Relativistic collisionless shocks and High Energy Astrophysics

by Guy Pelletier, laboratoire d'Astrophysique

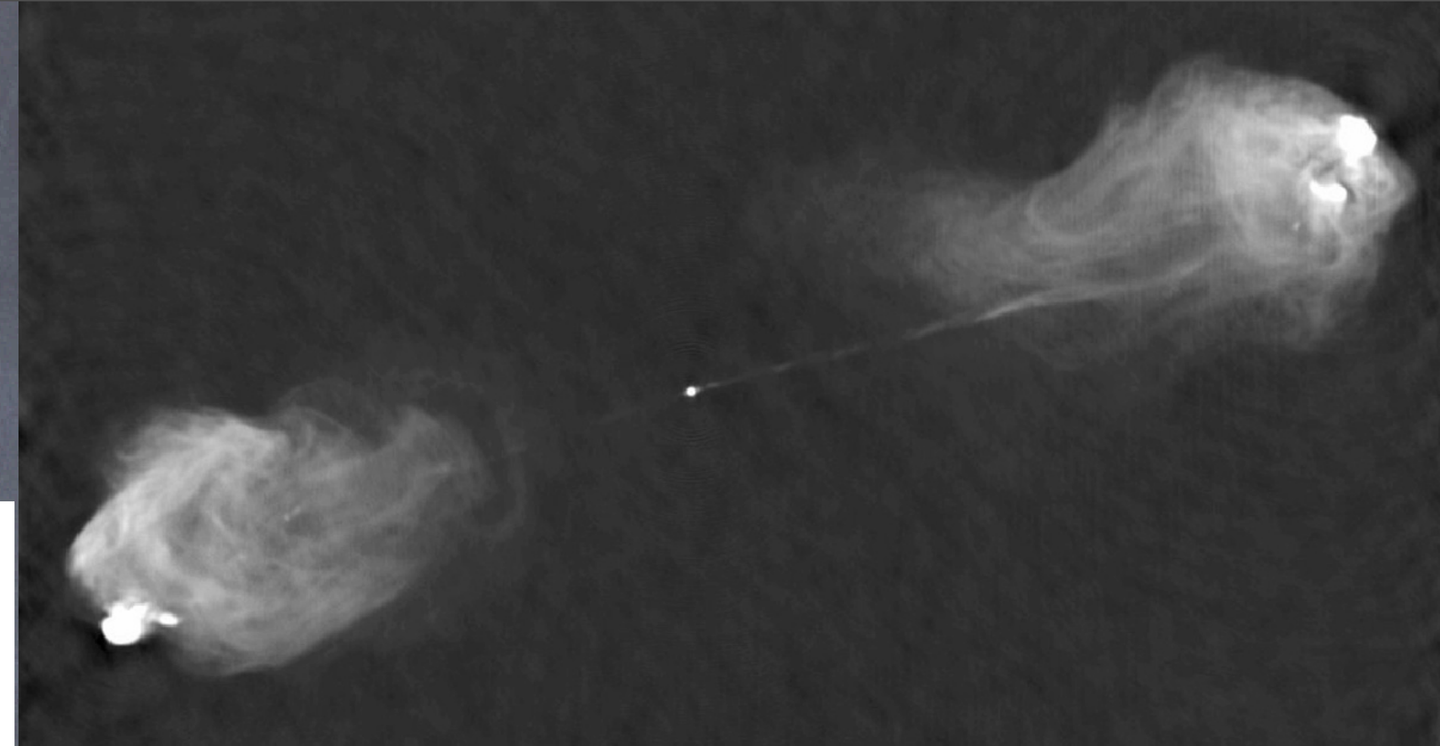
- "relativistic collisionless shock" Qu'es aquo?
- numerical experiments (PIC: Particles in Cells)
- importance in HE Astrophysics. Radiation of Gamma rays, neutrinos, cosmic rays etc. (AGNs, micro-Quasars, Pulsar Wind Nebulae, Gamma Ray Bursts etc)
- UHE Cosmic Ray origin?
- Laboratory experiments (at Laser facilities, LMJ...)

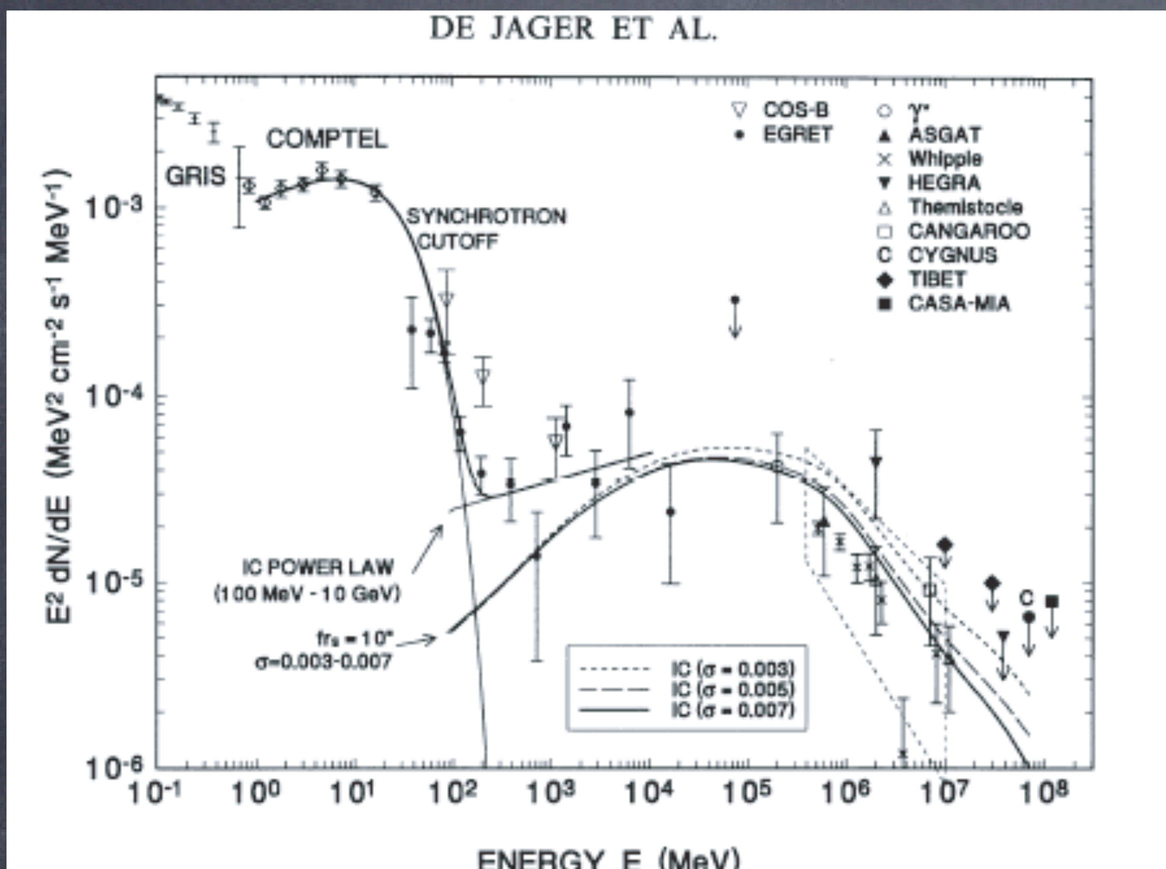
main collaborators in these tasks: Martin Lemoine,
------------------------------------Illya Plotnikov (PhD Student UJF)

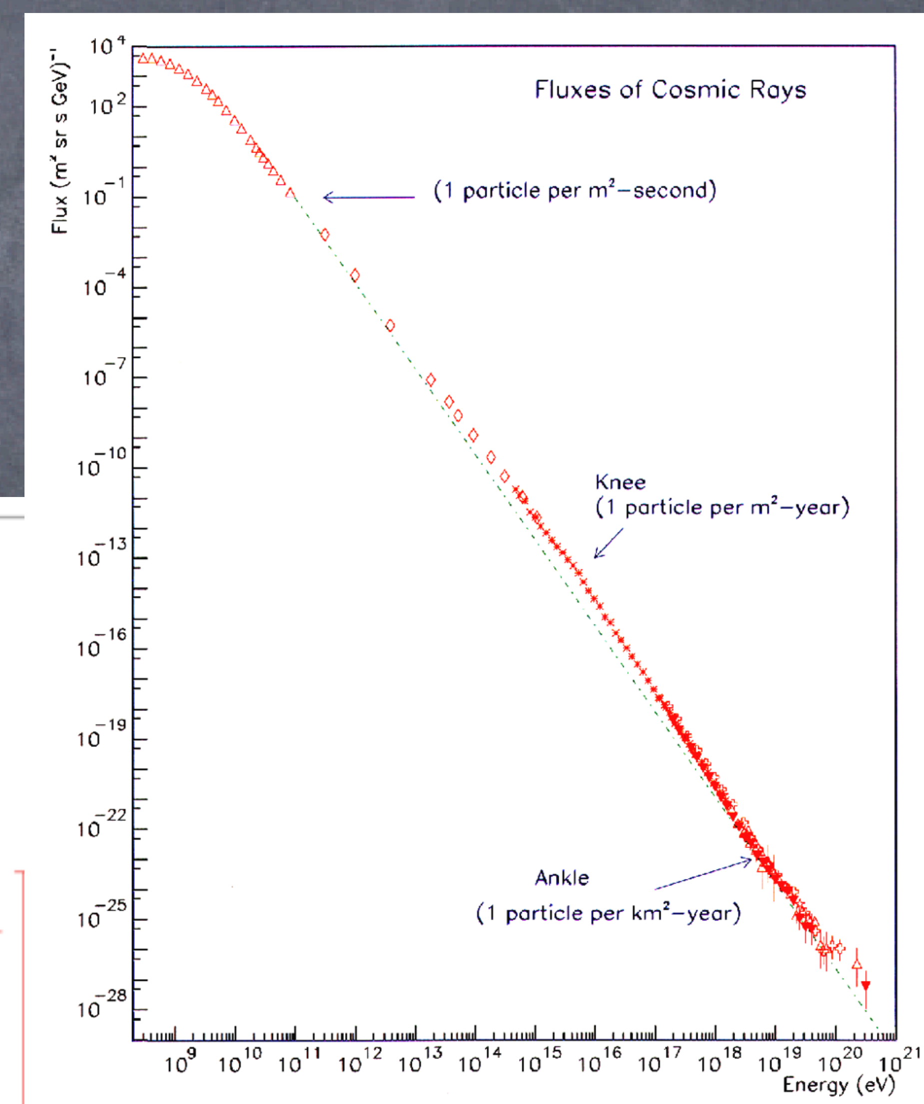
AGN Jets, micro-Quasars $\Gamma\sim 10$

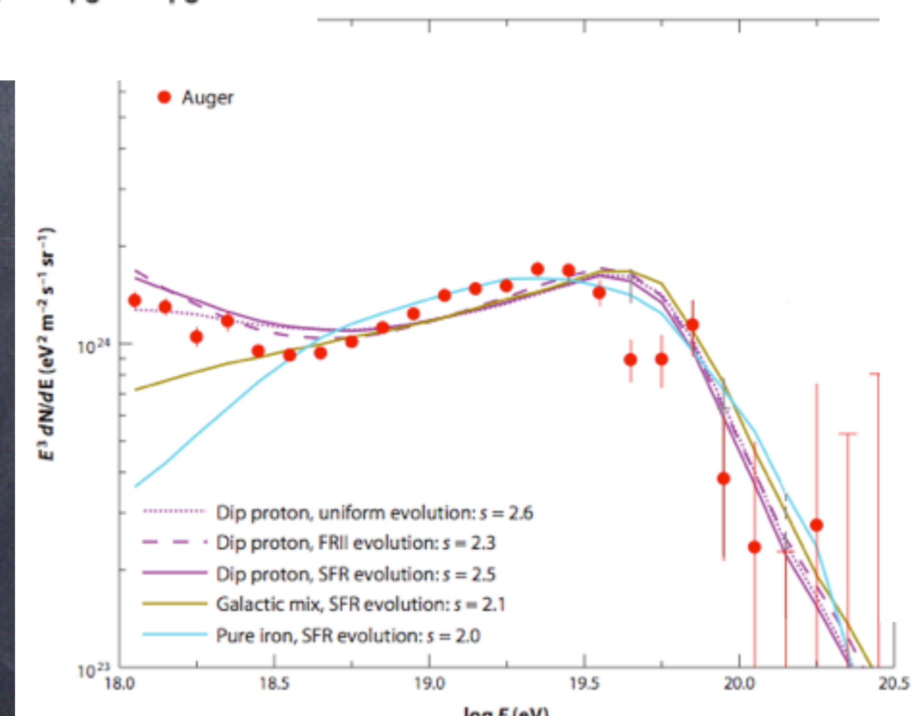
Pulsar e+e- wind $\Gamma\sim 10^3$- 10^6

Gamma Ray Bursts $\Gamma\sim 10^2$-10^3









Def "Lorentz factor" :

$$\gamma \equiv \frac{1}{\sqrt{1-\frac{v^2}{c^2}}}$$

$$\epsilon = \gamma m c^2$$

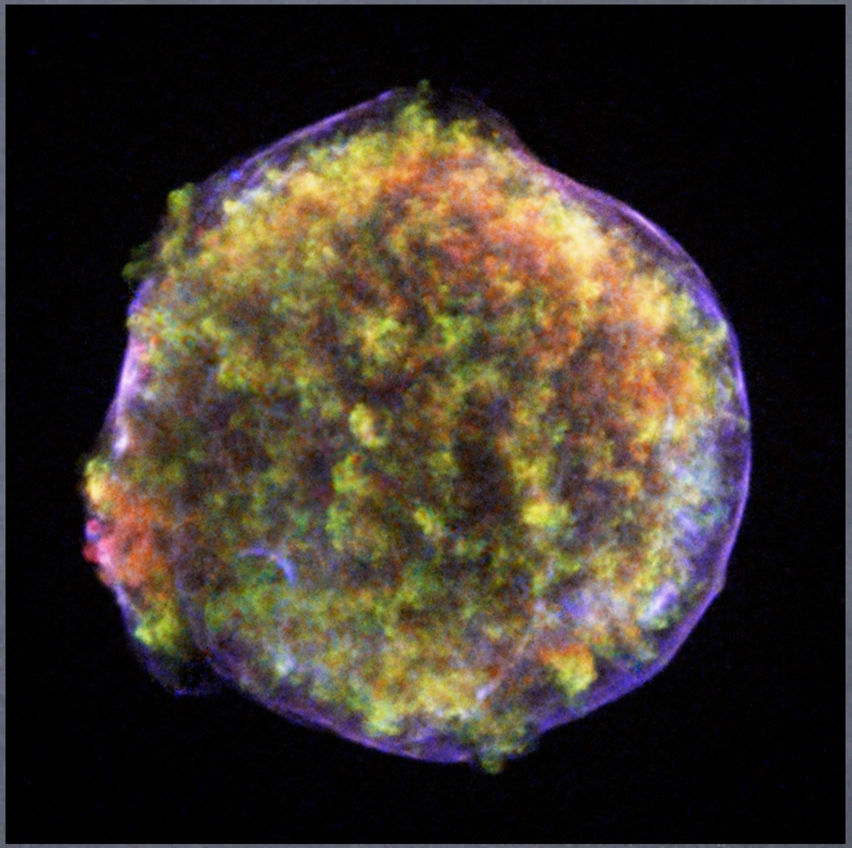
What is a relativistic collisionless shock?

- hudge mean free path
- isotropization: shock achieved when an isotropic distribution is set up downstream in a rest-frame moving at c/3 with respect to the front.
- collisionless dissipation: Landau (C. Villani). No entropy production unless phase space ripples smoothed out. (more generally Landau-synchrotron resonances).
- partial reflection of the incoming flow at an electromagnetic barrier => a coherent wave or turbulence. Self-sustaining NL front.
- micro-turbulence insures distribution isotropization, heating and more...

$$T_p \simeq 0.2\,\Gamma_s m_p c^2$$

$$T_e \sim T_p \ ?$$

B-field amplification or generation at shocks



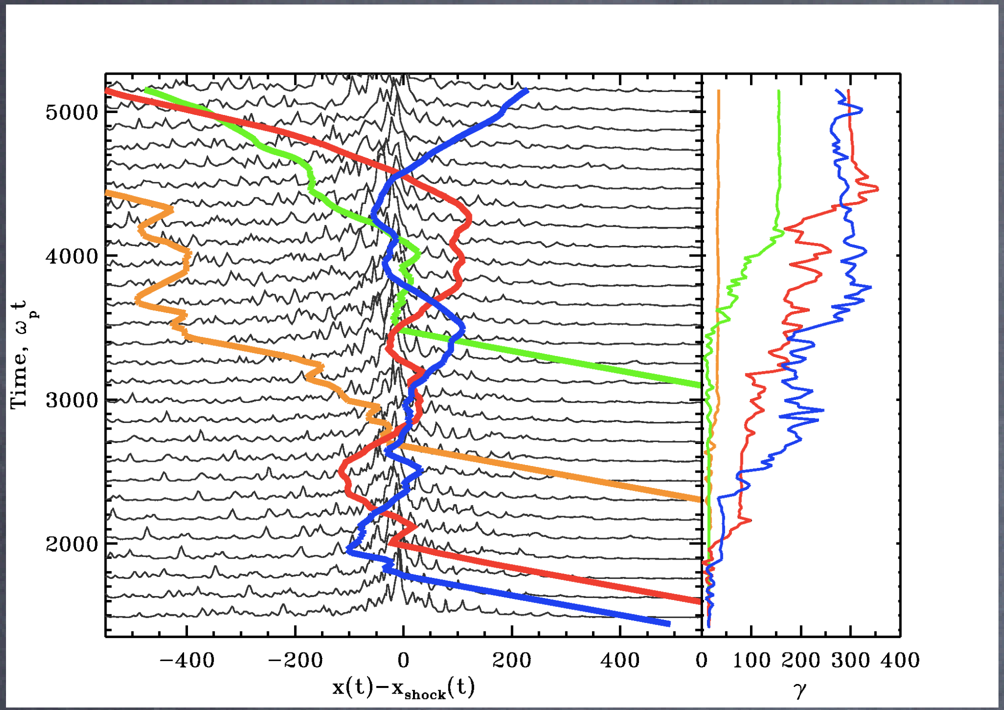
- Evidence of B amplification in SNRs (Chandra, XMM)
  (Cassam-Chenaï et al.)
  non-relativistic
  MHD turbulence

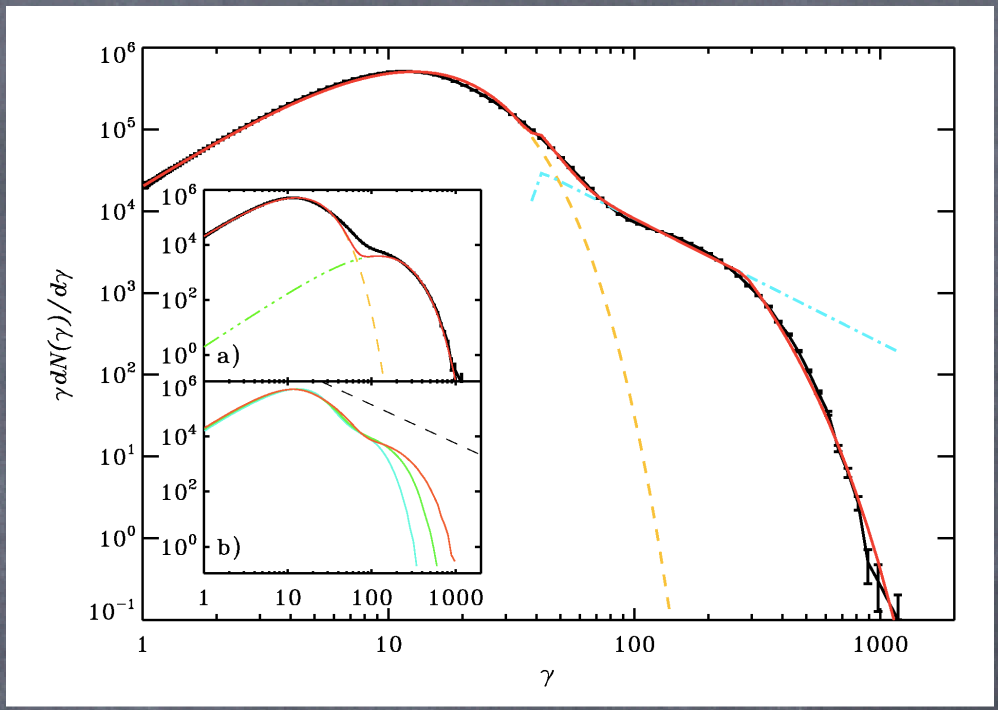
  current carried by CRs =>
  supplem Lorentz force => instability

  MHD simulations
  (Zirakashvili, Reville & Bell...)

- Indirect evidence of B-generation at the termination shock of GRBs
  (Li & Waxman 2006)
  relativistic shock,
  electromagnetic micro-turbulence (sub-MHD scale)

triptych of a collisionless relativistic shock





PIC simulation by
A. Spitkovsky 2008
pair plasma
$B_0 = 0$

Weibel turbulence

similar for $\sigma \ll 1$

Collisionless shock

Generation of Suprathermal particles

Generation of magnetic turbulence

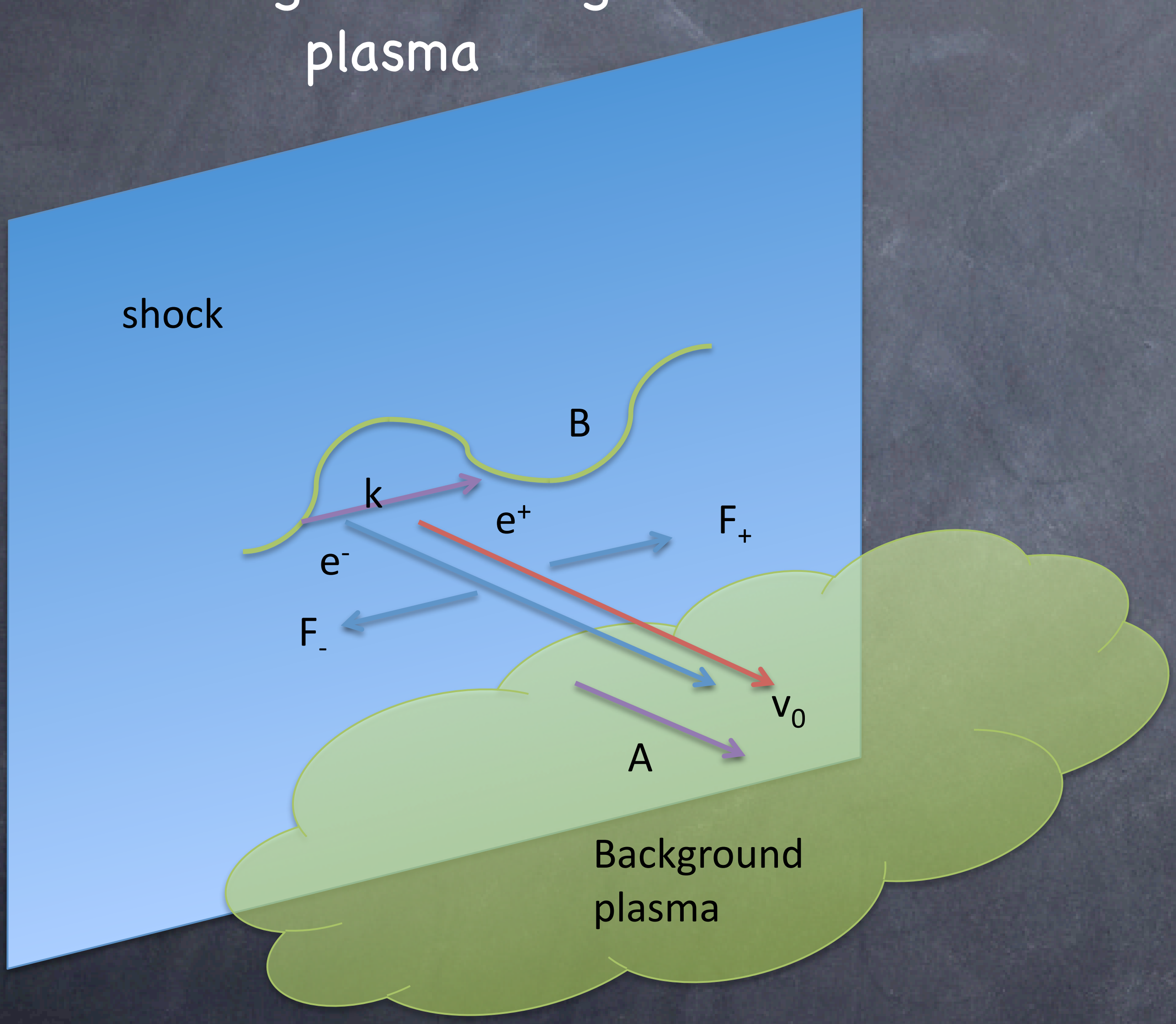
Radiations generated in the turbulent field

Fermi process,
power law spect s = 2.4

$$P_{cr} \equiv \xi_{cr}\Gamma_s^2\rho_0 c^2$$
$$\frac{B^2}{4\pi} \equiv \xi_B\Gamma_s^2\rho_0 c^2$$
$$F \equiv \xi_{rad}\Gamma_s^2\rho_0 c^2$$

Weibel instability (for e+e- plasma and beam)

relat neutral stream of e+e- interacting with background plasma



$$F_\pm = \pm e \frac{v_0}{c} \times B$$

$$\partial_t^2 A - c^2 \Delta A = 4\pi c \delta J$$

$$\delta J = -\frac{\omega_p^2}{4\pi c} A + v_0 \delta\rho_{el}$$

$$\partial_t^2 \delta\rho_{el} = -\frac{\omega_p^2}{4\pi} \frac{\xi\beta_0}{1+\xi} \Delta A$$

$$\text{with } \xi \equiv \frac{\omega_{pb}^2}{\omega_p^2} \simeq \xi_{cr}$$

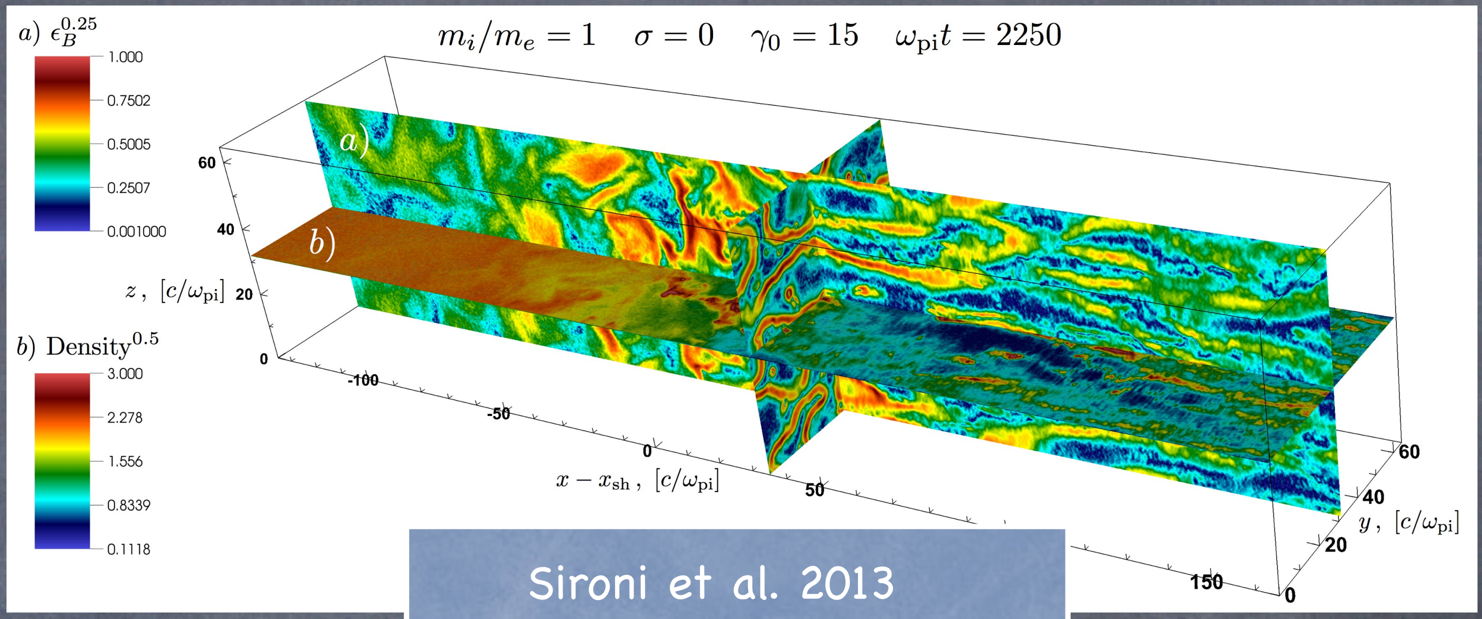
$$\text{growth rate} = \frac{\xi^{1/2} k v_0}{(1+k^2\delta^2)^{1/2}}$$

maximum rate : $\sqrt{\xi}\omega_p$

typical scale: $\delta = c/\omega_p$

Weibel turbulence

Filamentary structures (quasi 2D)
of size δ



Sironi et al. 2013

pairing of current filaments of
opposite polar

a kind of Debye screening

$$\frac{e\beta_0 A}{T} \mapsto A$$

similarity with 2D Hydro-turbulence

(Dauxois, Someria, Chavanis, Robert etc...)

$$\Delta A + \sinh A = 0$$

Polyakov, Duplantier etc (conformal invariance)

But charge separation => electrostatic effect (pre-heating)

particle reflection and scatting off B-structures

- growth of B perturbations until significant reflection of incomping particles =>

$$\frac{B^2}{4\pi} \sim \xi_{cr} n_0 m c^2$$

$$\xi_B \sim \xi_{cr}$$

- scattering rate for particle having $\gamma \geq \Gamma_s$

$$\nu_s \equiv \frac{< \Delta\alpha^2 >}{\Delta t} \sim \frac{e^2 B^2 \ell_c}{p^2 c} \sim \xi_{cr} \omega_p \frac{\Gamma_s^2}{\gamma^2}$$

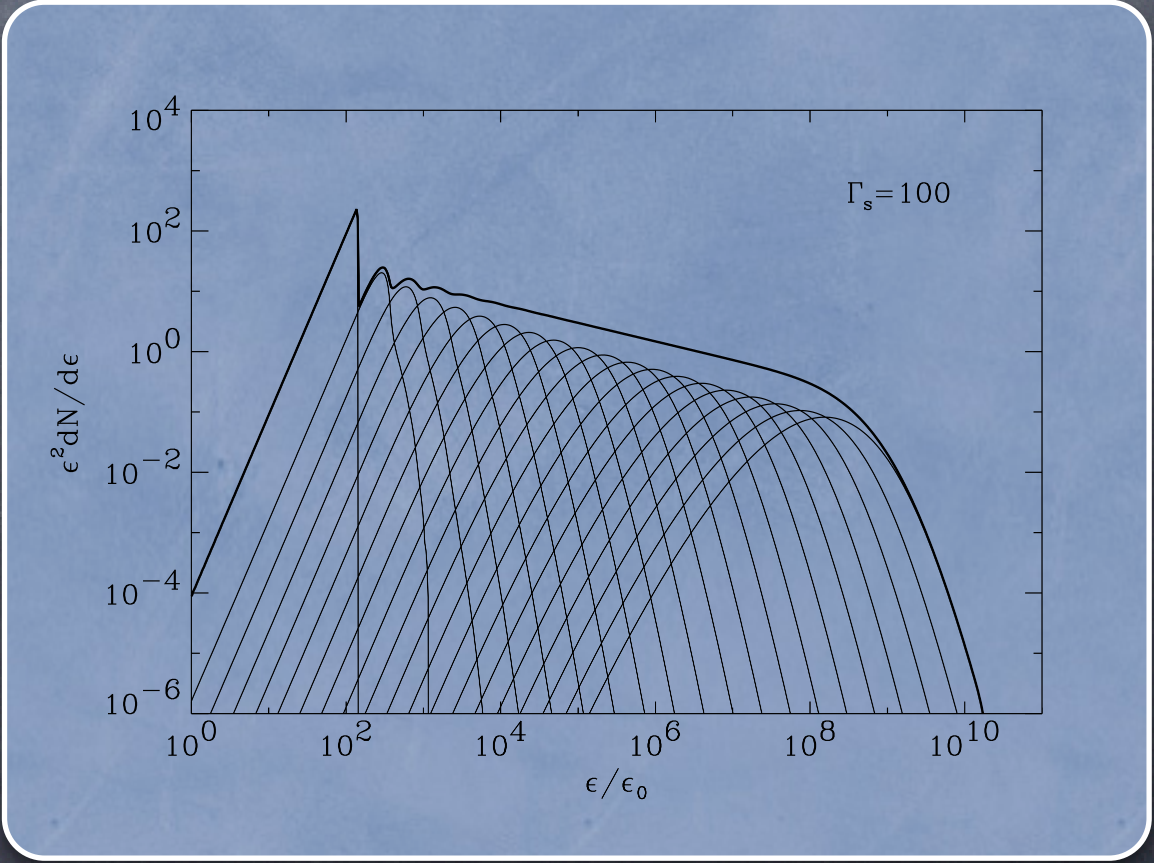
allows Fermi process as long as this rate larger than any loss rate or Larmor pulsation in the ambient mean field

Particle spectrum at a Relativistic Collisionless Shocks

Bednarz & Ostrowsky 98, Achterberg et al 01,
Galant et al 99, Kirk et al 00, Vietri 03, Ellison & Double 03

semi analytical results with Monte Carlo simulations

M. Lemoine & G.P. 03



relativistic shock =>
much more power in H.E. radiation;
but detailed budget?

How works Fermi process?
spectrum OK s=2.2-2.3,
scattering? turbulence generation?

what about more realistic situations with protons and ambient B-field?

- more electrostatic effect in protonic plasma.
But micro-turbulence => efficient electron pre-heating =>
e- relat mass comp with proton mass =>
similarity with e+e- situation

- The effect of an ambient B-field, serious issue

- classification of relativistic shocks as a function
of a “magnetization parameter”

Inhibition of Fermi process by the mean field

In front frame, ambient B_0 almost perp ->
phase space locking.
Similar with large scale turbulence.

Niemec et al. 06
Lemoine et al. 06

For Fermi process, scattering off micro-turbulence only.
intensity requirement

$$\sigma \equiv \frac{B_{t|f}^2}{4\pi\Gamma_s^2\rho_u c^2} = \frac{B_0^2 \sin^2\theta_B}{4\pi\rho_0 c^2}$$

$$\frac{\delta B^2}{4\pi} \equiv \xi_B \Gamma_s^2 \rho_0 c^2$$

$$\nu_s(\gamma) > \omega_{L,0}(\gamma) \Longrightarrow \sigma < \xi_B^2$$

$$\nu_s \propto \gamma^{-2}$$

RC energy limit due scattering inhibition:
OK with PIC simulation (Sironi et al. 13)

$$\gamma_{lim} \sim \Gamma_s \frac{\xi_B}{\sqrt{\sigma}}$$

RC energy limit at termination
shock of GRBs: $\sim 10^{16}$ eV

(G.P., Lemoine, Marcowith 09
Plotnikov et al. 12)

Transition towards micro-turbulent shocks with Fermi process for decreasing magnetization

$$\sigma < \xi_B^2 \sim \xi_{cr}^2 \ (10^{-2} - 10^{-3})$$

M. Lemoine & G.P. 09, 10, 13

Phenomenon entirely governed by plasma micro-physics

Electron heating at a relativistic shock. Radiation

(Plotnikov et al. 13)

- relativistic motions of e^- in an intense wave (Guérin, Mora, Laval 95-98)

$$a \equiv \frac{eE_w}{\omega_0 m_e c} \gg 1$$

fast heating to $T_e = a\, m_e c^2$

$$T_e \sim \xi_B \Gamma_s m_p c^2 \sim T_p$$

- similarly, motions in an intense micro B-field (J. Kirk & B. Reville 11)

$$a_w \equiv \frac{e\bar{B}\ell_c}{m_e c^2} \gg 1$$

a and a_w very large in p^+e^--plasma shock

- synchrotron-like radiation. opens diagnostic of the micro-field (see M. Lemoine 12-13)

Efficiency of relativistic shock acceleration

exemple of GRB termination shock
(Lemoine & G.P. 11,12 and Plotnikov et al. 13):

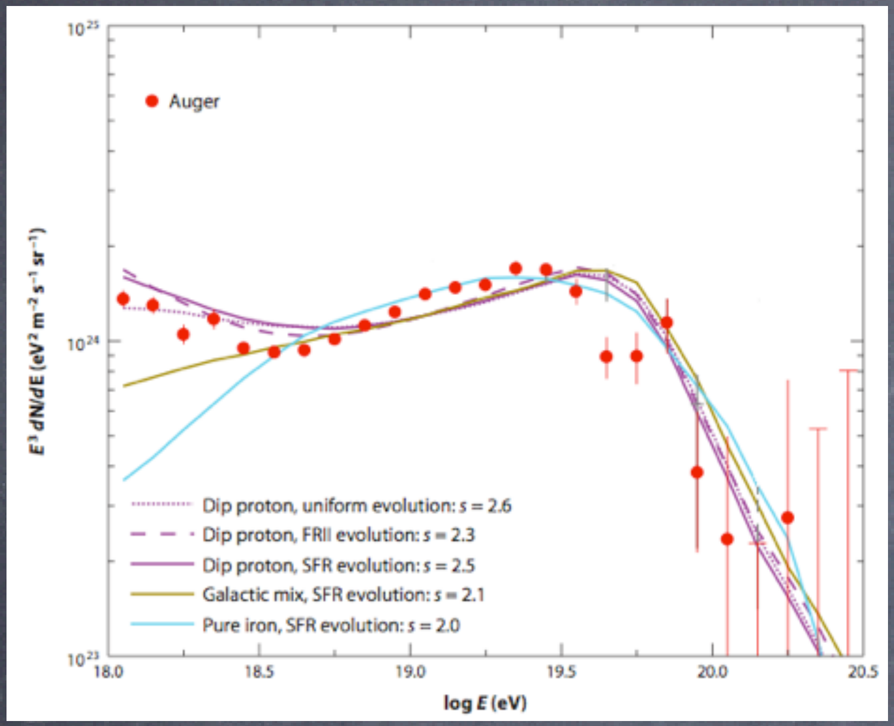
• protons accelerated up to 10^{16} eV
(scattering limit, expansion, escape same estimate)

• electrons accelerated up to $\gamma = 10^6$ (in co-moving frame)
(depending on density only)
synchrotron-like gamma rays up to a few GeV,
then SSC (see Wang et al. 13)

• high conversion of kinetic energy into radiation: 1-10%

$$\xi_{rad} \sim \xi_B \sim \xi_{cr}$$

About Ultra High Energy Cosmic Rays?



- UHECRs? Better with mildly relat shocks in ultra-relat flows: in AGN Jets and internal shocks of GRBs. (G.P. & M. Lemoine 10, 11)
  Radio galaxy Centaurus A suspected...

Conversion of kinetic energy into B turbulent energy similar, but in a much larger precursor (MHD scales) than in ultra-relativistic regime

(M. Lemoine 10, E. Waxman 95 ...)

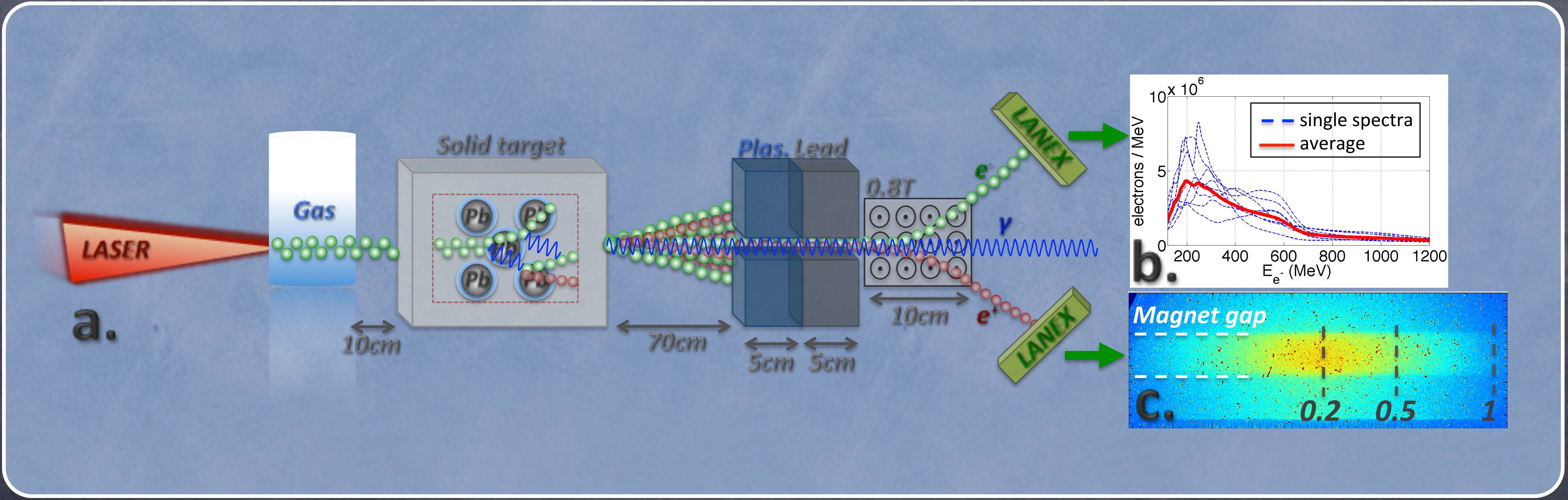
GZK cut off, composition issue (HIRES-OPA)

Experiments on Laser facilities (LMJ...)

Generation of sub-relativistic plasma streams of 100 MeV protons

Recent progress in the generation of

Ultra-relativistic streams of e+e- plasma



studies of collisionless shocks with many diagnostics


Thank you!
enjoy lunch break!