Efficient Fermi Acceleration in Relativistic Shocks

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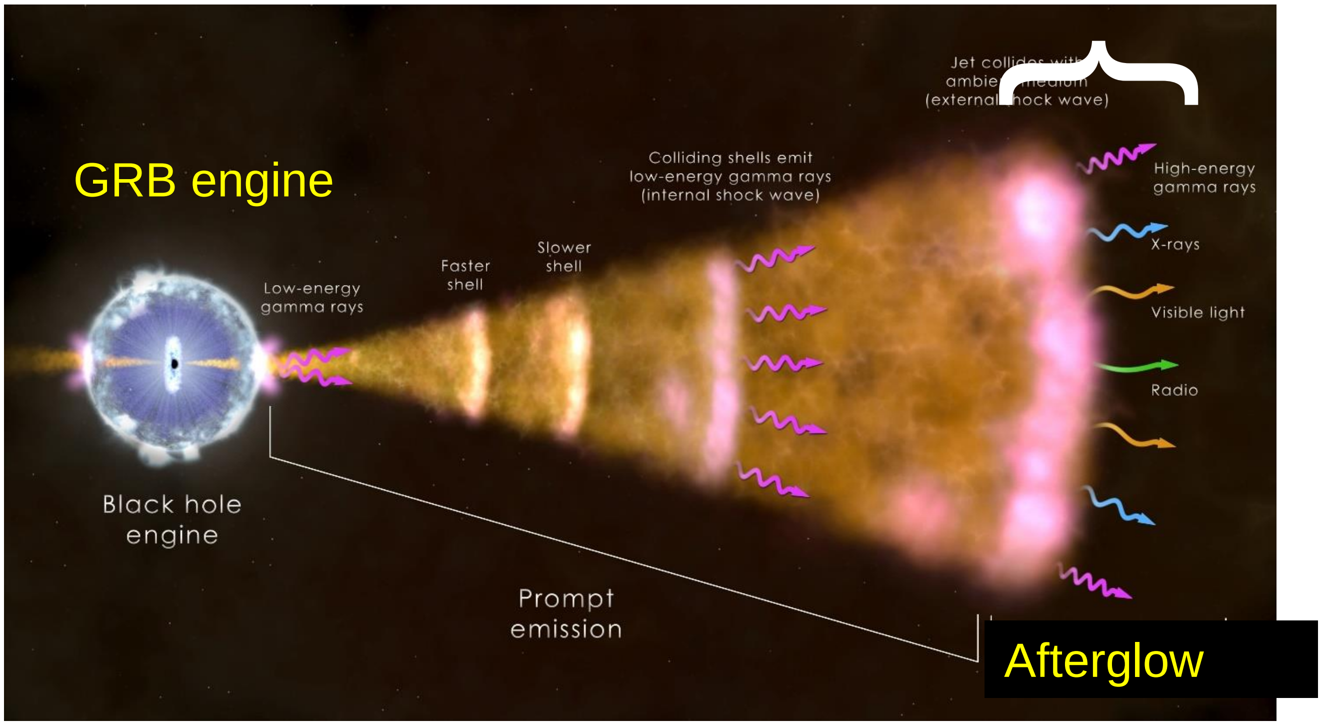
Relativistic shocks important in :

- ➔ **Gamma-ray bursts (GRBs)**
- ➔ **Type Ibc supernovae**
- ➔ **Pulsar winds**
- ➔ **Extra-galactic radio jets**

Consider Fermi Acceleration in GRB afterglows

Assume GRB afterglow produced as external shock moves through circumstellar medium

Afterglow



➔ **Forward shock starts ultra-relativistic, slows through trans-rel. phase, ends as non-relativistic shock**

➔ **Particles accelerated and radiation produced along the way**

Plasma physics of relativistic shocks is complicated :

- ➔ **Shock formation and structure**
- ➔ **Self-generation of magnetic turbulence**
- ➔ **Energetic particle injection and acceleration**

} **All coupled if Fermi Acc. is efficient**

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Relativistic shocks depend on plasma physics details !!

➔ **Particle-in-cell (PIC) simulations**

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Relativistic shocks depend on plasma physics details !!

➔ **Particle-in-cell (PIC) simulations**

BUT, when particle acceleration is efficient, important aspects of kinematics (energy & momentum conservation) can be described regardless of the plasma physics details

➔ **Monte Carlo simulations : not as complete as PIC simulations but computationally faster ➔ good for parameter surveys and estimates of UHECRs**

Monte Carlo techniques can explore nonlinear effects not modeled with analytic or hydro methods

1. **Model Ion and electron acceleration with simple assumptions for diffusion**
2. **Have "built-in" Thermal Leakage Injection model**
3. **Calculate photon emission from electrons and ions**
4. **Vary momentum dependence of scattering mean-free-path**
5. **Apply to GRB afterglow models by coupling acceleration to analytic or hydro models of jet** **(Don Warren: work in progress)**

Warning, still many important approximations

1) **Scattering is isotropic in plasma rest frame**
2) **No spatial dependence on scattering mean free path**
3) **Thermal leakage injection**
4) **No magnetic field amplification or cascading**
5) **Steady-state & plane-parallel**

If assume shock acceleration is efficient, then :

1) Nonlinear particle distributions have different shapes and normalizations from test-particle predictions ➔ not simple power laws

2) Extreme effects for electrons !!

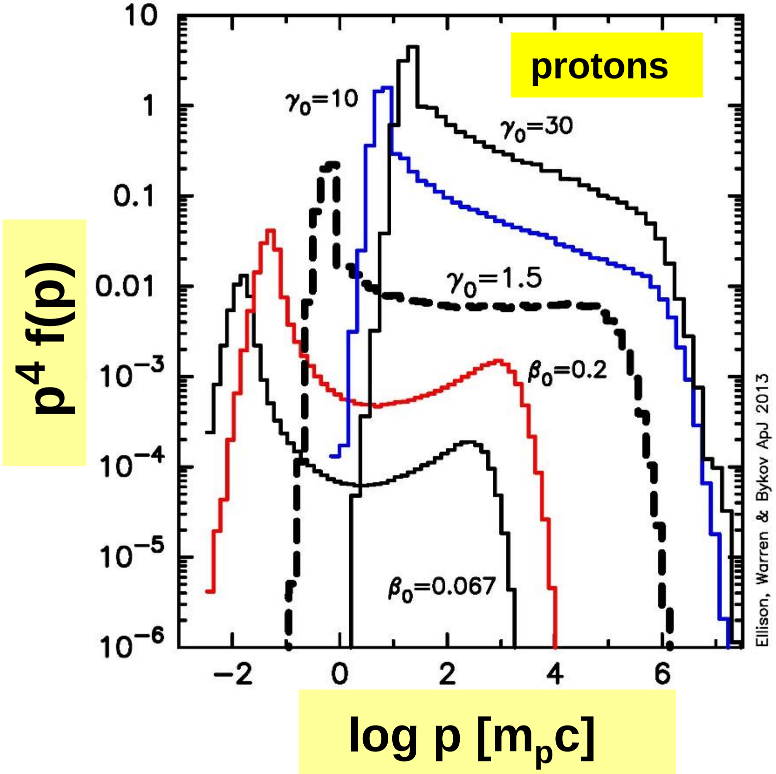
3) Photon emission very different between test-particle and self-consistent results

4) Must have consistent model, conserving energy and momentum, to determine absolute emissivity.

See recent relativistic shock papers for details and references:

Ellison, Warren & Bykov, ApJ 2013
Warren, Ellison, Bykov & Lee, MNRAS 2015

Nonlinear effects depend strongly on Lorentz factor, γ_0



Ellison, Warren & Bykov 2013

- ➔ As GRB afterglow shock slows it will transition from ultra-relativistic through trans-relativistic to non-relativistic speeds
- ➔ Ultra-rel: Steeper spectra but more dramatic differences from Lorentz transformations for light particles
- ➔ Non-relativistic: More pronounced NL effects from shock smoothing

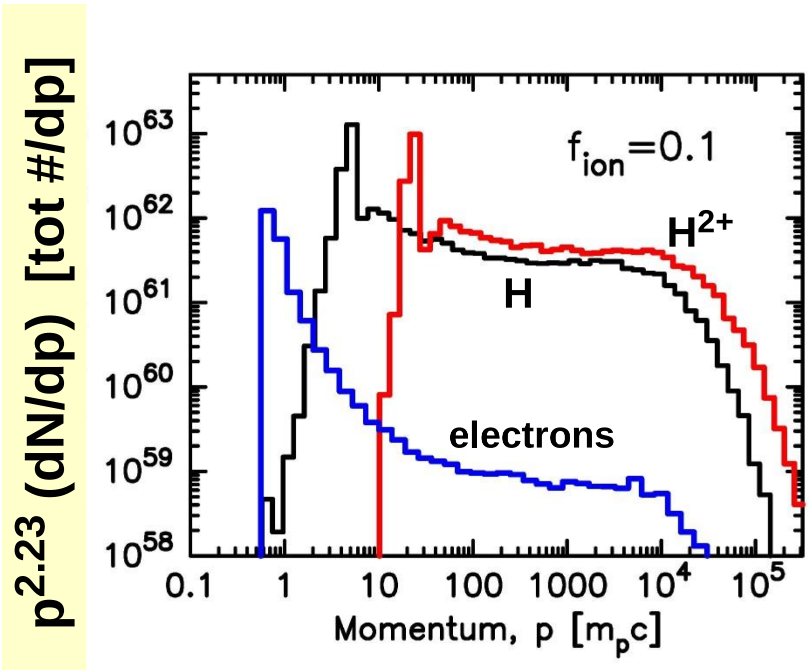
➔ Evolution in particle spectra
➔ Evolution in photon emission

➔ No single power law during time-evolution of afterglow
➔ Electron spectra vary more than protons as shock slows

Shock Lorentz factor γ = 10 with Bohm diffusion (Warren+ 2015)

Monte Carlo code injects and accelerates ions (H^+ & He^{2+}) and electrons consistently (within assumptions of model, of course).

Obtain consistent shock structure



H^+, He^{2+}, electrons

Summed shock frame spectra for particles between upstream and downstream shock boundaries

These are "full spectra" from "thermal" to maximum energies determined by finite shock size

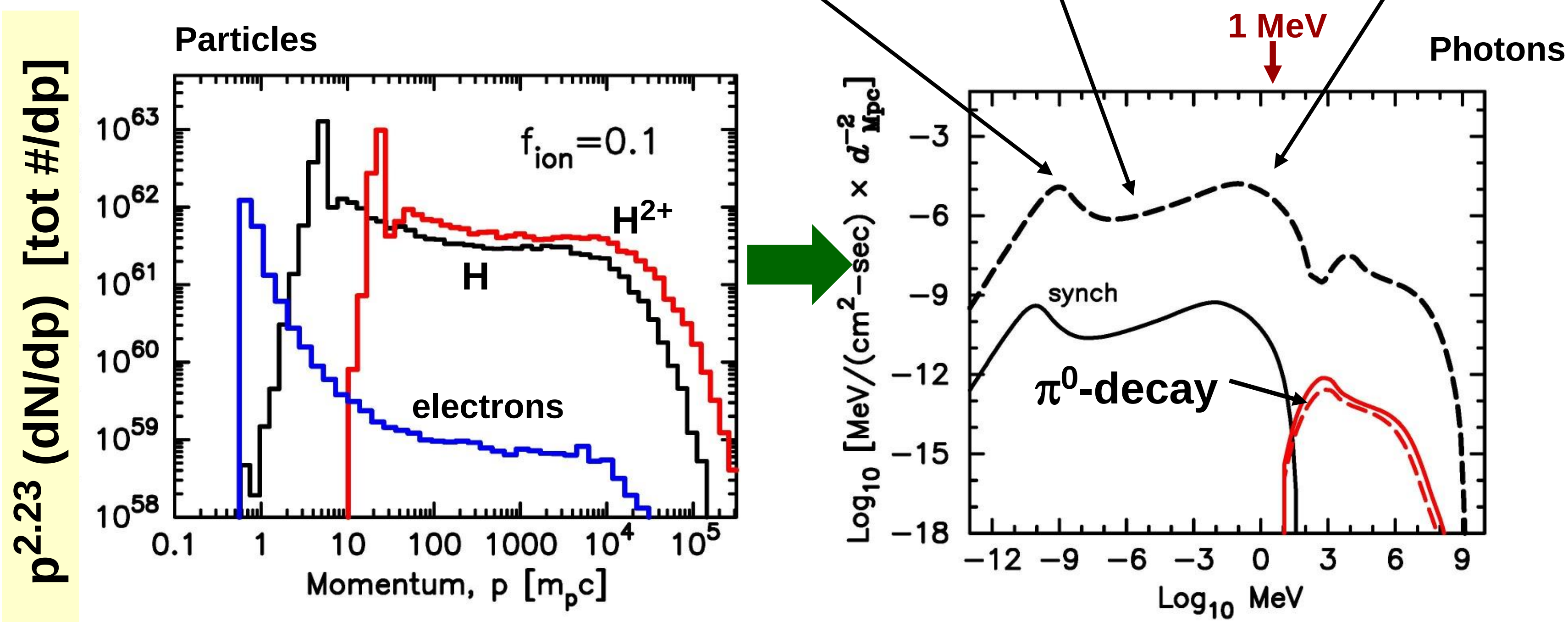
Transform particles to proper frames
Calculate radiation,
Transform radiation to observer frame
(see warren+ 2015 for details)

Shock Lorentz factor γ = 10 with Bohm diffusion (Warren+ 2015)

Non-power-law shape of synch. emission

Strong peak in synch from thermal electrons
Note: don't include synch-self-absorption here

Broad peak in synch near 1 MeV



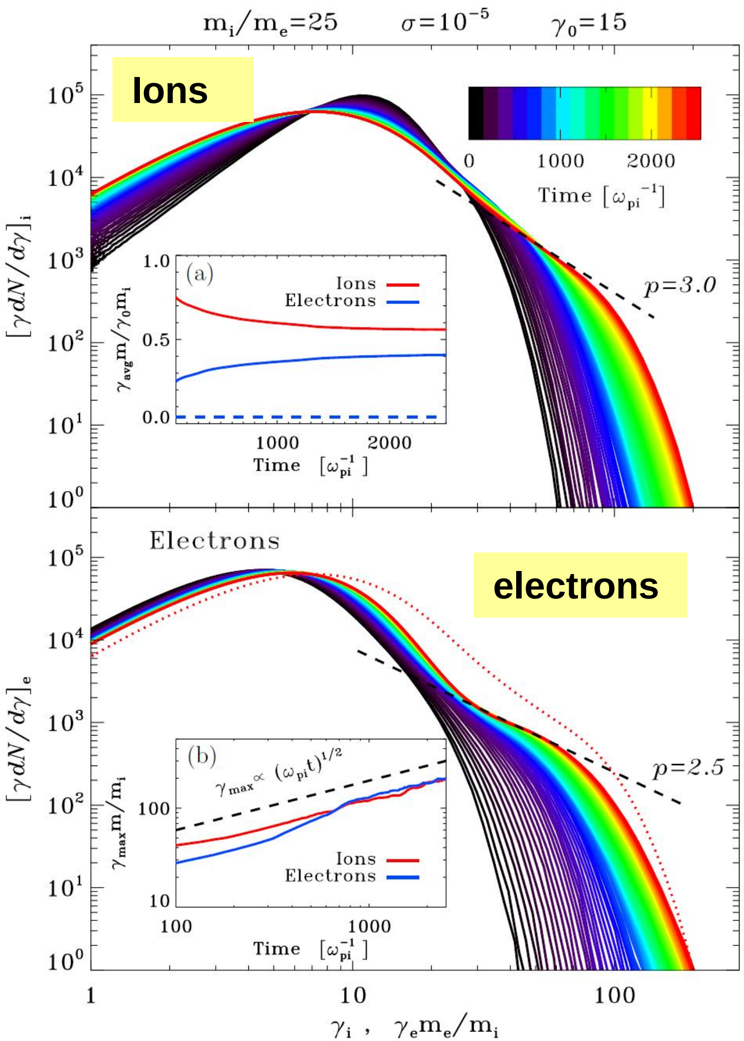
H^+, He^{2+}, electrons

Total synch, π^0-decay, and IC flux at Earth

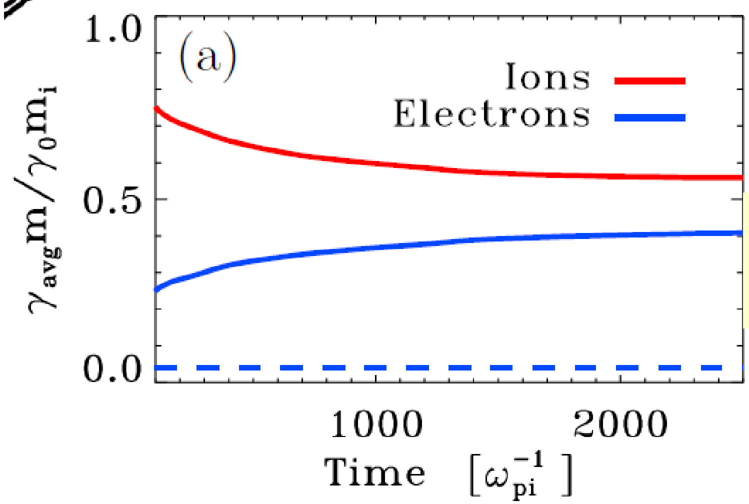
PIC simulations (Sironi+2013) see substantial transfer of energy from protons to electrons in relativistic shocks !!

PIC results: Fig 11, Sironi etal. 2013

~40% of energy transferred from protons to electrons in shock precursor !!



Energy in Ions and electrons



🡐 40% in e's

$\gamma_0 = 15$

$\sigma = 10^{-5}$ Unmagnetized case

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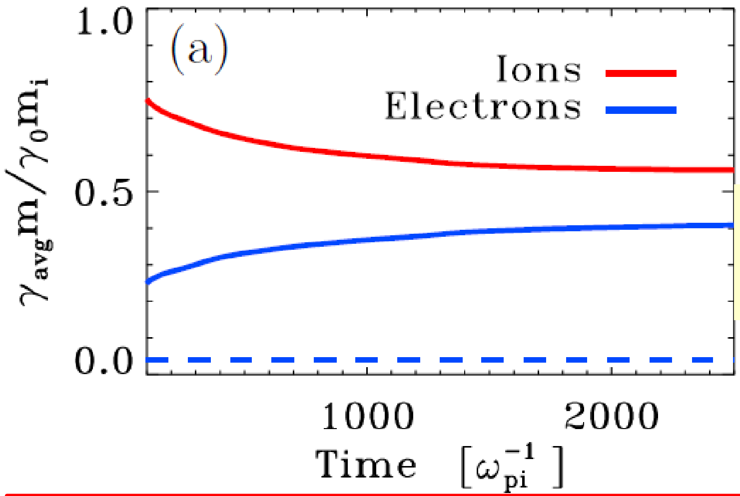


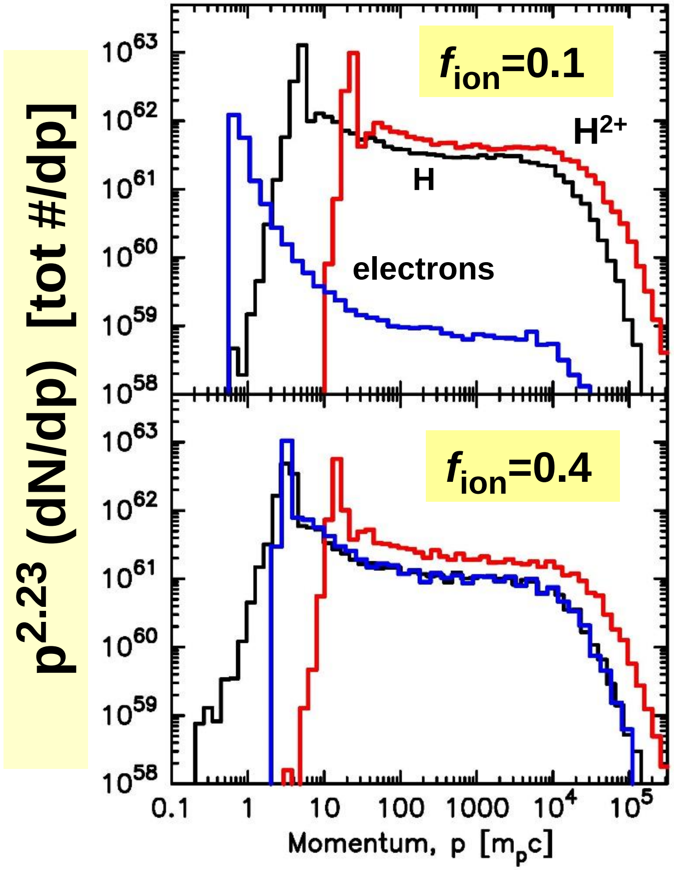
🡐 40% in e's

We parameterize this energy transfer with :

$$0 < f_{ion} < 1$$

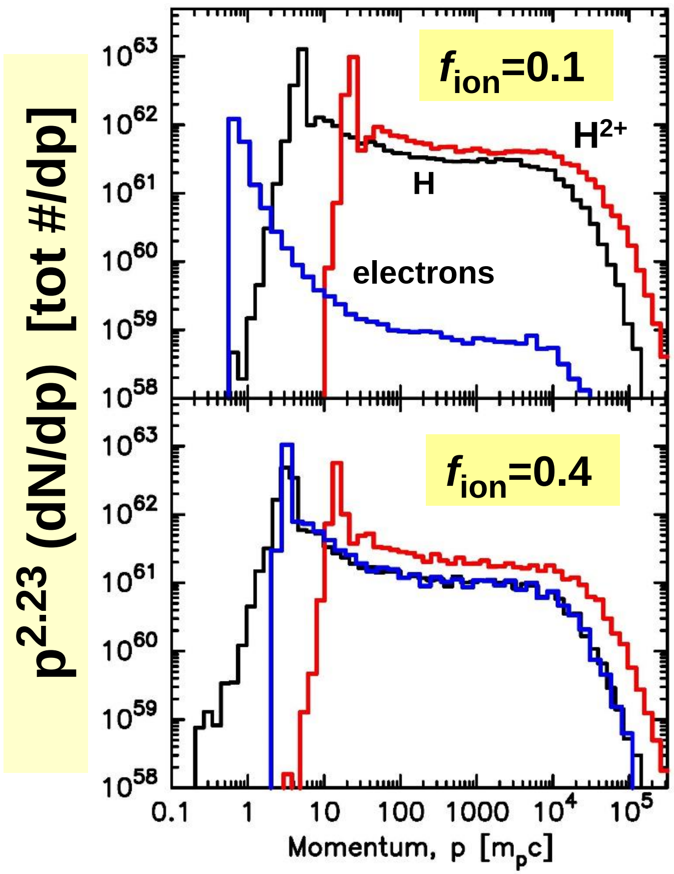
Fraction of ion energy → electrons in 1st shock crossing

Fraction of Ion energy transferred to electrons, f_{ion}, strongly influences photon emission in NL shocks

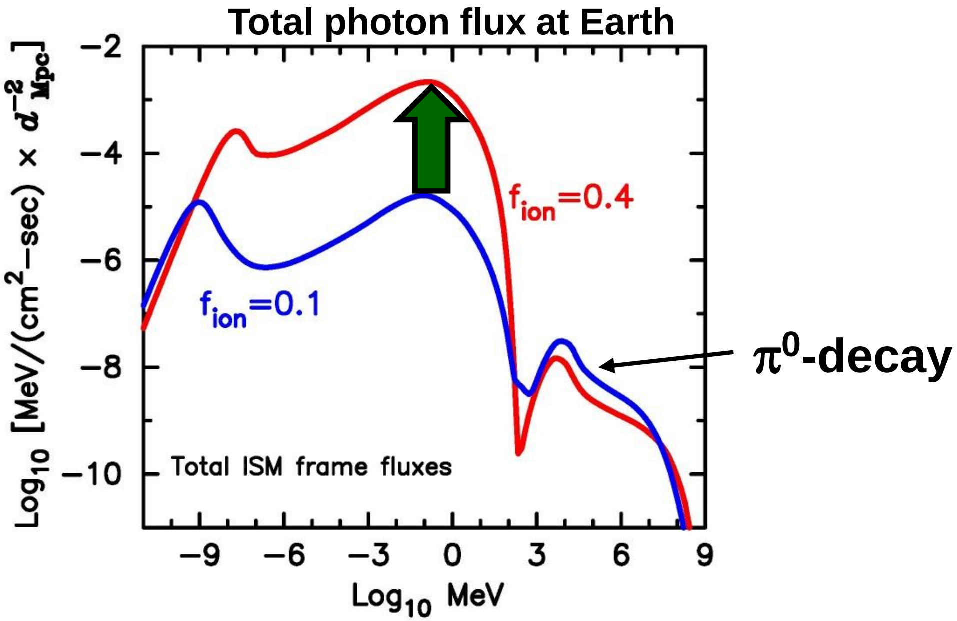


Warren+ 2015

Fraction of Ion energy transferred to electrons, f_{ion}, strongly influences photon emission in NL shocks



Warren+ 2015



➔ Increase in energy transfer from 10% to 40% gives x100 increase in synchrotron flux at ~MeV

➔ Small decrease in pion-decay emission

➔ NL effects influence electrons far more strongly than Ions

Consider momentum dependence of scattering mean free path, λ_{scat}

Ellison, Warren & Bykov submitted

Normally assume Bohm diffusion in efficient Fermi acceleration :

➔ strong, self-generated magnetic turbulence ➔ $\lambda_{\text{scat}} \propto$ gyroradius

$$\lambda_{\text{scat}} \propto r_g \propto p$$

p is particle momentum

➔ Idea: particles with r_g produce turbulence with $\lambda_{\text{turb}} \propto r_g$

➔ Some evidence for this in non-relativistic shocks: heliosphere and SNR shocks

BUT, in relativistic shock PIC simulations see Weibel instability

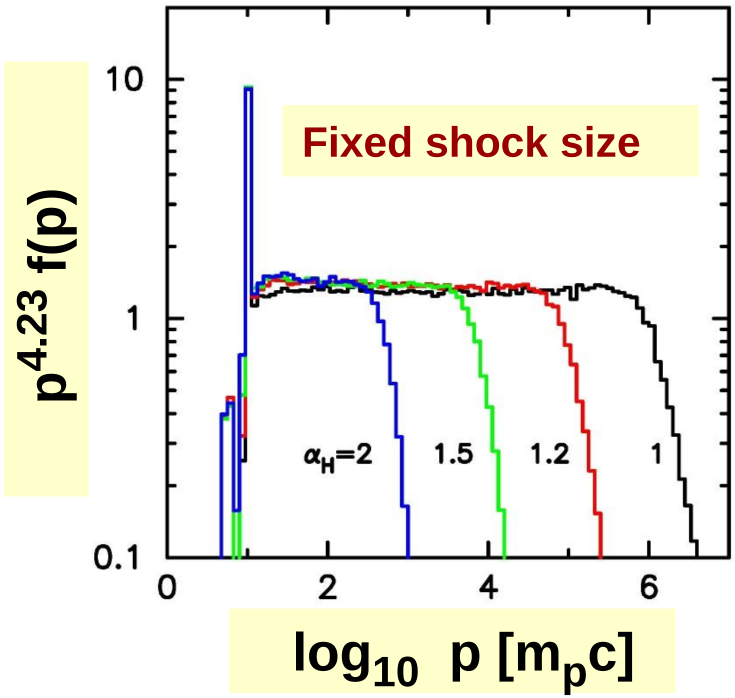
➔ short wavelength turbulence ➔

$$\lambda_{\text{scat}} \propto p^2 >> r_g$$

How does this change Fermi acceleration?

Monte Carlo results for Lorentz factor γ = 10 shock:

proton spectra



Test-particle results

If nonlinear back-reaction of CRs on shock structure is ignored (test-particle calculations), the *p*-dependence of λ_{scat} only changes scale

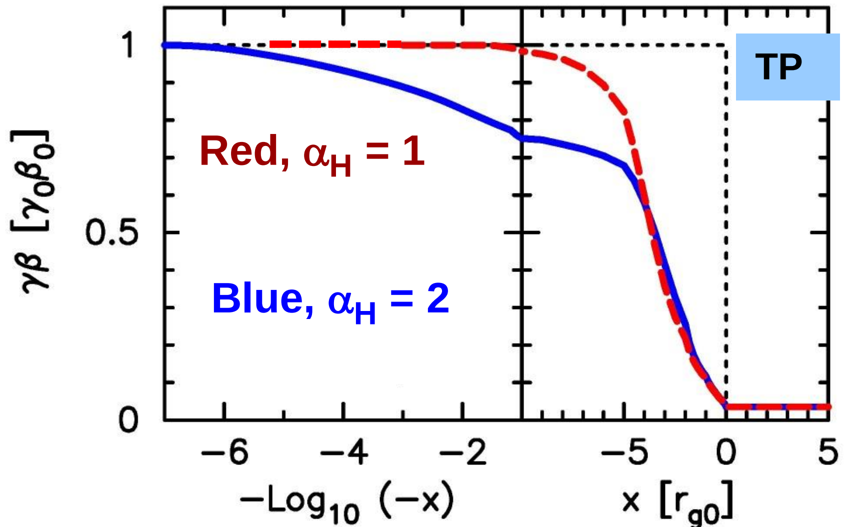
$$\lambda_{scat} \propto p^{\alpha_H}$$

In given shock, large α_H ➔ low maximum CR energy

Note: In unmagnetized relativistic shocks, geometry of background B-field unimportant (Sironi+2013).
Use parallel B-field geometry in MC

Shock structure determined by CR back-pressure

$\gamma\ \beta$ of plasma flow vs. x



Distance

$$\lambda_{\text{scat}} \propto p^{\alpha_H}$$

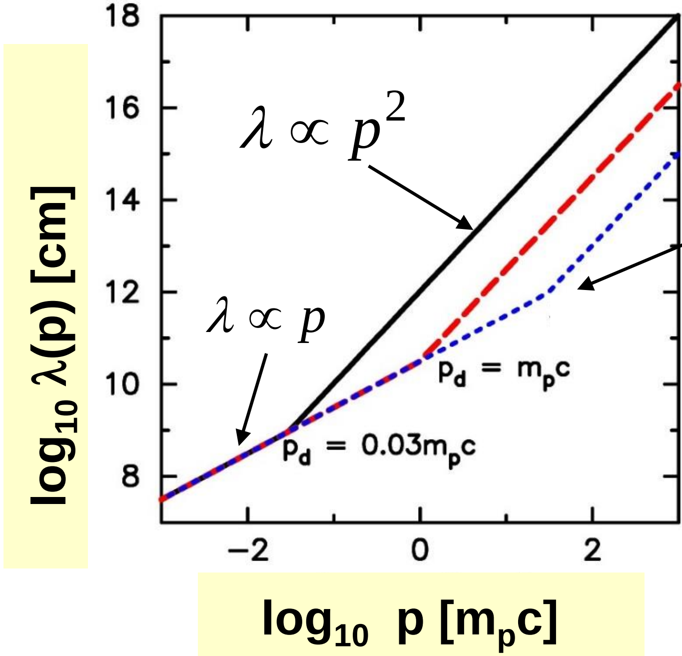
Upstream ← | → **Downstream**

Subshock

Shock size adjusted to give same maximum CR energy

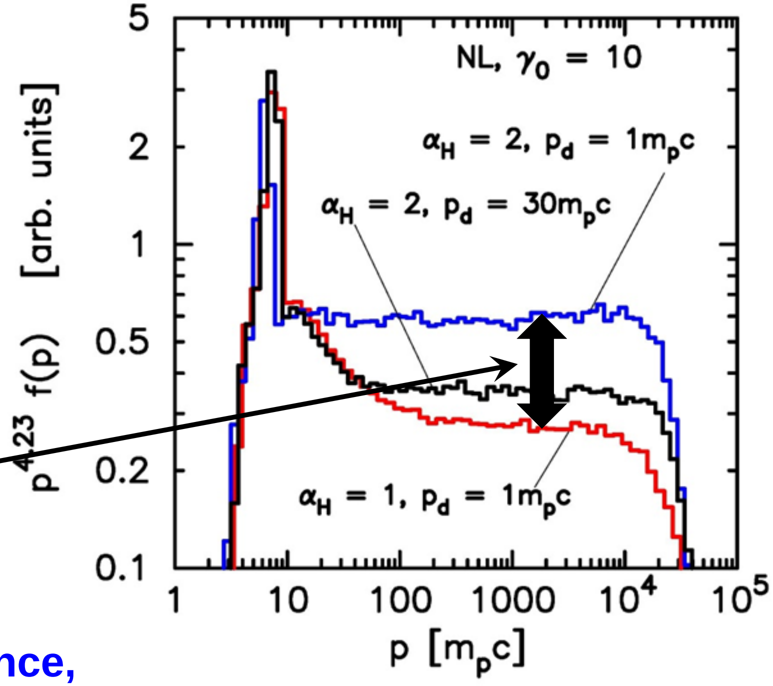
In self-consistent shock, Fermi acceleration has additional dependence on form for λ_{scat}(p), besides simple scaling

If $\alpha_H > 1$, $\lambda(p)$ can't be simple power law if require $\lambda(p) \geq r_g$



Must have break in $\lambda(p)$ at some momentum, p_d

protons



➔ Fermi acceleration depends on both α_H and p_d

➔ This is purely relativistic effect.

In parallel, non-rel. shocks no dependence, other than scale, on α_H or p_d

Monte Carlo Models of Relativistic Fermi Acceleration

1) Plasma physics complicated ➔ need PIC simulations of rel. shocks
   a) But, PIC simulations are limited in dynamic range

2) Self-generated turbulence and particle scattering not yet determined
   a) Weibel instability only part of story
   b) Need large PIC simulations to test for long-wavelength turbulence
   c) Momentum dependence for mean-free-path important

3) Important aspects of kinematics can be studied with Monte Carlo simulations
   a) MC has less plasma physics
   b) But, must conserve momentum & energy regardless of plasma physics details
   c) Parameterizations can be useful

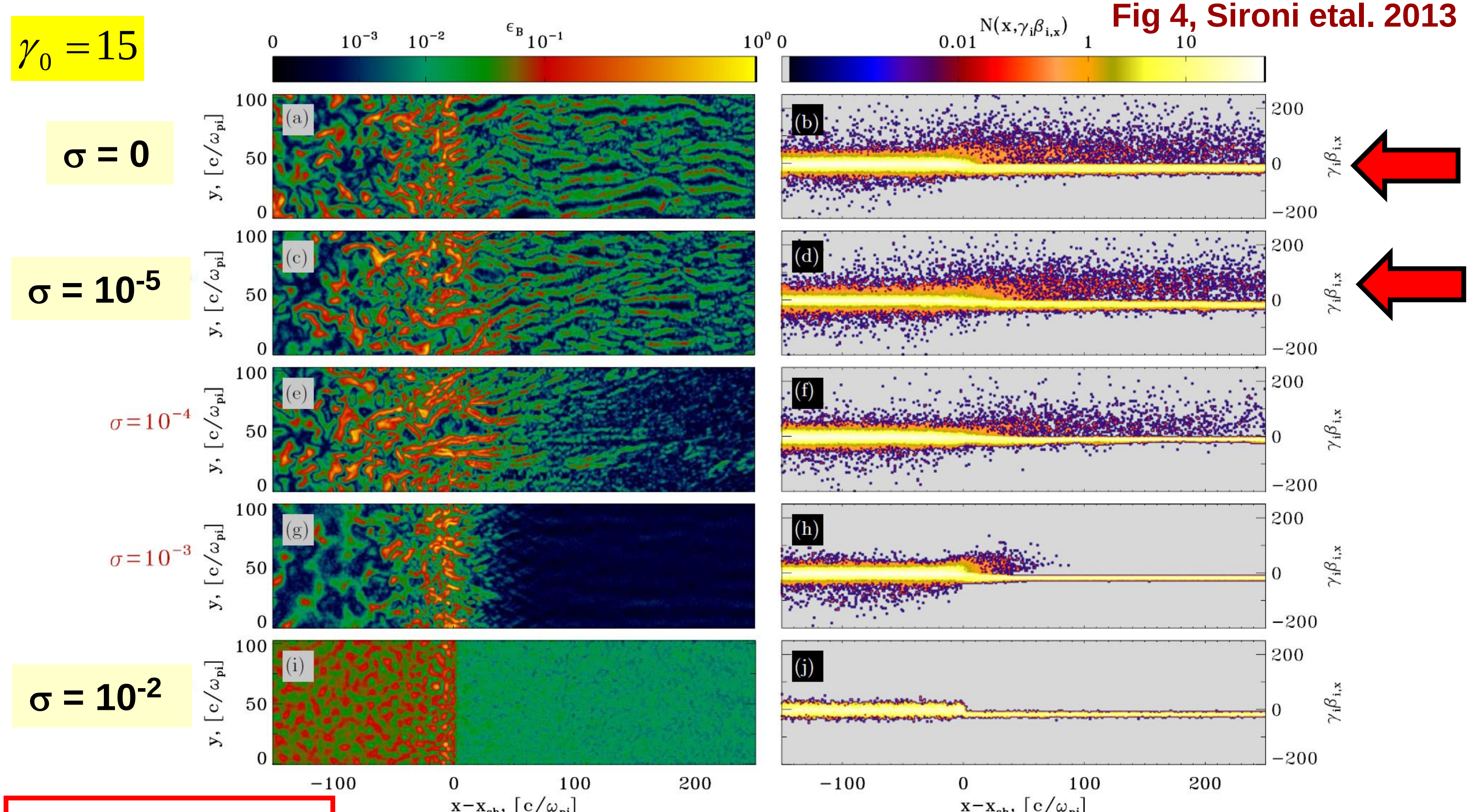
4) General properties of nonlinear Fermi acceleration :
   a) Spectral shape can differ from simple power law
   b) Self-consistent model needed for absolute normalization
   c) Electrons influenced more by NL effects than ions ➔ Photons!!
   d) Understanding "Unseen protons" critical for understanding sources

Extra Slides

Can we ignore obliquity? Sironi etal. 2013 : Low magnetization (low σ) relativistic shocks can effectively inject and accelerate particles regardless of obliquity !!

$\gamma_0 = 15$

Fig 4, Sironi etal. 2013



$$\sigma = \frac{B_{\rm ISM}^2}{4\pi n m_i c^2}$$

Perpendicular geometry and thermal injection are NOT show stoppers for rel. shocks

Low magnetization should apply for GRB afterglows