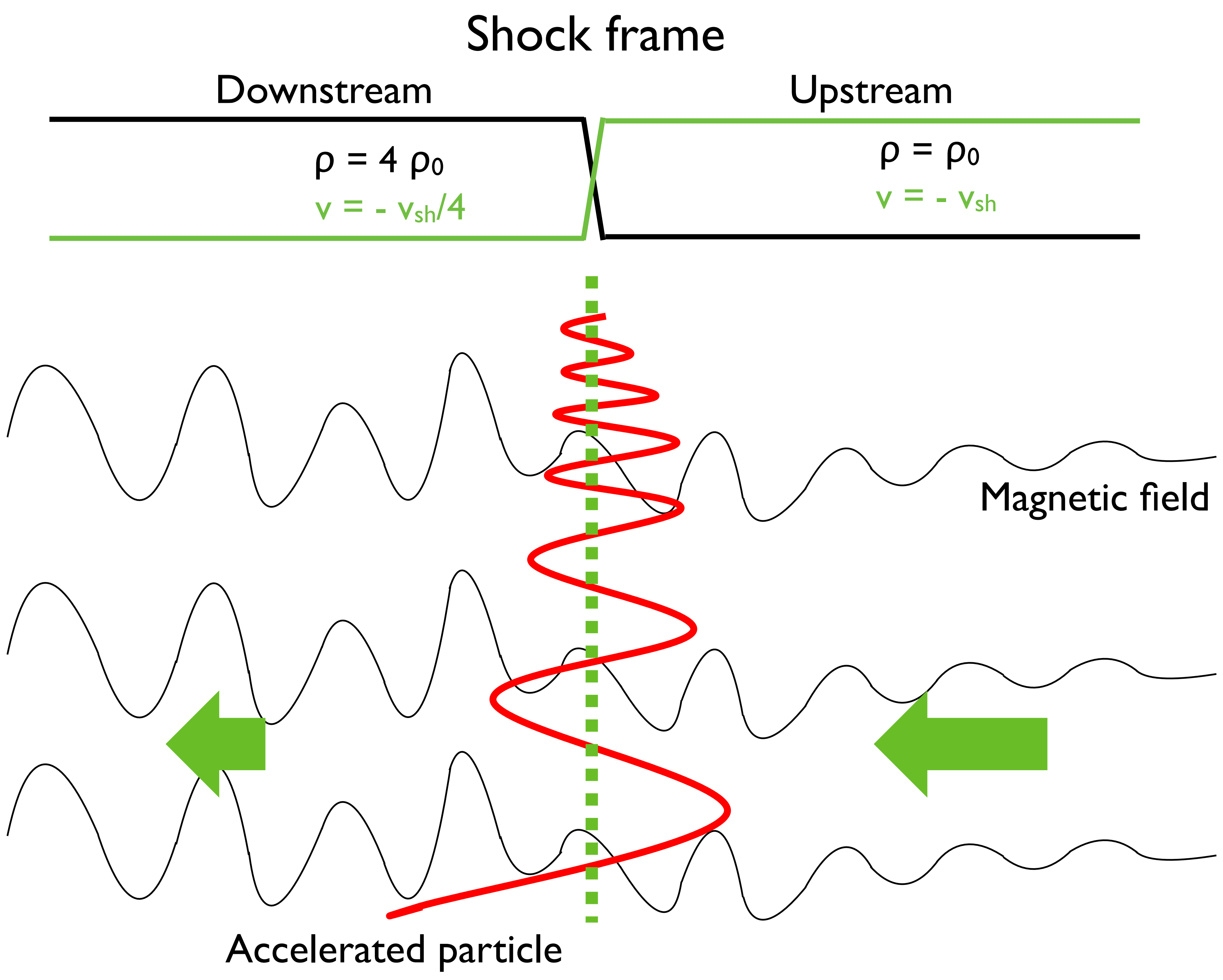
Power-law spectrum:

$$\frac{dN}{d\epsilon} \propto \epsilon^{-2}$$

The microphysics that controls the particle acceleration efficiency at the shock and magnetic field amplification is not yet well understood

* **Krymskii 1977, Axford, Leer, Skadron 1977, Bell 1978, Blandford & Ostriker 1978**

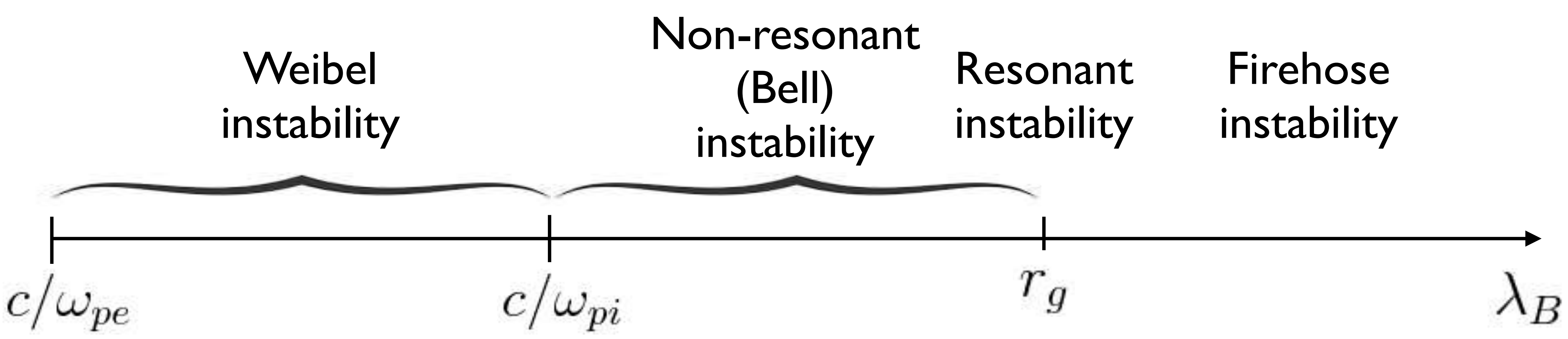
# Which processes control magnetic field amplification?



Efficient particle acceleration requires **strong magnetic fluctuations**

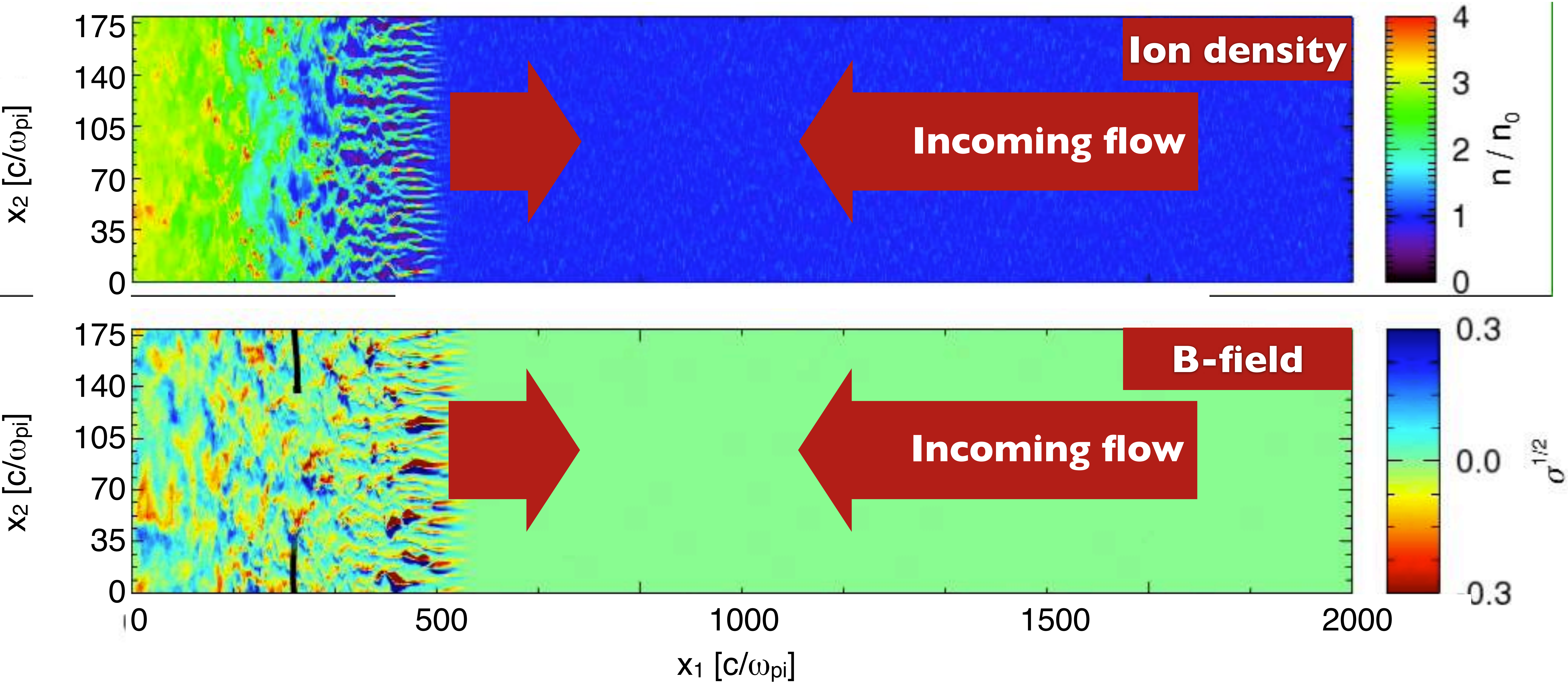
Fastest acceleration if scale of fluctuations comparable to Larmor radius of particles (Bohm diffusion)

$$\delta B \gg B \quad + \quad \lambda_B \sim r_g$$



**Nonlinear interplay between different instabilities is critical for particle acceleration but it is not clear how it depends on the shock and ambient plasma conditions**

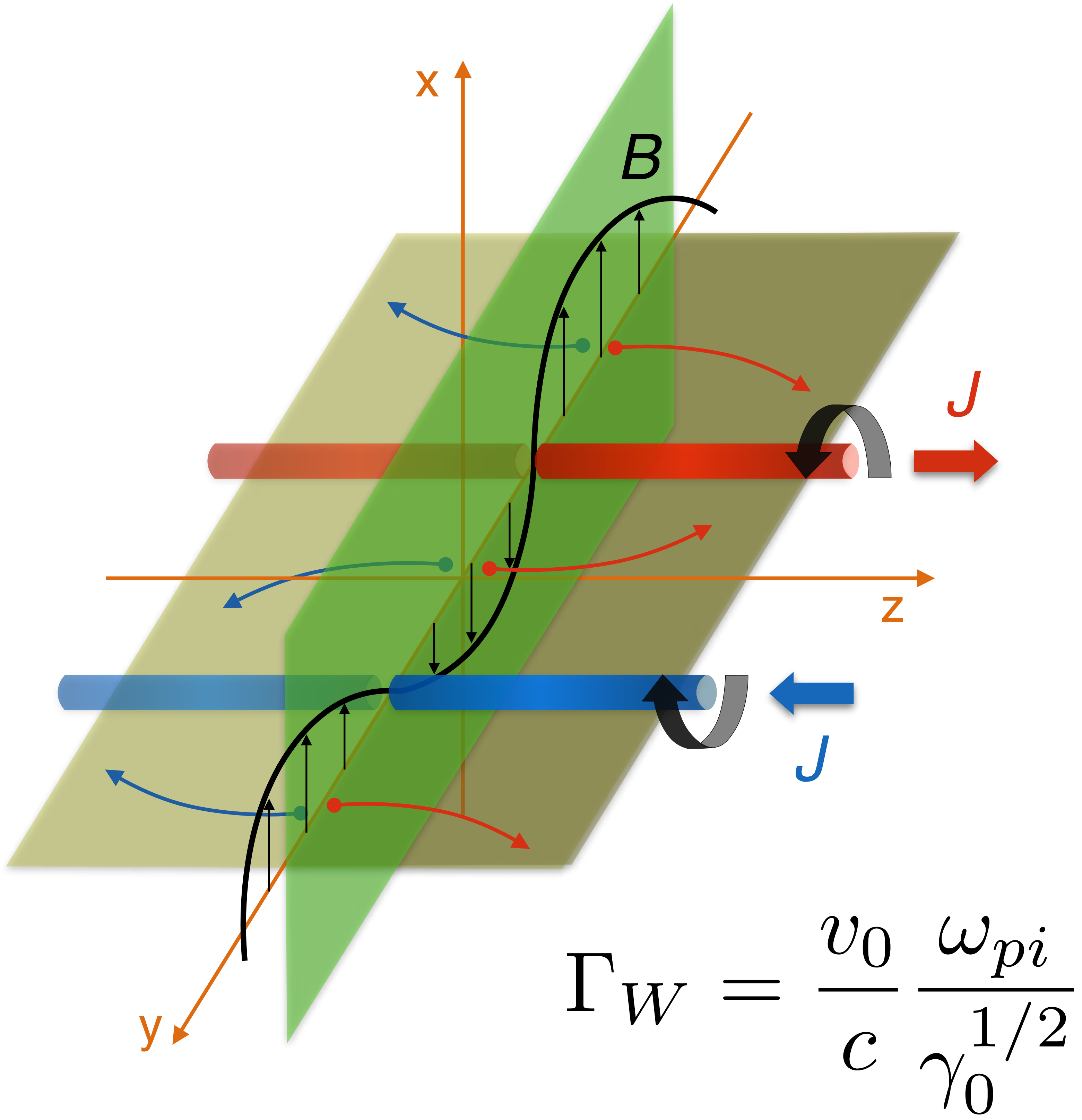
# Relativistic collisionless shocks in weakly magnetized plasmas



# Efficient development of high-energy power-law distribution

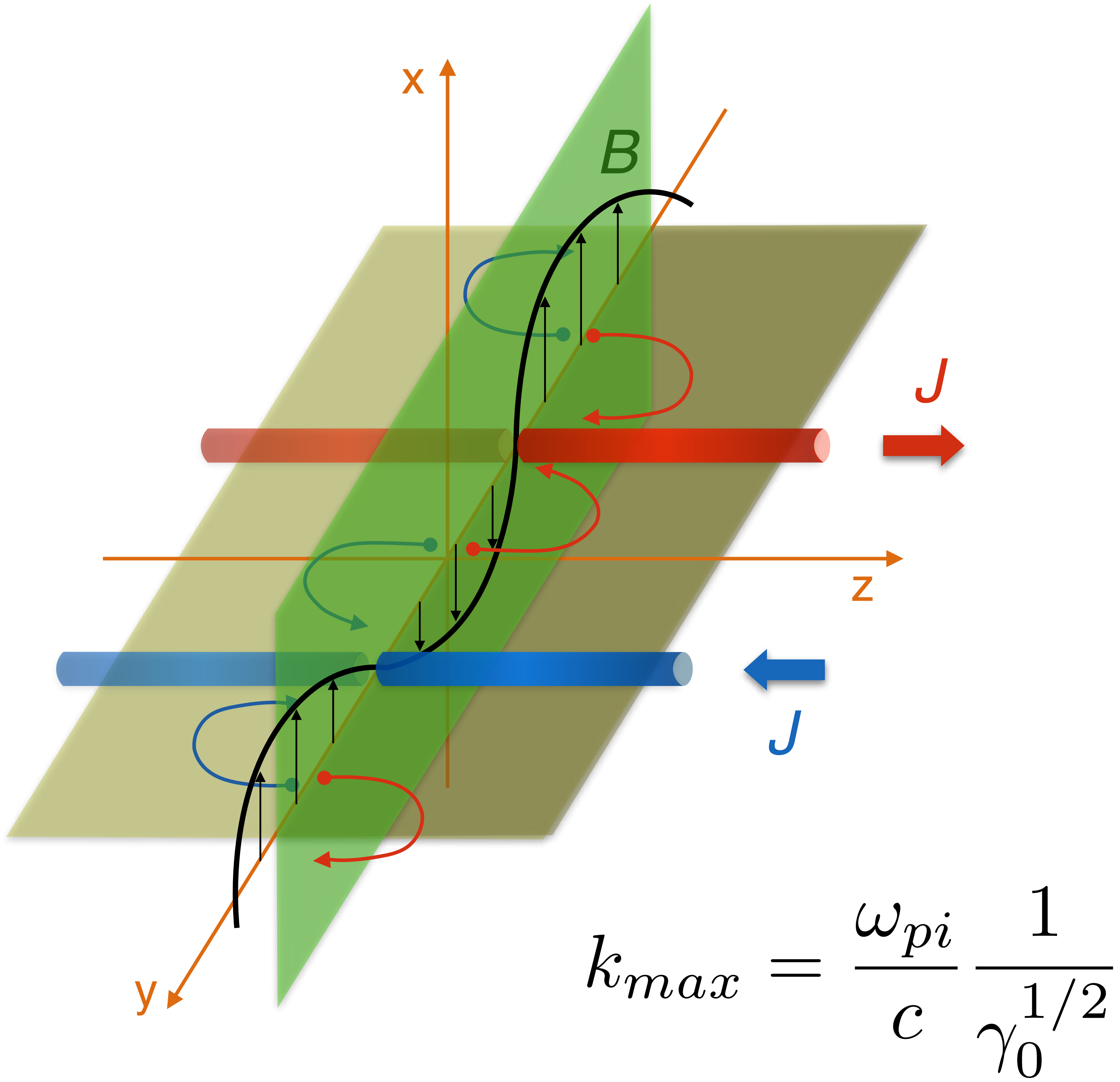
# Weibel instability amplifies B-fields at kinetic scales

Linear regime



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

Saturation



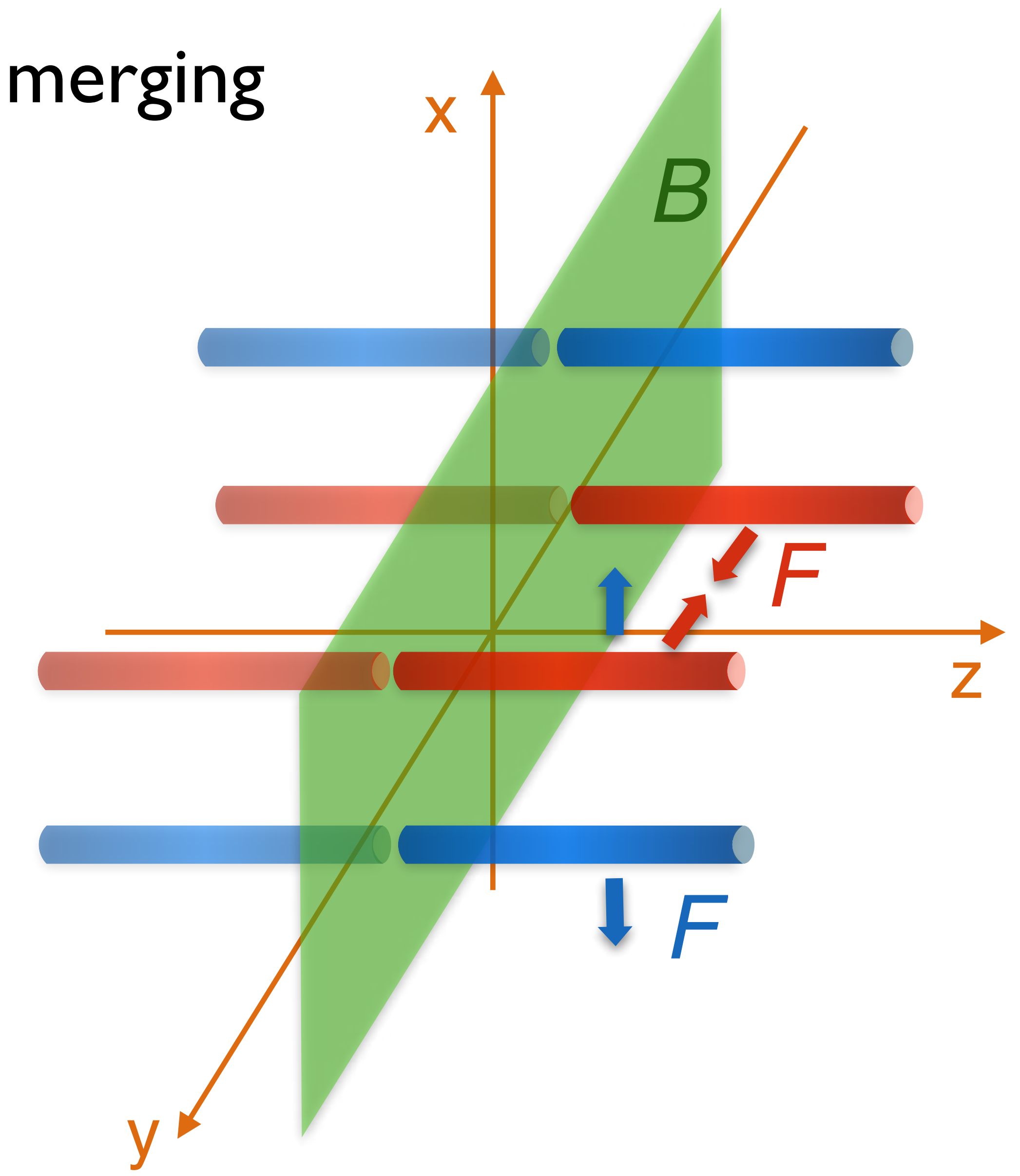
$$k_{max} = \frac{\omega_{pi}}{c}\frac{1}{\gamma_0^{1/2}}$$

**Instability can transfer 1-10% of kinetic energy of plasma flows into magnetic energy**

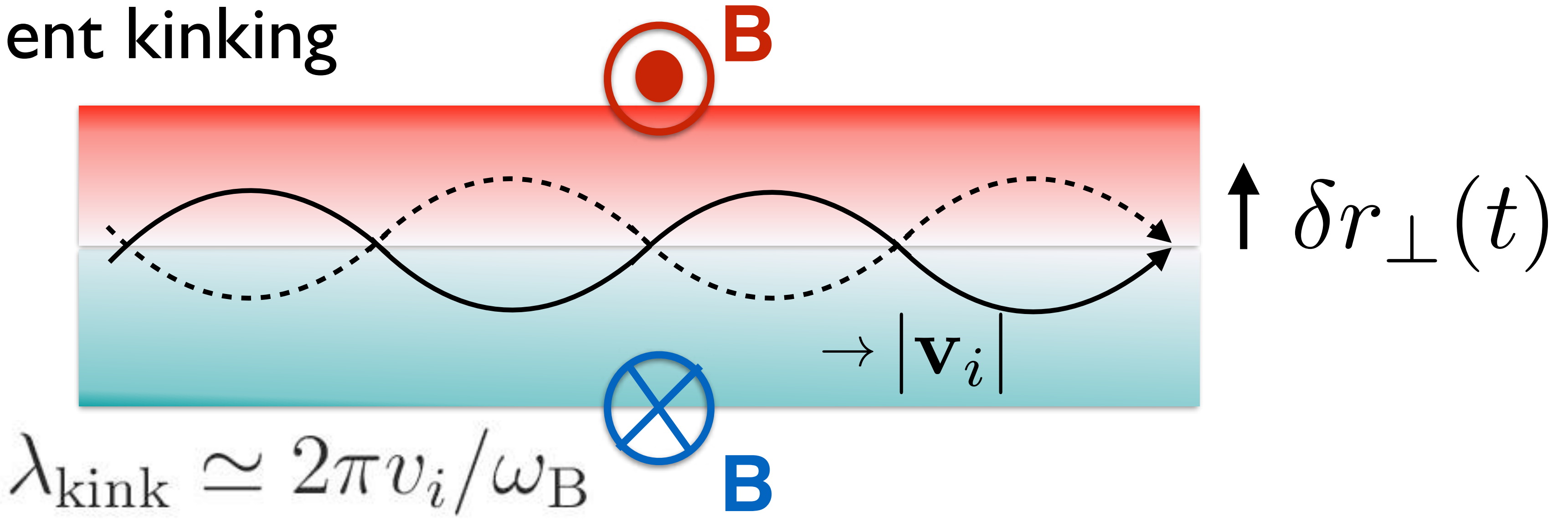
E. S. Weibel, PRL 2, 83 (1959); B. D. Fried, Phys. Fluids 2, 337 (1959)
A. Gruzinov & E. Waxman, APJ 511, 852 (1999); M. Medvedev & A. Loeb, ApJ 526, 697 (1999)

# Nonlinear evolution critical for onset of magnetic turbulence

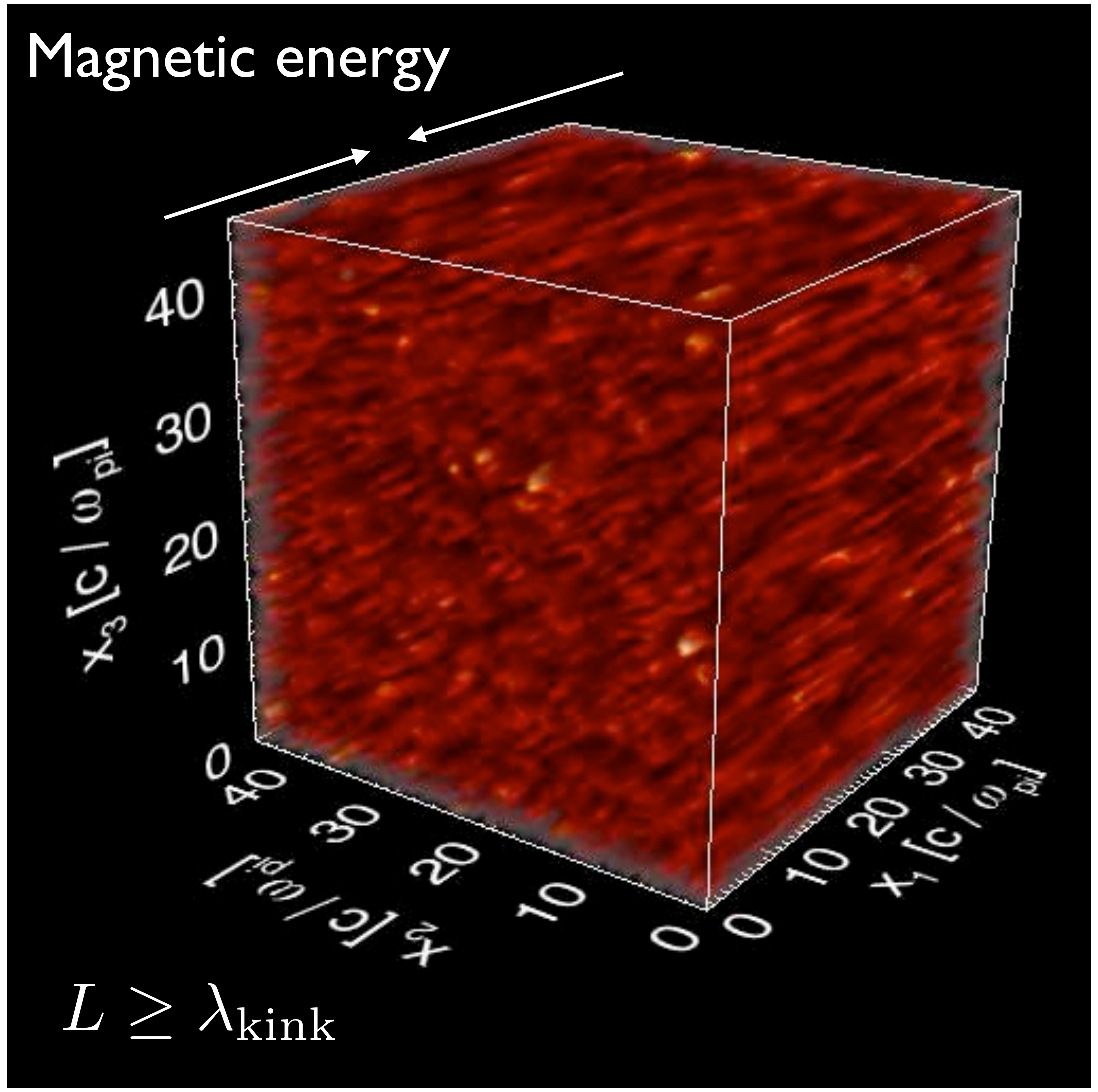
Filament merging



Filament kinking



$\lambda_{\rm kink} \simeq 2\pi v_i/\omega_{\rm B}$



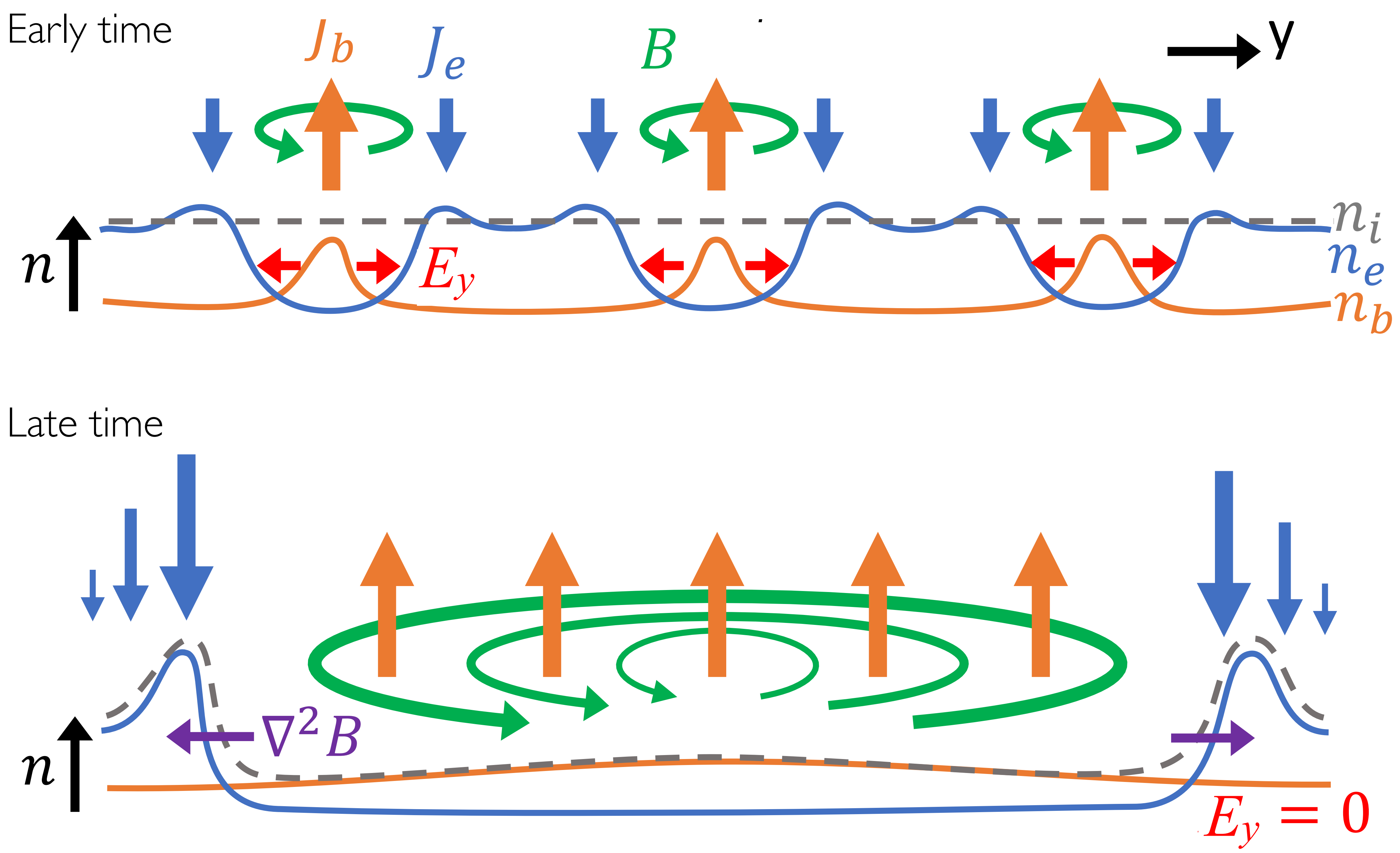
$L \geq \lambda_{\rm kink}$

**Competition between merging and kink-mode controls shock formation**

C. Ruyer and F. Fiuza, PRL 120, 245002 (2018); A. Grassi and F. Fiuza, PRR 3, 023124 (2021)

# Secondary instabilities dictate late time evolution

Magnetic field amplification by new plasma cavitation instability

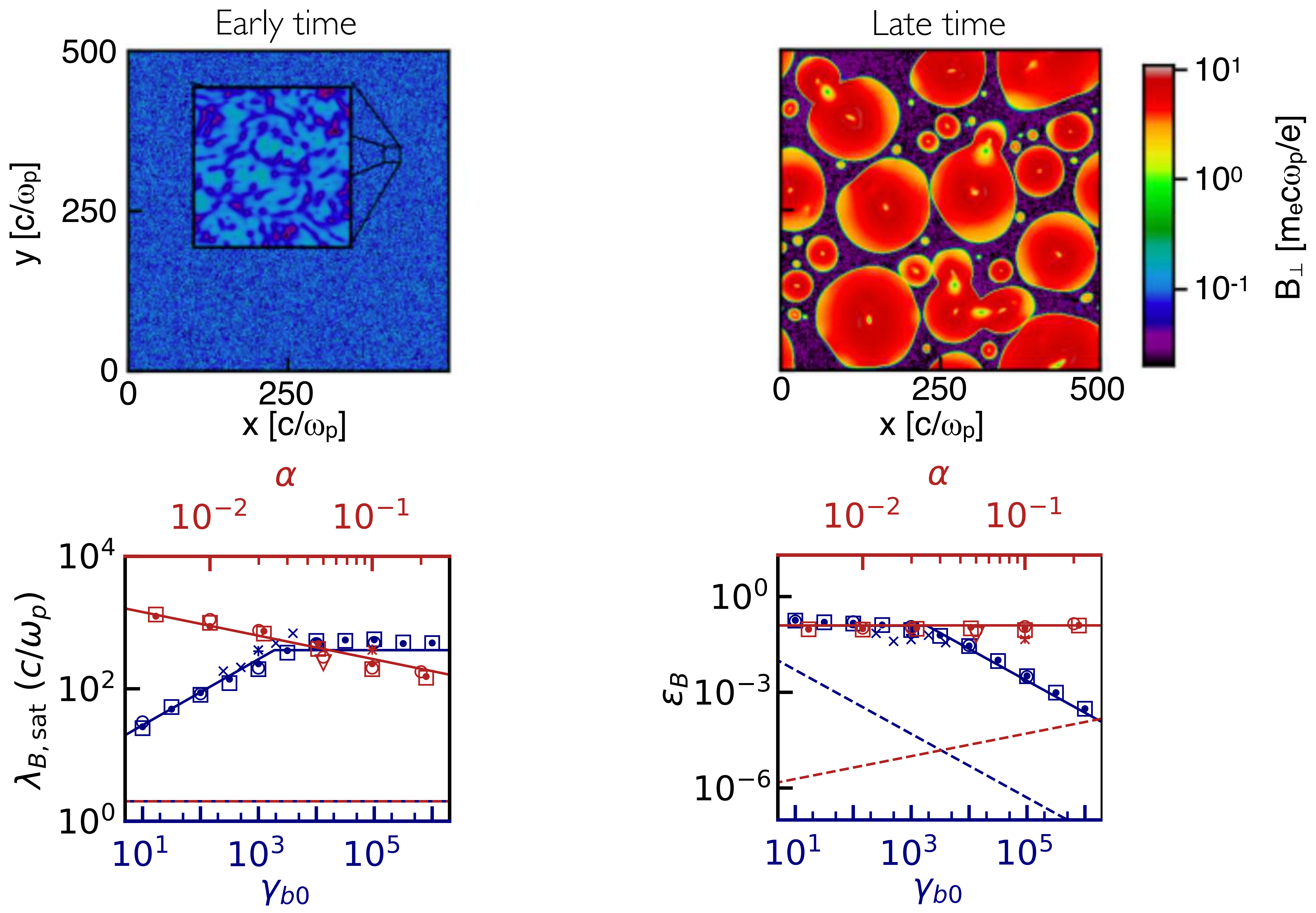


**Magnetic coherence scale ≫ plasma kinetic scale critical to explain GRB polarization and high-energy particle acceleration**

**J. R. Peterson, S. Glenzer, and F. Fiuza, PRL 126, 215101 (2021); ApJL 924, L12 (2022)**

# Late time evolution is also dictated by secondary instabilities

Magnetic field amplification by new plasma cavitation instability

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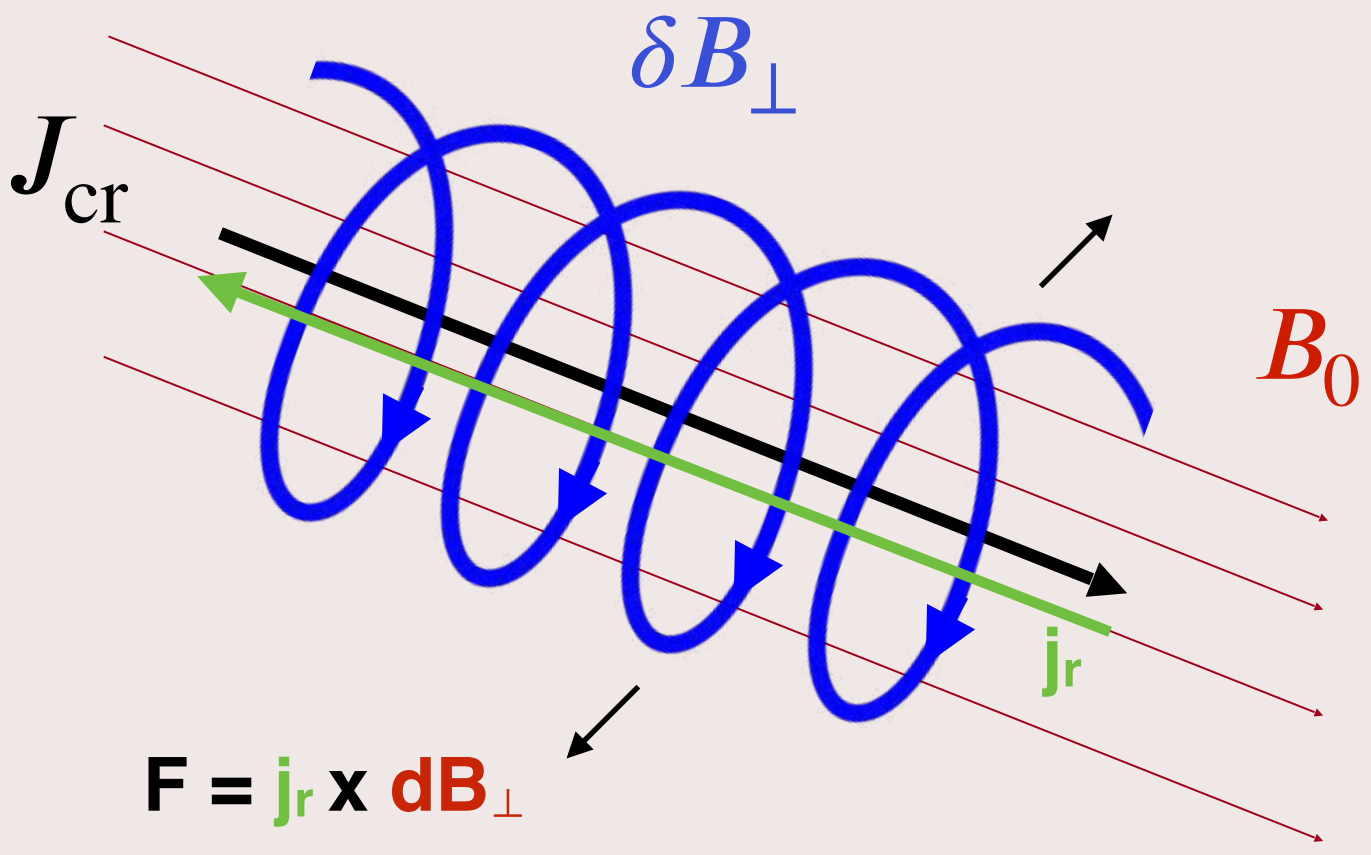
**Magnetic coherence scale ≫ plasma kinetic scale critical to explain GRB polarization and high-energy particle acceleration**

**J. R. Peterson, S. Glenzer, and F. Fiuza, PRL 126, 215101 (2021); ApJL 924, L12 (2022)**

# Nonresonant (Bell) and firehose instabilities can generate large-scale modes

## Nonresonant (Bell's) current-driven instability*

Driven by charged beam drifting along the external magnetic field

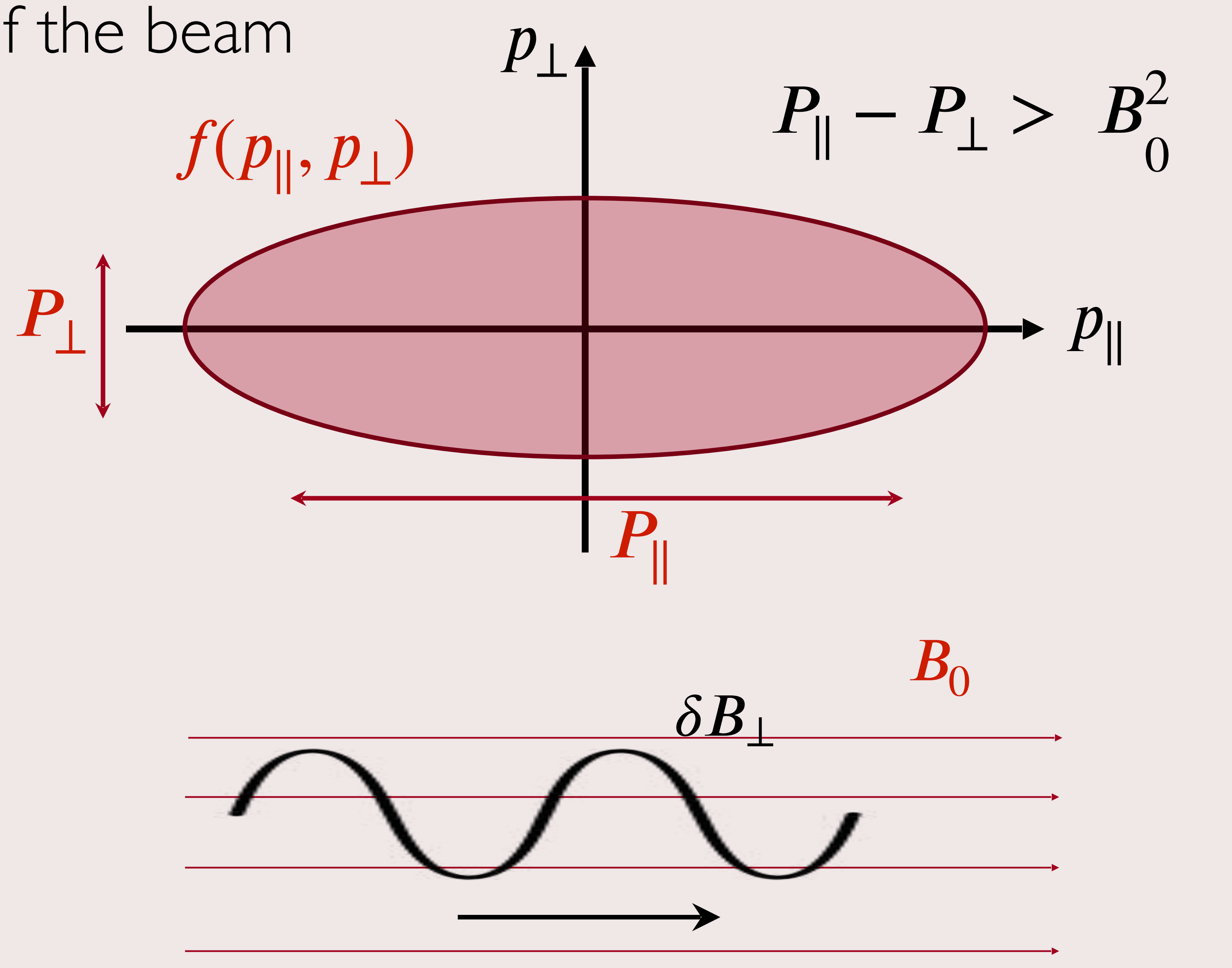


What is the dominant saturation mechanism?

- Equipartition (Bell 2004)
- Resonant pitch-angle scattering (Caprioli & Spitkovsky 2014)
- Background plasma acceleration (Riquelme & Spitkovsky 2009, Gargate et al. 2010)

## Firehose instability**

Driven by (ram or thermal) pressure anisotropy of the beam



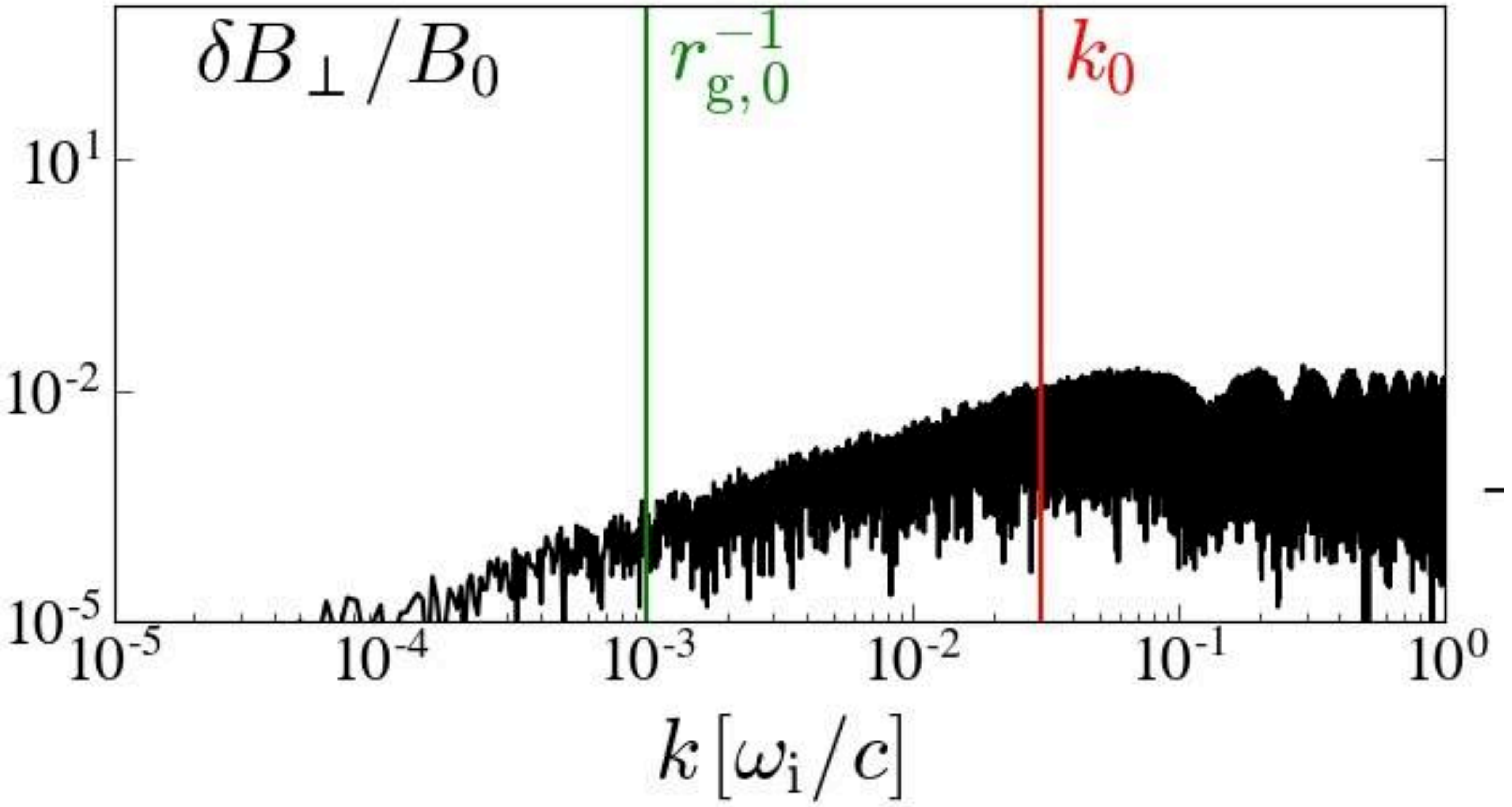
Dominant saturation mechanism?

- Thermal + magnetic pressure balance

*** A. R. Bell, MNRAS 353, 550 (2004); ** R. Z. Sagdeev & A. A. Vedenov (1959); E. N. Parker (1961)**

# Nonlinear mode coupling important for B-field amplification at large scales

**Fully-kinetic PIC simulations with OSIRIS**



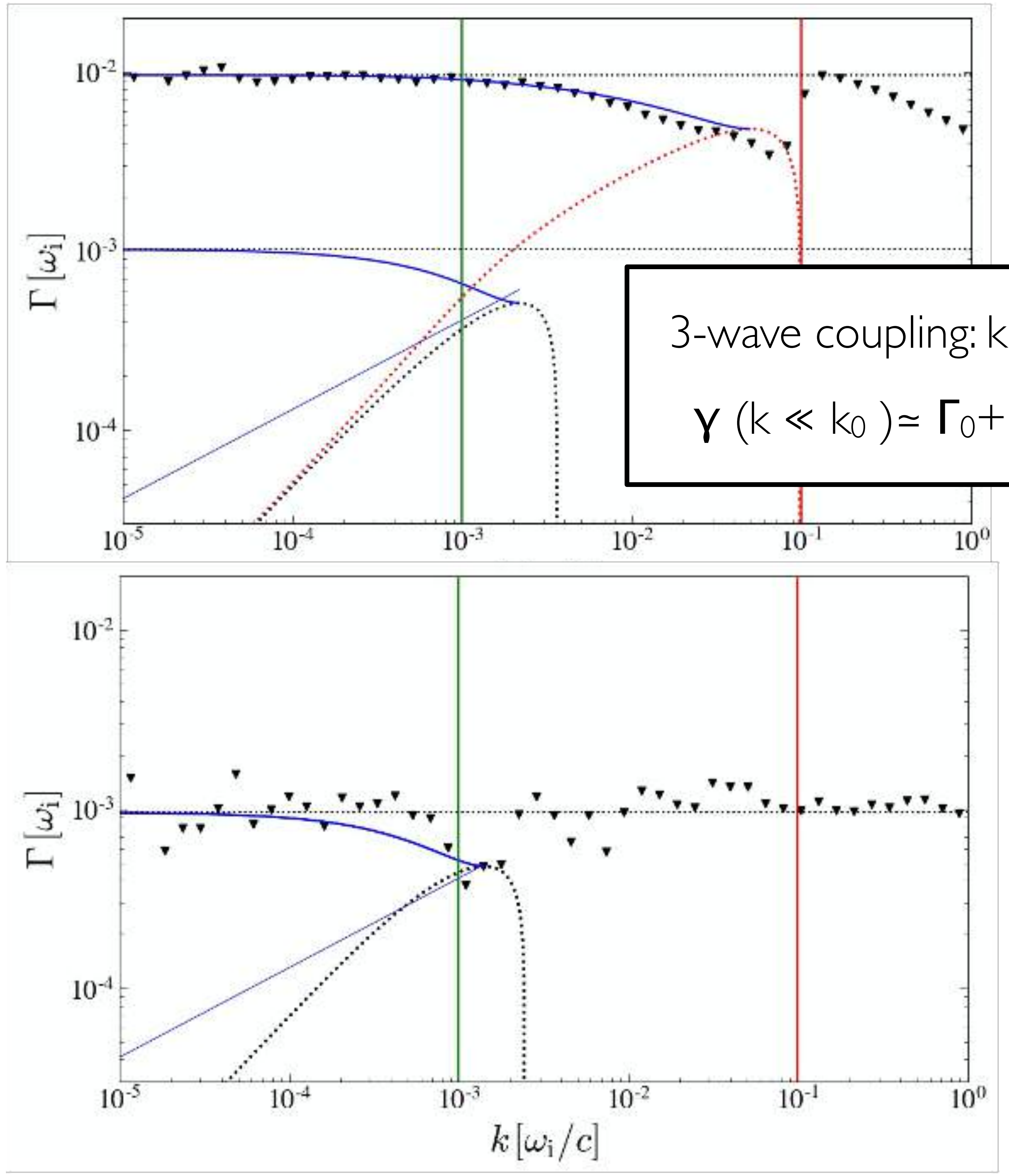
- short-scale limit (Bell)

$$\omega = \beta_A \left( k^2 - k\, k_0 \right)^{1/2},\ k_0 = J_{cr}/B_0$$

- Large-scale limit (firehose)

$$\omega = k\, \beta_A \left( 1 - \frac{P_{ram}}{B_0^2} \right)^{1/2}$$

**Nonlinear mode coupling**



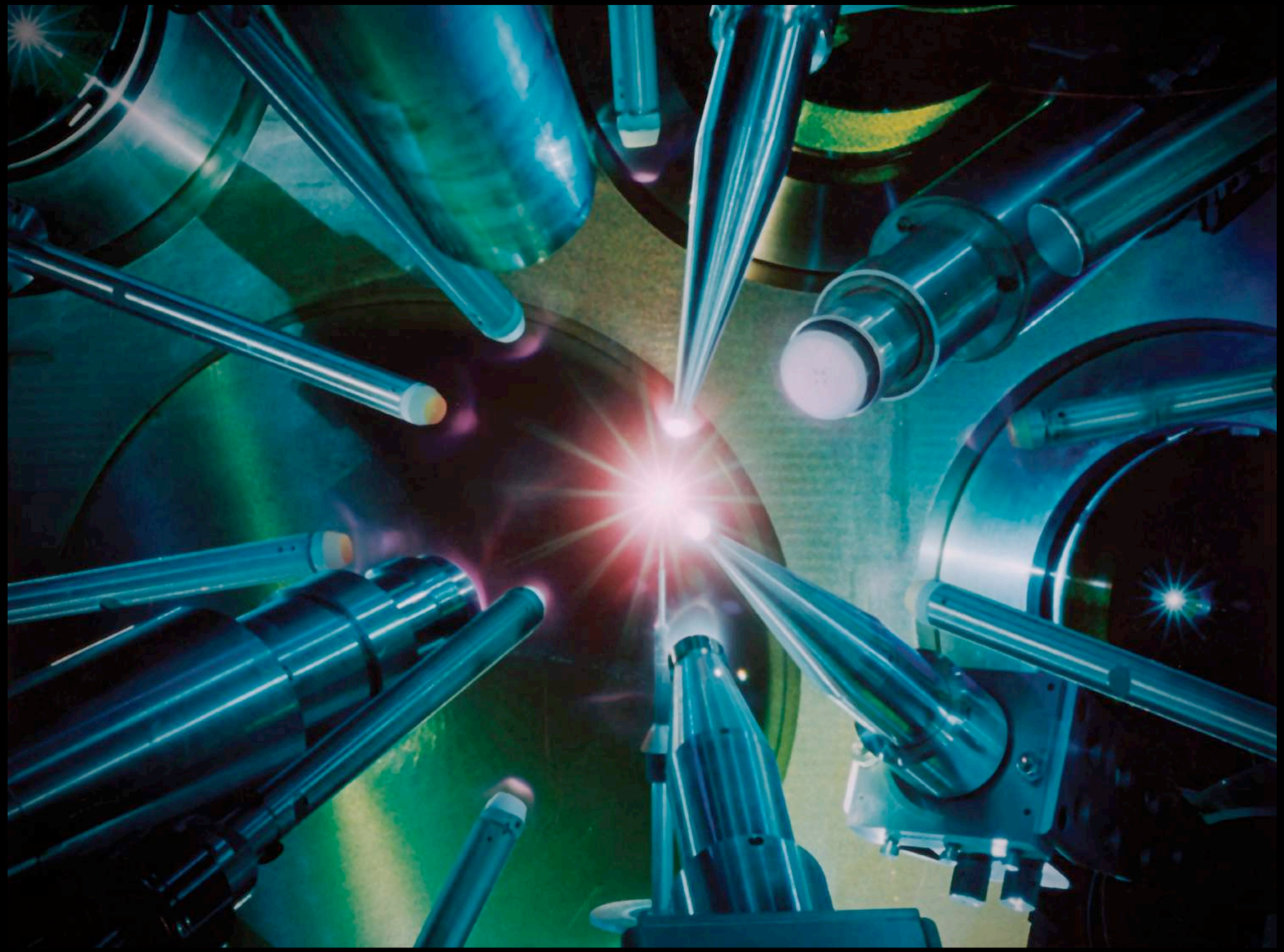
3-wave coupling: $k_1 = k_0 - k_2$

$\gamma\ (k \ll k_0) \simeq \Gamma_0 + \Gamma_2 = 2\Gamma_0$

**A. Vanthieghem and F. Fiuza, in preparation**

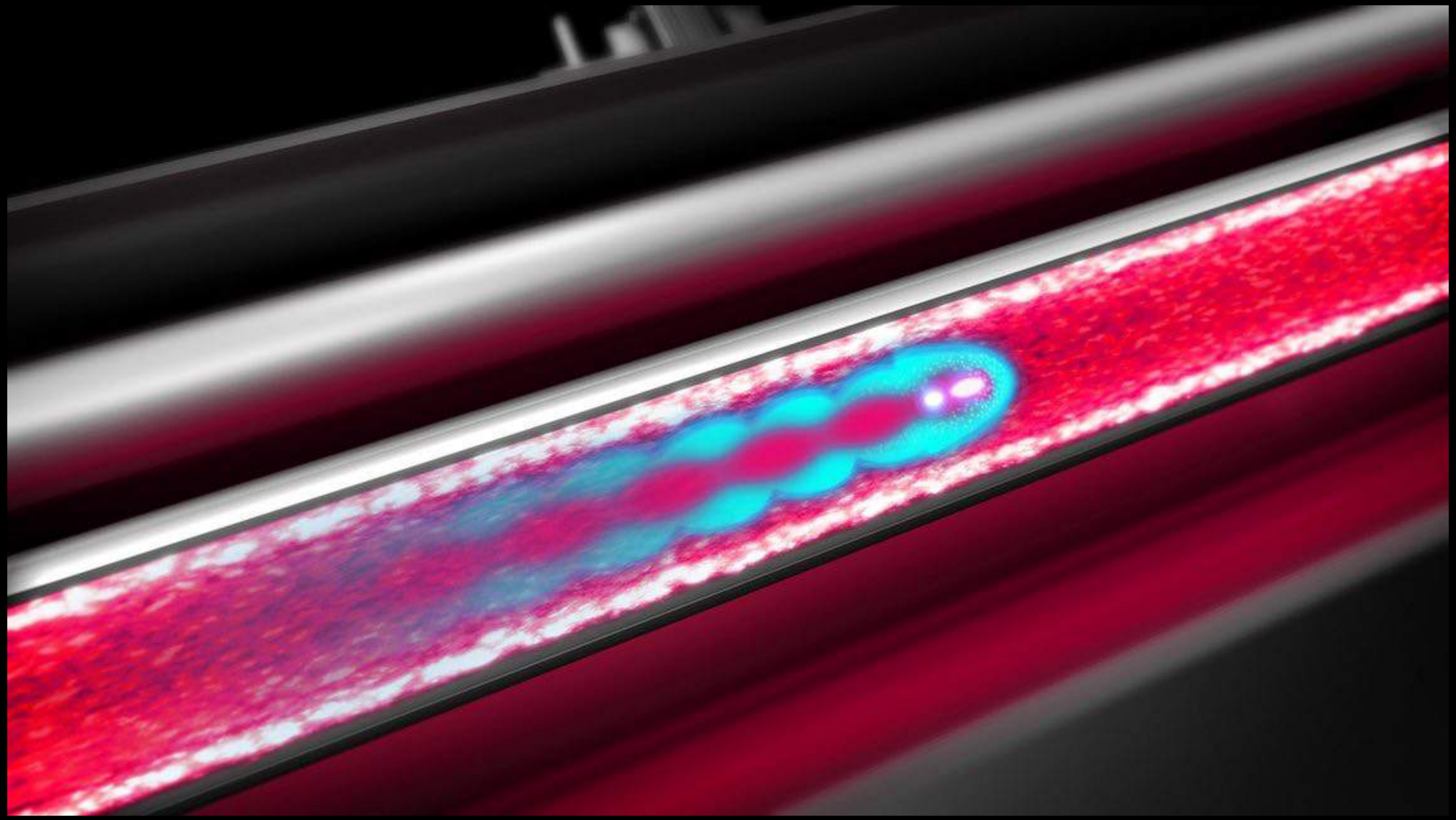
# Can laboratory experiments help unveil the nonlinear evolution of CR-driven instabilities?

High-intensity and high-energy lasers



OMEGA EP @ LLE

High-intensity and high energy particle beams

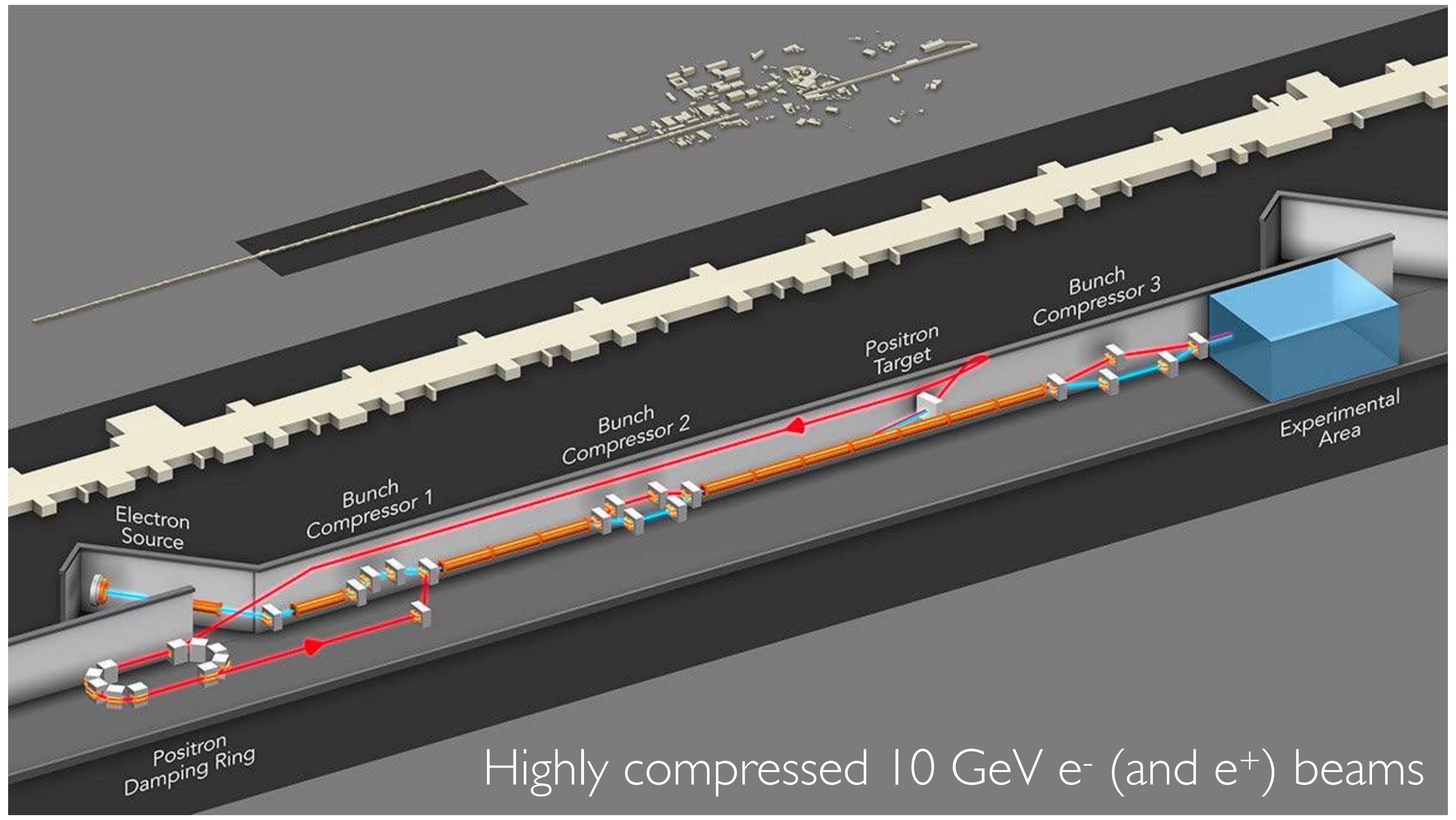


FACET-II @ SLAC

We are not going to put a GRB in a bottle!
… but can we test critical theoretical aspects and validate models/codes?

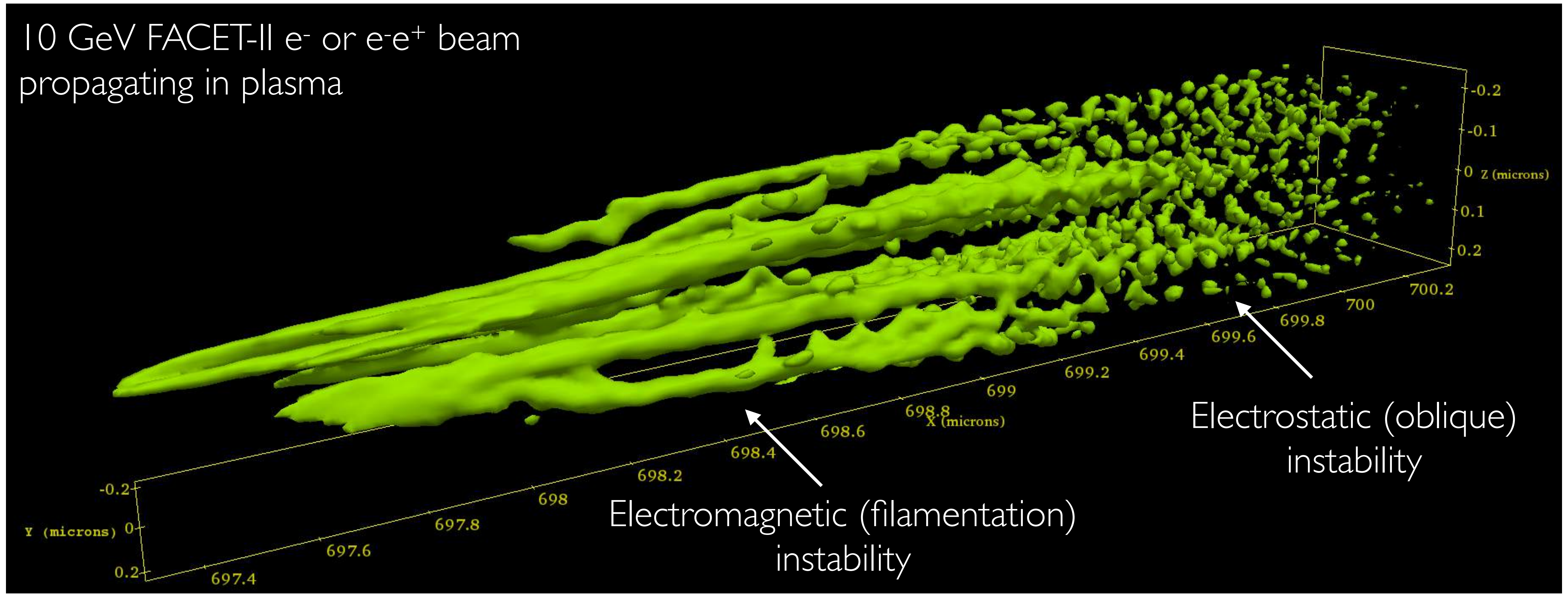
# Studying filamentation instability with FACET-II

FACET-II could explore nonlinear competition between cosmic-ray driven instabilities



Highly compressed 10 GeV e$^-$ (and e$^+$) beams

Approved FACET-II experiment E-305: beam filamentation and bright gamma-ray bursts



10 GeV FACET-II e$^-$ or e$^-$e$^+$ beam propagating in plasma

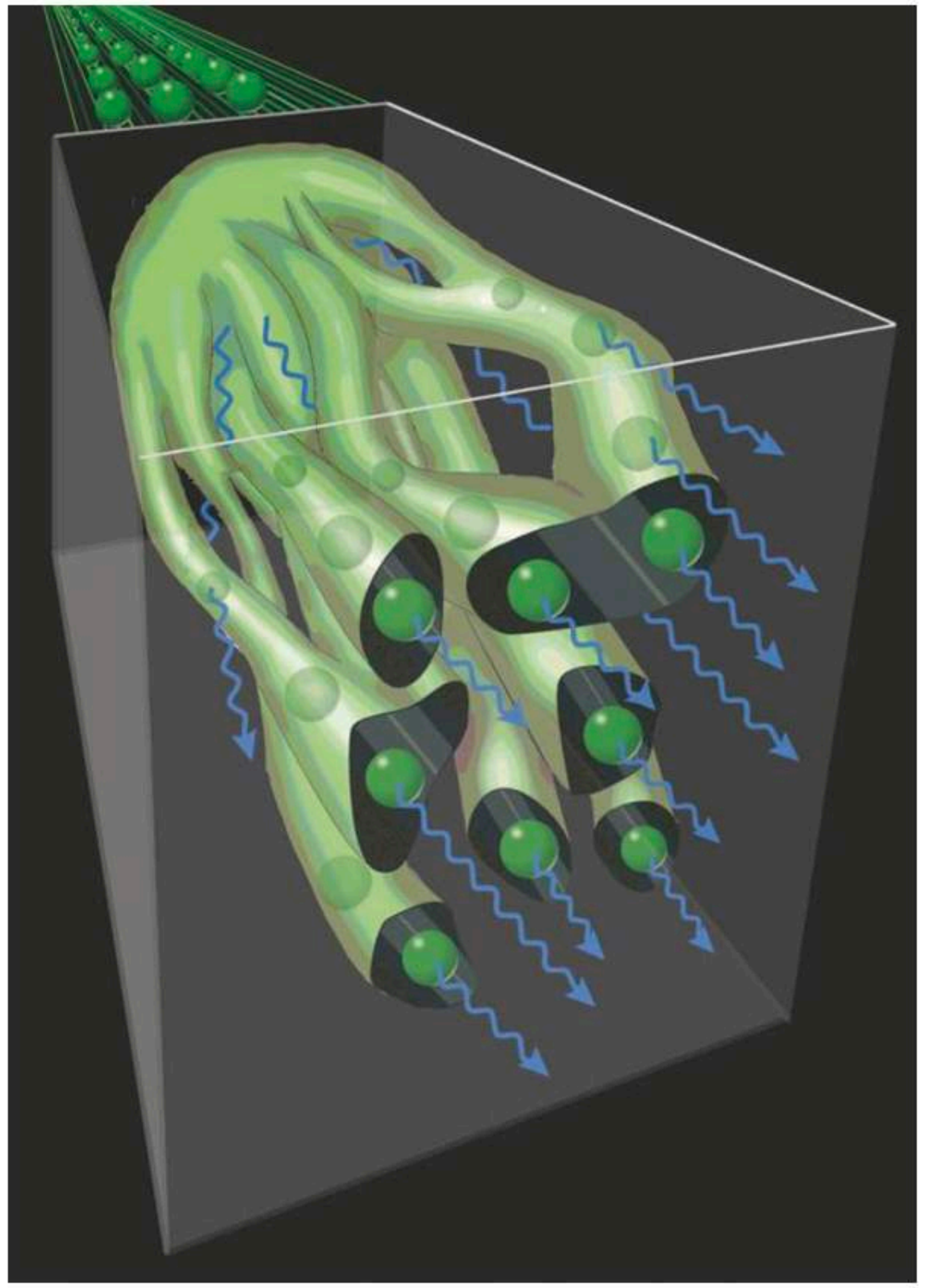
Electrostatic (oblique) instability

Electromagnetic (filamentation) instability

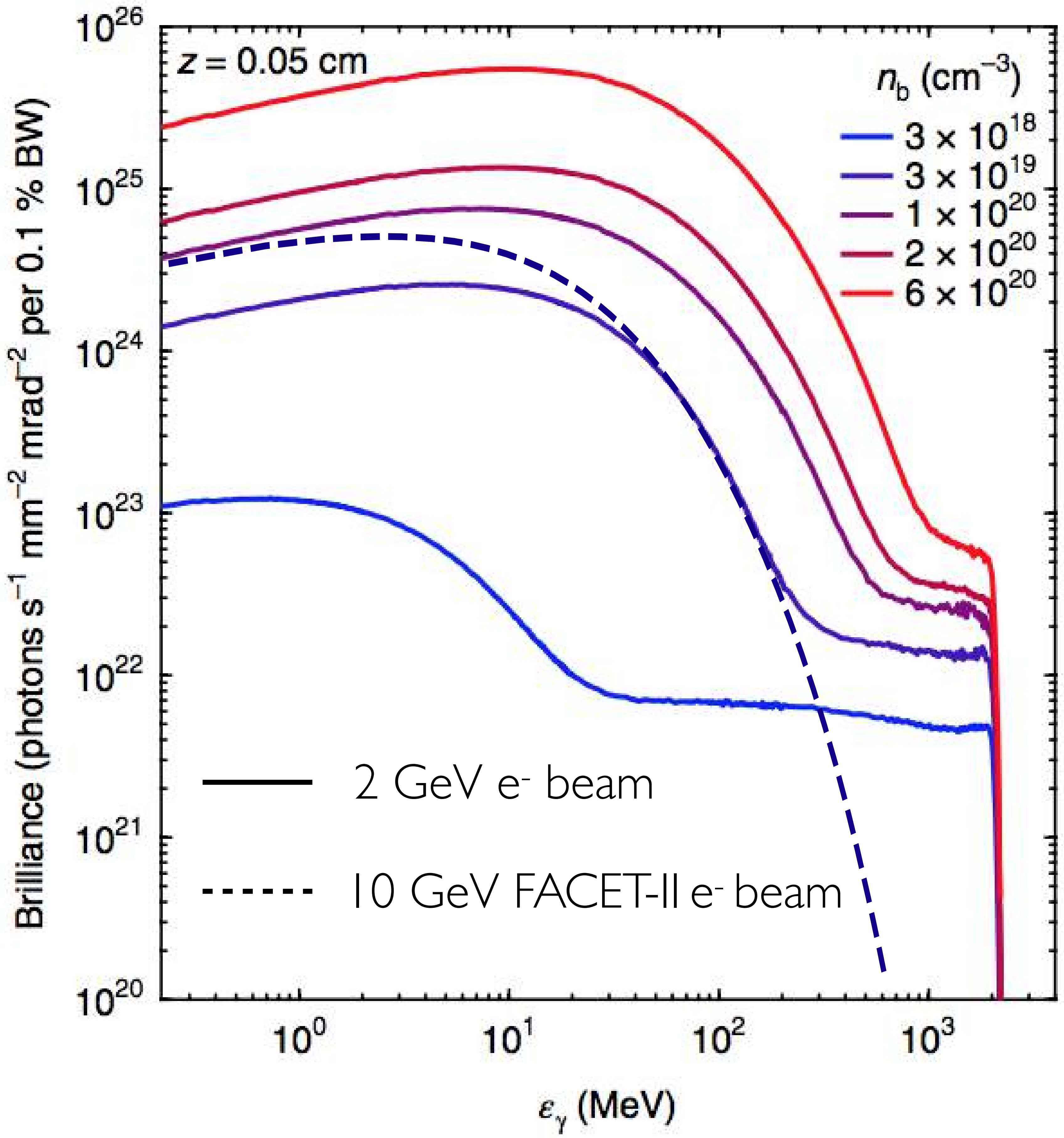
A. Sampath et al. PRL (2021), P. Claveria et al, PRR (2022)

# High brilliance gamma-ray flashes

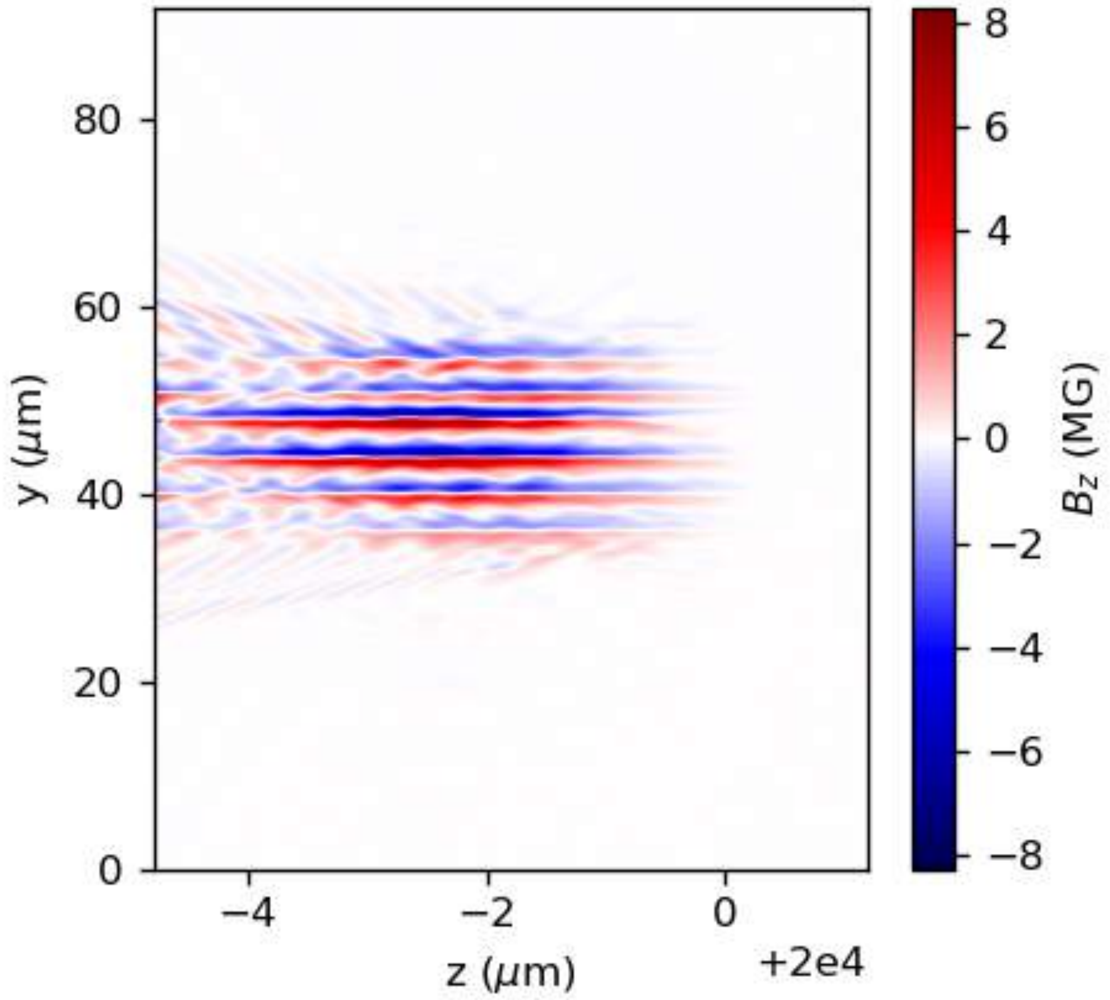
Synchrotron emission is self-amplified B-fields



Gamma-ray source with unprecedented high brilliance



B-fields for propagation over 2 cm gas jet

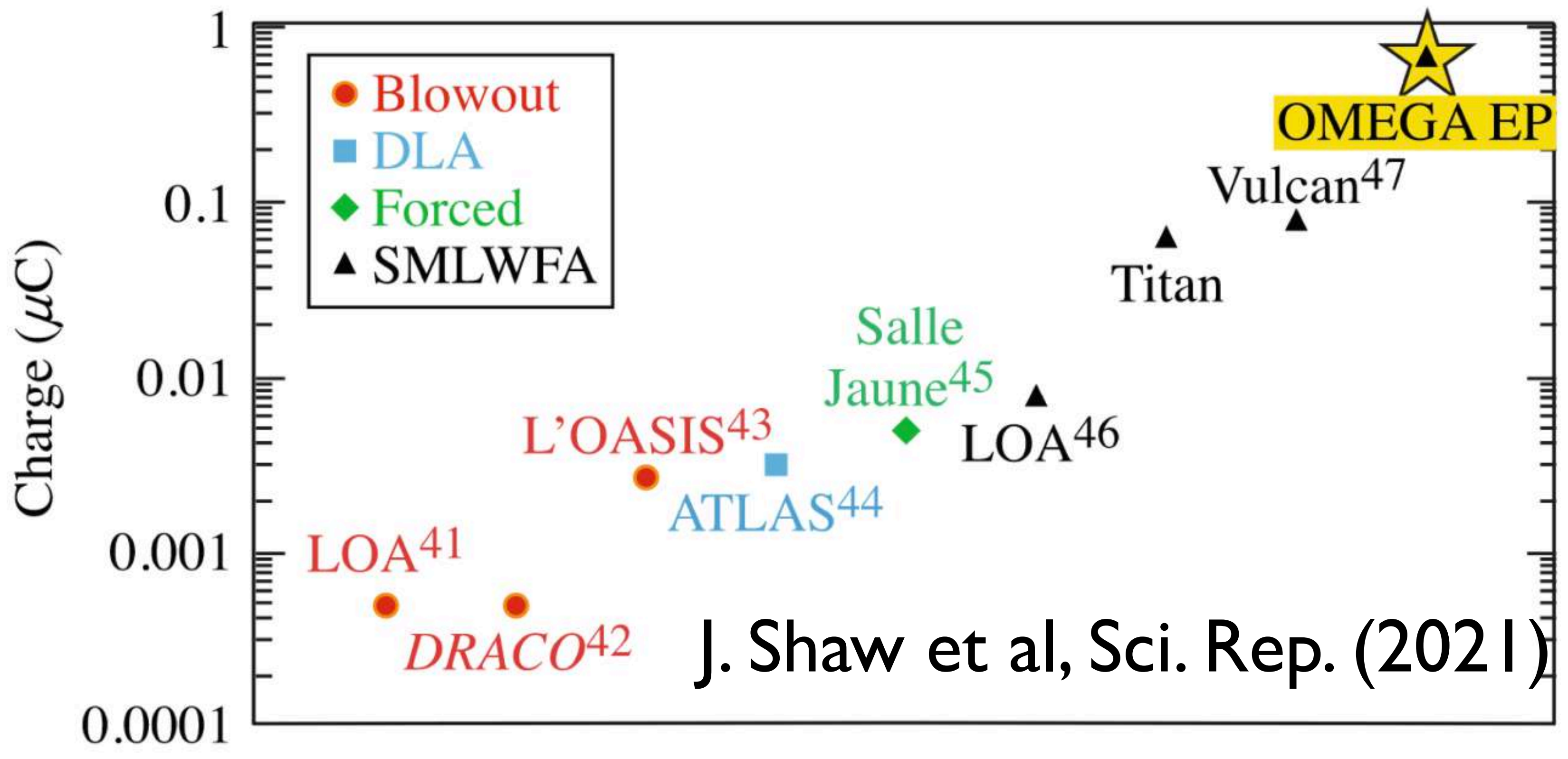


**A. Benedetti et al, Nature Photonics 12, 319 (2018)**
**F. Fiuza et al, Snowmass LOI 2021**

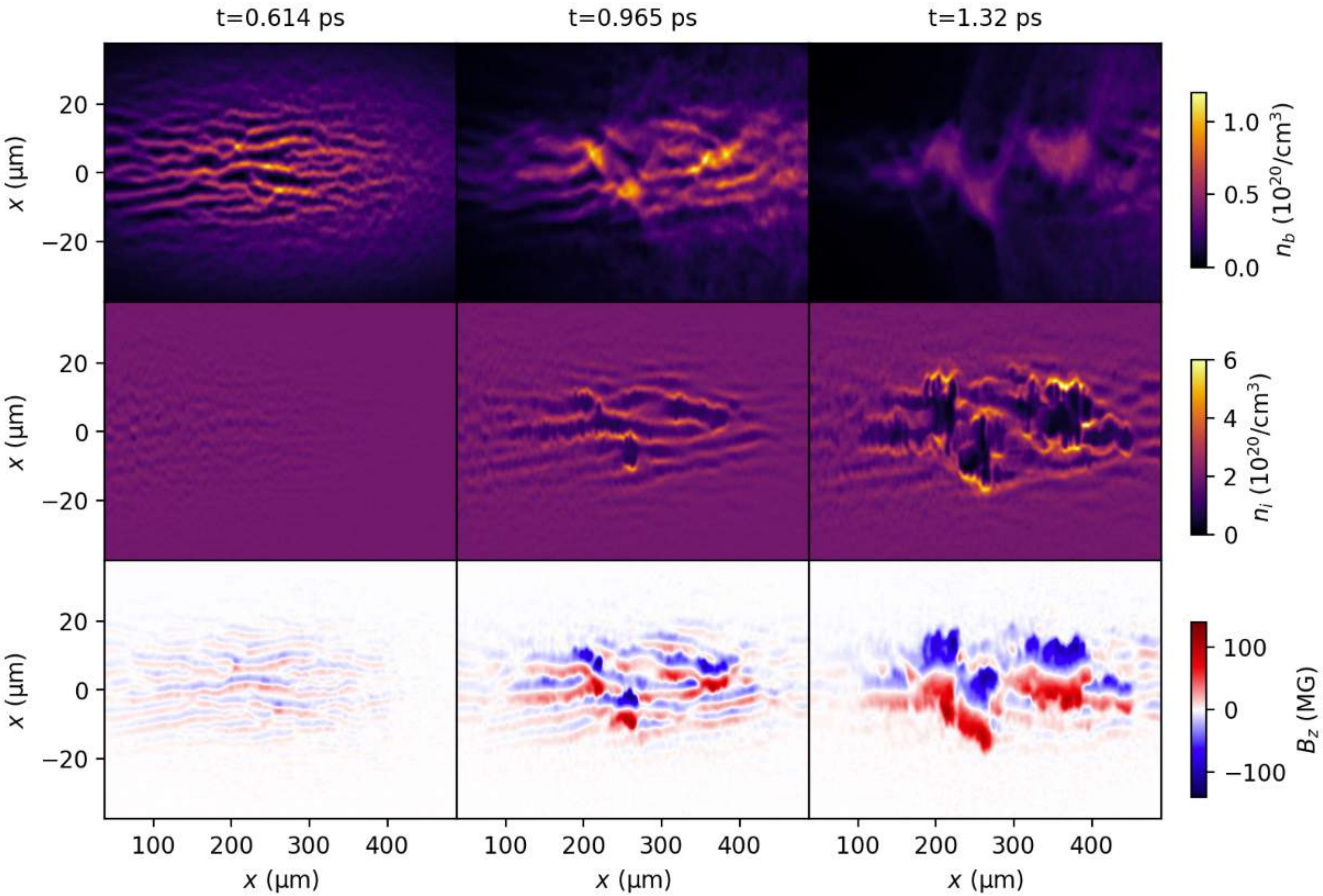
# Caviation instability driven by µC laser-driven electron beams

Self-modulated LWFA regime explored at OMEGA EP

1 kJ, 1ps laser → 1 µC, 200 MeV ($\eta \sim 10\%$)



J. Shaw et al, Sci. Rep. (2021)



With NIF ARC or PETAL (assuming similar efficiency)

10 kJ laser → 10 µC, 50 MeV

Caviation instability could be driven to nonlinear regime

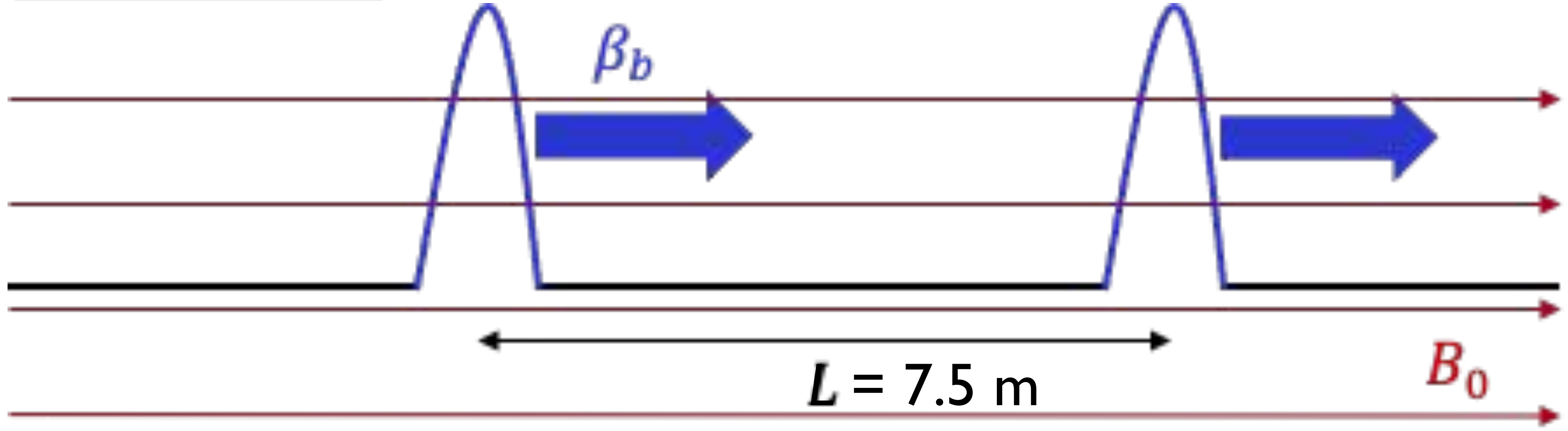
$\varepsilon_b = 40$ MeV, $\tau_b = 1.5$ ps, $\sigma_\perp = 25$ µm, $n_b/n_0 = 0.2$

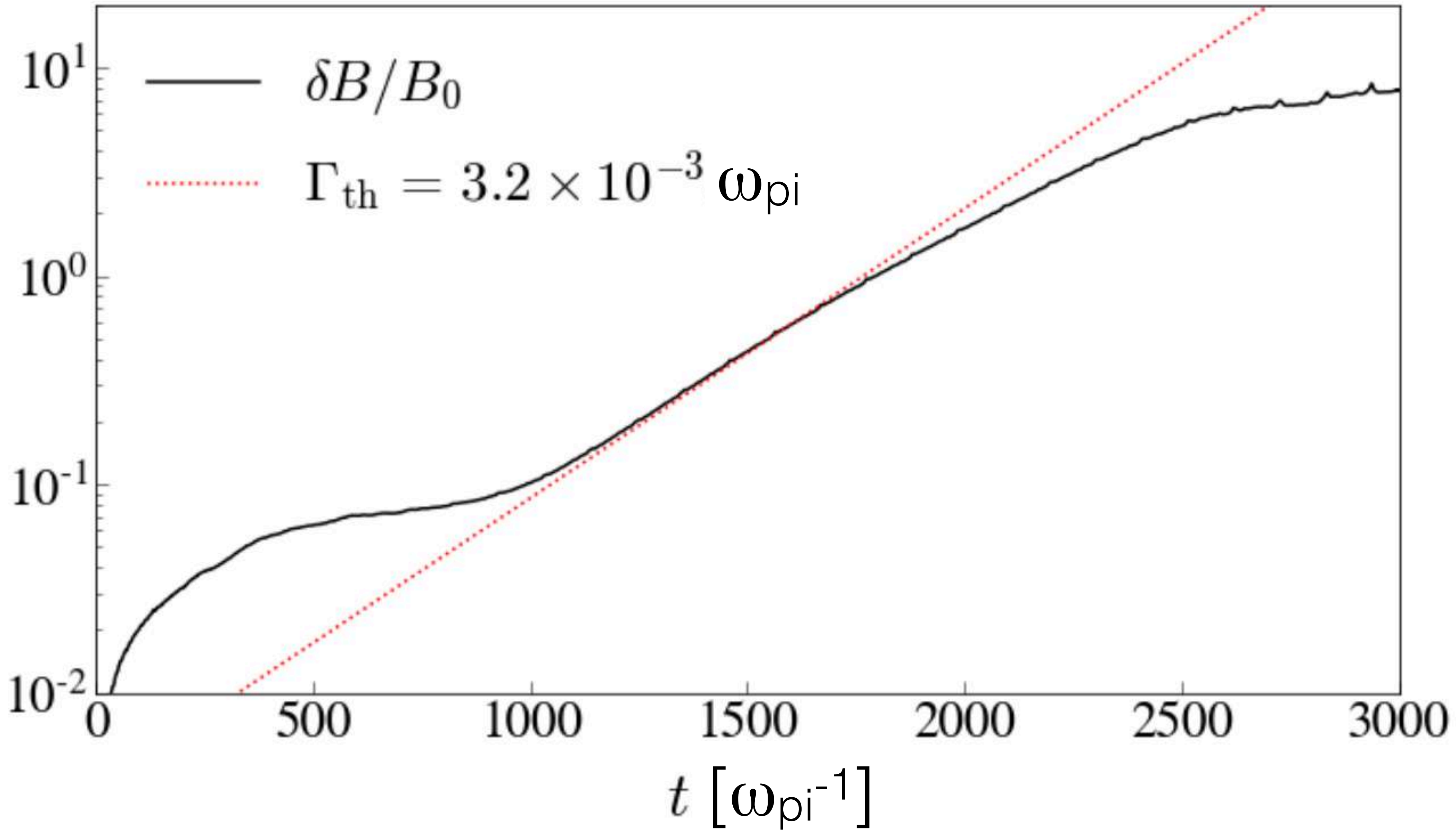
**J. R. Peterson and F. Fiuza, in preparation**

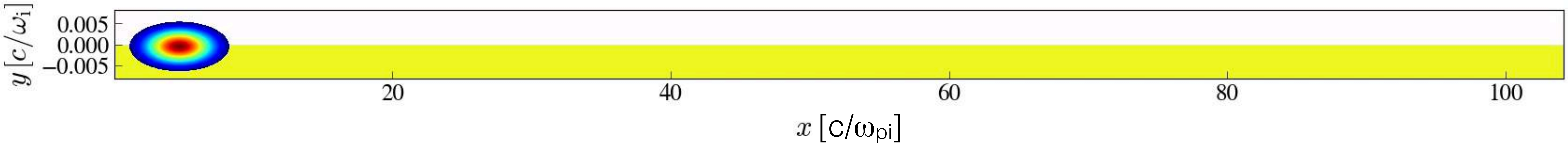
# Bell instability driven by proton bunch train from SPS at CERN

- Bunch density: $4\times10^{12}$ cm$^{-3}$
- $\sigma_z$ =12 cm
- $\sigma_r$ =0.02 cm
- Proton energy: 400 GeV

- $n_0 \simeq 10^{13}\mathrm{cm}^{-3}$
- $B_0 \simeq 0.2$ T

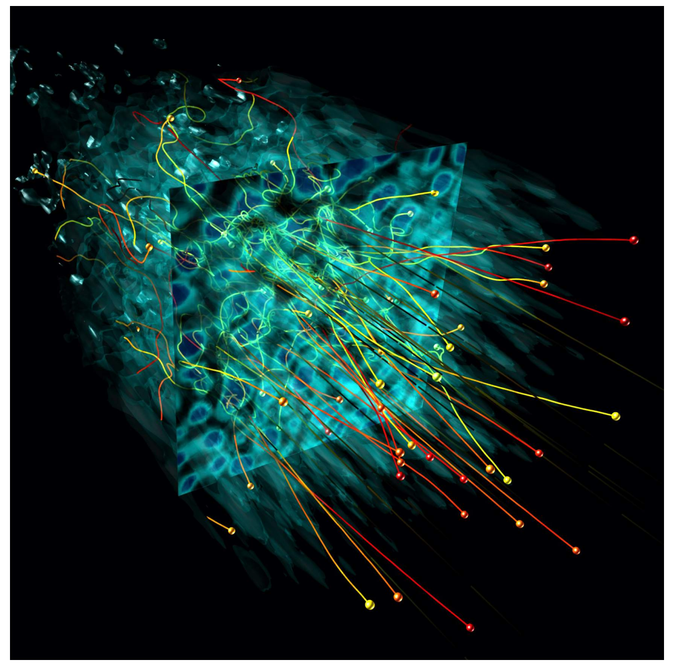




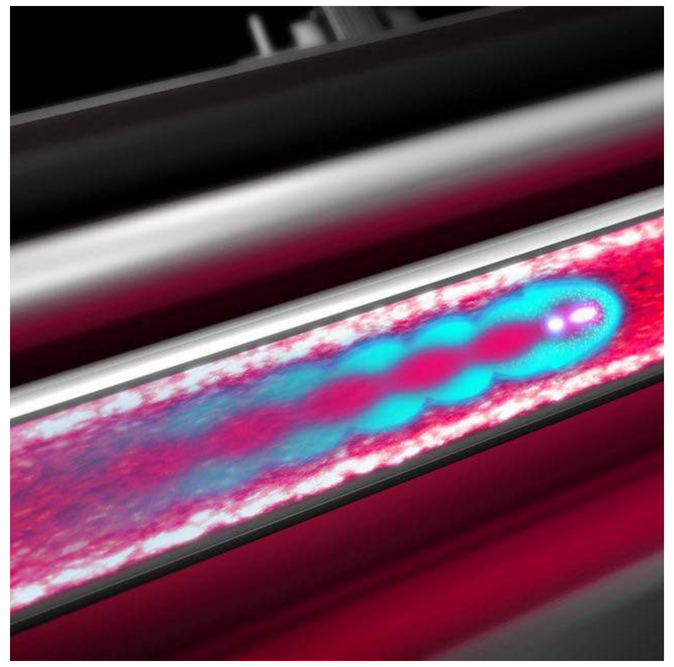


**A. Vanthieghem and F. Fiuza, in preparation**

# Opening new windows into cosmic accelerators



**Astrophysical observations reveal that astrophysical plasmas are extraordinary particle accelerators** and insist on the need to understand better the plasma physics at these extreme environments



The combination of first-principles simulations and laboratory experiments is **opening new windows** into the physics of cosmic-ray driven instabilities that can **advance our understanding of particle acceleration** and…

… **establish new connections** between **plasma-based accelerators** and **high-energy astrophysics** with far-reaching implications for our understanding of the most spectacular phenomena in the Universe