Numerical simulation of particle acceleration in CME shocks

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Presenter

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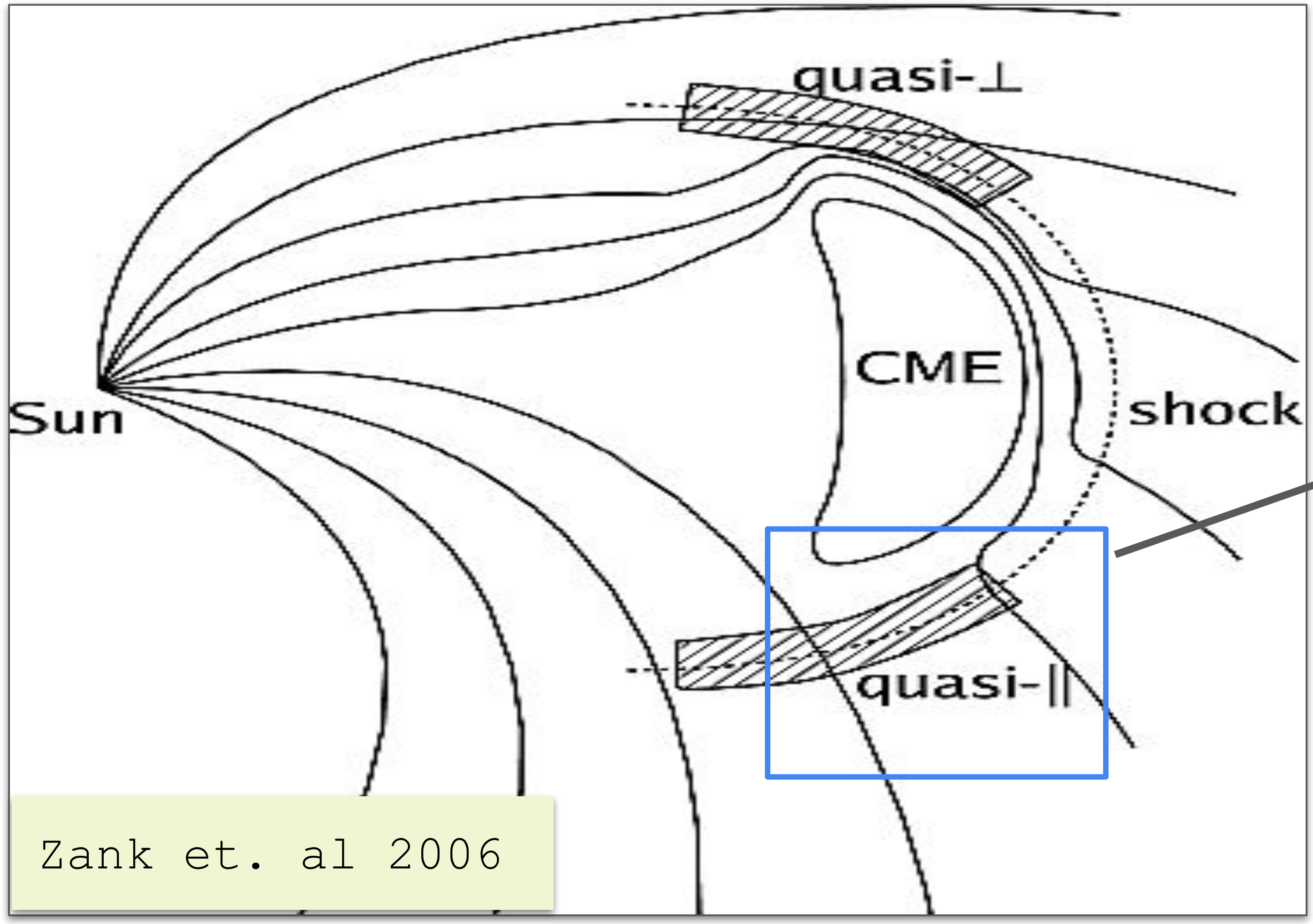
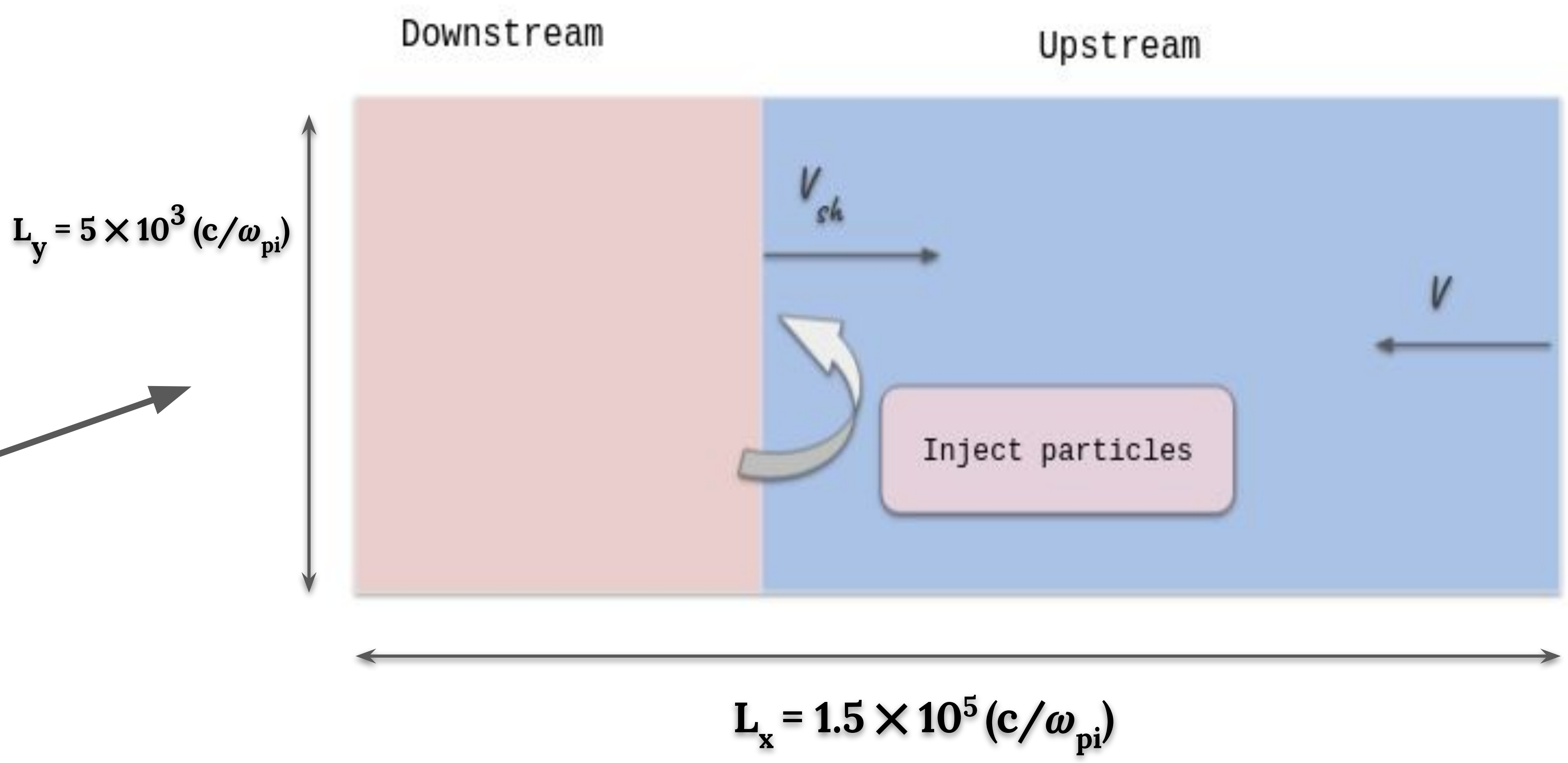
MHD-PIC simulation of ICME shock:



Zank et. al 2006

Shock formation using piston method



- Background solar wind plasma - MHD approach
- Injected particles - PIC approach

Initial solar wind parameters:

- $n = 5\ \mathrm{cm}^{-3}$
- $T = 5.e5\ \mathrm{K}$
- $v = -1850\ \mathrm{km/s}$ ←
- $M_A = 19 = v_{\mathrm{upstream}} / v_{\mathrm{Alfvén}}$

$V_{SW} = 500\ \mathrm{km/s}$
$V_{CME} = 2250\ \mathrm{km/s}$

Role of instabilities in shock upstream:

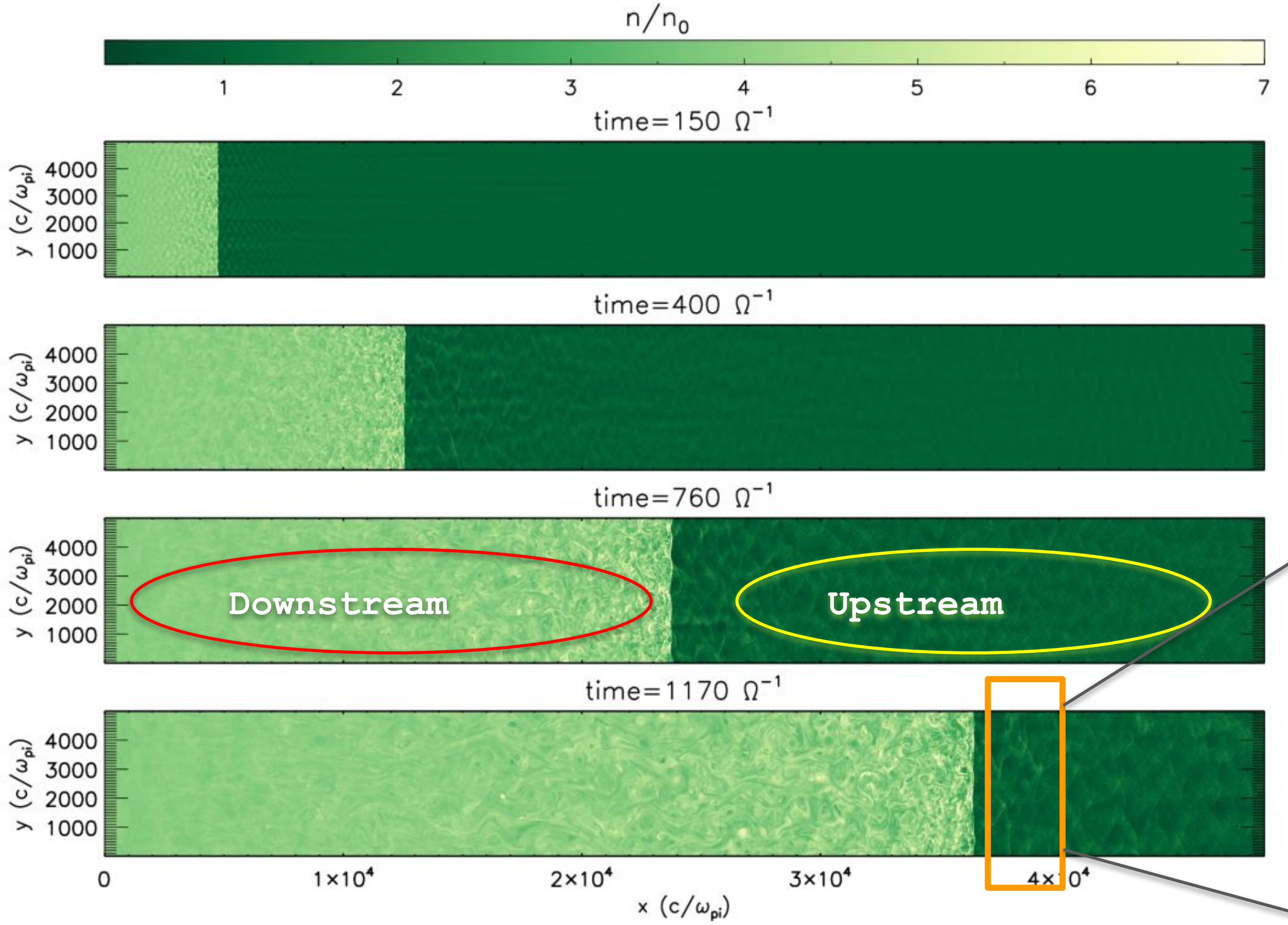
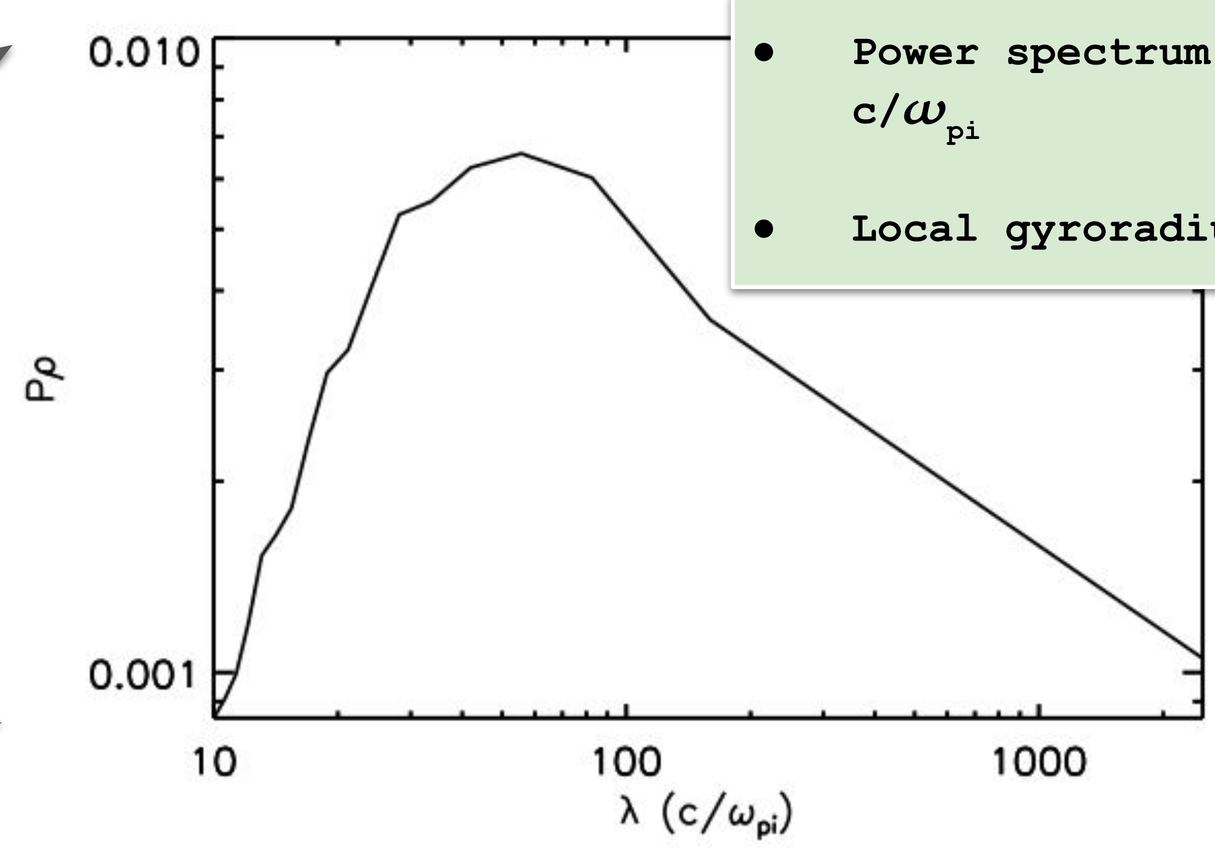


Figure 1. Density evolution of the parallel shock (M_A = 19), moving towards right. Only a fraction of the simulation domain is depicted here.

- Streaming of high energy particles induces instabilities - **resonant** and **non-resonant** instabilities in the shock upstream.
- Density cavities(shown in fig 1.) are the result of such instabilities as evidenced.
- Size of the cavities are determined by the gyro-radius of local particle distribution.



- **Power spectrum peaks at = 55 c/ω_{pi}**
- **Local gyroradius = 58 c/ω_{pi}**

Figure 2. Fluctuating mass density power spectrum during the near-saturation phase of the simulation

Role of instabilities in shock upstream:

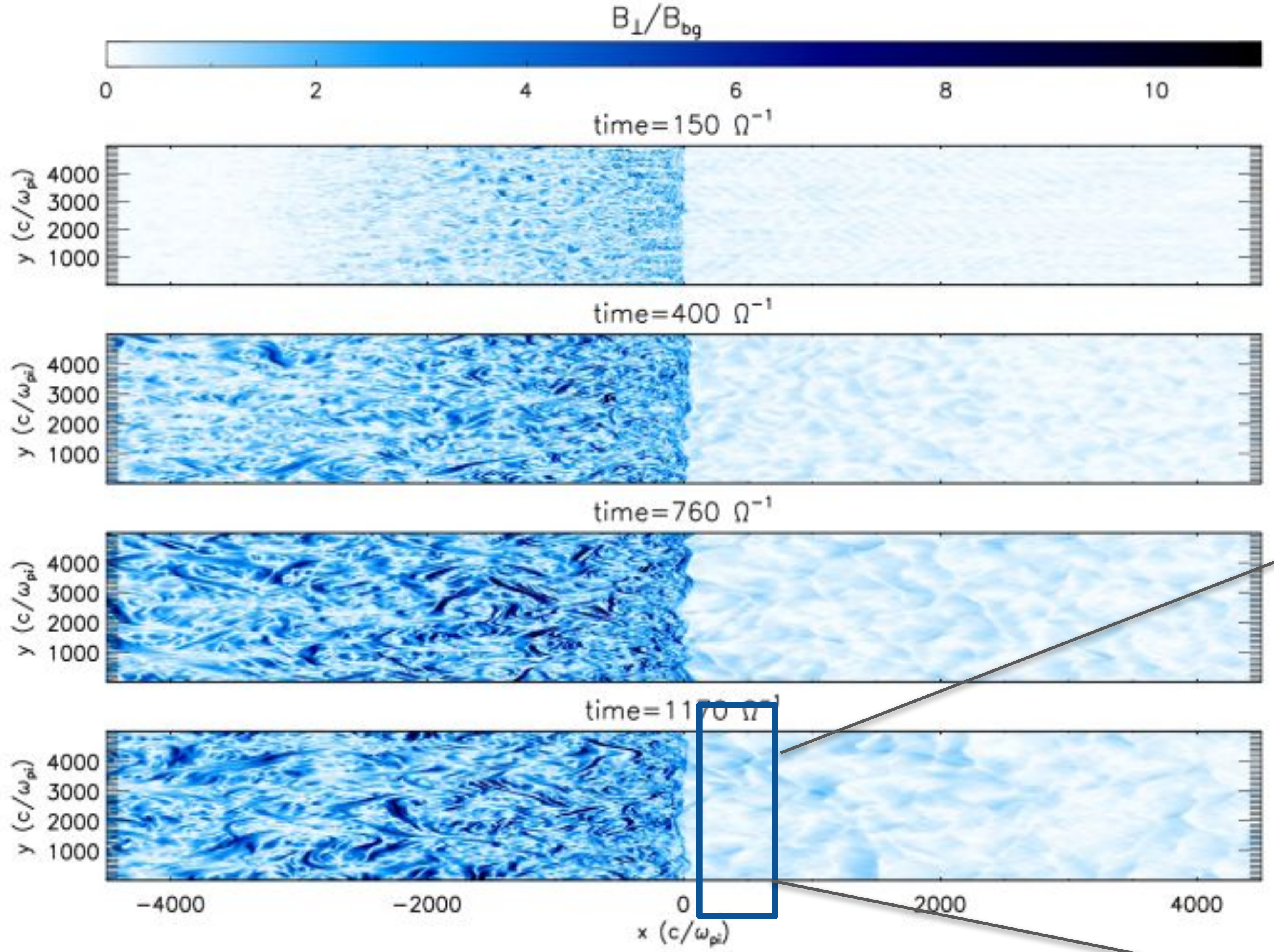
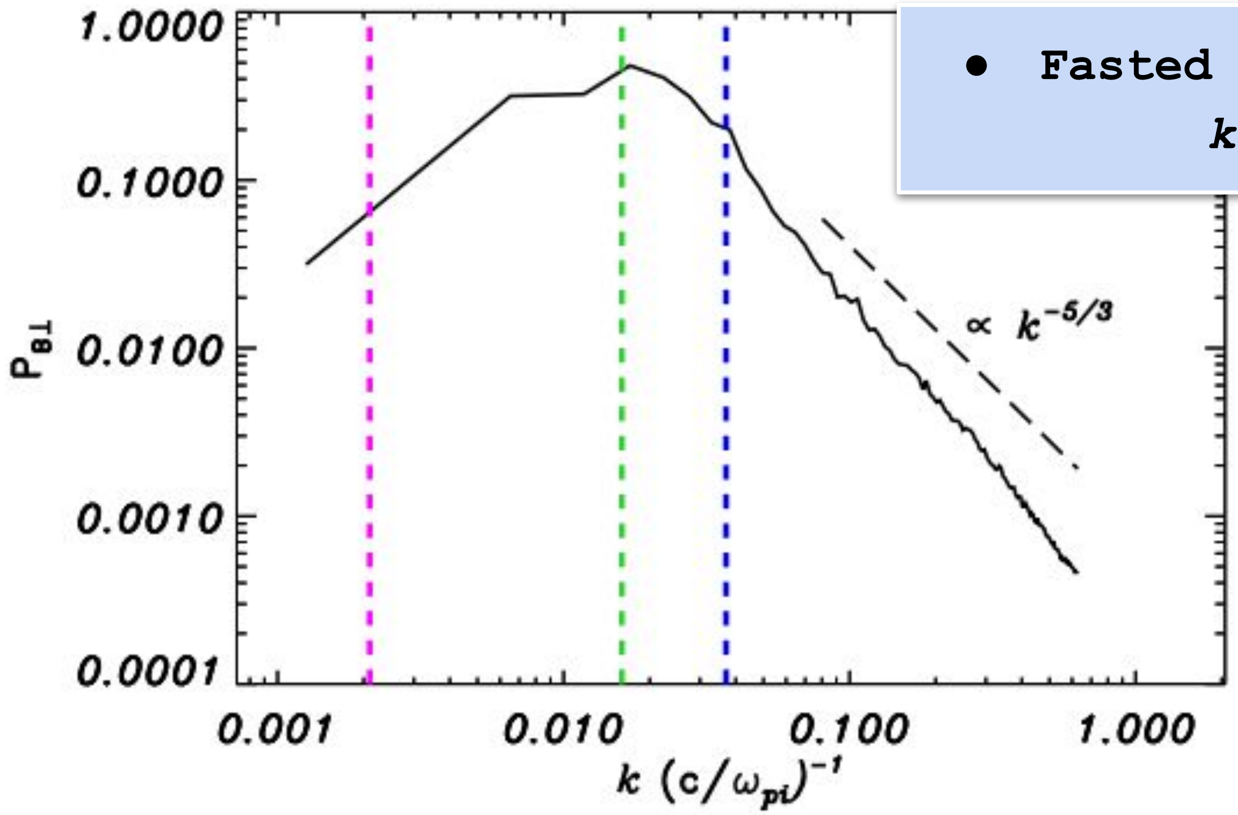


Figure 3. Transverse magnetic field evolution around the shock. For every time snap, the shock location is re-centered at x = 0.

- **Resonant instability:**
  Alfven waves initiated by the energetic particles resonate with the particles' gyro-radii.

- **Non-resonant(Bell) instability:**
  Current induced by the energetic particles perturbs the initial magnetic field, back-reacts on the fluid by inducing Lorentz force.

- Transverse magnetic power spectrum **peaks at the Bell mode** -system is mainly current driven.



- **Fasted growing Bell mode:**
  $k_f = J/2B_{bg}$

Figure 4. Transverse magnetic energy power spectrum calculated in a region just ahead of the shock.

Magnetic field enhancement in the shock downstream:

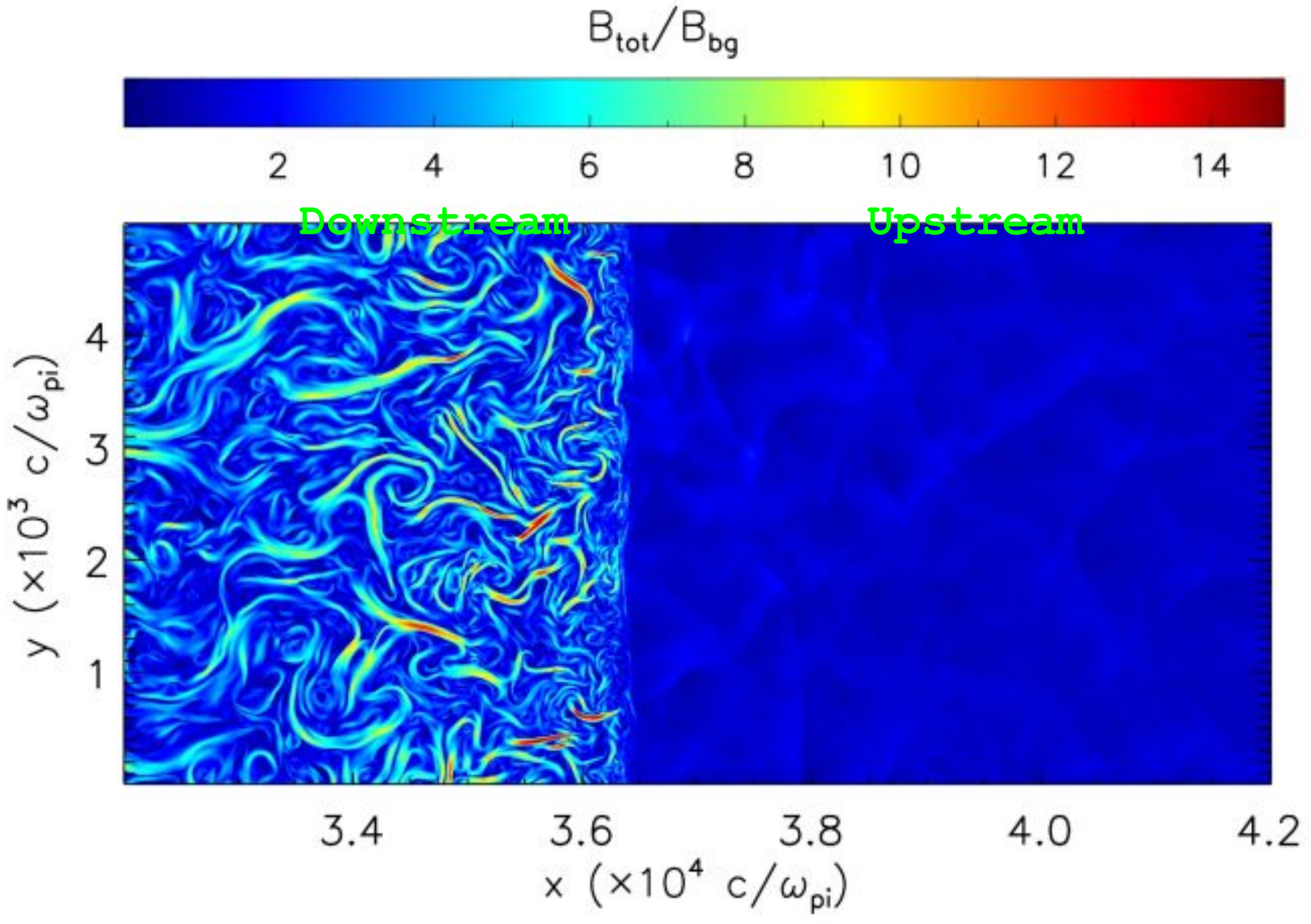


Figure 5. Total magnetic field contour close to the shock front.

- Downstream magnetic field is not only more turbulent but also amplified as compared to the upstream magnetic field.
- Certain locations in the downstream shows magnetic amplification larger than one expects from shock compression of the pre-amplified magnetic field in shock upstream by the Bell instability.
- This excess amplification is because of the **small scale dynamo** acting in the downstream region induced by the Richtmyer-Meshkov Instability at the corrugated shock front.

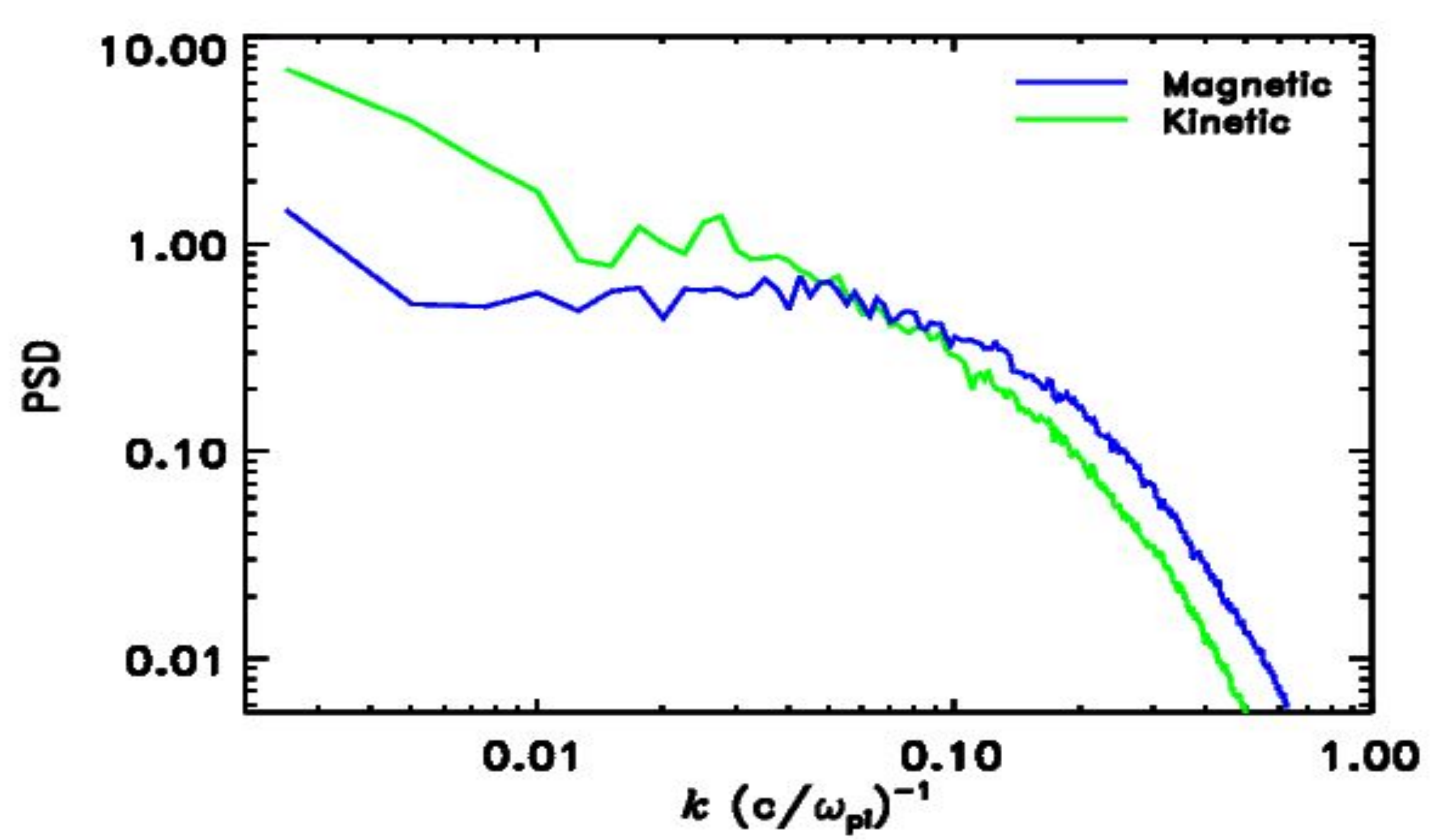


Figure 6. Kinetic and magnetic energy power spectra in the downstream region just behind the shock. After a certain scale, magnetic power spectrum exceeds the kinetic one, indicating the presence of small scale dynamo in shock downstream.

Particle energisation in parallel shock:

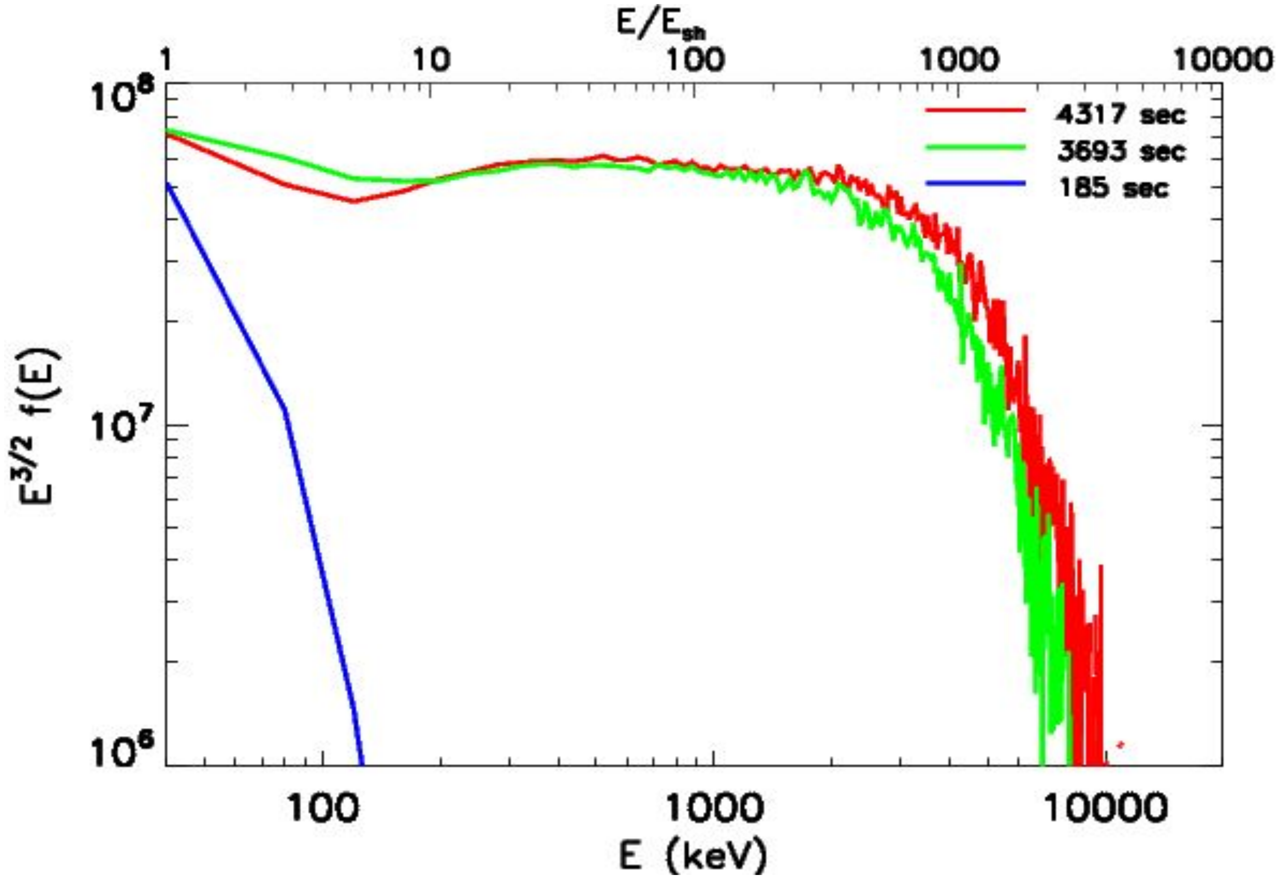
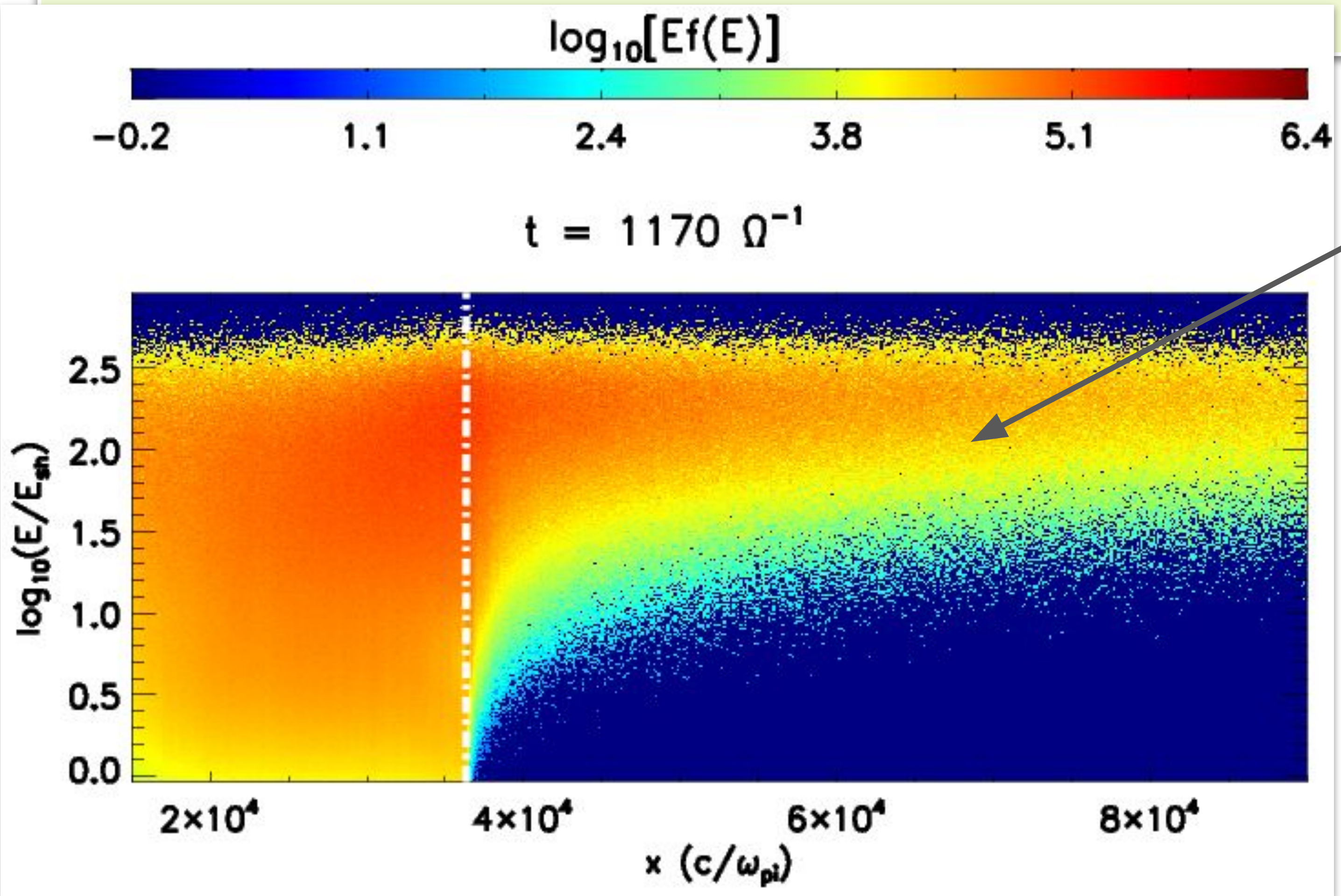


Figure 7. Evolution of downstream particle-energy spectra ($E^{3/2}$ compensated). Flattening of the spectra ensures DSA is an efficient mechanism in particle acceleration.

- Magnetic fluctuations act as scattering centres for the escaping particles away from the shock, confining them close to the shock front.
- Particles undergo repetitive reflections across the shock gaining energy every time they cross the shock front - **Diffusive Shock Acceleration (DSA)**.
- DSA dominates the particle acceleration mechanism in parallel shock where the particle energy spectrum follows a power law **$f(E) \propto E^{-3/2}$** as evident from fig 7.



Escaping of high energy particles.

Figure 8. 2D energy spectrum, showing the particle energy distribution as a function of position x. High energy particles outrunning the shock are evident from this 2D spectrum confirming the commencement of particle acceleration.

Particle energisation in quasi-perpendicular shock:

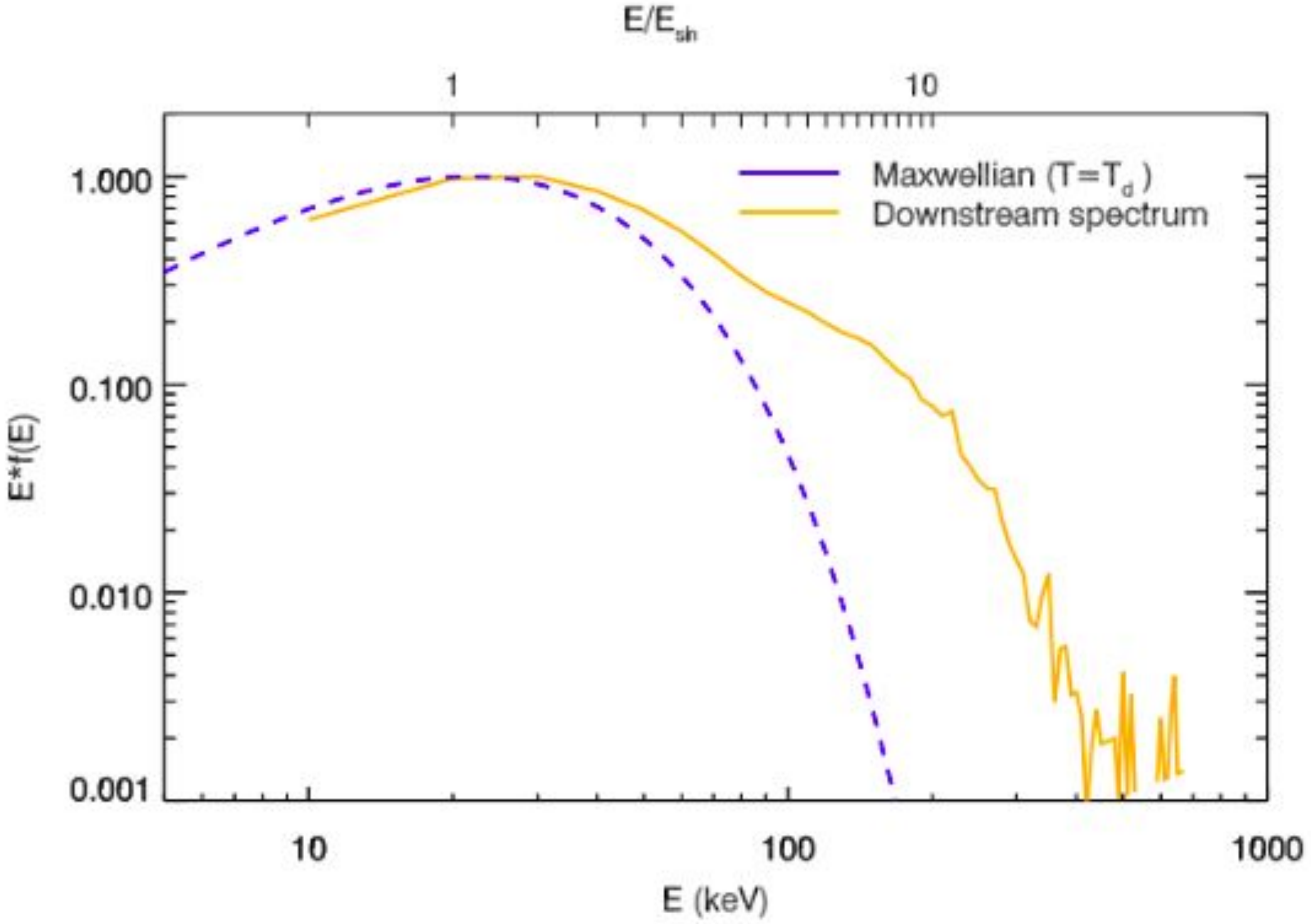
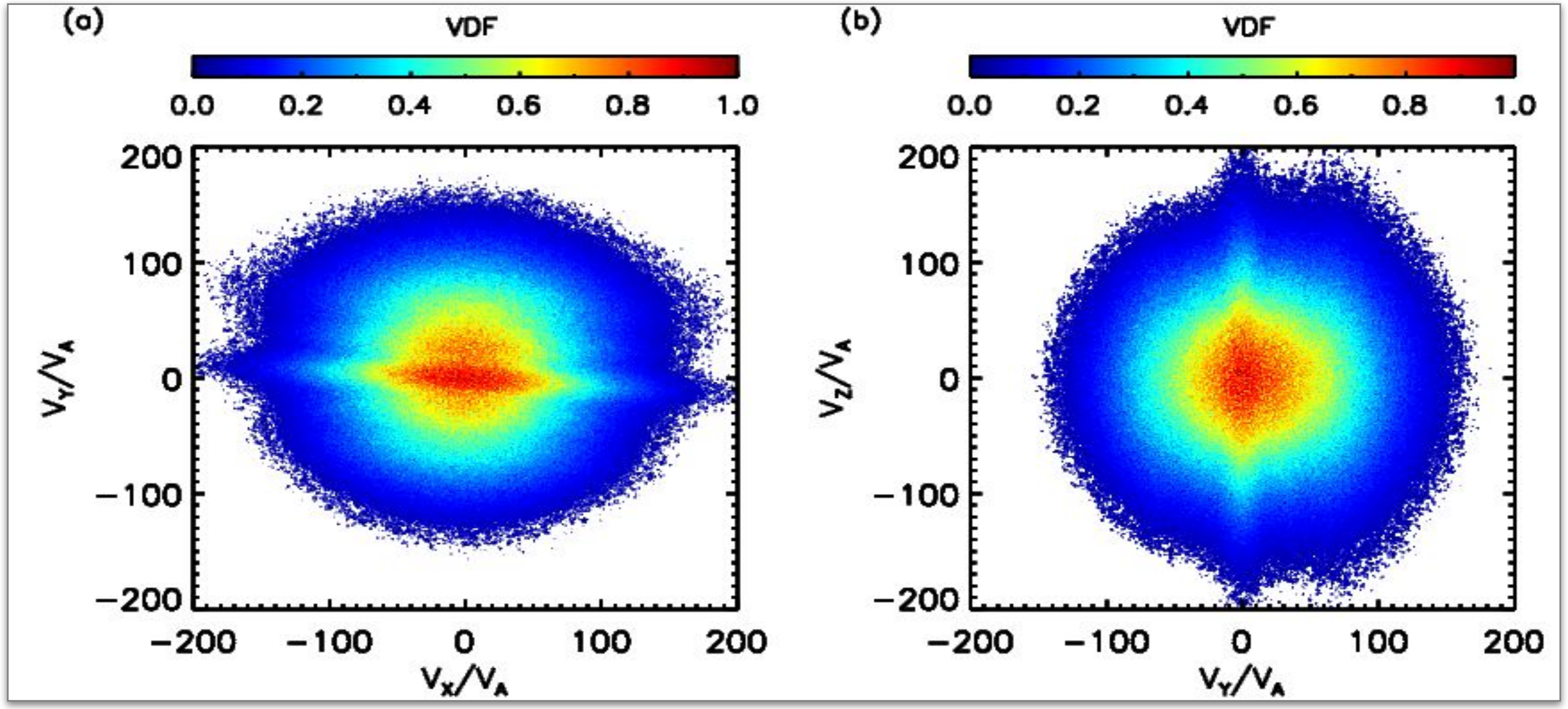


Figure 9. Injected and saturated particle energy spectra for quasi-perpendicular shock with $M_A=19$.

- Anisotropy in particles velocity distribution along with the orientation of magnetic field in the shock downstream confirms the activation of SDA in quasi-perpendicular shock.

- Particle energisation is less as compared to the parallel shock of same Alfvenic mach.
- Particles hardly escape the shock upstream- no evidence of magnetic fluctuations required for DSA for particle energisation.
- **Shock Drift Acceleration(SDA)** plays a dominant role in accelerating the particles in this case.



Observational aspects from simulation findings :

Parallel shocks

- Diffusive Shock Acceleration plays a dominant role in parallel shock where particle energy spectrum follows a power law: $f(E) \propto E^{-3/2}$
- Streaming of high energy particles induce instabilities in the shock upstream.
- Bell instability dominates the upstream magnetic power spectrum.
- Small scale dynamo plays important role in the amplification of downstream magnetic field.

Quasi-perpendicular shocks

- Particles are less energised as compared to the parallel shocks.
- Shock Drift Acceleration in perpendicular shocks accelerates the particles.
- Anisotropy in particles' velocity distributions along with the magnetic field orientation may confirm the role of SDA in quasi-perpendicular shock.

Sow Mondal et al., under review, ApJ, 2021