The mystery behind the most powerful accelerators in the universe

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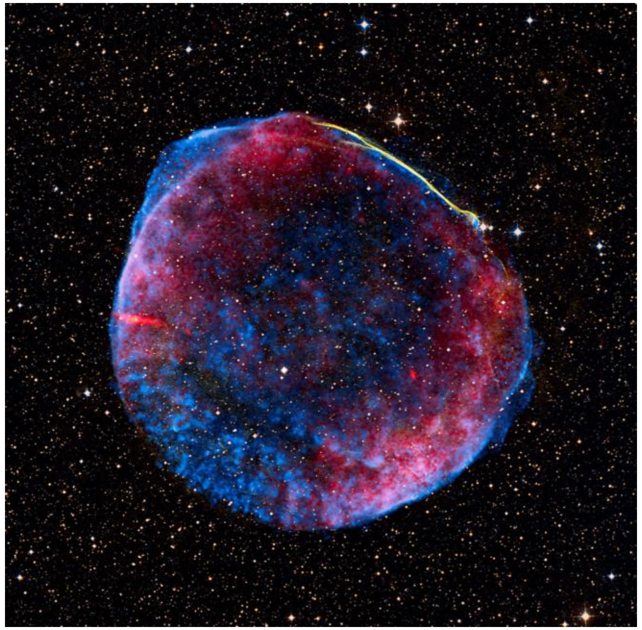

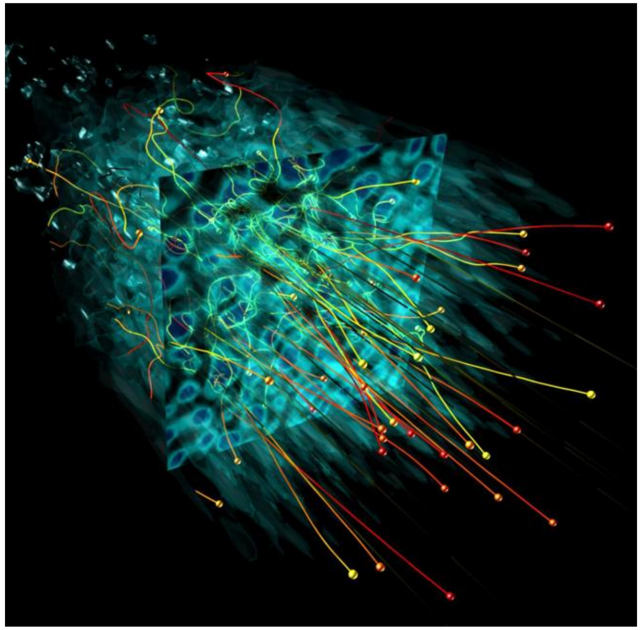

ipfn INSTITUTO DE PLASMAS E FUSÃO NUCLEAR

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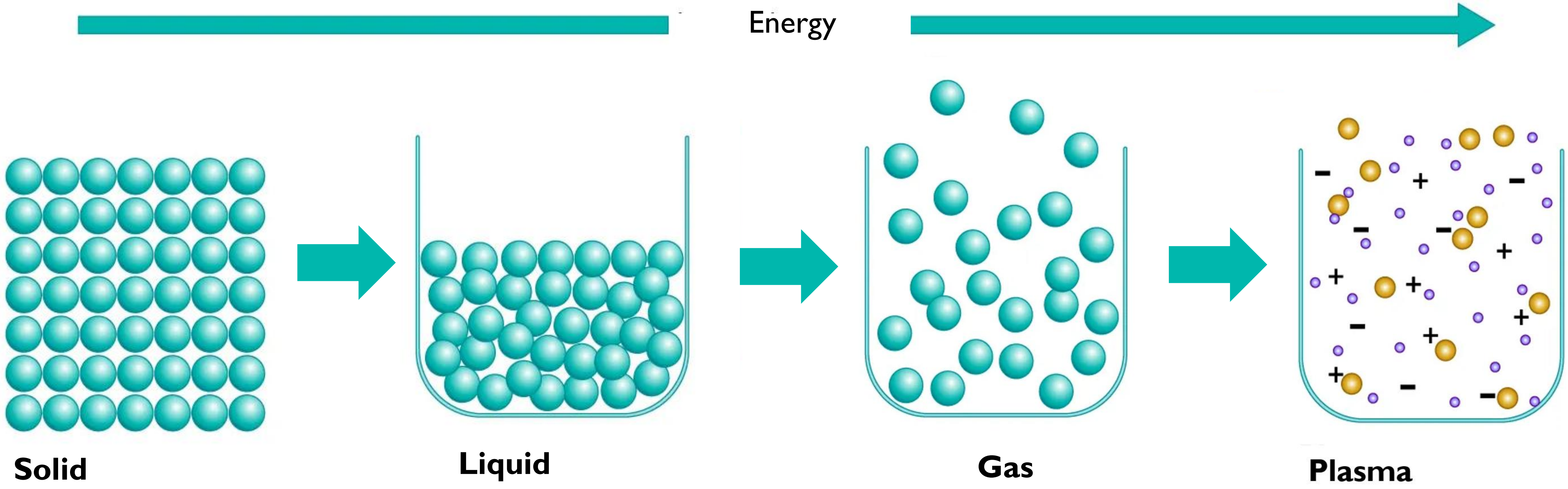
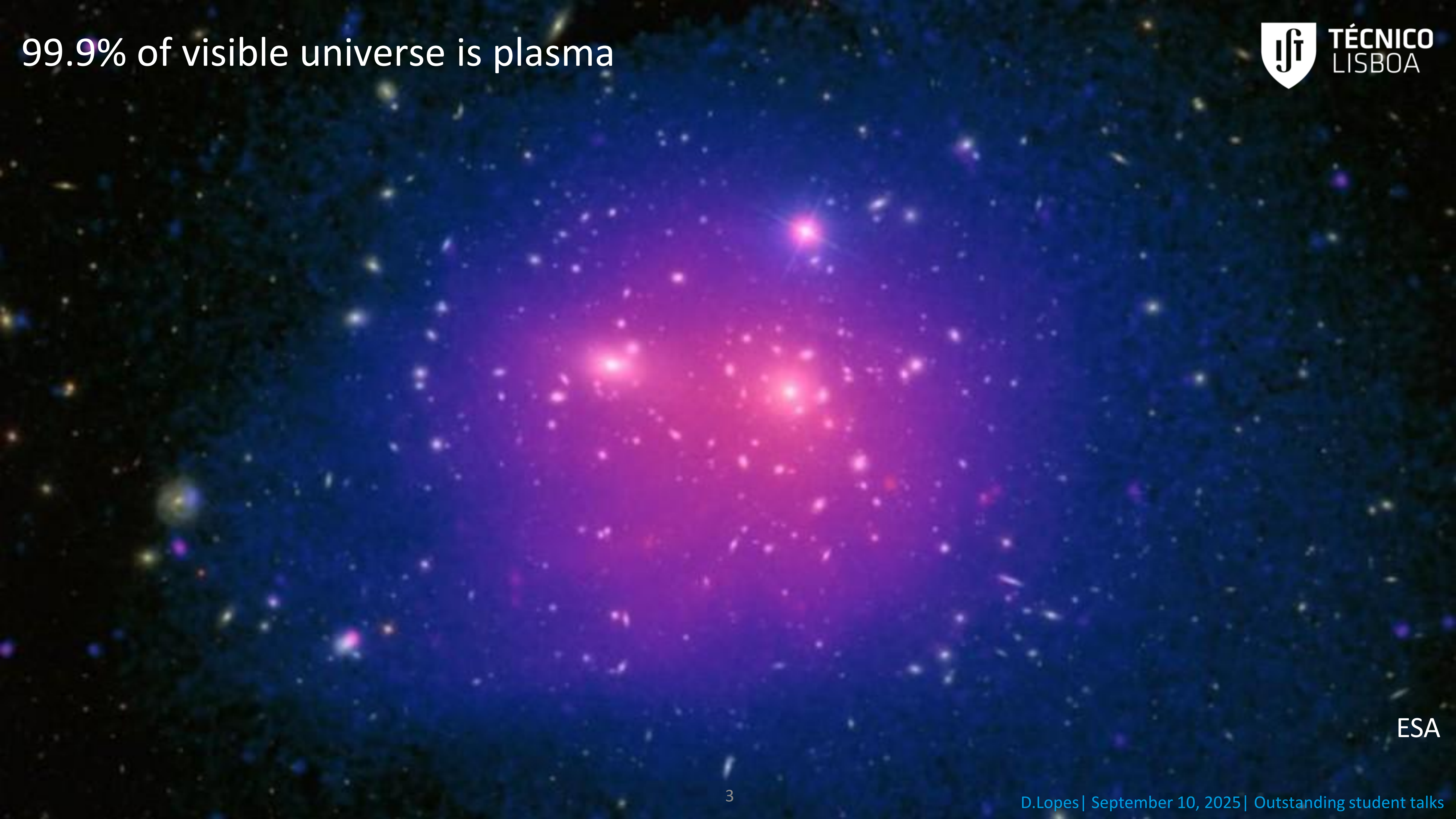
What is a plasma?

States of matter

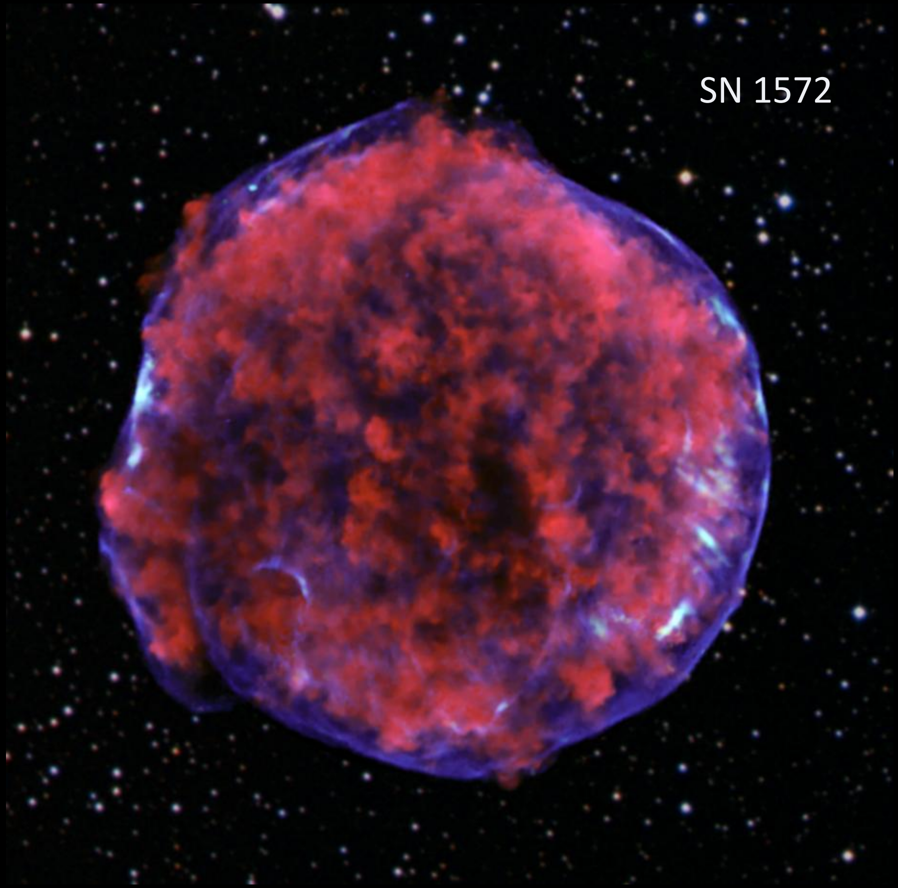


99.9% of visible universe is plasma


ESA

Supernovae as the ultimate cosmic ray accelerators

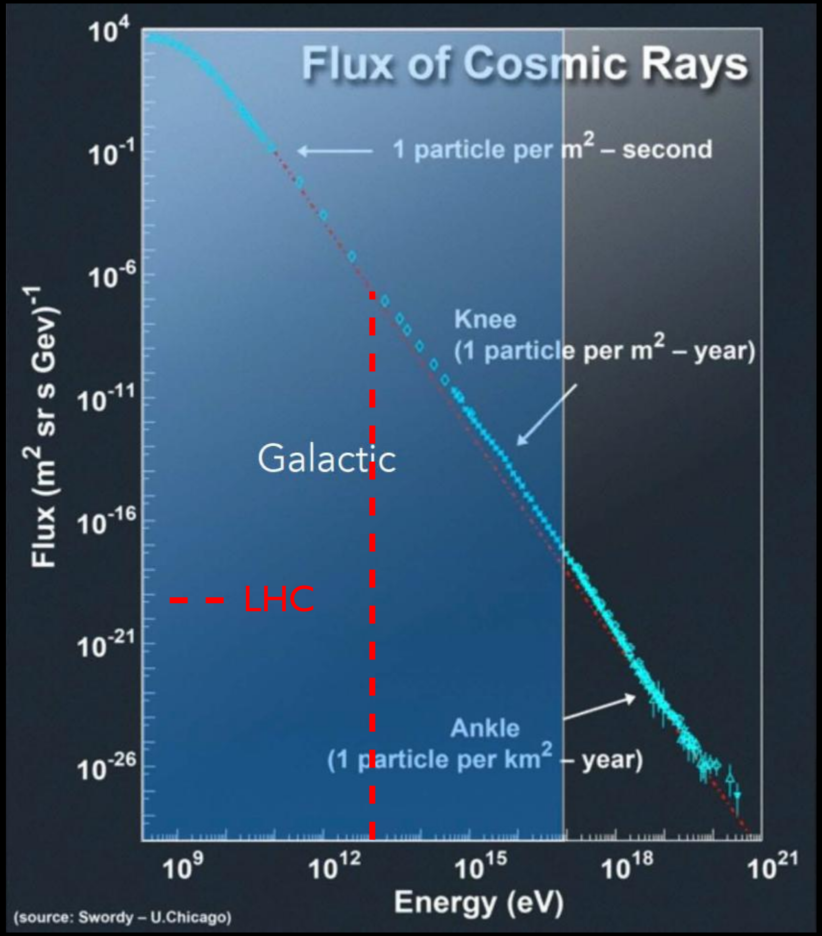
Supernova remnants



1 pc = 3×10^{16} m

NASA

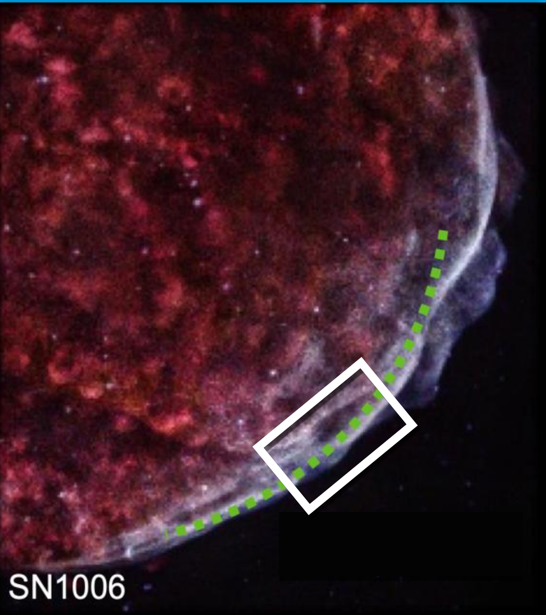
10 – 30% energy fraction converted into cosmic rays

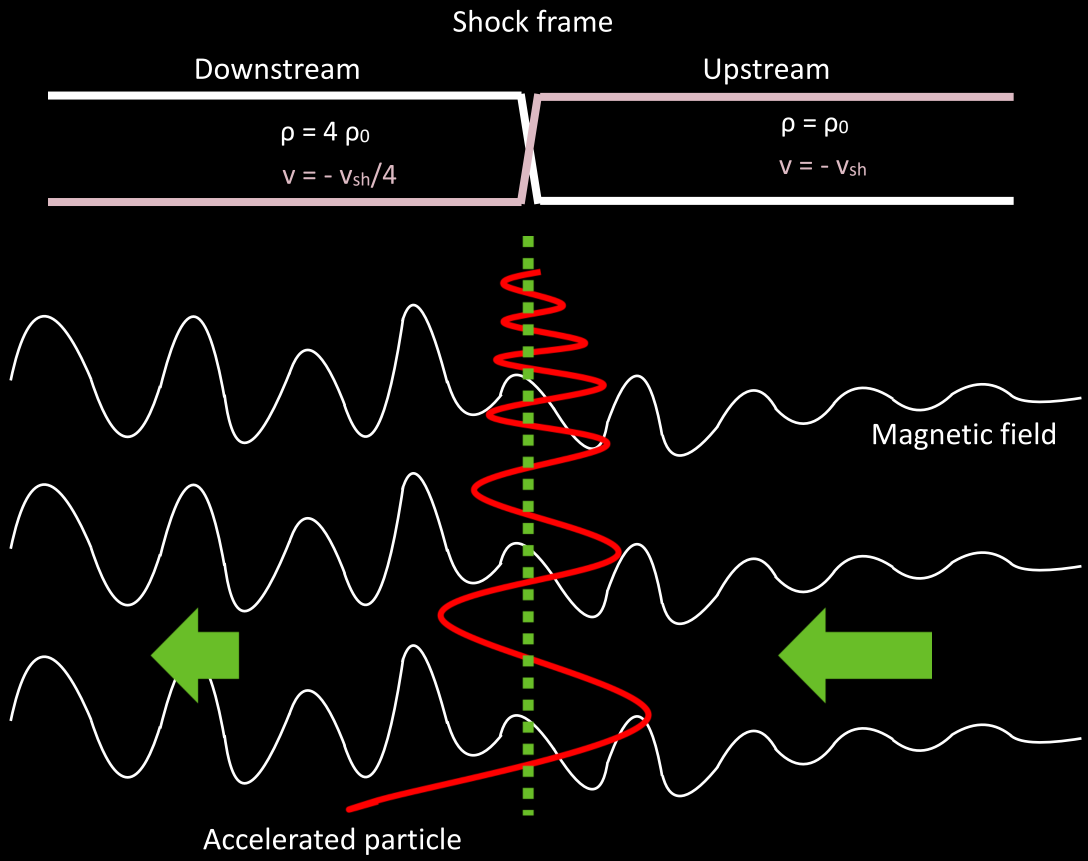


(source: Swordy – U.Chicago)

* Helder et al 2009, Ackermann et al 2013

Fermi acceleration in collisionless shocks





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

Fractional energy gain per shock crossing:

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

Fractional particle loss per shock crossing:

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

Power-law spectrum:

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

Elegant solution to power-law particle acceleration across wide range of systems

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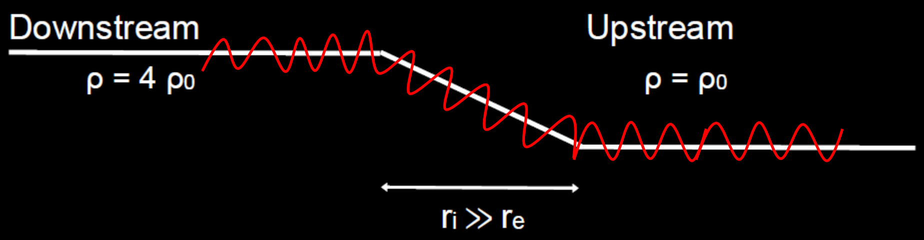
* Krymskii 1977, Axford, Leer, Skadron 1977, Bell 1978, Blandford & Ostriker 1978

Riding Giants: how to create plasma jet skis

Shock transition typically defined by ion Larmor radius



Electrons need to be pre-accelerated to start crossing the shock front

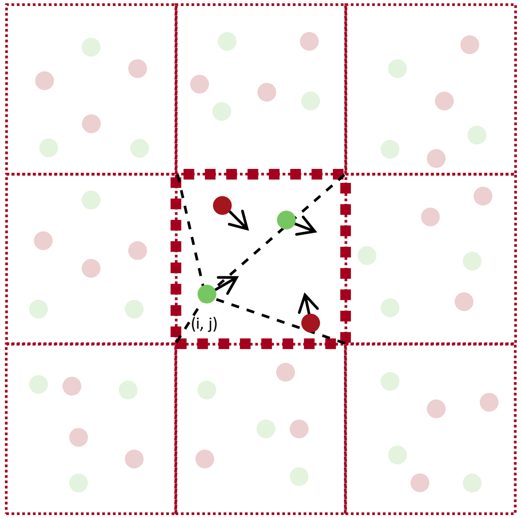
Riding Giants (2004)

Particle injection is determined by microscopic plasma processes and is not well understood

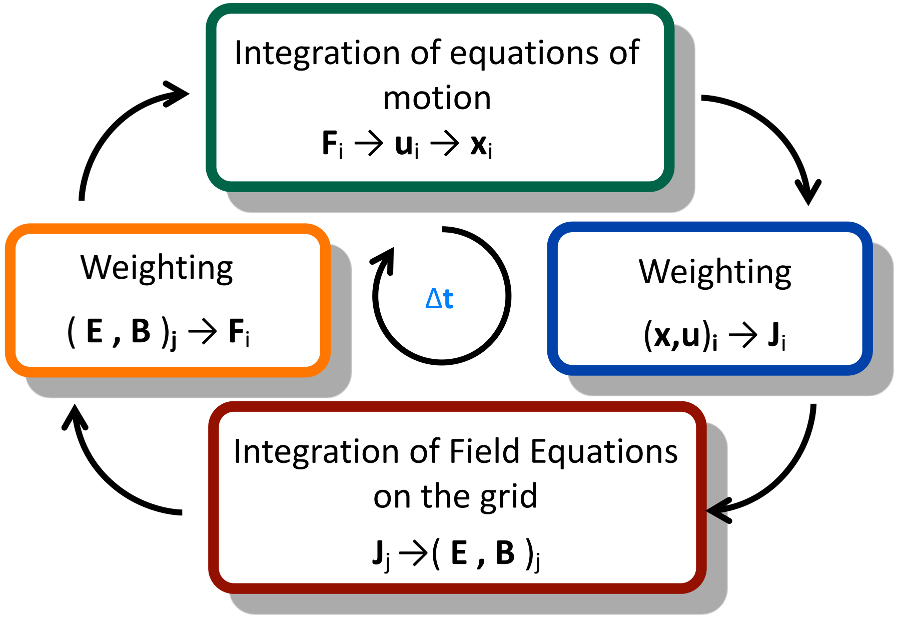
Kinetic simulations are critical to study microphysics of shocks

For our study, we will rely on large scale simulations, using a method called Particle-In-Cell (PIC).

Particle-in-cell (PIC): kinetic plasma simulations



$$\frac{d\mathbf{u}}{dt} = \frac{q}{m}\left(\mathbf{E} + \frac{1}{\gamma c}\mathbf{u}\times\mathbf{B}\right)$$



Integration of equations of motion

$\mathbf{F}_i \to \mathbf{u}_i \to \mathbf{x}_i$

Weighting

$(\mathbf{E}, \mathbf{B})_j \to \mathbf{F}_i$

Δt

Weighting

$(\mathbf{x},\mathbf{u})_i \to \mathbf{J}_i$

Integration of Field Equations on the grid

$\mathbf{J}_j \to (\mathbf{E}, \mathbf{B})_j$

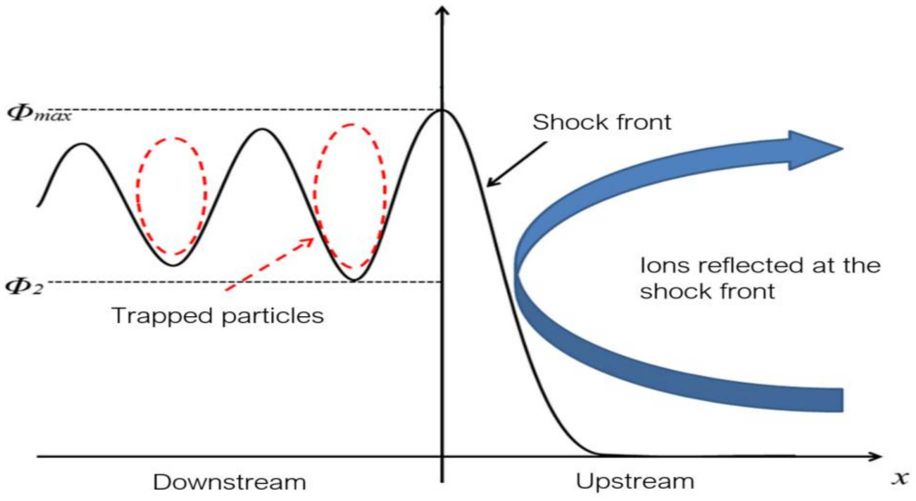
$$\frac{\partial \mathbf{E}}{\partial t} = c\vec{\nabla}\times\mathbf{B} - 4\pi\mathbf{j}$$

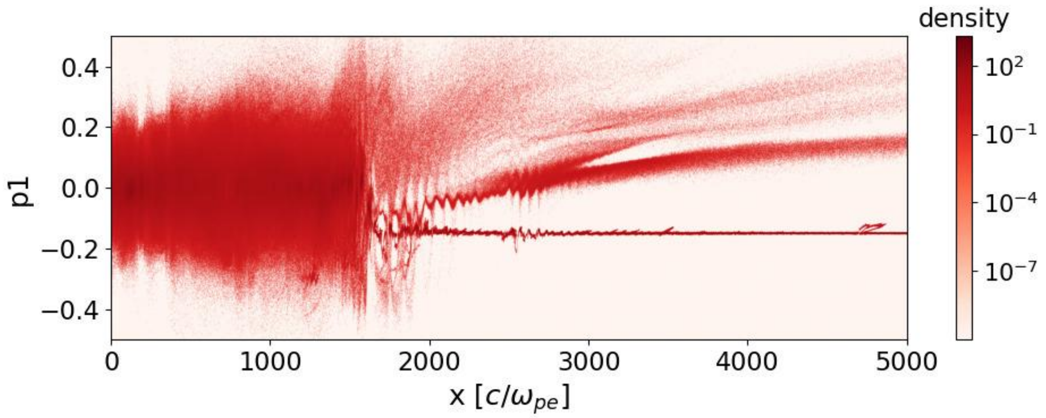
$$\frac{\partial \mathbf{B}}{\partial t} = -c\vec{\nabla}\times\mathbf{E}$$

Dawson, Buneman, 1960's; Birdsall and Langdon, 1985

Ion’s role: the key to magnetic field amplification

Ions play an important role in shocks





Ion’s behaviour and influence

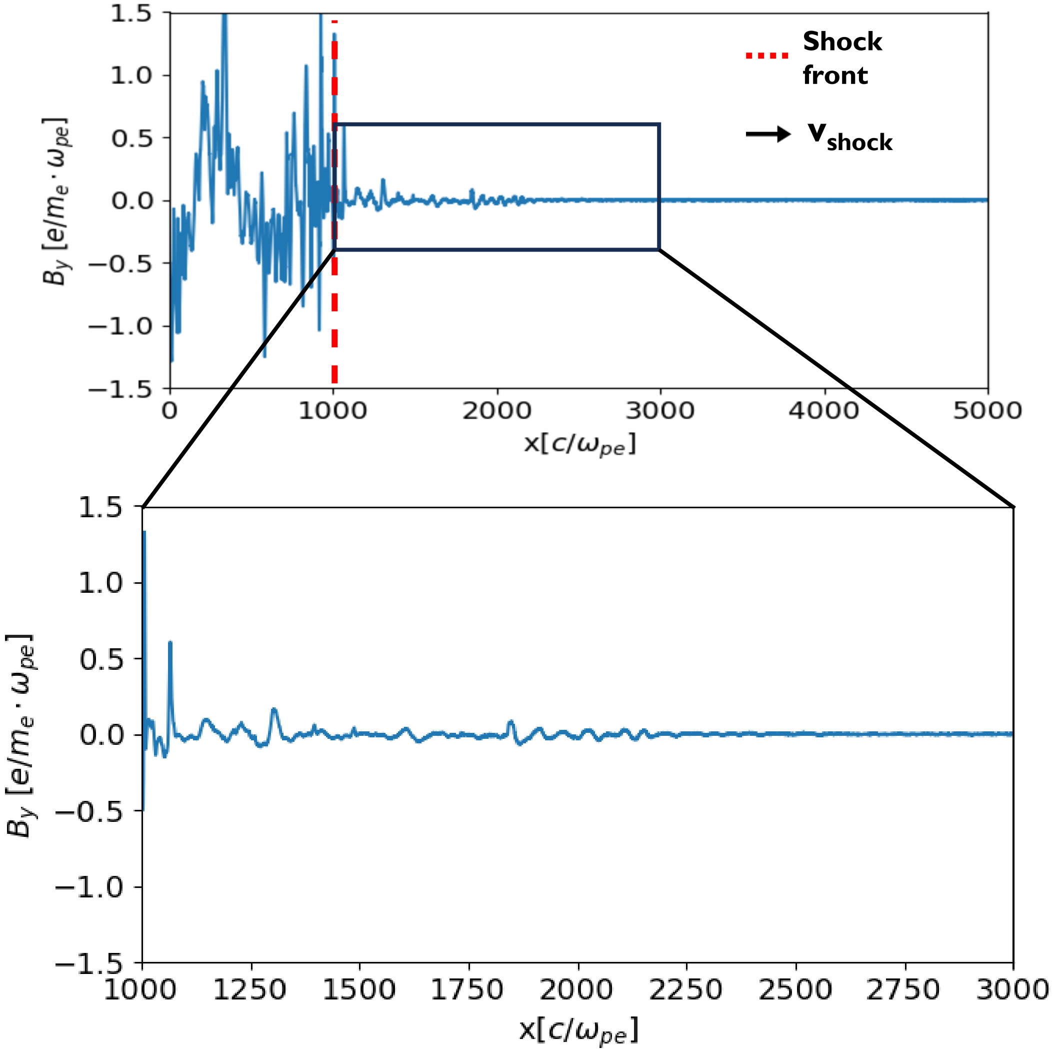
- Ions get reflected in the shock front
- The density of reflected ions might be crucial in controlling magnetic field amplification upstream of the shock.

We will artificially inject cosmic rays and study their impact on the magnetic fields and particle injection.

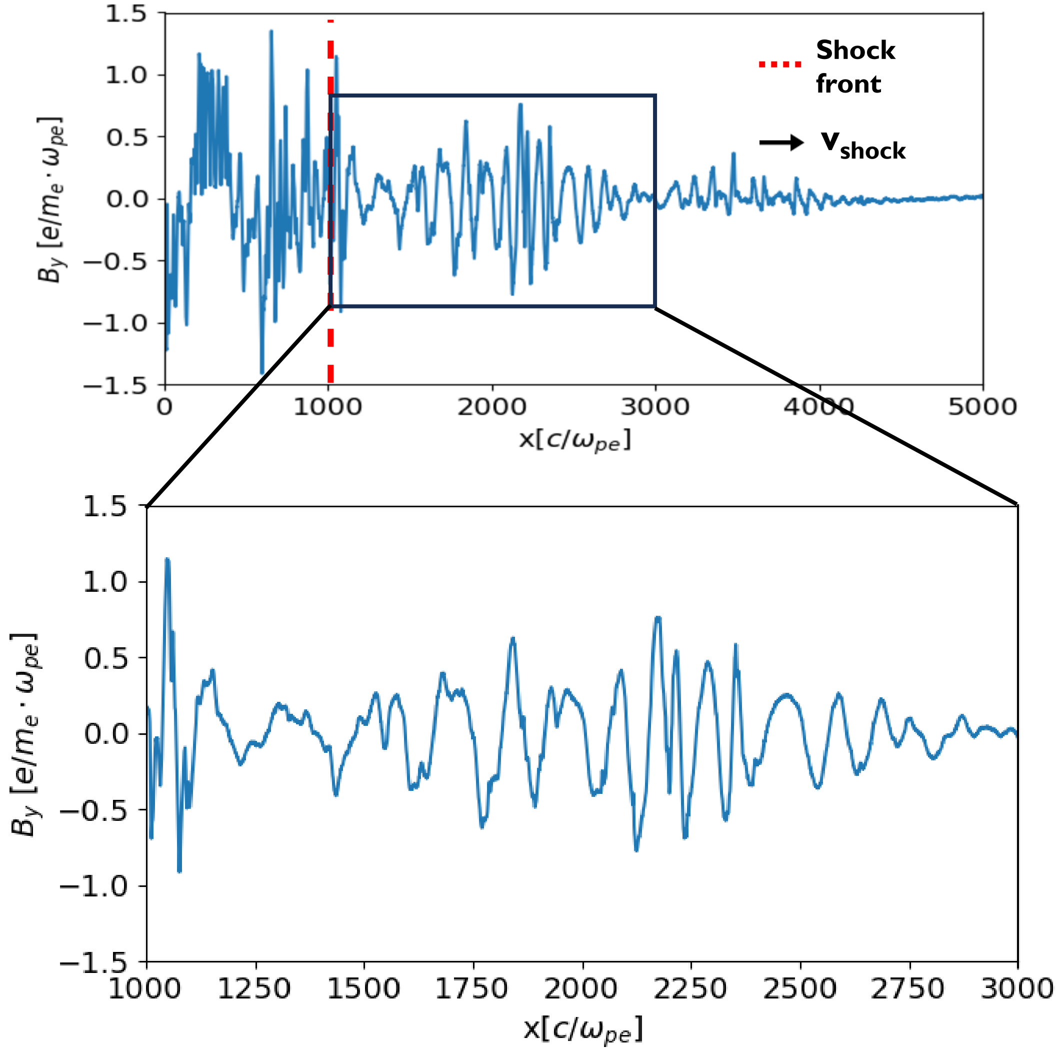
S. G. Lucek, A. R. Bell, MNRAS 314, 65 (2000); A. R. Bell, MNRAS 353, 550 (2004)

Ion reflection leads to magnetic field amplification

Magnetic field with ion density α ≈ 0,01

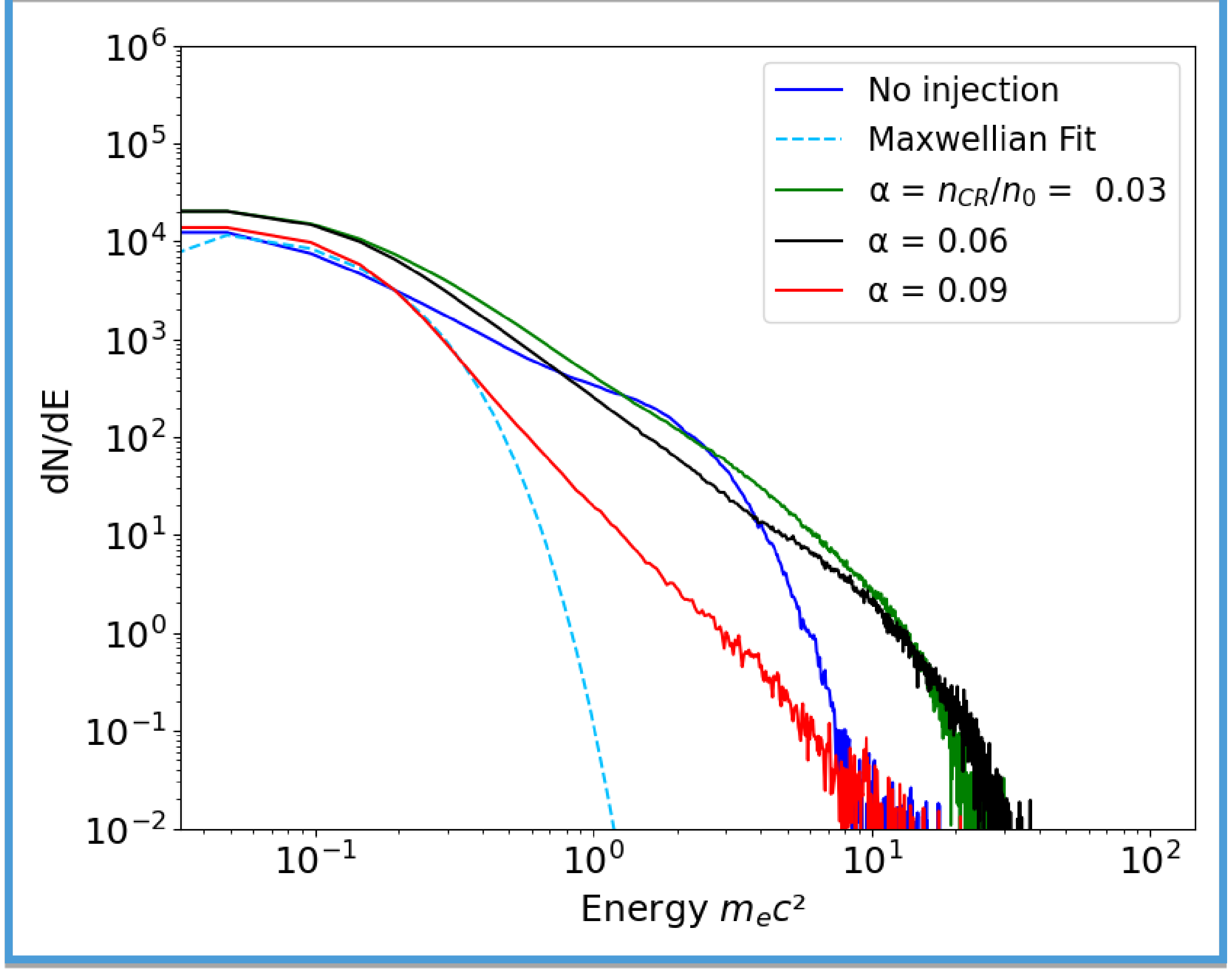


Magnetic field with ion density α ≈ 0,09

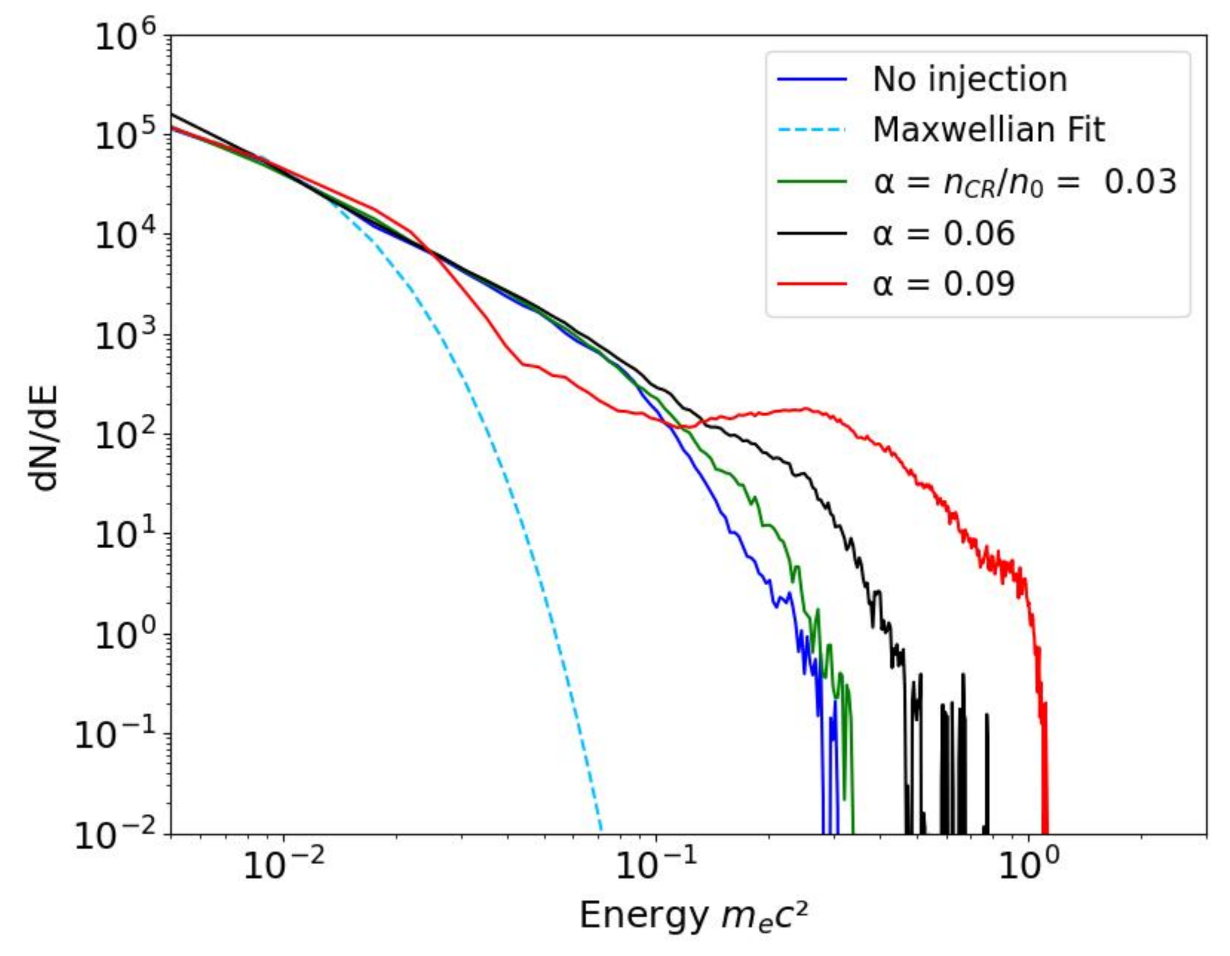


Cosmic ray injection affects the energy spectra

Electron acceleration decreases with increasing CR density



Ions acceleration increases with increasing CR density



Cosmic ray injection affects the energy spectra

Recap and future perspectives

- Supernovae generate shocks that are capable of accelerating particles to extremely high energies;
- The mechanisms by which particles enter these shocks are still unknown;
- Using simulations, we have studied the effect of several factors, such as ion density on magnetic fields and particle injection into these shocks;
- In the future, we will extend this analysis to more parameters, with the ultimate goal of developing a consistent model capable of describing both injection and acceleration.

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Particles colide…until they don´t

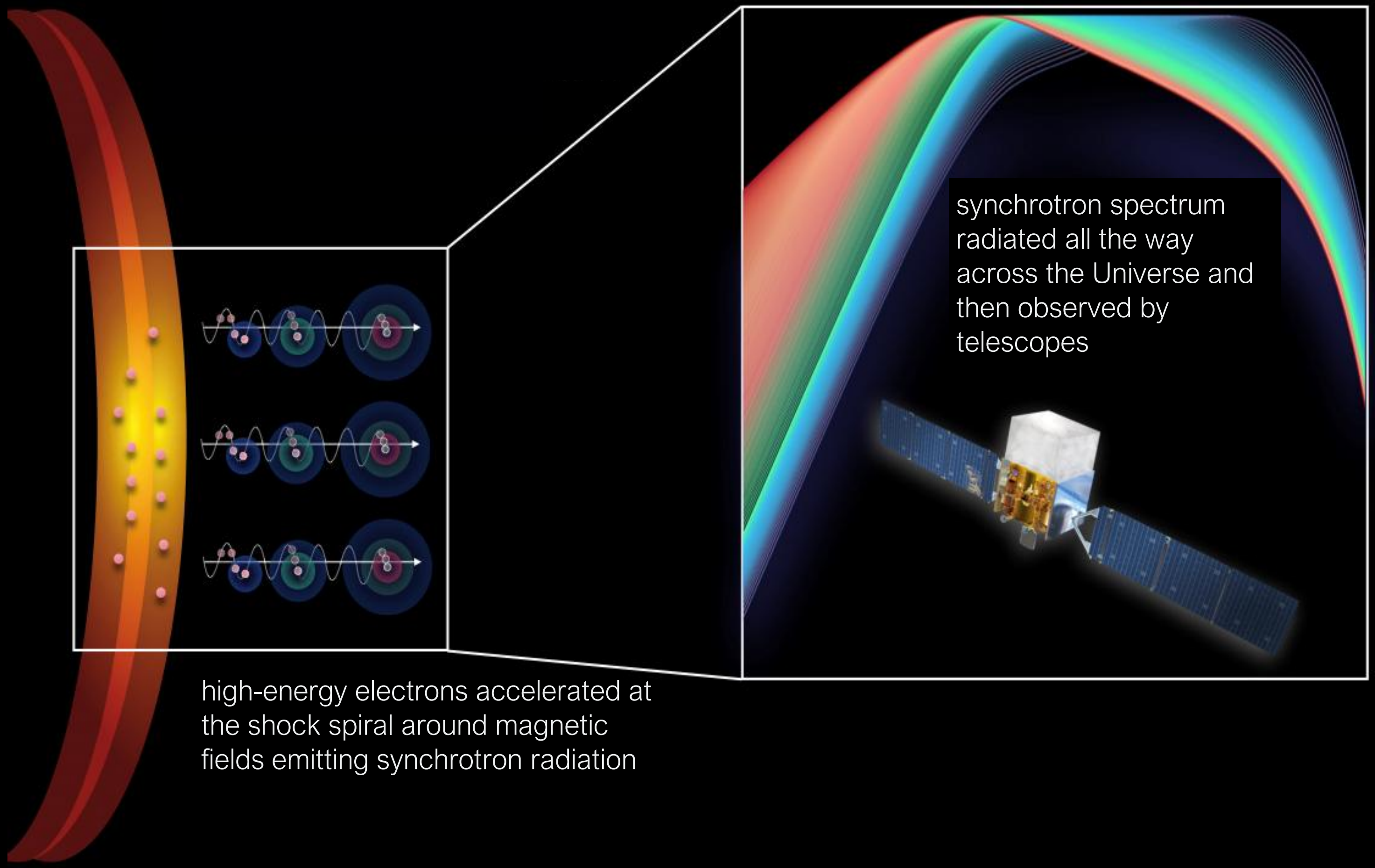
Collisional shocks

Mediated by particle collisions

Collisionless shocks

Mediated by electromagnetic interactions

Cosmic Rays: Detection and expectation



synchrotron spectrum radiated all the way across the Universe and then observed by telescopes

high-energy electrons accelerated at the shock spiral around magnetic fields emitting synchrotron radiation

We’ve detected highly energetic electrons accelerated at SNRs;

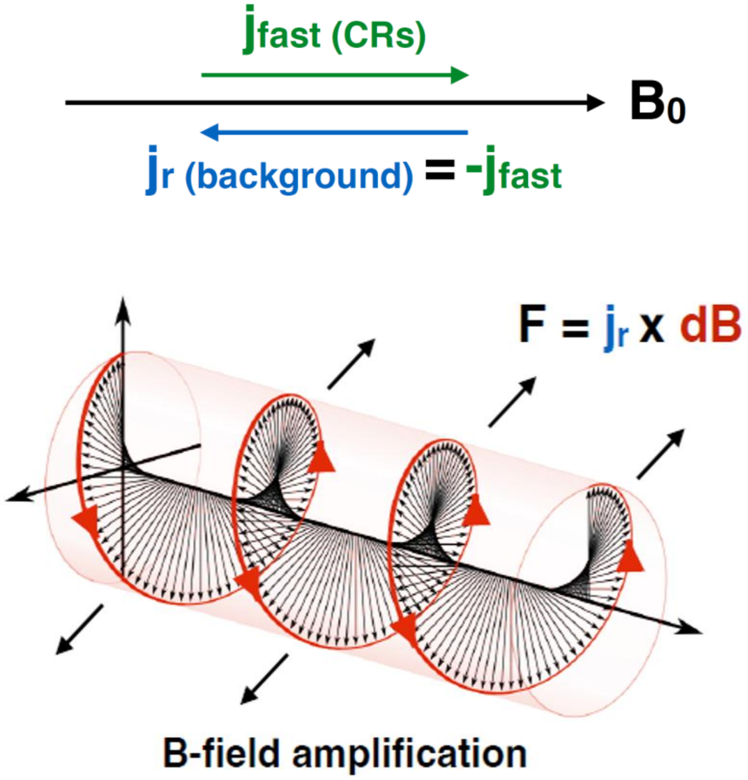
However, no sign of equivalently energetic ions was seen, despite the composition of cosmic rays.

So, are the shocks that efficiently accelerate electrons also good at accelerating ions?

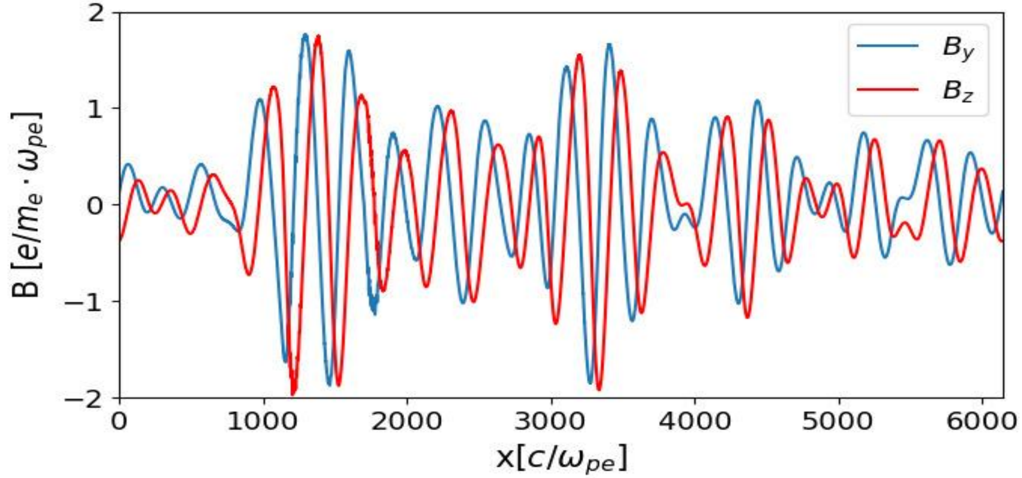
adapted from J. M. Burgess

Bell instability: the key to magnetic field amplification

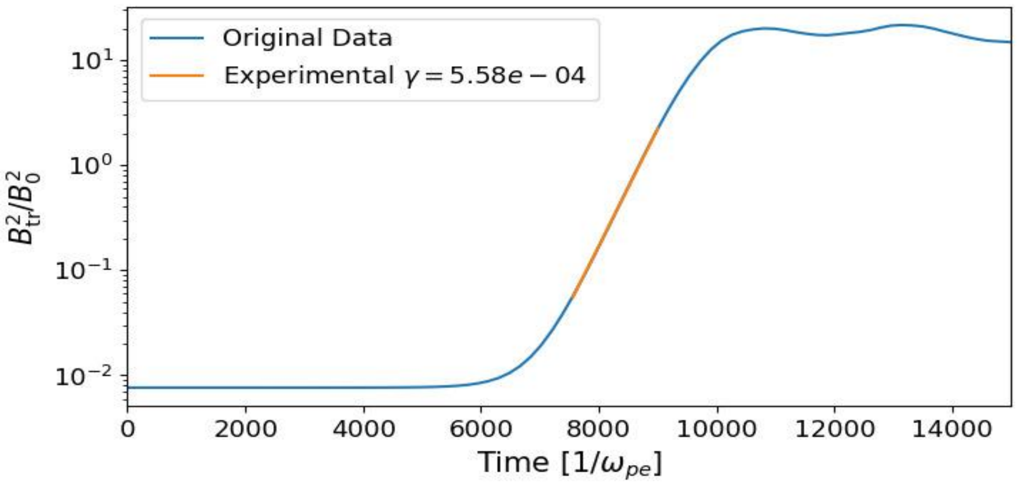
Fast streaming particles lead to magnetic field amplification



Our kinetic simulations give consistent results



Magnetic energy density



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

Bell dispersion relation

Dispersion relation for Bell instability

$$\omega^2 - v_A^2 k^2 \pm \zeta v_s^2 \frac{k}{r_{g1}}(1-\sigma_1) = 0$$

$$\sigma_1 = k r_{g1} \int_0^{1/k r_{g1}} \sigma_p(\lambda)\, d\lambda, \quad \text{with } \lambda = \frac{1}{k r_g}$$

$$\sigma_p(\lambda) = \frac{3}{4}\lambda(1-\lambda^2)\left[\ln\left(\frac{1+\lambda}{1-\lambda}\right) + i\pi\right] + \frac{3}{2}\lambda^2$$

v_A= Alfven velocity

ζ = Dimensionless parameter determining the strength of the CR driving term;

r_{g1} = Larmor radius of CR with momentum p_1

Dispersion plot shows different regimes

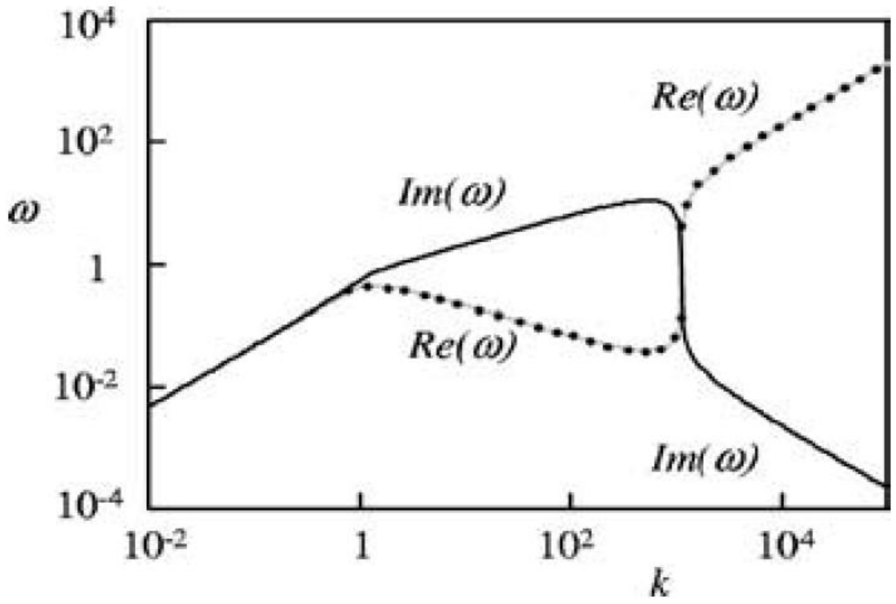
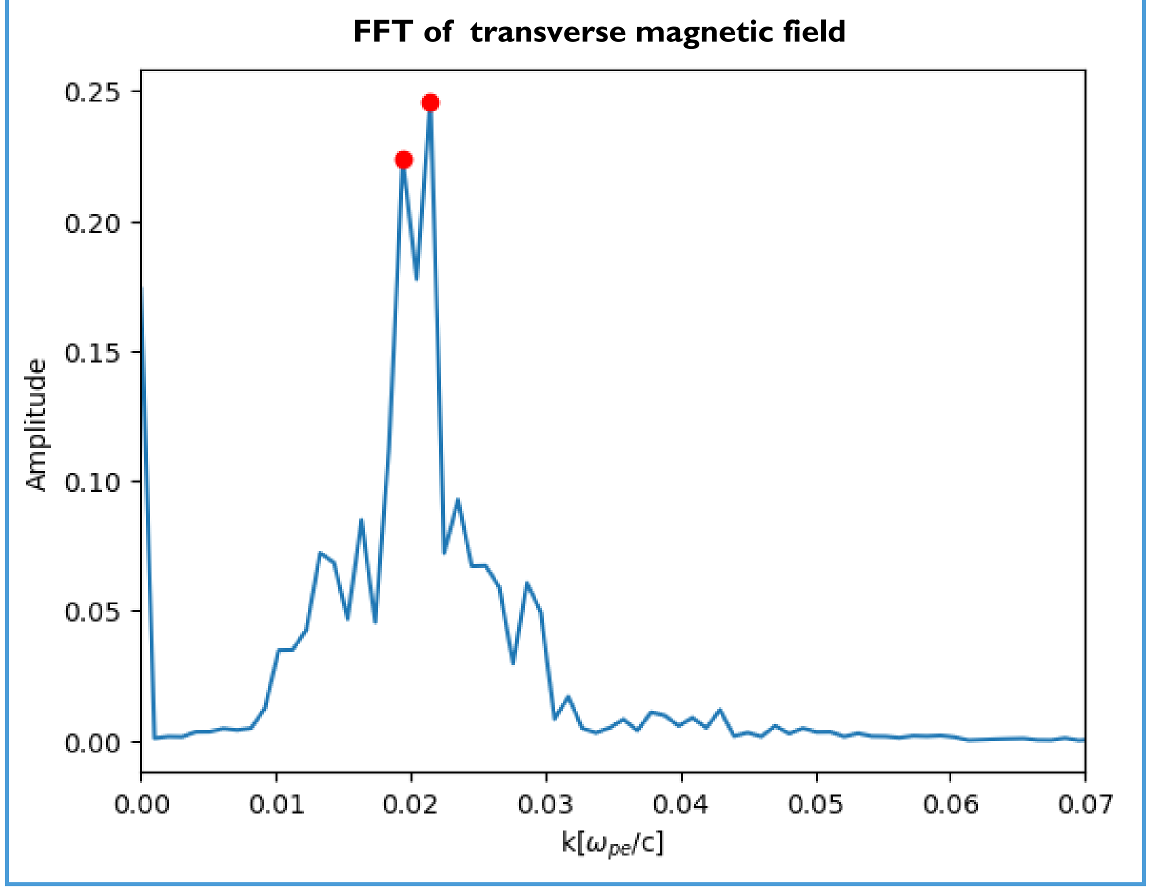


Figure: Plot taken from the original article by A. Bell

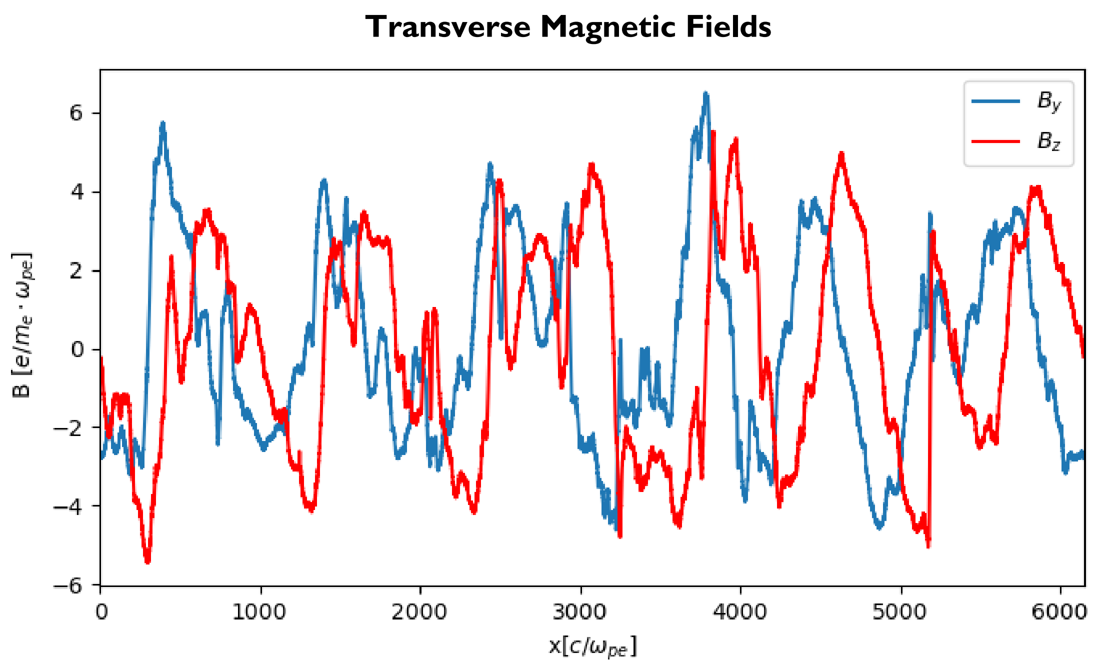
$$k_{max} = \frac{\zeta}{2}\frac{v_s^2}{v_A^2}\frac{1}{r_{g1}} \qquad \gamma_{max} = \frac{\zeta}{2}\frac{v_s}{v_A}\frac{v_s}{r_{g1}}$$

Bell growth modes

FFT shows a clear preferred mode

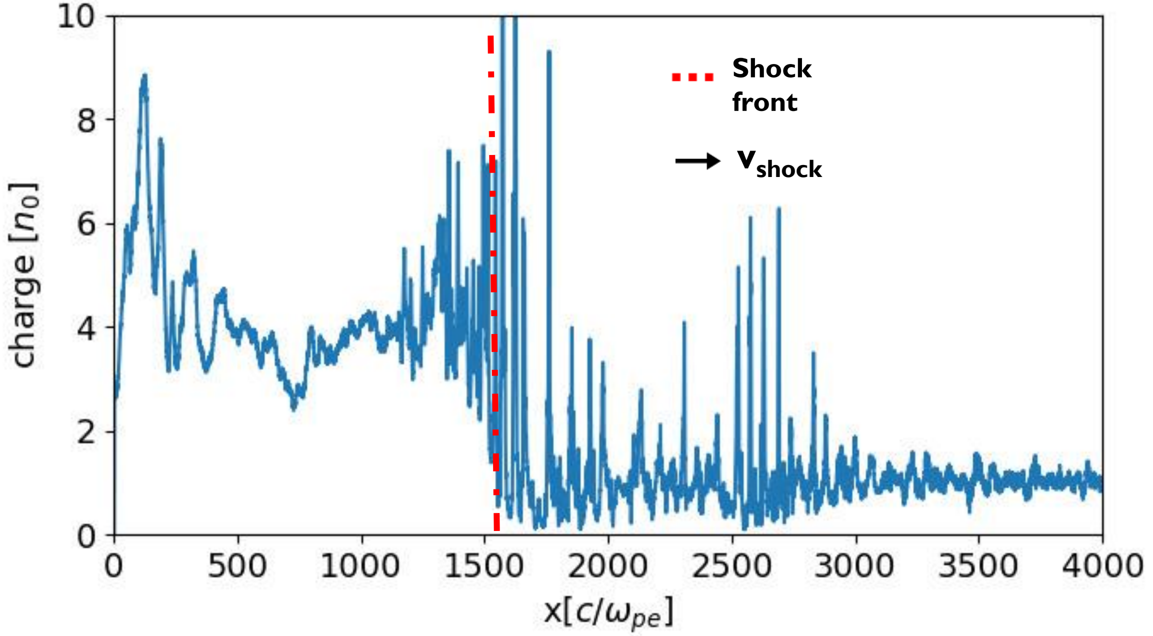


After a long time, the instability migrates to longer wavelengths

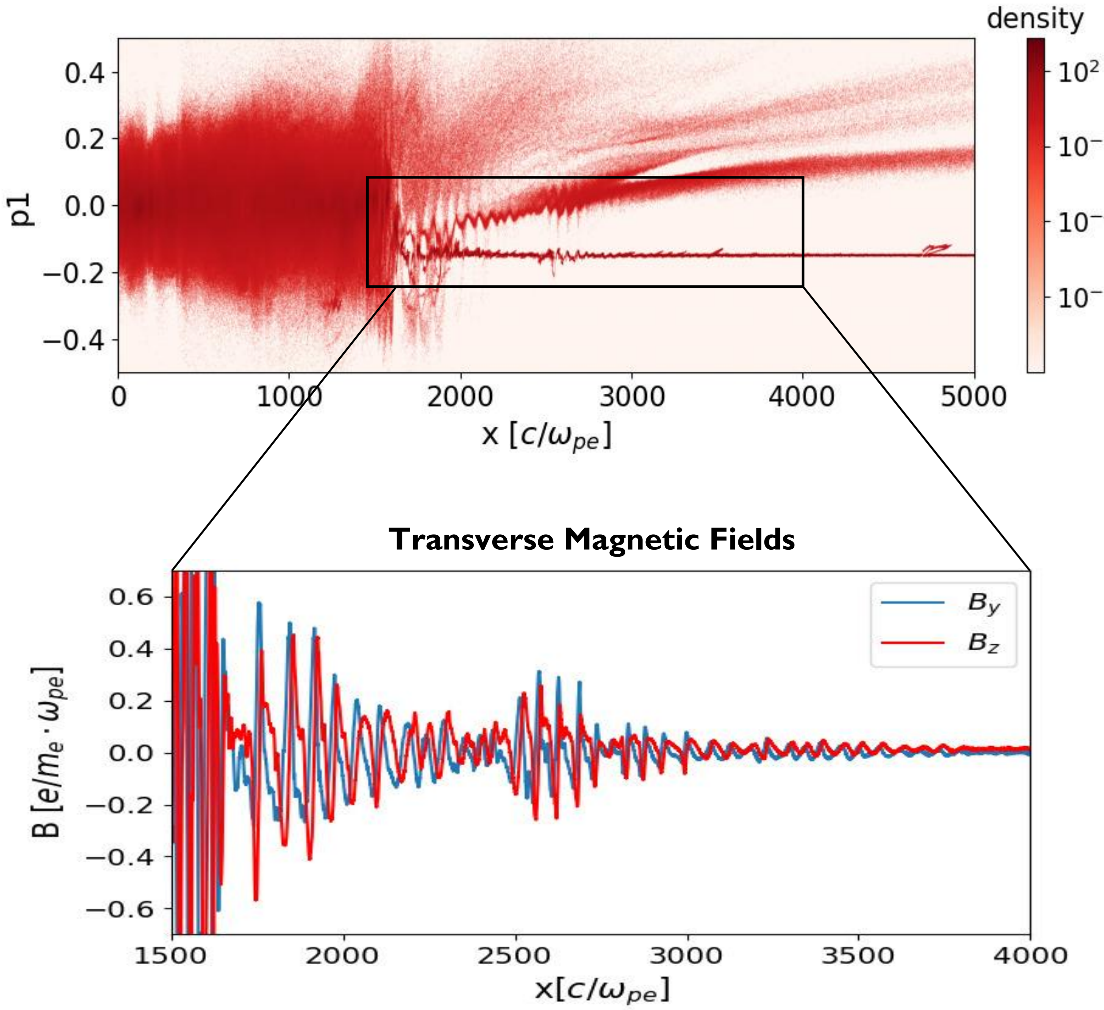


Shock simulations show signs of magnetic field amplification

Charge density profile shows a clear shock

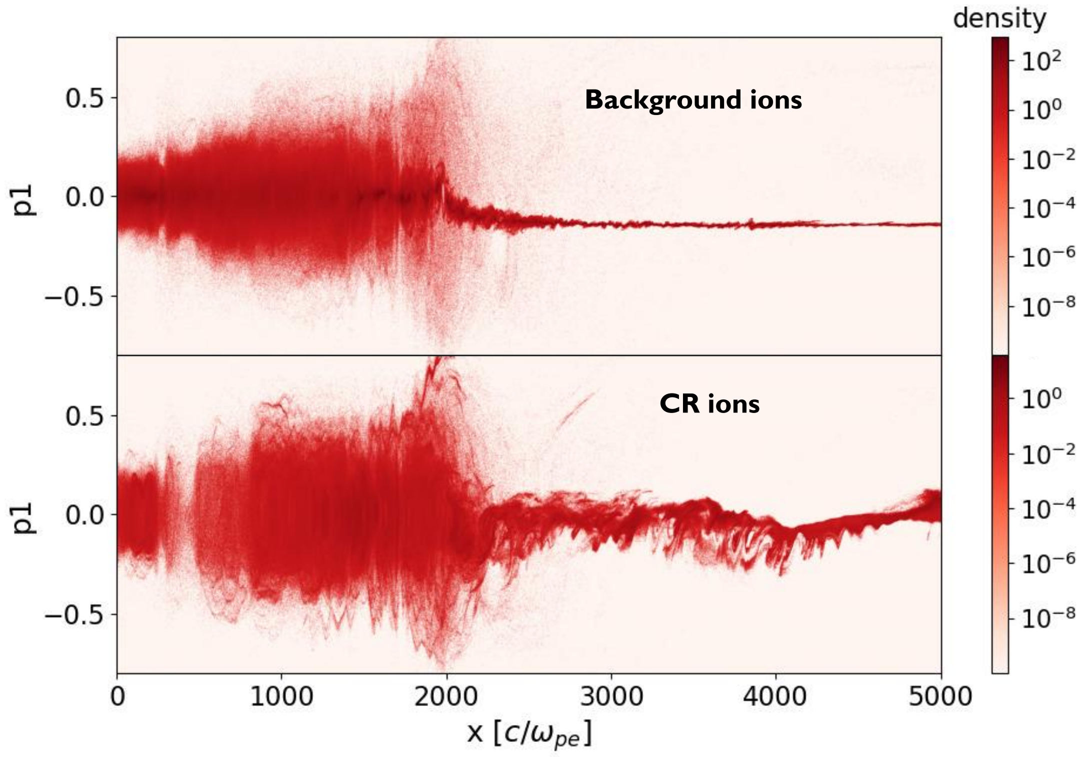


Reflected ions and B-field amplification can be detected

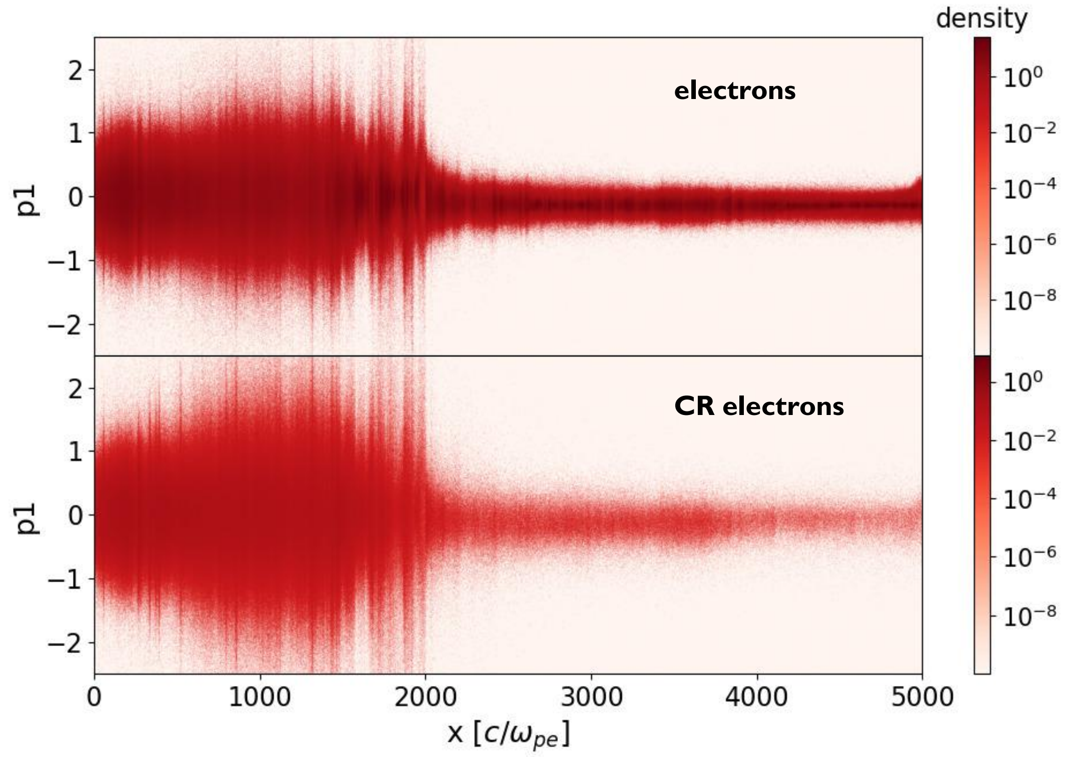


A deeper look into CR injection

CR ions are distinguishable from background ions



CR electrons mimic the behavior of electrons



Despite initially neutral, CR electrons get immediately stopped, turning practically indistinguishable from background electrons.