宇宙線と磁場

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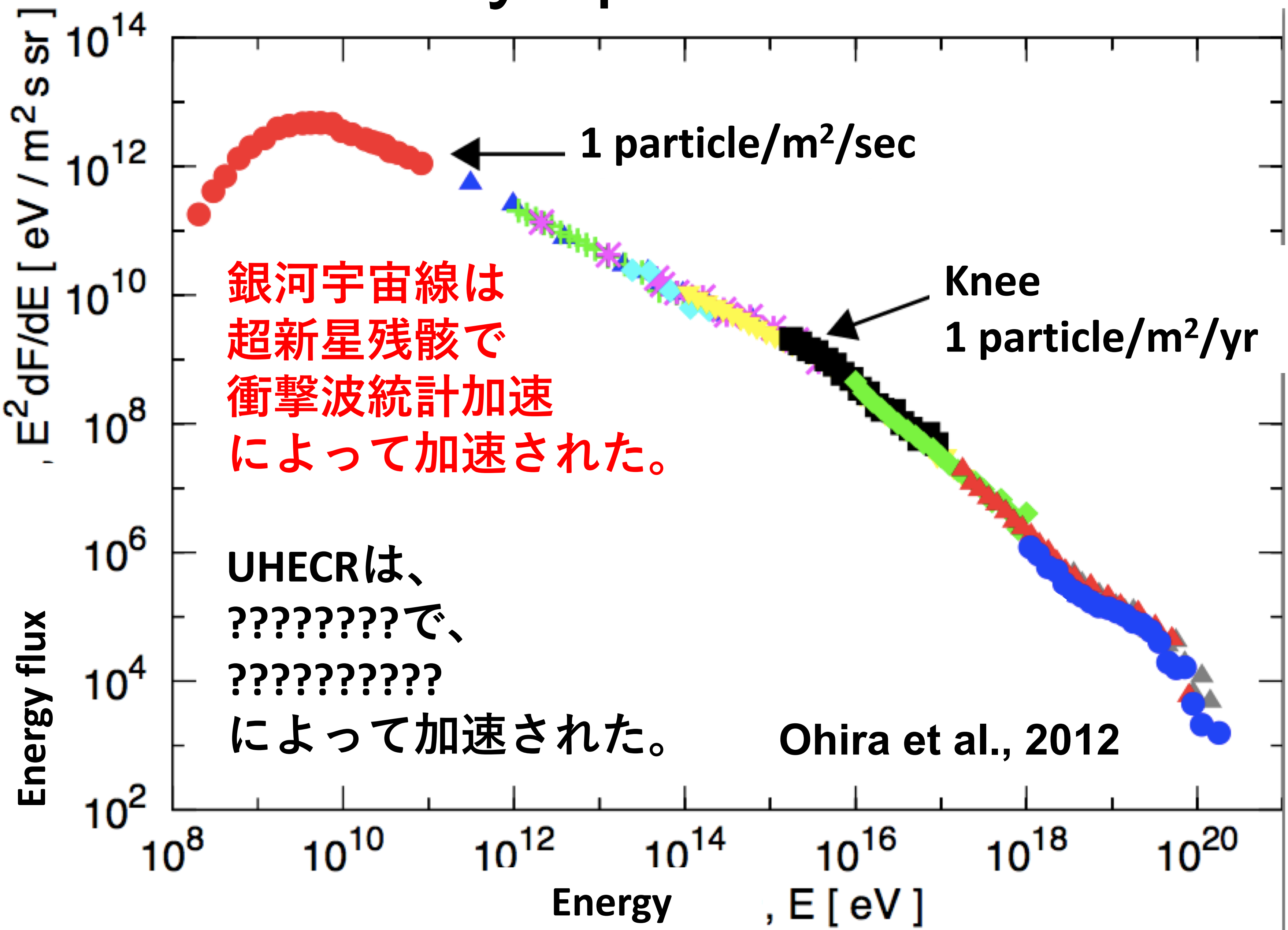
内容

・z=0の宇宙線

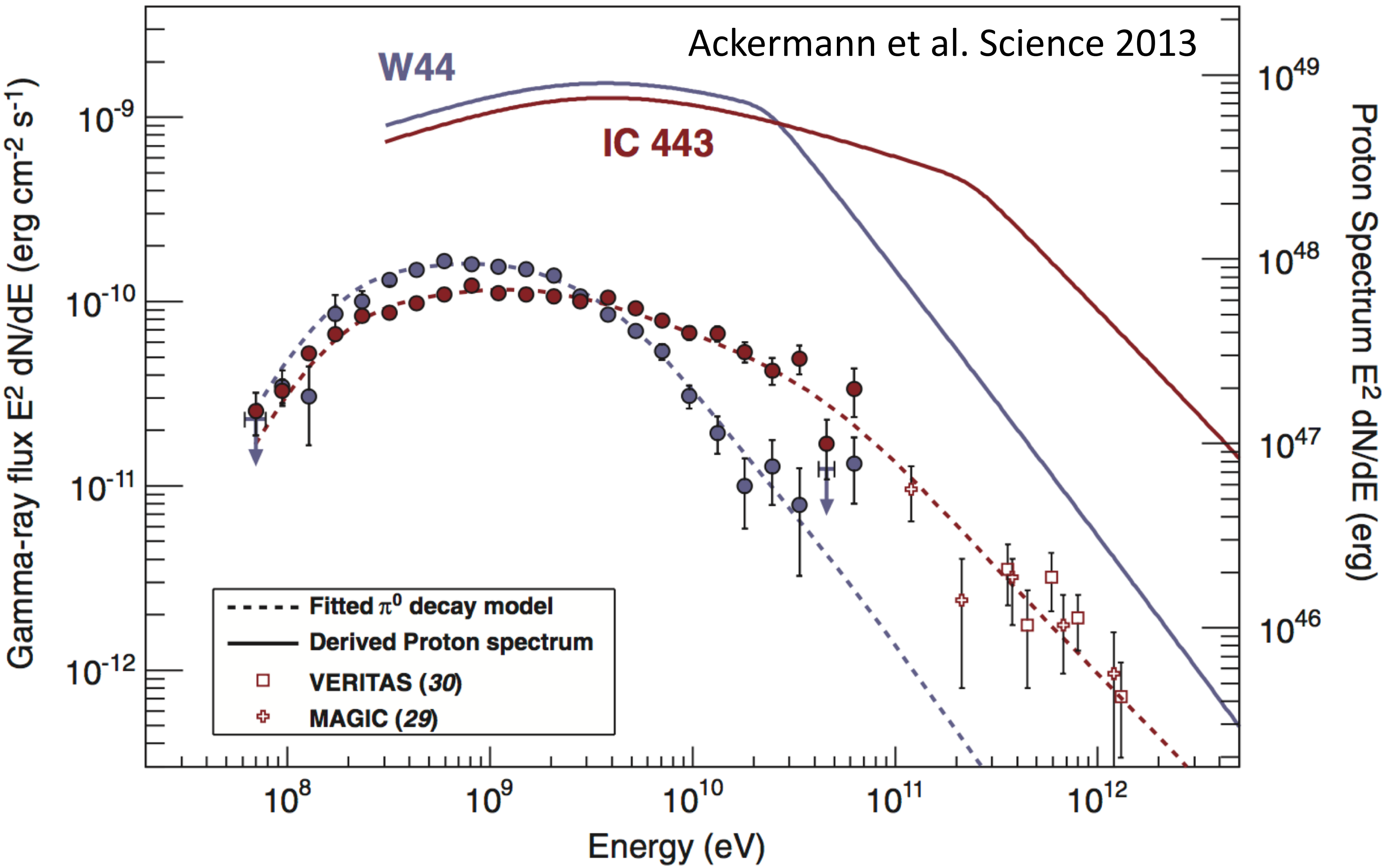
・z=20の宇宙線による磁場の生成

・z=20の宇宙線

Cosmic-ray spectrum at z = 0



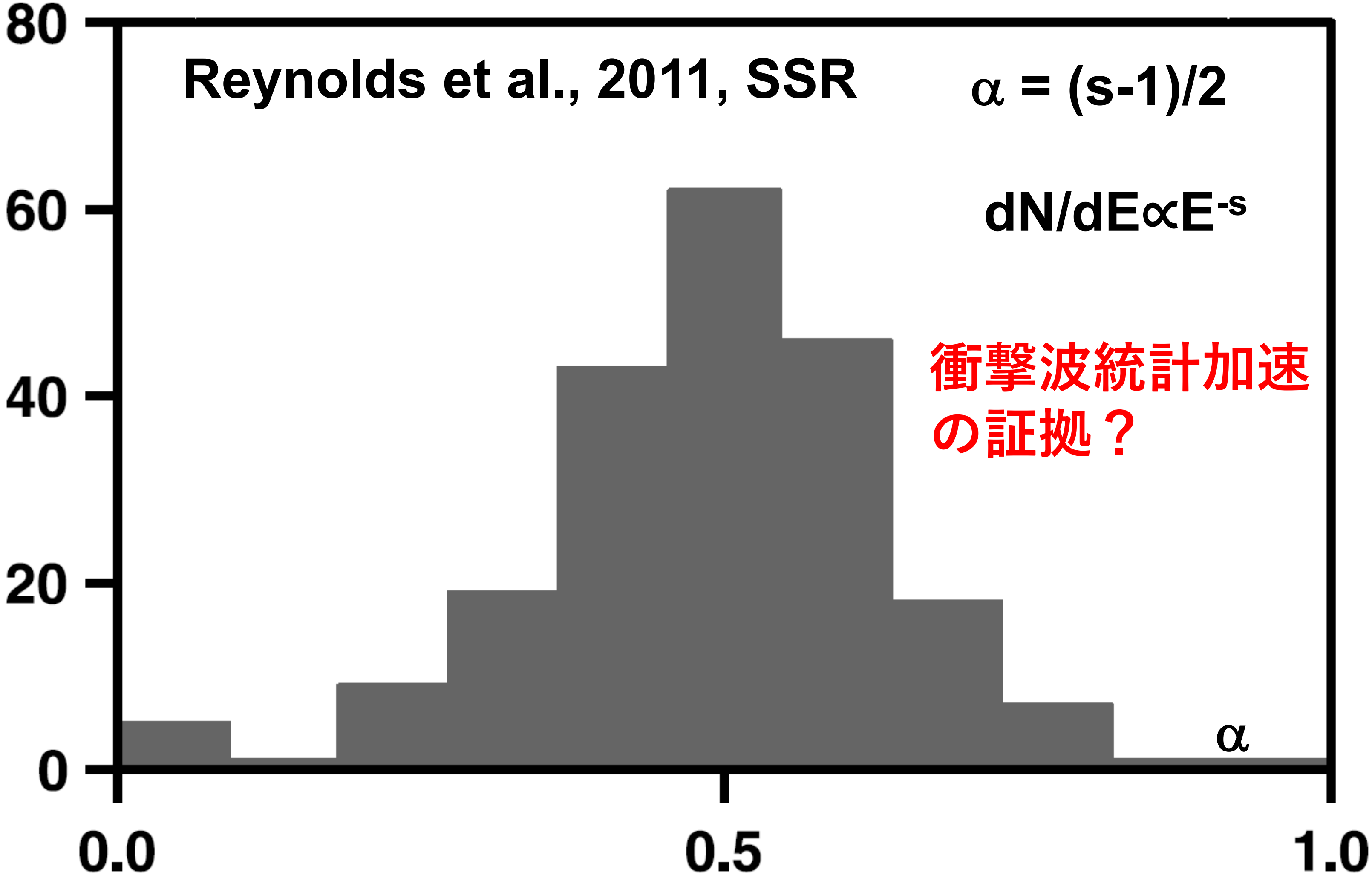
超新星残骸の観測（その１）



GeVガンマ線やTeVガンマ線の観測は、E_{CR} ~ 10% $E_{SN,51}$ と矛盾しない。
(Acero et al. ApJS 2016, Abdalla et al. arXiv:1802.05172)

超新星残骸の観測(その2)

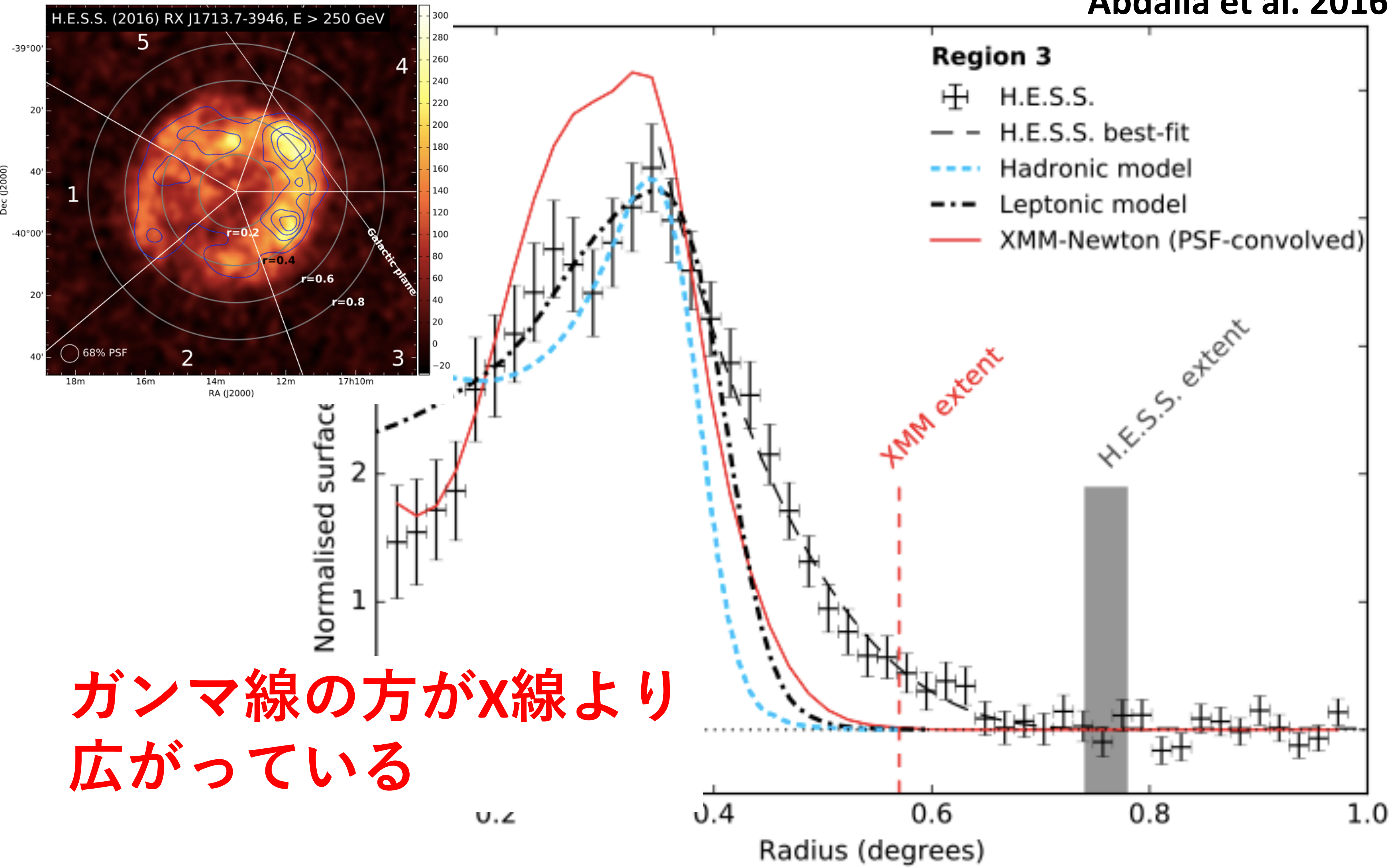
Spectral index of radio synchrotron flux, $f_\nu \propto \nu^{-\alpha}$



The standard DSA predicts s = 2　(α = 0.5)

超新星残骸の観測（その3）

Abdalla et al. 2016



ガンマ線の方がX線より
広がっている

加速粒子の衝撃波上流の空間分布

$$\frac{\partial n}{\partial t} = \frac{1}{r^2}\frac{\partial}{\partial r}\left(Dr^2\frac{\partial n}{\partial r}\right)$$

$r_0 = u_0 t$ で定常注入, D = const., $r > r_0$での解は

$$n(r,t) = C\frac{r_0}{r}\exp\left\{-\frac{(r-r_0)}{D/u_0}\right\}$$

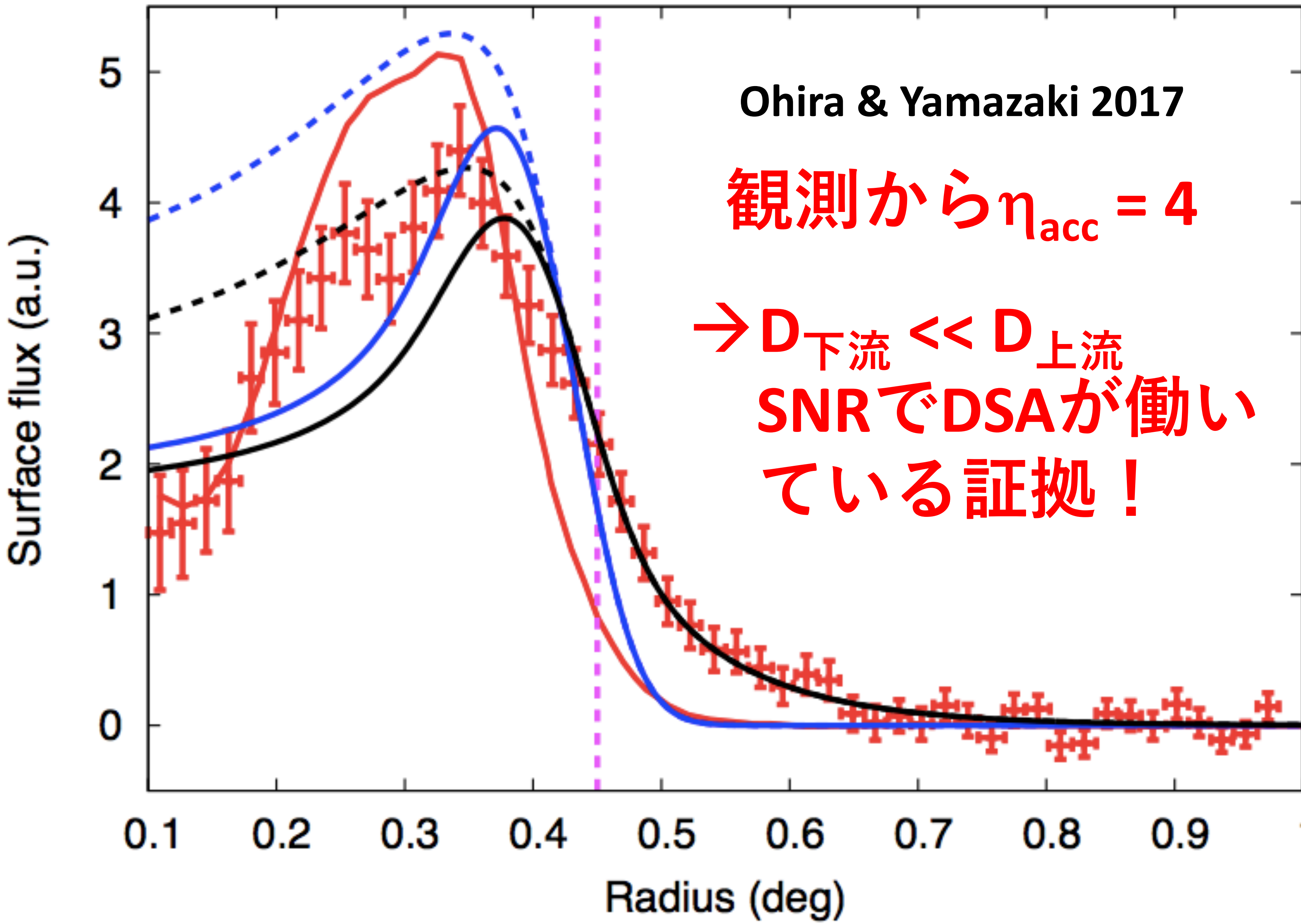
$t = t_{acc} \rightarrow E_{max,age}$, ($t = r_0/u_0$, $t_{acc} = \eta_{acc} D / u_0^2$)

$$L_{diff}(E_{max,age}) / r_0 = D/u_0 r_0 = 1 / \eta_{acc}$$

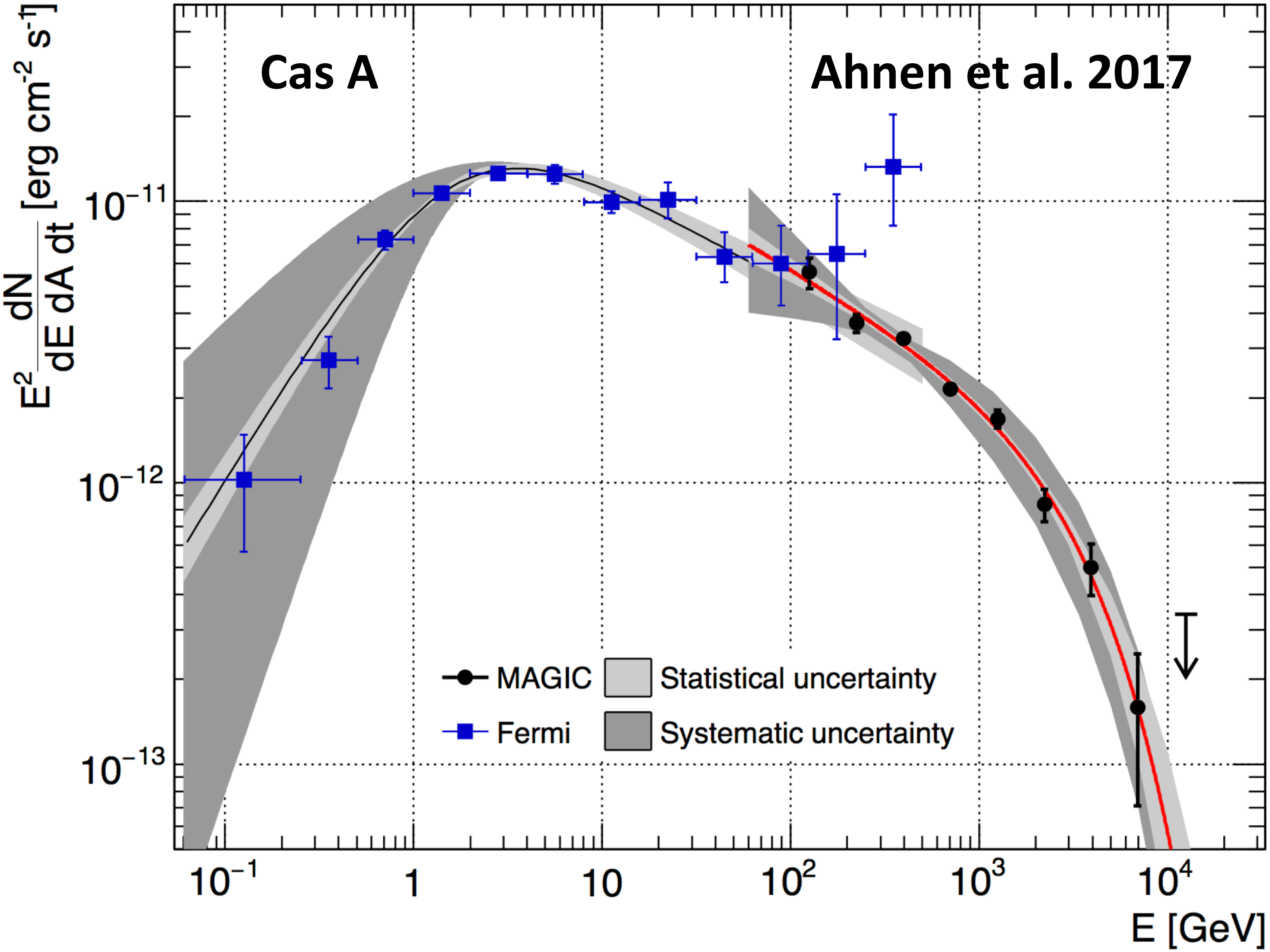
Ohira & Yamazaki 2017

DSA理論の予言はη_{acc} >= 4。 $D_{下流} << D_{上流}$の極限で $\eta_{acc} = 4$。

超新星残骸の観測(その3)



超新星残骸の観測(その4)



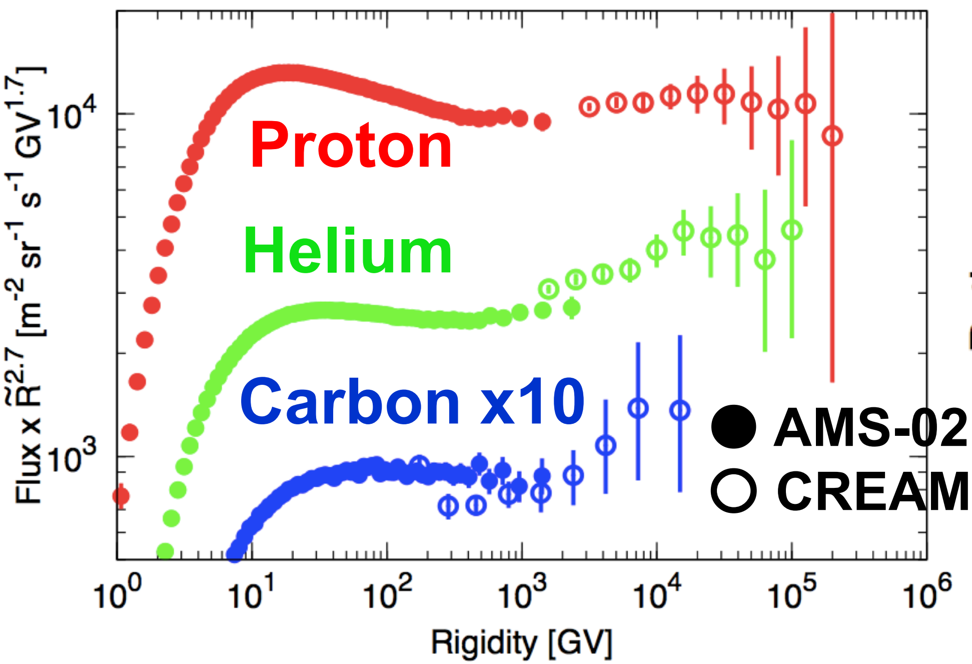
$E_{\gamma,c}$ = 3.5TeV

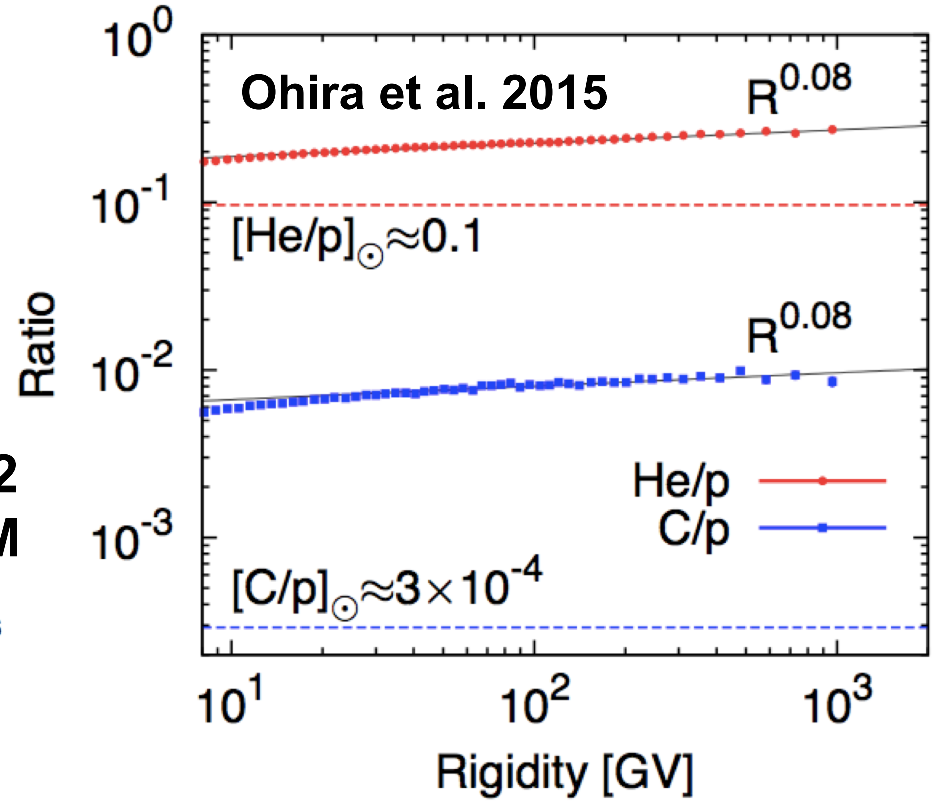
$E_{p,c}$ = 12TeV

U_{CR} ~ 10^{50} erg

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

最近の宇宙線直接観測の結果(その1)



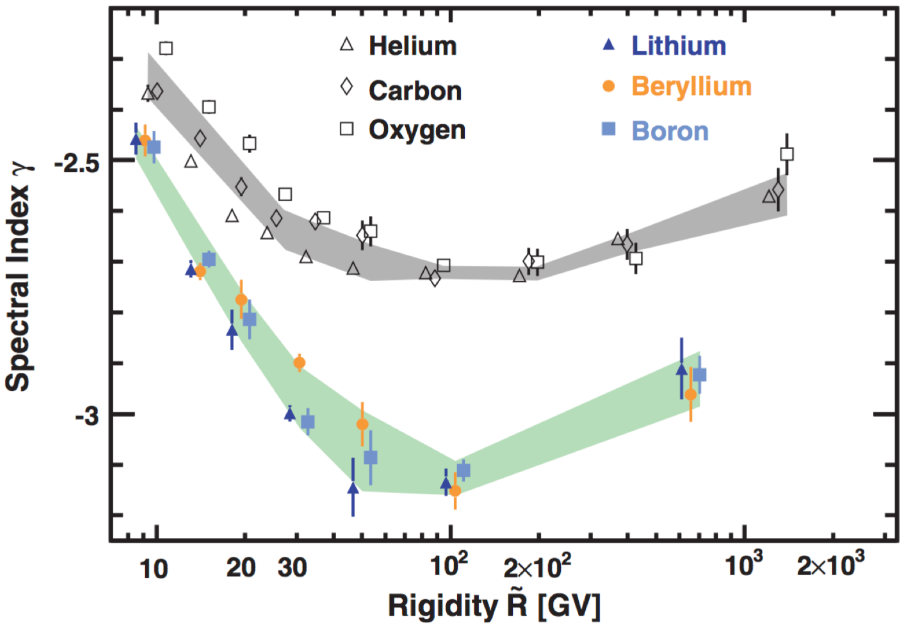


Spectra of CR p and He (and C) break at R~300GV.

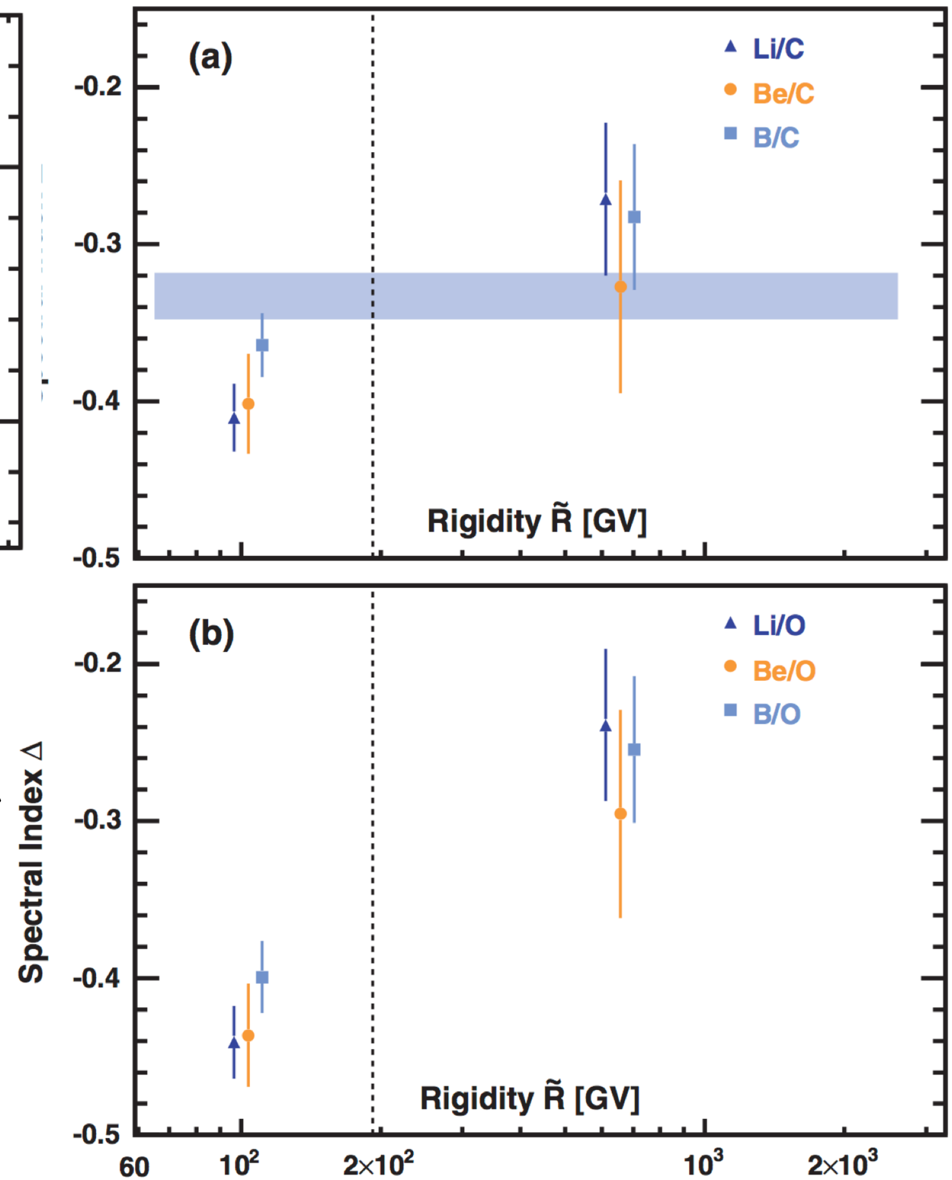
Spectra of CR He and C are harder than that of CR p.

陽子以外の宇宙線原子核の観測が面白い結果を出している。
SNRの観測からも、宇宙線原子核の情報が欲しい

最近の宇宙線直接観測の結果(その2)

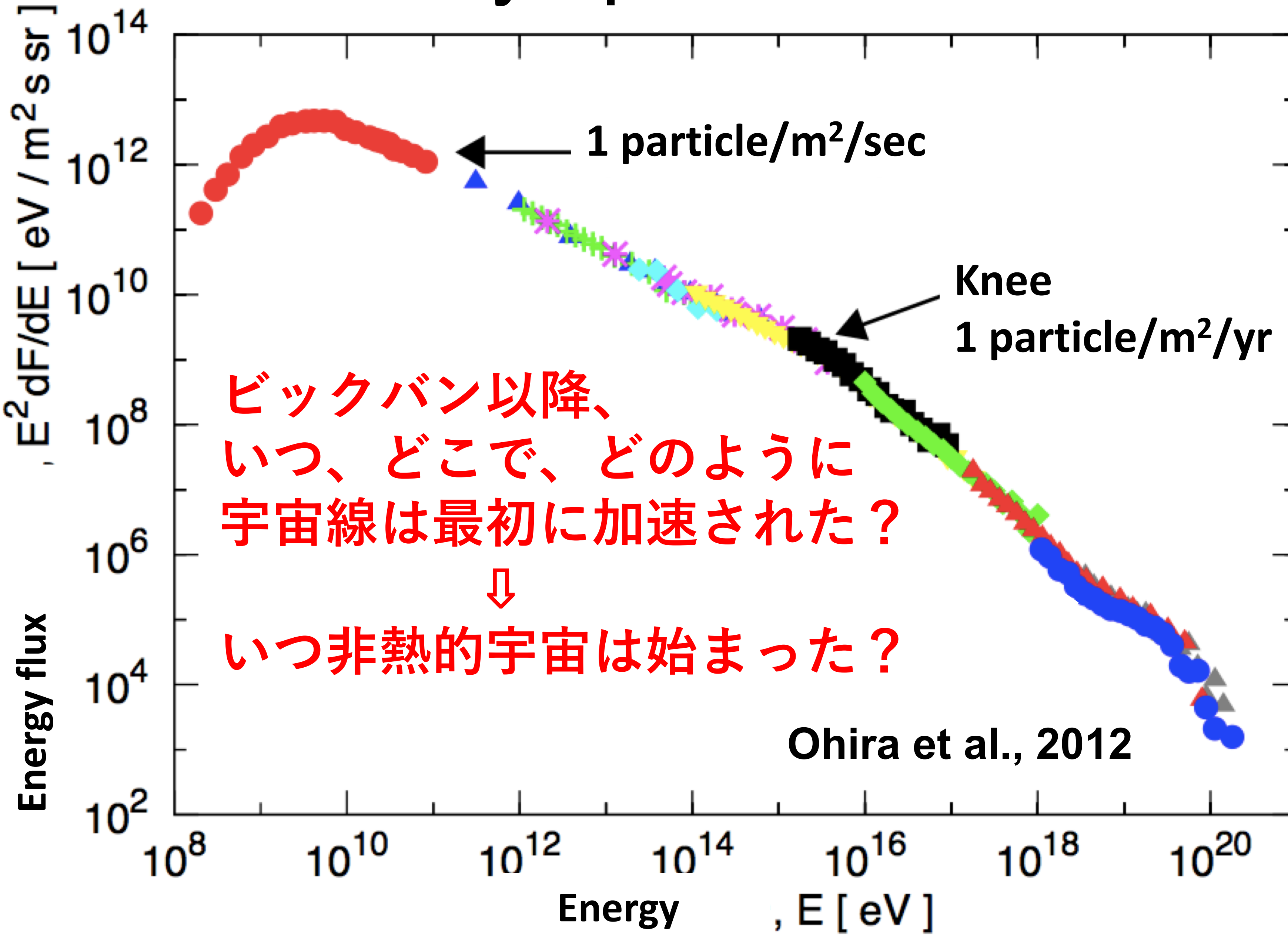


Aguilar et al. PRL, 2018



p, He, C, O の宇宙線スペクトルで見えているR~200GV のhardeningは、銀河内の伝搬中に作られことを意味する。

Cosmic-ray spectrum at z = 0



Heating of the primordial gas by CRs

Sazonov & Sunyeav 2015

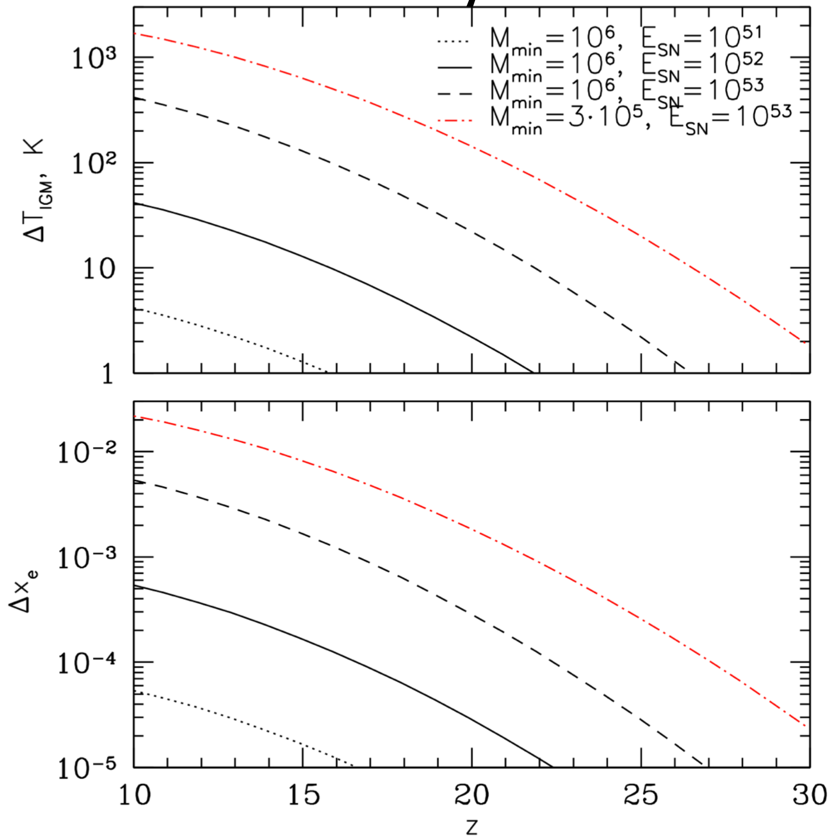


Figure 1. Increment of the IGM temperature (upper panel) and of the ionization fraction (lower panel) caused by LECRs from primordial SNe, as a function of redshift, for three values of the SN explosion energy, $E_{SN} = 10^{51}$ erg (dotted), 10^{52} erg (solid) and 10^{53} erg (dashed). The other parameters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

Leite et al. 2017

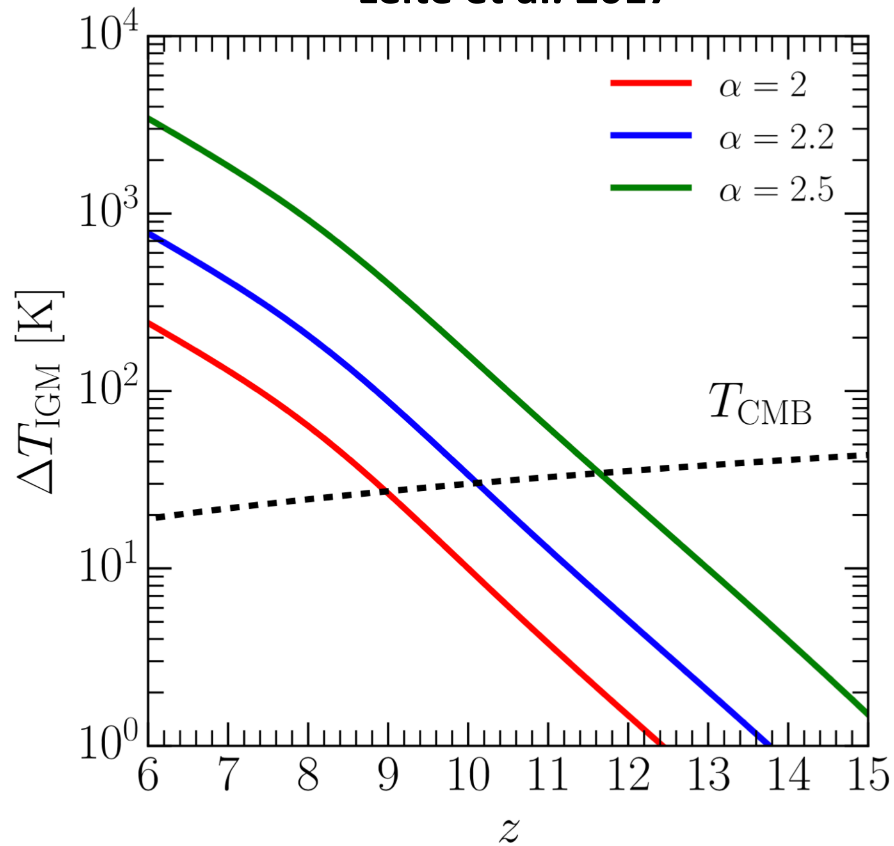


Figure 7. Increment of the average IGM temperature by CRs as a function of redshift for three values of the CR injection slope. The CMB temperature at the same redshift is shown by the dashed line.

Cosmic rays can ionize and heat the primordial gas.

Observation of 21 cm line in radio

Stopping length of free streaming CRs

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

Sazonov & Sunyeav 2015

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

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

Stopping length of X rays

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

Mean distance between halos

$R \sim 50\text{kpc}$

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

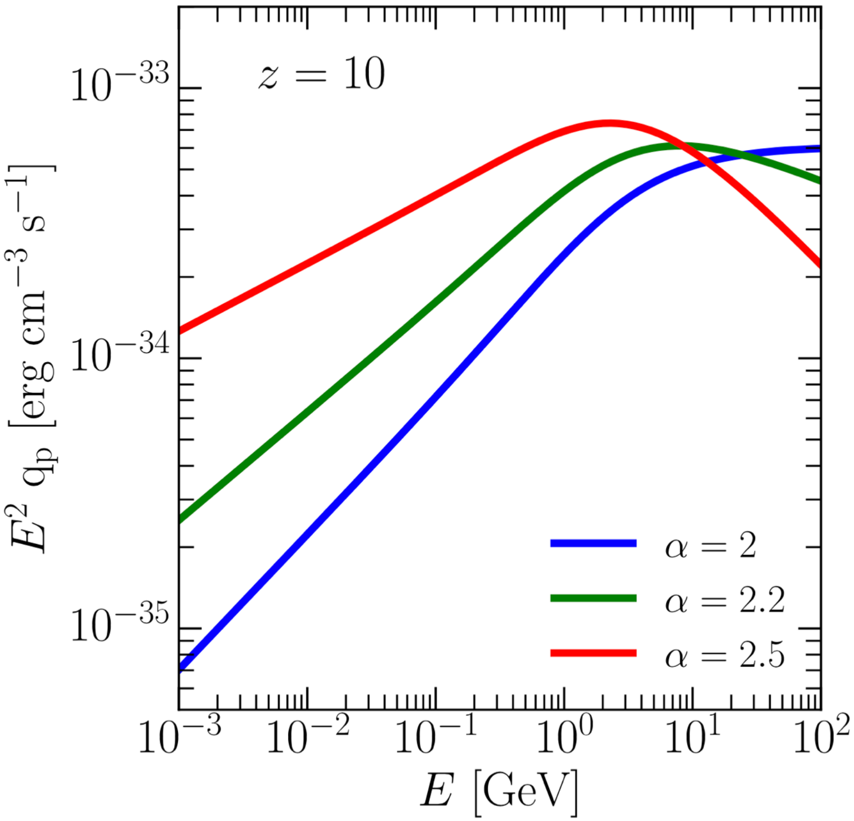


Figure 3. Source function of CR protons with respect to their kinetic energy at $z = 10$ for a spectrum slope $\alpha = 2$ (blue line), 2.2 (green) and 2.5 (red).

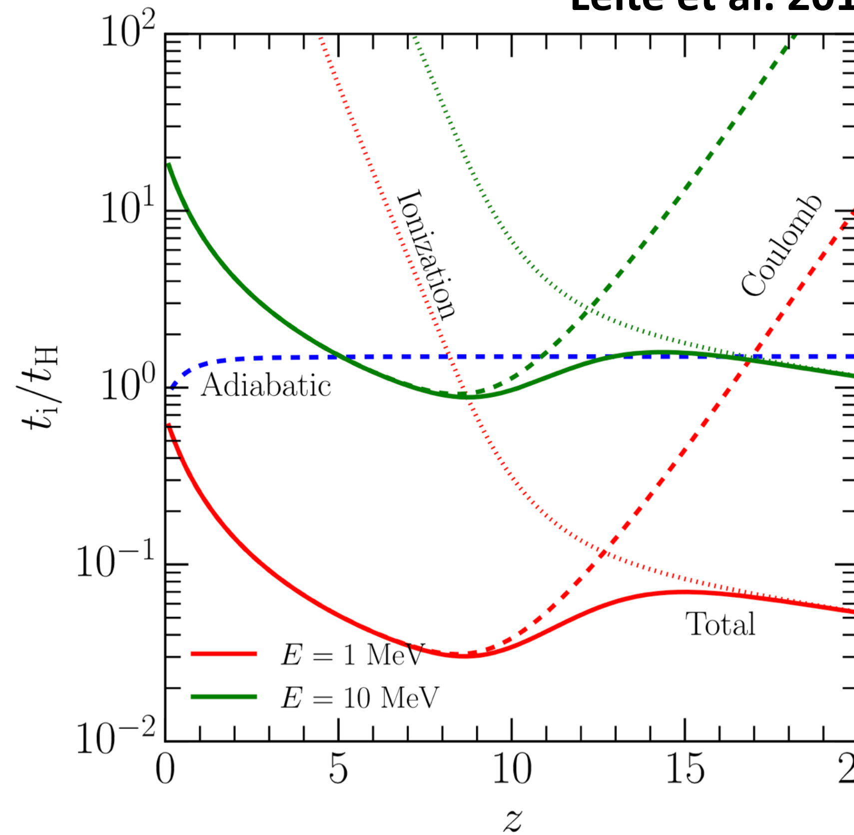


Figure 4. Energy-loss time-scales (see equations [25–27]) normalized to the Hubble time for CR protons of 1 and 10 MeV. The adiabatic time-scale (blue dashed line) is independent of the particle energy.

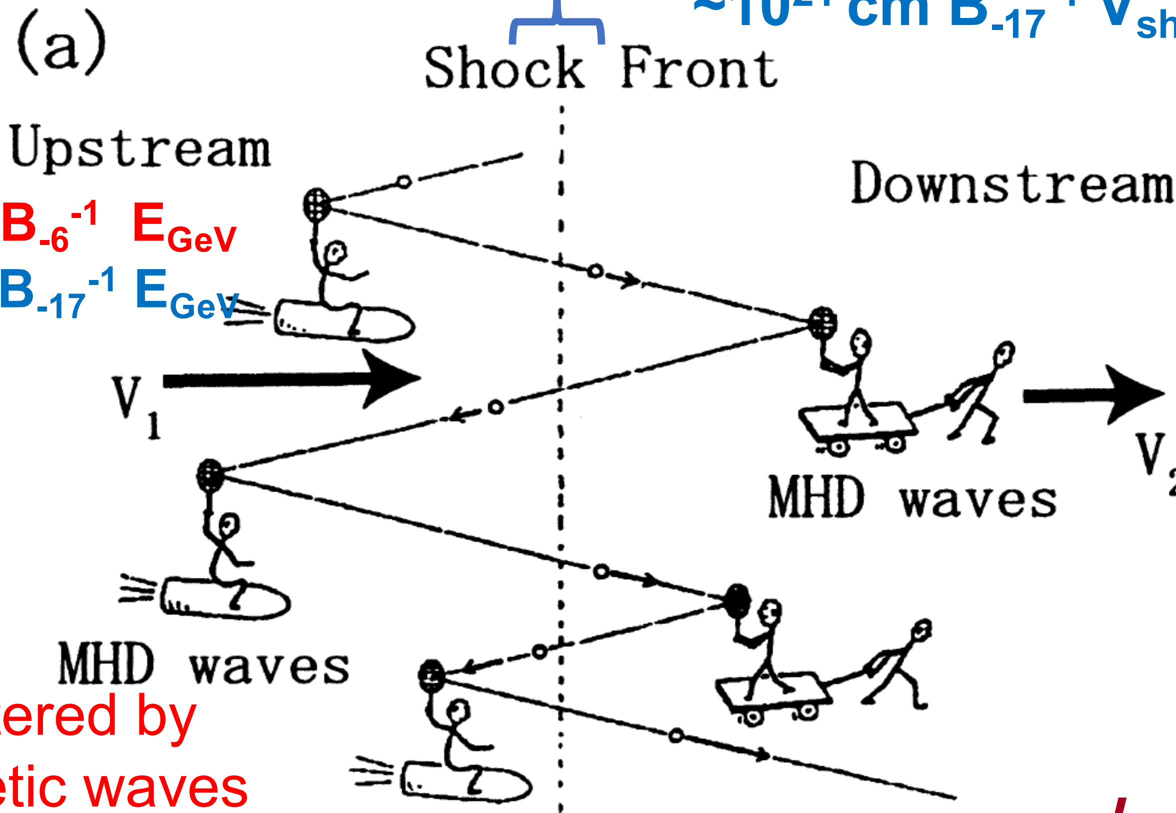
What is the maximum energy of the first CRs?

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

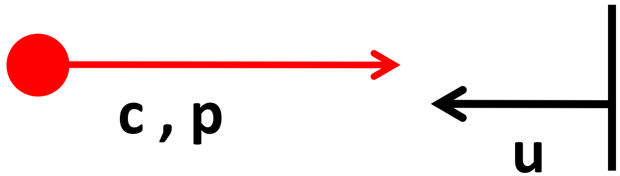
Electromagnetic waves are excited by CRs.

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

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

Acceleration time of DSA

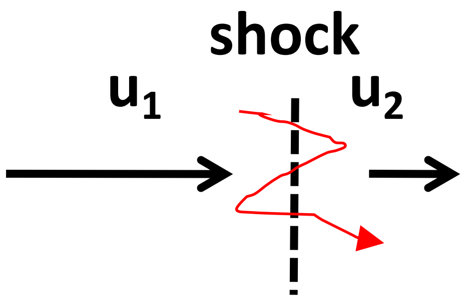
Momentum change by particle scattering, Δp



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 $z \sim 20$ (Yoshida et al. 2003).
$M = 10 - 1000\ M_{sun}$ (Hirano et al. 2014)

They explode at $z \sim 20$.

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 $z=20 \sim 10^6\ M_{sun}$ (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)

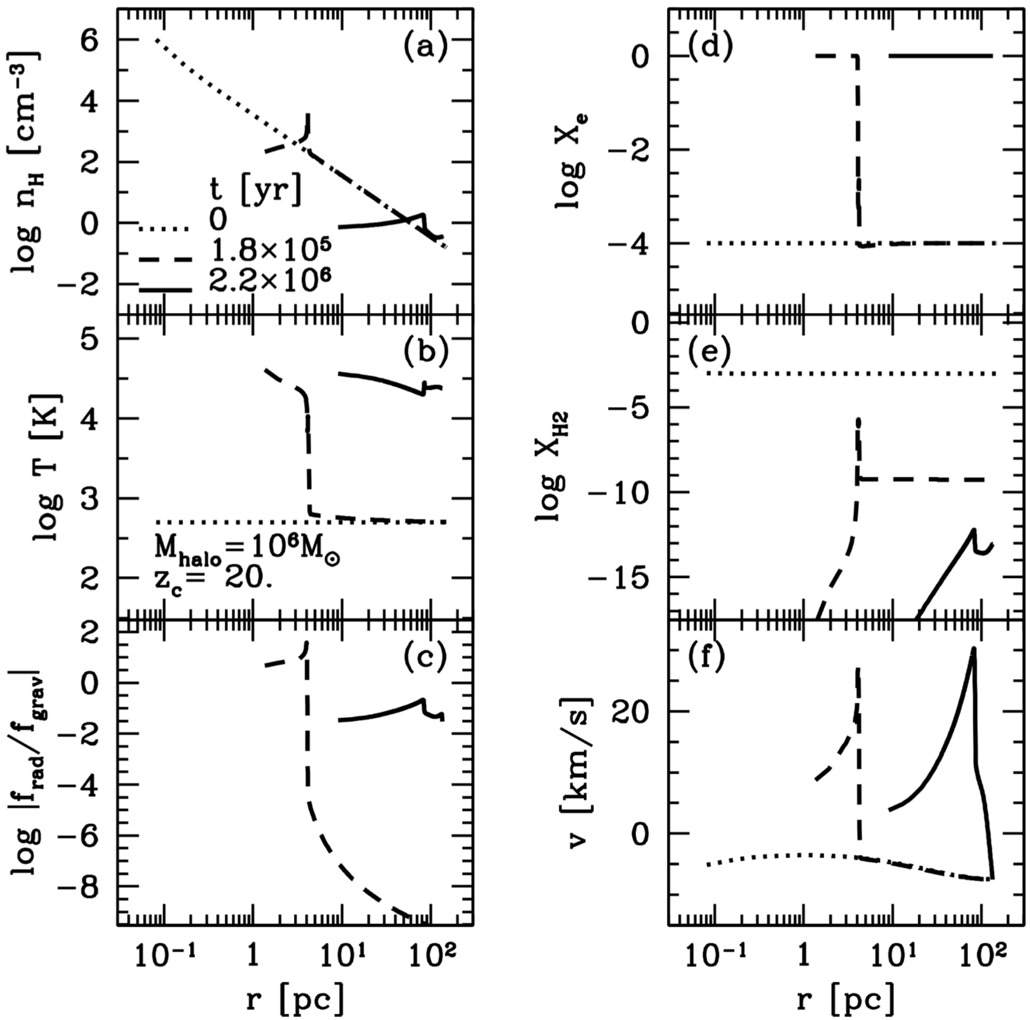
The shock dissipation is due to atomic collision.

→ No cosmic ray is accelerated.

For $z < 10$, halos with $M \sim 10^{10}\ M_{sun}$ 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: $n \sim 1\ cm^{-3}$, $T \sim 1$ eV, $f_i \sim 1$, $B < 10^{-17}$ G, $u_{CMB} \sim 4\text{x}10^4$ eV cm^{-3}

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

Gyro radius r_g > 1kpc >> 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 $T_e \sim m_e V_{sh}^2 >> T_p \sim 1$eV.

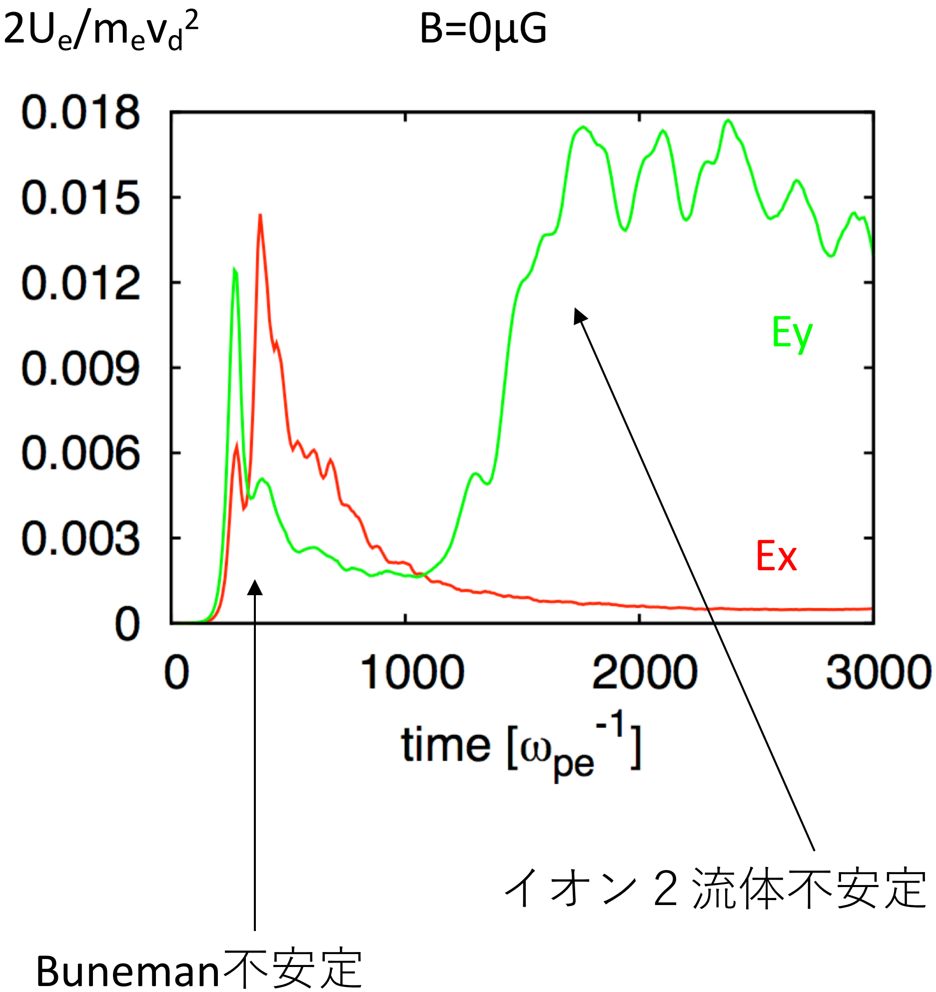
3) Then, the ion-ion twostream instability becomes most unstable mode (electrostatic mode).

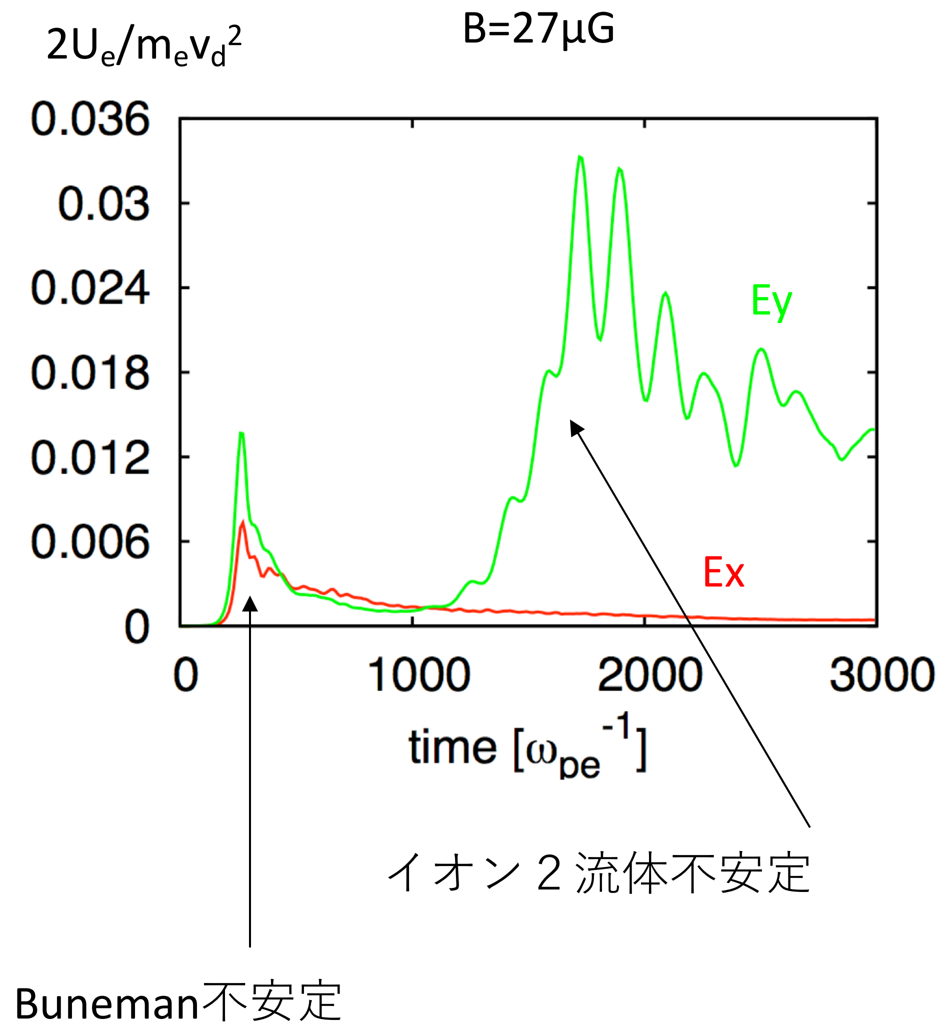
4) Then, ions are heated to $T_p \sim T_e \sim m_e V_{sh}^2$ (Ohira & Takahara 2007,2008).

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.

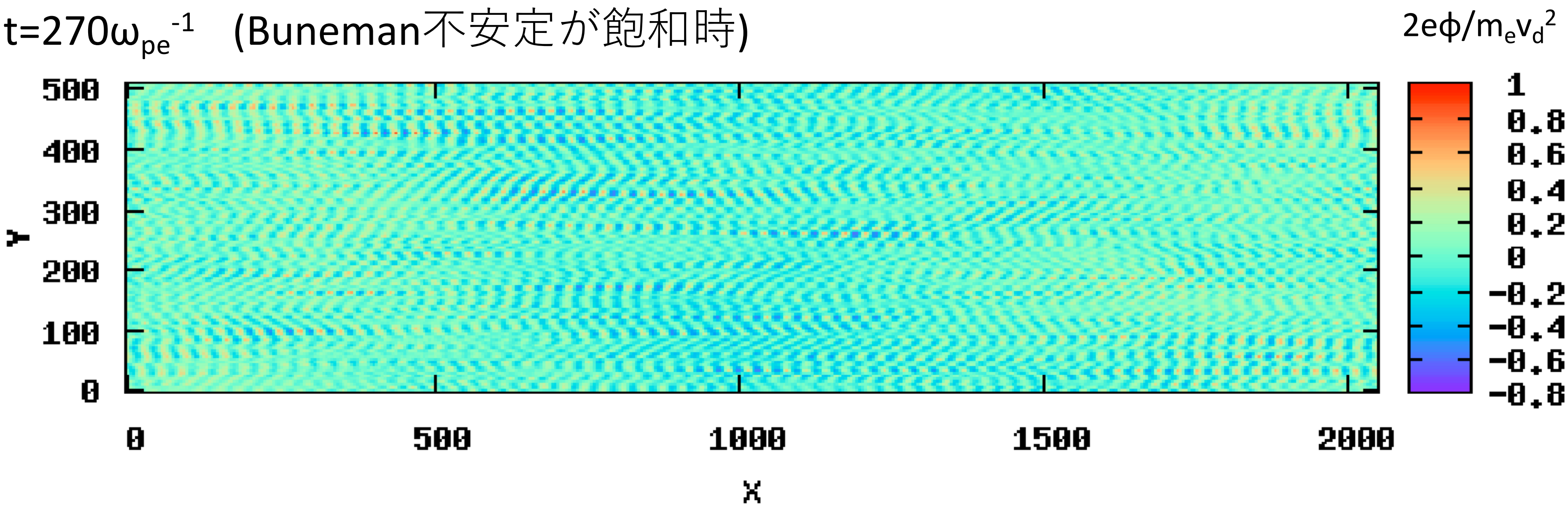
計算結果（電場の時間変化）



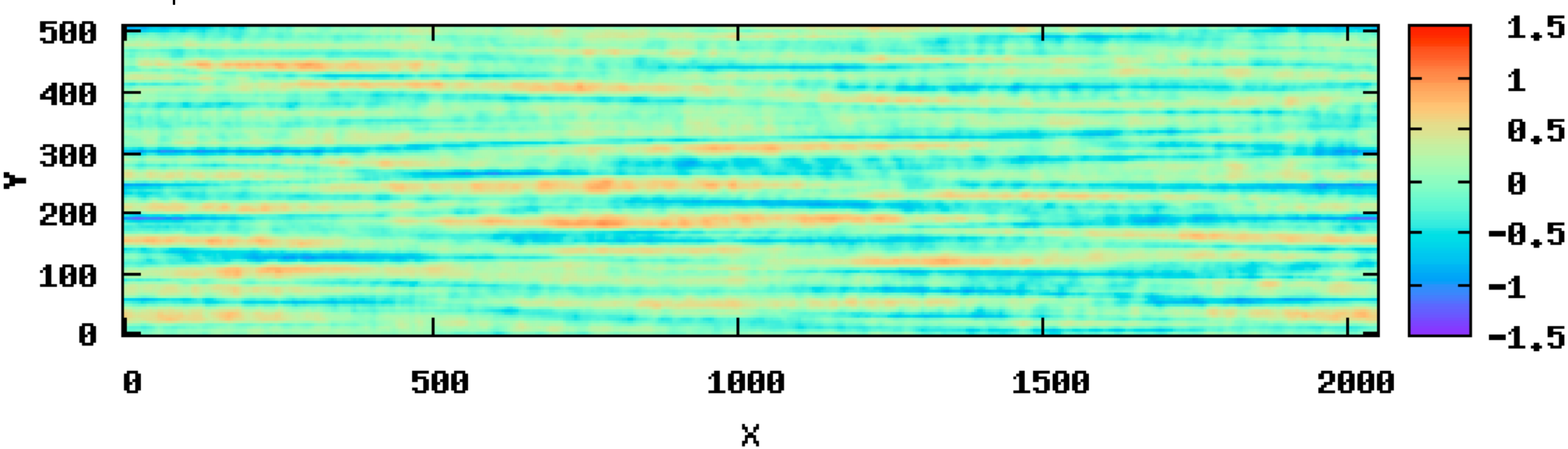


計算結果（静電ポテンシャル構造 B=0）

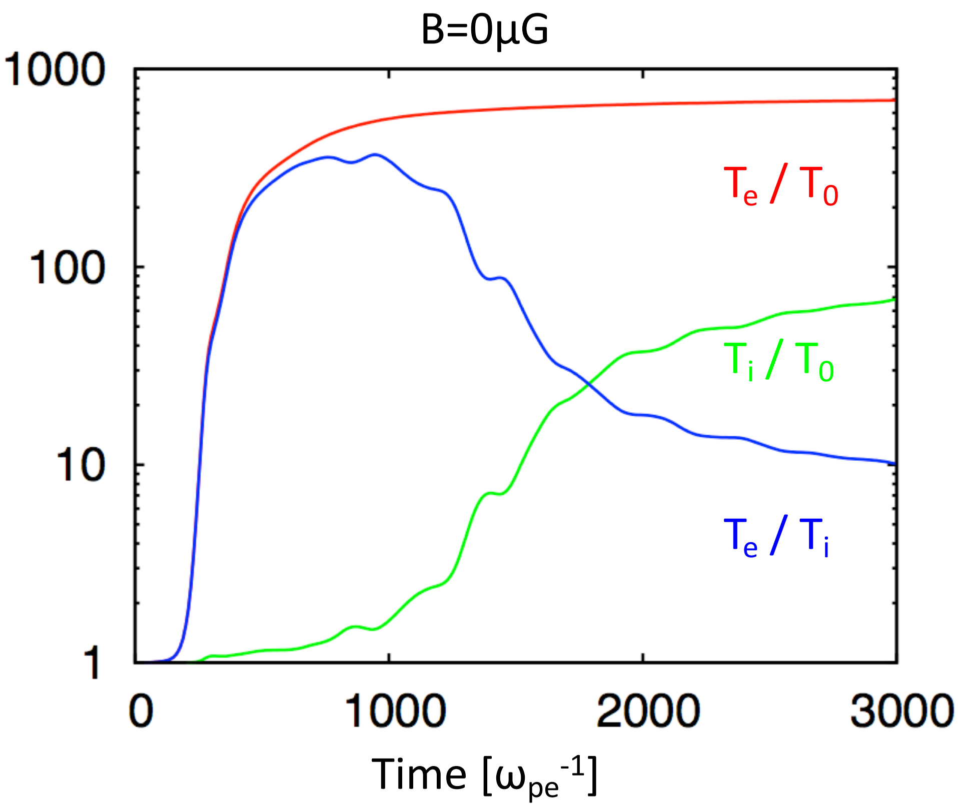
$t=270\omega_{pe}^{-1}$ (Buneman不安定が飽和時)

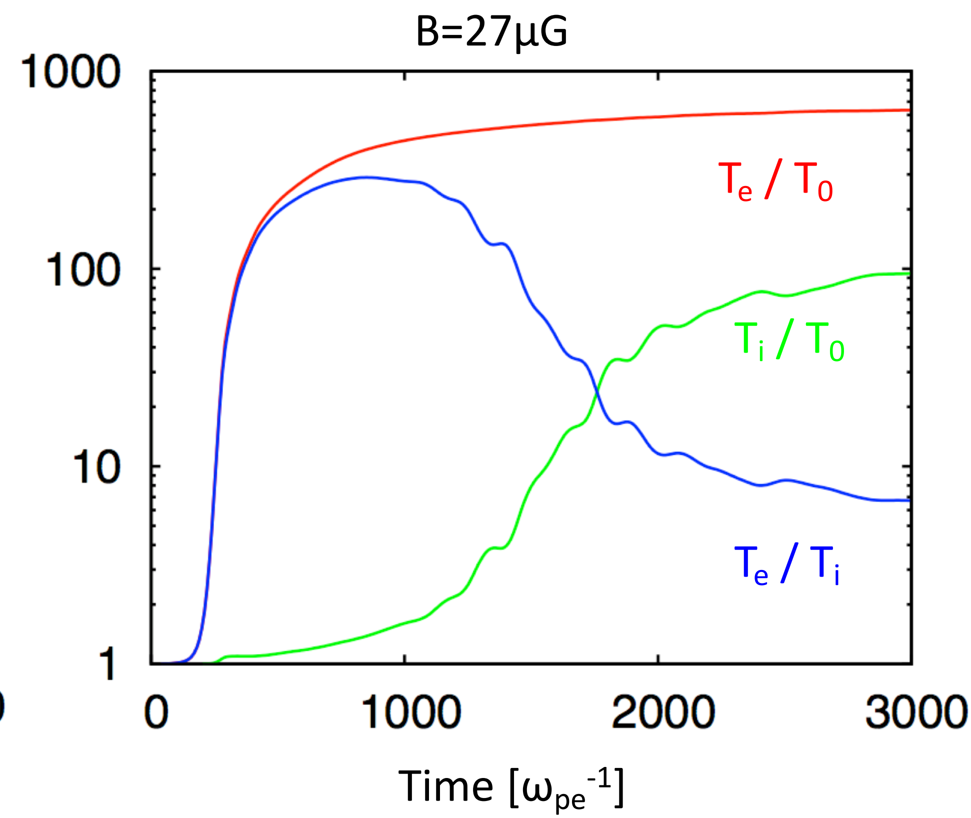


$t=1740\omega_{pe}^{-1}$ (イオン二流体不安定が飽和時)



計算結果（温度比の時間変化）

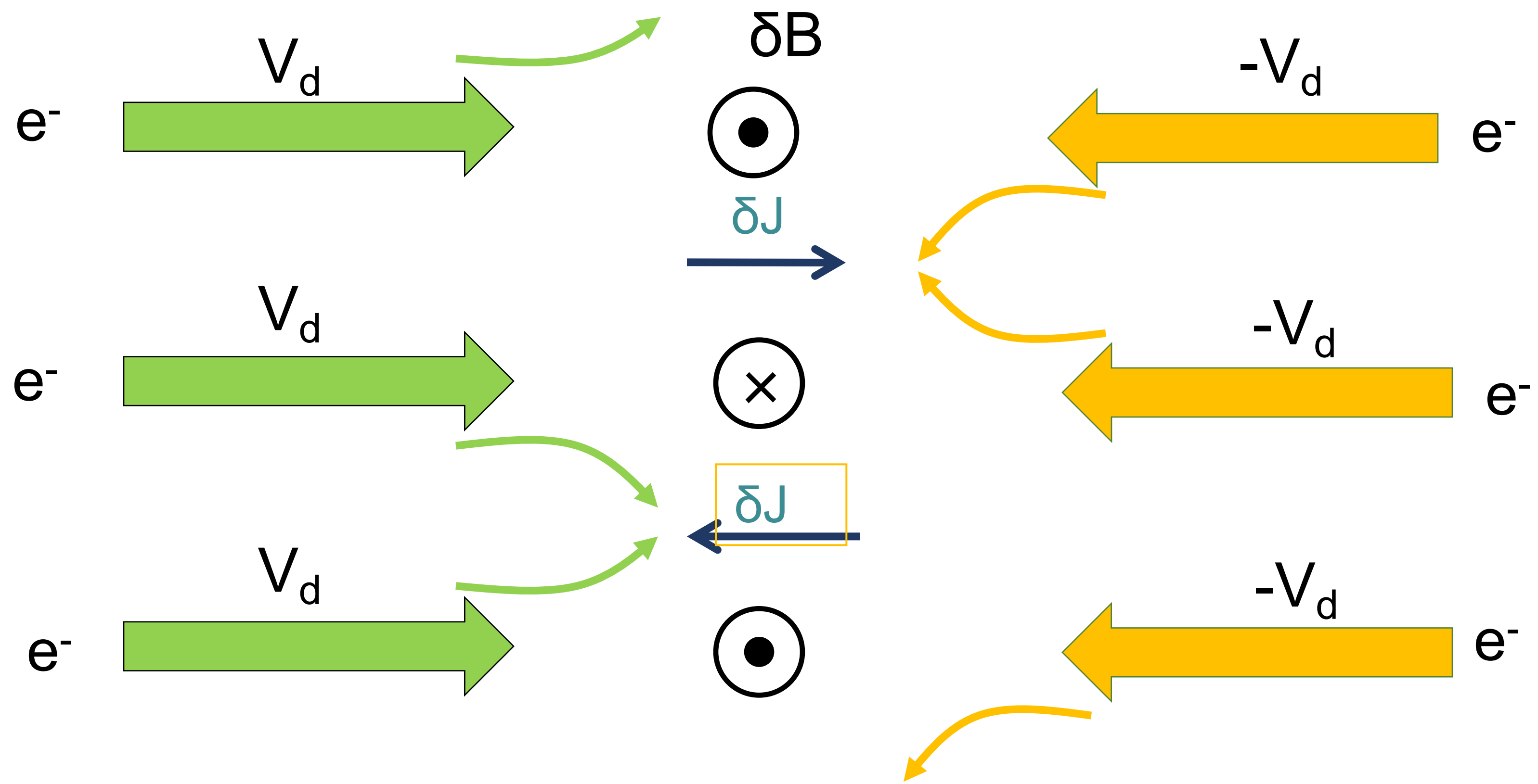




イオン２流体不安定によるイオン加熱によってT_e / T_iが下がる。
その結果イオン音波不安定の成長率を下げる。

$$\frac{\gamma}{\omega_r} = \sqrt{\pi}\left(\frac{m_e}{m_i}\right)^{1/2}\left[\left(\frac{v_d}{v_{th,i}} - 1\right) - \left(\frac{m_i}{m_e}\right)^{1/2}\left(\frac{T_e}{T_i}\right)^{3/2} e^{-T_e/2T_i}\right]$$

Weibel instability



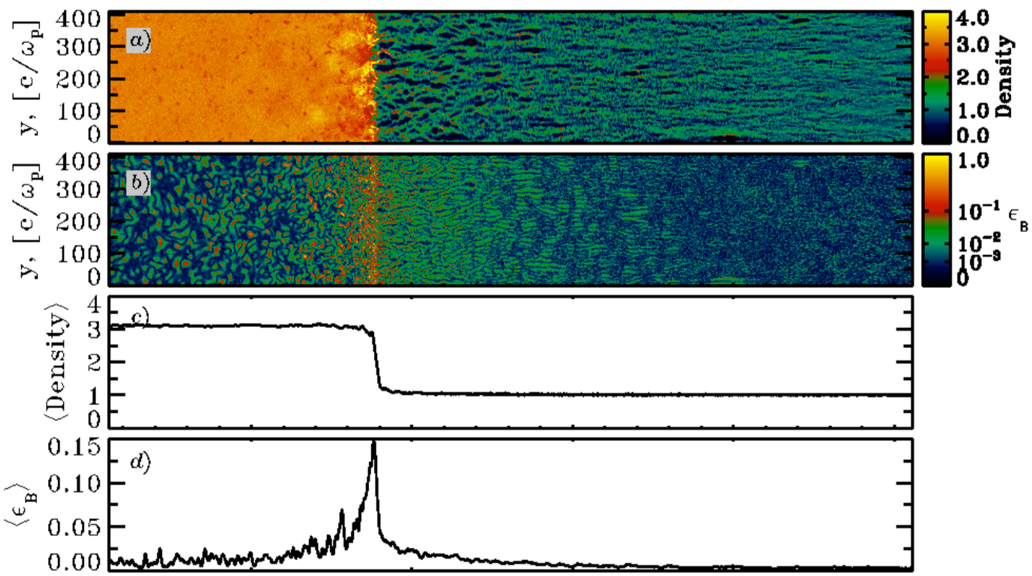
$V_d \perp k$

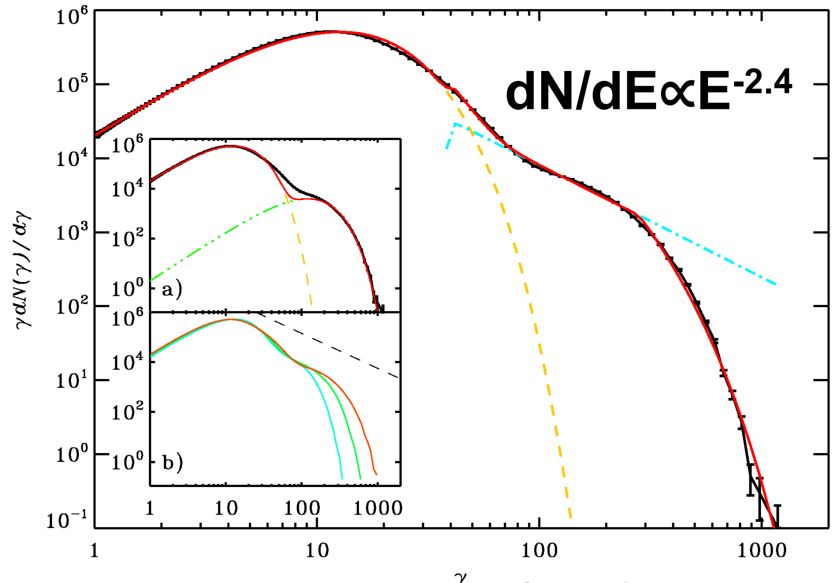
Growth rate $\mathrm{Im}[\omega] = (V_d/c)\, \omega_p$

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.





Spitkovsky 2008

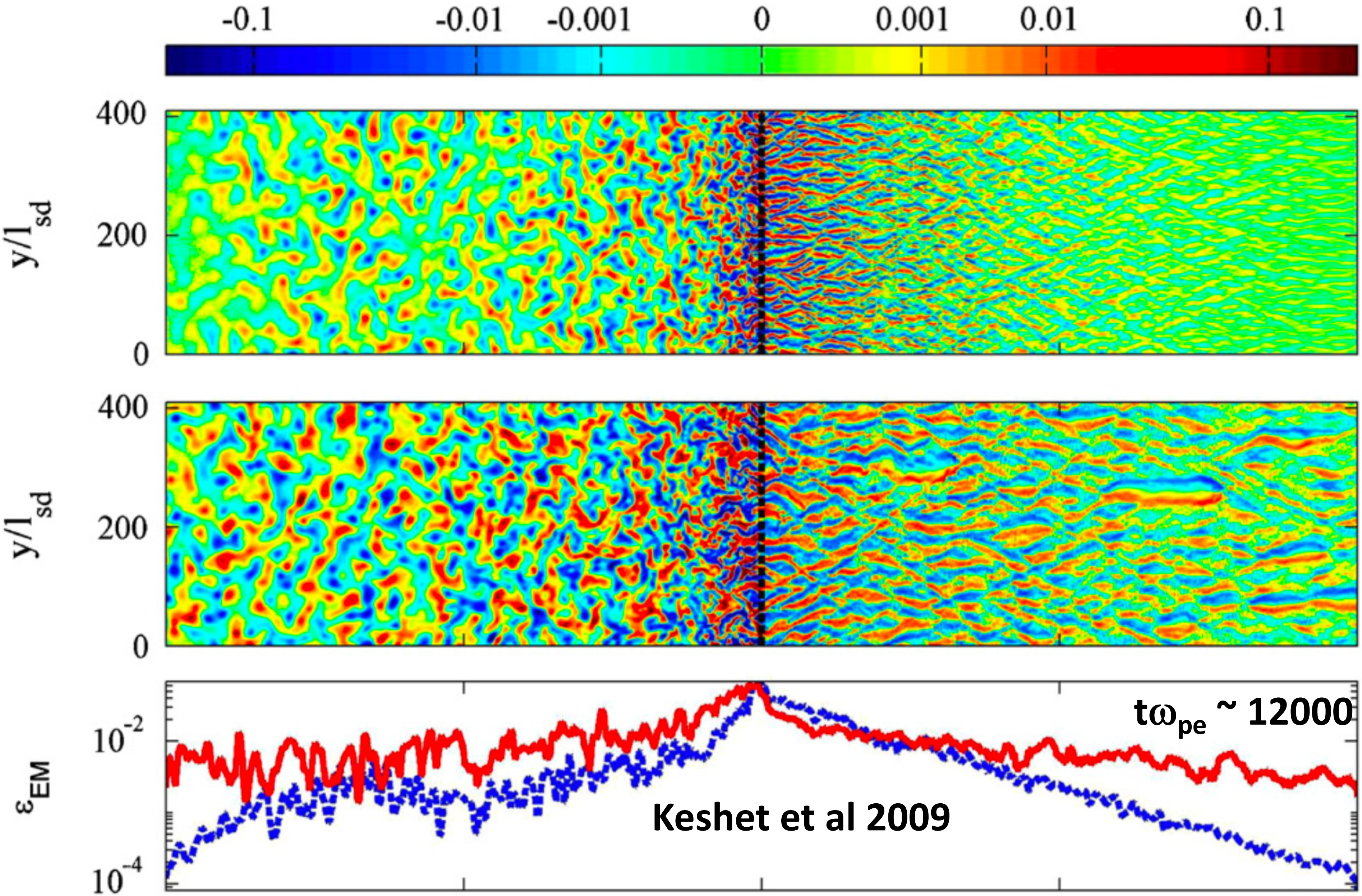
Spectral index ~ 2.4

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)

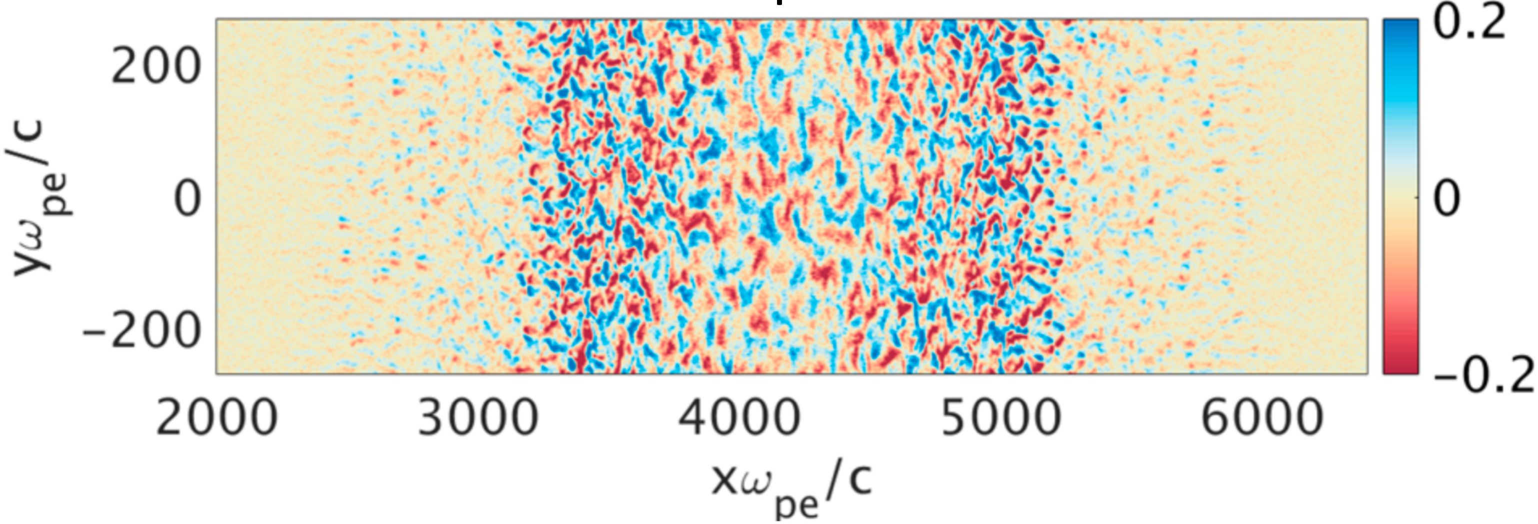
e^{+-} relativisitic unmagnetized shock



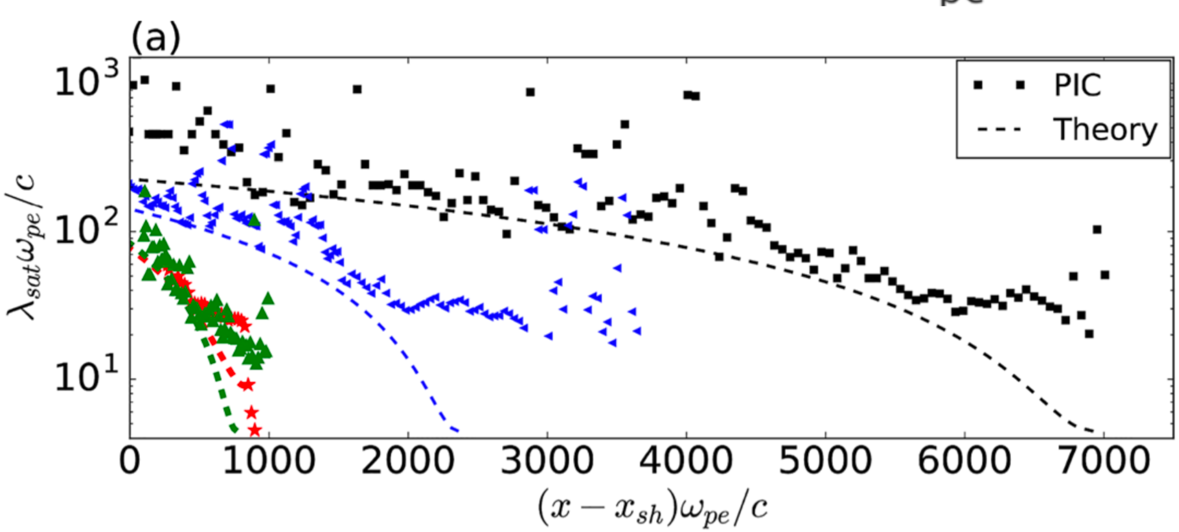
イオンワイベル不安定性が作る磁場の空間スケール（2D simulation）

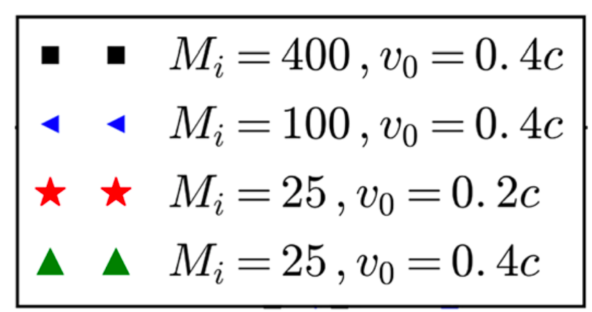
Ruyer et al. PoP 2017

$t\omega_{pe}$ ~ 4800



$t\omega_{pe}$ ~ 17000

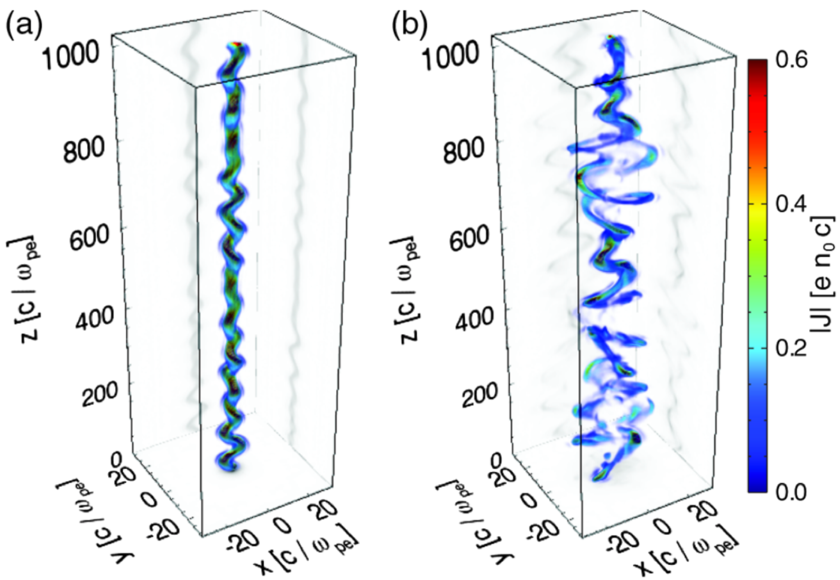


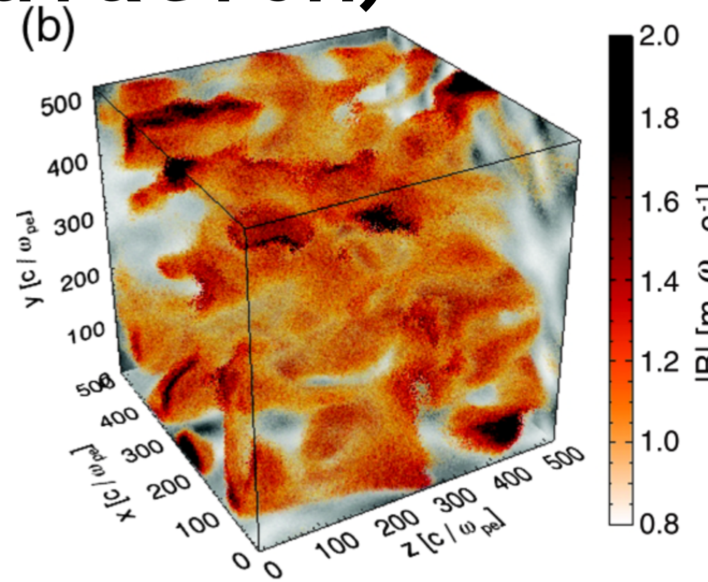


$\lambda_{\delta B}$ ~ 10 c/ω_{pi}

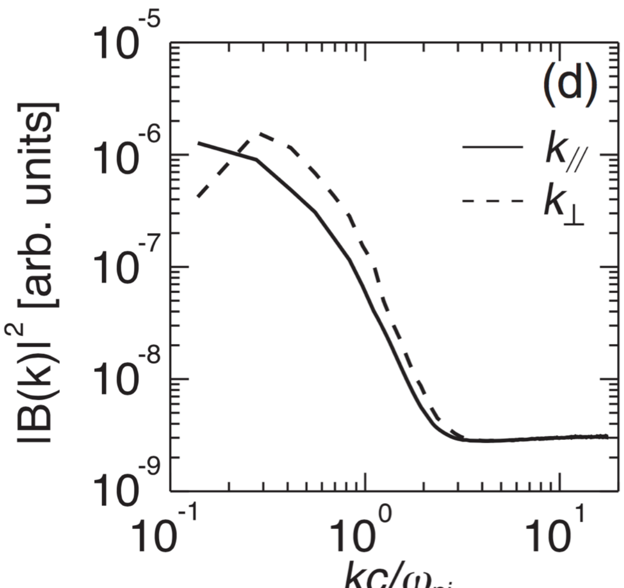
イオンワイベル不安定性が作る磁場の空間スケール（3D simulation）

Ruyer & Fiuza PRL 2018





Drift kink instabilityにより
イオンの電流構造が壊れる。



最大不安定になる波長

$\lambda_{\delta B} \sim 10\ c/\omega_{pi}$

Acceleration time scale of DSA in the nonrelativistic Weibel mediated shock

Acceleration time of DSA, $t_{acc} = 4D/u_{sh}^2$

Length scale of δB, $\lambda_{\delta B} = \alpha\, c/\omega_{pp}$ **$\omega_{pp}^2 = 4\pi n e^2/m_p$**

Gyro radius, $r_g = cp/e\delta B$

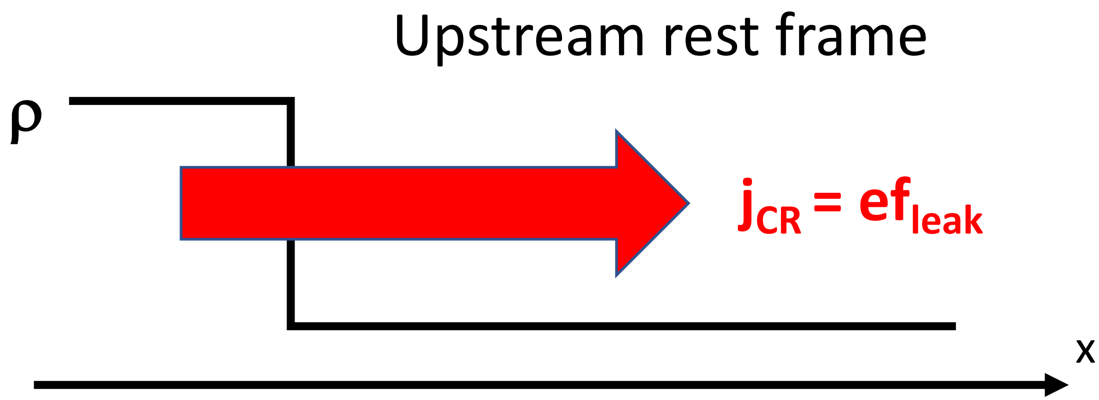
$\delta B^2/8\pi = \varepsilon_B\, m_p n u_{sh}^2/2 \rightarrow r_g/\lambda_{\delta B} = (p/m_p u_{sh})\, \varepsilon_B^{-1/2} >> 1$ for CR protons

For $r_g/\lambda_{\delta B} >> 1$, $D = 2\pi v r_g^2/\lambda_{\delta B}$ (e.g. Plotnikov et al. 2011,Subedi et al. 2017)

$$t_{\mathrm{acc},s} = \frac{40\pi}{\alpha \epsilon_{\mathrm{B}} \beta_{\mathrm{sh}}^4} \frac{\bar{p}^3}{\sqrt{\bar{p}^2 + (m_s/m_{\mathrm{p}})^2}} \omega_{\mathrm{pp}}^{-1}$$

$\bar{p} = p/m_p c$

δB generated by the CR current



f_{leak}: number flux density of CRs

$\nabla \times B = 4\pi j_{CR}/c \rightarrow \delta B/\lambda_{\delta B} \sim 4\pi e f_{leak}/c$, $\lambda_{\delta B} \sim \alpha c/\omega_{pp}$

η = [CR energy flux] / [upstream kinetic energy flux] ~ 0.1

$$\eta = \frac{f_{\rm leak}(\gamma_{\rm p}-1)m_{\rm p}c^2}{n m_{\rm p} u_{\rm sh}^3/2} \rightarrow \epsilon_{\rm B} = \left(\frac{\alpha f_{\rm leak}}{n u_{\rm sh}}\right)^2 = \frac{\alpha^2\eta^2\beta_{\rm sh}^4}{4(\gamma_{\rm p}-1)^2}$$

$\sim 10^{-8}$

for $\gamma_p \sim 2, \alpha \sim 10, \eta \sim 0.1, \beta_{sh} \sim 0.01$

Maximum energy of first CR protons

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

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

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

→ $E_{max,p}(t_{Sed}) \sim 190$ MeV $\alpha_{,1}^{6/7} \eta_{,-1}^{4/7} E_{SN,51} M_{ej,34}^{-19/24} n_{,0}^{1/21} \ll 3$ PeV

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

Cooling time of CRs due to the Coulomb loss, $t_{\rm cool} = 1.51 \times 10^{15}$ sec $n_{,0}^{-1}\bar{p}^3$

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

$E_{max,p}(t_c) \sim 3.2$ MeV → CRs with E<~ 3MeV cannot escape from the first SNRs.

Maximum energy of first CR electrons

電子は、最高エネルギー陽子の拡散長によって制限される。

$D_{e,max} = D_{p,max} \rightarrow v_{e,max}\, p_{e,max}^2 = v_{p,max}\, p_{p,max}^2 \rightarrow p_{e,max}^2 \propto p_{p,max}^3$

$D = 2\pi v r_g^2 / \lambda_{\delta B}$

$E_{max,e}(t_{Sed}) \sim 470\ \mathrm{MeV}\ \alpha_{,1}^{9/14}\, \eta_{,-1}^{3/7}\, E_{SN,51}^{3/4}\, M_{ej,34}^{-19/28}\, n_{,0}^{1/28}$

Sedov期($t > t_{Sed}$)

$E_{max,e}(t) = E_{max,e}(t_{Sed})\, (t/t_{Sed})^{-57/70}$

陽子のE_{max}がcoolingで決まる時期 ($t > t_c \sim 43\, t_{Sed}$)

$E_{max,e}(t) = 22\ \mathrm{MeV}\, (t/t_c)^{-9/5}$

冷却が効かないので、加速された電子は全て、SNRから逃走可能。

CR acceleration by other types of supernovae

- Fast ejecta of normal core-collapse SNe

$V_{sh} \sim 2.2 \times 10^9$ cm/s $E_{SN,51}^{7/16} M_{ej,34}^{-5/16} D_{12}^{-1/8} t_4^{-1/8}$, $\rho_{ej} \propto r^{-10}$, $\rho_{CS} = Dr^{-2}$

→ $E_{max,p} \sim 1.5$ GeV $\alpha_{,1}^{3/4} \eta_{,-1}^{1/2} E_{SN,51}^{49/64} M_{ej,34}^{-35/64} D_{12}^{-3/32} t_4^{-7/32}$

- Pair instability SNe

$M_{ej} \sim 2 \times 10^{35}$ g , $E_{SN} \sim 10^{53}$ erg → $E_{max,p} = 2.7$ GeV

- Pulsational pair instability SNe

$M_{ej} \sim 10^{34}$ g , $E_{SN} \sim 10^{51}$ erg → $E_{max,p} = 190$ MeV

$M_{ej} \sim 10^{34}$-10^{35} g, $E_{SN} \sim 10^{51}$ erg → $E_{max,p} = 23$ - 190 MeV

- Direct collapse to black holes (~ 30% of first stars)

$M_{ej} \sim 10^{30}$-10^{33} g, $E_{SN} \sim 10^{47}$ erg → $E_{max,p} = 0.15$ - 77 MeV

Accretion shocks at z <~ 10

Z <~ 10 で崩壊するDark matter halo (M ~ 1010 Msun) の降着衝撃波なら、V_{sh} >~ 100km/s となり、衝撃波上流を下流からの放射で電離可能。

$T_{e,up}$ ~ 1 eV → $v_{th,e}$ = 420 km/s > V_{sh}

→ Only the Weibel ins. Is unstable.

First SNRと同じ議論が使える。

陽子の最高エネルギーは、クーロンロスで決まり、

$E_{max,p} \sim 330\ \mathrm{keV}\ \alpha_{,1}^{3/2}\ \eta_{,-1}\ \beta_{sh,-3}^{4}\ n_{,-1}^{-1/4}$

電子は、最高エネルギー陽子の拡散長によって制限される。

$E_{max,e} \sim 4.1\ \mathrm{MeV}\ \alpha_{,1}^{9/2}\ \eta_{,-1}\ \beta_{sh,-3}^{4}\ n_{,-1}^{-1/4}$

電子だけ、上流側に逃走可能。

Summary

When, where, how were first cosmic rays accelerated?

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

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 ~ 190 MeV.
CRs (2 MeV < E < 190 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. On the other hand, CR e- can escape.

First CRs can generate magnetic fields.