

# Acceleration and escape of first cosmic rays

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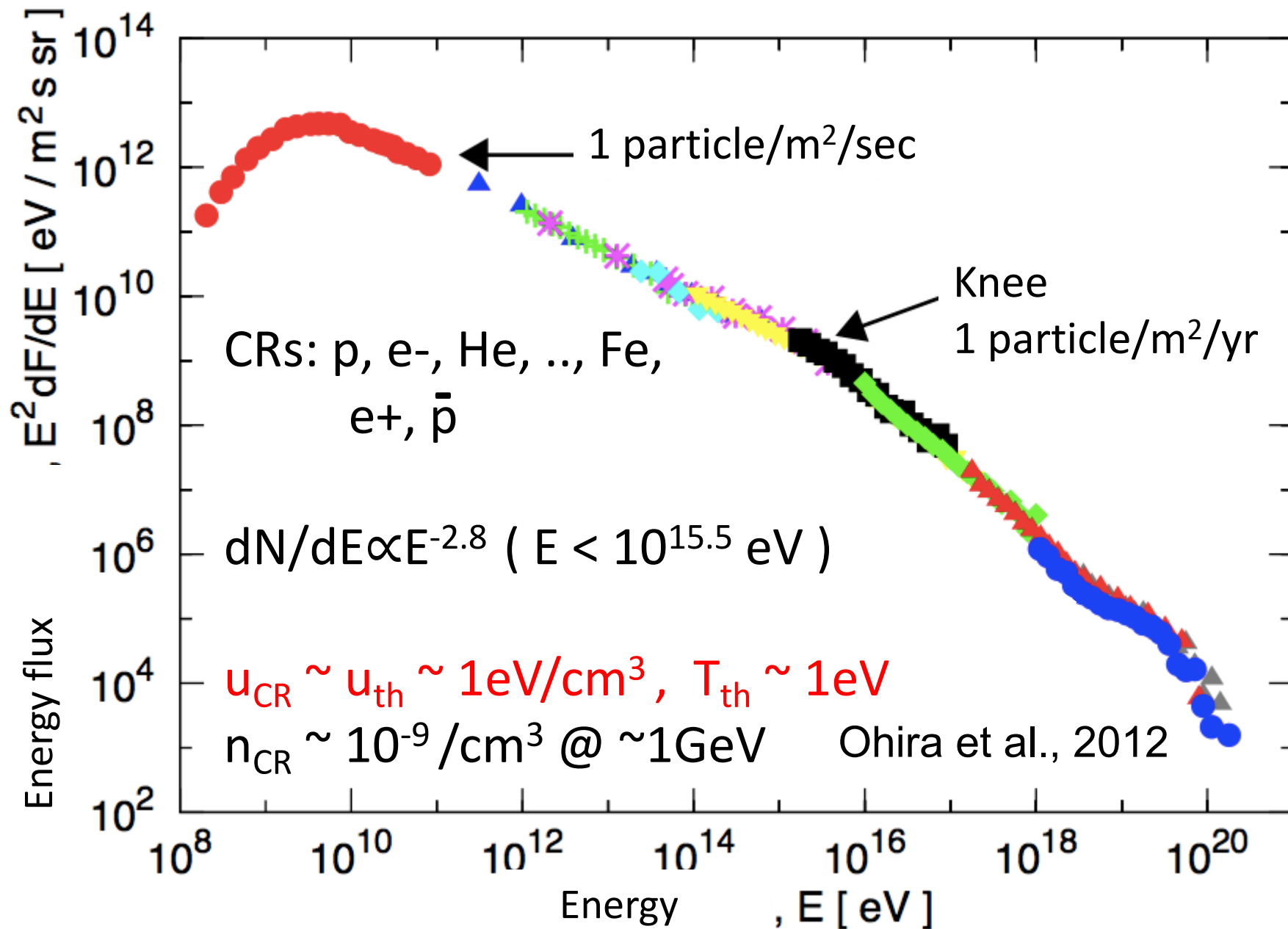
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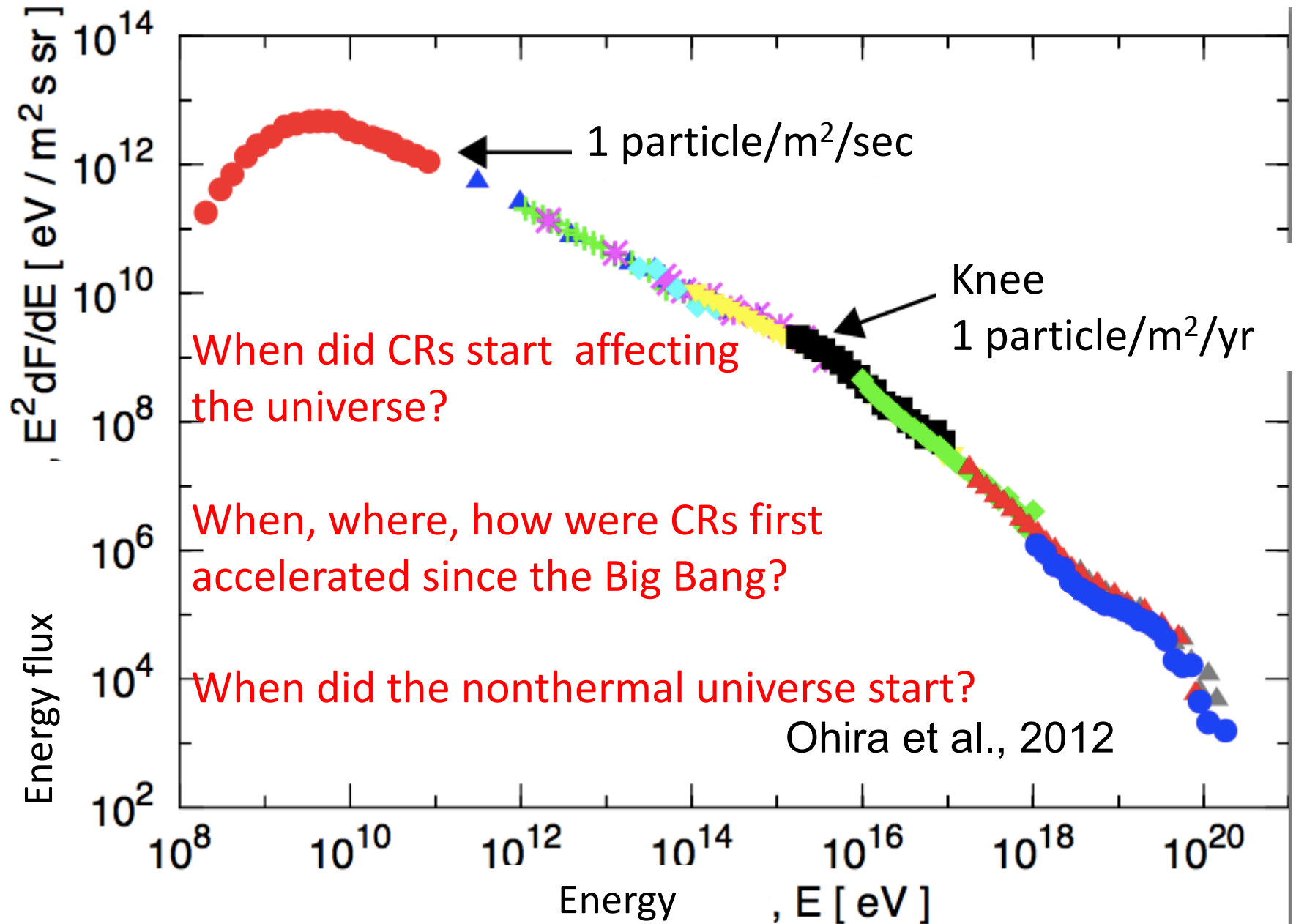
Ohira & Murase (2018)

- When, where, how were CRs first accelerated?
- First supernova remnant and accretion shocks
- Acceleration of first cosmic rays by the first SNR

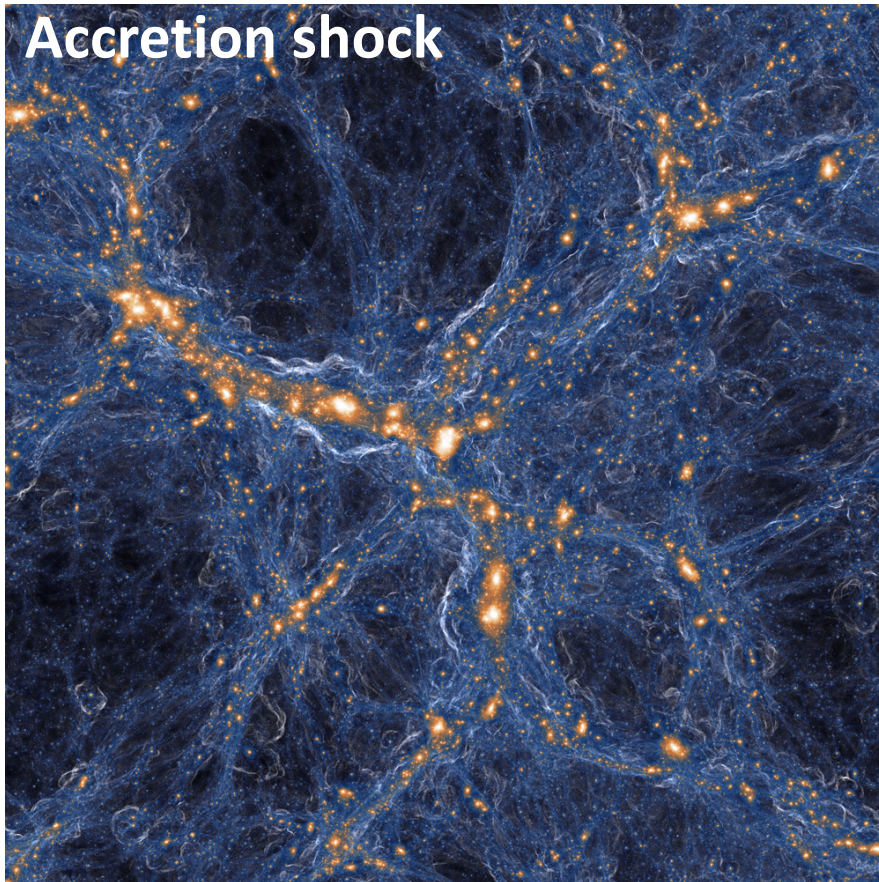
# Cosmic-ray spectrum in the current universe



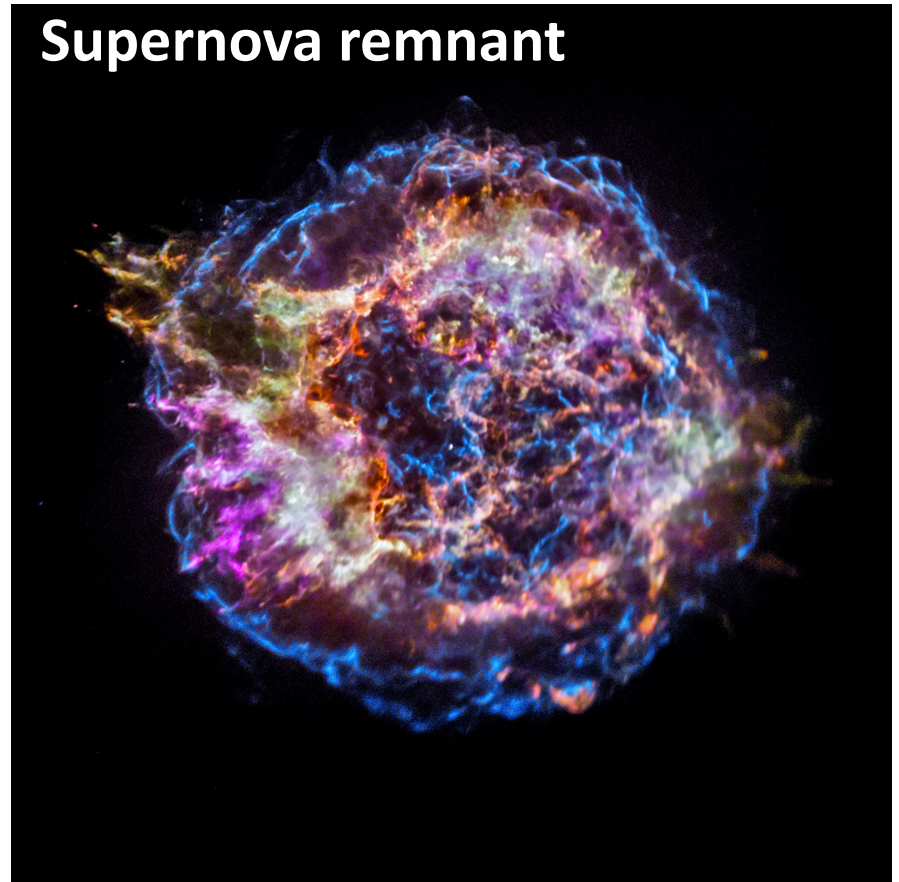
# Cosmic-ray spectrum in the current universe



# Accretion shocks in the structure formation vs. first supernova remnants



IllustrisTNG project  
<http://www.tng-project.org/>



NASA/CXC/SAO

# First supernova remnants vs. accretion shocks

First stars are formed at  $1.8 \times 10^8$  yrs after the Big Bang ( $z \sim 20$ ) (Yoshida et al. 2003).

$M = 10 - 1000 M_{\text{sun}}$  (Hirano et al. 2014)

Their lifetime is  $\sim 10^6$  yr.

They explode at  $1.8 \times 10^8$  yrs after the Big Bang.

Most matters are still neutral at  $1.8 \times 10^8$  yr, but surrounding matters are ionized by the first stars. (Kitayama et al. 2004)

- The shock is a collisionless shock.
- Cosmic rays could be accelerated.

Only small objects can be formed because of the uniform expansion of the universe.

$M \sim 10^6 M_{\text{sun}}$  at  $z \sim 20$  ( $3\sigma$ )

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

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

The shock dissipation is due to atomic collision.

- No cosmic ray is accelerated.

# Collisionless shock of the first SNR

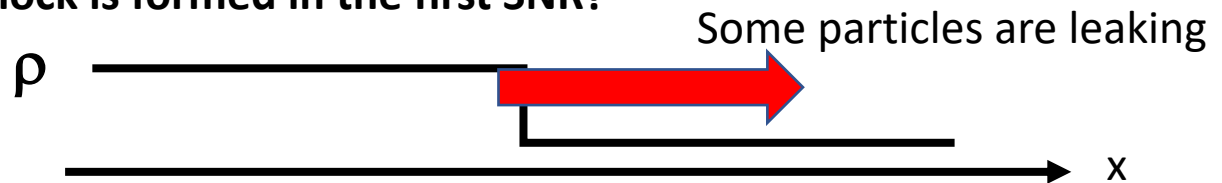
Upstream plasma:  $n \sim 1 \text{ cm}^{-3}$ ,  $T \sim 1 \text{ eV}$ ,  $f_i \sim 1$ ,  $B < 10^{-17} \text{ G}$ ,  $u_{\text{CMB}} \sim 4 \times 10^4 \text{ eV cm}^{-3}$

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

Kitayama et al. 2004, Doi & Susa 2011

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

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



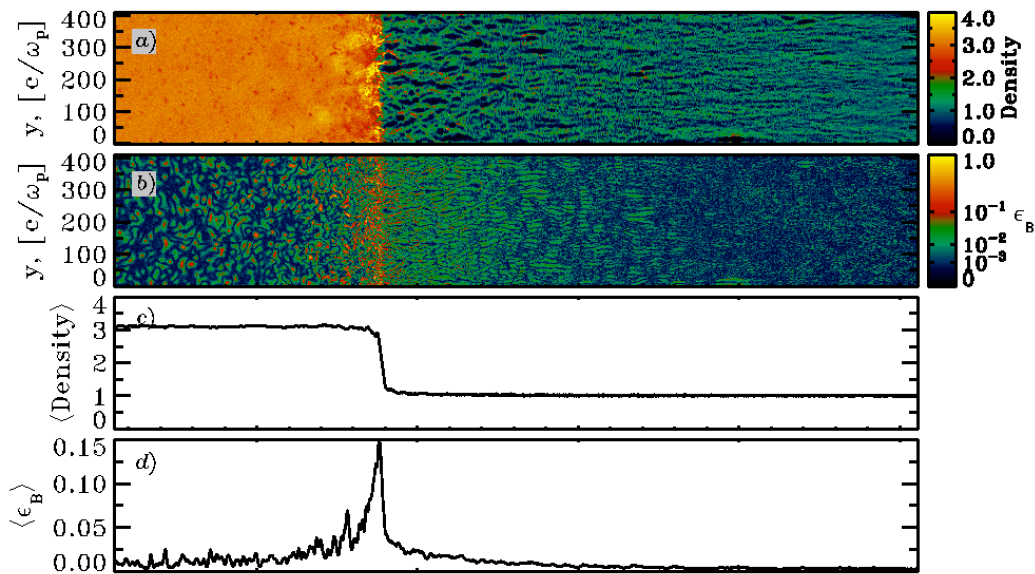
- 1) The Buneman is the most unstable mode (electrostatic mode).
- 2) Electrons are strongly heated by the Buneman instability to  $T_e \sim m_e V_{\text{sh}}^2 \gg T_p \sim 1 \text{ eV}$ .
- 3) Then, the ion-ion twostream instability becomes most unstable mode (electrostatic mode).
- 4) Then, ions are heated to  $T_p \sim T_e \sim m_e V_{\text{sh}}^2$  (Ohira & Takahara 2007, 2008).
- 5) The ion Weibel instability becomes the most unstable mode (electromagnetic mode).

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

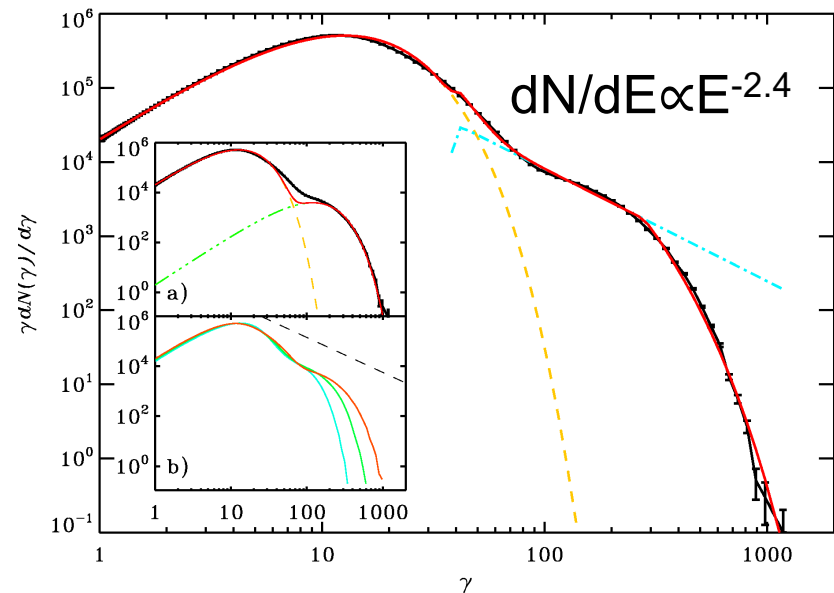


# PIC simulations of Weibel mediated shocks

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



Spitkovsky 2008



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

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

Kato & Takabe (2008)

# Acceleration time scale of DSA in the nonrelativistic Weibel mediated shock

Acceleration time of DSA,  $t_{\text{acc}} \sim t_{\text{sc}} (v/u_{\text{sh}})^2$  (Krymsky et al. 1979, Drury 1983)

To estimate  $t_{\text{acc}}$ , we need to estimate the scattering time,  $t_{\text{sc}}$ .

Length scale of  $\delta B_{\text{Weibel}}$ ,  $\lambda_{\delta B} = \alpha c/\omega_{\text{pp}}$  ( $\omega_{\text{pp}}^2 = 4\pi n e^2/m_p$ )

Interaction time between a particle and the each wave,  $\Delta t = \lambda_{\delta B} / v$

Scattering angle at each interaction,  $\Delta\theta \sim F_{\text{Lorentz}} \Delta t/p$   
 $\sim e(v/c)\delta B_{\text{Weibel}} \Delta t/p \sim \lambda_{\delta B} / r_g$

After N interactions,  $\Delta\theta_N \sim N^{1/2} \Delta\theta$

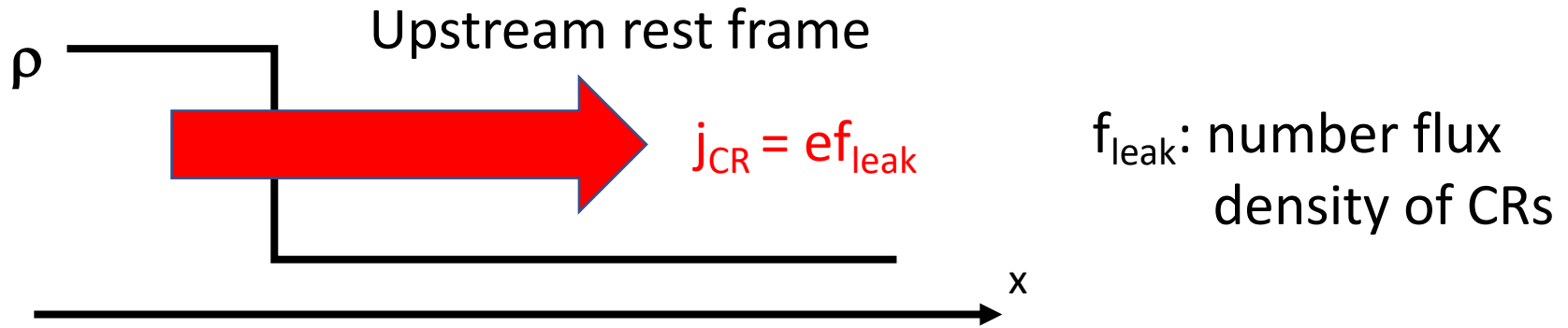
$\Delta\theta_N \sim \pi/2 \rightarrow N_{\pi/2} \sim (\pi/2\Delta\theta)^2$  ( $r_g = cp/e\delta B_{\text{Weibel}}$ )

$t_{\text{sc}} = N_{\pi/2} \Delta t \sim r_g^2/v\lambda_{\delta B} \sim c^2 p^2 / e^2 \delta B_{\text{Weibel}}^2 v \lambda_{\delta B}$   $\leftarrow$  To estimate  $t_{\text{sc}}$ , we need to estimate  $\delta B_{\text{Weibel}}$ .

(e.g. Plotnikov et al. 2011, Subedi et al. 2017)



# $\delta B$ generated by the CR current



$$\nabla \times B = 4\pi j_{CR}/c \rightarrow \delta B_{Weibel} \sim 4\pi ef_{leak} \lambda_{\delta B}/c$$

The CR current depends on the number of accelerating CRs. However, DSA theory does not tell us it.

Therefore, we introduce a free parameter  $\eta$  to estimate  $f_{leak}$ .

$$\eta = [\text{CR energy flux}] / [\text{upstream kinetic energy flux}]$$

$$\eta = \frac{f_{leak}(\gamma_p - 1)m_p c^2}{nm_p u_{sh}^3/2}$$

$$\lambda_{\delta B} = \alpha c/\omega_{pp}$$

$$\delta B_{Weibel} \sim 0.1 \mu G \text{ for } \gamma_p \sim 2, \alpha \sim 10, \eta \sim 0.1, u_{sh}/c \sim 0.01$$

# Maximum energy of first CR protons

$$t_{\text{acc},p} \approx \frac{40\pi \hat{p}^7}{\alpha^3 \eta^2 \beta_{\text{sh}}^8} \omega_{\text{pp}}^{-1} \quad (\text{for } \hat{p} = p/m_p c \ll 1)$$

Ohira & Murase (2018)

$t_{\text{acc}} \propto u_{\text{sh}}^{-8} \rightarrow$  CRs are efficiently accelerated for the free expansion phase.

$$t_{\text{acc},p} = t_{\text{free}} = 4.1 \times 10^{10} \text{ sec } E_{\text{SN},51} M_{\text{ej},1}^{5/6} n_0^{-1/3}$$

$$\rightarrow E_{\text{max},p}(t_{\text{free}}) \sim 110 \text{ MeV } \alpha_{,1}^{6/7} \eta_{,-1}^{4/7} E_{\text{SN},51} M_{\text{ej},34}^{-19/21} n_{,0}^{1/21} \ll 10^{15} \text{ eV}$$

For  $t > t_{\text{free}}$ ,  $u_{\text{sh}} \propto t^{-3/5}$ .  $t_{\text{acc},p} = t \rightarrow E_{\text{max},p}(t) = E_{\text{max},p}(t_{\text{free}}) (t/t_{\text{free}})^{-38/35}$

Cooling time of CRs due to the Coulomb loss,  $t_{\text{cool}} = 1.51 \times 10^{15} \text{ sec } n_0^{-1} \bar{p}^3$

For  $t > t_c \sim 43 t_{\text{free}}$ , the maximum energy is limited by the cooling.

$$E_{\text{max},p}(t_c) \sim 3 \text{ MeV} \rightarrow \text{CRs with } E < \sim 3 \text{ MeV cannot escape from the first SNRs.}$$

# Summary

CRs have important roles in many astrophysical systems.

When, where, how did CRs start affecting?

When, where, how were first cosmic rays accelerated?

Accretion shocks of the structure formation in the early universe cannot accelerate cosmic rays because the upstream gas is neutral.

Supernova remnants of first stars accelerate first cosmic rays to  $\sim 110$  MeV at  $1.8 \times 10^8$  years after the BigBang ( $z \sim 20$ ).

The first CRs are accelerated by the diffusive shock acceleration.

The first CRs ( $3 \text{ MeV} < E < 110 \text{ MeV}$ ) can escape from the first SNRs and heat the primordial gas.

Ohira & Murase (2018)