Particle Acceleration in Astrophysics

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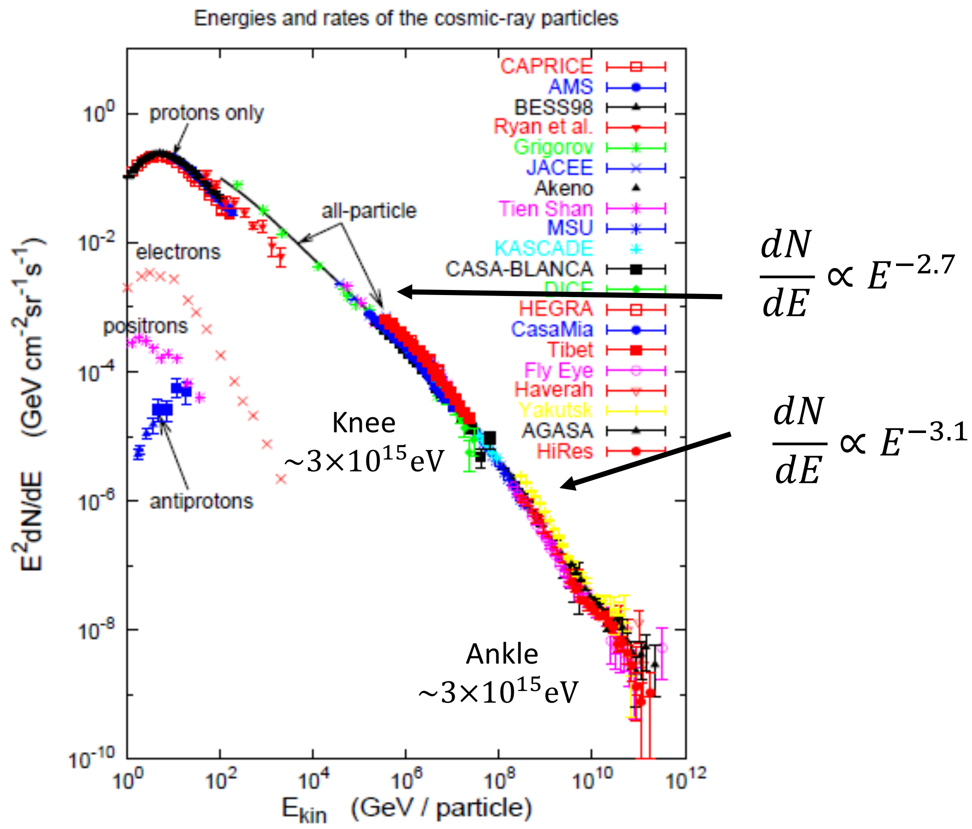
Cosmic Rays (CRs): Introduction

- CRs refer to the high-energy extraterrestrial particles.
- CRs contribute an energy density of $1 \mathrm{eV/cm^3}$.
- CRs are essentially collisionless.
- Most CRs drift and diffuse in magnetic field.



Gaisser (2005)

CRs: Early Research

- Victor Hess (1912): Measured the ionizing radiation in the atmosphere thorough a series of balloon experiments and concluded the radiation came from out of the earth.
- Robert Millikan (1925): Named it "Cosmic Rays" .
- Jacob Clay (1927): Confirmed CRs were charged particles.
- **Where are they from?**
- Baade and Zwicky (1934): First proposed CRs originated from supernova remnants (SNRs).

Hess (center) on the balloon (wikipedia)

CRs Acceleration: General Considerations

- Lorentz Force: $\frac{d(\gamma v)}{dt} = \frac{q}{m}(E + \frac{v}{c} \times B)$
- Magnetic Fields do not work!
- $E_{\perp} = -\frac{v_{\text{flow}}}{c} \times B$
- Only moving fields can work!
- $E_{\parallel}$
- Zero in ideal MHD!

Towards the Origin of CRs: Fermi Acceleration

- Enrico Fermi (1949): Particles are accelerated in ISM thorough collisions with “moving magnetic fields”.

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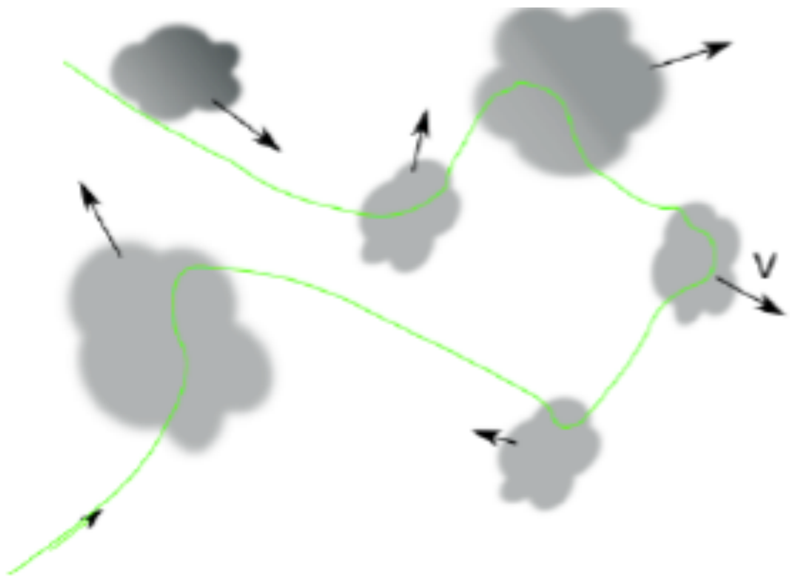
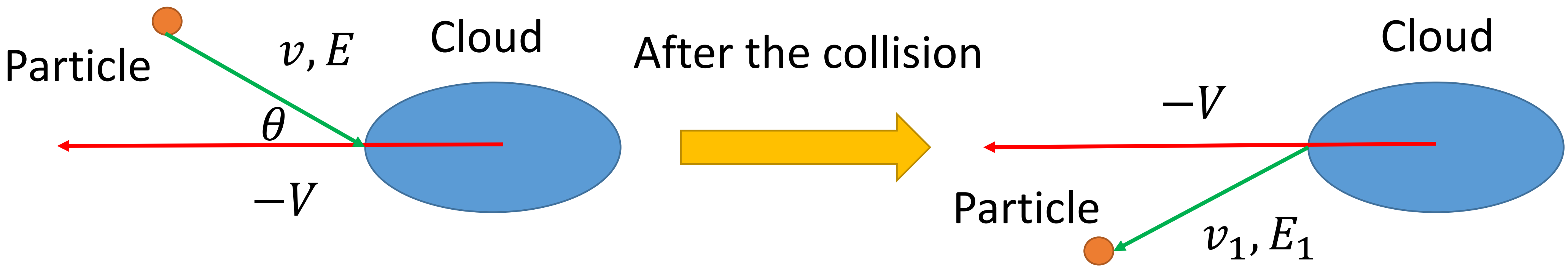


An illustration for Fermi’s model.

(The magnetic fields are carried by non-relativistic moving clouds in ISM . CRs randomly scatter from the clouds and statistically gain energy.)

Second-Order Fermi Acceleration :



- $E_1 = \gamma_V^2 E\left(1 + \frac{2Vv\cos\theta}{c^2} + \frac{V^2}{c^2}\right)$;
- $\frac{E_1 - E}{E} = \frac{\Delta E}{E} \approx \frac{2Vv\cos\theta}{c^2} + \frac{V^2}{c^2}$ (Expand to 2nd order of $\frac{V}{c}$);
- $f(\theta)d\theta = \frac{1}{2}(1 + \frac{V\cos\theta}{c})\sin\theta d\theta$ (The distribution function of θ);
- $\left\langle\frac{\Delta E}{E}\right\rangle \approx \frac{8}{3}\frac{V^2}{c^2}$

Energy Spectrum:

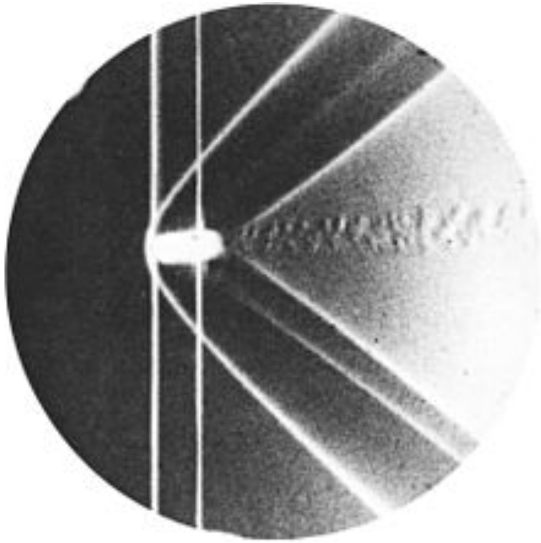
- CRs gain energy at a rate that is proportional to their energy, and escape from the acceleration region in a Poisson process with energy-independent probability.
- Two scale time τ_{acc} and τ_{esc}.
- Initially, N_0 particles with energy E_0;
- After time t, $E = E_0 e^{t/\tau_{acc}}$, $N = N_0 e^{-\frac{t}{\tau_{esc}}} = N_0 \left(\frac{E}{E_0}\right)^{-\frac{\tau_{acc}}{\tau_{esc}}}$;
- $\frac{dN}{dE} \propto E^{-(1+\frac{\tau_{acc}}{\tau_{esc}})}$ Power-law energy spectrum!

Disadvantages of 2nd-order Fermi Acceleration:

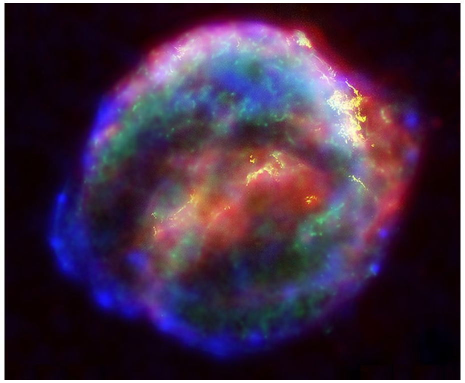
- Normally $\frac{V}{c} \sim 10^{-4}$, so 2rd-order Fermi Acceleration is too slow to drive particles to high energy.
- The process can produce a power-law energy spectrum, but the power-law index is unconstrained.
- There exists injection threshold energy for particle to overcome ionization loss.

First-Order Fermi Acceleration: Diffusive Shock Acceleration (DSA)

- Bell(1978);Blandford & Ostriker (1978) proved the 1st order Fermi Acceleration could happened at the shock front.

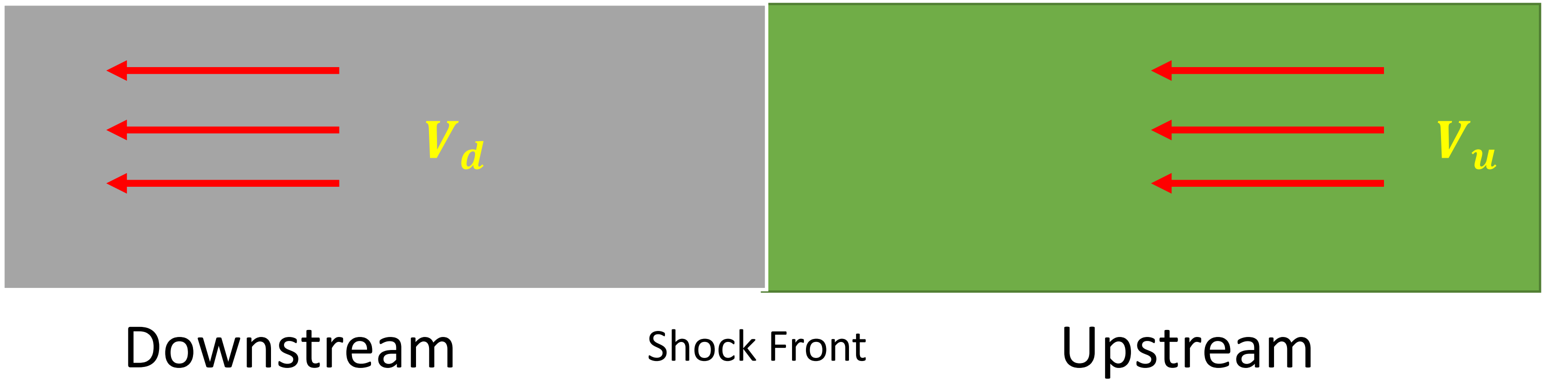


Shocks are formed when the perturbation in a fluid propogates faster than the sonic speed. Here is a picture of the shock on a flying bullet (E.Mach & P. Salcher 1887).



Shocks are common in astrophysics environment, e.g. supernova explosion and Gamma ray bust. Left: SNRs; Right:GRBs. (wikipedia)

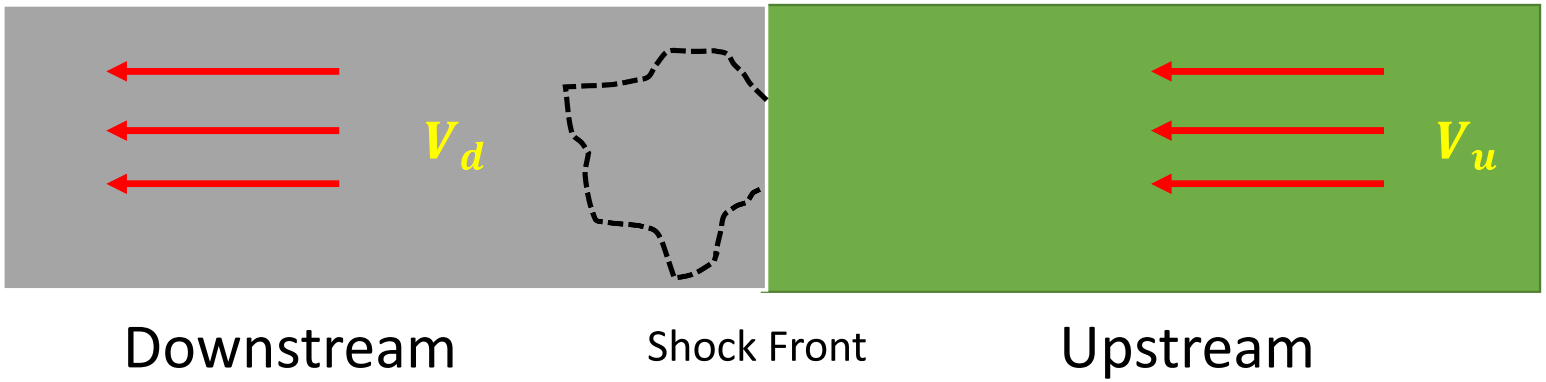
Physics of Shock:



- Discontinuity:

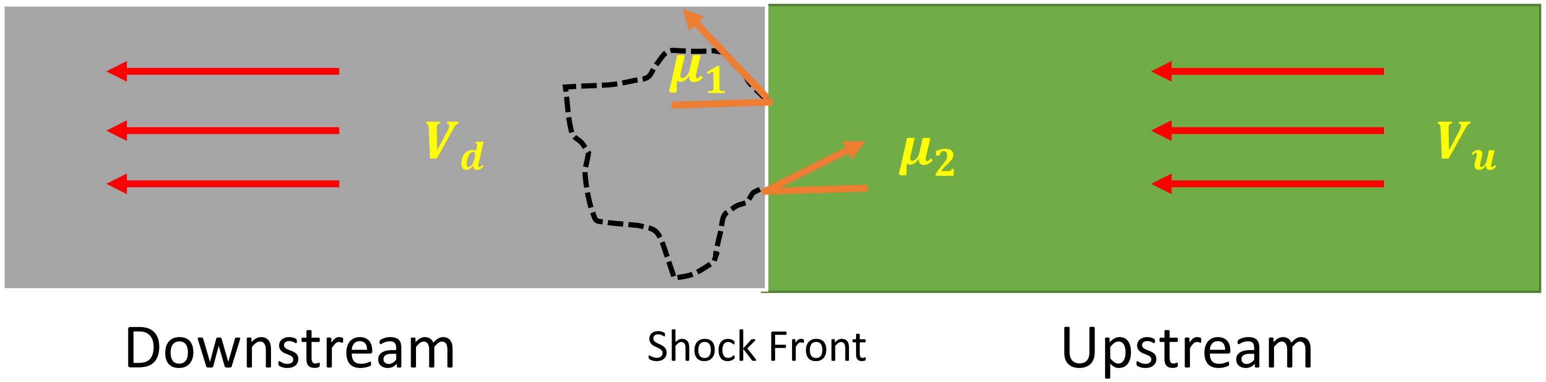
  e.g. In high-Mach limit, $\frac{\rho_d}{\rho_u} = \frac{v_u}{v_d} = r = 4$ (r is the compression ratio)
- Converging Flow
- Energy Dissipation

Physics of Shock:



- Particles diffuse due to the turbulence.

Physics of Shock:



- Energy initially in upstream frame : E_1;
- Energy in downstream frame : $E_2 = \gamma_V E_1(1 + \beta\mu_1)$;
- Energy finally in upstream frame: $E_1' = \gamma_V E_2(1 - \beta\mu_2)$;
- $\left\langle \frac{\Delta E}{E_1} \right\rangle = \frac{4}{3}\beta$
- $\beta = (V_d - V_u)/c, \gamma_V = (1 - \beta^2)^{-1/2}$

Energy Spectrum:

- Define the probability of CRs remain in accelerated region after one cycle:
- J_+: the flux of CRs entering the shock from upstream
- J_-: the flux of CRs returning to upstream from downstream
- J_∞: the flux of CRs escaping in far downstream
- $\mathrm{P} = \frac{J_-}{J_+} = \frac{J_-}{J_- + J_\infty}$
- Index for power-law: $s = 1 + \frac{3}{r-1}$ ($s = 2$ when $r = 4$)
- From convection-diffusion equation:
- $f(p) \propto p^{-4} \rightarrow f(E) \propto E^{-1.5}$(non-relativistic particle)

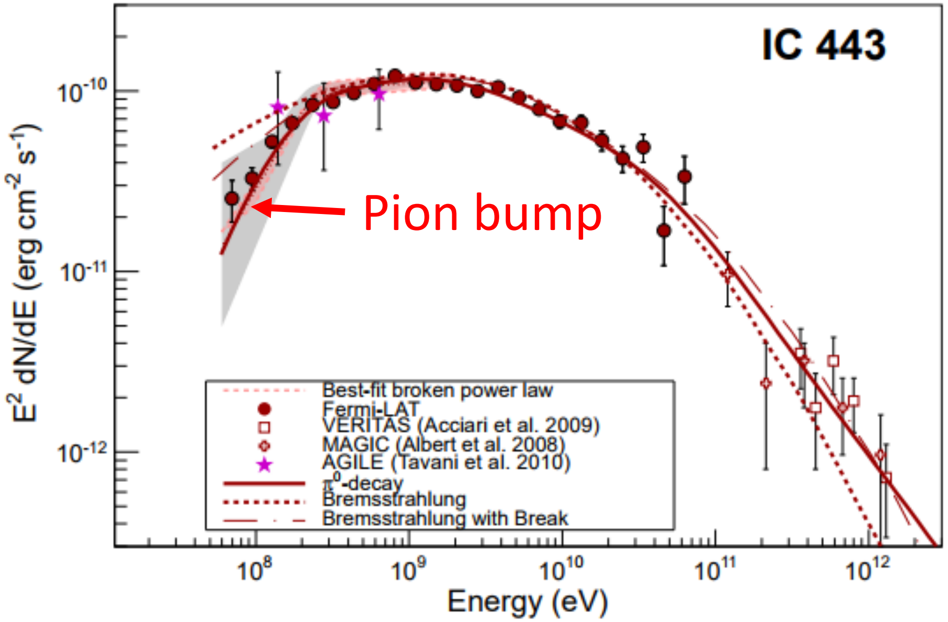
  $f(E) \propto E^{-2}$ (relativistic particle)

Acceleration Rate:

- In one acceleration cycle for CRs (upstream-downstream-upstream):
- The duration time: $t_{\mathrm{cycle}} = \frac{4D_u}{V_u c} + \frac{4D_d}{V_d c}$;
- D_u and D_d is the diffusion coefficient in upstream or downstream;
- Acceleration rate: $\frac{dE}{dt} = \frac{4(V_{\mathrm{d}} - V_{\mathrm{u}})}{3c} \frac{E}{t_{\mathrm{cycle}}}$;
- In Bohm limit, $\frac{dE}{dt} = \mathrm{const} \rightarrow E_{max} \propto t$
- Without radiation loss, the total energy increases linearly with time!

Maximum energy achieved in SNRs:

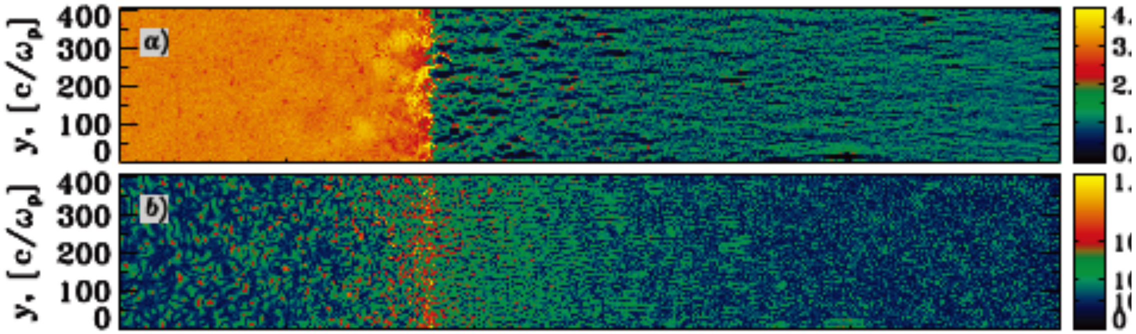
- For a SNR shock, $t \sim 10^3 years, V_u \sim 5000 kms^{-1}, B_u \sim 10\mu G$,
- The estimated maximum energy is $\sim \mathrm{PeV}(10^{15}\mathrm{eV})$!
- For higher energy, we should consider other sources!



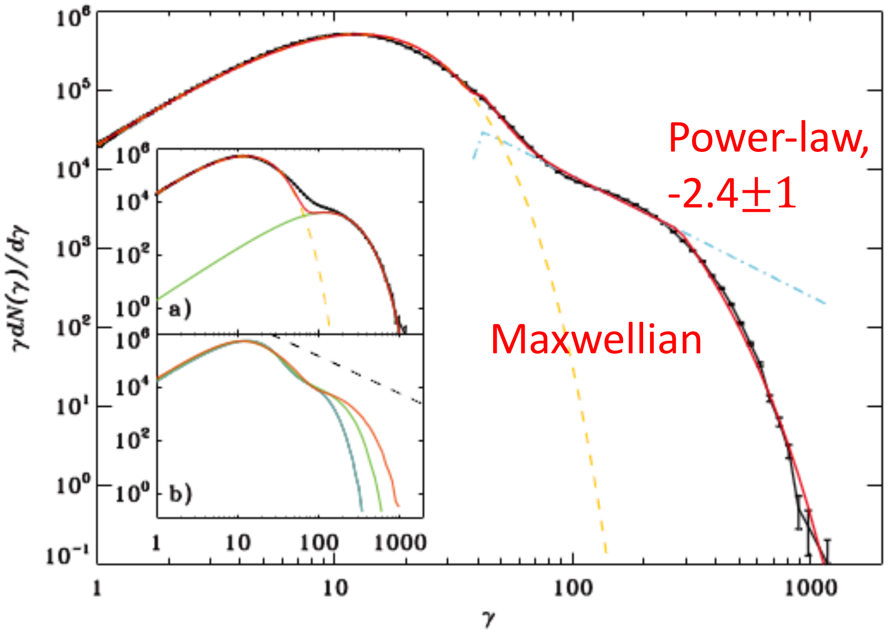
CRs acceleration in SNRs can be tested by e.g. the generated γ-ray emission. (Energy Spectrum of SNR IC443, M. Ackermann et al. 2013)

Numerical Simulations (1):

A. Spitkovsky (2008) first simulated a self-consistent particle acceleration process with collisionless relativistic shock in electron-positron pair plasmas



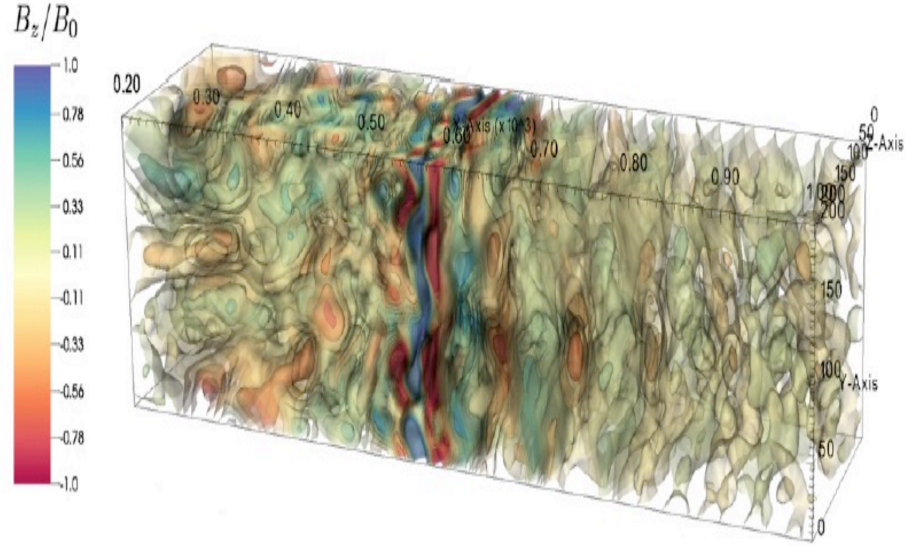
Density and magnetic energy density on the simulation plane (Spitkovsky 2008)



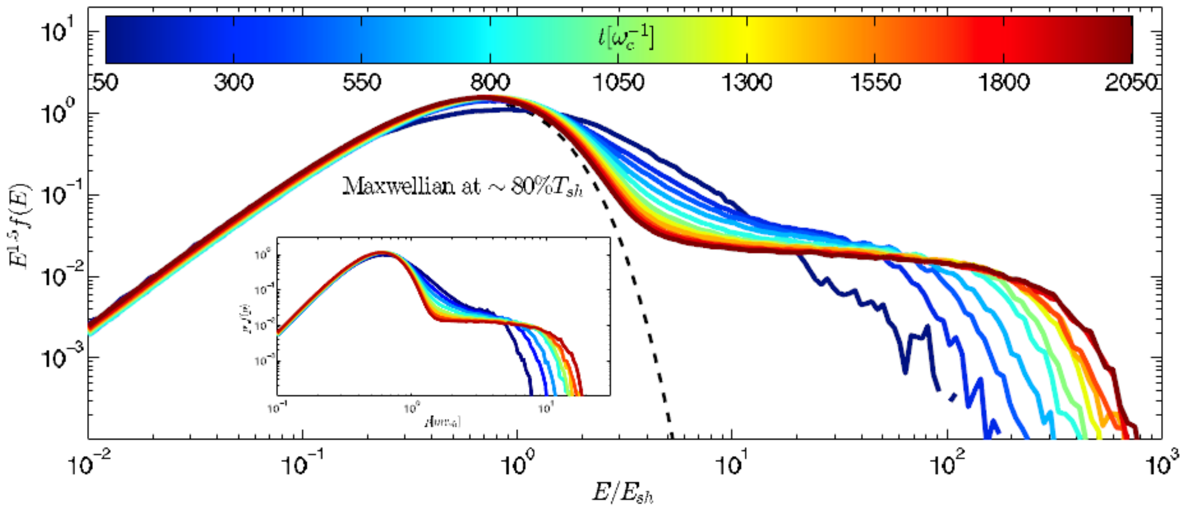
Particle energy spectrum (Spitkovsky 2008)

Numerical Simulations (2):

- D.Caprioli & A. Spitkovsky (2013): simulated the self-consistent particle acceleration process with non-relativistic shock.



Self-generated Magnetic fields in the simulation box, (D.Caprioli & A. Spitkovsky 2013)



Downstream ion energy spectrum at different times (D.Caprioli & A. Spitkovsky 2013)

Summary:

- Cosmic Rays are high energy extraterrestrial particles and important in astrophysics.
- Diffusion shock acceleration can explain the power-law properties of CRs energy spectrum.
- Most CRs are thought to be come from SNRs, and there have been some evidence.
- Present numeric simulations can have a self-consistent acceleration process.

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8. Xuening Bai's Lecture Notes Available on His Webpage.