Atelier CFRCos: Shock, turbulence and particle acceleration in (relativistic) MHD

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« PIC-MHD simulations of particle acceleration in a magnetized turbulence »

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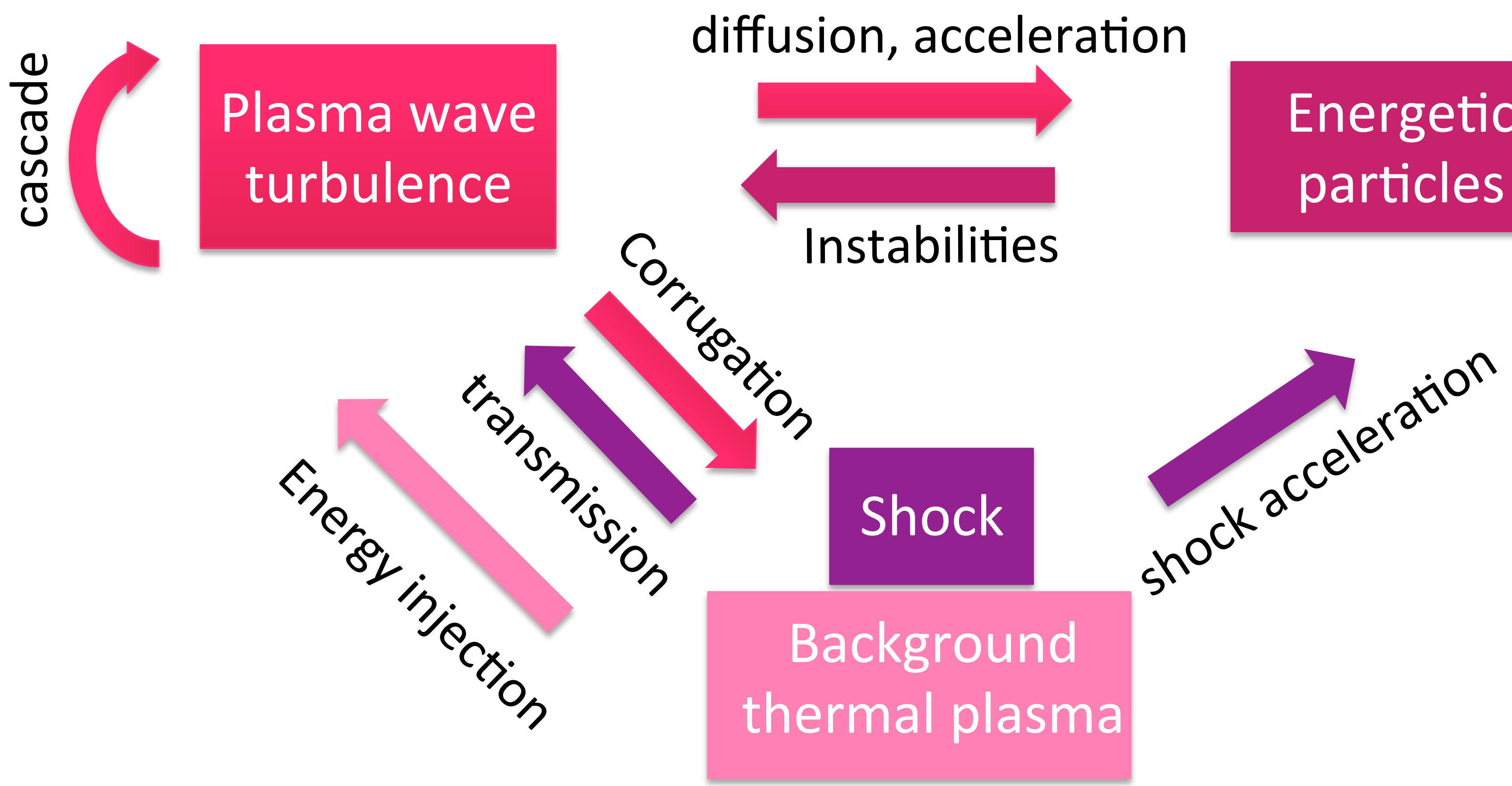
Outline

I. Introduction, motivations

II. Shock interacting with perturbations: resonant corrugation

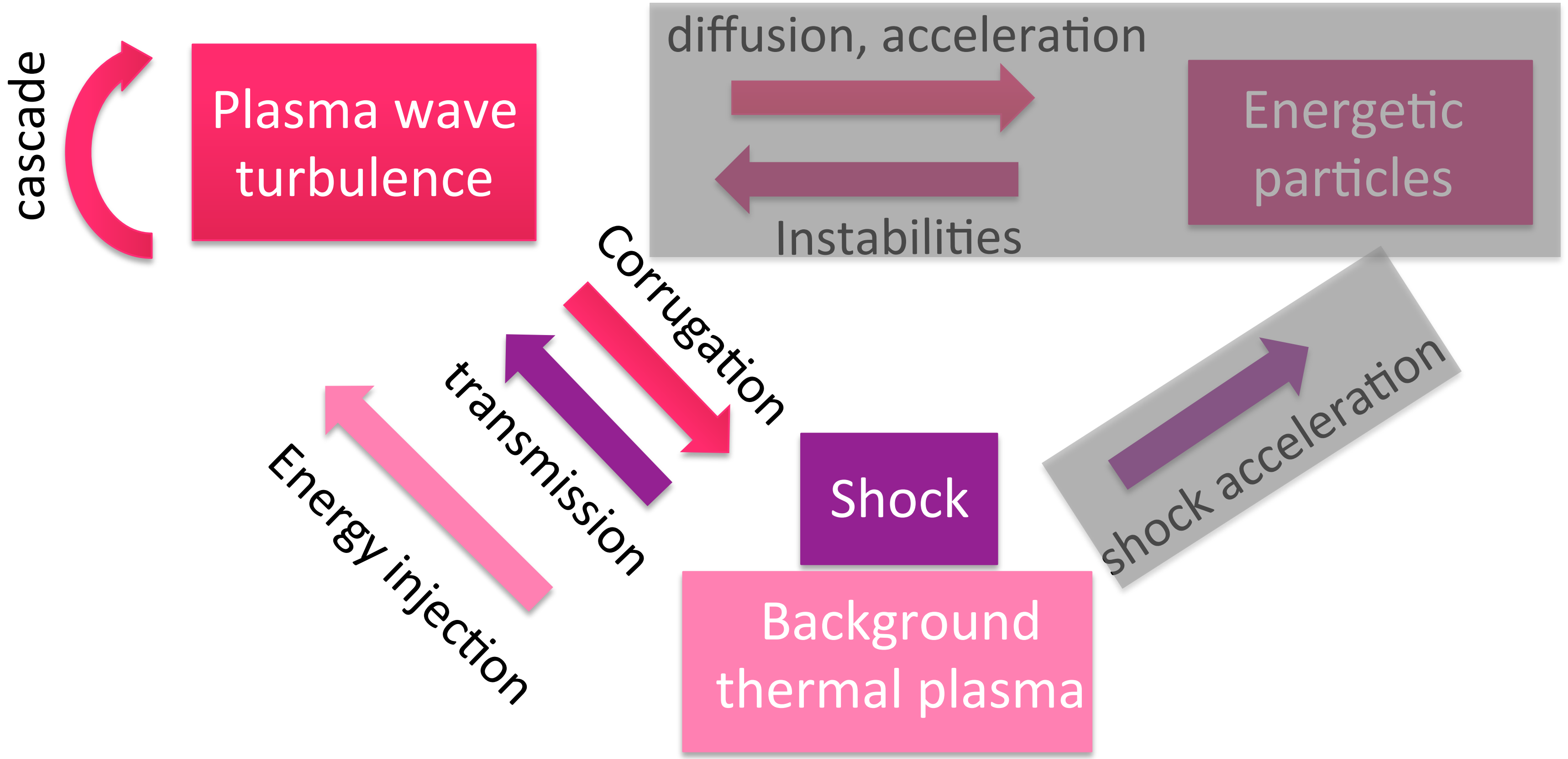
III. Outlook, ongoing work on particle acceleration by turbulence

I. Introduction: Particle acceleration, shocks & turbulence



- Scales involved spans several orders of magnitude ⟶ simulations on limited range of scales (e.g.. kinetic for PIC simulations or macroscopic for MHD simulations).

I. Introduction: Particle acceleration, shocks & turbulence

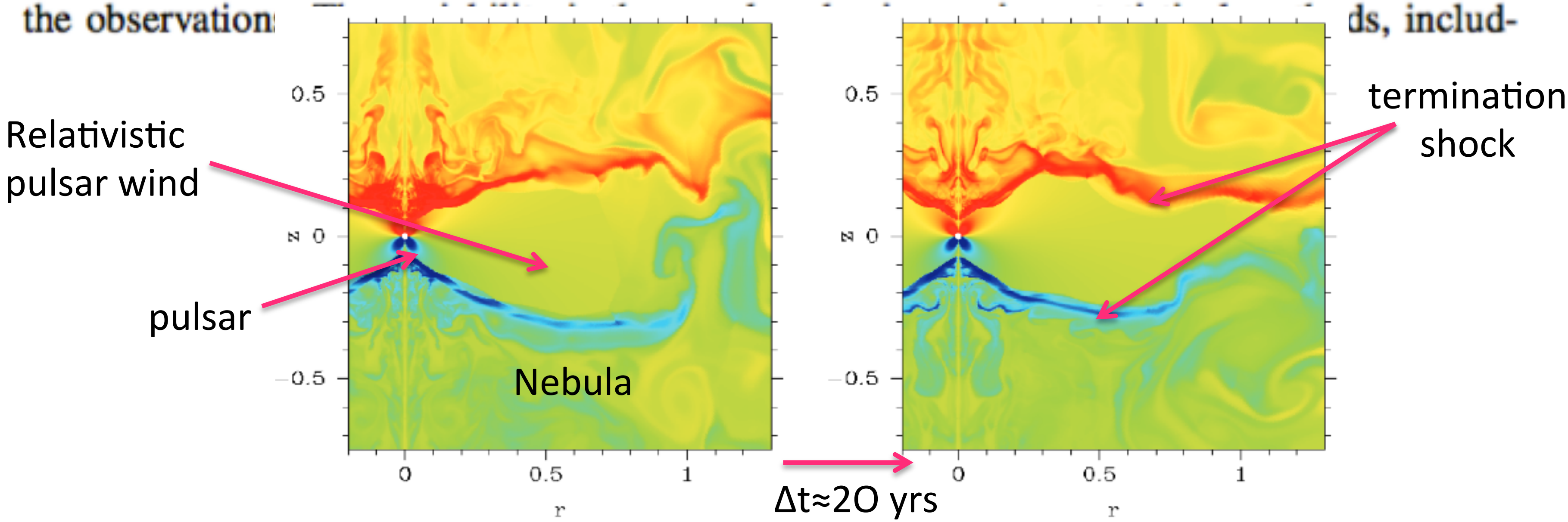


- **Next part**: work related to the issue of shock-turbulence interactions, in the framework of MHD

I. Some works giving possible astrophysical implications

- *Observations of ‘wisps’ in magnetohydrodynamic simulations of the Crab Nebula* Camus et al., 2009, Mon. Not. R. Astron. Soc. 400, 1241

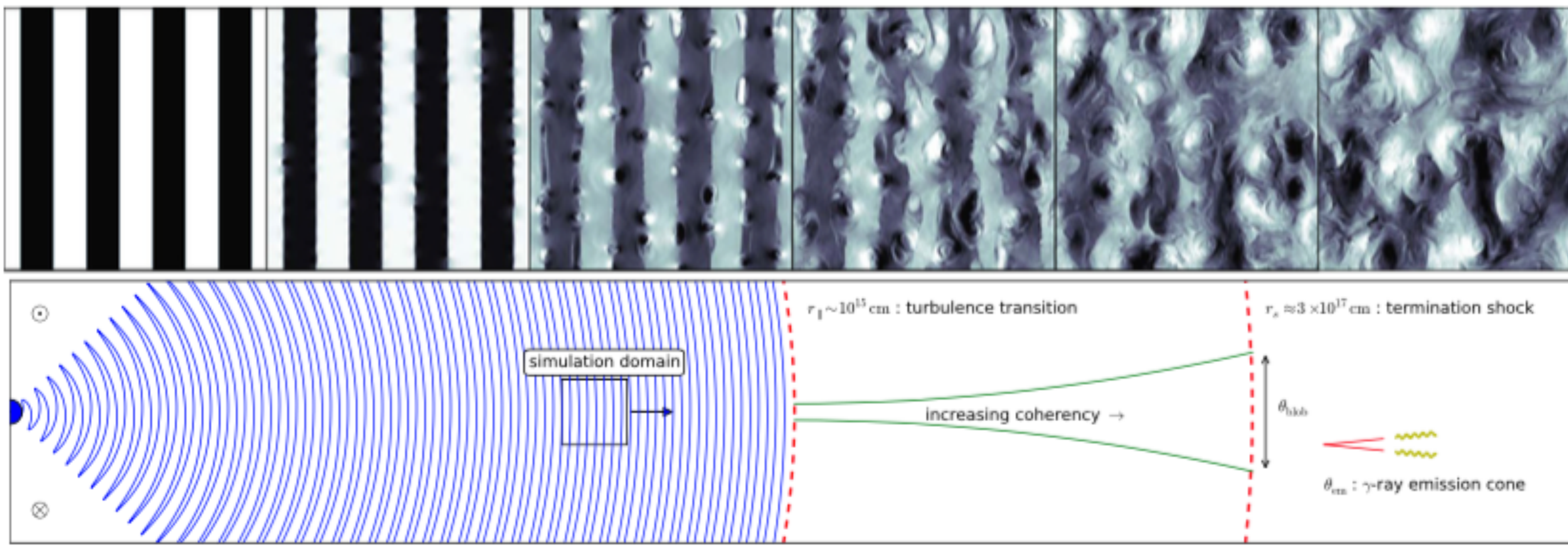
In this paper, we describe results of new high-resolution axisymmetric relativistic magnetohydrodynamic (MHD) simulations of pulsar wind nebulae. The simulations reveal strong breakdown of the equatorial symmetry and highly variable structure of the pulsar wind-termination shock. The synthetic synchrotron maps, constructed using a new more accurate approach, show striking similarity with the well-known images of the Crab Nebula obtained by *Chandra* and the *Hubble Space Telescope*. In addition to the jet–torus structure, these maps reproduce the Crab’s famous moving wisps whose speed and rate of production agree with the observation ... ds, includ-



I. Some works giving possible astrophysical implications

- *Crab flares due to turbulent dissipation of the pulsar striped wind,*
  Zrake,2016, ApJ 823

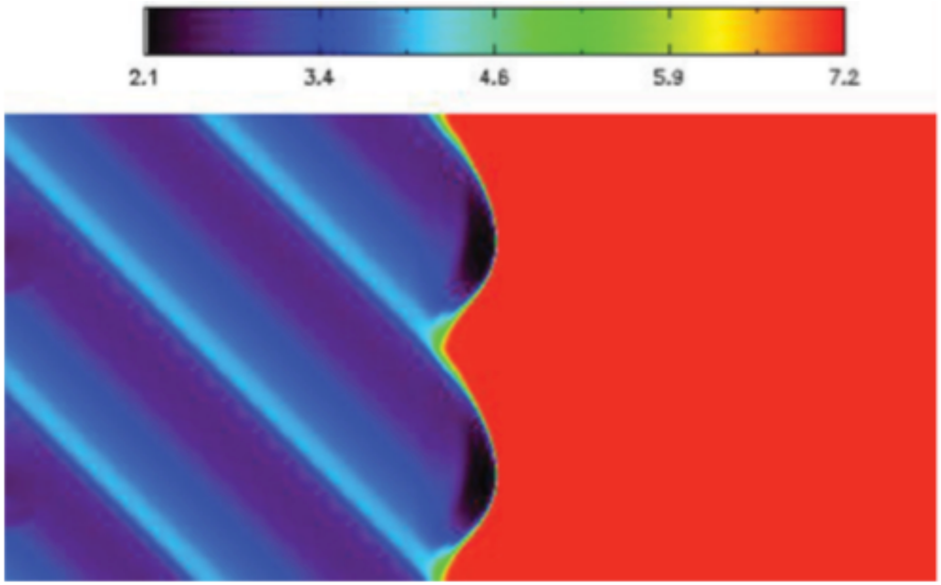
We interpret γ-ray flares from the Crab Nebula as the signature of turbulence in the pulsar's electromagnetic outflow. Turbulence is triggered upstream by dynamical instability of the wind's oscillating magnetic field and accelerates non-thermal particles. On impacting the wind-termination shock, these particles emit a distinct synchrotron component $F_{\nu,\mathrm{flare}}$, which is constantly modulated by intermittency of the upstream plasma flow. Flares are observed when the high-energy cutoff of $F_{\nu,\mathrm{flare}}$ emerges above the fast-declining nebular emission around 0.1–1 GeV. Simulations carried out in the force-free electrodynamics approximation predict the striped wind to become fully turbulent well ahead of the wind-termination shock, provided its terminal Lorentz factor is $\lesssim 10^4$.



I. Some works giving possible astrophysical implications

- *Crab GeV flares from the corrugated termination shock* *Lyutikov, Balsara and Matthews, 2012,* Mon. Not. R. Astron. Soc. 422, 3118–3129 (2012)

In this work we investigate analytically and via numerical simulations the electromagnetic signatures expected from the large-amplitude low-frequency magnetosonic waves generated within the Crab nebula which induce the corrugation perturbations of the termination shock. As a result, the oblique termination shock produces a time-dependent, mildly relativistic post-shock flow. Using the relativistic magnetohydrodynamic version of the RIEMANN code, we simulate the interaction of the termination shock with downstream perturbations. We demonstrate that mild Doppler boosting of the synchrotron emission in the post-shock flow can produce bright, short time-scale flares.



Lorentz factor at early times. The strong variation (a factor of 2) in the post-shock Lorentz factor leads to strong variation in the Doppler boosting along some lines of sight, which leads to spikes in the intensity.

I. Special relativistic ideal MHD (SRMHD)

- Ideal MHD: fluid description of perfectly conducting plasma
- Governing equations: mass, energy, momentum conservation equations + evolution equation of ***B*** + div(***B***)=0 constraint
- SRMHD → need covariant formalism

c=1, μ_0=1.

Introducing
$$b^\mu = \left[u^i B_i, \left(\boldsymbol{B} + u^i B_i \boldsymbol{u}\right)/u^0\right],$$
$$T^{\mu\nu} = \left(w + b_\alpha b^\alpha\right) u^\mu u^\nu + \left(p + \frac{b_\alpha b^\alpha}{2}\right) \eta^{\mu\nu} - b^\mu b^\nu,$$
$${}^*F^{\mu\nu} = u^\mu b^\nu - u^\nu b^\mu,$$

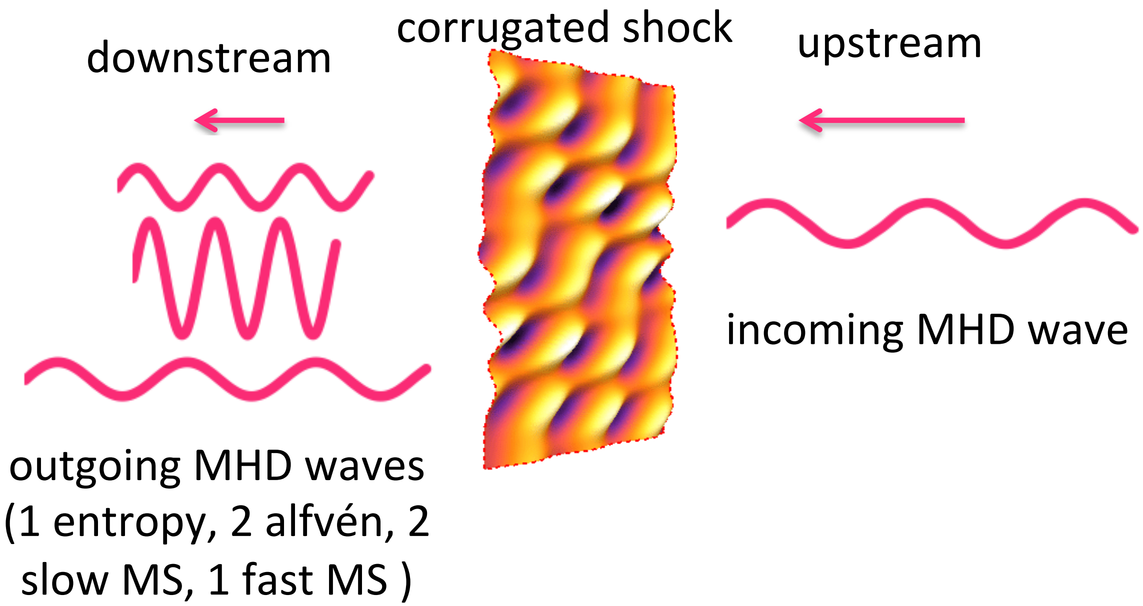
the governing equations read:
$$\nabla_\alpha(\rho u^\alpha) = 0,$$
$$\nabla_\alpha T^{\alpha\beta} = 0,$$
$$\nabla_\alpha {}^*F^{\alpha\beta} = 0.$$

Notations:
u^μ: 4-velocity
B: magnetic field
p: thermal pressure
w: enthalpy density
ρ: proper density
$\eta^{\mu\nu}$: Minkowsky metric

- 7 linear waves

II. Shocks interacting with perturbations

- Theoretical study of the linear response of a relativistic shock to an harmonic MHD wave (Lemoine et al, 2016, ApJ 827)



→ resonance for some wave vectors.

Observable in simulations of finite amplitude incoming waves?

- Program: **MPI-AMRVAC**
  finite volumes solver + constrained transport

Updates cell centered quanties by computing flux at the cell borders

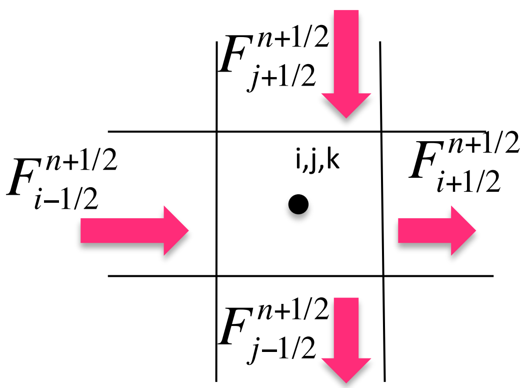
Ensures div(***B***)=0

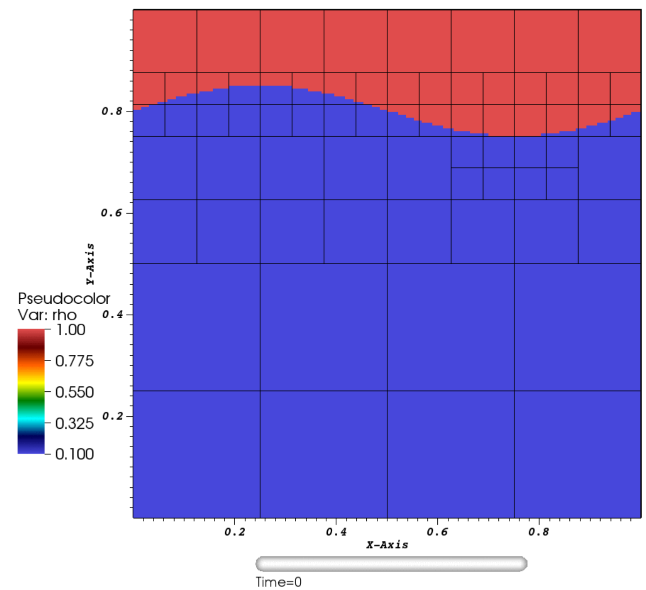
Adaptive Mesh Refinement: adapts grid to zone of interest

Volume & time average

$$\frac{\partial D(t,\mathbf{r})}{\partial t} + \nabla \cdot \mathbf{f}(t,\mathbf{r},D) = 0$$

$$\langle D \rangle_i^{n+1} - \langle D \rangle_i^{n} + \frac{\Delta t}{\Delta V}\left(F_{i+1/2}^{n+1/2} - F_{i-1/2}^{n+1/2} + \ldots\right) = 0$$

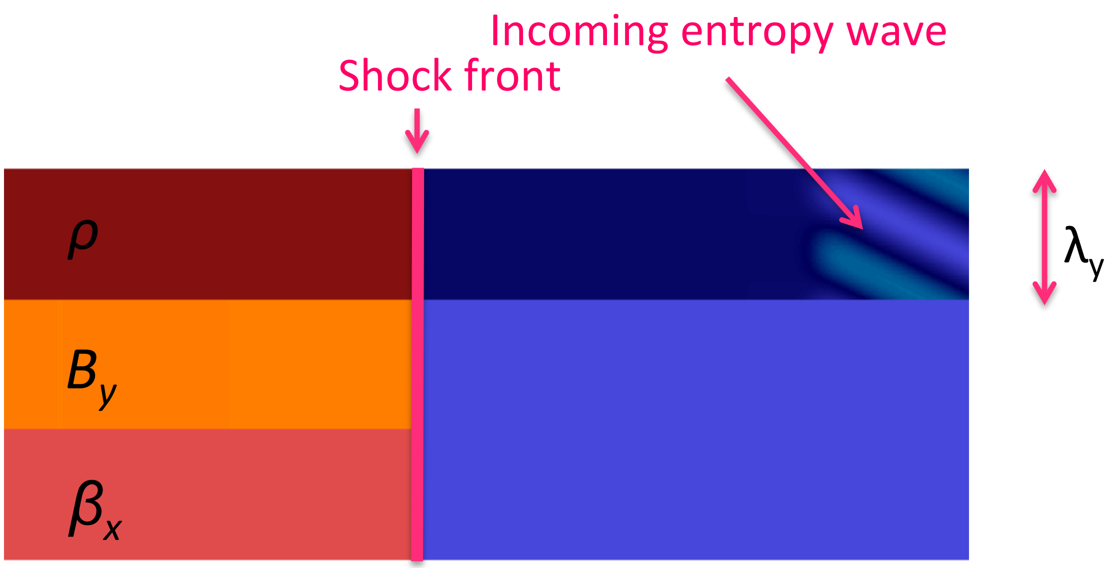


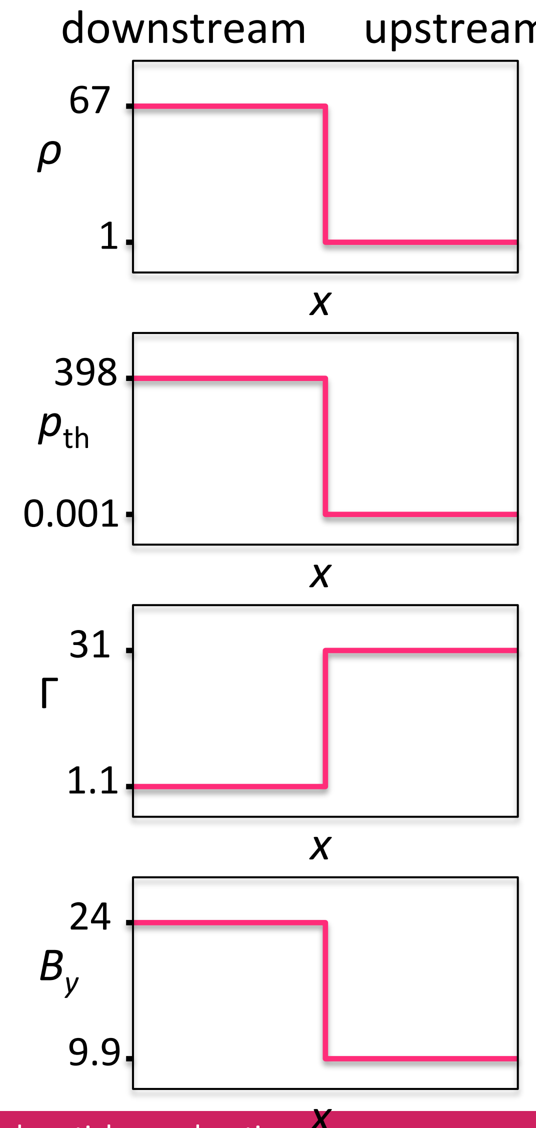


Example of simulation of the Rayleigh-Taylor instability

Simulation example: entropy wave interacting with a relativistic shock

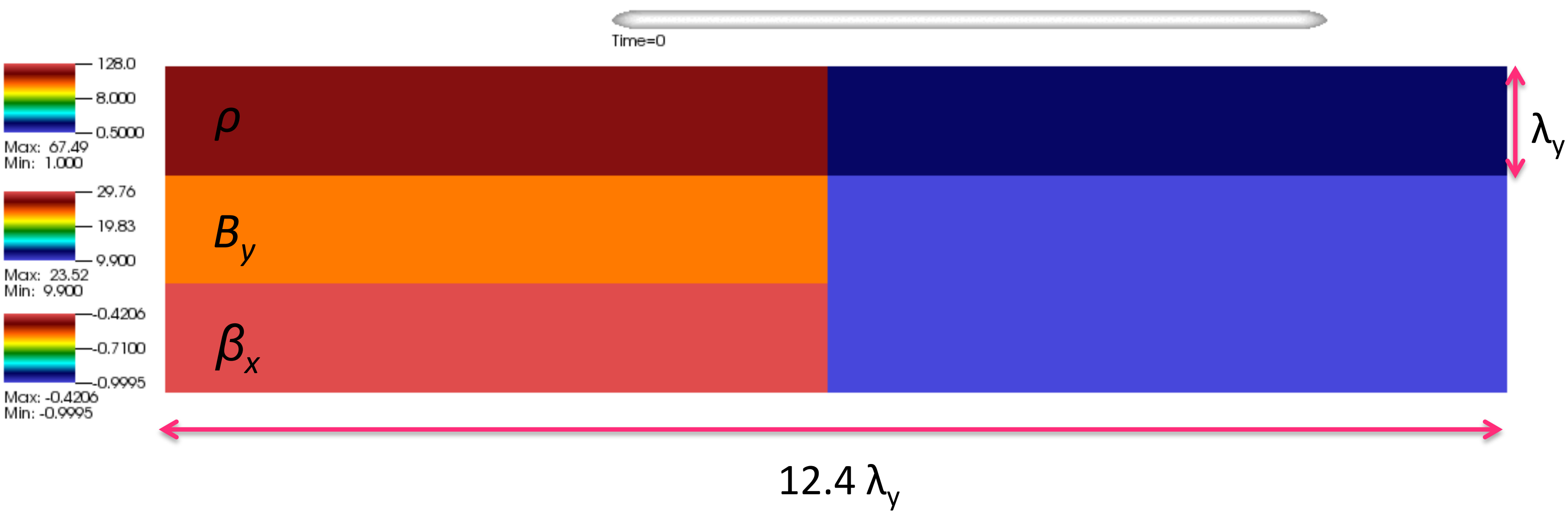
- Entropy wave: pertubations in ρ
- Perturbation amplitude: $\delta\rho/\rho$ = 45%





Simulation example: entropy wave interacting with a relativistic shock

- Entropy wave: pertubations in ρ
- Perturbation amplitude: $\delta\rho/\rho$ = 45%
- Relative Lorentz factor: 20
- Upstream magnetization: σ=0.1

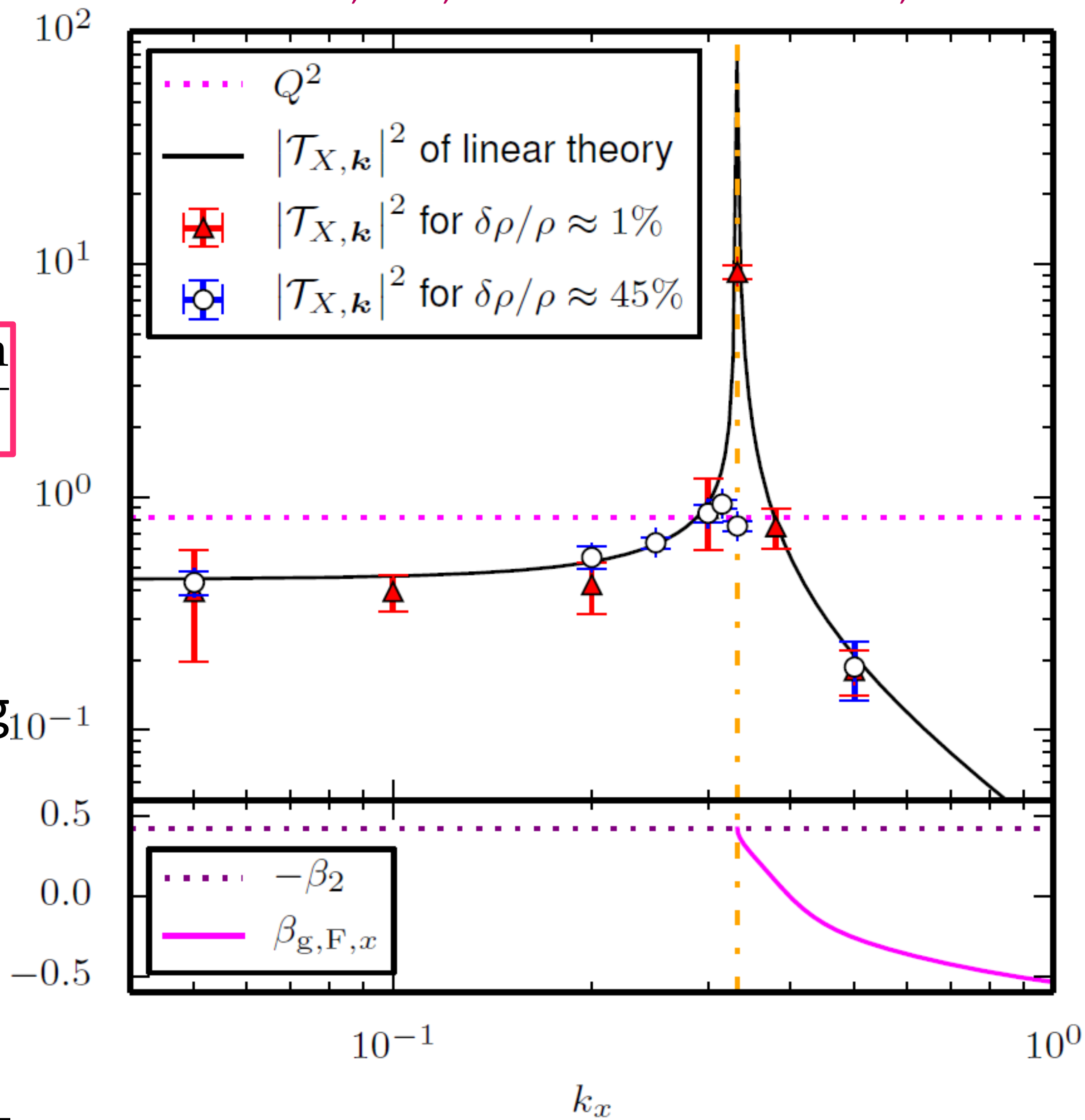


- Transfer function (in downstream rest frame)

$$\mathcal{T}_{X,\boldsymbol{k}} \propto \frac{\text{ampli of corrugation}}{\text{ampli of wave}}$$

- Resonance: longitudinal group velocity of outgoing fast mode= shock velocity

Demidem et al, 2018, Mon. Not. R. Astron. Soc. 475, 2713–2723



II. Shocks interacting with perturbations

Summary (Demidem et al, 2018, Mon. Not. R. Astron. Soc. 475, 2713–2723):

SRMHD simulations of interaction of upstream monoλ MHD mode with shock show existence of **universal** (i.e. for both relativistic/sub-relativistic velocities & strong/weak magnetizations) **resonant response of shock** to perturbations.

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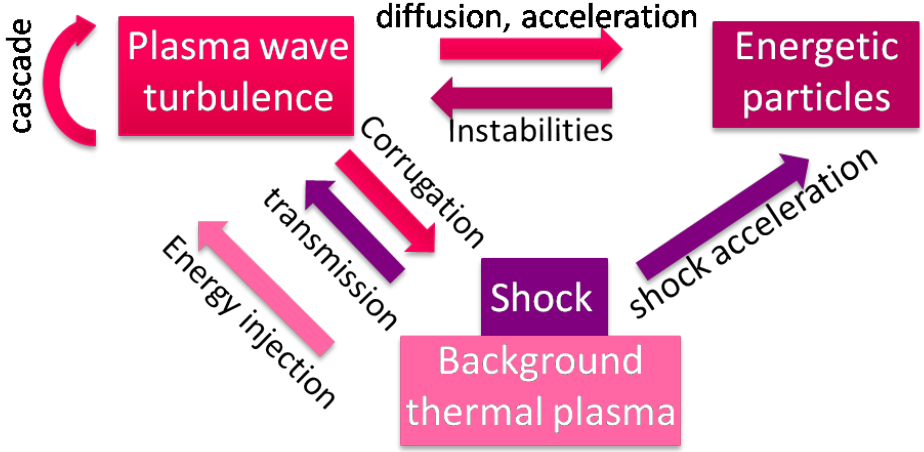
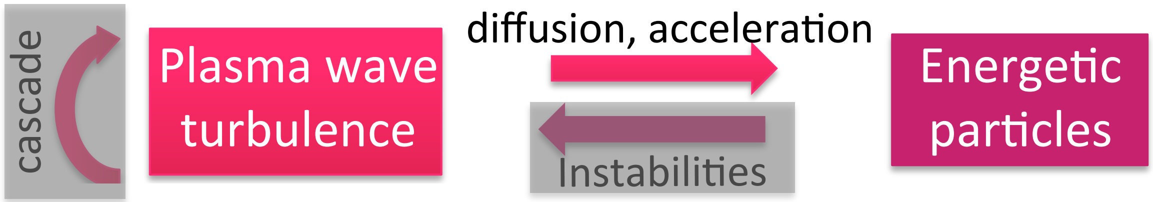
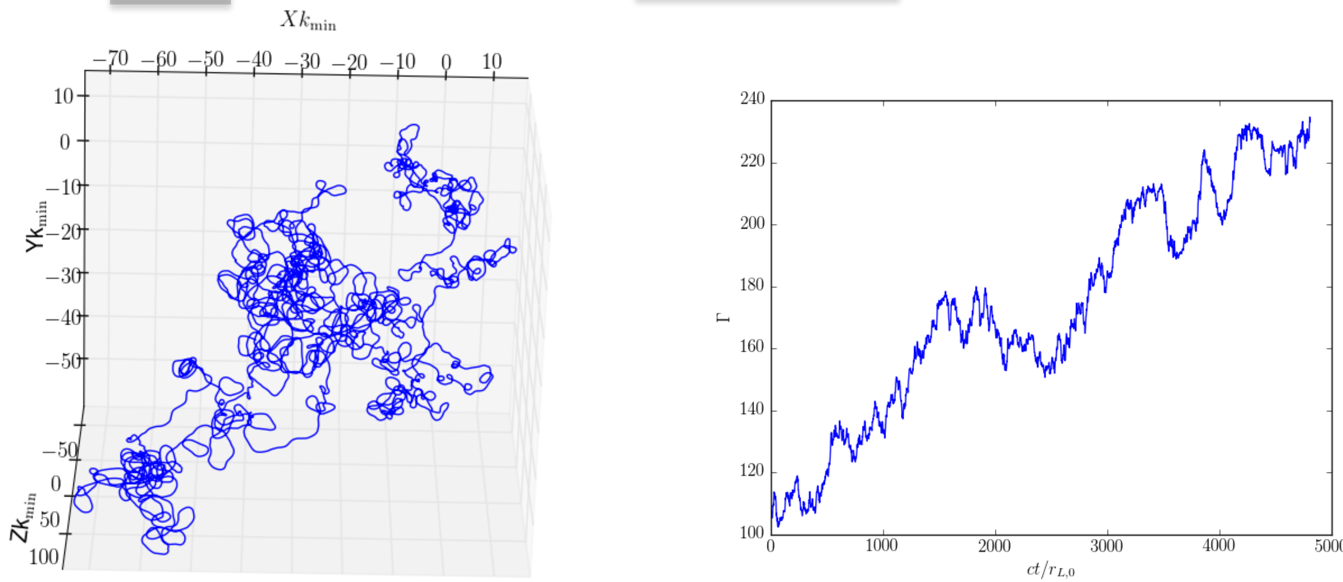


Outlook:

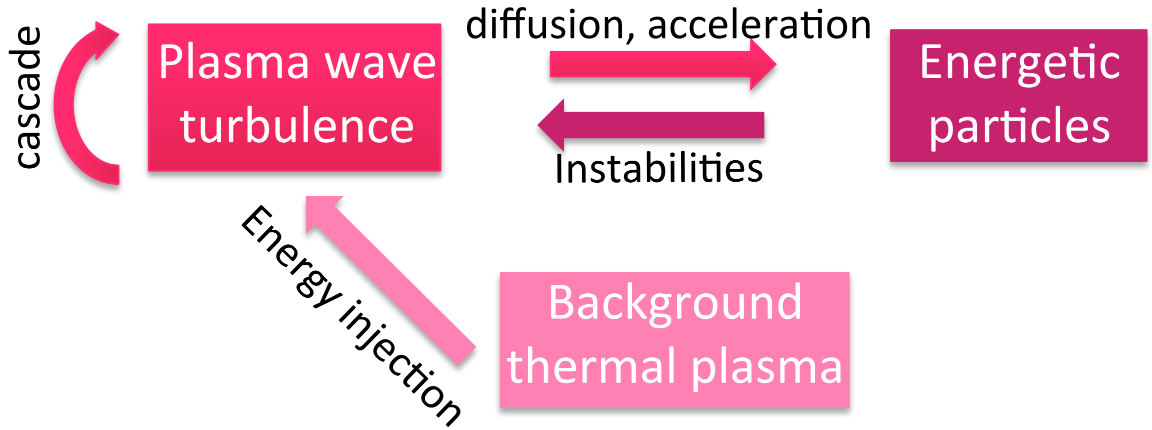
- Impact of the corrugation on particle acceleration?
- van Marle et al 2018: PI[MHD]C simulations of **non-relativistic** shocks, observed corrugation induced by accelerated particles which in turn affected particle acceleration efficiency.





Example of trajectory and Lorentz factor evolution of a particle

Ongoing work 1: Monte Carlo simulations of test particles evolving in prescribed (relativistic) wave-turbulence ⟶ diffusion coefficients



Ongoing/future work 2:

Particles in relativistic turbulence from dynamic SRMHD simulations and back reaction