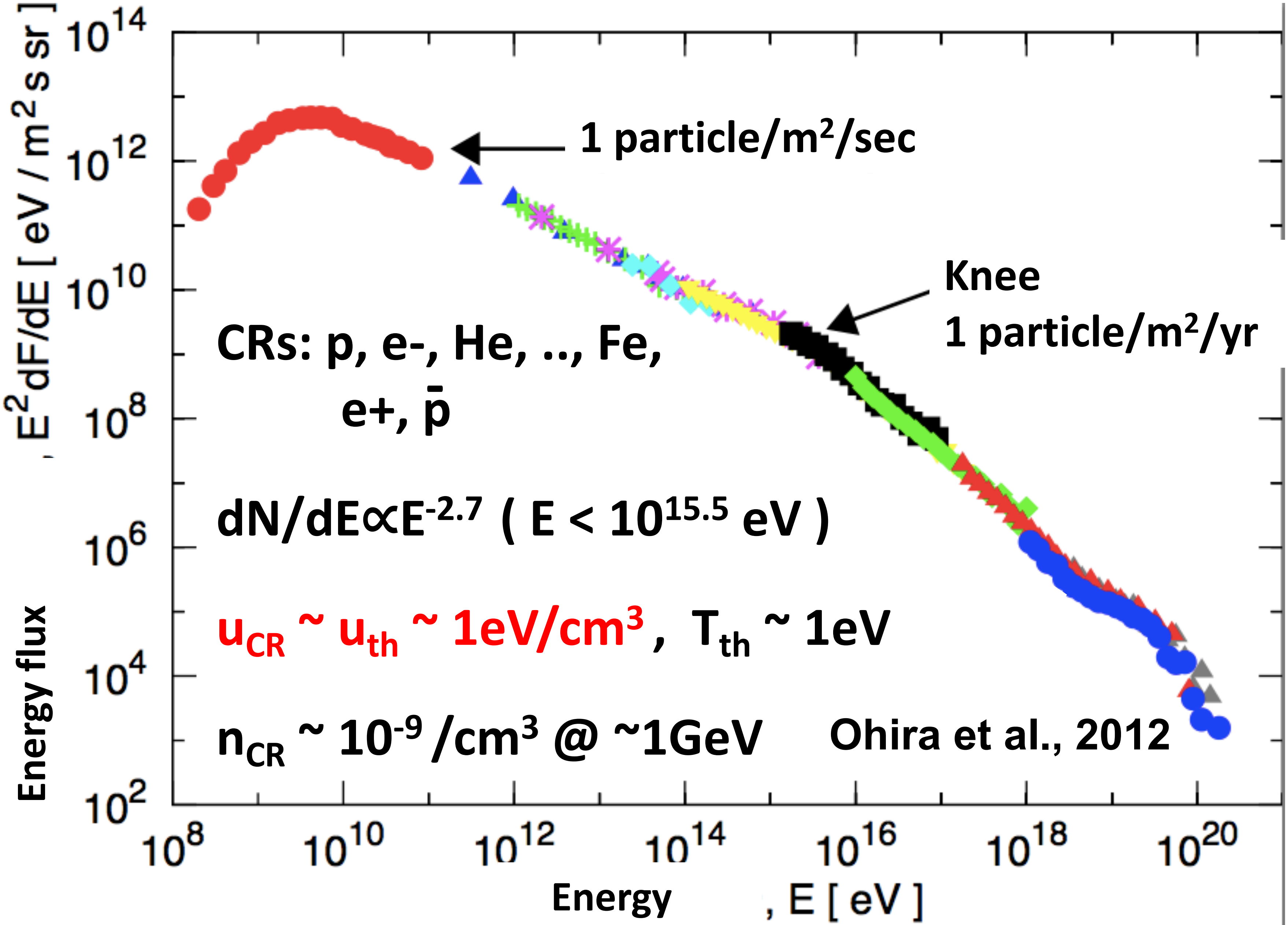
Magnetic field generation by the First cosmic ray

Yutaka Ohira The University of Tokyo

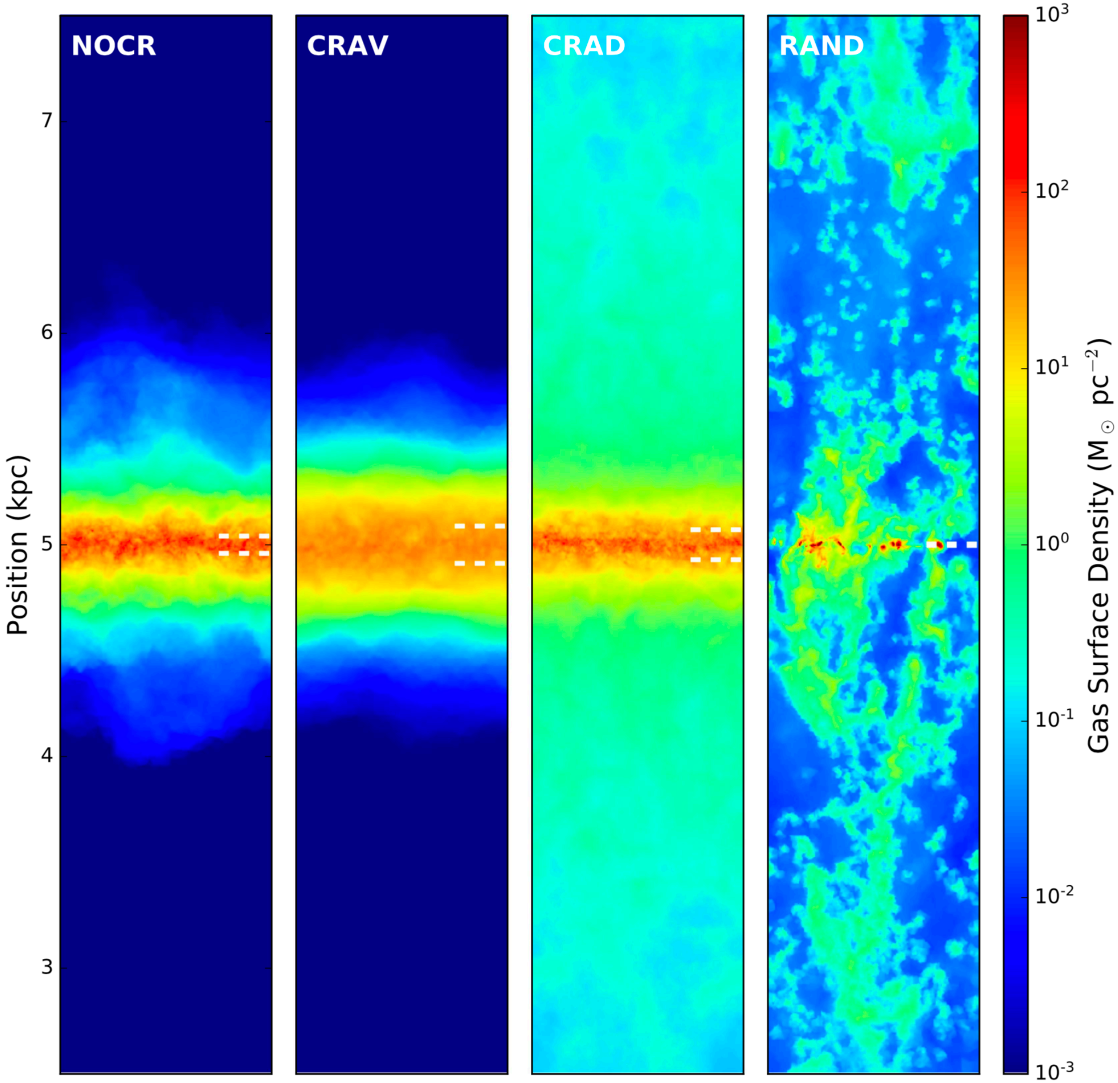
Contents

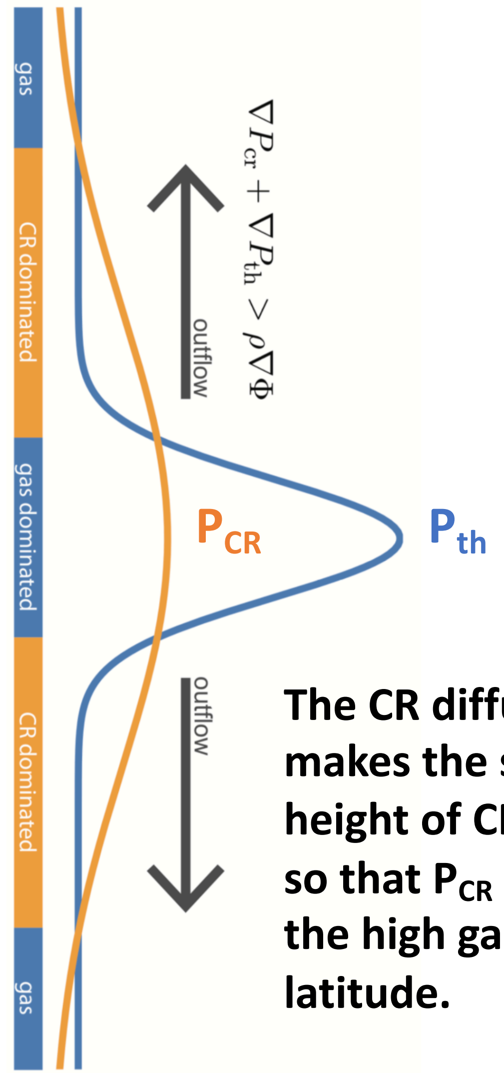
- First cosmic rays @z~20
- Genialized Ohm's law for three components plasma
- Magnetic field generation by the return current 1
- Magnetic field generation by the return current 2

Cosmic-ray spectrum in the current universe



CRs drive galactic winds





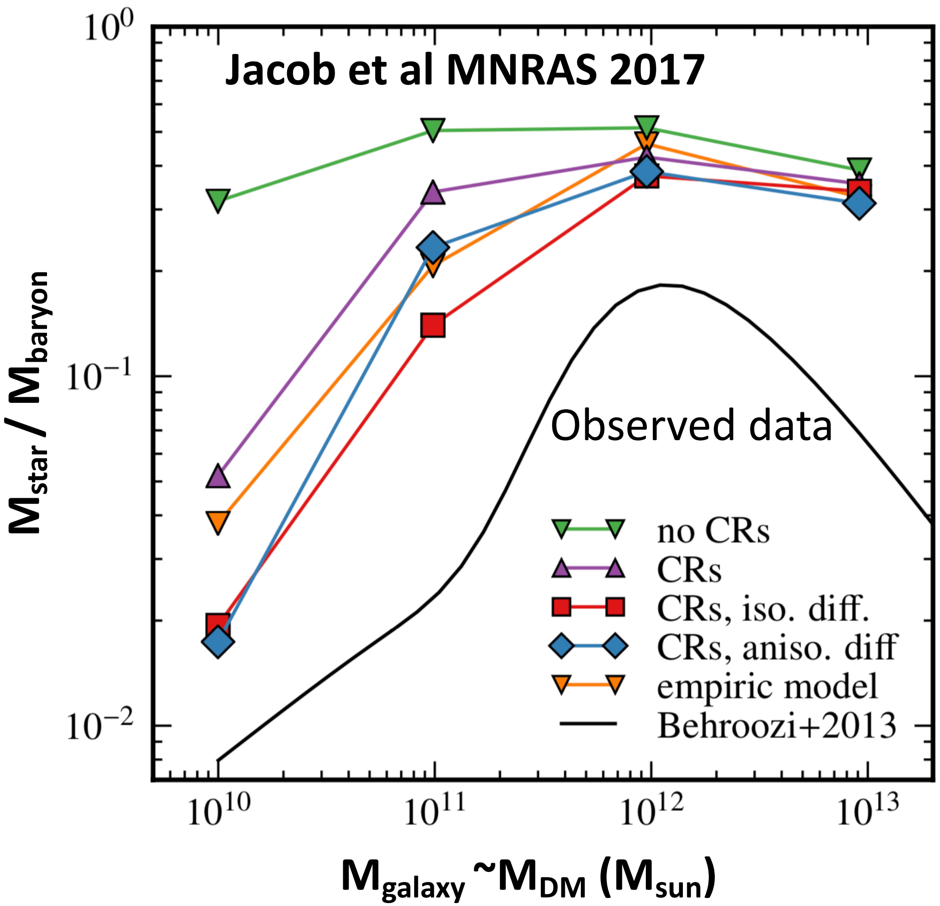
The CR diffusion makes the scale height of CRs large, so that $P_{CR} >> P_{th}$ at the high galactic latitude.

↑ $P_{CR} \neq 0$, No CR diffusion.

↑ $P_{CR} \neq 0$, CR diffusion. P_{CR} drives winds.

Simpson et al, ApJL 2016

CRs reduce star formations



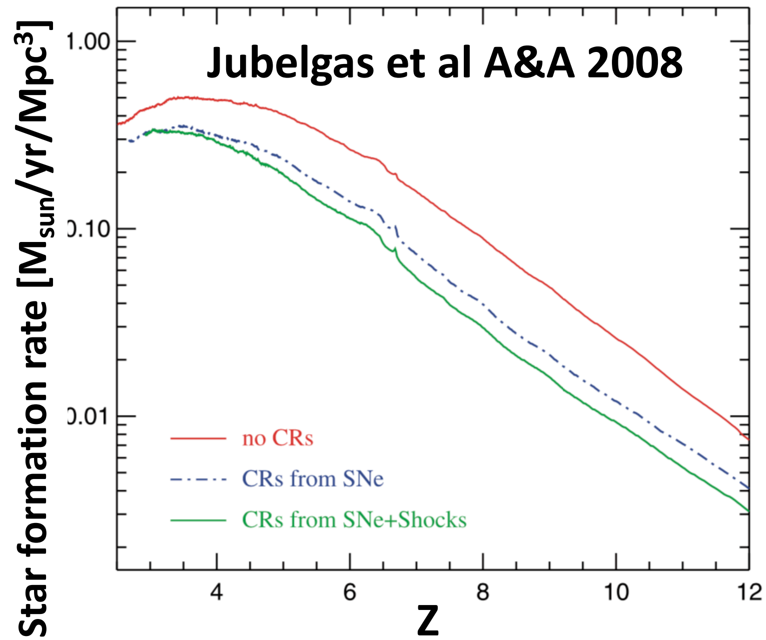


Fig. 21. Evolution of the cosmic star formation rate density in simulations of galaxy formation at high redshift. We compare results for three simulations that include different physics, a reference simulation without cosmic ray physics, a simulation with CR production by supernovae, and a third simulation which in addition accounts for CR acceleration at structure formation shocks with an efficiency that depends on the local Mach number.

CRs suppress the cooling of gas and drive galactic winds, so that CRs reduce star formations in low mass galaxies. Not only CRs from SNRs but also CRs from accretion shocks could be important.

Heating of the primordial gas by CRs

Sazonov & Sunyeav 2015

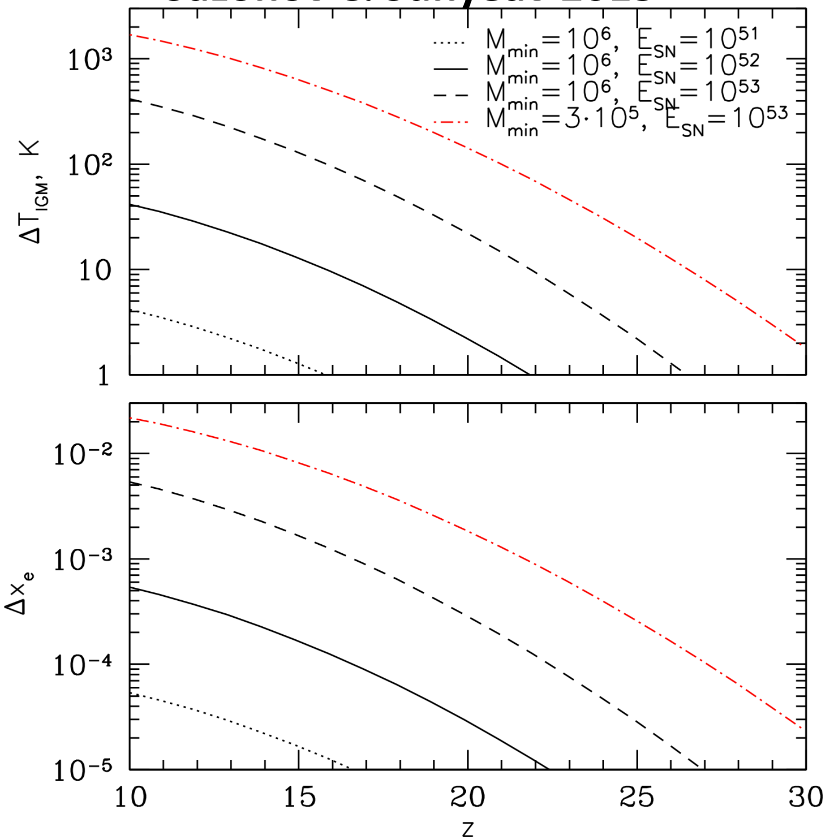


Figure 1. Increment of the IGM temperature (upper panel) and of the ionization fraction (lower panel) caused by LECRs from primordial SNe, as a function of redshift, for three values of the SN explosion energy, $E_{\rm SN} = 10^{51}$ erg (dotted), 10^{52} erg (solid) and 10^{53} erg (dashed). The other 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

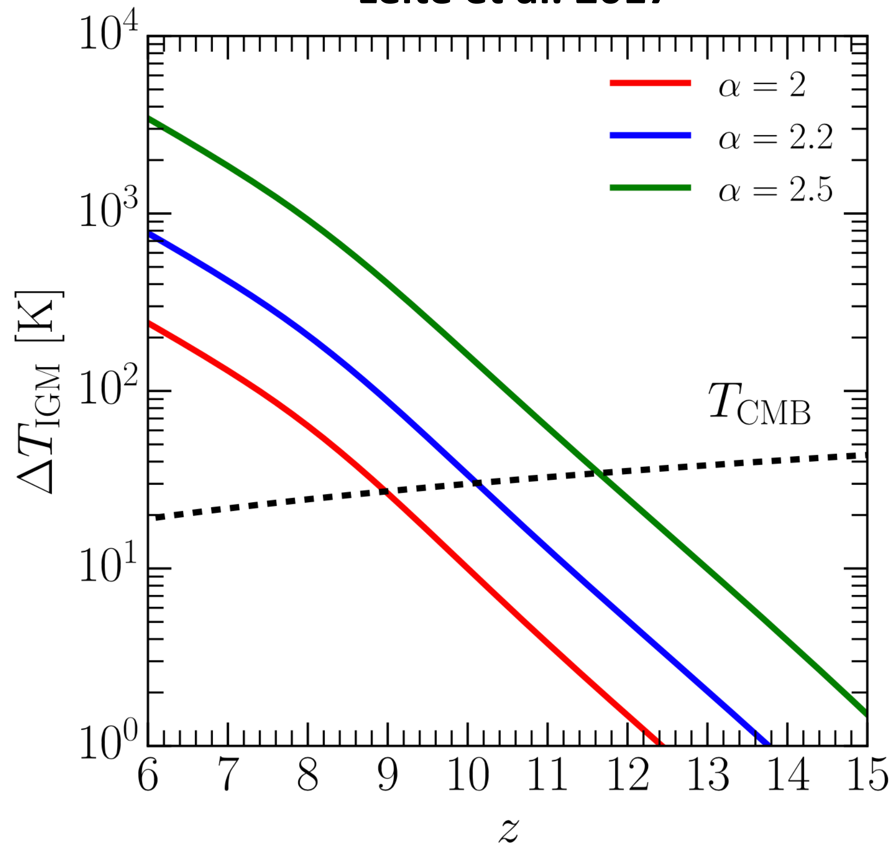
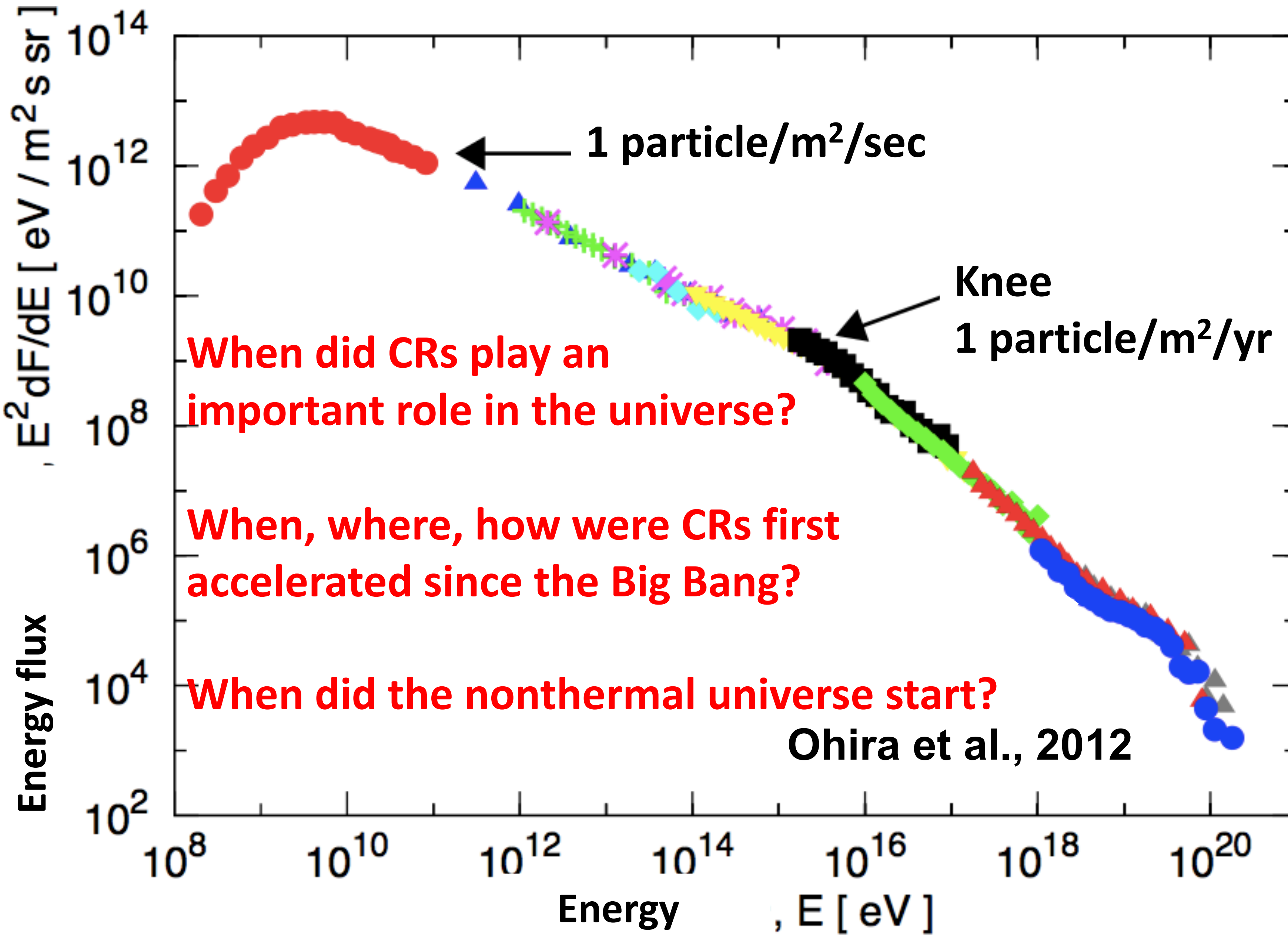


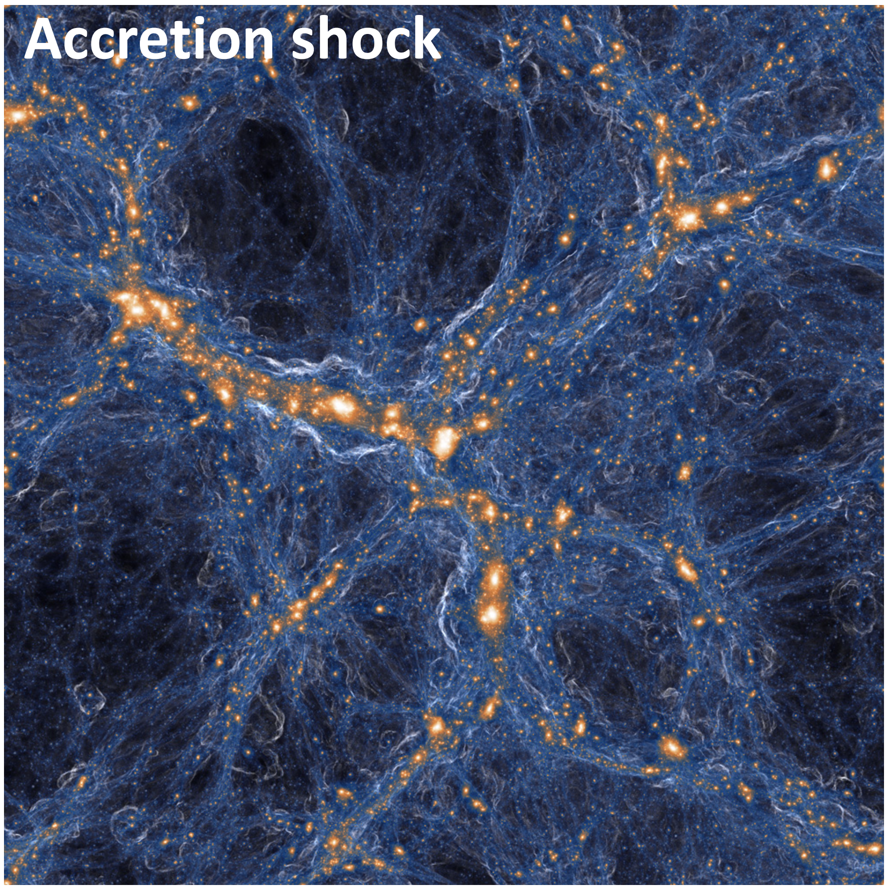
Figure 7. Increment of the average IGM temperature by CRs as a function of redshift for three values of the CR injection slope. The CMB temperature at the same redshift is shown by the dashed line.

Cosmic rays can ionize and heat the primordial gas at z > 10.

Cosmic-ray spectrum in the current universe



Accretion shocks in the structure formation vs. fist supernova remnants



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

NASA/CXC/SAO

First supernova remnants vs. accretion shocks

First supernova remnant @ Z ~ 20

First star are formed at 1.8×10^8 yrs after the Big Bang (z~20) (Yoshida et al. 2003).

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

Their lifetime is ~ 10^6 yr.
They explode at 1.8×10^8 yrs after the Big Bang.

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

→ Weibel mediated nonrelativistic collisionless shock

→ **Cosmic rays can be accelerated to ~GeV.**

Accretion shock @ Z ~ 20

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

$M \sim 10^6\ M_{sun}$ at z~20 (3σ)

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

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.**

Ohira & Murase, PRD 2019

Cosmic-ray current and e⁻ return current

In the early universe, there are free electrons, $f_e \sim 10^{-4}$.

$$\underbrace{\frac{1}{c}\frac{\partial \vec{E}}{\partial t}}_{①} = \nabla \times \vec{B} - \underbrace{\frac{4\pi}{c}\vec{j}}_{①} \qquad \underbrace{\frac{1}{c}\frac{\partial \vec{B}}{\partial t} = -\nabla \times \vec{E}}_{③} \qquad \underbrace{\frac{D\vec{u}_e}{Dt} = -\frac{e}{m_e}}_{②}\left(\vec{E} + \frac{\vec{u}_e}{c} \times \vec{B}\right)$$

① The electric field is generated by J_{CR}, $E \propto - J_{CR}$.

② The electric fields accelerate e^-, which generates J_e.

③ For $L > c/\omega_{pe}$, ∇xE is small, so that free electrons cancel J_{CR} before the magnetic field is generated.

With in $t \sim \omega_{pe}^{-1} \sim 0.01$ sec $n_{e,-7}^{-1/2}$, $J_{tot} = J_{CR} + J_e = 0$.

$n_b \sim 10^{-3}$ cm^{-3} @ z = 20

→ $0 = -n_e + n_p + n_{CR}$, $0 = J_e + J_{CR}$ (in the proton rest frame)

Magnetic field generation in a two-component plasma

$$\partial \boldsymbol{B}/\partial t = -c\boldsymbol{\nabla} \times \boldsymbol{E}$$

Generalized Ohm's law →

$$\frac{\partial}{\partial t}\left(\sum_s q_s n_s \boldsymbol{V}_s\right) + \boldsymbol{\nabla}\cdot\left(\sum_s q_s n_s \boldsymbol{V}_s \boldsymbol{V}_s\right) = \sum_s \frac{q_s^2 n_s}{m_s}\left(\boldsymbol{E} + \frac{\boldsymbol{V}_s \times \boldsymbol{B}}{c}\right) + \sum_s \frac{q_s}{m_s}\left(\boldsymbol{f}_s - \boldsymbol{\nabla} p_s\right)$$

If B = 0 at t = 0, the left hand side = 0, Vs x B = 0.

By ignoring contributions from protons,

$$\boldsymbol{E} = -(\boldsymbol{\nabla} p_{\mathrm{e}} - \boldsymbol{f}_{\mathrm{e}})/e n_{\mathrm{e}}$$

↑ Biermann battery
Biermann (1950)

↑ e.g. Harrison battery (radiation force)
Harrison (1970)

Magnetic field generation in a three component plasma.

$$\partial \boldsymbol{B}/\partial t = -c\boldsymbol{\nabla} \times \boldsymbol{E}$$

Generalized Ohm's law →

$$\frac{\partial}{\partial t}\left(\sum_s q_s n_s \boldsymbol{V}_s\right) + \boldsymbol{\nabla}\cdot\left(\sum_s q_s n_s \boldsymbol{V}_s \boldsymbol{V}_s\right) = \sum_s \frac{q_s^2 n_s}{m_s}\left(\boldsymbol{E} + \frac{\boldsymbol{V}_s \times \boldsymbol{B}}{c}\right) + \sum_s \frac{q_s}{m_s}\left(\boldsymbol{f}_s - \boldsymbol{\nabla} p_s\right)$$

Astrophysical plasmas are at least three-component plasmas.

Electron, ion, and cosmic ray

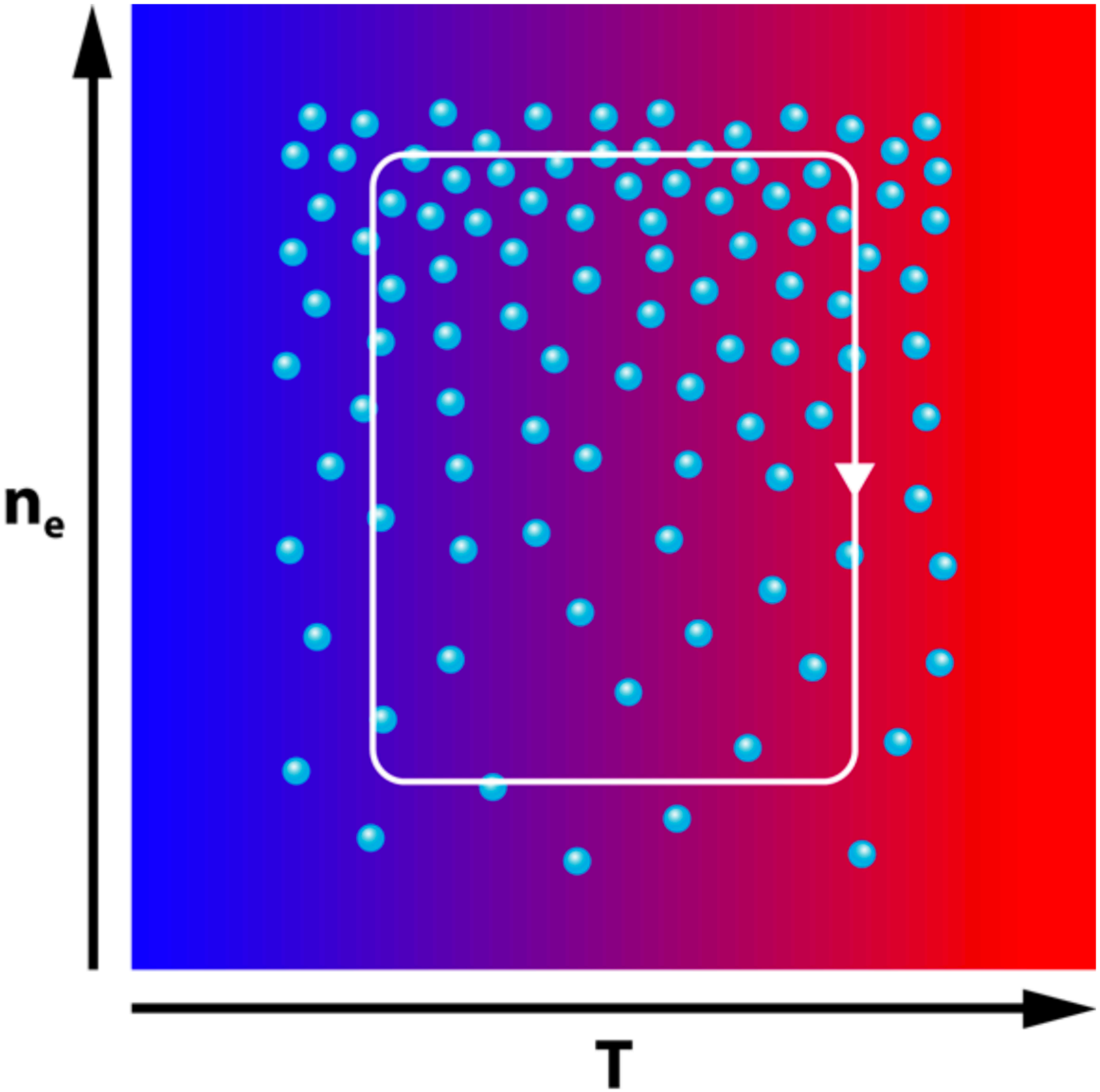
If one of the three plasmas has some inhomogeneities, the second term on the left hand side does not always vanish, which has not been considered for the magnetic field generation.

$$\boldsymbol{E} = \frac{m_e}{e^2 n_e}\boldsymbol{\nabla}\cdot\left(\sum_s q_s n_s \boldsymbol{V}_s \boldsymbol{V}_s\right)$$

←New battery mechanism

Ohira ApJL 2020

Physical mechanism of the Biermann battery



Zweibel 2013

$$\partial \mathbf{V}_e/\partial t = - \nabla p_e / \rho_e$$

∇x

$$\partial(\nabla x \mathbf{V}_e)/\partial t = - \nabla \rho_e \, x \nabla p_e / \rho_e^2$$

$$||$$

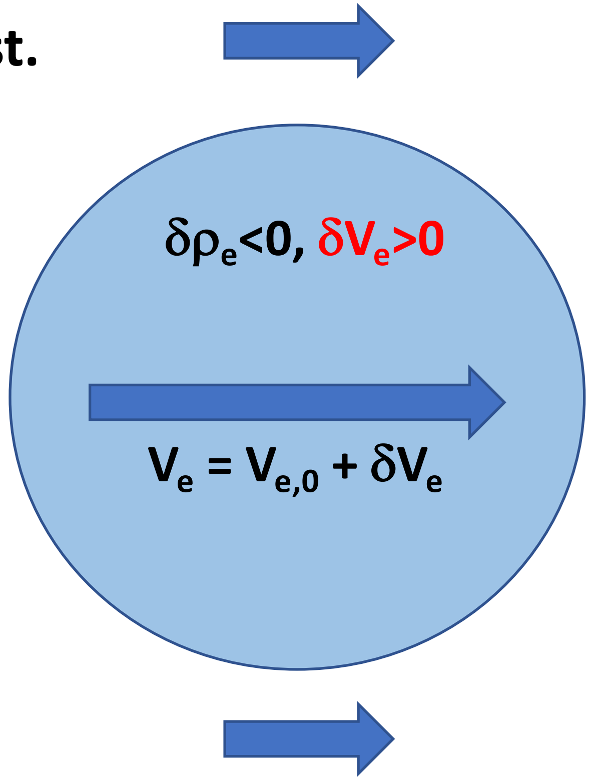
$$\partial \omega_e/\partial t$$

Physical mechanism of our battery 1

J_{CR} = const.

P = const.

$\delta\rho_e = 0,\ V_e = V_{e,0}$



$\delta\rho_e = 0,\ V_e = V_{e,0}$

$$\partial \mathbf{V}_e / \partial t = - \mathbf{V}_e \cdot \nabla \mathbf{V}_e$$

∇x

$$\partial(\nabla \times \mathbf{V}_e)/\partial t = - \nabla \times (\mathbf{V}_e \cdot \nabla \mathbf{V}_e)$$

||

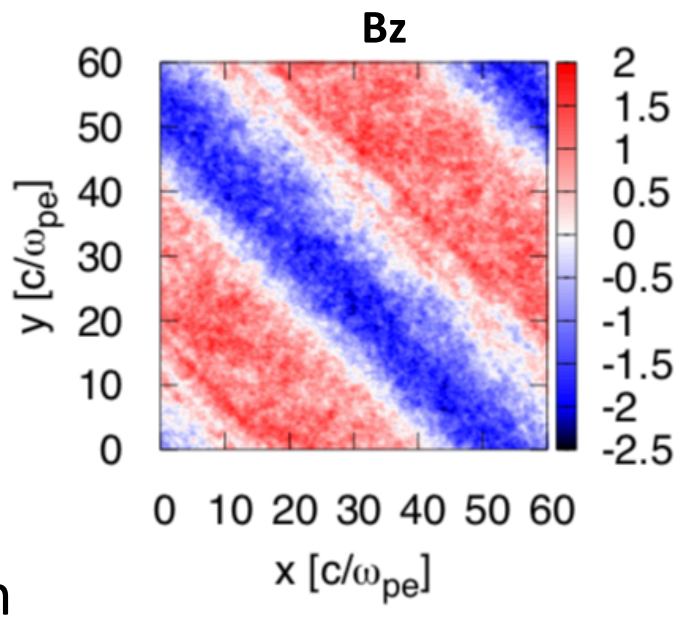
$$\partial \omega_e / \partial t$$

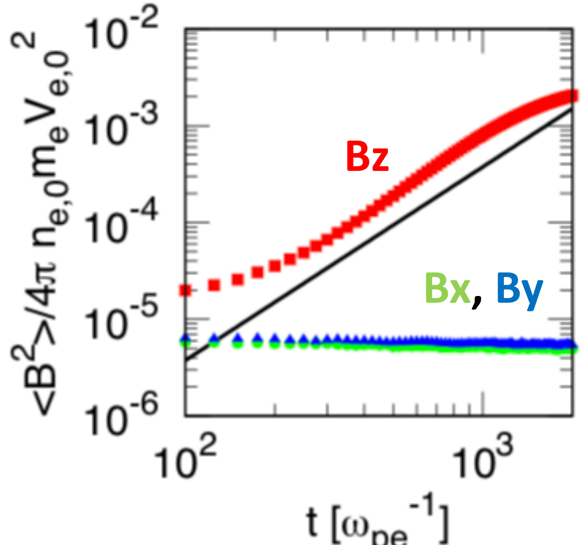
Example for a nonuniform density field

Initial condition of three plasmas

$$n_e = n_{e,0}\left\{1+\delta\sin\left(\frac{2\pi}{L}(x+y)\right)\right\}^{-1/2},$$
$$n_p = n_e - n_{b,0},$$
$$n_b = n_{b,0},$$
$$T_e = T_0(n_{e,0}/n_e),$$
$$T_p = T_0(n_{e,0}/n_e),$$
$$\boldsymbol{V}_e = V_{e,0}(n_{e,0}/n_e)\boldsymbol{e}_x,$$
$$\boldsymbol{V}_p = \boldsymbol{0},$$
$$\boldsymbol{V}_b = V_{b,0}\boldsymbol{e}_x,$$

PIC simulation (Ohira ApJL 2020)





The solid line shows the analytical solution.

Analytical solution

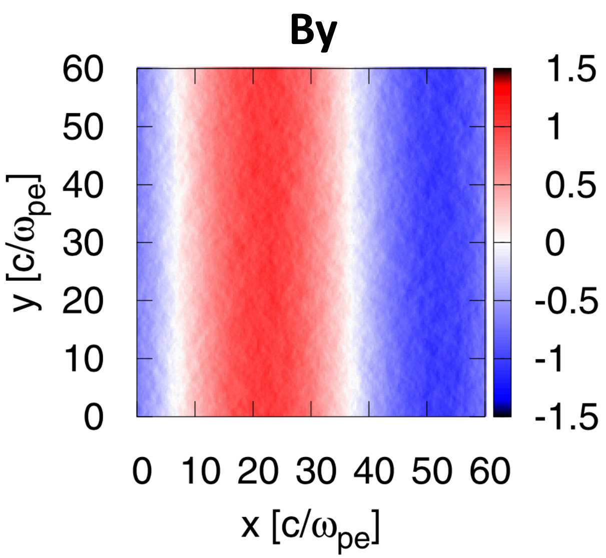
$$\boldsymbol{B} = \frac{2\pi^2 m_e c V_{e,0}^2 \delta t}{eL^2}\sin\left(\frac{2\pi}{L}(x+y)\right)\ \mathbf{e}_z.$$

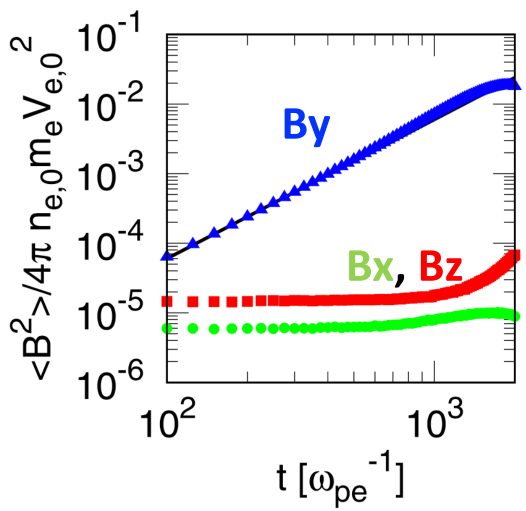
Example for a nonuniform velocity field

Initial condition of three plasmas

$$n_{\mathrm{e}} = n_{\mathrm{e},0},$$
$$n_{\mathrm{p}} = n_{\mathrm{e},0} - n_{\mathrm{b},0},$$
$$n_{\mathrm{b}} = n_{\mathrm{b},0},$$
$$\boldsymbol{V}_{\mathrm{e}} = V_{\mathrm{e},0}\left\{\boldsymbol{e}_{\mathrm{x}} + \delta \sin\left(\frac{2\pi}{L}x\right)\boldsymbol{e}_{\mathrm{z}}\right\},$$
$$\boldsymbol{V}_{\mathrm{p}} = \frac{n_{\mathrm{e},0} - n_{\mathrm{b},0}}{n_{\mathrm{e},0}} V_{\mathrm{e},0}\delta \sin\left(\frac{2\pi}{L}x\right)\boldsymbol{e}_{\mathrm{z}},$$
$$\boldsymbol{V}_{\mathrm{b}} = V_{\mathrm{b},0}\boldsymbol{e}_{\mathrm{x}}.$$

PIC simulation (Ohira ApJL 2020)





The solid line shows the analytical solution.

Analytical solution

$$\boldsymbol{B} = \frac{4\pi^2 m_{\mathrm{e}} c V_{\mathrm{e},0}^2 \delta t}{eL^2} \sin\left(\frac{2\pi}{L}x\right) \mathbf{e}_{\mathrm{y}}$$

The Biermann battery induced by the return current

$$\frac{\partial p_{\rm e}}{\partial t} + \boldsymbol{V}_{\rm e} \cdot \boldsymbol{\nabla} p_{\rm e} = -\gamma p_{\rm e} \boldsymbol{\nabla} \cdot \boldsymbol{V}_{\rm e} \Longrightarrow p_{\rm e} = p_{\rm e,0} \exp\left(-\gamma t \frac{\partial V_{\rm e}}{\partial x}\right)$$

($\nabla p_e = 0$ at $t = 0$, $\boldsymbol{V}_e = V_e \boldsymbol{e}_x$)

Since $n_e \sim n_p + n_{CR}$ = constant in time, even though $\nabla p_e \times \nabla n_e = 0$ at $t=0$,

$\nabla p_e \times \nabla n_e \neq 0$ is possible at $t > 0$.

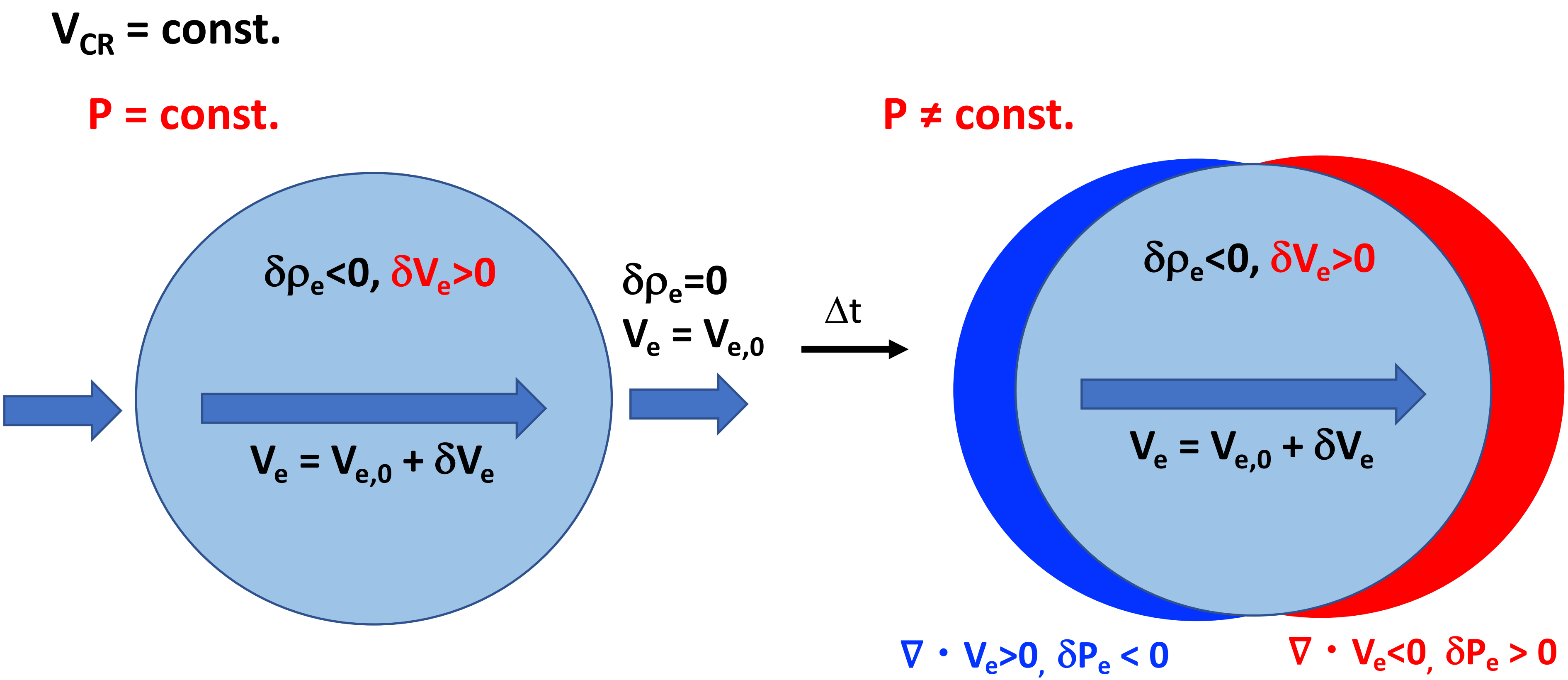
Ohm's law → $\boldsymbol{E} = \frac{m_{\rm e}}{e^2 n_{\rm e}} \boldsymbol{\nabla} \cdot \left(\sum_s q_s n_s \boldsymbol{V}_s \boldsymbol{V}_s \right) - \frac{\boldsymbol{\nabla} p_{\rm e}}{e n_{\rm e}}$

$\partial \boldsymbol{B} / \partial t = -c \boldsymbol{\nabla} \times \boldsymbol{E}$, J_{CR} = constant, and $V_p = 0$, $n_e = n_e(x,y,z)$

$$\frac{\partial \boldsymbol{B}}{\partial t} = \frac{m_{\rm e} c}{2e} \boldsymbol{\nabla} \times \frac{\partial V_{\rm e}^2}{\partial x} \boldsymbol{e}_{\rm x} - \frac{c p_{\rm e} \gamma t}{e n_{\rm b} V_{\rm b}} \boldsymbol{\nabla} V_{\rm e} \times \boldsymbol{\nabla} \frac{\partial V_{\rm e}}{\partial x}$$

Ohira (2020) in preparation

Physical mechanism of our battery 2



ρ_e doesn't change due to the charge neutrality.

In a region of $\nabla \cdot V_e < 0$, electrons are compressed.

As a result, ∇p_e is generated and $\nabla \rho_e \times \nabla p_e \neq 0$.

Order of magnitude estimate

$$\frac{\partial \boldsymbol{B}}{\partial t} = \underline{\frac{m_e c}{2e} \boldsymbol{\nabla} \times \frac{\partial V_e^2}{\partial x} \boldsymbol{e}_x} - \underline{\frac{c p_e \gamma t}{e n_b V_b} \boldsymbol{\nabla} V_e \times \boldsymbol{\nabla} \frac{\partial V_e}{\partial x}}$$

Pop III SN rate ~ 10^{-7}/Mpc^3/yr, E_{CR} ~ 10^{50} erg/SN → u_{CR} ~ $3\text{x}10^{-6}$ eV/cm^3 @z~20

n_{CR} ~ $3\text{x}10^{-14}$ /cm^3 @z~20

n_e ~ 10^{-7}/cm^3 @z~20 → V_e ~ (n_{CR} / n_e) (V_{CR} / c) ~ 0.1 km/s (V_{CR} / c) @z~20

T_e ~ 300 K @z~20 → $V_{th,e}$ ~ 100 km/s

$B \sim 7.5 \times 10^{-26}$ G $V_{e,0.1km/s}^{\;2}\, L_{kpc}^{\;-2}\, t_{100Myr}$

$B \sim 7.5 \times 10^{-22}$ G $V_{th,e,100km/s}^{\;2}\, V_{e,0.1km/s}\, L_{kpc}^{\;-3}\, t_{100Myr}^{\;2}$

These are sufficiently large to be the seed of the magnetic field in current galaxies (e.g. Davis et al. 1999).

Summary

Cosmic rays and magnetic fields have important roles in many current astrophysical systems.

When, where, how did CRs and magnetic fields start to affect?

When, where, how were first cosmic rays accelerated?

When, where, how were magnetic fields were first generated?

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

After the first CRs escape from the first SNRs, they could generate the seed of magnetic fields in the current universe.

The electron return current generate magnetic fields if there is an inhomogeneity.