Why Fermi acceleration is so challenging at relativistic shocks

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Astroplasma program KITP 2009

paper to appear in MNRAS, Astro-ph arXiv:0904.2657v2

1st level of comparison between non-relativistic and relativistic regimes of Fermi process

non-relativistic	relativistic
small gain, many cycles (Fokker-Planck)	large gain (≈2), few cycles (Markovian but not F-P)
scattering over large distances upstream upstream distrib almost isotropic	particles rapidly caught up by the shock upstream ($\alpha \sim 1/\Gamma_s$) upstream distrib very anisotropic
slow acceleration $t_{acc} > t_s >> t_L$	fast acceleration $t_{acc} \approx t_L$
B quasi-parallel most frequent ($\sin\theta_B < 1$) subluminal	B quasi-perp most frequent ($\Gamma_s \sin\theta_B > 1$) superluminal

various shock structures

i) subluminal or non-magnetized shocks

ii) In the case of e^+e^- plasma, just a magnetic barrier that reflects part of the incoming particles

iii) ep superluminal shock

ramp, foot, overshoot

resistive length ~ δ_e

$$\ell_r = \frac{\eta c}{4\pi}$$

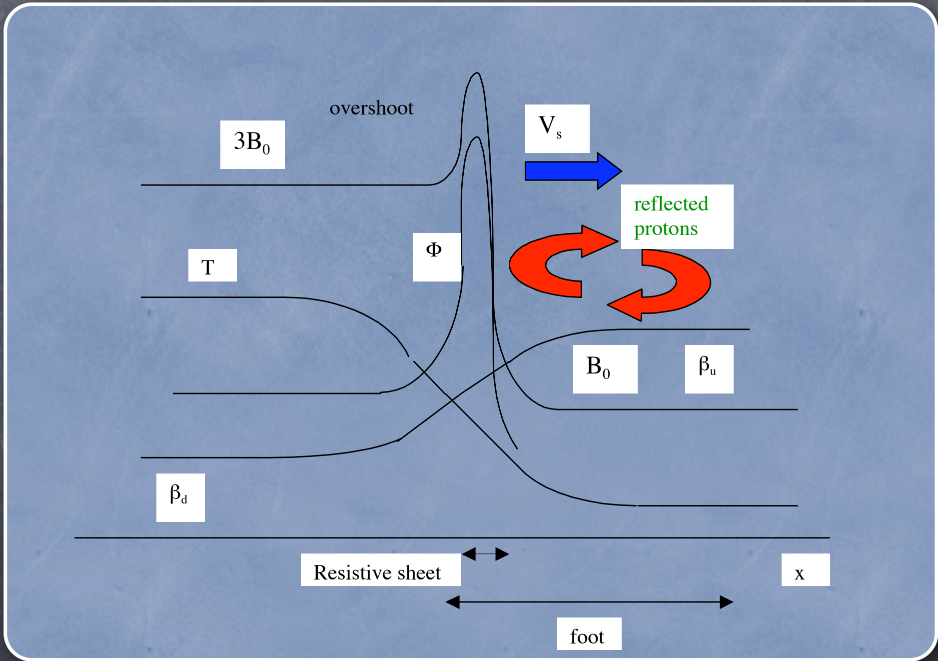
much smaller than foot length ~ r_{LF}

$$\ell_F = \frac{\Gamma_s V_s}{\omega_{ci}}$$

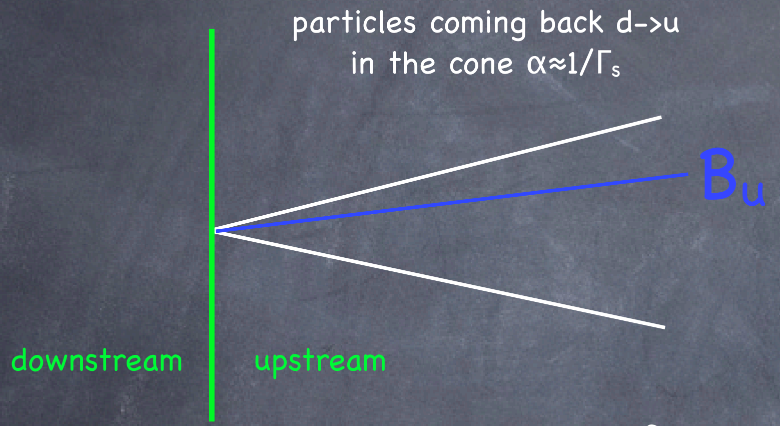
potential barrier for incoming protons

$$e\Delta\Phi \sim \Gamma_s m_p c^2$$

$T_p \sim \Gamma_s m_p c^2$, $T_e \sim T_p$?



scattering in the sub-luminal configuration



$\Gamma_s \sin\theta < 1$

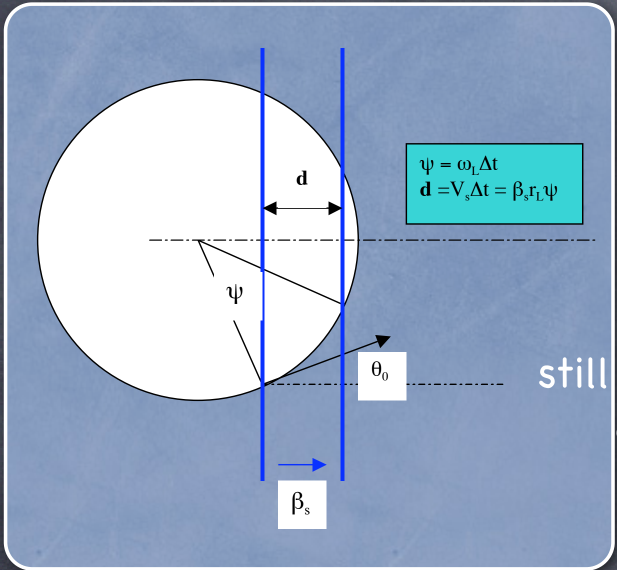
a fraction $(1-\Gamma_s \sin\theta)^2$ of incoming particles flows along the mean field with no limitation; precursor length limited by turbulent scattering

- self-generation of electro-magnetic turbulence

very anisotropic streaming generates instabilities
beam-plasma type: Weibel (non-resonant)
Oblique Two Stream (resonant)
MHD-type, return current (Bell)

PIC simulations:
A. Spitkovsky, L. Sironi
Hededal, K. Nishikawa et al.
M. Dieckmann, L. Drury et al.
Katz, Keshet, Waxmann
B. Lembège

scattering issue in superluminal case
i) in the precursor



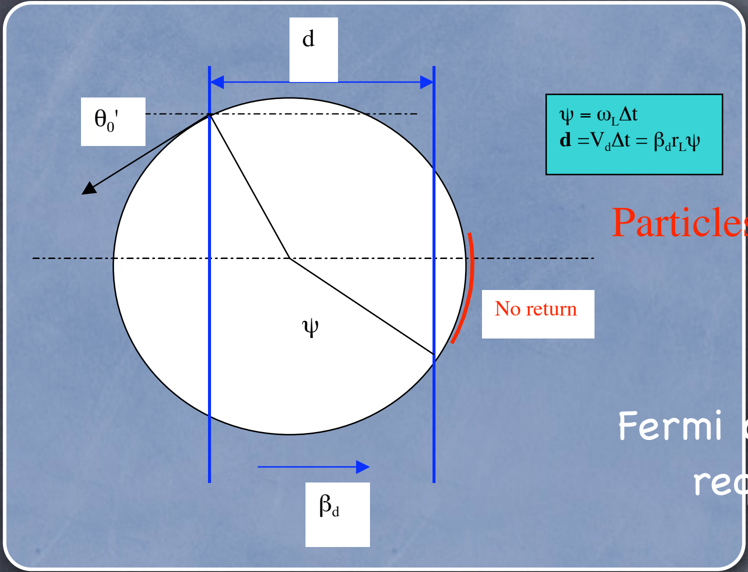
penetration length (d->u): r_{LF}
$\Rightarrow r_{Lu}(1-\beta_s)/\Gamma_s \sim r_{Lu}/\Gamma_s^3$

still an MHD scale (for $\beta_A\Gamma_s<1$), but no MHD instability can grow fast enough for first F-generations:
$l = c/\omega_{cp}\Gamma_s$, but growth rate $< \omega_{cp}$

Only micro turbulence by kinetic instabilities can be triggered and may scatter particles on that scale

However when a precursor has been developed by micro-turbulence over larger scales (r_L^2/l_c), then MHD instabilities can grow over a time shorter than the convection time

scattering issue in super-luminal case
ii) downstream



$\forall \theta_0 \in I_{no\,ret} = (\theta_*, \theta_{cr})$, no return upstream

and $I_{ud} \subset I_{no\,ret}$

Particles coming back u->d flow in the sector of « no return »

particles magnetically entrained
by the downstream flow if $t_s > t_L$

Fermi cycles possible only if $t_s < t_L$. Non-MHD condition
requiring very intense small scale fluctuations.
different scattering law.

Excitation of such micro-turbulence can be done upstream only
(strong anisotropy required) and then transfered downstream

scattering condition more easily fulfilled downstream than upstream ⇒

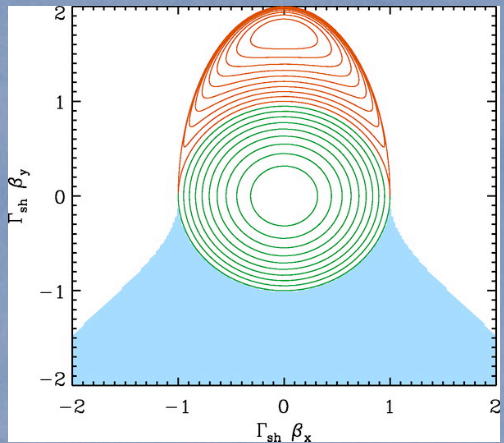
Fermi cycles of semi diffusive type-semi drift type

t_s increases faster than t_L with energy ⇒ intrinsic energy cut off

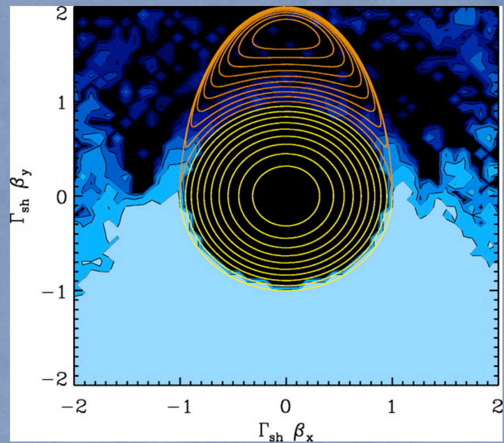
(not explained by energy loss)

scattering issue with no mean field

Maps of egress and ingress particles in 2D-velocity space



Mapping from downstream to upstream and back to upstream, as measured in the upstream rest frame.



Each contour represents a drop in return probability by a factor of 2.4.

Monte Carlo simulations, Kolmogorov turbulence, compressed downstream, full trajectory description

Lemoine, G.P., Revenu (06)

similar behavior than the superluminal mean field configuration as long as $l_c \gg r_L$

Large scale modes behave like a mean field that lock phase space

Therefore ordinary turbulence cannot make Fermi process operative.

An intense short scale turbulent spectrum,

i.e. with $\delta B/B \gg 1$ on scales $< r_{Lu}/\Gamma_s^3$

Niemiec, Pohl, Ostrowsky 06

excitation of micro-instabilities upstream in superluminal configuration

- in non-relativistic case, MTSI

- ultra-relativistic case very interesting: upstream penetration during $t_L/\Gamma_s \Rightarrow$

  almost linear beam pervading the ambient plasma

- beam particles unmagnetized !

- The nature of the instabilities depends essentially on the magnetization of the ambient particles

- non-resonnant interaction: Weibel instability

- unusual resonnant interaction with magnetic modes in a transverse field!..
  quasi Tcherenkov resonance

micro-instabilities with a mean field

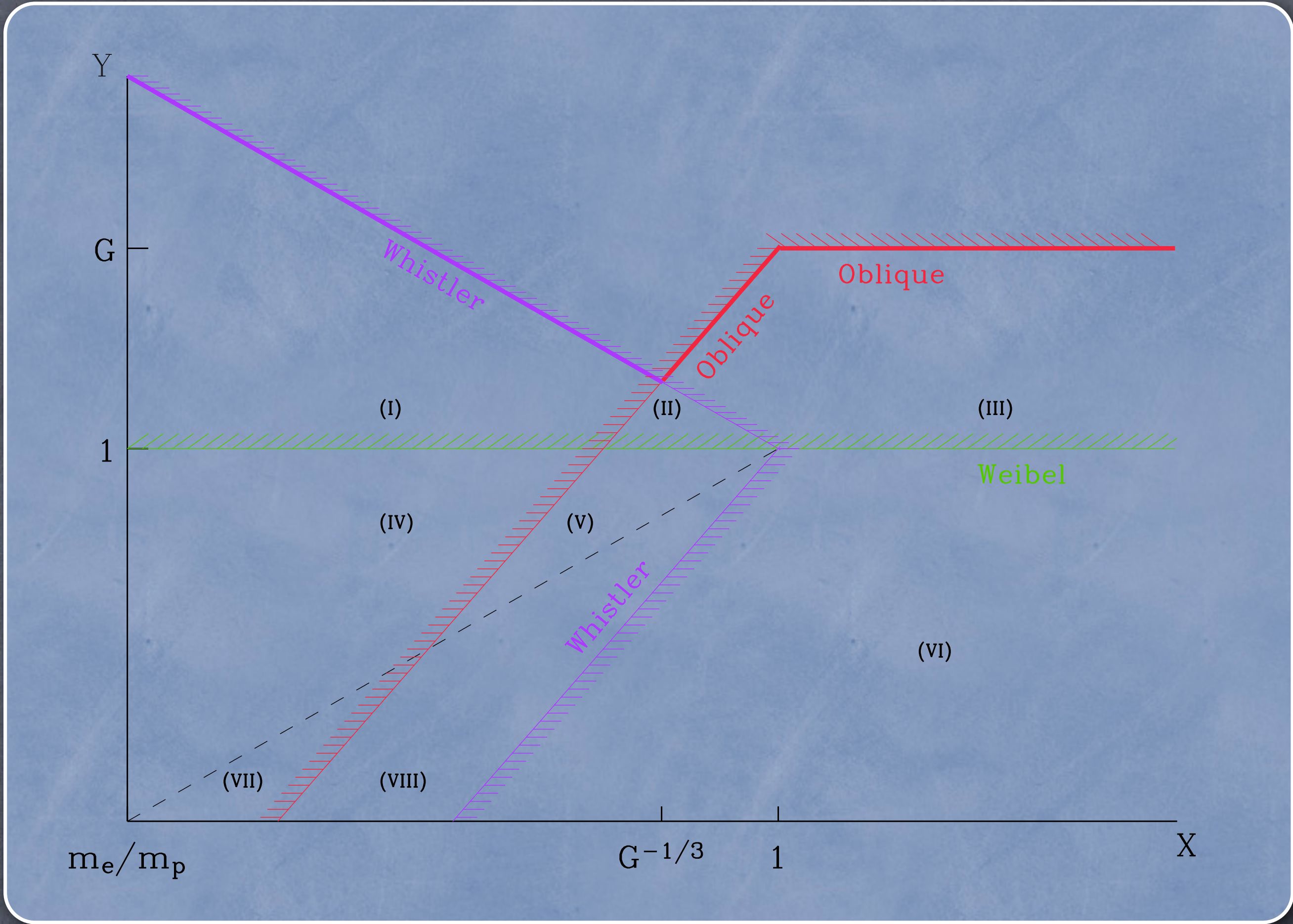
e-p plasma superluminal shock

magnetization:
$\sigma = B^2/4\pi\rho c^2$

CR-conversion factor:
$\xi_{cr} = P_{cr}/\rho\Gamma_s^2 c^2$

critical transition via whistler waves generation

when $\Gamma_s < 800$
for $\sigma < \sigma_{crit}$
$= \xi_{cr} m_p/m_e\Gamma_s^3$

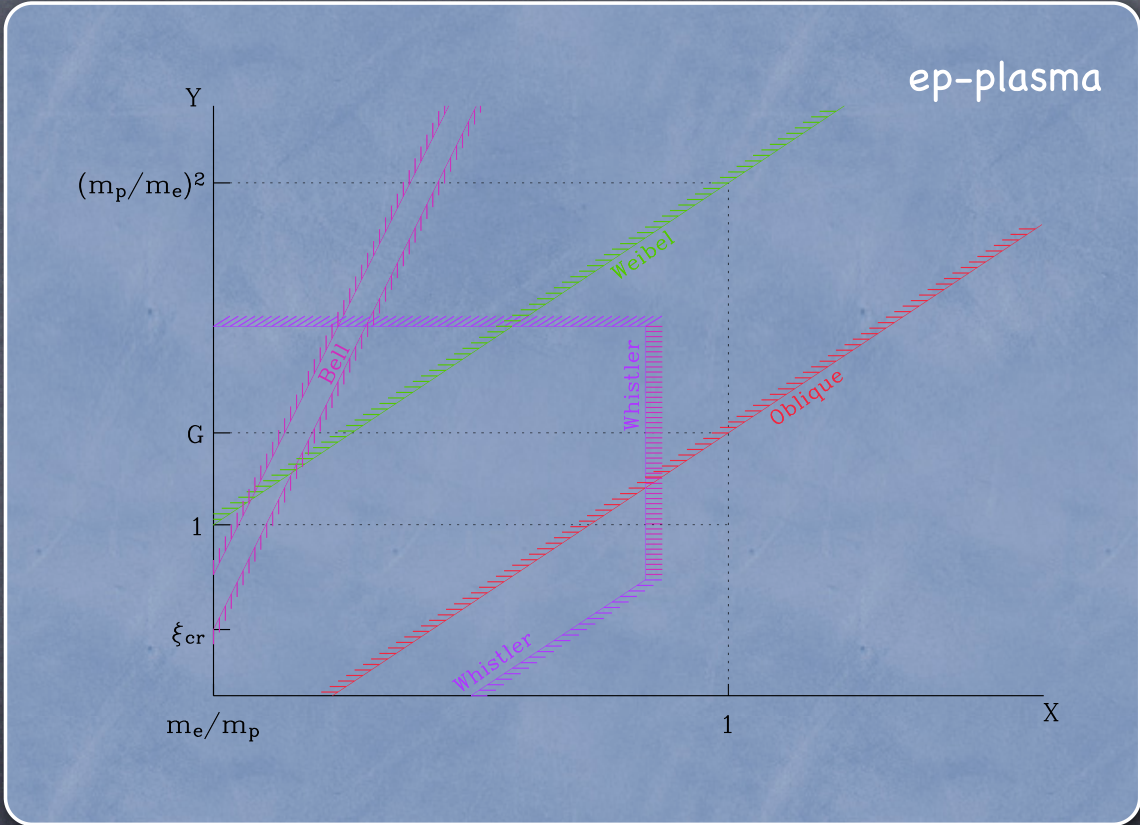


$X = \Gamma_s\ m_e/m_p$ $\quad$ $Y = \Gamma_s^2\sigma/\xi_{cr}$

(M. Lemoine & G.P. 09) (for OTSI, see A. Bret et al.)

$G = (\xi_{cr} m_e/m_p)^{-1/3} > 1$

Growth of instabilities in a quasi-parallel B



depending on Γ_s the dominant instability is
Weibel instability or resonant excitation of whistlers

The case of electron-positron plasma

- no whistler nor low hydrid modes

- Weibel instability and OTSI

OTSI is dominant in superluminal configuration,
but requires a fairly weak magnetization:
$\sigma < \sigma_{crit} = \xi_{cr}^{2/3}/\Gamma_s^2$.

OTSI is dominant in subluminal configuration
since it requires only $\sigma < \sigma_{crit} = \xi_{cr}$

whereas Weibel instability requires $\sigma < \xi_{cr}/\Gamma_s^2$
(incoming particles non-magnetized)

- Comparison with L. Sironi & A. Spitkovsky simulation:

$\sigma_{SS} = 0.1 \Rightarrow \sigma = 0.05\ \Gamma_s^2 \Rightarrow$ both OTSI and Weibel instabilities are quenched by too much magnetization. Only TSI can develope.

other secondary instabilities

- resonant interaction with extraordinary modes (hybrid) ionic and electronic

- when extended precursor, also Bell instability, compressive instability (G.P., M. Lemoine & A. Marcowith 08), and also Alfvén waves through quasi-Tcherenkov resonance

- remark: if non-linear saturation, fastest growing modes not necessarily the most important from an energetic point of view

Nature and role of the micro-instabilities

- Weibel and whistler modes (low phase velocity e.m. modes) suitable for scattering (quasi Tcherenkov resonance with whistler allows scattering for any particle e, p at all energy)

- OTSI modes mostly electrostatic, with 20% e.m. component. Produce scattering anyway, but also energy transfer at the same rate.

- Extraordinary modes are excited mostly on their electrostatic component. The long wavelength approximation of the ionic branch matches with the MHD compressive instability (G.P., M.L. & A.M.). They participate to the heating process in the "foot" region of the shock.

- Even the resonant forward modes are caught up by the shock front ($V_\varphi < V_s$), because of the frequency red-shift due to the interaction

How modes are converted downstream?

If $T_e \sim T_p \sim \Gamma_s m_p c^2$ downstream, similar to a pair plasma,
No whistler, nor hybrid modes.

Continuous conversion of upstream whistler
to downstream right Alfvén modes?

The answer is yes!

generation of right helicity

More detailed conclusions at the conference...