Fermi Acceleration at Relativistic Shocks, Generation of Electromagnetic Turbulence and Performances

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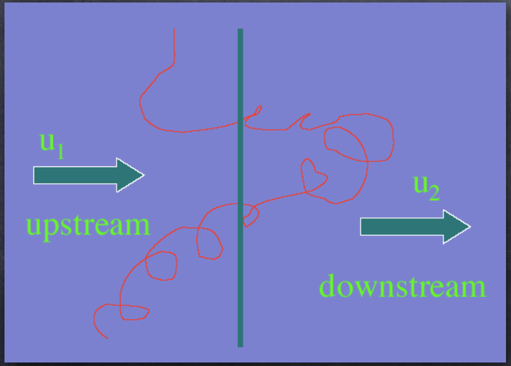
- inhibition of Fermi cycles by the mean field (superluminal regime generic for UR-shocks)
- the challenge of the generation of e.m. turbulence upstream
- a critical transition towards the onset of Fermi cycles
- performances of acceleration

see "On electromagnetic instabilities at ultra-relativistic shock waves"
in astro-ph (arXiv0904.2657v2) to appear in MNRAS

Relativistic Fermi process with no mean field

(Achterberg & Gallant, Kirk et al., Ostrowski & Bednarz, Ellison & Double, Lemoine & Pelletier)

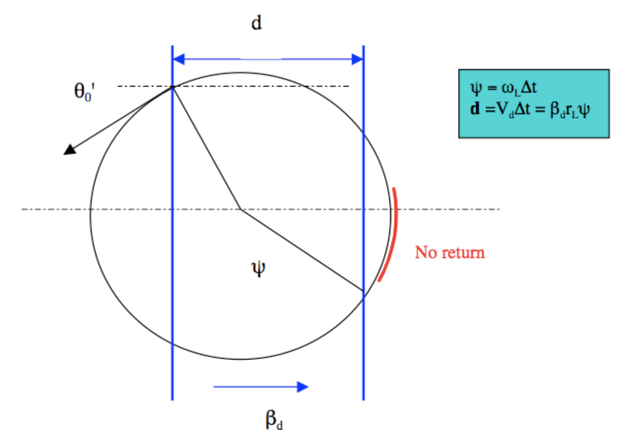
- shock forms with microinstabilities (OTSI, Weibel); front motion characterized by $\Gamma_s \gg 1$. Width of a few tens of inertial length c/ω_p
  (Moiseev & Sagdeev 65, Medvedev & Loeb 99, Spitkovsky 08...)
- growth of instabilities, turbulent scattering and Fermi cycles granted



- after the first Fermi cycle (gain of Γ_s^2), gain by a factor 2, sizable proba for return
- power law spectrum with universal index s=2.2
- short acceleration time scale.

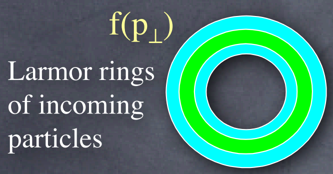
inhibition of F-cycles by the mean field

(Niemiec, Pohl, Ostrowski 06, Lemoine, Pelletier, Revenu 06)



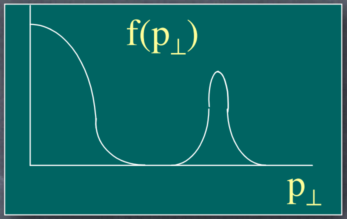
- most relativistic shocks are "superluminal": particles don't move along the field lines ($\sin \theta_B > 1/\Gamma_s$)
- particles undergo at most one and half cycles ⇒ energy gain Γ_s^2
- the same with a turbulent field with large coherence length (Kolmogorov)
- penetration time upstream: t_L/Γ_s ⇒ maximum penetration length/shock r_L/Γ_s^3 (measured in upstream restframe)
- only intense turbulence at scales shorter than r_L/Γ_s^3 can produce scattering of supra-thermal particles for further Fermi cycles

Synchrotron maser instability in superluminal field



$G=0.1\ (\Gamma/\delta\Gamma)\sigma_e^{1/4}$

(Y. Lyubarsky 06)



- For σ not too small, particle ring ⇒

  inverted population
  ⇒ synchrotron maser

- governs shock formation (for e^+e^- Gallant & al 92)
  downstream thermalization through synchrotron absorption

- In e^+e^-p-plasma development of a power law tail (Hoshino & Arons 91)

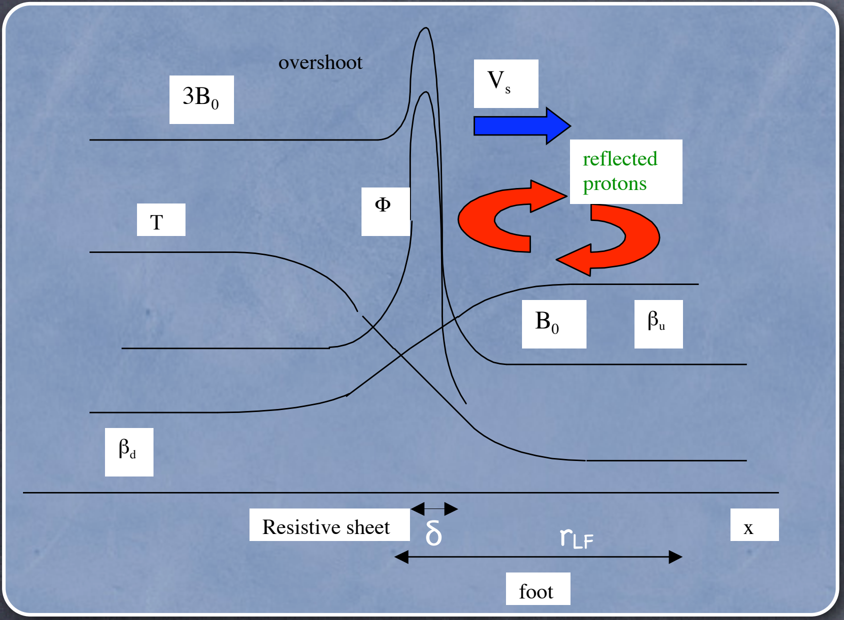
- in ep-plasma and e^+e^-p-plasma SMI developes and generates intense wake field also ⇒

  thermalization of electron and protons when electrons enter in relativistic regime of oscillation (Y. Lyubarsky 06)

- Generation of suprathermal particles by the wake field expected (M. Hoshino 08)
  but not possible in e^+e^- plasma
- at low enough σ SMI quenched and overseded by growth of microturbulence ⇒ scattering and thermalization

  in e^+e^- plasma, it occurs at $\sigma < 10^{-3}$ (Amato, Arons, Spitkovsky ?)

superluminal relativistic shock at low but finite magnetization



- reflection on magnetic barrier for e^+e^- plasma

- reflection on potential barrier for ep plasma
  $T_p \sim \Gamma_s m_p c^2 \quad T_e \sim \Delta U$
  foot (r_{LF}), ramp, overshoot
  short transition layer δ

- upstream reflected particles trigger micro-instabilities in the ion “foot”

- increment over r_L/Γ_s^3 (in proper upstream frame) larger than 1 for low enough magnetization → ...

micro-instabilities with a mean field

against short penetration upstream

e-p plasma
superluminal shock

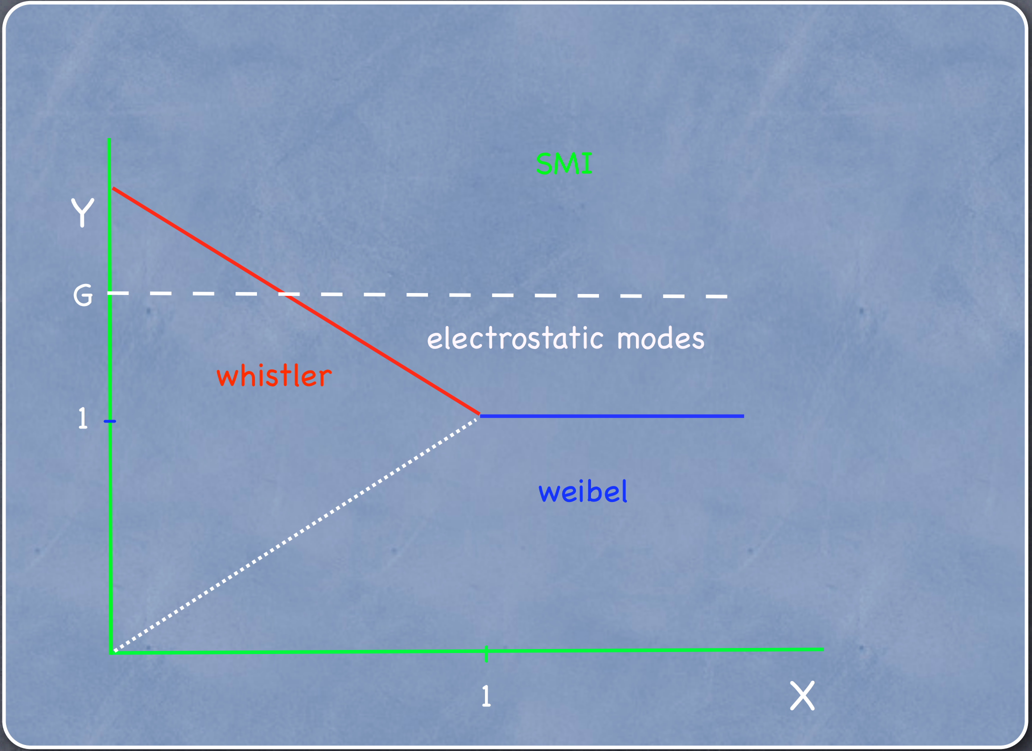
magnetization:
$\sigma = B^2/4\pi\rho c^2$

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

- critical transition
via whistler waves
generation

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

OK with M. Dieckmann et al. 08
L. Sironi & A. Spitkovsky?



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

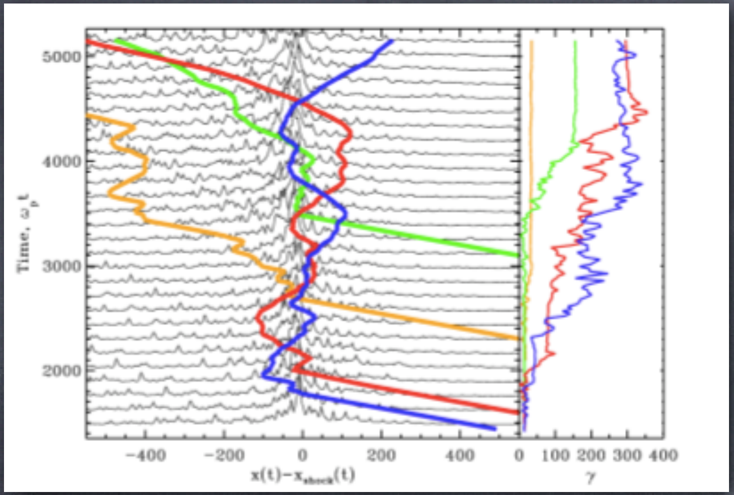
$G = (\xi_{cr} m_e/m_p)^{-1/3} \sim 20$

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

- threshold: $\sigma_{Weibel} = \xi_{cr}/\Gamma_s{}^2$
- Thermal effects...

G. Pelletier. workshop on particle acceleration in AGNs. Meudon 2010

e^+–e^- plasma



(no whistler waves)

A. Spitkovsky 2008 (unmagnetized)

Fermi process ab initio together with
generation of micro-turbulence
Weibel instability, filaments

- $\Gamma_s \approx 20$, $\xi_{cr} \approx 10^{-1}$, $\xi_{e.m.} \approx 10^{-2}$
spectrum index $s \approx 2.4$

- with a mean field (M. Lemoine & G.P. 09) critical transition through the excitation of oblique two stream instability : $\sigma < \sigma_{crit} = \xi_{cr}^{2/3}/\Gamma_s^2$

(quasi Tcherenkov resonant interaction)

- Weibel instability excited for $\sigma < \xi_{cr}/\Gamma_s^2$

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

scattering and Fermi cycles

- once e.m. turbulence excited upstream for $\sigma<\sigma_{crit}$, waves are transmitted downstream where scattering can take place. (However conversion of modes still to be analyzed).

- condition for breaking mean field inhibition downstream:
  ($\tau_s < \tau_L$) $\sigma < \sigma^* = \chi \xi_{e.m.}^2$ (coherence length $l_c = \chi c/\omega_p$)

  where the e.m. conversion factor $\xi_{e.m.} = U_{e.m.}/\rho\Gamma_s^2c^2$

- However turbulent scattering still difficult upstream; regular deflection by mean or large scale field. So When FP works, hybrid regime: DSA downstream, drift upstream

- maximum energy achieved ($\tau_s \propto \varepsilon^2$): $\varepsilon_{max}=\Gamma_s m_p c^2(\sigma^*/\sigma)^{1/2}$

- sufficient condition for working : $\sigma< \sigma_{crit} < \sigma^*$ so that $\xi_{e.m.} > (2\sigma_{crit}/\chi)^{1/2}$ (weak turbulence sufficient)

for which cosmic events?

even weak the mean field is constraining!

- Blazar jets? magnetization too strong (alternatives: 2nd order Fermi acceleration, shear Fermi acceleration, reconnections)
- hot spots of FR2 jets? magnetization too strong. But relativistic shocks? mildly or sub-relativistic OK.
- pulsar wind terminal shock? magnetization too strong (alternative: pair wind carrying baryons, leads to power law spectrum not through Fermi process (Hoshino & Arons 91) or wake field associated with Synchrotron Maser Instability? (Hoshino 09)). But also there is a region of weak field.
- terminal shock of Gamma Ray Bursts? Yes! $\sigma_{ism} \sim 10^{-9}$, $\sigma_{crit} \sim 10^{-6}$
- maximum energy measured in obs frame: $\varepsilon_{max} = \Gamma_s^2 m_p c^2 (\sigma_{crit}/\sigma)^{1/2}$
  OK for the electrons and jitter radiation (Medvedev 00, Kirk & Reville 09).
- But UHECRs? Still opened

criterium for accelerator candidate completely reconsidered

- Hillas criterium ($\varepsilon_{max} = \Gamma ZeBR$) not appropriate
- because based on Larmor resonance with largest scale MHD modes. Direct cascade of MHD turbulence and Larmor resonance relation $r_L(\varepsilon) \sim \lambda \leq l_c \sim R$ ruled out for Fermi acceleration at relativistic shocks.
- With relativistic shocks, when Fermi process operative, it works with sub-Larmor turbulence; and $\varepsilon_{max} \propto B^{-1} \Gamma_s^{-1/2}$

main issues for PIC simulations

(Spitkovsky & Sironi, Nishikawa, Hededal, Hoshino, Dieckmann, Katz, Keshet, Waxmann, Nordlung, Lembège, etc.)

- identification of the instabilities and their role in the shock structure. Importance of whistler (identified in Dieckmann et al. 08) versus Weibel waves. Role of fast q-electrostostatic modes?
- Characterizing the reflection process; importance of the electrostatic barrier in a proton-electron plasma
- effective coherence length as a function of particle energy (Keshet et al. 09, Medvedev & Zakutnyaya 09) : $l_c = \chi(\varepsilon)c/\omega_p$
- turbulence level, spectrum, relevant NL effects
- checking the law of critical magnetization and relevant instabilities at the transition