Particle acceleration in relativistic flows

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Outlines

- Introduction: astrophysical context.
- Acceleration processes: shocks: theory and simulations (also shear and reconnection).
- Astrophysical implications: Origin of ultra high energy Cosmic Rays, radiation from relativistic sources
- Perspectives & Conclusions.

Some recent reviews:

Specific to relativistic flows

[1] Bykov A & Treumann R A 2011 Astronomy & Astrophysics Review, 19, 42

[2] Bykov A. et al 2012 Space Science Review 173 309

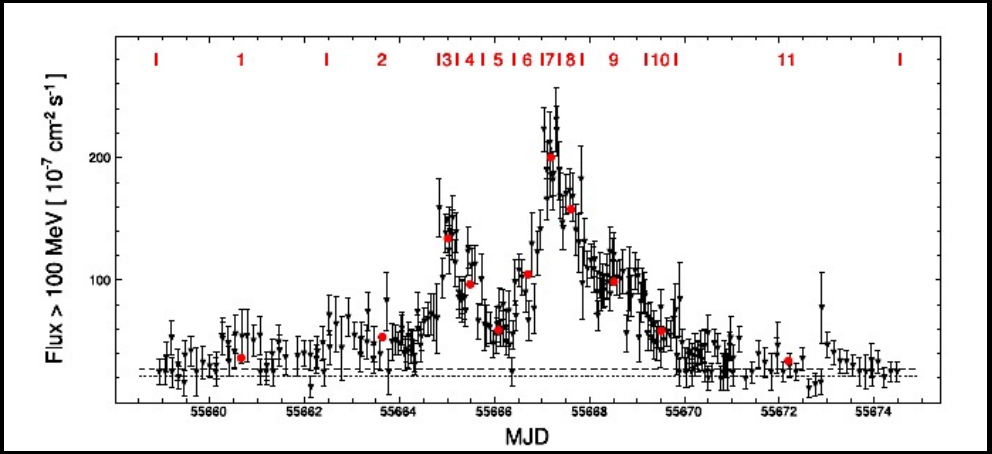
[3] Sironi L, Keshet U , Lemoine M 2015 Space Science Review 191 519

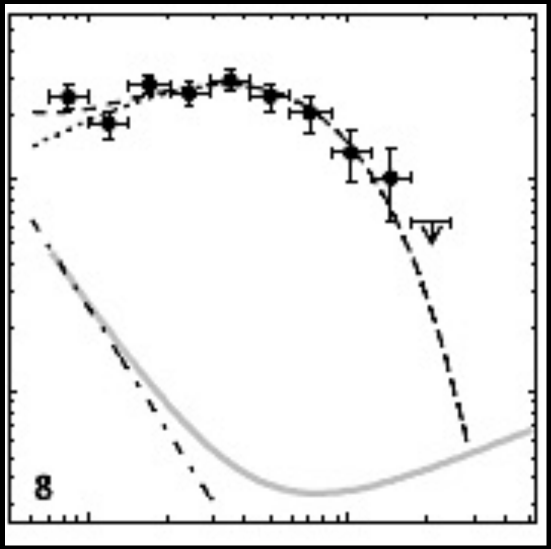
Non relativistic (magnetospherical and astrophysical) and relativistic flows + laser experiments

[4] Marcowith A et al Reports on Progress in Physics, to be published 2016

Astrophysical context: Gamma-rays

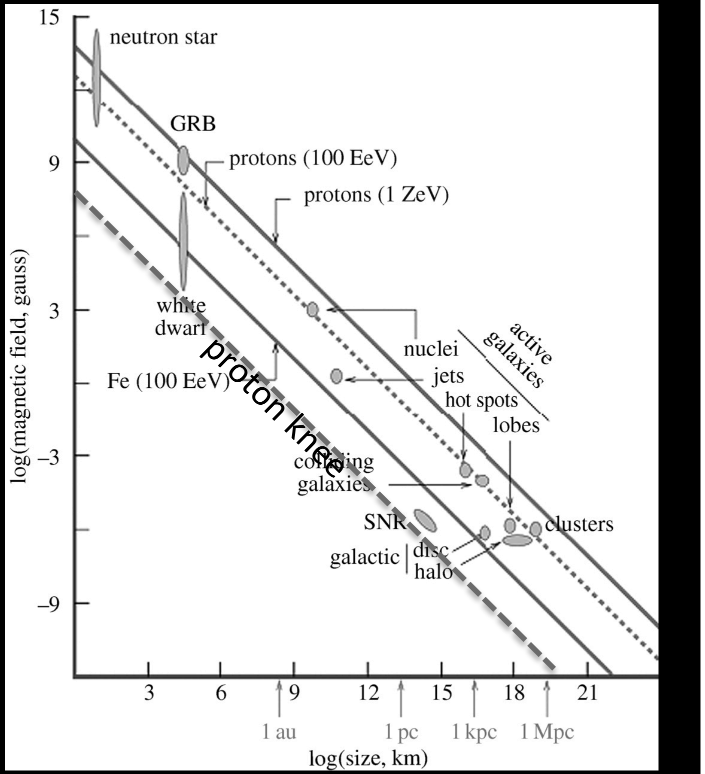
- High-energy processes from relativistic sources:
  - Gamma-ray bursts: Fermi legacy (Piron'15)
  - Active galactic nuclei: GeV and TeV day or less timescale variations (eg PKS 2155-304, T~2 min) (Abramowski+10)
  - Pulsars wind nebulae: the case of intra-day gamma-ray flares of the Crab nebula, $E_{max,ph}$ ~ GeV (Abdo+11, Tavani+11, Buehler & Blandford'15)





Astrophysical context: cosmic Rays

- Origin of ultra-high energy cosmic rays in the range PeV-EeV-ZeV … probing the cosmic accelerators (D.Allard this meeting)
    - Ice Cube PeV neutrinos (an extragalctic origin ?) (Aartsen+14, Kadler +16)
    - Kascade Grande: where the galactic component does end ? (Apel+13)
    - AUGER measurements (CR composition light->heavy beyond 10 EeV, anisotropy, GZK/source cut-off ?) (Aab+15, Lemoine'13, Parizot'14)



Requirements from observations

The challenge is to provide …

- Mechanisms able to produce power-laws.
- Particle acceleration up to or beyond 10^{20}eV (so 5-6 order of magnitude above the LHC).
- Mechanisms able to reproduce variability.
- A way to generate magnetic field turbulence.

From years 1949-1954 the interplay of electric (for energy gain) and magnetic (for scattering) perturbations is known to accelerate particles and to produce power-laws: Fermi mechanisms.

Main results for non-relativistic shocks

see: Bell'78a'78b, Drury'83, Kirk'94

- High Mach shocks $V_{sh}/(c_s,V_a)>1$ produce a compression with a factor r=4
- Fermi acceleration includes:
  - Injection: Particle are injected with energies > Thermal heated gas.
  - Acceleration: Particles get accelerated by repeated shock crossing.
  - ➢ Relative energy gain at each cycle (eg up-down-upstream) :
    $\Delta E/E \sim (V_{sh}/c)\,(r-1)/r$
  - ➢ Probability to escape downstream at each cycle:
    $P \sim V_{sh}/rc$

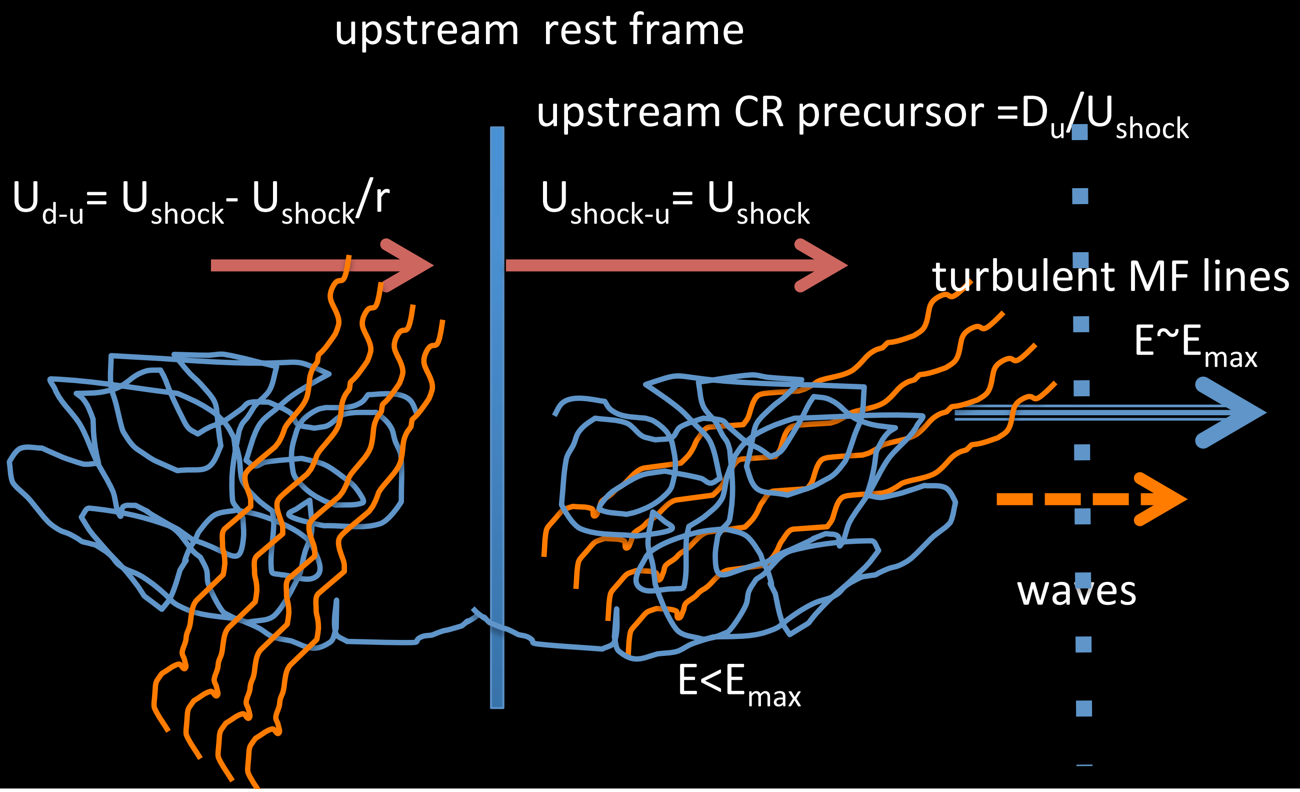
Both do not explicitly depend on the particle energy => shock distribution is a power-law $-d\log(N)/d\log(E) = s_E$

$s_E = (r+2)/(r-1) = 2$ (strong shocks r=4).

or in term of momentum distribution $s_p = s_E + 2 = 3\,\beta_u/(\beta_d - \beta_u)$

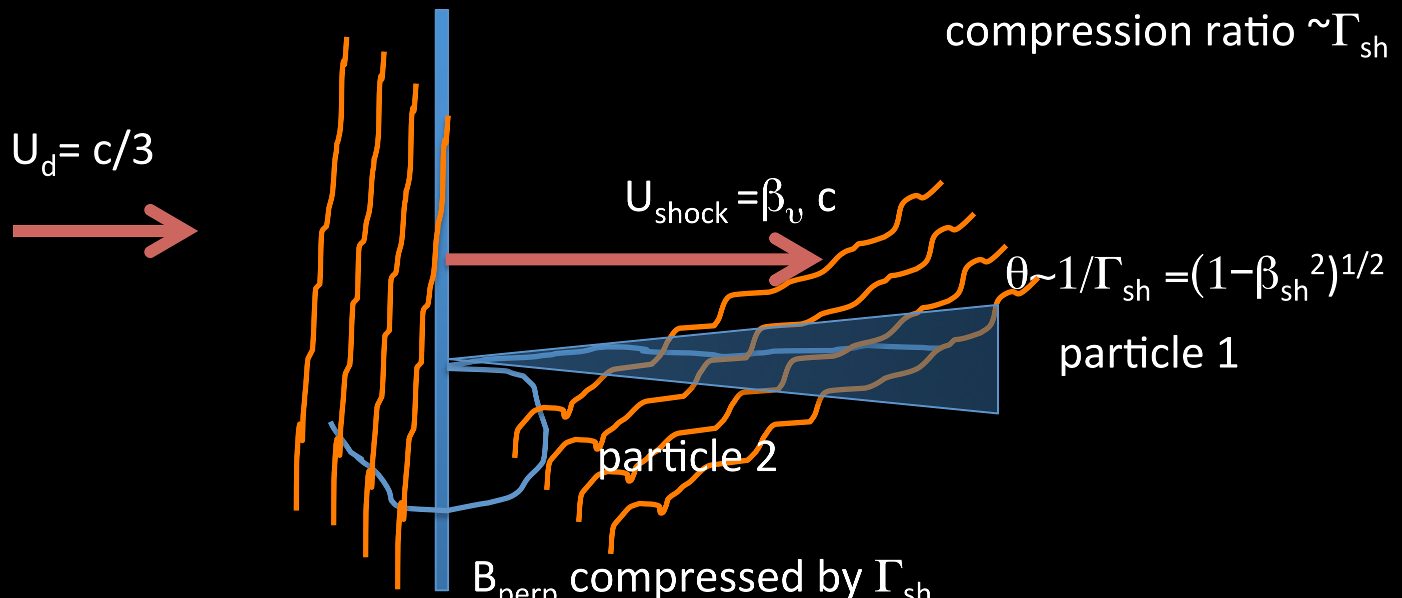
Diffusive shock acceleration

- Particles can reach high energies with repeated high number $N=(E/\Delta E)$ shock crossings.
- Random walks due to scattering on self-generated turbulence: the particles create the perturbations needed for the shock acceleration process to work.
- Streaming instabilities are preferred (Lucek & Bell'01, Bell'04 ….)



Fermi acceleration at relativistic shocks: partly diffusive acceleration.

- Shock supersonic, super-Alfvénic but with U_{sh}~c
- Inject energetic particles from thermal pool or re-accelerated.
- Upstream particles can not have a random walk in space <u>outside</u> a cone of size $1/\Gamma_{sh}$.



upstream rest-frame

compression ratio $\sim\Gamma_{sh}$

U_d= c/3

$U_{shock} = \beta_\upsilon$ c

$\theta \sim 1/\Gamma_{sh} = (1-\beta_{sh}^2)^{1/2}$

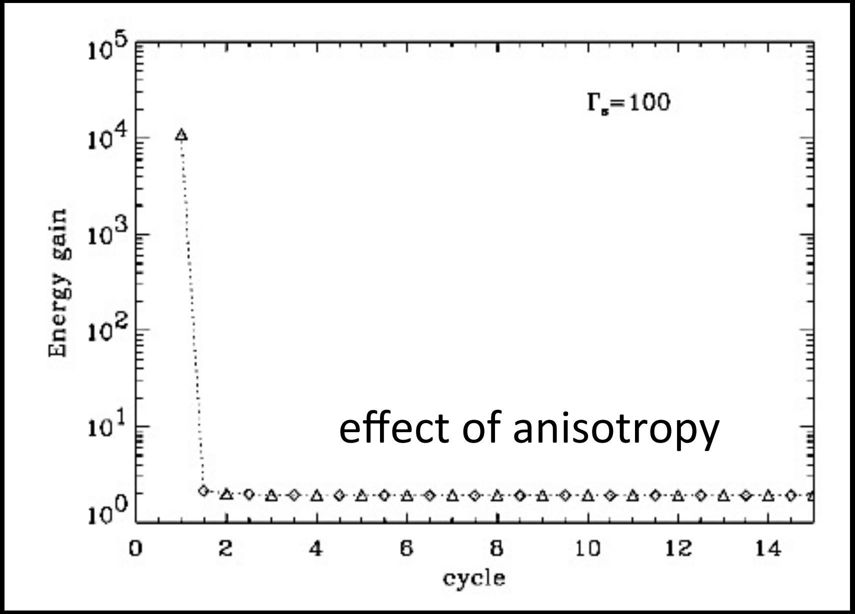
particle 1

particle 2

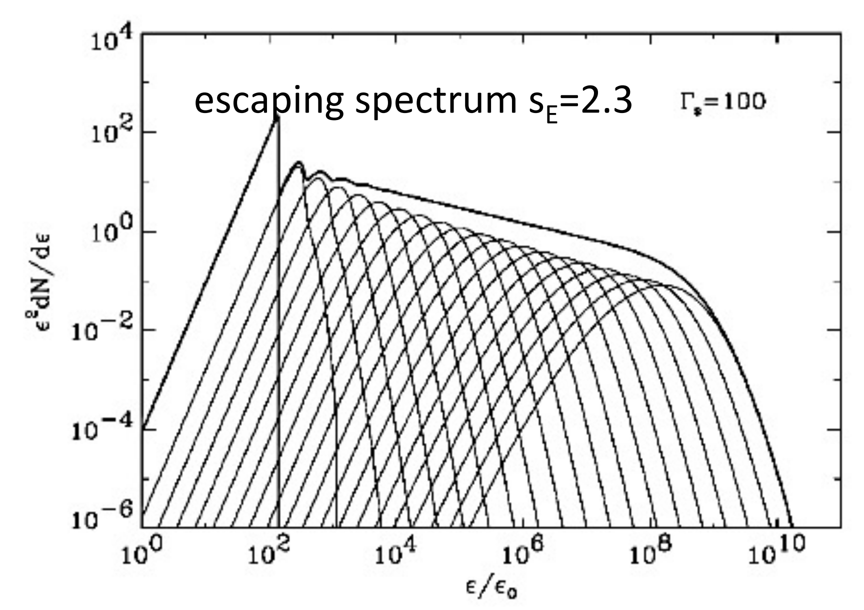
B_{perp} compressed by Γ_{sh}

Fermi cycles in relativistic shocks

- If we start from an isotropic particle distribution upstream the first u-d-u cycle leads to an energy gain $\Gamma_{sh}{}^2$
- but hence due to anisotropy effect (previous slide)=> gain factor 2 only for further cycles.
- But one must now include magnetic field effects correctly (only isotropic diffusion in space assumed here).



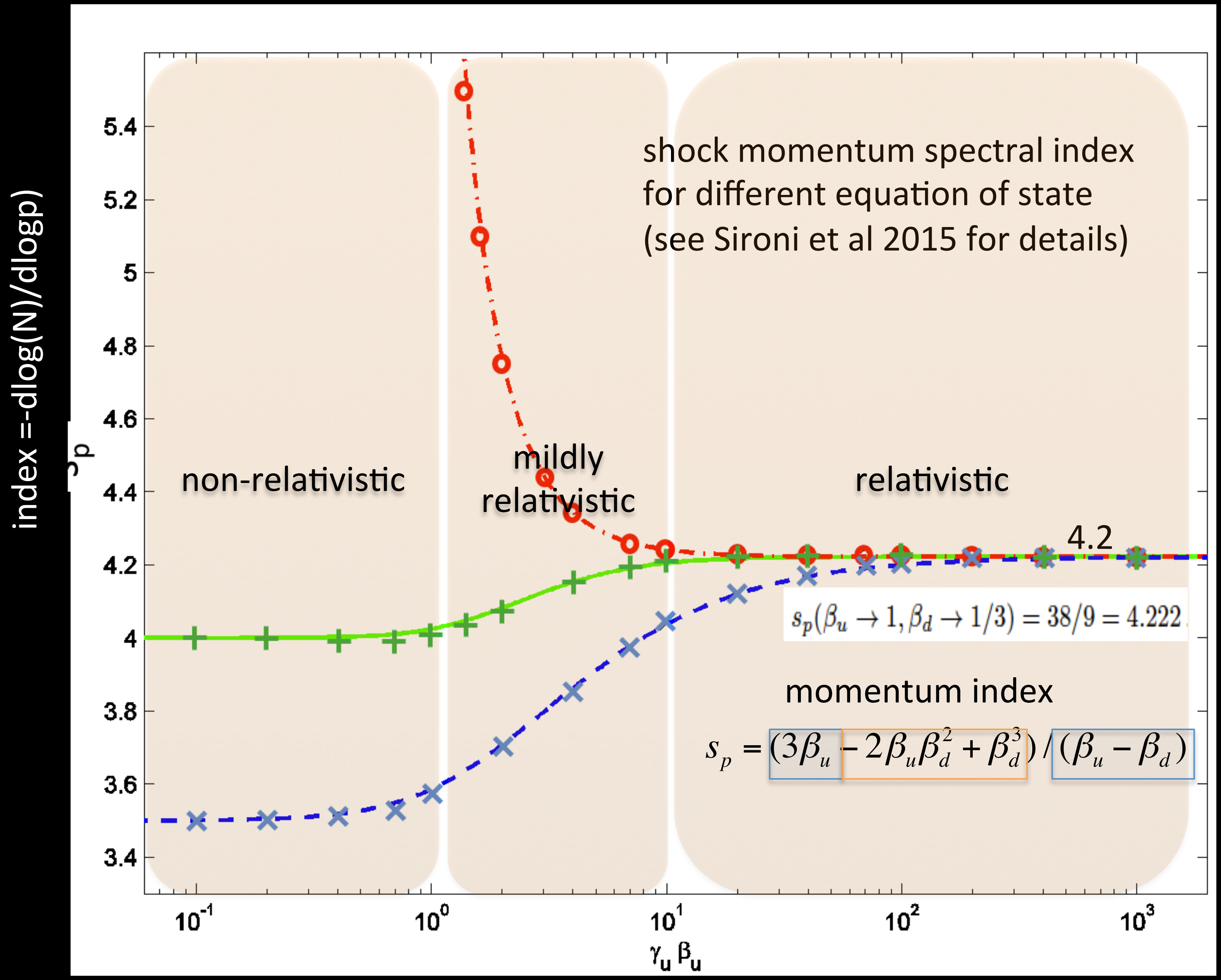
effect of anisotropy



escaping spectrum s_E=2.3

Lemoine & Pelletier'03

Main result: If turbulence is isotropic downstream s_p=4.2



shock momentum spectral index for different equation of state (see Sironi et al 2015 for details)

$$s_p(\beta_u \to 1, \beta_d \to 1/3) = 38/9 = 4.222$$

momentum index

$$s_p = (3\beta_u - 2\beta_u\beta_d^2 + \beta_d^3)/(\beta_u - \beta_d)$$

Non-relativistic
Relativistic

An important parameter: upstream magnetization

- Definition: (shock-rest frame)

$$\sigma = \frac{B_0^2}{4\pi\gamma_u(\gamma_u - 1)n_* mc^2} = \left(\frac{u_a}{c}\right)^2$$

$$\varepsilon_B = \frac{\delta B^2}{B_0^2}\sigma$$

B_0 large scale MF.

γ_u shock Lorentz factor as seen in the upstream rest frame.

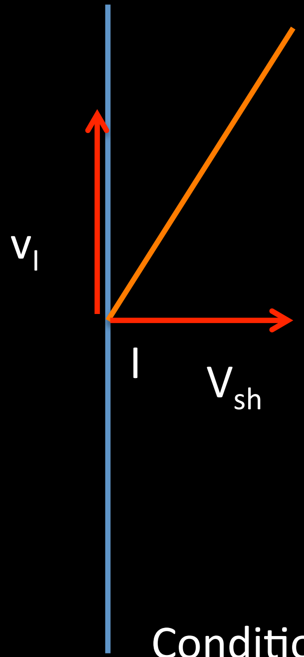
- If σ is high ($>10^{-2}$) shock= compression of background magnetic field.

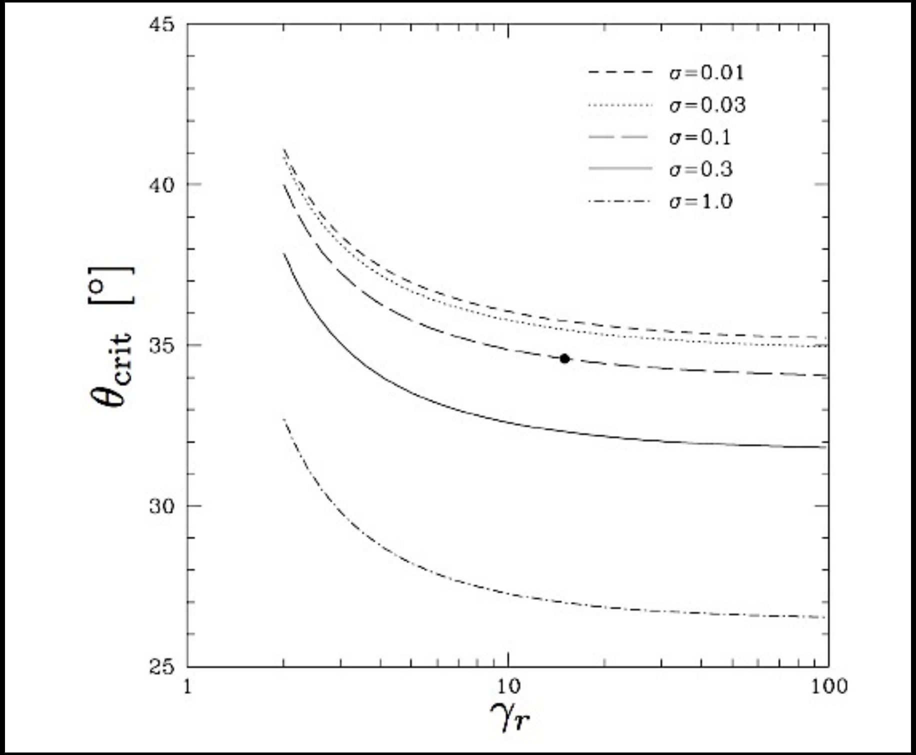
- If σ is low ($<10^{-3}$) shock= mediated by magnetic field produced by microscopic turbulence.

Sub-/Super-luminal shock

- Velocity of I= point of intersection of MF lines with the shock front

Subluminal $V_I<c$
Superluminal $V_I>c$



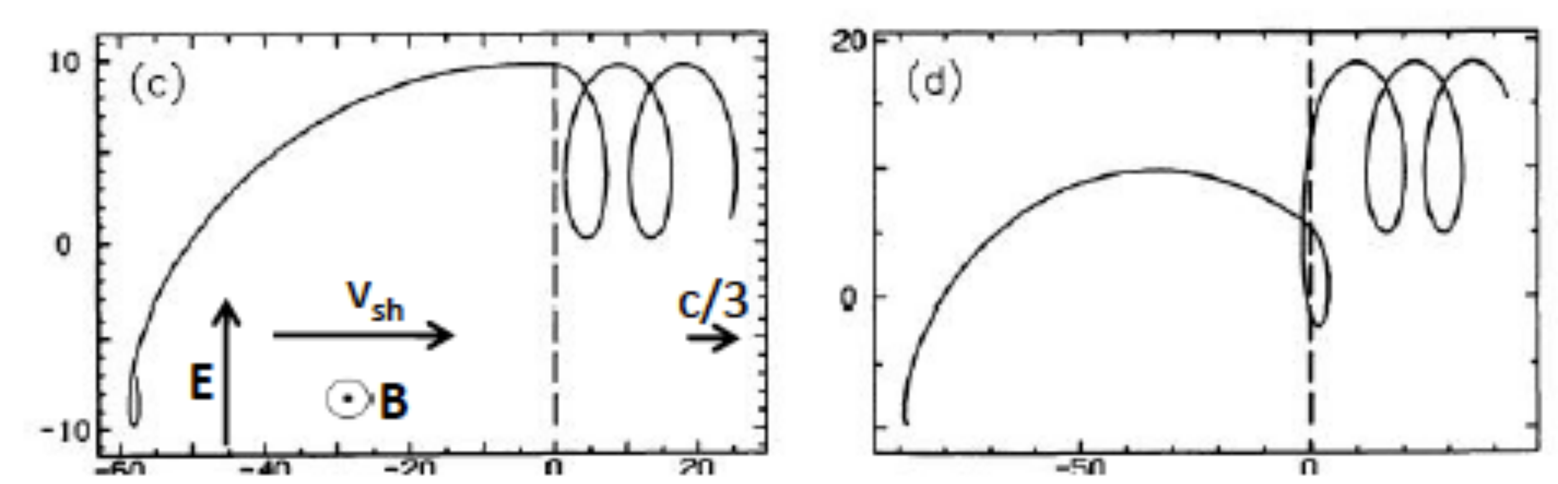


Condition for particles to escape upstream by sliding along the front Sironi & Spitkovsky’09

Fermi cycles in relativistic shocks

But the magnetic field in the shock rest-frame is perpendicular and superluminal => escape downstream 3/2 cycle at max.

Begelman & Kirk’90



One problem: In the shock restframe B_t is compressed by Γ_{sh}, B_l is unchanged => superluminal relativistic shocks are generic.

* So we need some turbulence => Several issues:

- ➢ What is the nature of the upstream turbulence?
- As regular MF are superluminal hence add turbulence ? Strong impact of upstream magnetization … If σ is high and $L_{coh} > r_L$ conclusion remains the same.
- So we need $L_{coh} < r_L$: microscopic turbulence (Pelletier+09)

a. A big problem here the energetic particle precursor is very small (because the shock is fast) => quasi no room to trigger waves.

b. Usually need to produce high magnetic field amplification upstream either (eg gamma-ray bursts see Li & Waxman 2006).
NB: Points (a) and (b) are in tension each other.

- ➢ What is the nature of downstream turbulence?
- Important as it controls the acceleration timescale.
    a. Isotropic downstream turbulence ? strong magnetic compression along the shock front (Lemoine & Revenu'06) but upstream micro-turbulence is anisotropic and longitudinal also (Plotnikov+11)
    b. Survival of the turbulence downstream (Lemone'13'15).

Recent theoretical efforts

- Necessary conditions for particle acceleration in low σ cases: (Pelletier+09).

$$A = \frac{\delta B}{B_{back}} >> 1,$$

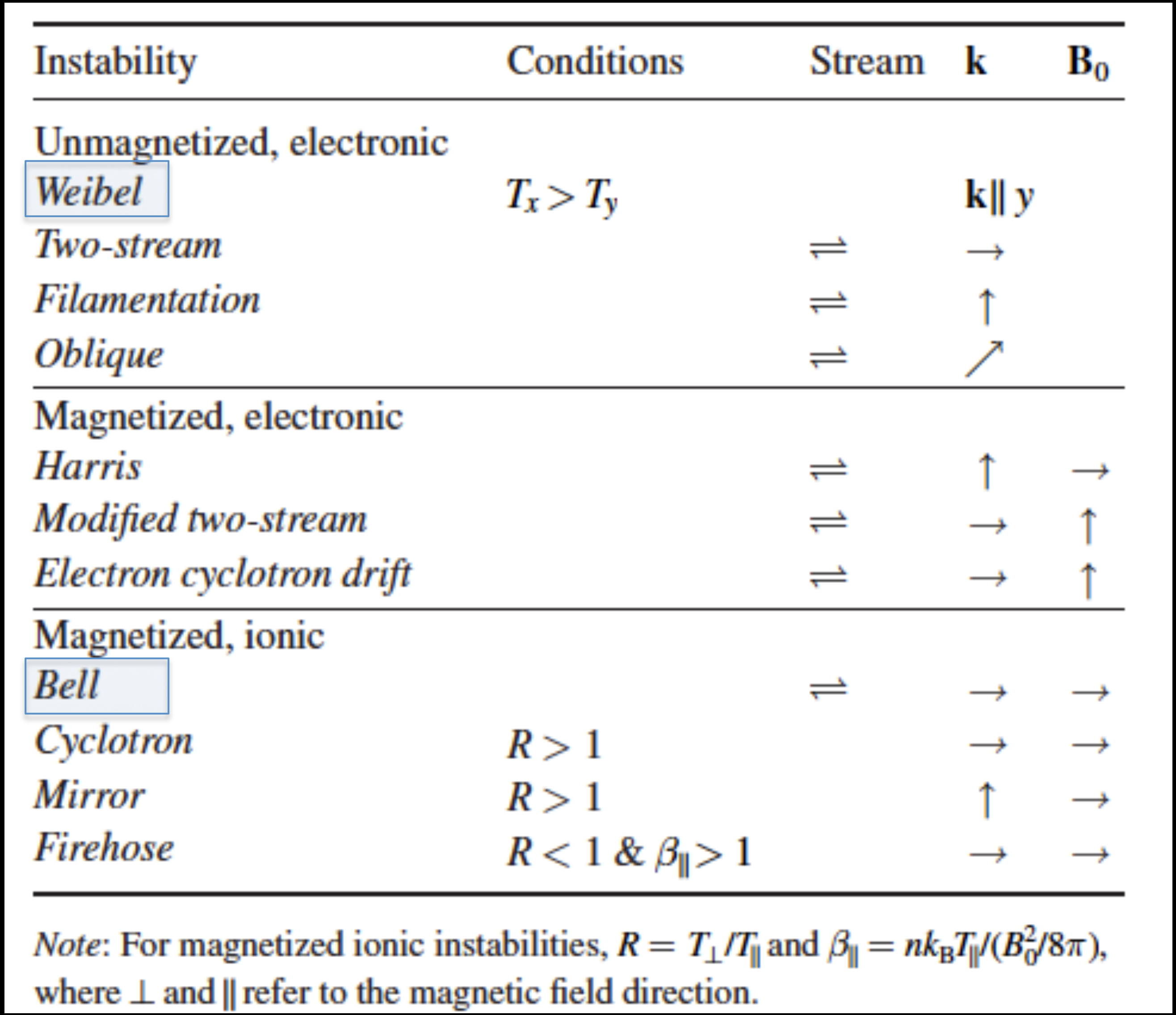
$$L_{coh} << r_L$$

The turbulence has to be strong and to develop at small scales.

- What kind of turbulence ? The nature of the turbulence depends on the dominant instability as source of magnetic field.
- Itself it depends on shock and ambient medium properties: Lorentz factor, background magnetization $\sigma_u = (V_a/c)^2$, background MF obliquity (sub- or super-luminal shocks)… (effect of neutrals) (Sironi+15,Marcowith+16).

➢ Need for a parametric survey => Efforts years 2006-now.

Interlude: instabilities at shocks



Instability	Conditions	Stream	$\mathbf{k}$	$\mathbf{B}_0$
Unmagnetized, electronic				
Weibel	$T_x > T_y$		$\mathbf{k} \parallel y$	
Two-stream		⇌	→	
Filamentation		⇌	↑	
Oblique		⇌	↗	
Magnetized, electronic				
Harris		⇌	↑	→
Modified two-stream		⇌	→	↑
Electron cyclotron drift		⇌	→	↑
Magnetized, ionic				
Bell		⇌	→	→
Cyclotron	$R > 1$		→	→
Mirror	$R > 1$		↑	→
Firehose	$R < 1$ & $\beta_\parallel > 1$		→	→

Note: For magnetized ionic instabilities, $R = T_\perp / T_\parallel$ and $\beta_\parallel = n k_B T_\parallel / (B_0^2/8\pi)$, where $\perp$ and $\parallel$ refer to the magnetic field direction.

see Marcowith+16, Bret'09

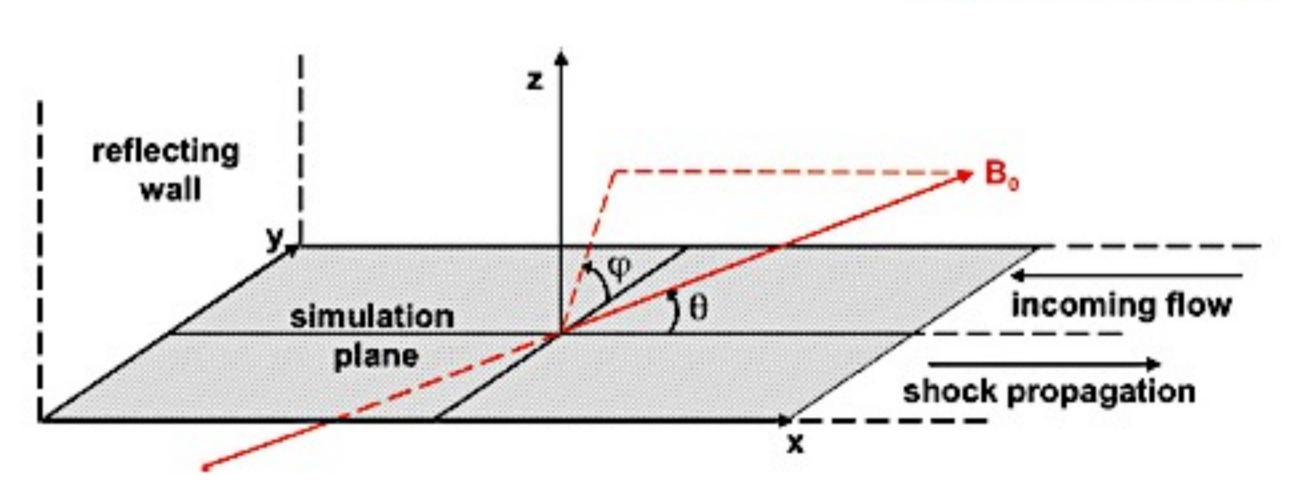
Partice-In-Cell simulations

Simulation set-up (Sironi & Spitkovsky'11a)

2.5D PIC simulations

$m_e/m_i=16$

$\Gamma=15$

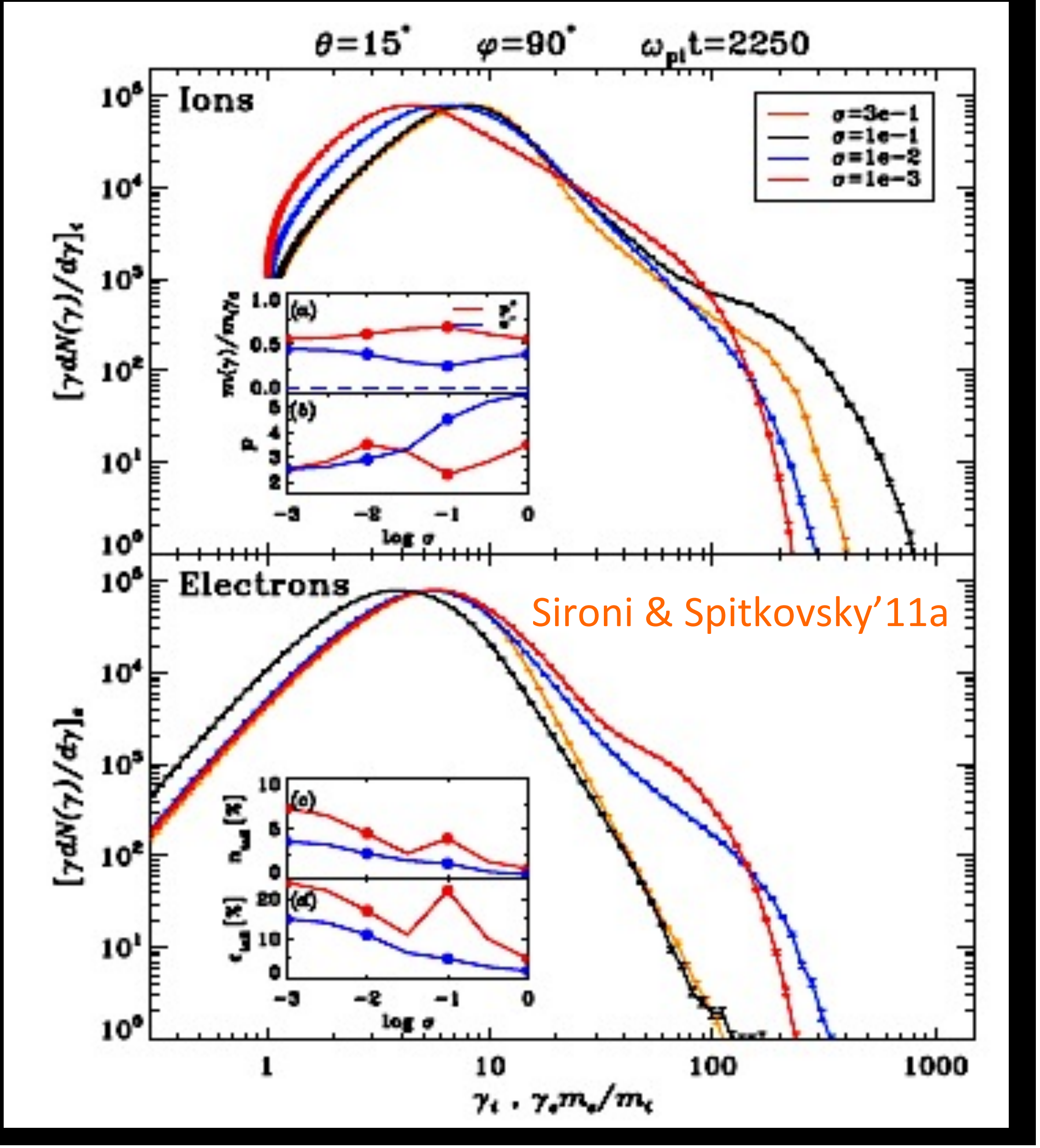


PIC simulations

Subluminal shocks: effects of magnetization

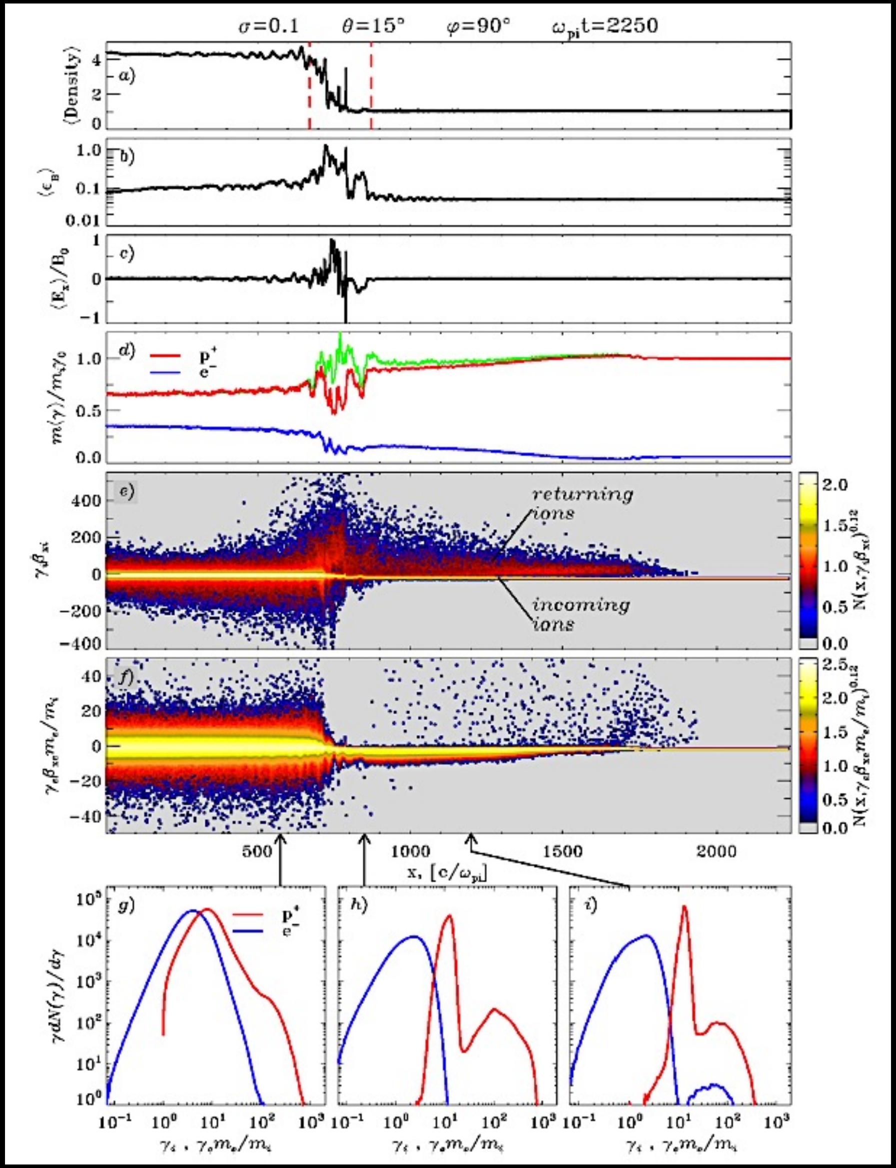
Protons accelerated at all σ but with different slopes (harder spectra at low σ).

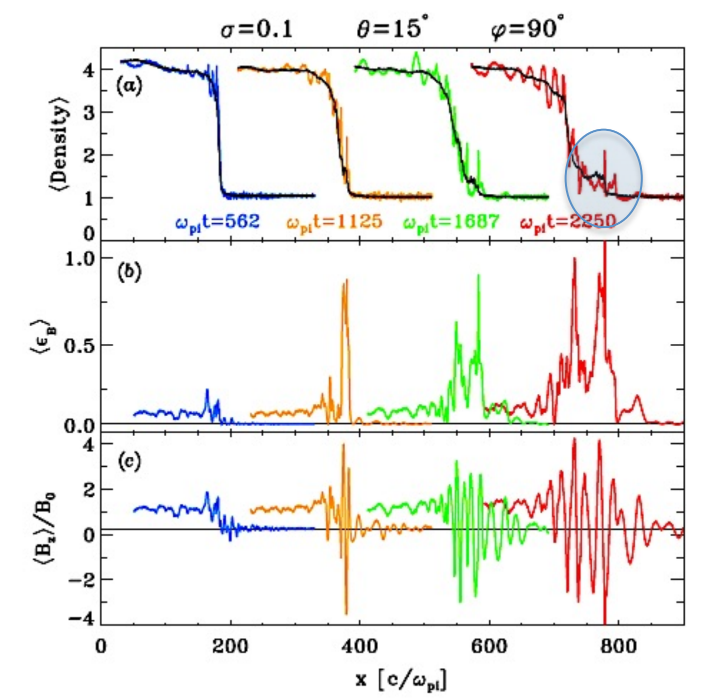
Electrons accelerated only at low σ



Sironi & Spitkovsky’11a

PIC simulations





Subluminal magnetized shocks: mediation by streaming instability

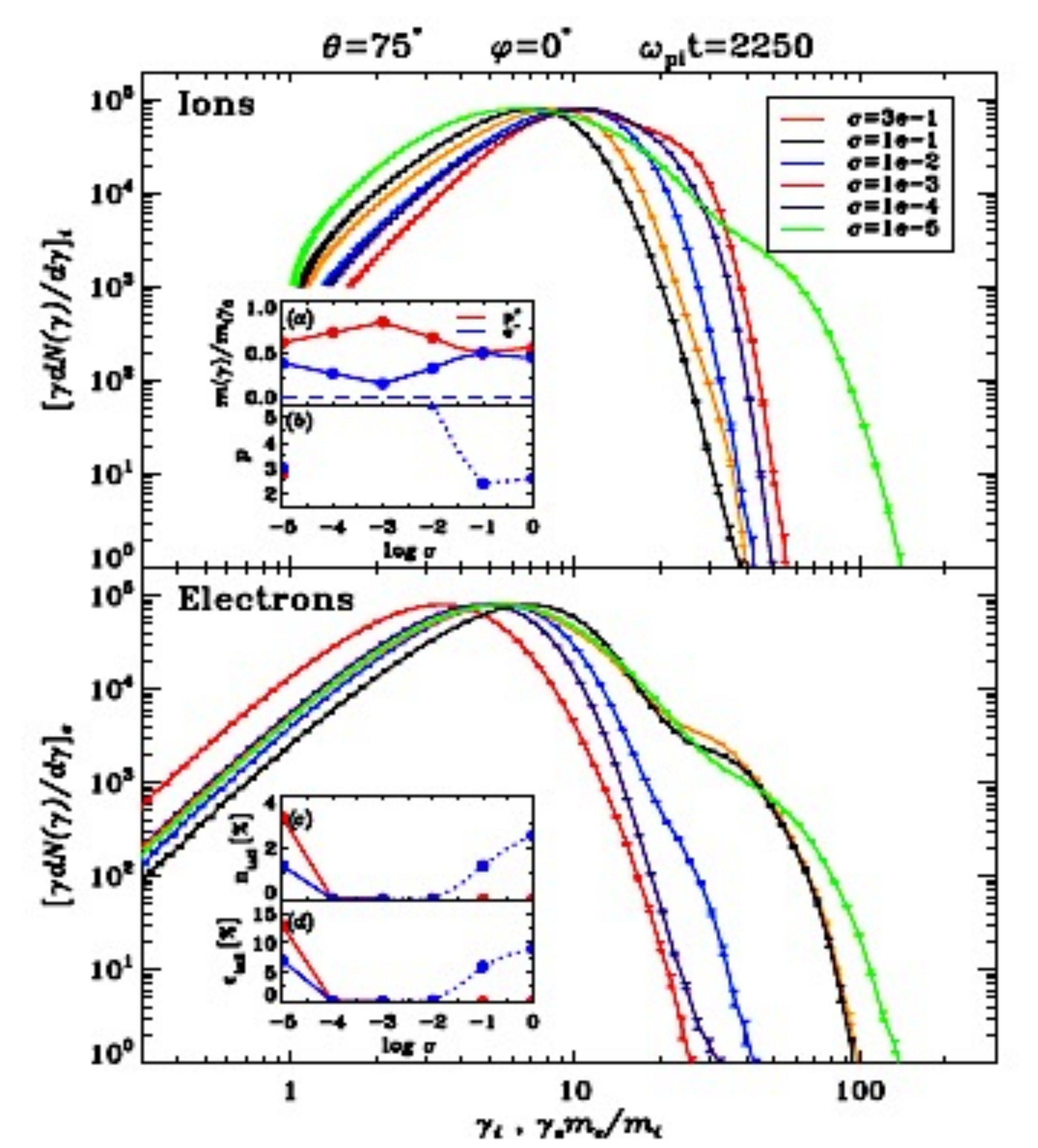
PIC simulations

<u>Superluminal shocks</u>: effects of magnetization

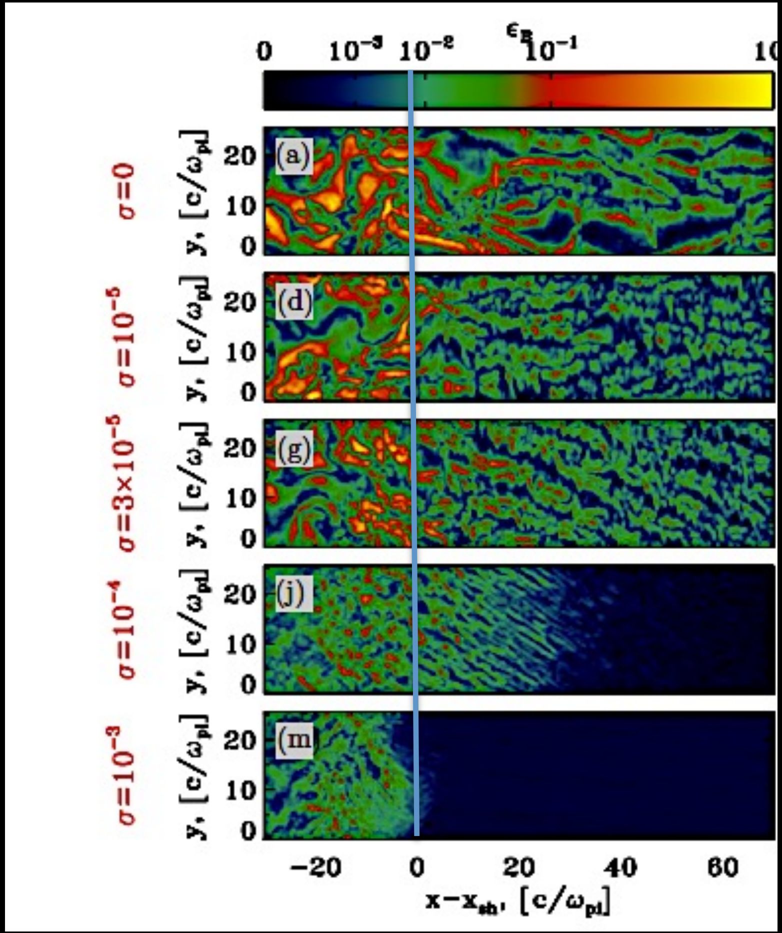
No proton acceleration except at low σ

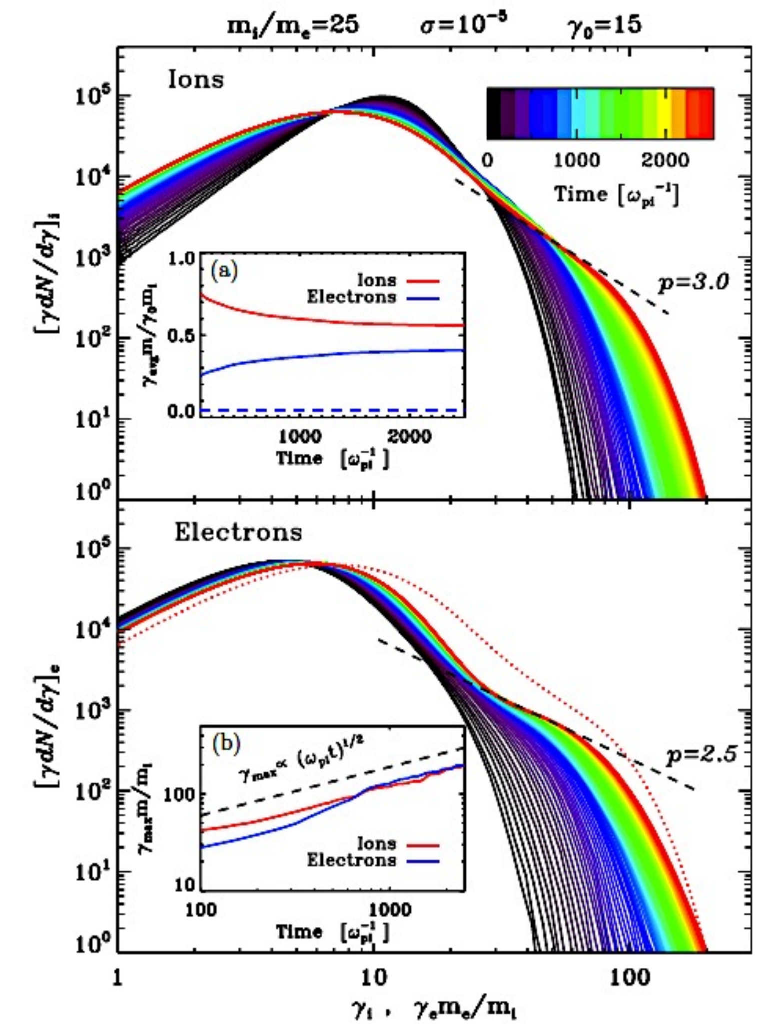
No electron acceleration except at low σ

Sironi & Spitkovsky’11a



Low magnetization Weibel mediated shocks

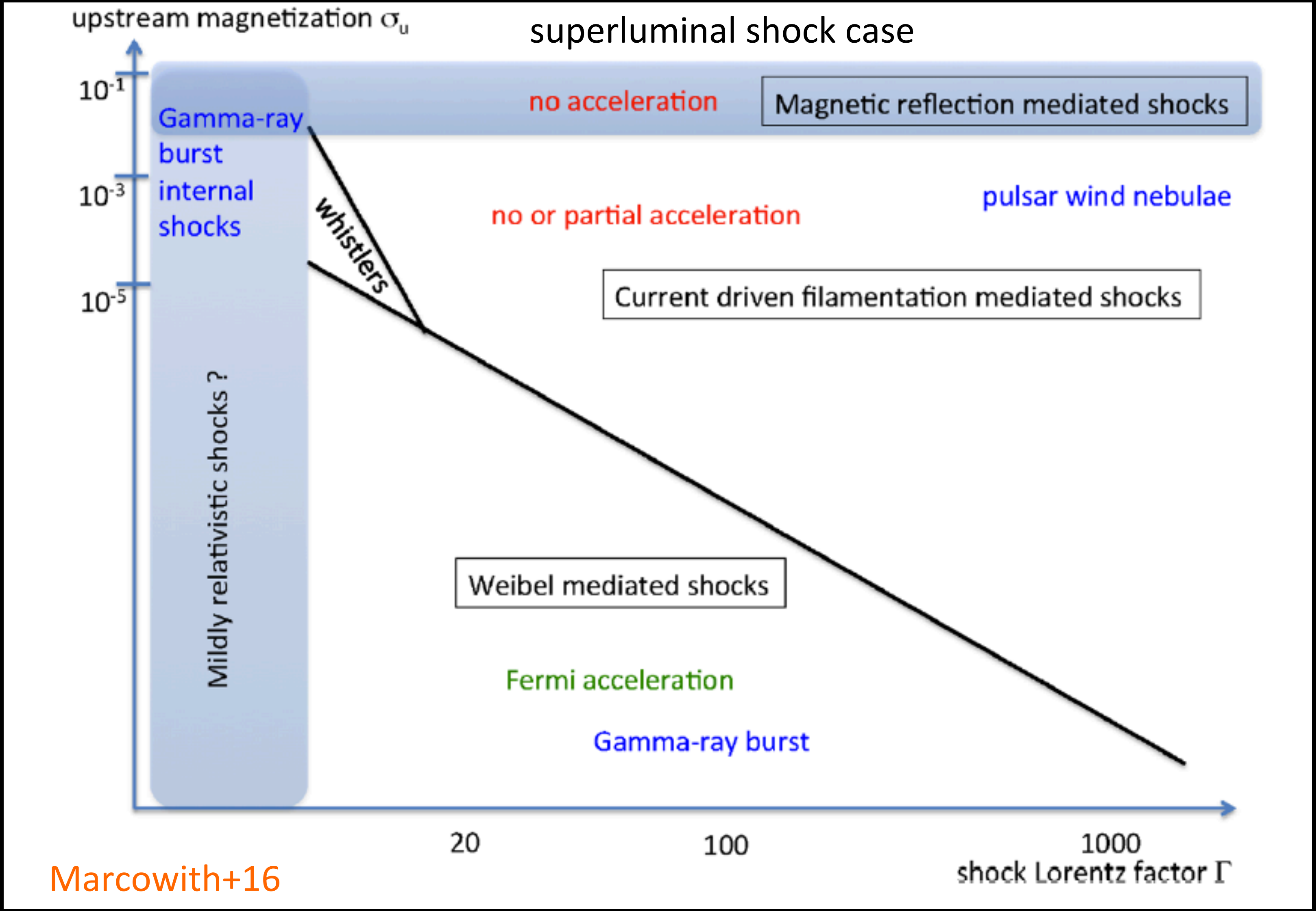




Softer indices than in isotropic diffusion (2.5-3 vs 2.22) because the waves have a drift wrt to the background fluid.

Numbers & energetics: 1% in number and 20% in energy imparted into CRs.

Acceleration regimes: an overview



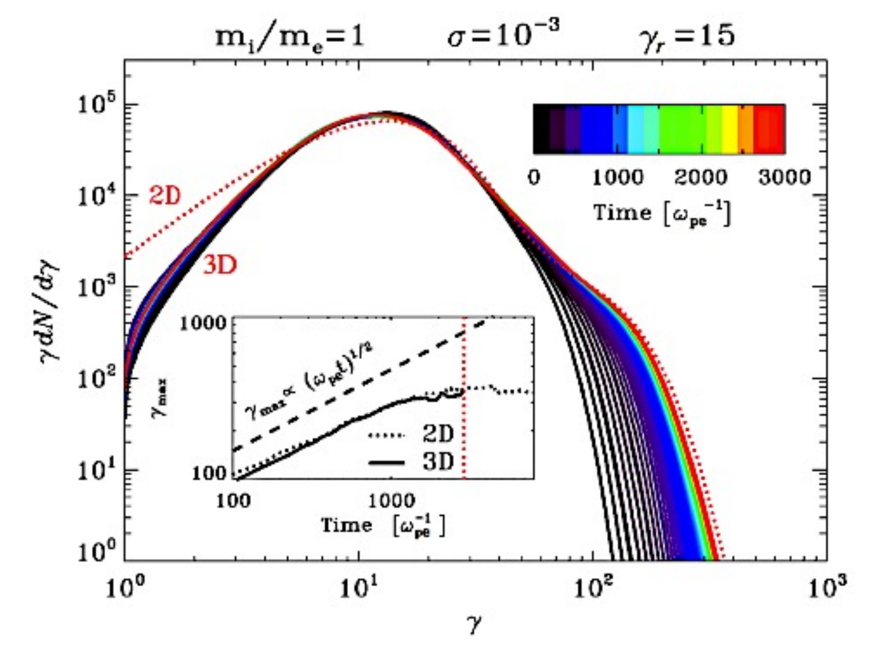
Marcowith+16

Relativistic shocks: acceleration in microscopic turbulence

In microscopic turbulence: diffusion coefficient scales as E^2 so

$T_{acc}=R_L^2/L_c c$ gives E_{max} raises as $t^{1/2}$
(Sironi+13, Plotnikov+11,+13)

Saturation as $\sigma^{-1/4}$



Sironi+13

Astrophysical implications: UHE-CRs

- Relativistic shock acceleration performances:
  - Massive star wind magnetization is very low (GRB afterglow)

$$\sigma = \frac{B_{\rm W}^2}{4\pi n m_i c^2} \simeq 1.7 \times 10^{-8} B_{\rm W,-5}^2 n_{-0.5}^{-1}$$

Sironi+13
Plotnikov+13

  - Typical maximum energy for protons

$$\gamma_{{\rm sat},i}^{\rm up} \simeq 1.3 \times 10^7\, E_{0,54}\, A_{11.5}^{-1}\, \sigma_{-8}^{-1/4}\, R_{16}^{-1}$$

(= 13 PeV)

and γ_e~10^8 (50 TeV) for electrons => 30 GeV photons.

- How to accelerate EeV-ZeV CRs ?
  - Mildly relativistic shocks (larger precursors, obliquity is less a problem, MHD instabilities could arise (Pelletier+09, Casse+13).
  - Ion acceleration in young millisecond pulsar winds ? Lemoine+15

Conclusions

- Huge analytical and numerical efforts these last ten years.

- Fermi acceleration can work in relativistic shocks but at low σ:
    - Shock mediation by microscopic turbulence (Weibel instability)
    - But as diffusion proceeds as E^2, and due to limited space of growth of the turbulence => Maximum energies limited to 10 PeV (propagation in massive star winds) (at least could produce (IceCube?)PeV neutrinos).
    - Maximum electron energies => a few tens of TeV => GeV radiation (Fermi observations of GRBs).

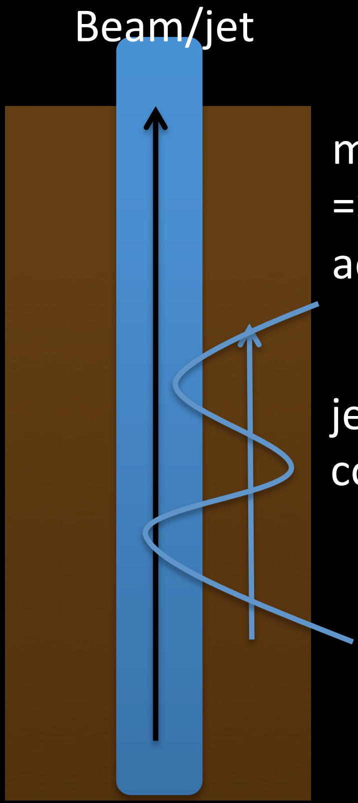
- Origin of EeV-ZeV hadrons still unclear :
    - mildly relativistic shocks ? AGNs, internal GRB shocks, microquasars …
    - Pulsar contribution ? powerful young millisecond pulsars (still to be observed).

Back-up slides

Other processes

Shear flow acceleration

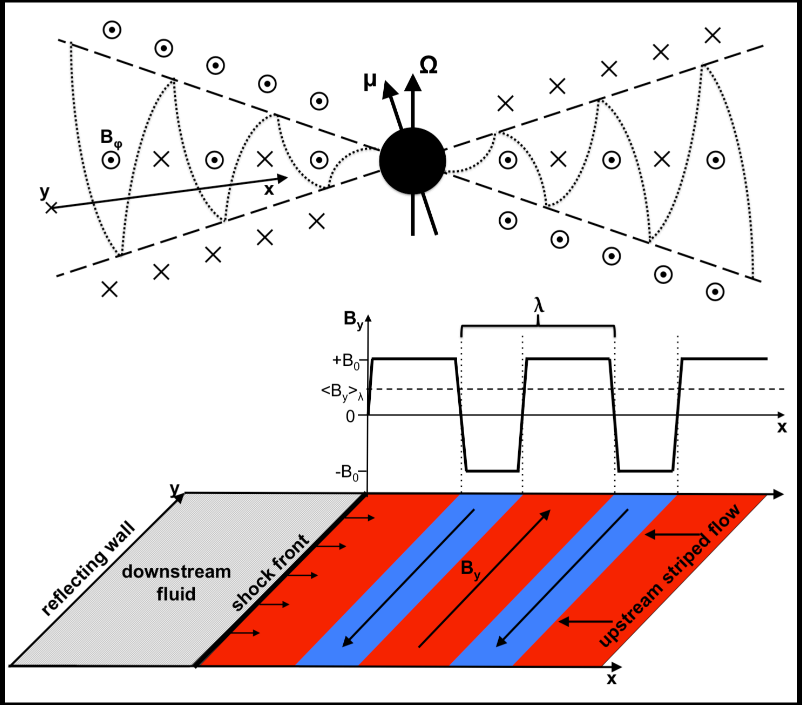
Magnetic reconnection



Beam/jet

multiple crossings => Fermi-like acceleration

jet/back-flow/cocoon



Striped pulsar winds

or tangential velocity profile

Rieger & Duffy'04'05'06

but any turbulent magnetized shocked relativistic flow should also be subject to reconnection.

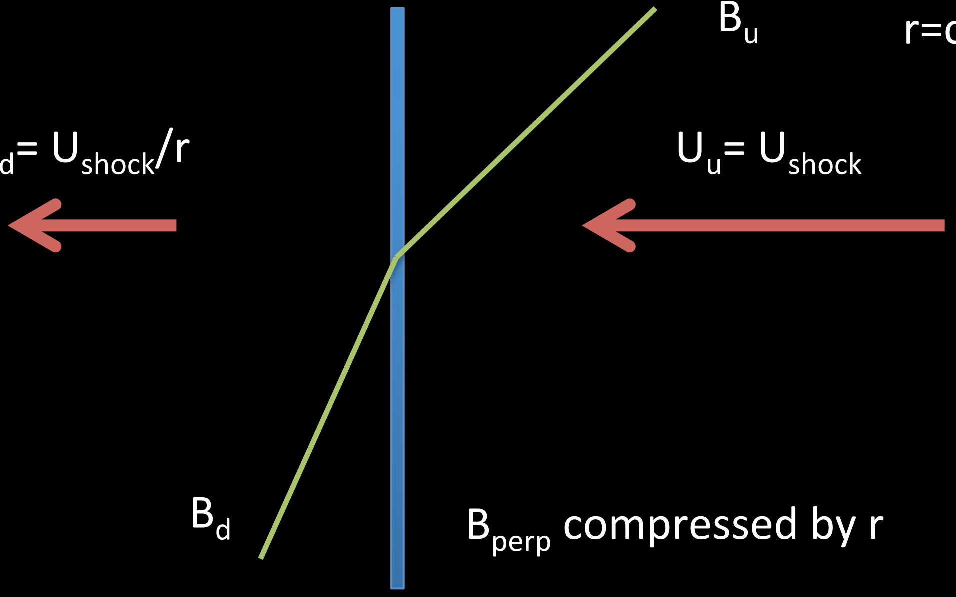
Sironi & Spitkovsky'11b

Fermi acceleration at non-relativistic shocks: diffusive acceleration.

Principle

Recipe: you need

- A shock (supersonic, superAlfvénic).
- Inject energetic particles from thermal pool.
- Waves (electromagnetic perturbations) with a large spectra in wavelength (fully developed turbulence is better) up- and downstream the shock front.



shock rest-frame

B_u

r=compression ratio

mass flux conserved

$U_d = U_{shock}/r$

$U_u = U_{shock}$

magnetic flux conserved

B_d

B_{perp} compressed by r

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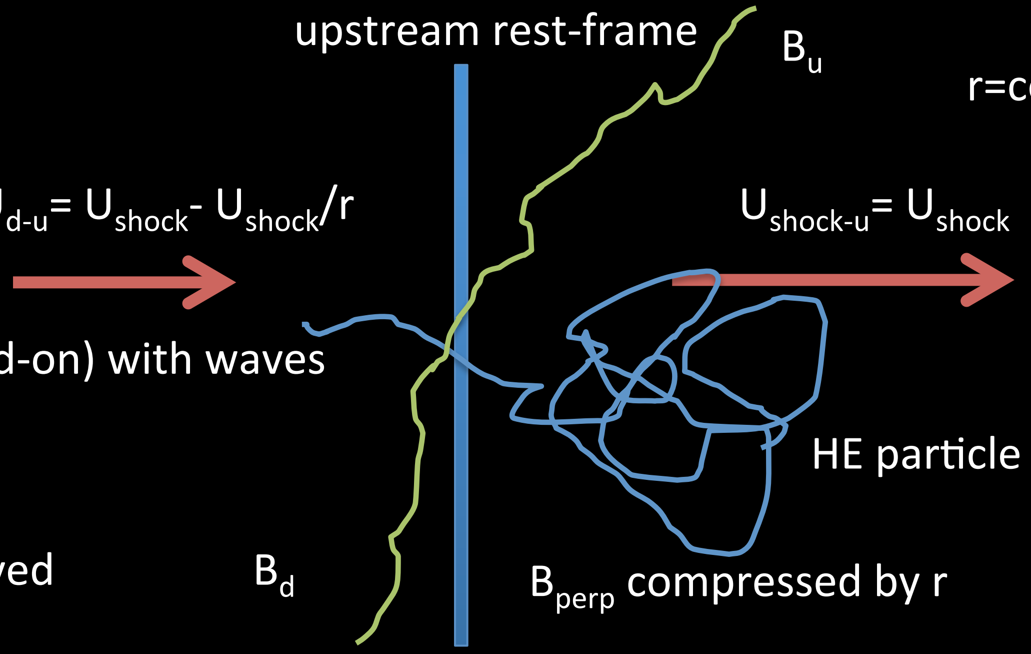

upstream rest-frame

r=compression ratio

$U_{d\text{-}u} = U_{shock} - U_{shock}/r$

$U_{shock\text{-}u} = U_{shock}$

First interaction (head-on) with waves moving
$V_{sc} \sim U_{shock} - U_{shock}/r$

magnetic flux conserved

B_{perp} compressed by r

Fermi acceleration at non-relativistic shocks: diffusive acceleration.

Principle

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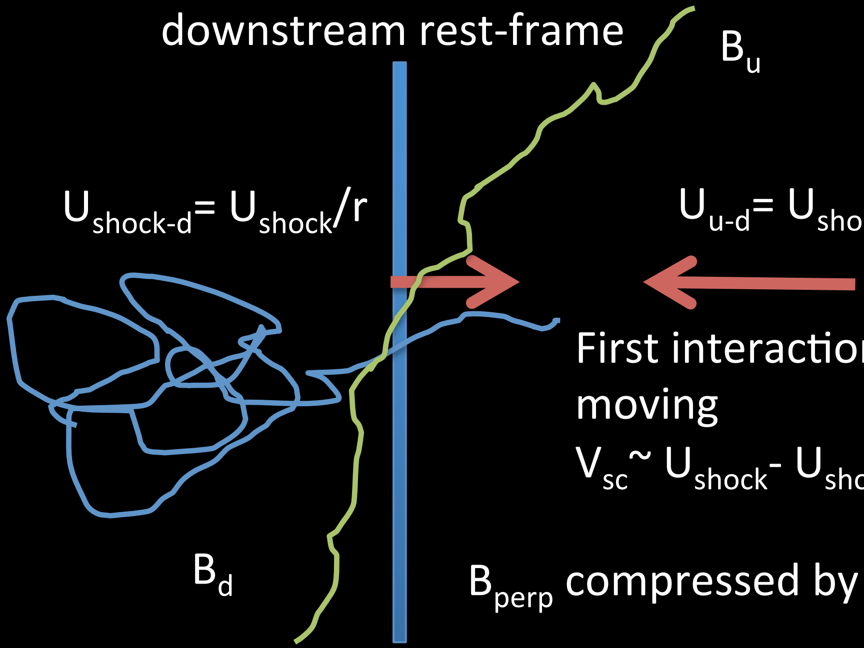


downstream rest-frame

B_u

r=compression ratio

$U_{shock-d} = U_{shock}/r$

$U_{u-d} = U_{shock} - U_{shock/r}$

HE particle

First interaction (head-on) with waves moving

$V_{sc} \sim U_{shock} - U_{shock}/r$

magnetic flux conserved

B_d

B_{perp} compressed by r

Fermi acceleration at non-relativistic shocks: diffusive acceleration.

Principle (see Bell ’78: microscopic model)

- At each shock crossing interaction with a wave ($\lambda \sim r_L = E/ZeB$) moving at $V_{sc} = U_u - U_d$
- Relative energy gain per cycle is V_{sc}/c (relativistic particle) is constant ⇔ Fermi process.

Fermi acceleration at non-relativistic shocks: diffusive acceleration.

Results

(see reviews by Drury 1983 Reports on Prog. Phys., Blandford & Ostriker 1987, Malkov & Drury 2001, Schure et al 2012, Marcowith et al 2016)

- As (for relativistic particles) the escape probability downstream is ~U_d/c => shock solution is a power-law.
- Index s_E =-dlog(N)/dlog(E) = (r+2)/(r-1)=2 for r=4 (or s_p= -dlog(N)/dlog(p)=4)

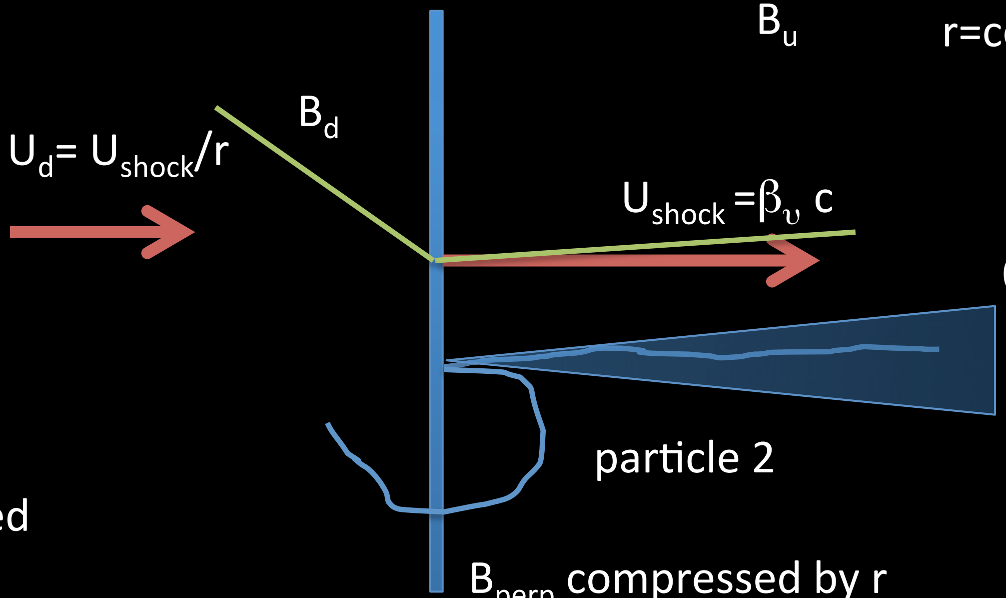
Fermi acceleration at non-relativistic shocks: diffusive acceleration.

Issues

- Energetic particles (hadrons) carry pressure, that can be 10-50% of the shock ram pressure (strong difference with heliospheric and magnetospheric shocks)
- HE particles are believed (and now simulated: e.g. Bai X N et al 2015: PIC-MHD simulations) to produce the turbulence
  - ⇒ Magnetic field amplification by HE particles in a precursor.
  - ⇒ Highly non-linear game thermal/non-thermal plasmas and magnetic field.
- Injection ? likely other acceleration process are important: shock drift acceleration: Caprioli et al 2015: di (relativistic and thermal protons treated as kinetic)-Hydrid (electrons as fluid) simulations, Caprioli & Spitkovsky 2015 PIC simulations)

Fermi acceleration at relativistic shocks: partly diffusive acceleration.

- Shock supersonic, superAlfvénic but with U_{sh}~c
- Inject energetic particles from thermal pool.
- Upstream particles can not have a random walk outside a cone of size $1/\Gamma_{sh}$.
- This requires are quasi-parallel background magnetic field…



upstream rest-frame

B_u

r=compression ratio

B_d

mass flux conserved

$U_d = U_{shock}/r$

$U_{shock} = \beta_\upsilon$ c

$\theta \sim 1/\Gamma_{sh} = (1-\beta_{sh}^2)^{1/2}$

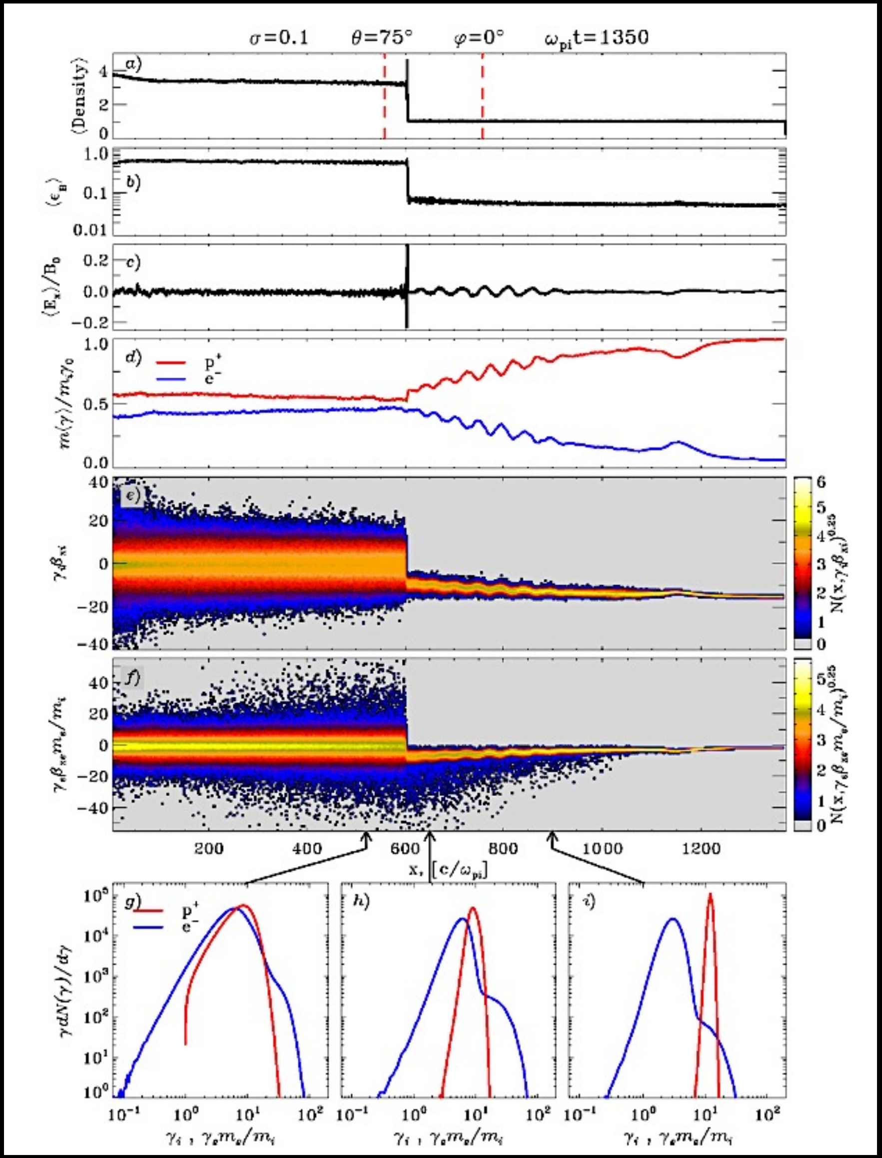
particle 1

particle 2

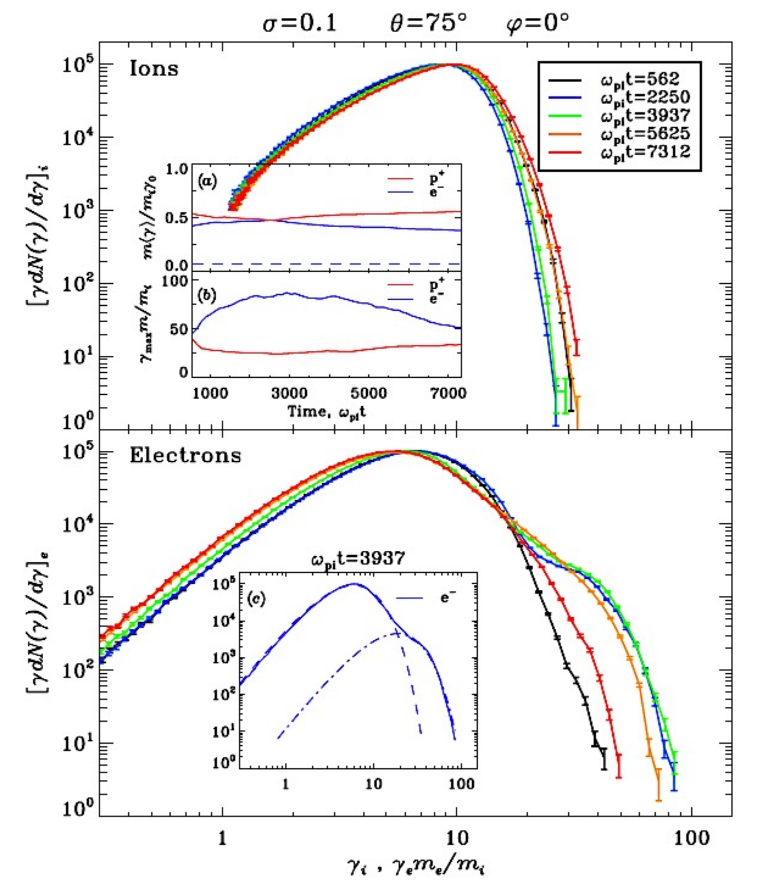
magnetic flux conserved

B_{perp} compressed by r

PIC simulations



<u>Superluminal magnetized shocks</u>: no acceleration, electron heating by maser synchrotron instability.



Acceleration mechanisms: Fermi acceleration

- Fermi acceleration at shocks: energy gain by successive shock crossings up to high relativistic energies.

BUT

Issue 1: The process is highly non-linear: analytical formulation difficult.

Issue 2: Specific to relativistic flows: mixing of electric and magnetic effects up- and downstream the shock front, particle distribution highly anisotropic.