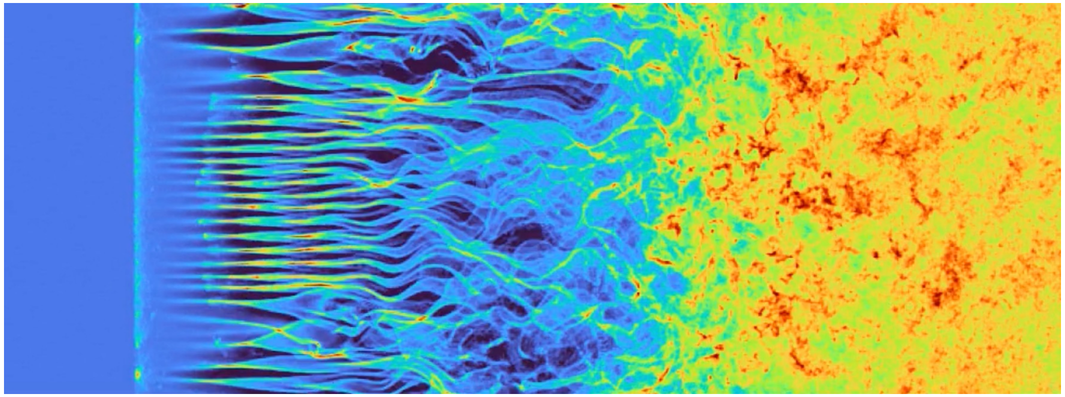
Physics of Relativistic Shocks

Illya Plotnikov (IRAP)

Scientific symposium on particle acceleration and transport from Heliospheric perspective

Toulouse, June 28th 2023

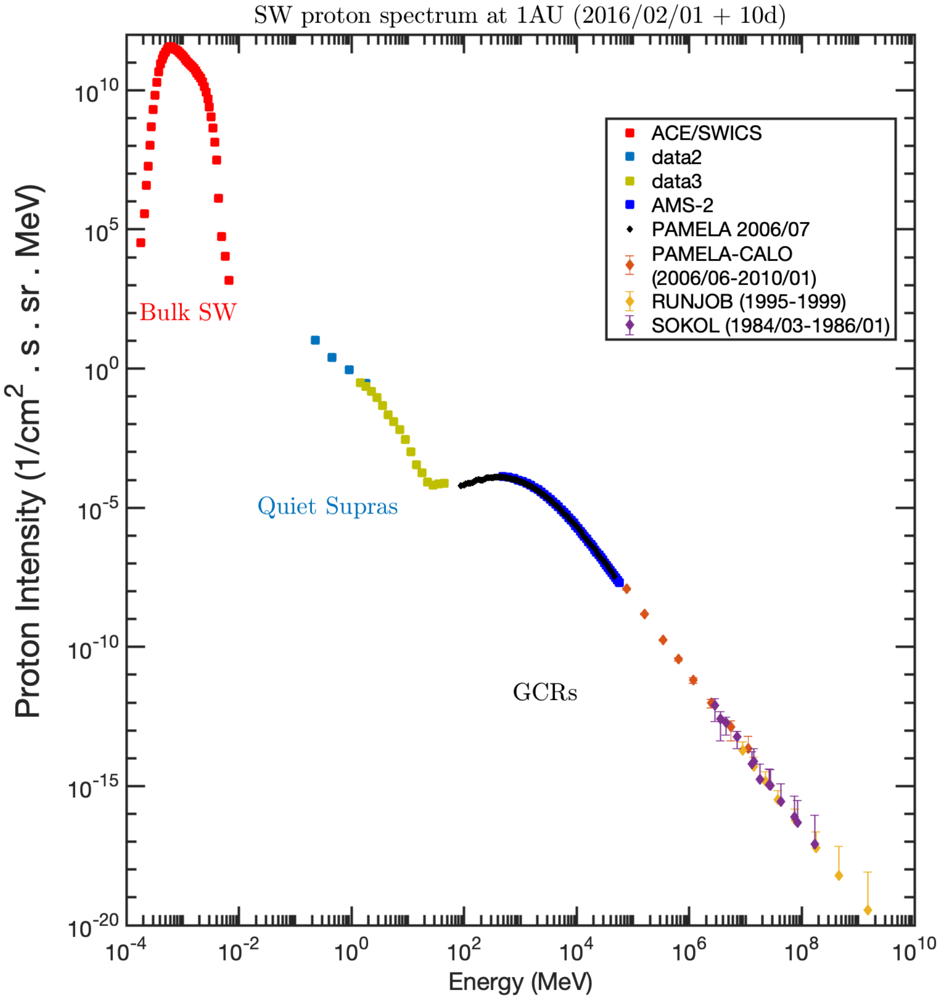


Context

Spectrum: Solar wind & SEPs & Cosmic Rays

Energy Distribution function

- Charged particle flux measured **in-situ** (in space).
- ~keV part: thermal Solar Wind at V ~ 400 km/s and T ~ 10 eV
- keV-10 keV supra-thermals
- 10 keV – GeV: non-thermals (SEPs).
- > GeV: Galactic Cosmic Rays



Done using OMNIWeb tool: https://omniweb.gsfc.nasa.gov/ftpbrowser/flux_spectr_m1.html

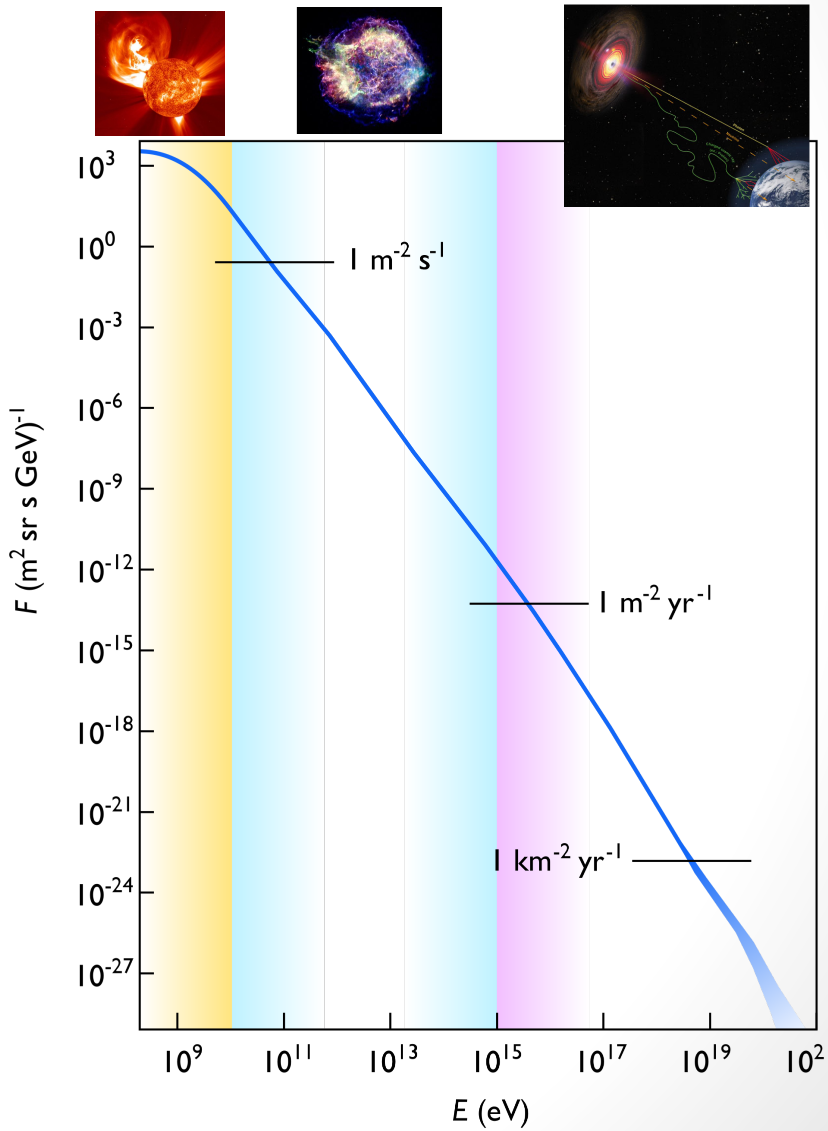
Context

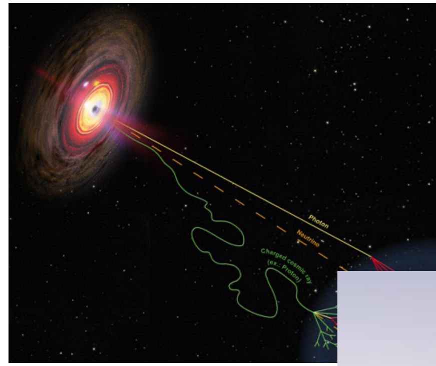
Spectrum: Solar wind & SEPs & Cosmic Rays

Towards Cosmic Rays of highest energies

- Charged particle flux measured on ground and in space by dozens of observatories.
- One of most impressive power-laws in astrophysics.
  « (second) Great Power Law In The Sky ». First one is for turbulence.
- Fantastic energies, above 10^{20} eV.

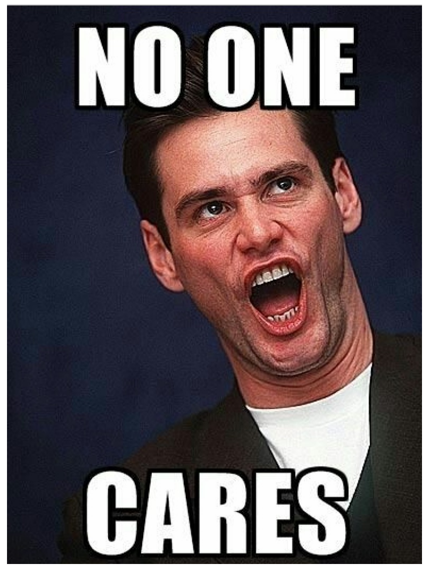
  (> kinetic energy of a tennis ball launched at 100 km/h)





-UHECRS
-Gamma rays
-HE neutrinos

About Relativistic shocks?



Physics of Multimessenger astronomy rely largely on relativistic regime of: shocks, turbulence, and reconnection

Credits: Martin Lemoine, IAP

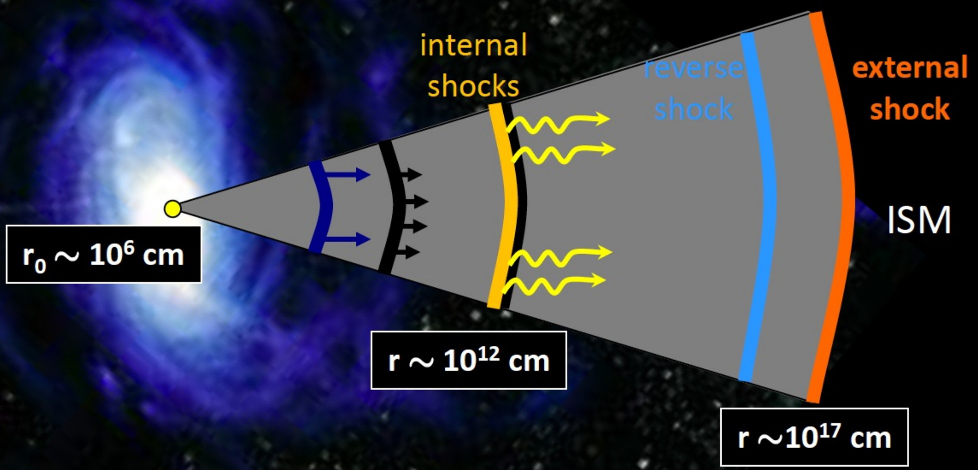
Where relativistic shock occur: GRBs

Gamma-ray bursts

… gamma-ray bursts: burst (<1 sec → 1000sec) of gamma radiation, with erratic time behavior in the MeV range, followed by a slowly decaying afterglow

… at the origin: collapse of massive stars (long?), coalescence of compact objects (short)?

… canonical description: narrow jet accelerated to large Lorentz factor $\Gamma \sim$ 100-1000

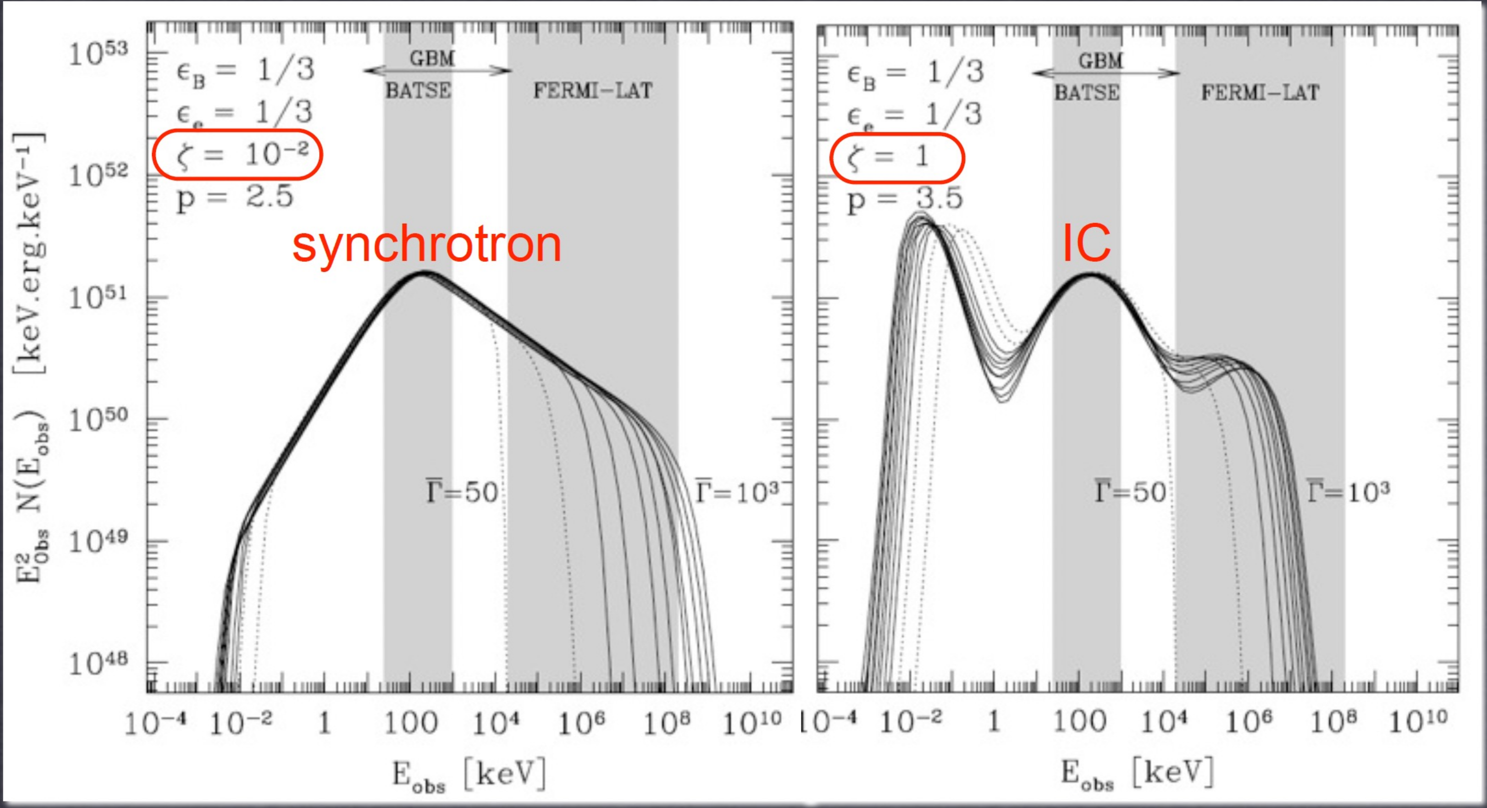


… prompt MeV radiation: dissipation of jet bulk kinetic (magnetic?) energy

… afterglow: dissipation of jet energy through a strong collisionless relativistic shock with the surrounding medium
shock heating of swept up electrons and shock acceleration

Parameterizing our ignorance

- ζ_e : fraction of electrons in nonthermal tail
- ε_e : fraction of flow energy in electron nonthermal tail
- ε_B : fraction of flow energy in post-shock magnetic fields



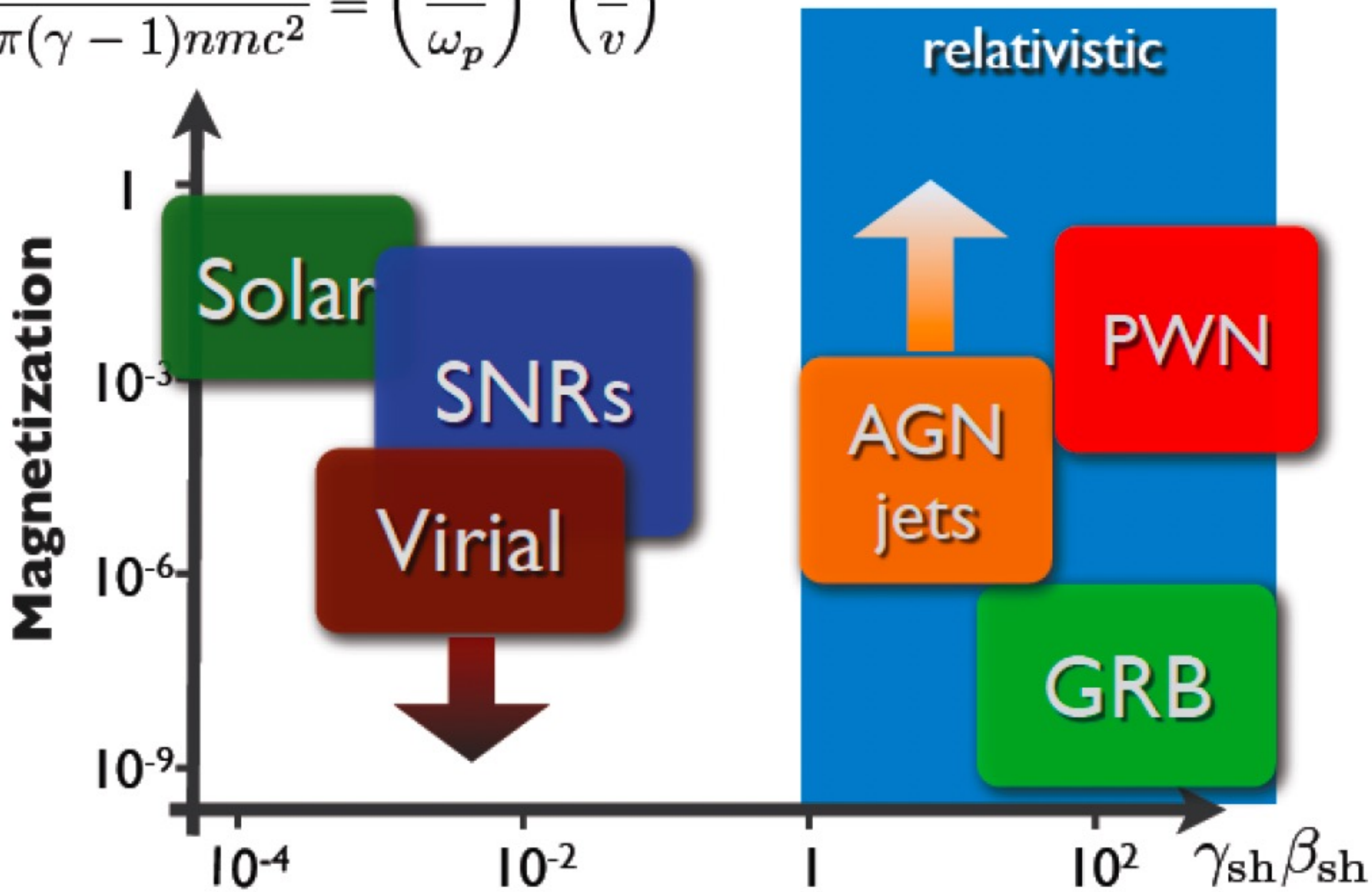
(Bosnjak et al 09)

Which values are obtained in real shocks?

Slide by A. Spitkosky

The landscape of collisionless astro/space shocks

$$\sigma \equiv \frac{B^2}{4\pi(\gamma-1)nmc^2} = \left(\frac{\omega_c}{\omega_p}\right)^2 \left(\frac{c}{v}\right)^2$$



Adapted from A. Spitkovsky

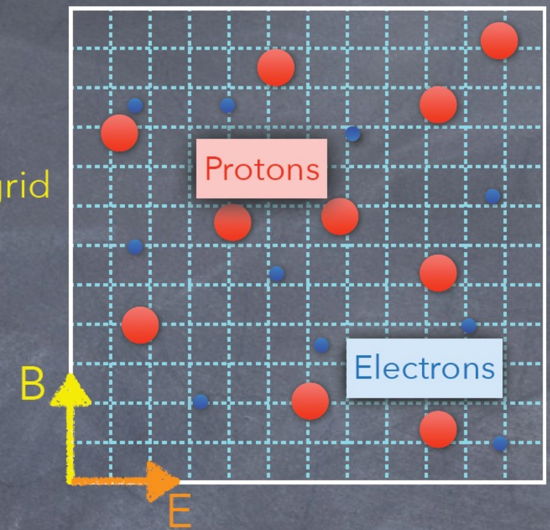
Kinetic simulations

Method

Classical textbooks: Birdsall & Langdon (PIC)
Lipatov (Hybrid-PIC)

Full-PIC and Hybrid-PIC techniques

- Full-PIC approach
  - Define electromagnetic fields on a grid
  - Move particles via Lorentz force
  - Evolve fields via Maxwell equations
  - Computationally very challenging!

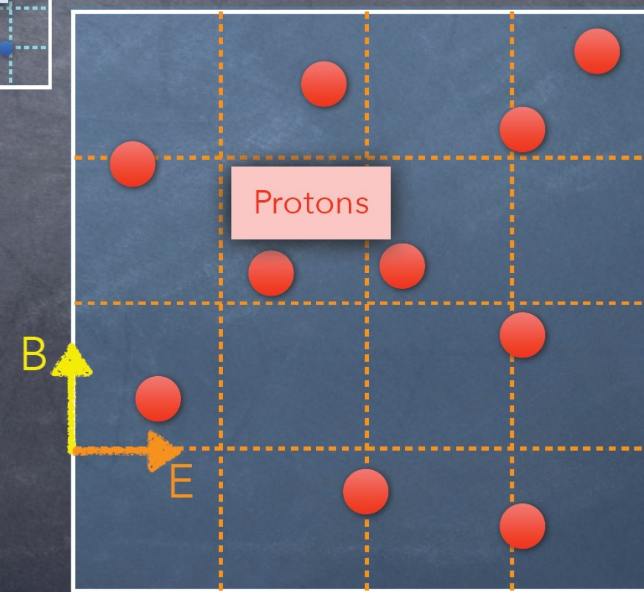


- Hybrid approach: Fluid electrons - Kinetic protons

(Winske & Omidi; Burgess et al., Lipatov 2002; Giacalone et al.; DC & Spitkovsky 2013-2018, Haggerty & DC, 2019…)

  - massless electrons for more macroscopical time/length scales

$$\mathbf{E} = -\frac{\mathbf{V}_i}{c} \times \mathbf{B} + \frac{1}{4\pi n\, e}(\nabla \times \mathbf{B}) \times \mathbf{B} - \frac{T_e}{n}\nabla n^{\gamma_e}$$



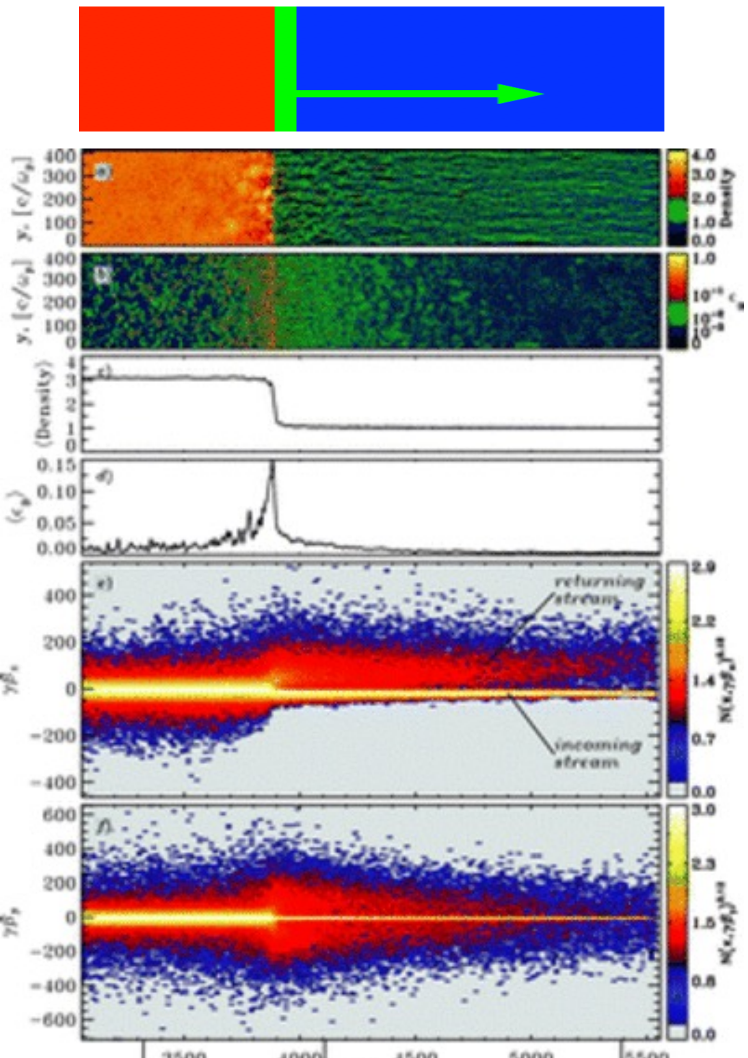
Credits: D. Caprioli

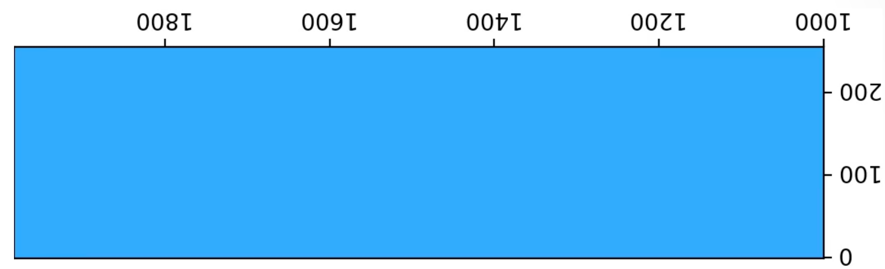
Relativistic shocks simulations

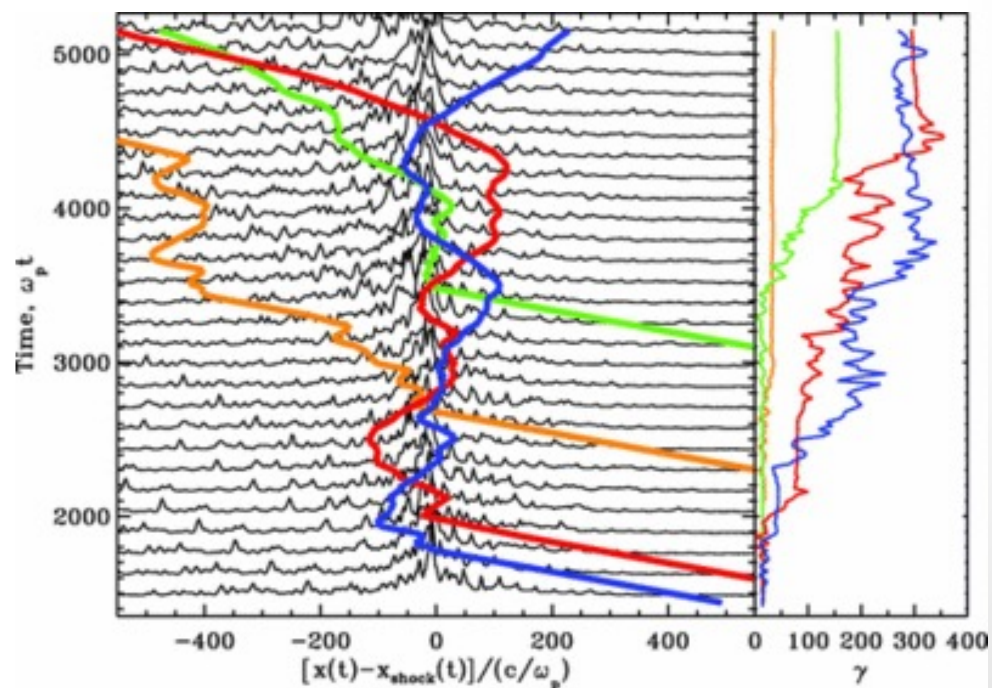
First ab-initio demonstration of Fermi I process

First principle demonstration of Fermi process

Spitkovsky, ApJL, 2008

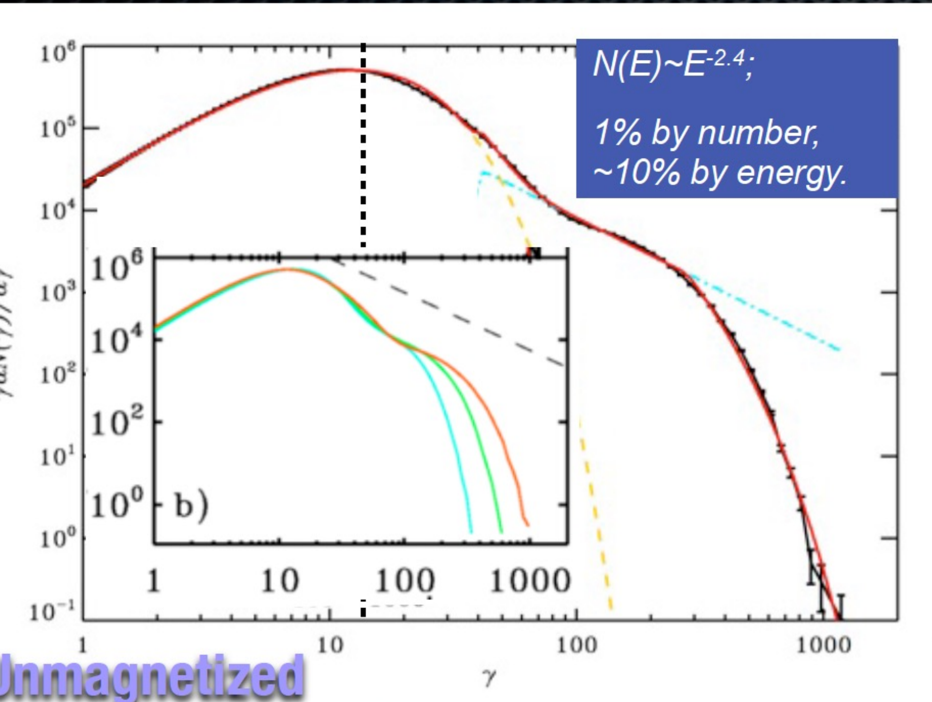


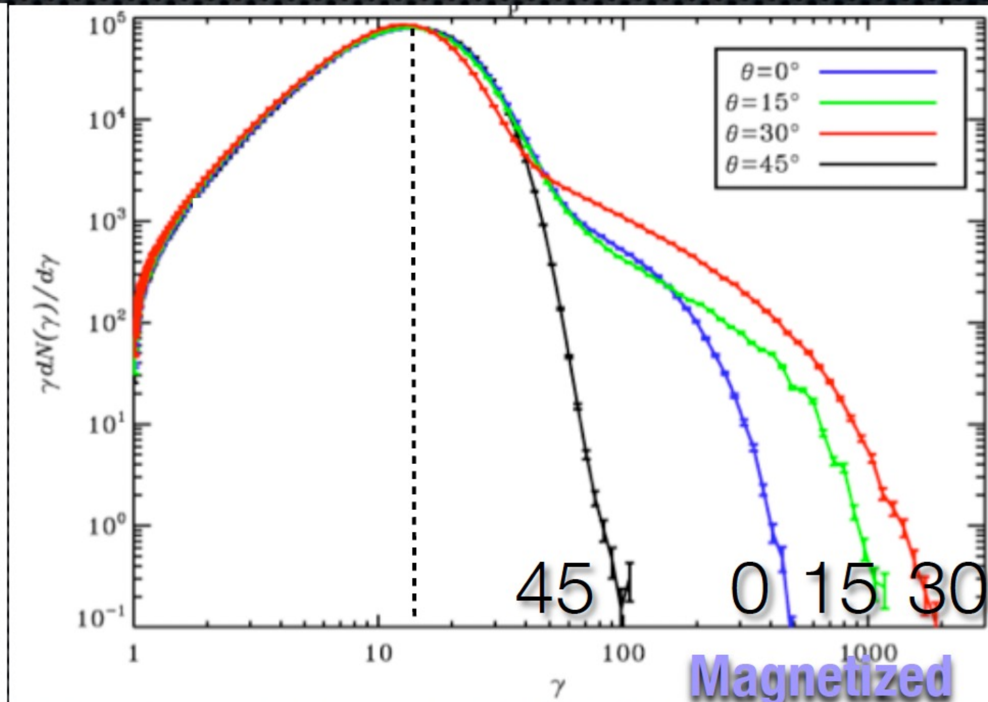


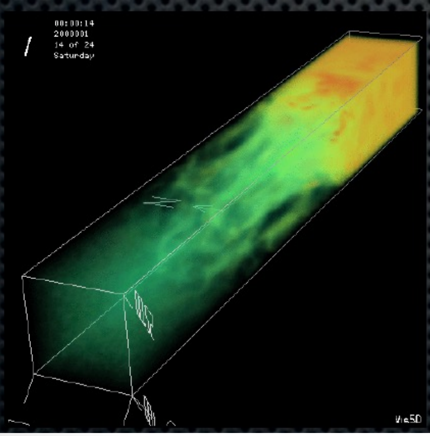


Particle acceleration:

Sironi & AS 09

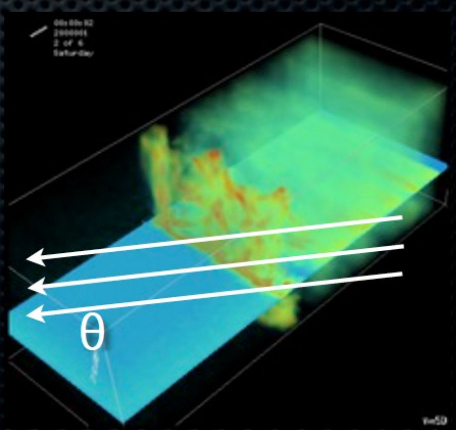






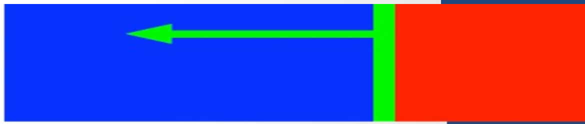
Conditions for acceleration in relativistic shocks:

low magnetization of the flow or quasi-parallel B field.



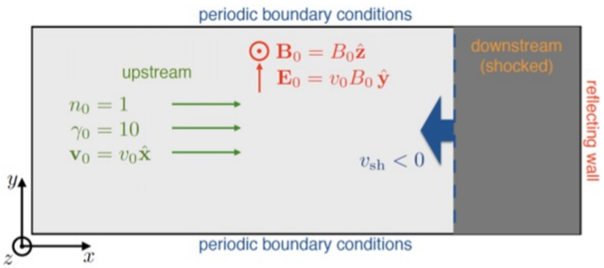
Credits: A. Spitkovsky, L. Sironi

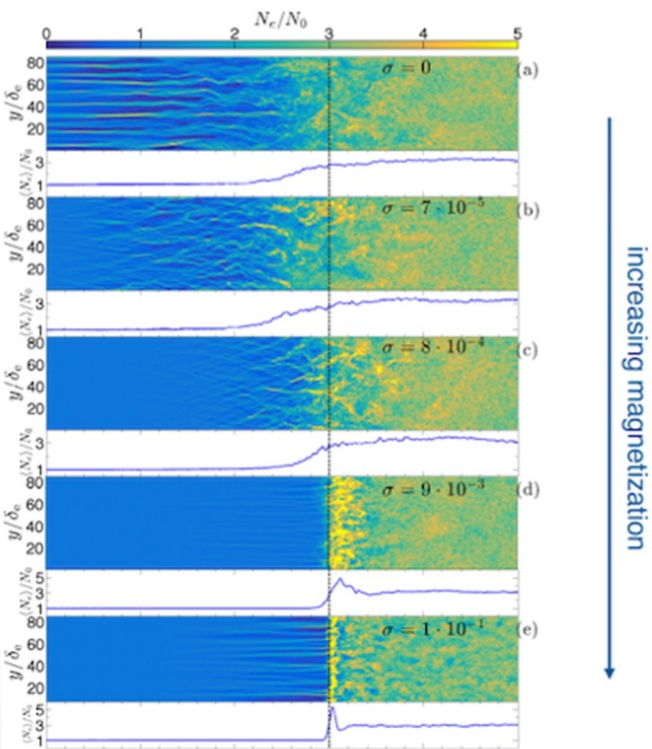
Relativistic shocks simulations

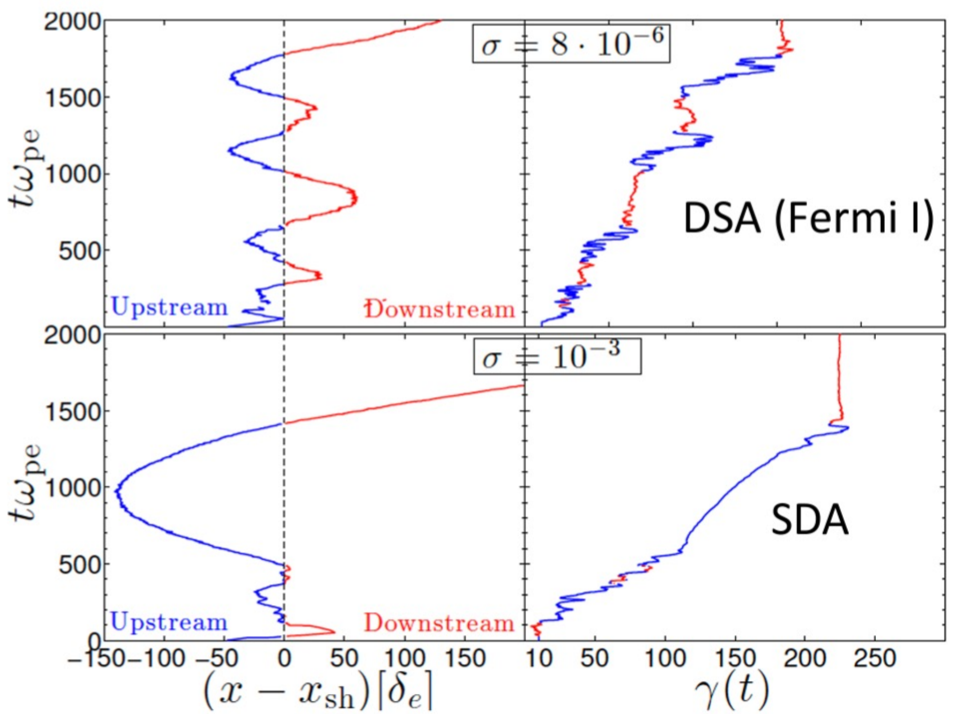


Fermi I process: dependence on magnetization

Sironi, Sptikovsky, Arons, ApJ, 2013
Plotnikov, Grassi, Grech, MNRAS, 2018
-> Dependence on upstream plasma magnetization

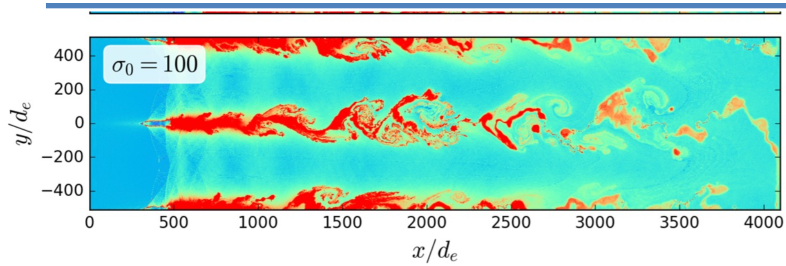


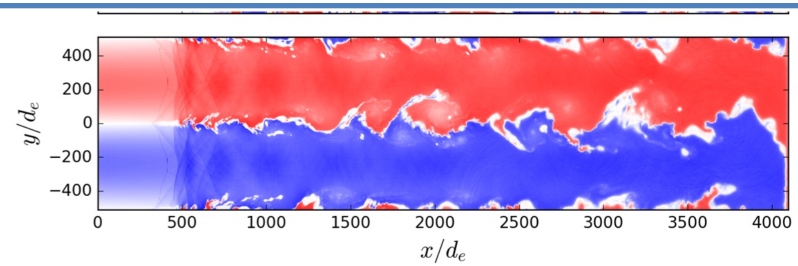


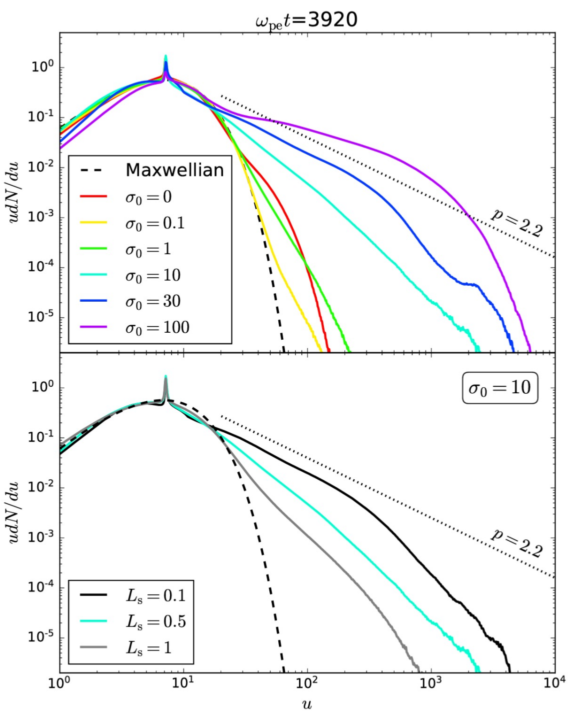


Recent progress

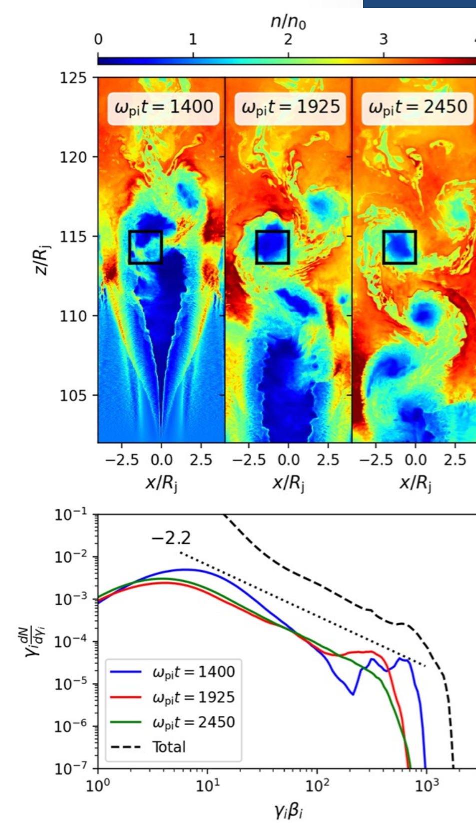
Making the geometry more realistic







- PWNe termination shok –like (Cerutti & Giacinti 2020, A&A)
- Extragalactic jets termination shocks (Cerutti & Giacinti 2023)
- Turbulent upstream plasma (Demiden et al 2023, Bresci et al 2023)



Recent interest: Fast Radio Bursts (FRBs)

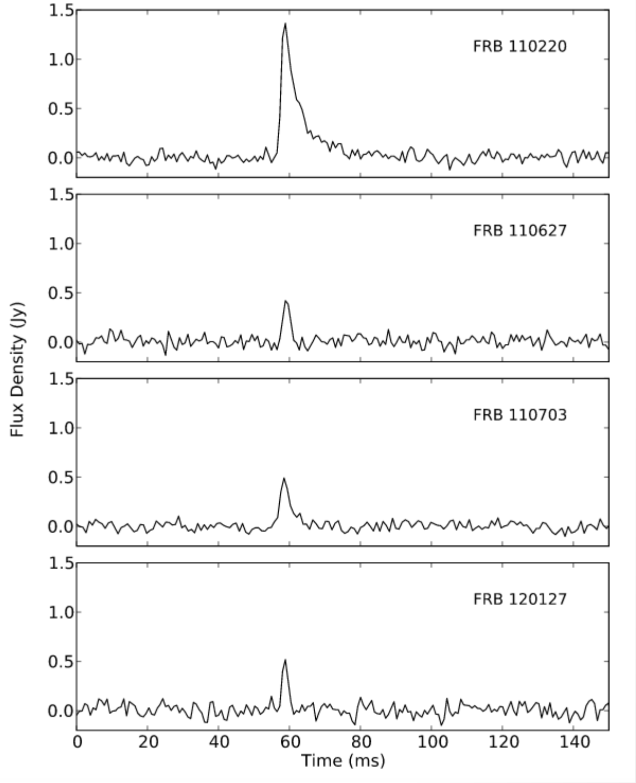
What are FRBs?

FRB Newsletter Volume 1, Issue 14 — October 2020

Total FRB count: 137
Repeaters: 22
Host galaxies: 13

- Short (ms) and intense (Jy) pulses in ~GHz frequency band
- Unknown emission mechanism but must be coherent:

  Brightness temp. $T_B \sim 10^{35}$ K
- Extragalactic sources (magnetars favoured for repeaters). One known Galactic source (magnetar SGR 1935+2154)
- Reviews by, e.g., Katz 18, Popov et al 18, Petroff et al 19, Cordes & Chatterjee 19



Thornton et al 13

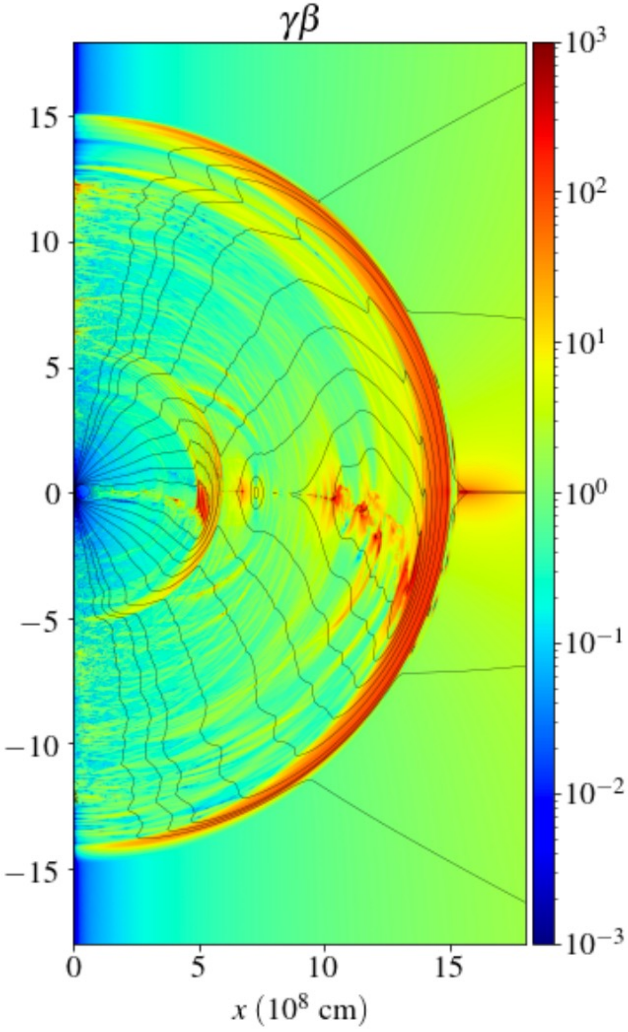
Synchrotron Maser for FRBs?

- One of few coherent mechanisms in plasma astrophysics (review by Melrose 86)
- Magnetar flares may be associated with powerful and relativistic blast waves (Lyubarsky 2014, Beloborodov 2017, talk by Y. Yuan yesterday) …
- …where SM is expected to be efficient (Langdon et al 88, Gallant et 92)
- However, efficiency, spectrum and polarization of emission are typically postulated and poorly constrained by non-linear physics

Global picture in magnetar-blast wave context

Formation of the blast in global simulations

Yuan et al, ApJ, 2020



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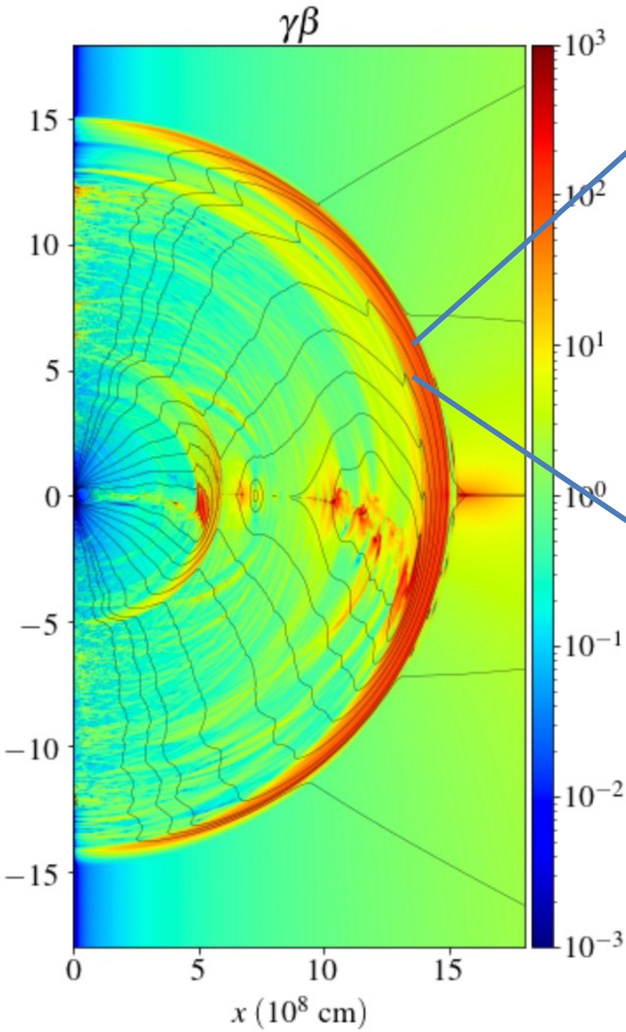
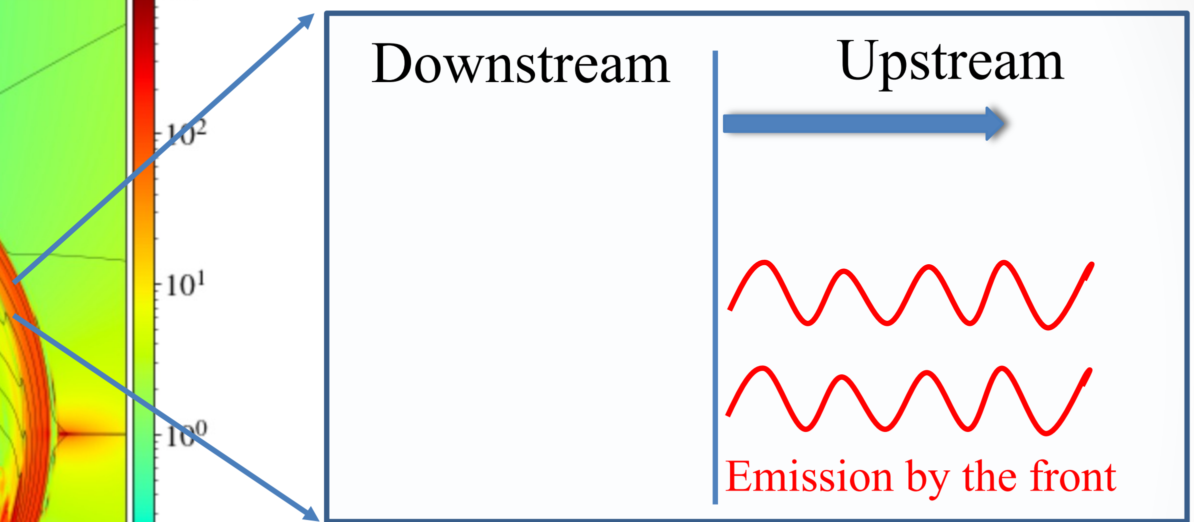


SM emission at the external shock



Detailed modelling by

Beloborodov 2017, 2020, ApJ

Metzger, Margalit & Sironi, 2019, MNRAS

Margalit et al, 2019, 2020, ApJ

Yamasaki et al, 2020, ApJ

1D PIC Simulations ($e^- - e^+$ plasma)

Precursor wave train emission by the shock

Density

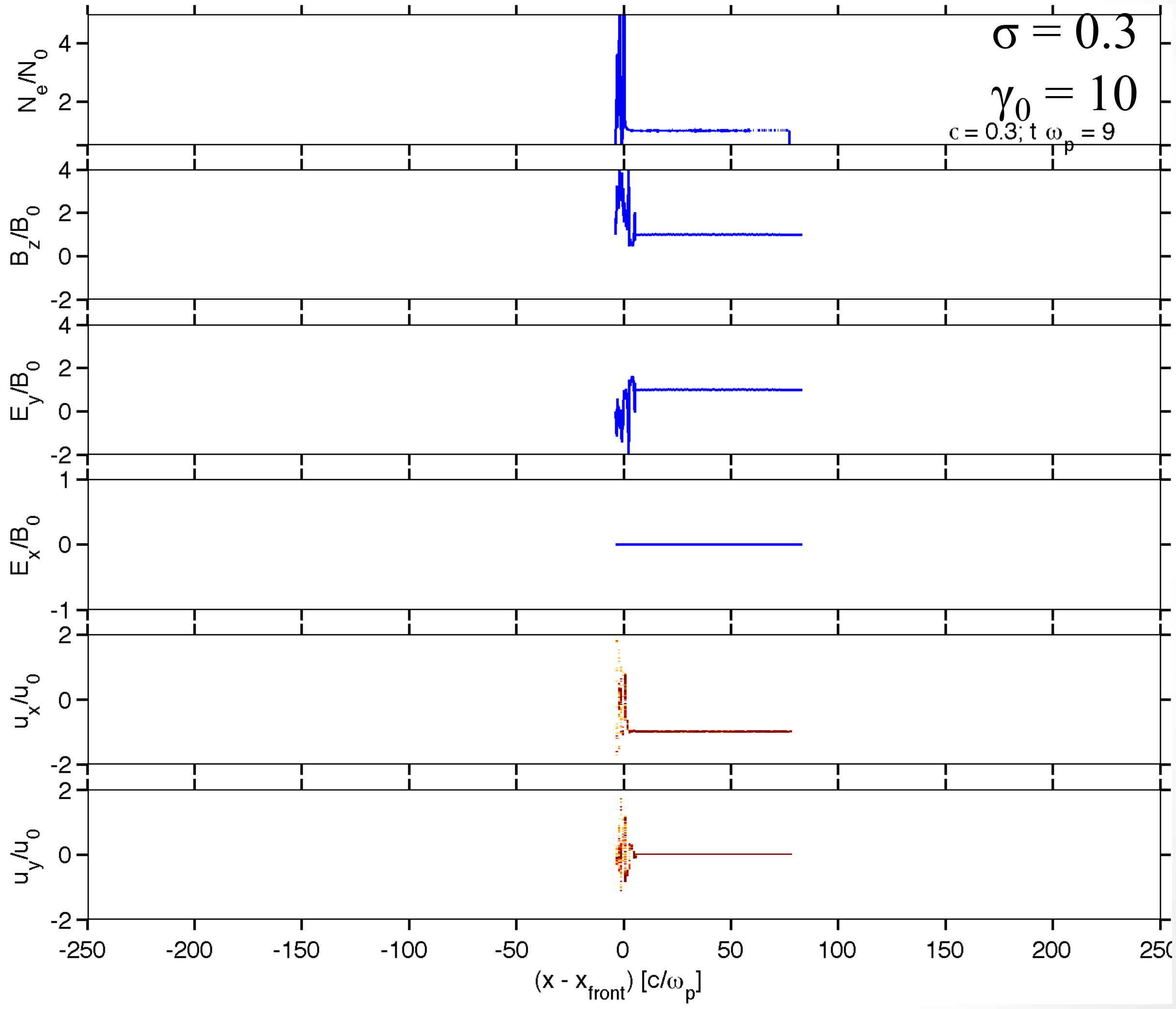
Bz

Ey

Ex

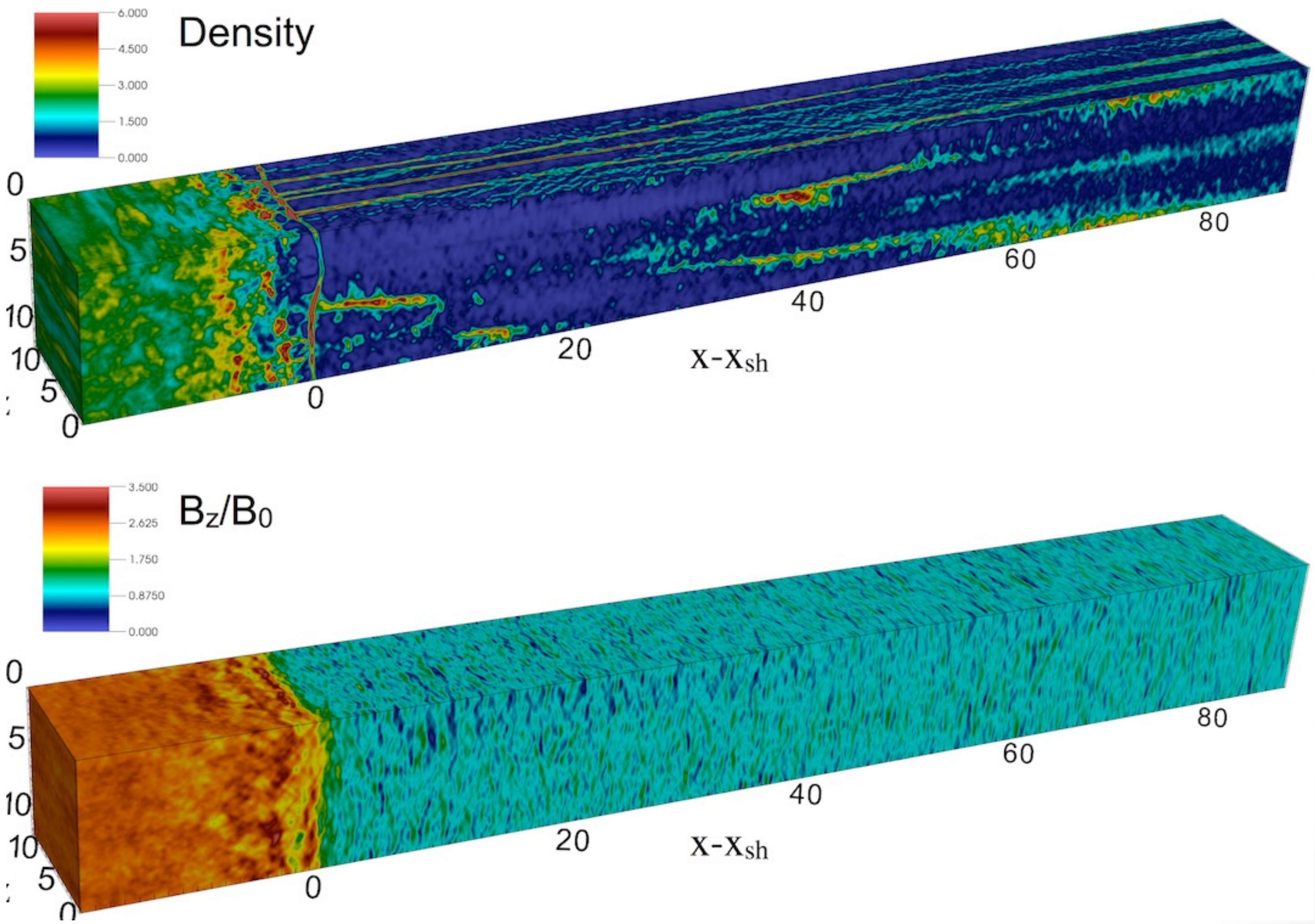
x-px

x-py



Plotnikov & Sironi, 2019

3D very similar to 2D & 1D



Sironi et al, PRL, 2021

Summary

- Relativistic shock physics are needed in understanding the compact objects activity.
- Recent progress in understaning the phenomenology and particle acceleration properties: PIC simulations
- Intruguing analogy with FRBs: type II and type III solar radio events.
  - Type III: magnetar magnetospheric emission (lots of emission mechanisms)
  - Type II: blast wave (synchrotron maser)

  PIC simulations provide non-linear scalings on the efficiency of this emission, spectum, and polarization.