Particle Acceleration: Relativistic Shocks

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Understanding Relativistic Jets,
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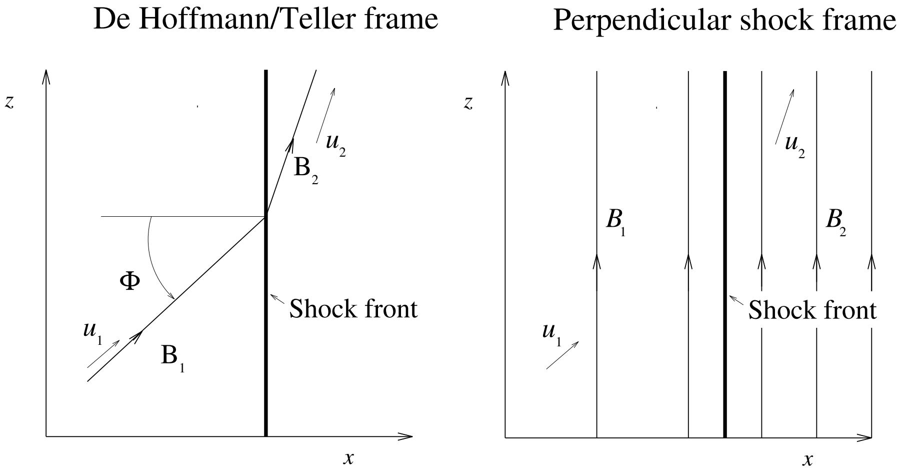
Outline

Basic properties of relativistic shocks

- Equation of state softens as particles become relativistic
- Relativistic electrons + nonrelativistic ions: increased compression
- All components relativistic: compression $\to 3$
- But if Poynting flux significant: less compression

Sub- and superluminal shocks



Frame-independent classification via speed of intersection point of B and shock: $v_{\rm inter} < c$ subluminal, $v_{\rm inter} > c$ superluminal

MHD + test particles

Assumptions:

- Particles *scattered* by *magnetic fluctuations* embedded in local fluid
  - No energization away from shock front $v_{\mathrm{A}} \ll v_{\mathrm{shock}}$
  - Spatial diffusion if particle speed $\gg v_{\mathrm{shock}}$
  - Otherwise scattering in pitch-angle, or just random deflections
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Kinematic gain in energy measured in local fluid frame at each shock crossing

Finite escape probability downstream

MHD+ test particles

If particles tied to field lines, then

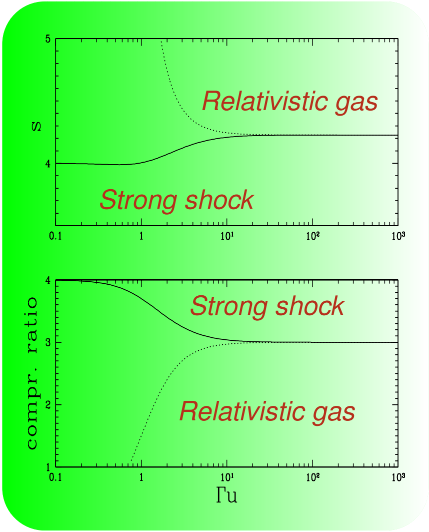
- only *subluminal* shocks can accelerate by the 1st order Fermi process
- oblique shocks $\rightarrow$ provide particles with a higher effective compression

Small length-scale magnetic fluctuations
needed at superluminal shocks

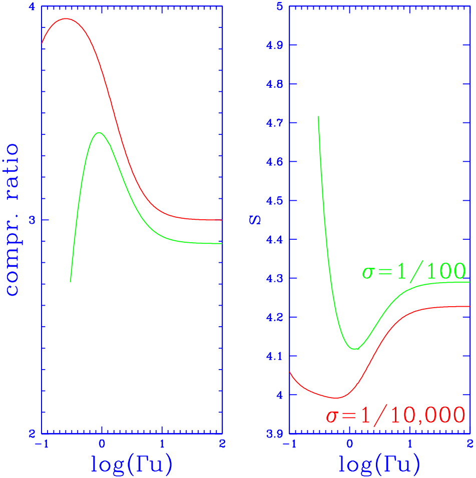
Eigenfunction expansion
$\Rightarrow$ angular dependence:

$$\frac{\exp\left(-\frac{1+\mu_s}{1-\mu_s u/c}\right)}{(1-\mu_s u/c)^s}$$

As $\Gamma \to \infty$, $s \to 4.23$
Universal index?



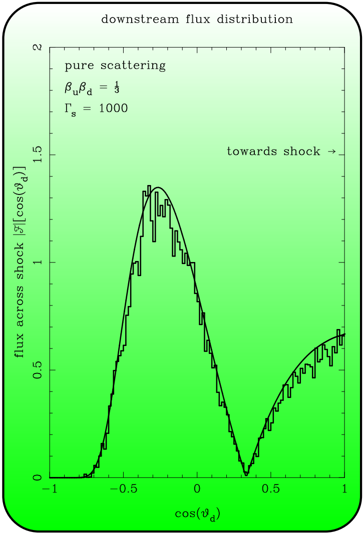
Effect of finite σ



Monte-Carlo

Comparison of MC/analytic angular distributions

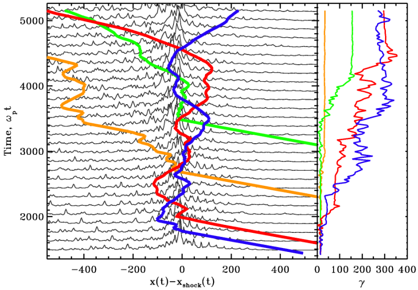
Achterberg et al
MNRAS 328, 393 (2001)



2D PIC simulations, pair plasma

Spitkovsky (2008)
Martins et al (2009)

- Unmagnetized e^+e^- plasma
- Bulk $\Gamma \approx 30$
- Field generated by Weibel instability
- *Ab initio* demonstration of 1st order Fermi process at a shock front?

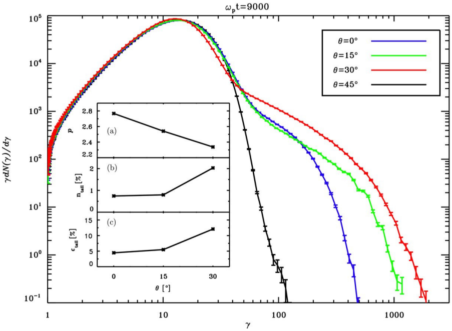


- 1% of particles in power-law tail
- Cut off at $\sim 100\times$ peak, growing in time
- $\mathrm{d}\ln N/\mathrm{d}\ln\gamma = -2.4 \pm 0.1$

Oblique shocks

Sironi & Spitkovsky (2009)

- Magnetized e^+e^- plasma
- Shock generated by magnetic reflection
- Qualitative agreement with test-particle picture



Summary MHD+ picture

- Encouraging qualitative agreement with PIC simulations
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- Spectra softer than $E^{-2} \rightarrow$ MHD++ maybe not so interesting for relativistic shocks

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BUT

Strong suspicion that at relativistic shocks magnetic field is either generated (in GRB's) or annihilated (in pulsar wind termination shocks)

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- *Collisionless* MHD requires assumptions about the particle stress-energy tensor (e.g., cold plasma)
- Turbulent resistivity? Hall MHD? Gyro-kinetic?
- Also based on expansions in the small parameters:

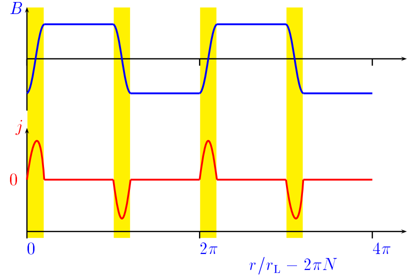
  Larmor radius/wavelength
  wave frequency/gyro frequency
  wave frequency/plasma frequency

Options

What is missing for *relativistic* shocks?

- As sheets pass through an MHD shock, B reverses

The pulsar striped wind



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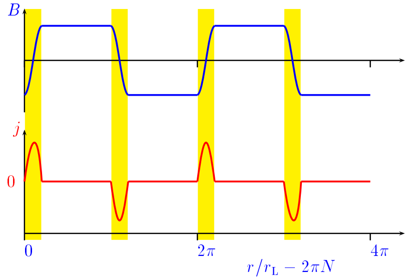

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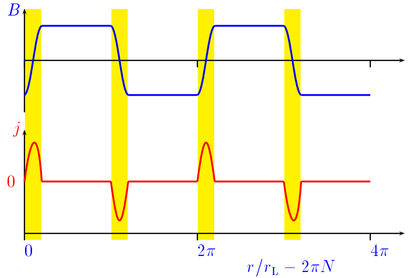

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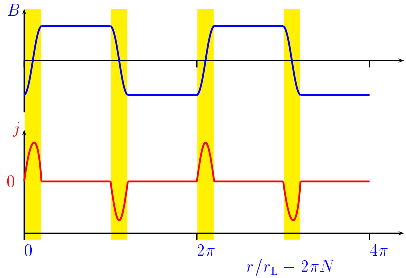

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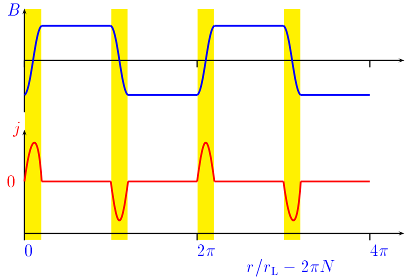

Electromagnetic modes important for relativistic, Poynting-flux dominated flows

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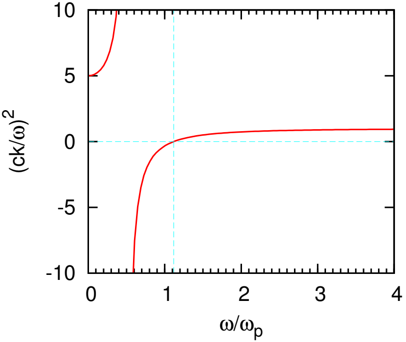
- Numerical implementation possible (Koide et al 2010) but collision terms introduce subtleties
- Strong waves in cold fluids tractable analytically (1970's: Dawson, Clemmow, Max, Perkins, Kennel, Pellat, Asseo. . .)

Dispersion relations

- Linear dispersion relation
  - cold $e^{\pm}$ plasma
  - perpendicular propagation
  - linear polarisation, X-mode



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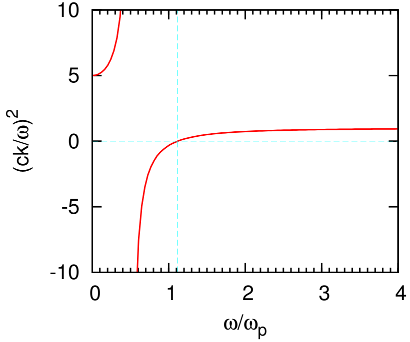

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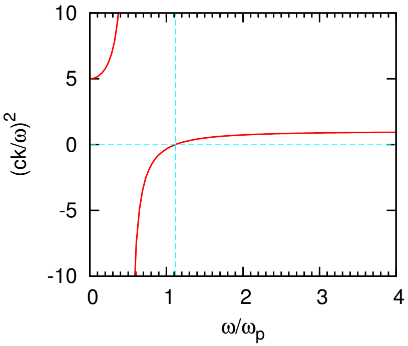
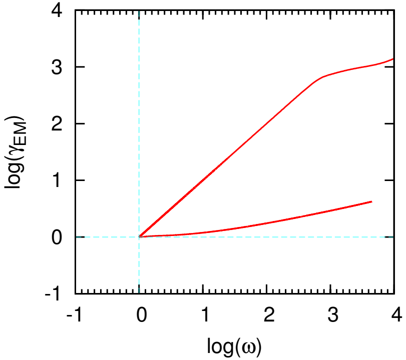
- Wave properties depend on amplitude



Dispersion relations

- Fixed energy flux per particle (μ parameter)
- Fixed momentum flux per particle ($\equiv$ fixed σ in MHD)



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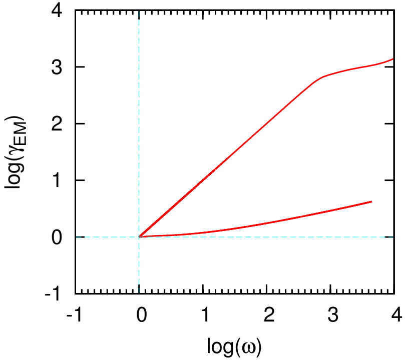

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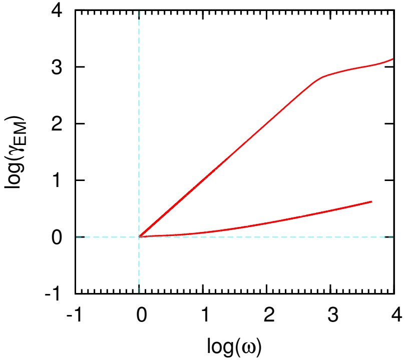
- Strong waves in equipartition: thermalization $\rightarrow$ particle acceleration



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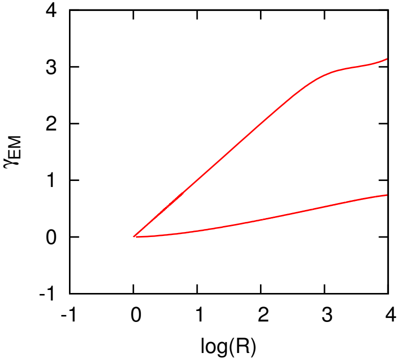

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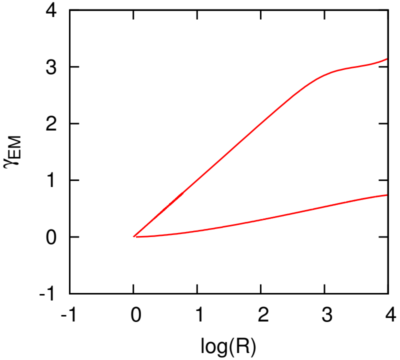

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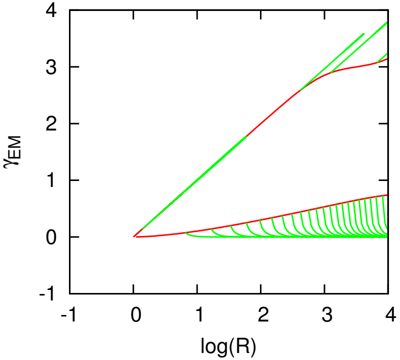

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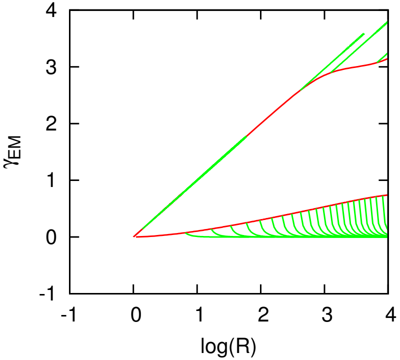

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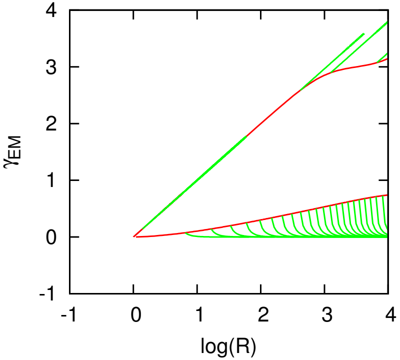
- Instabilities...



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- Return of 1st order Fermi for high energy particles?