Acceleration and Escape of First Cosmic Rays

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- First supernova remnant vs. accretion shocks
- Acceleration of first cosmic rays by the first SNR
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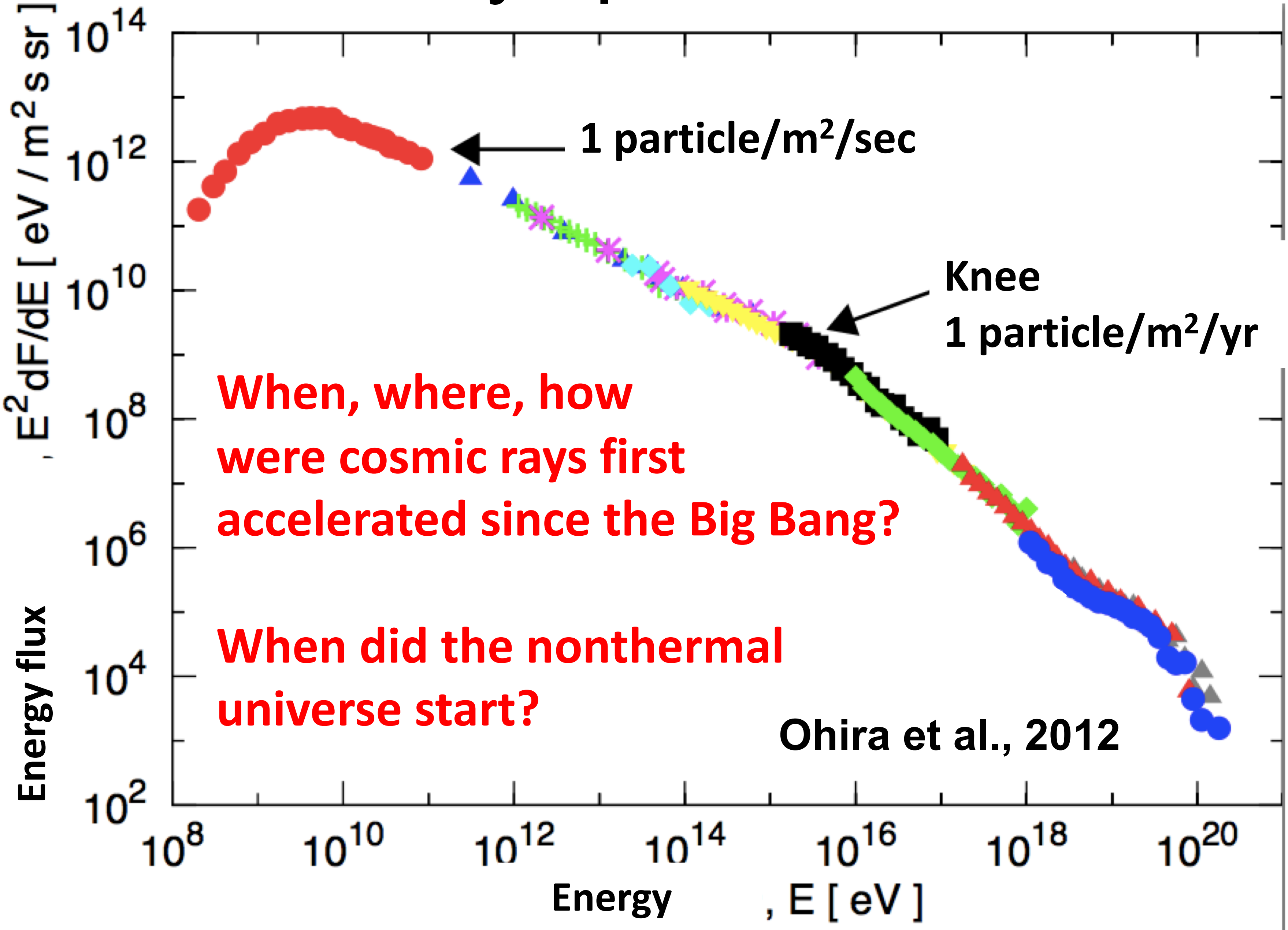
Cosmic-ray spectrum at z = 0



1 particle/m^2/sec

Knee
1 particle/m^2/yr

Ohira et al., 2012

When, where, how were cosmic rays first accelerated since the Big Bang?

When did the nonthermal universe start?

Heating of the primordial gas by CRs

Sazonov & Sunyeav 2015

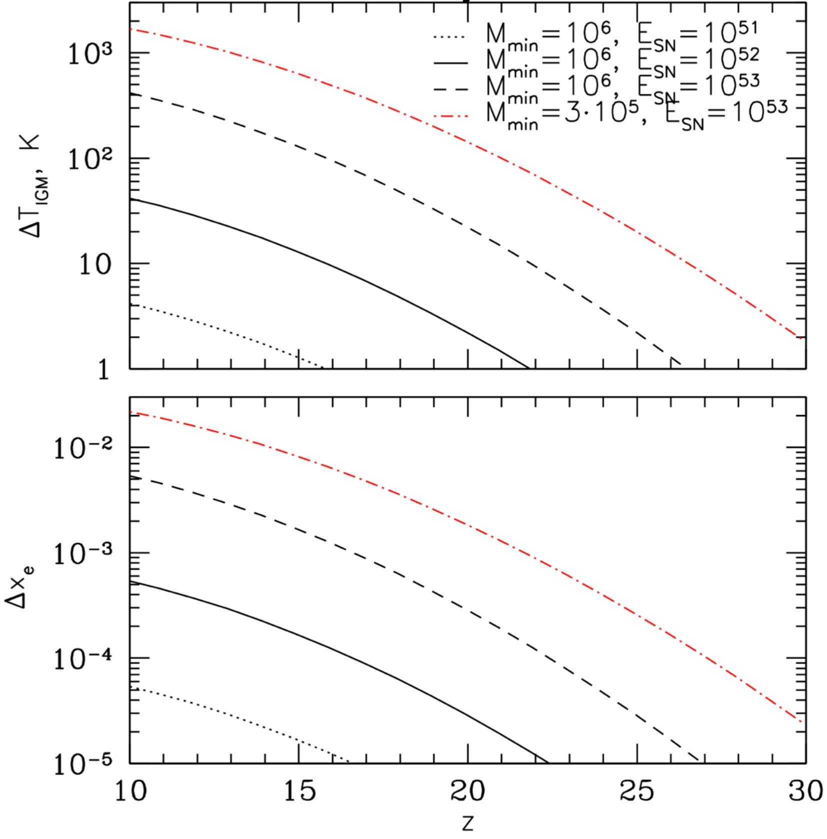


Figure 1. Increment of the IGM temperature (upper panel) and of the ionization fraction (lower panel) caused by LECRs from primordial SNe, as a function of redshift, for three values of the SN explosion energy, $E_{\rm SN} = 10^{51}$ erg (dotted), 10^{52} erg (solid) and 10^{53} erg (dashed). The other parameters are $f_{\rm SN} = 1$, $M_{\rm min} = 10^6\ {\rm M}_\odot$, $M_{\rm max} = 10^7\ {\rm M}_\odot$, $\eta = 0.05$ and $f_{\rm heat} = 0.25$. For $E_{\rm SN} = 10^{53}$ erg also a model with a lower minimum halo mass, $M_{\rm min} = 3 \times 10^5\ {\rm M}_\odot$, is presented (dash–dotted).

Leite et al. 2017

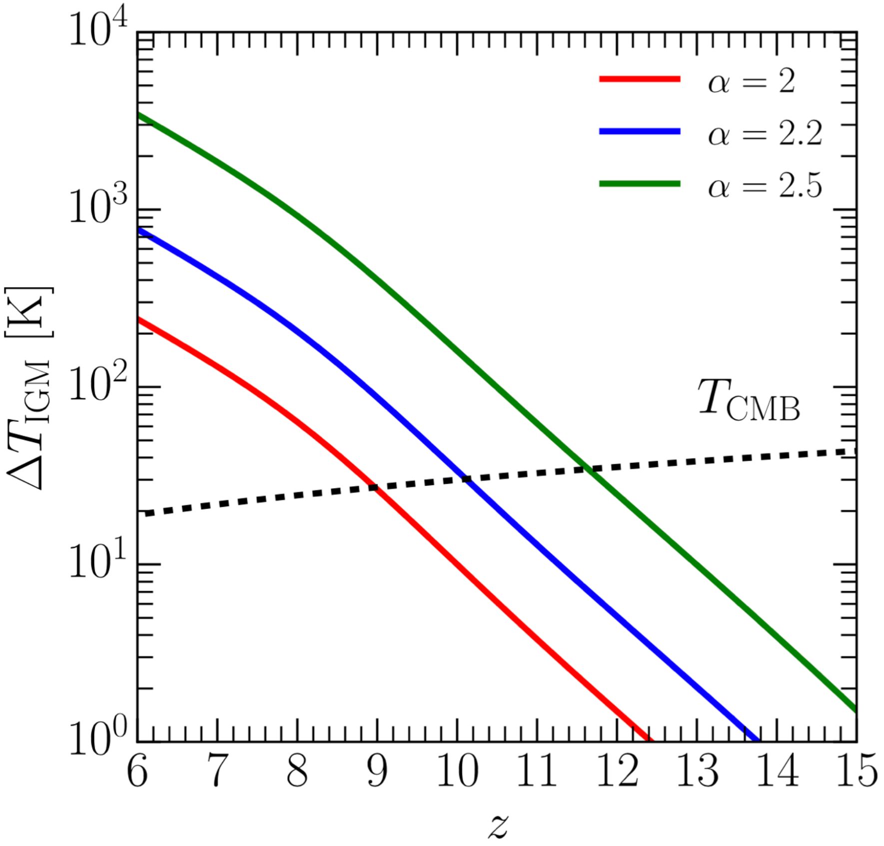


Figure 7. Increment of the average IGM temperature by CRs as a function of redshift for three values of the CR injection slope. The CMB temperature at the same redshift is shown by the dashed line.

Cosmic rays can ionize and heat the primordial gas.

Observation of 21 cm line in radio

Stopping length of free streaming CRs

$R_{free} \sim 1\mathrm{Mpc}\ ((1+z)/21)^{-3}\ (E_{CR}/10\mathrm{MeV})^{2}$

Sazonov & Sunyeav 2015

Diffusion length during the cooling time due to ionization loss (for $l_{mfp} = r_g$)

$R_{diff,B} \sim 30\mathrm{kpc}\ ((1+z)/21)^{-3/2}\ (E_{CR}/10\mathrm{MeV})^{5/4}\ (B/10^{-16}\mathrm{G})^{-1/2}$

Stopping length of X rays

$R_{Xray} \sim 100\mathrm{kpc}\ ((1+z)/21)^{-3}\ (E_{Xray}/\ 0.3\mathrm{keV})^{3.2}$

Mean distance between halos

$R \sim 50\mathrm{kpc}$

Information about CRs and magnetic fields at z ~ 20 could be obtained from the observation of 21 cm line in radio.

CRs with E <~ 10 MeV heat the primordial gas

Leite et al. 2017

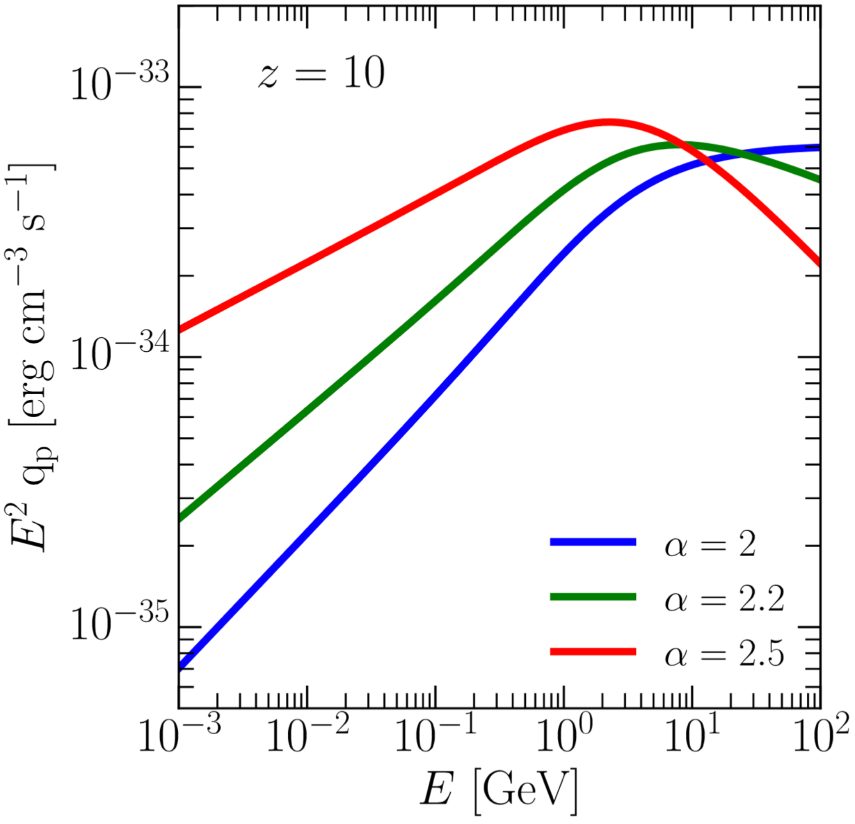


Figure 3. Source function of CR protons with respect to their kinetic energy at $z = 10$ for a spectrum slope $\alpha = 2$ (blue line), 2.2 (green) and 2.5 (red).

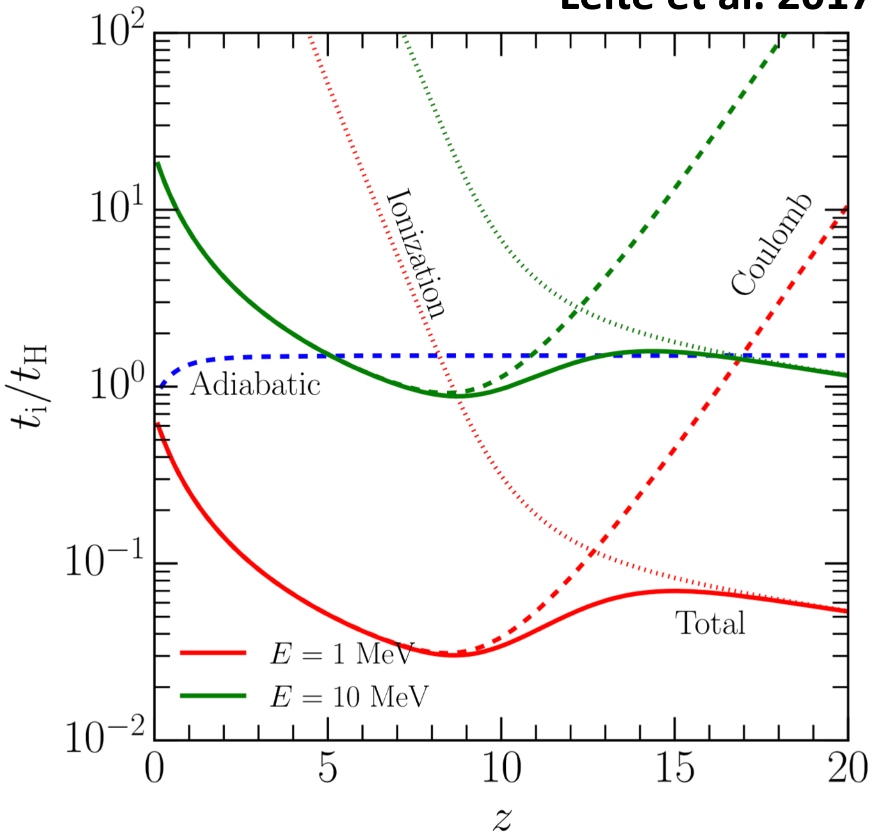


Figure 4. Energy-loss time-scales (see equations [25–27]) normalized to the Hubble time for CR protons of 1 and 10 MeV. The adiabatic time-scale (blue dashed line) is independent of the particle energy.

What is the maximum energy of the first CRs?

Can the first CRs escape from the source?

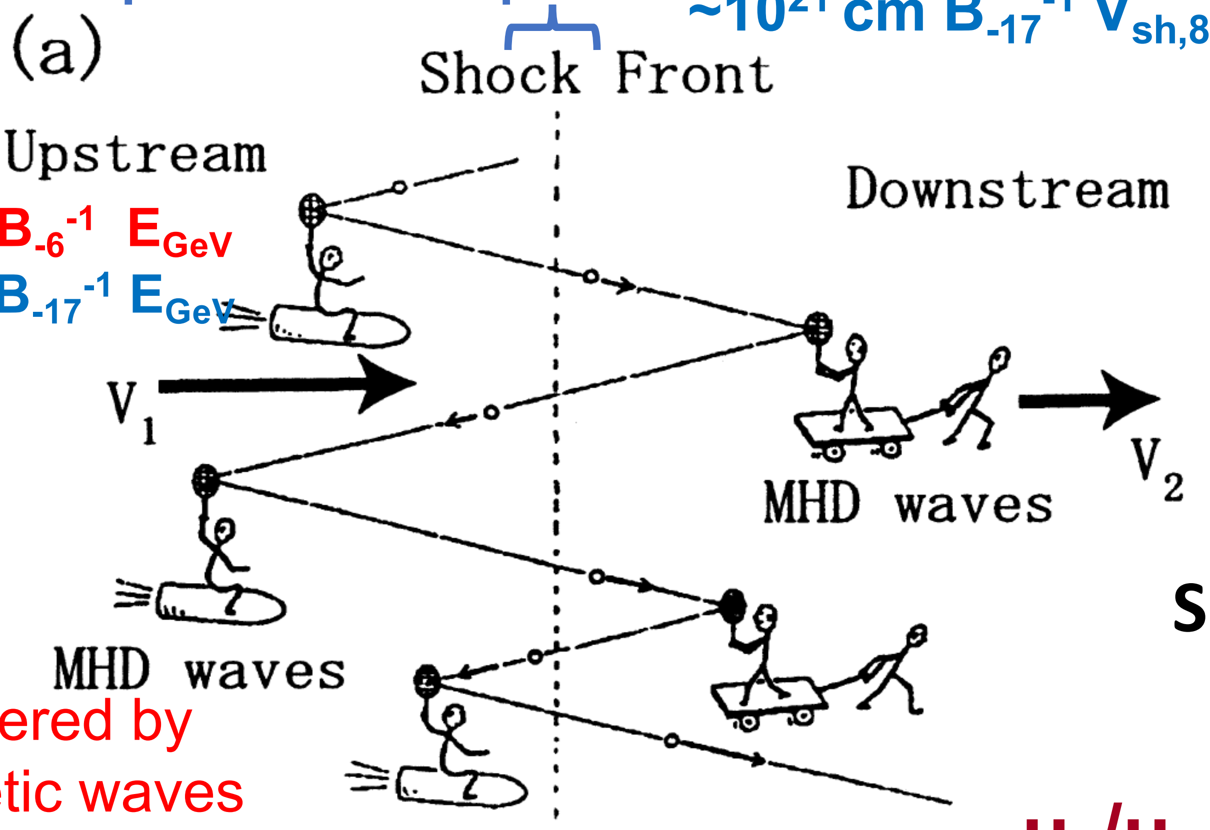
Diffusive Shock Acceleration(DSA)

$r_{gyro,p} \sim 10^{10}$ cm B_{-6}^{-1} $V_{sh,8}$

$\sim 10^{21}$ cm B_{-17}^{-1} $V_{sh,8}$

$L_{diff} \sim 10^{14}$ cm B_{-6}^{-1} E_{GeV}

$\sim 10^{25}$ cm B_{-17}^{-1} E_{GeV}



Scholer

CRs are scattered by Electromagnetic waves

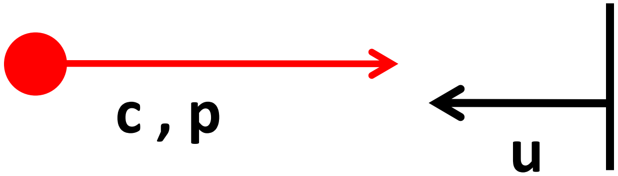
Electromagnetic waves are excited by CRs.

$$\frac{dN}{dE} \propto E^{-s} \qquad s = \frac{u_1/u_2 + 2}{u_1/u_2 - 1} = 2$$

Axford 1977, Krymsky 1977, Blandford&Ostriker 1978, Bell 1978

Acceleration time of DSA

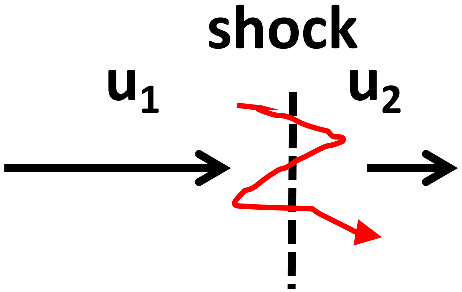
Momentum change by particle scattering, Δp



After scattering,

$$\Delta p = 2\frac{u}{v}p$$

For a shock,



Δp per one cycle is

$$\Delta p = \frac{4(u_1 - u_2)}{3v}p = \frac{u_1}{v}p$$

Time of one cycle, Δt ~ residence time in the upstream region

CR column density ~ $n_{CR}\,(D_{xx}/u_{sh})$ ~ $n_{CR}\,v\,\Delta t$

CR density x diffusion length CR flux x residence time

$t_{acc} = p\,\Delta t/\Delta p \sim D_{xx} / u_{sh}^2$ (Krymsky et al. 1979, Drury 1983)

First supernova remnants vs. accretion shocks

First star are formed at z ~ 20 (Yoshida et al. 2003).
$M = 10 – 1000\ M_{sun}$ (Hirano et al. 2014)

They explode at z ~ 20.

Shock velocity is $V_{sh} \sim 6000\text{km/s}\ E_{SN,51}^{1/2}\ M_{ej,34}^{-1/2}$.

Surrounding maters are ionized by the first stars. (Kitayama et al. 2004)

$B_{ISM} \sim 10^{-17}$ G (Doi & Susa 2011).

An unmagnetized nonrelativistic collisionless shock is formed.

The ion Weibel instability dissipates the upstream ion at the shock (Kato & Takabe 2008).

Cosmic rays could be accelerated by the shock.

Halo mass that can collapse at z=20 ~ $10^6\ M_{sun}$ (3σ)

$V_{sh} \sim V_{vir} \sim 10^6\ \text{cm/s}\ M_6^{1/3}\ ((1+Z)/20)^{1/2}$

Upstream matters are neutral.
(To ionize the upstream matters, $V_{sh} > 10^7$ cm/s
Dopita et al. 2011)

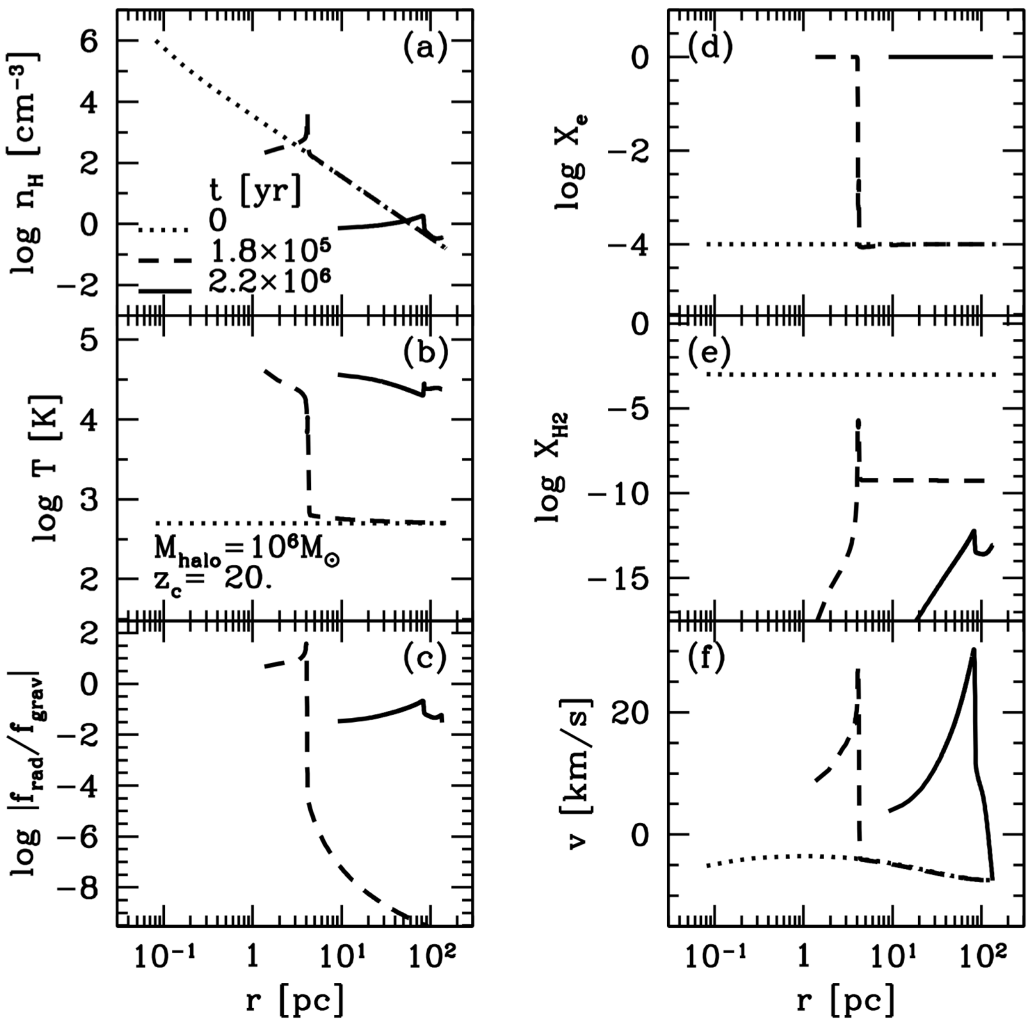
The shock dissipation is due to atomic collision.

→ No cosmic ray is accelerated.

For z < 10, halos with M ~ $10^{10}\ M_{sun}$ can collapse and ionize the upstream matters, so that CRs could be accelerated by the accretion shock at z < 10.
However, …..

Ionization by the first star

Kitayama et al. 2004



of an H II region around a massive star with $M_{star} = 200\ M_\odot$ inside a halo with $M_{halo} = 10^6\ M_\odot$ and $w = 2.0$ at $z_c = 20$. Radial profiles are ed lines), 1.8×10^5 yr (*dashed lines*), and 2.2×10^6 yr (*solid lines*) for (*a*) hydrogen density, (*b*) temperature, (*c*) ratio of radiation force to d) electron fraction, (*e*) H_2 fraction, and (*f*) radial velocity. [*See the electronic edition of the Journal for a color version of this figure.*]

HII region

$n \sim 1$ cm^{-3}

$T \sim 1$ eV

$f_i \sim 1$ ← fully ionized

$B < 10^{-19} – 10^{-17}$ G

(Doi & Susa 2011)

First supernova remnants

$V_{sh} \sim 0.01c\ E_{SN,51}^{1/2}\ M_{ej,1}^{-1/2}$

$t_{Sedov} \sim 1$ kyr $E_{SN,51}^{-1/2}\ M_{ej,1}^{5/6}\ n_{,0}^{-1/3}$

$R_{Sedov} \sim 4$ pc $M_{ej,1}^{-1/3}\ n_{,0}^{-1/3}$

Collisionless shock of the first SNR

Upstream plasma: $n \sim 1\ \mathrm{cm}^{-3}$, $T \sim 1$ eV, $f_i \sim 1$, $B < 10^{-17}$ G, $u_{CMB} \sim 4\times10^{4}\ \mathrm{eV\ cm}^{-3}$

SNR shock: $V_{sh} \sim 0.01c\ E_{SN,51}{}^{1/2} M_{ej,1}{}^{-1/2}$

Gyro radius $r_g > 1$kpc $\gg R_{SNR}$ → The initial background B is negligible.

What types of collisionless shock is formed in the first SNR?

1) The Buneman is the most unstable mode (electrostatic mode).

2) Electrons are strongly heated by the Buneman instability to $T_e \sim m_e V_{sh}^2 \gg T_p \sim 1$eV.

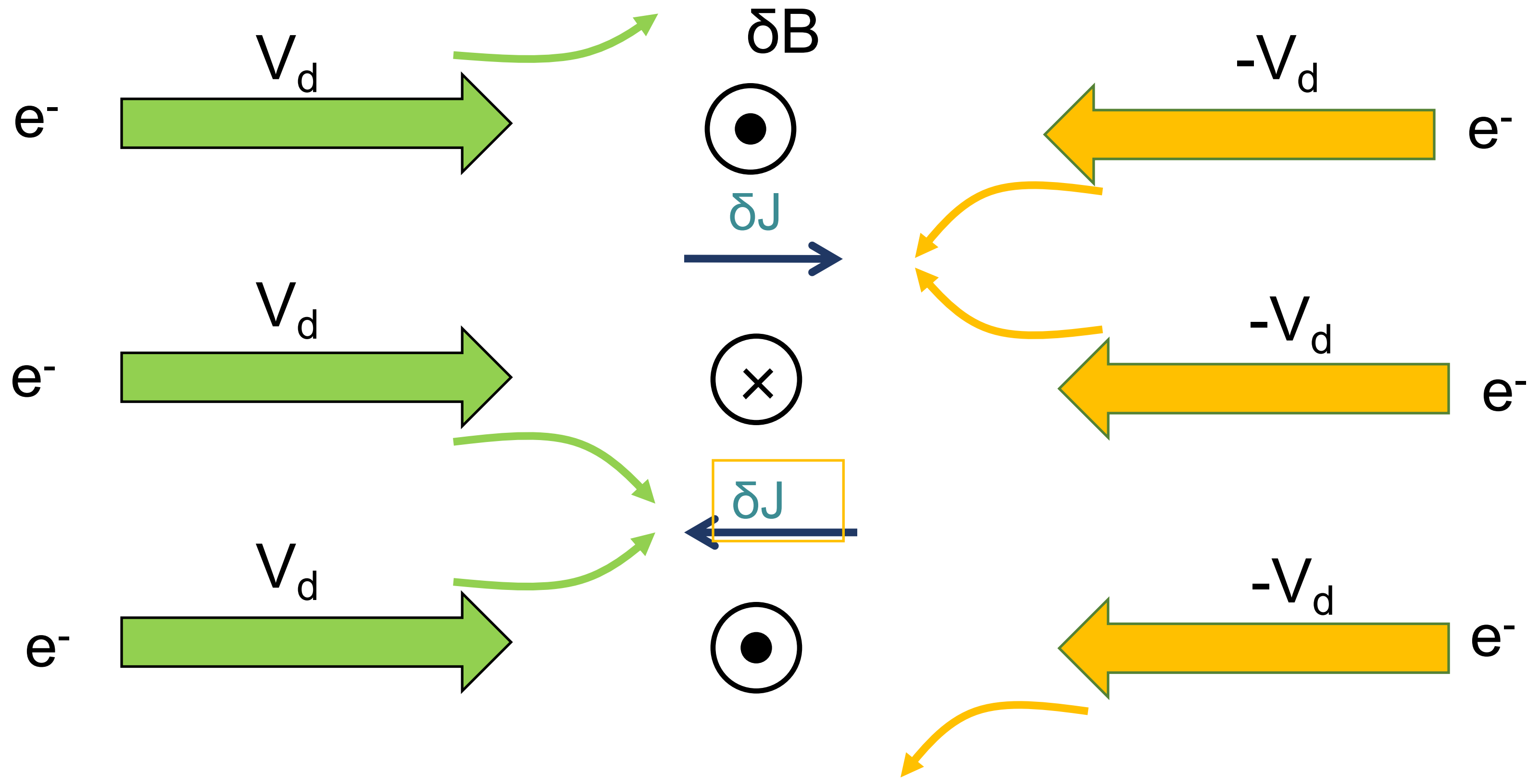
3) Then, the ion-ion twostream instability becomes most unstable mode (electrostatic mode).

4) Then, ions are heated to $T_p \sim T_e \sim m_e V_{sh}^2$ (Ohira & Takahara 2007,2008).

5) The ion Weibel instability becomes the most unstable mode (electromagneteic mode).

Most of the kinetic energy of protons are not dissipated by the early electrostatic instabilities. Therefore, collisionless shocks driven by the first supernova remnant is nonrelativistic Weibel mediated shocks.

Weibel instability



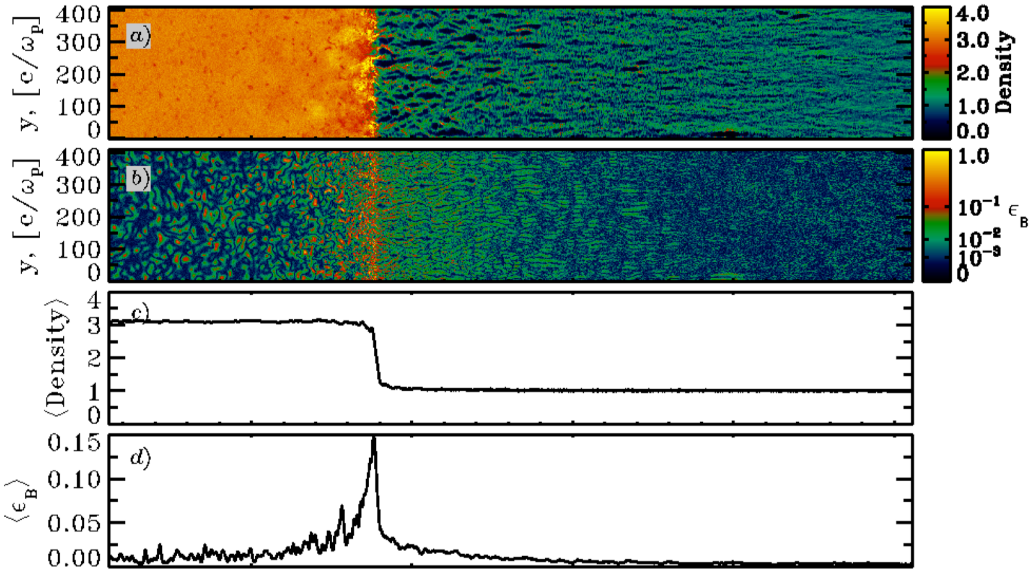
$V_d \perp k$

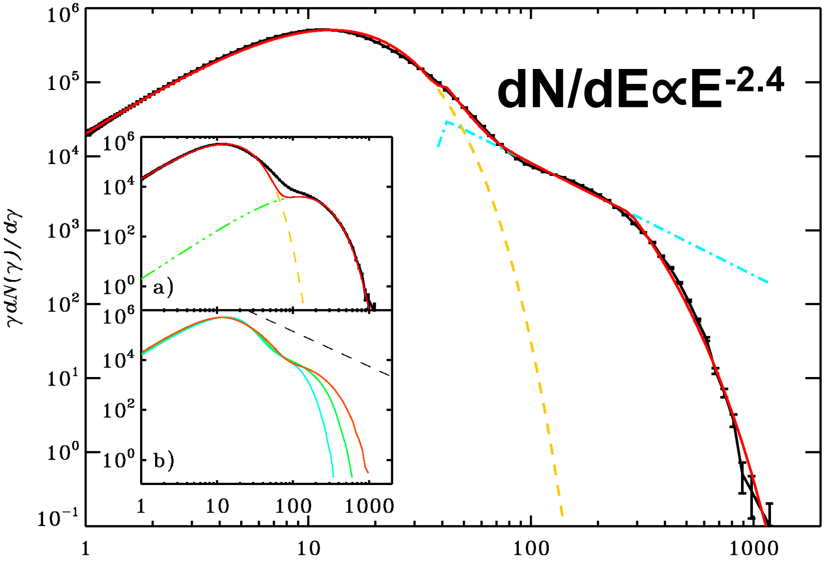
Growth rate **$\mathrm{Im}[\omega] = (V_d/c)\,\omega_p$**

Wave length **$k^{-1} = c / \omega_p$**

PIC simulations of Weibel mediated shocks

Particle-in-cell simulations solve Maxwell equations and equation of motions for many charged particles.





$dN/dE \propto E^{-2.4}$

Spitkovsky 2008

Spectral index ~ 2.4

For a relativistic Weibel mediated shock, the PIC simulation shows that particles are accelerated by DSA.

For V_{sh} ~ 0.1c, DSA is not observed in PIC because of the short simulation time.

Kato & Takabe (2008)

Summary

When, where, how were first cosmic rays accelerated?

First CRs could be investigated by observations of 21cm in radio.

^{6}Li ?

Accretion shocks of the structure formation at z~20 cannot accelerate cosmic rays because the upstream gas is neutral.

Supernova remnants of first stars accelerate first cosmic rays to ~ 400 MeV.
CRs (4 MeV < E < 400 MeV) can escape from the first SNRs and heat the primordial gas.

Accretion shocks of the structure formation at z<10 can accelerate CR protons to ~300keV but they cannot escape to the far upstream because of the ionization loss. However, CR e- can escape.