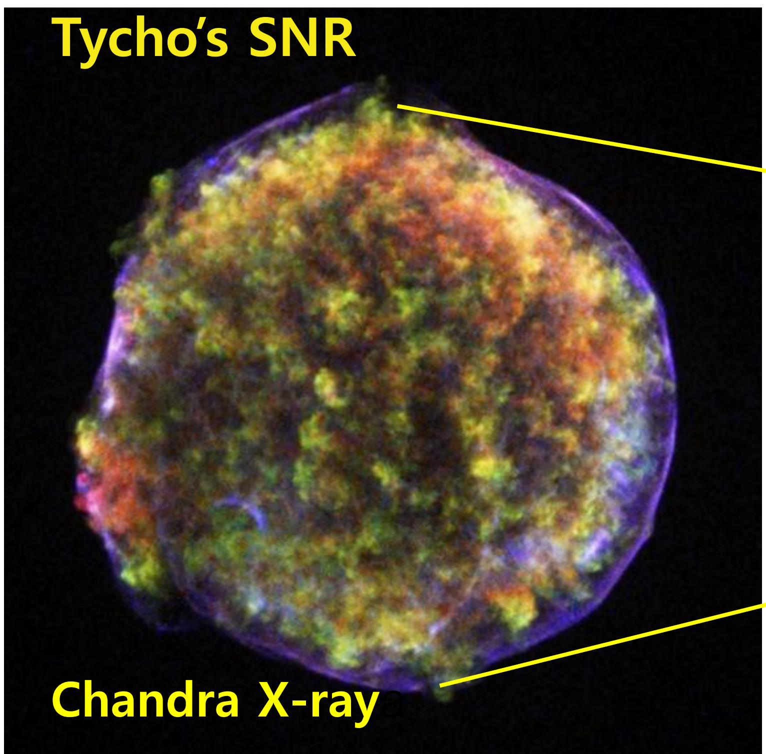
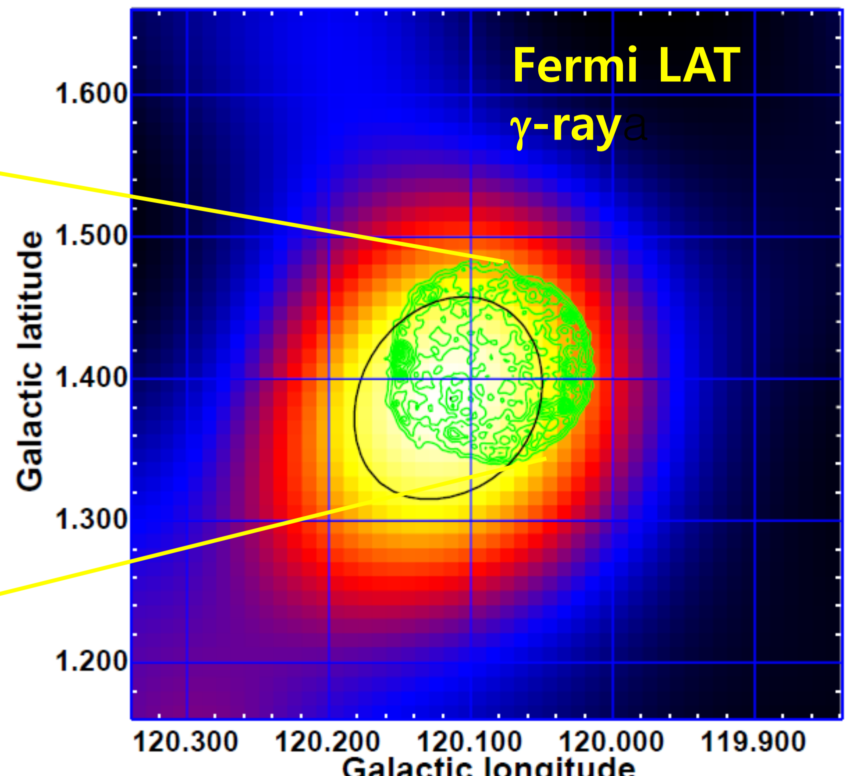
Problems in Estimating Non-thermal Radiation from Supernova Remnants

Hyesung Kang

Pusan National University, Pusan, Korea

SNR = shock → CR acceleration → non-thermal radiation

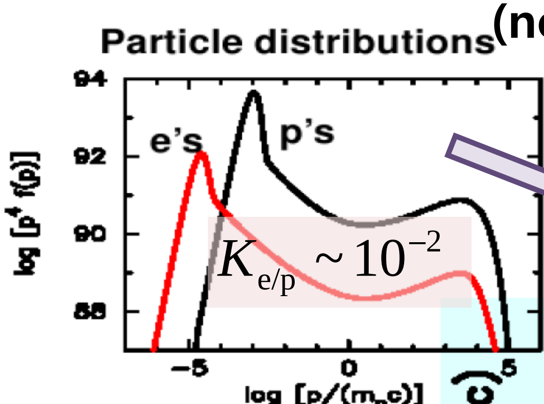




Nonthermal radiation from CRs accelerated at SNR shocks

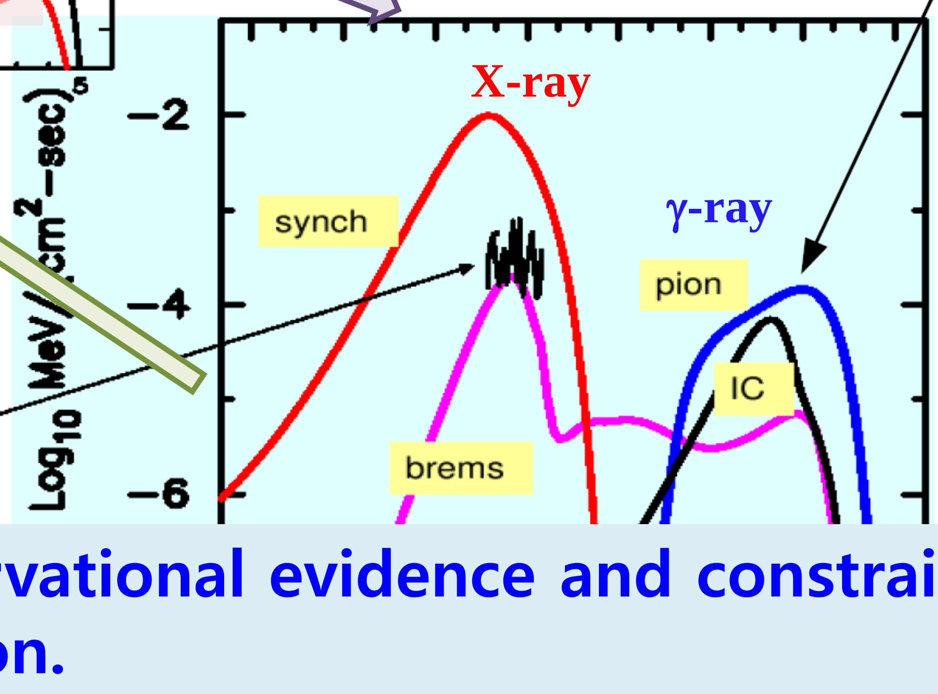
- CR e + B field → Synchrotron (radio – X-ray)
- thermal & nonthermal bremsstrahlung
- CR p + p→ π^0 decay → 100 GeV γ-ray
- CR e + CMBR → Inverse Compton scattering →TeV γ-ray

(nonlinear DSA)



predict F_ν

Pion decay and IC are competitive mechanisms



infer f(p) & verify DSA

GeV-TeV γ-ray : Hadronic vs. Leptonic origin (protons vs. electrons) depends on

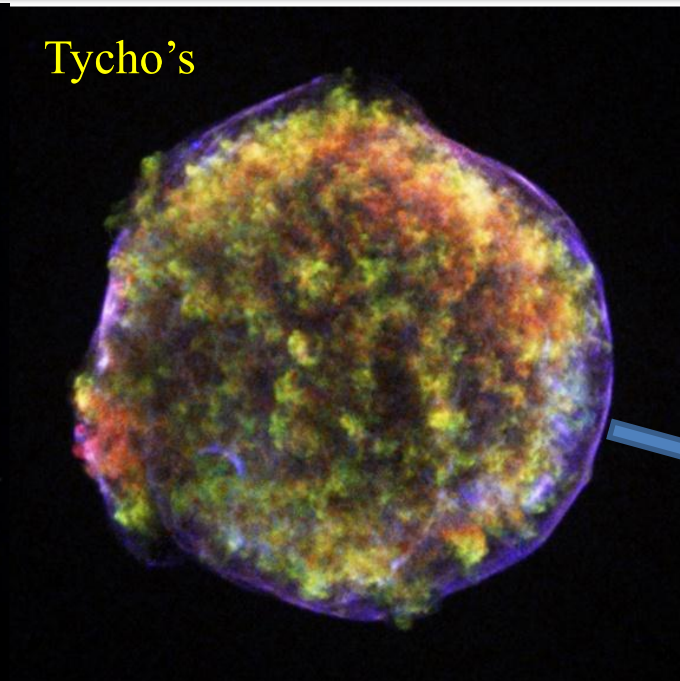
$K_{e/p} \sim 10^{-4} - 10^{-2}$

$n_0 \sim 0.003 - 0.3\ \text{cm}^{-3}$

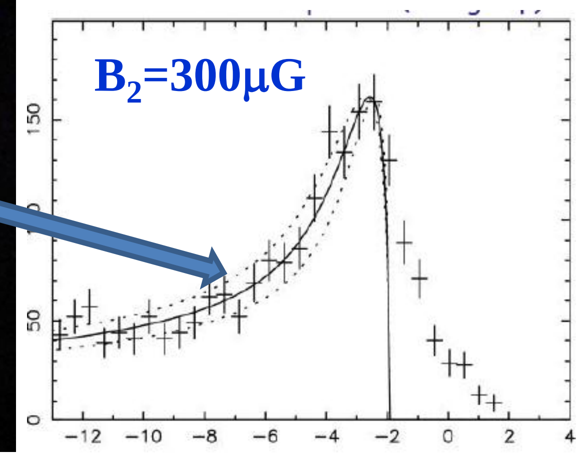
$B_2 \sim 30 - 300\ \mu\text{G}$

Provide observational evidence and constraints for CR acceleration.

X-ray observation ➔B field amplification



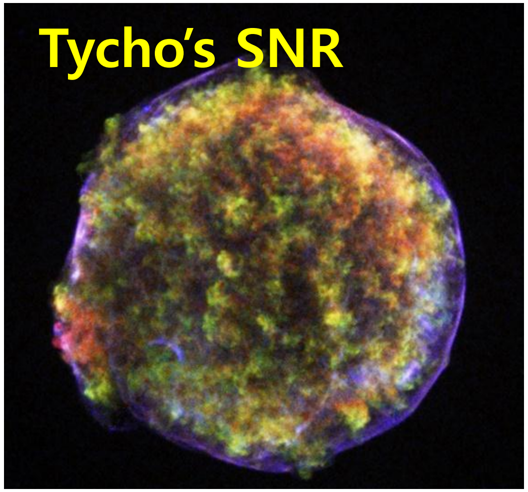
Chandra X-ray
Images of
SN Ia Remnants



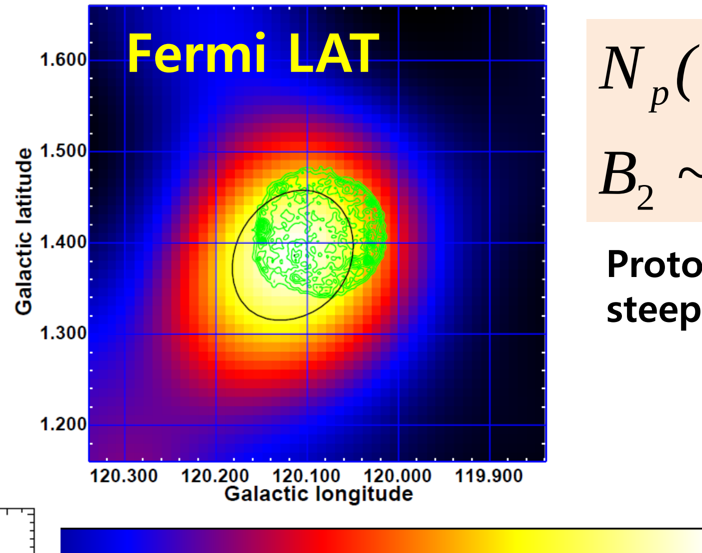
- thin filaments of nonthermal X-ray indicating fast synchrotron cooling
- B_2 ~ a few 100 μG (mag. field amplification Bell & Lucek 2000, Bell 2004)

  higher than ISM field of ~5 μG
- CR electrons with E_{ele} ~ 10's TeV

γ-ray emission from Tycho's SNRs➔ steep proton spectrum



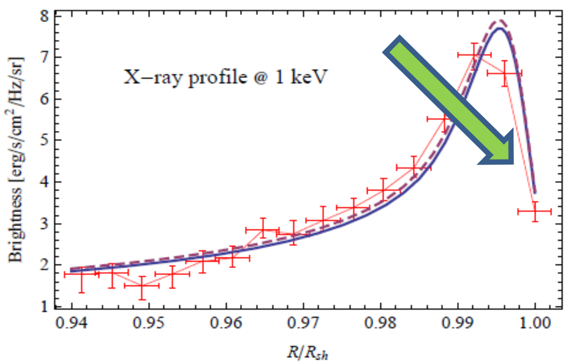
Giordano et al 2011



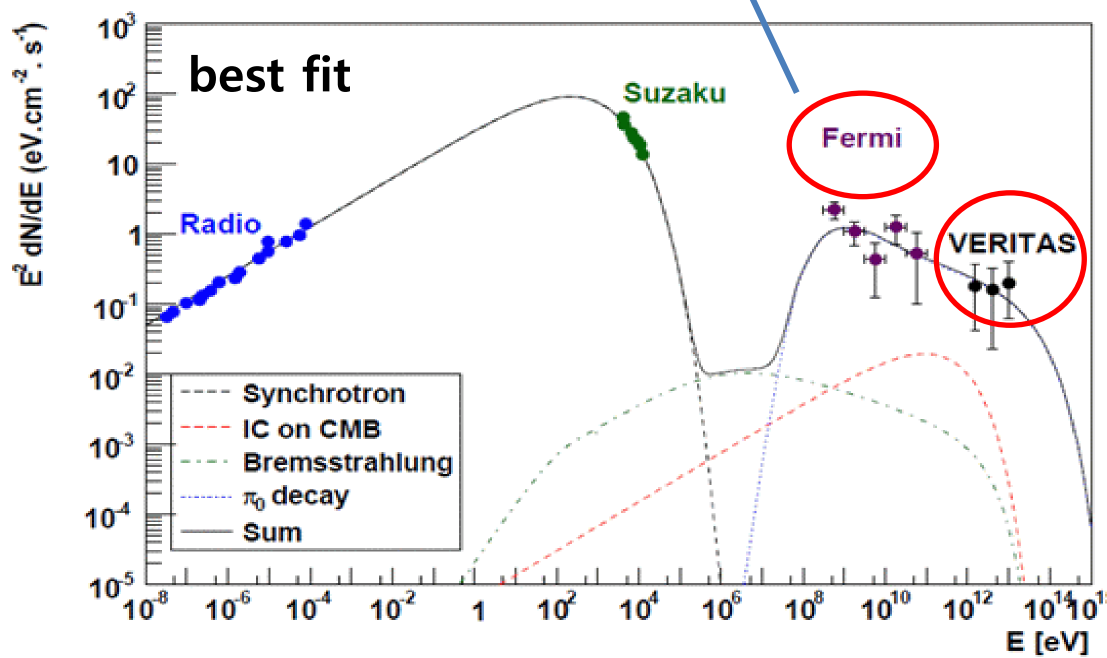
$$N_p(E) \propto E^{-2.3}$$

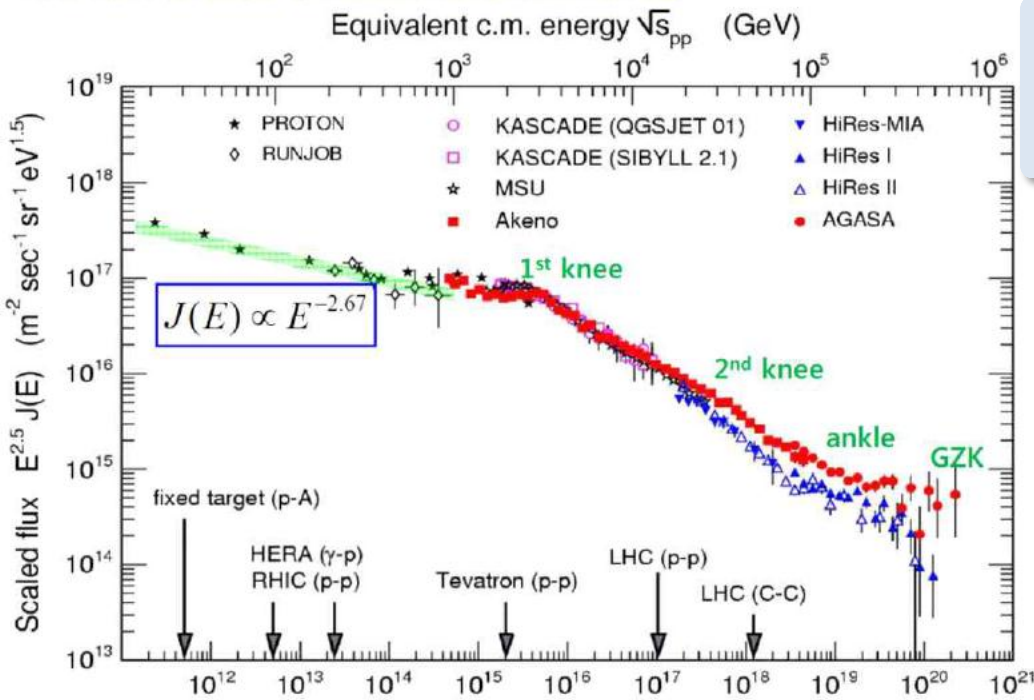
$$B_2 \sim 200\mu G$$

Proton spectrum from γ-ray spectrum steeper than test-particle power-law



Projected X-ray emission (B_2=300 μG)
Chandra X-ray data at 1 keV.





Observed CR spectrum at Earth: J(E)➔ source spectrum N(E)

$J(E) \propto E^{-2.7}$ below the knee

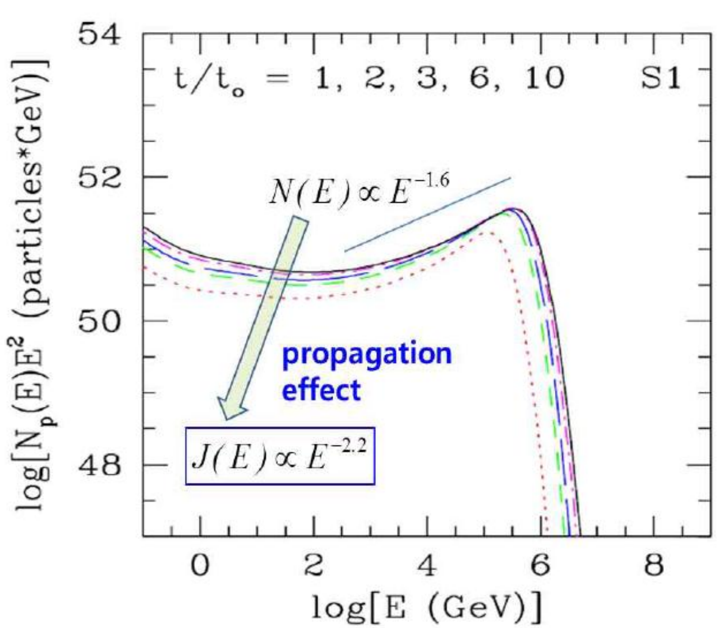
mean propagation length : $\Lambda \propto E^{-0.6}$

$\Rightarrow N(E) \propto E^{-2.2}$ at source

(Ave et al. 2009)

- consistent with γ-ray observation
- steeper than the test-particle power-law

Nonlinear DSA simulation of SNR



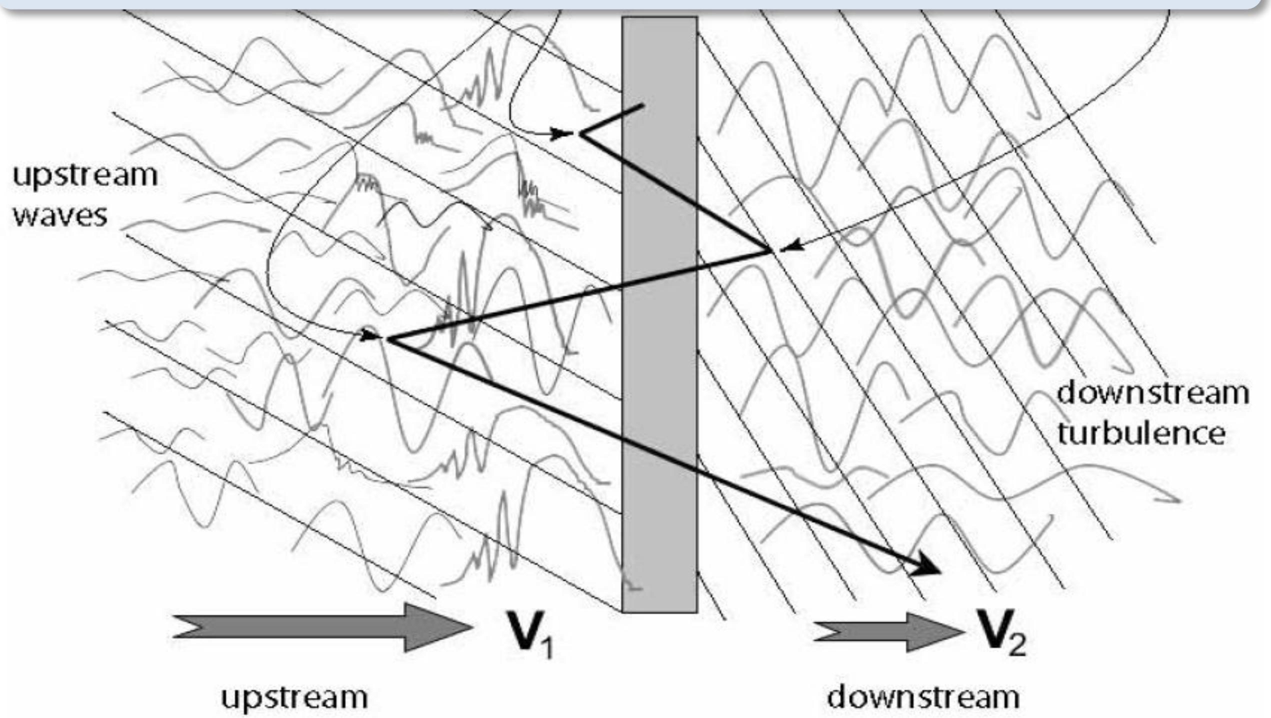
nonlinear DSA predicts :

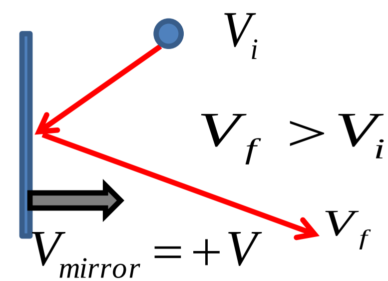
$N(E) \propto E^{-1.6}$

Trouble with nonlinear DSA ??

Basics of Diffusive Shock Acceleration

Particle Acceleration at Shocks: Fermi 1st order





Collision with approaching mirrors → gain energy

Alfven waves in a converging flow act as converging mirrors

→ particles are scattered by waves and isotropized in local fluid frame

→ cross the shock many times, gain $\frac{\Delta p}{p} \sim \frac{u_1 - u_2}{v}$ at each shock crossing

Test-particle spectrum ➔ non-thermal radiation spectrum

$f(p)$: isotropic part of momentum distribution function

$$f(p) \propto p^{-q} \quad \text{: power-law}$$

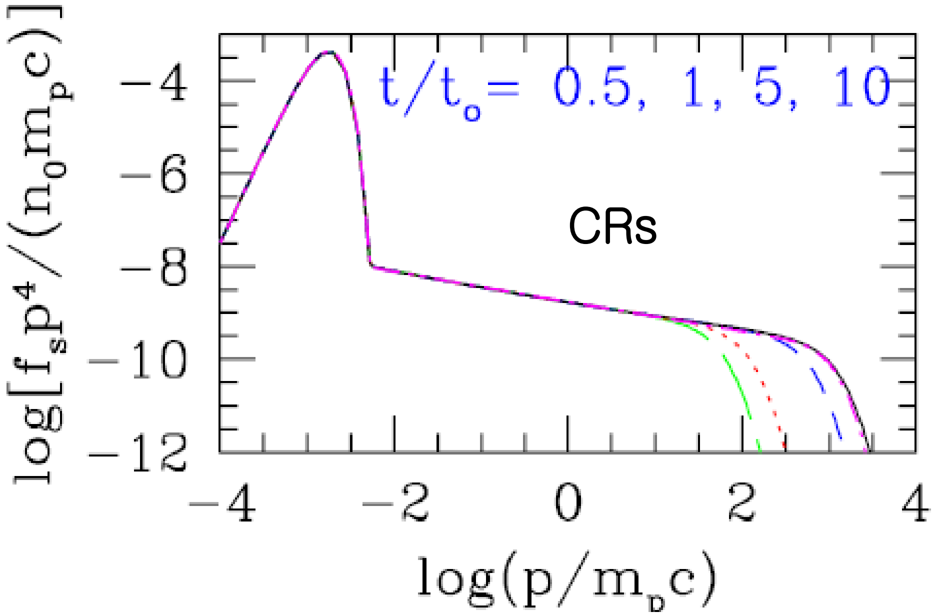
$$q = \frac{3V_2}{V_1 - V_2} = \frac{3r}{r-1}$$

r = compression ratio

for $M >> 1$, $r = 4, q = 4$

$$N(E) \propto E^{-\gamma} \qquad \gamma = q - 2 = 2$$

DSA kinetic simulation: M_s=5 shock
thermal + power-law distribution



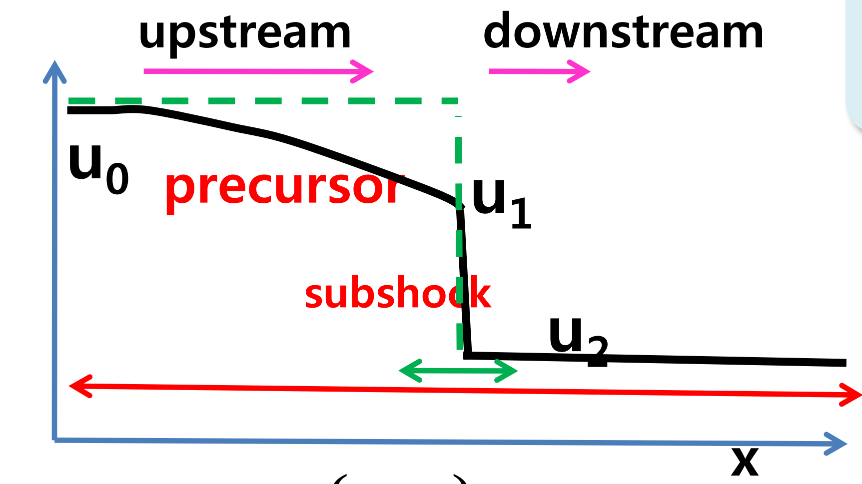
electron synchrotron + IC scattering photon spectrum at shock

$$j_\nu \propto \nu^{-\alpha}, \ \alpha_{syn(IC)} = (q-3)/2, \ \alpha_{syn(IC)} \approx 0.5 \ \text{for} \ q = 4$$

proton + p collision $\Rightarrow \pi^0$ decay γ-ray spectrum

$$j_\nu \propto \nu^{-\alpha}, \ \alpha_{\pi^0} \approx (q-2)/2, \ \alpha_{\pi^0} \approx 1 \ \text{for} \ q = 4$$

Test-particle vs. CR modified shock



when $P_{CR} \sim \rho u_s^2$

for $\kappa(p) = \kappa^* p^{\alpha}$

momentum dependent diffusion

-shock precursor develops

-Particles with different *p* experience different Δu due to precursor

$$l_{diff}(p_{\min}) = \frac{\kappa(p_{\min})}{u_s} \rightarrow u_1 - u_2$$

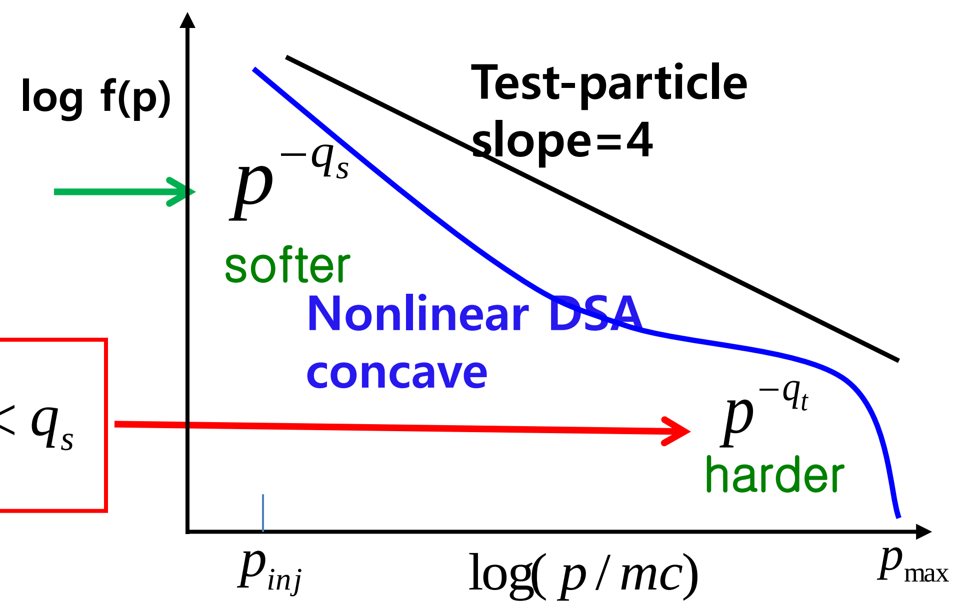
$$l_{diff}(p_{\max}) = \frac{\kappa(p_{\max})}{u_s} \rightarrow u_0 - u_2$$

across the subshock

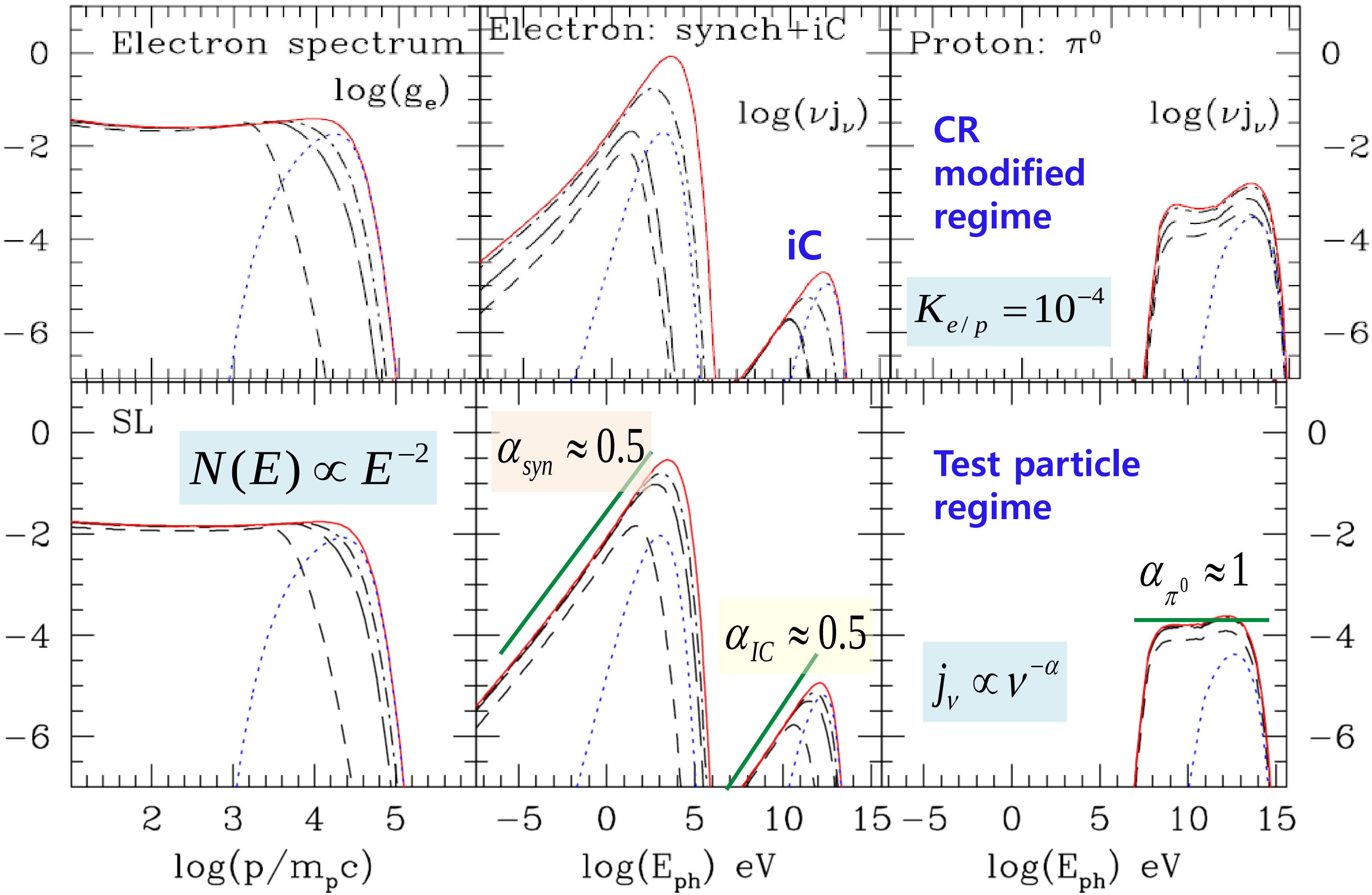
$$q_s = \frac{3 \cdot (u_1)}{u_1 - u_2} > 4$$

across the total shock

$$q_t = \frac{3 \cdot (u_0)}{u_0 - u_2} < q_s$$



Nonthermal Radiation from SNR: DSA simulations Kang, Edmon, Jones 2012



at different locations: upstream, shock, & 3 downstream locations

B field amplification via plasma instabilities

streaming CRs upstream of shocks
→ **excite resonant Alfven waves**
→ **amplify B field (Bell 1978, Lucek & Bell 2000)**

$$\lambda_w \sim r_g(p)$$

resonant waves

B field lines, t = 1.5

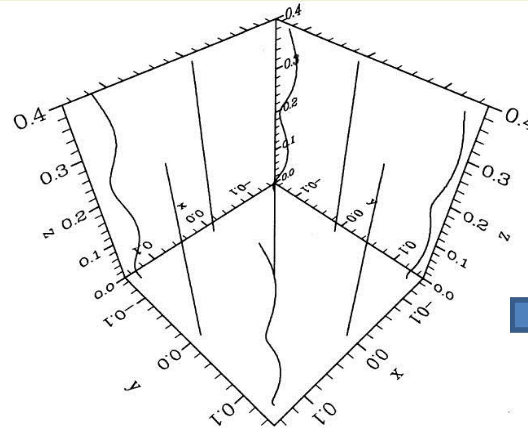


Figure 8. Magnetic field lines at $t = 0$ for the three-dimensional run.

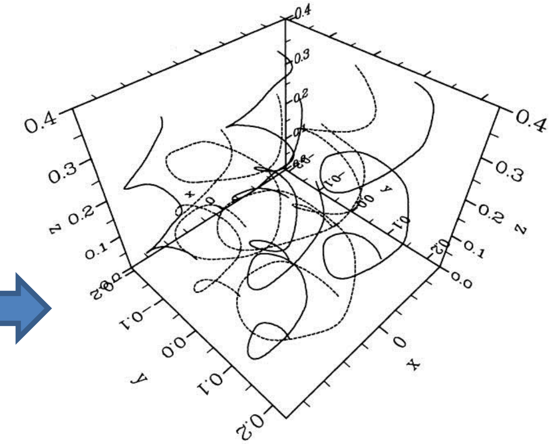
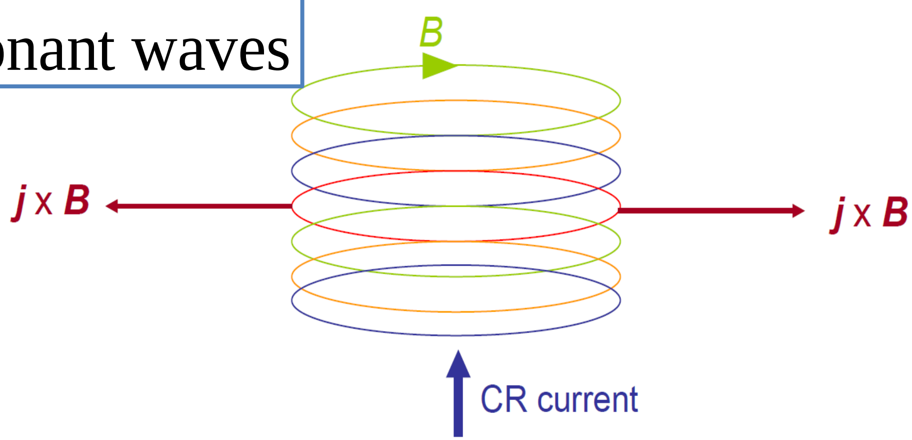


Figure 9. Magnetic field lines after 1.5 CR gyrations for the three-dimensional run.

$$\lambda_w << r_g(p)$$

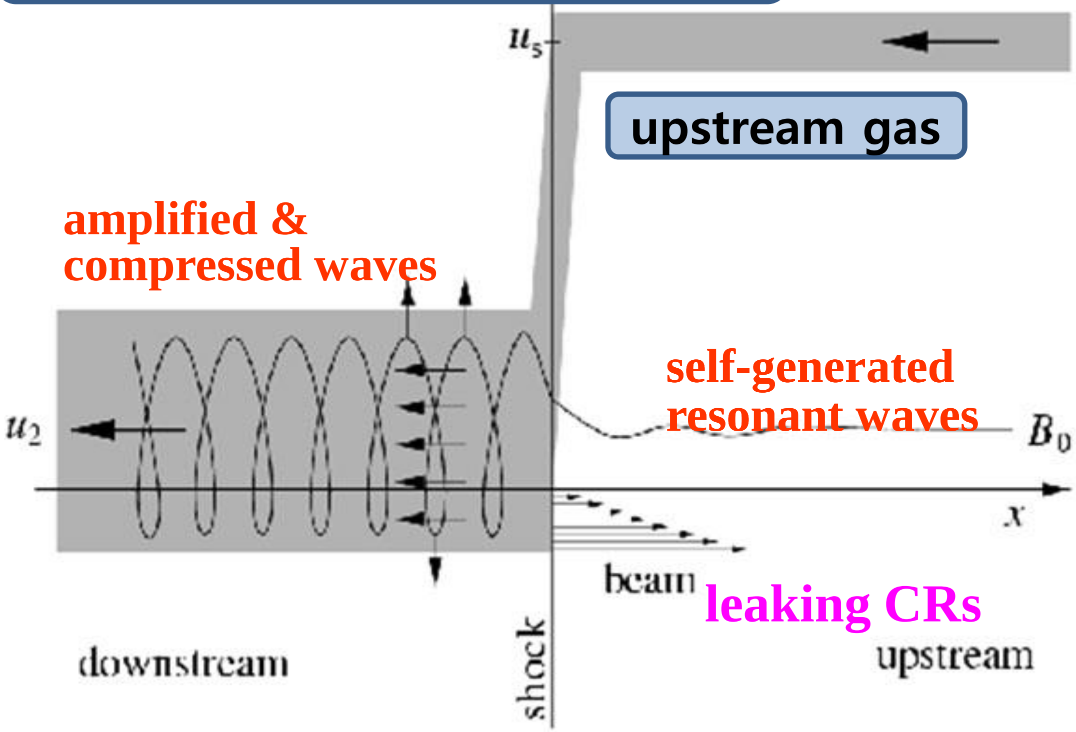
nonresonant waves



Streaming CRs

Cosmic-ray current drives nonresonant instability by stretching field lines (Bell, 2004)

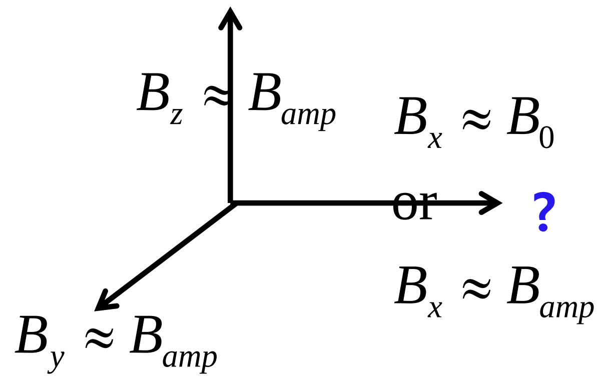
Wave excitation & drift

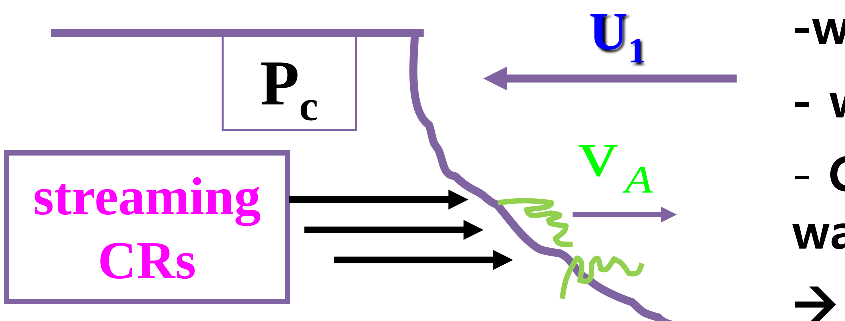


$$v_A = \frac{B_{\parallel}}{\sqrt{4\pi\rho}}$$

slow or fast drift ?

$B_{\parallel} \approx B_0$ or $B_{\parallel} \approx B_{amp}$





Bell 1978

-waves are generated by streaming instability.

- waves drift upstream with $u_w \approx v_A$

- CRs are scattered and isotropized in the wave frame

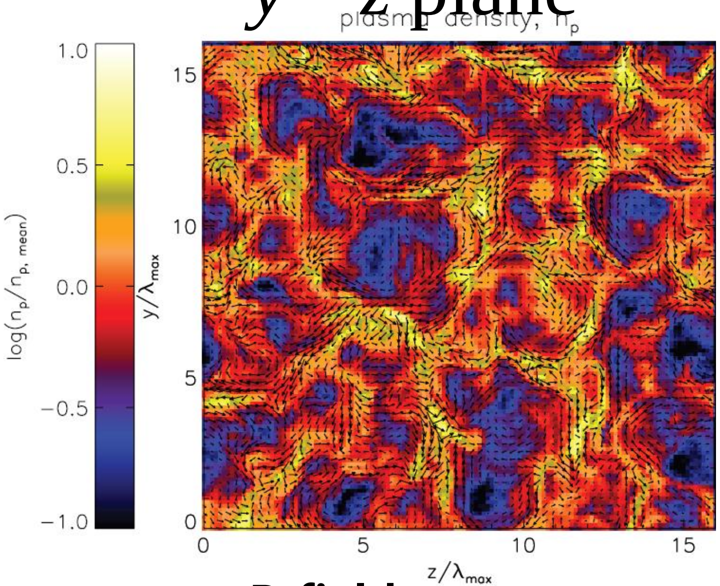
→ smaller Δu $\Rightarrow u - v_A$

→ less efficient acceleration

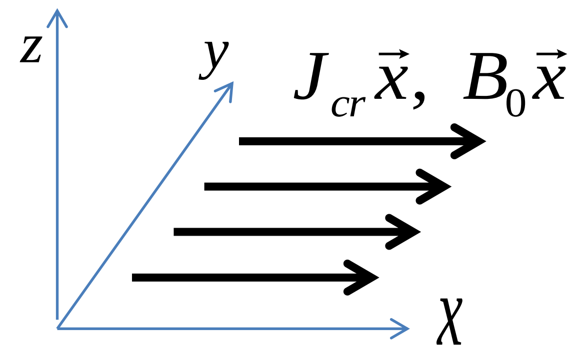
Bell's CR current driven instability

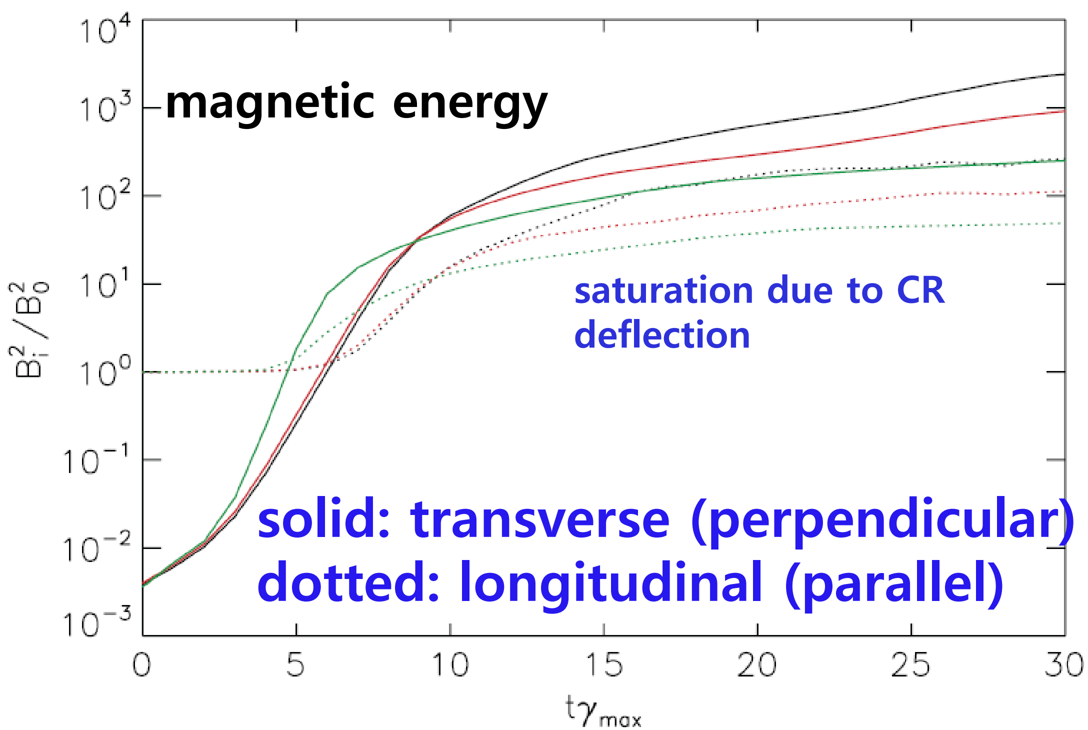
Riquelme & Spitkovsky 2009 PIC (Particle in Cell) simulation

$y - z$ plane



arrows= B fields

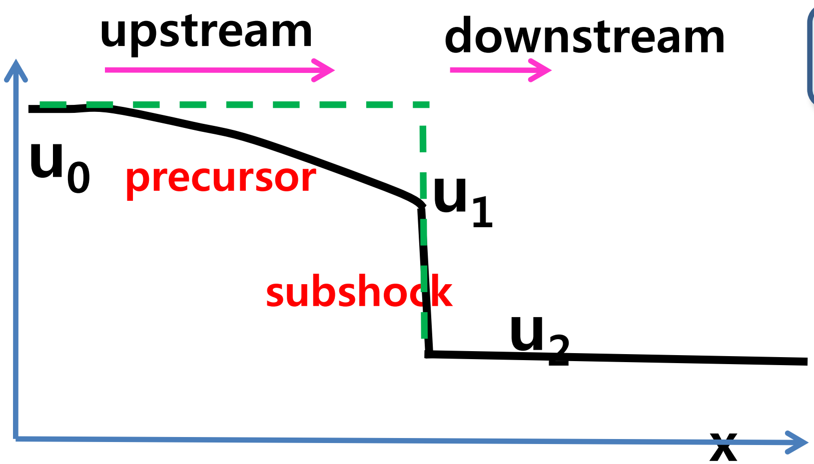




Confirmation of Bell's CR current driven instability

→ $\dfrac{B_x}{B_0} \sim 10$ (parallel) $\quad \dfrac{B_{y(z)}}{B_0} \sim 30$ (perpendicular)

CR modified shock structure



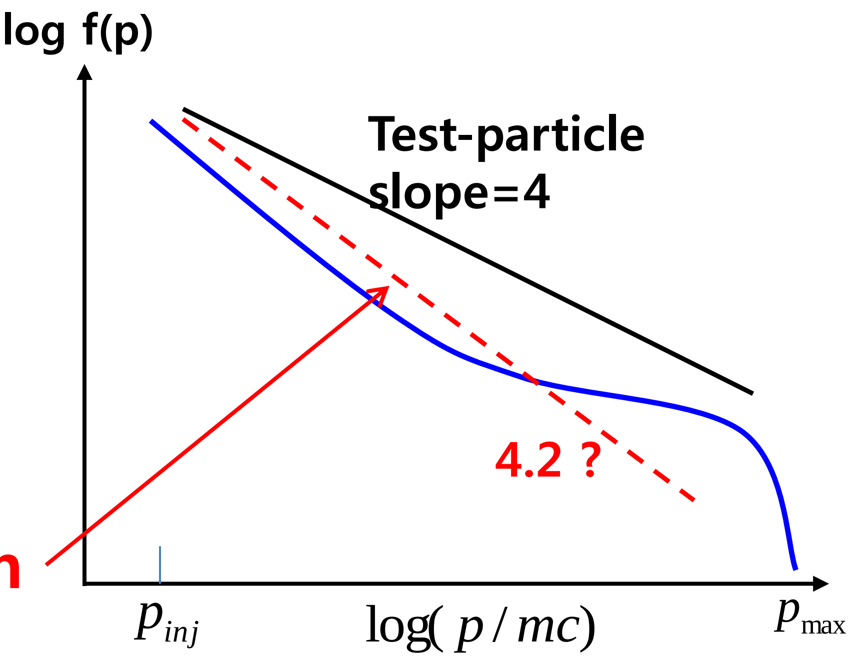
$$v_A = \frac{B_{\parallel}}{\sqrt{4\pi\rho}} \quad \text{Alfven speed}$$

across the subshock

$$q_s = \frac{3\cdot(u_1 - v_A)}{u_1 - v_A - u_2}$$

across the total shock

$$q_t = \frac{3\cdot(u_0 - v_A)}{u_0 - v_A - u_2}$$



Alfvenic drift → softer spectrum

higher CR modification

$\Rightarrow$ larger B_1 & B_2 $\Rightarrow$ larger v_A

$\Rightarrow$ steeper slope $\Rightarrow$ less efficient acceleration

Highly nonlinear problem !

DSA kinetic simulations of SNRs

Basic Equations for DSA Simulations in diffusion approximation

(1D plane quasi-parallel shock)

$$\frac{\partial \rho}{\partial t} + \frac{\partial (u\rho)}{\partial r} = -\frac{2}{r}\rho u$$

$$\frac{\partial (\rho u)}{\partial t} + \frac{\partial}{\partial r}(\rho u^2 + P_g + P_c) = -\frac{2}{r}\rho u^2$$

ordinary gasdynamics EQs + P_c terms

$$\frac{\partial (\rho e_g)}{\partial t} + \frac{\partial}{\partial r}(\rho e_g u + P_g u) = -u\frac{\partial P_c}{\partial r} - \frac{2}{r}(\rho e_g u + P_g u) + W - L$$

W = wave dissipation heating, L = thermal energy loss due to injection

Diffusion Convection Eq. with wave drift effect

$$\frac{\partial f}{\partial t} + (u+u_w)\frac{\partial f}{\partial r} = \frac{1}{3r^2}\frac{\partial}{\partial r}[r^2(u+u_w)]\cdot p\frac{\partial f}{\partial p} + \frac{1}{r^2}\frac{\partial}{\partial r}[r^2\kappa(r,p)\frac{\partial f}{\partial r}] + Q(r,p)$$

$$\Rightarrow P_c = \frac{4}{3}\pi m_p c^2 \int_0^\infty f(p)\frac{p^4 dp}{\sqrt{p^2+1}} : \text{CR pressure}$$

$u_w \approx +v_A$ in upstream, $u_w \approx 0$ or $-v_A$ in downstream,

$\kappa(x,p) \approx \kappa^* p(\rho/\rho_0)^{-1}$: Bohm-like diffusion

$Q(x,p)$ = thermal leakage injection

Phenomenological models for wave-particle interactions

(See Caprioli 2012, Lee, Ellison, Nagataki 2012)

- **Alfven speed :** $V_A = \dfrac{B_0 + (B(r) - B_0) f_A}{\sqrt{4\pi\rho(r)}}$ with $f_A \sim 0.1 - 0.5$

parallel component of B field

- **B field amplification via plasma instabilities :**
depends on the modification (precursor) due to CR pressure

$$\frac{B(r)^2}{B_0^2} = 1 + (1-\omega_H)\frac{4}{25} M_{A,0}^2 \frac{(1-U(r)^{5/4})^2}{U(r)^{3/2}} \quad \text{in upstream } (r > R_s),$$

$$\frac{B_2}{B_1} = \sqrt{\frac{1}{3} + \frac{2}{3}\left(\frac{\rho_2}{\rho_1}\right)^2} \quad r = R_s\,; \quad B(r) = B_2 \cdot \frac{\rho(r)}{\rho_2} \quad \text{in downstream } (r < R_s),$$

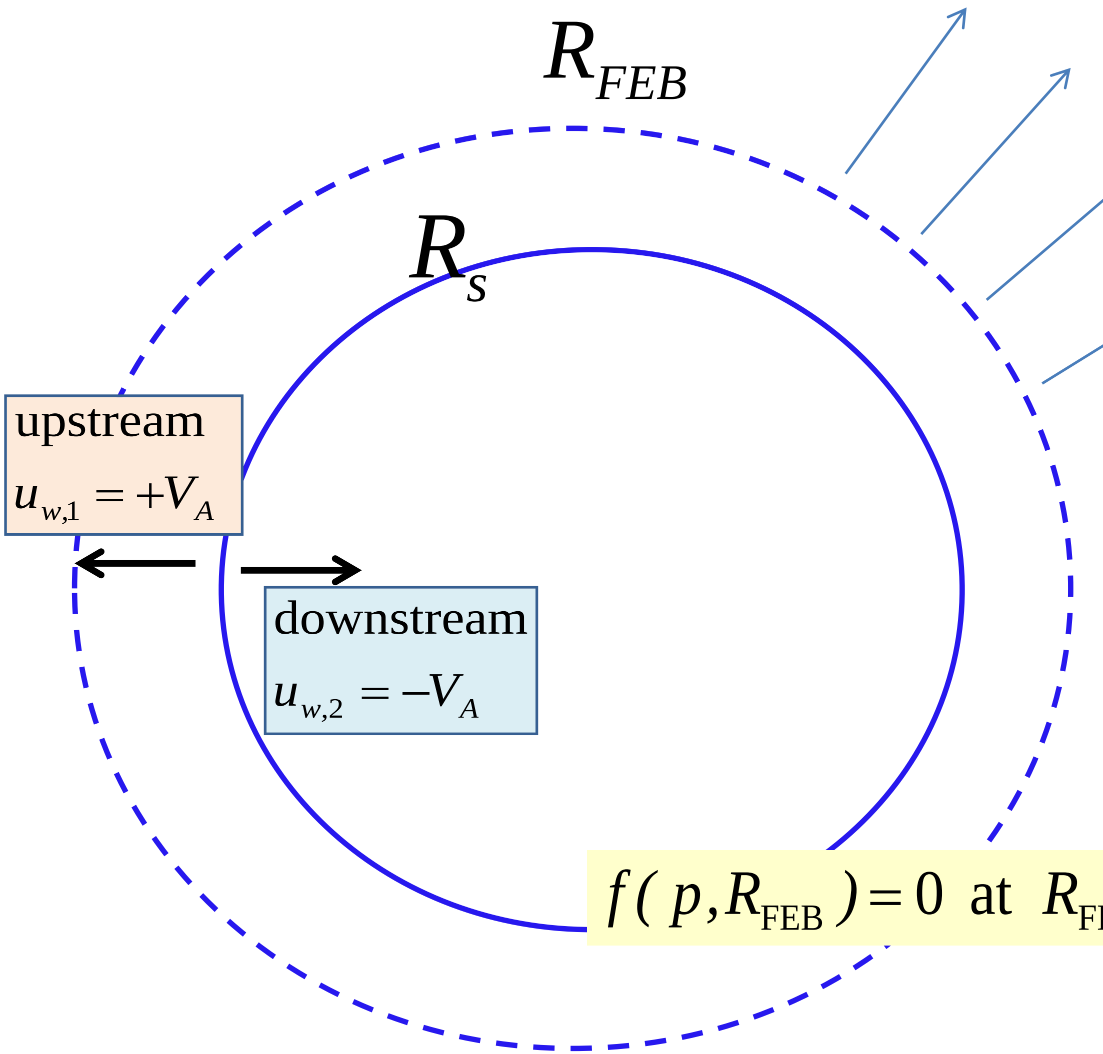
compression across the shock

$$\text{where } U(r) = [V_s - u(r)]/V_s\,, \quad M_{A,0} = V_s(t)/V_{A,0}, \quad V_{A,0} = B_0/\sqrt{4\pi\rho_0}$$

- **Gas heating due to wave dissipation :** $W(r,t) = -\omega_H \cdot V_A(r)\dfrac{\partial P_c}{\partial r}$ with $\omega_H \sim 0.5$

- **Free Escape Boundary:** $f(p, R_{FEB}) = 0$ at $R_{FEB} = \xi \cdot R_s$ where $\xi = 1.1\text{-}1.5$

Escape of highest energy CRs from SNRs



if $\dfrac{\kappa(p)}{u_s} > R_{FEB} - R_s$

or $r_g(p) > R_s$

➔ **escape freely from the shock**

dissipation of waves in the upstream region
➔ weaker scattering
➔ escape

$$f(p, R_{\mathrm{FEB}}) = 0 \text{ at } R_{\mathrm{FEB}} = \xi \cdot R_s \quad \text{where} \quad \xi = 1.1\text{-}1.5$$

SNR Model

$M_{ej} = 1.4\, M_\Theta, \quad E_o = 10^{51}$ ergs

$n_{ISM} = 0.3\, cm^{-3}, \; T_0 = 3\times10^4$ K,

$B_0 = 5\mu G$

$\Rightarrow M_s, \; M_A$

DSA model parameters

$\varepsilon_B = 0.23$: injection

$f_A = 0.1-1.0$: V_A Alfven speed

$\omega_H = 0.5$: wave dissipation

$R_{FEB} = (1.1-1.5)\cdot R_s$: FEB

upstream drift :

$u_{w,1} = +V_A$

downstream drift :

$u_{w,2} = 0$

Model parameters

Name[b]	n_H (cm^{-3})	T_0 (K)	r_o (pc)	t_o (years)	f_A [c]	ω_H [d]	ζ [e]	$u_{w,2}$ [f] (km s^{-1})	$v_{A,0}$
W1	0.3	3×10^4	3.18	255.	1.0	0.5	0.1	0	16.8
W2	0.3	3×10^4	3.18	255.	1.0	0.1	0.1	0	16.8
W3	0.3	3×10^4	3.18	255.	0.1	0.5	0.1	0	16.8
W4	0.3	3×10^4	3.18	255.	1.0	0.5	0.1	$-v_A$	16.8

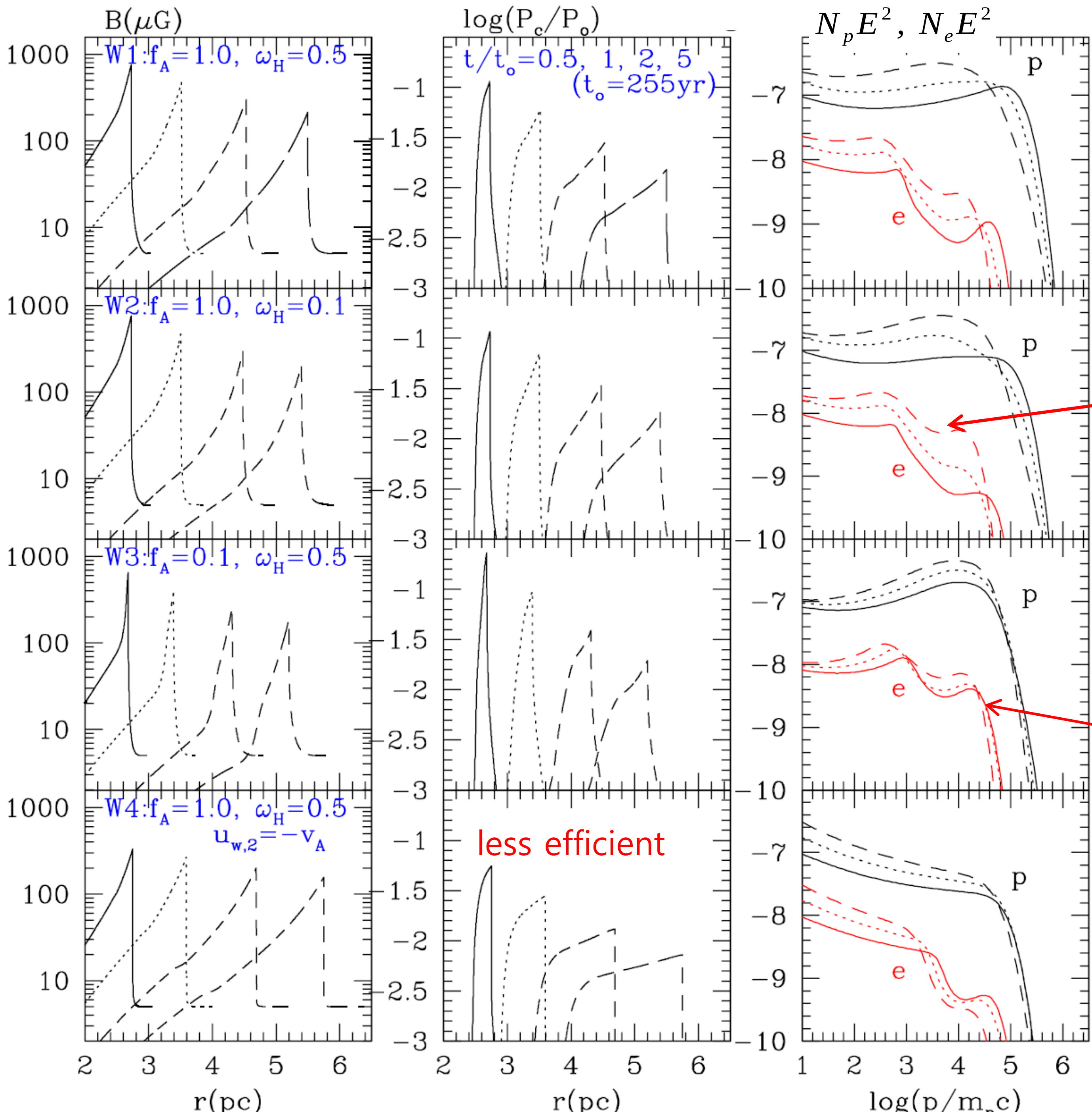
Strong shocks:

$$M_A \approx 180\cdot\left(\frac{u_s}{3000\text{ km/s}}\right), \; V_A = 16.8\text{ km/s}$$

$$M_s \approx 115\cdot\left(\frac{u_s}{3000\text{ km/s}}\right), \; c_s = 26\text{ km/s}$$

$$V_A = \frac{B_0 + (B(r)-B_0)f_A}{\sqrt{4\pi\rho(r)}}$$

$$\frac{B(r)^2}{B_0^2} \sim (1-\omega_H)\frac{4}{25}M_{A,0}^2\frac{(1-U(r)^{5/4})^2}{U(r)^{3/2}}$$



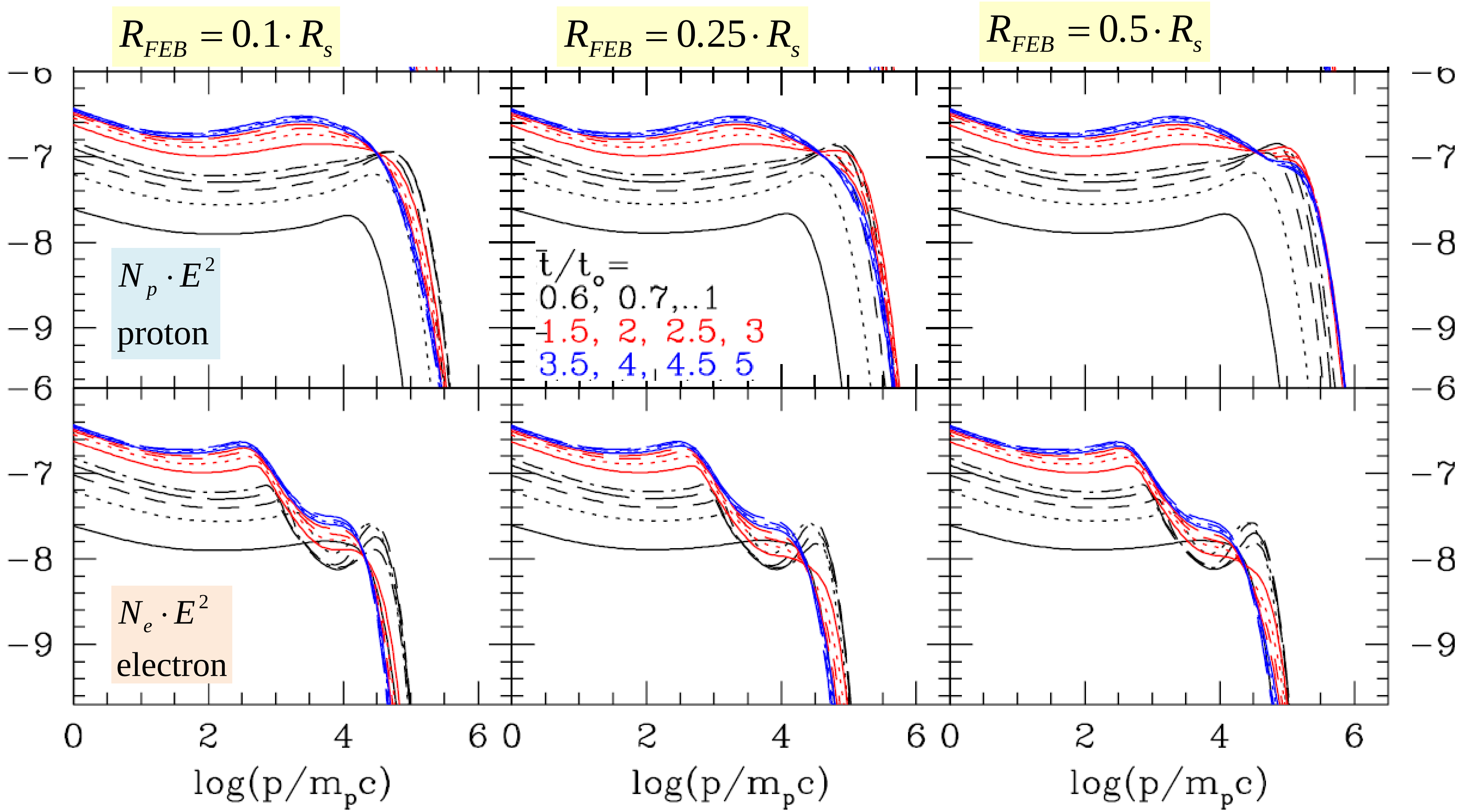
- greater $B \rightarrow$ higher $p_{p,max}$
- history of $B(\mathrm{r,t})$ controls the shape of highest end of CR spectrum

Electron cooling depends on the history of B(r,t).

upstream component: due to lower B_1

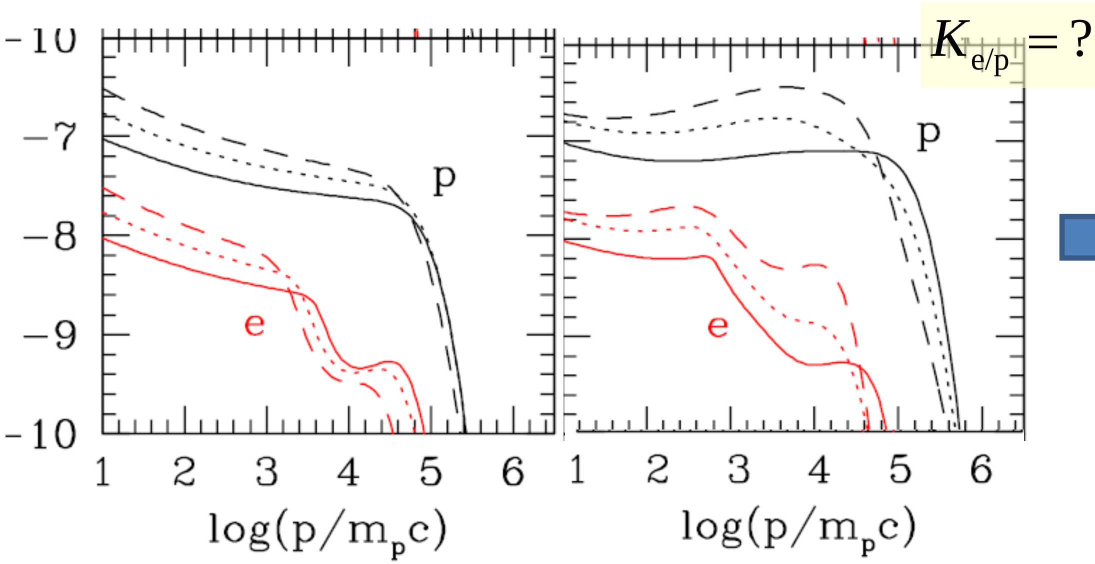
downstream drift: $u_{w,2} = -V_A$

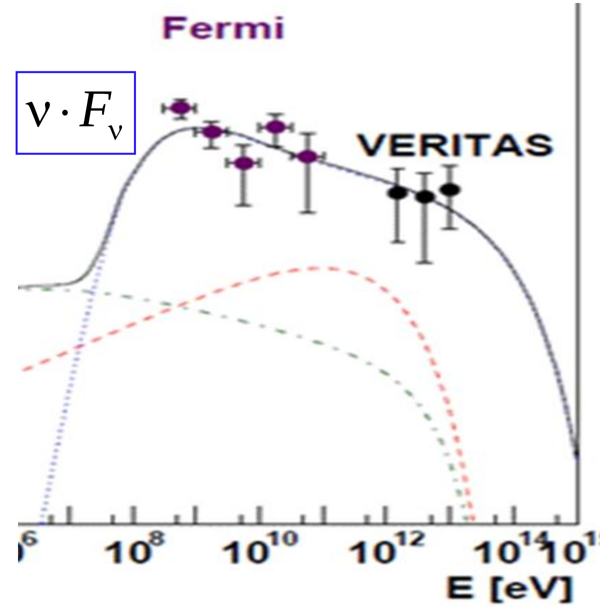
Effects of Free Escape Boundary



- greater $R_{FEB} \rightarrow$ higher $p_{p,max}$
- R_{FEB} controls the shape of highest end of proton spectrum

Highest End of CR spectrum determines GeV-TeV γ-ray emission.
So details of DSA modeling are important.





DSA model parameters

$\varepsilon_B = 0.2 - 0.23$: injection

$f_A = 0.1 - 1.0$: $V_A(r,t)$ Alfven speed

$\omega_H = 0.5$: wave dissipation, MFA

$R_{FEB} = (1.1 - 1.5)\, R_s$: FEB

time-dependent evolution

$T_0 \Rightarrow M_s(t)$: sonic Mach no. $\Rightarrow$ CR efficiency

n_0 & $B_0 \Rightarrow M_{A,0}$: Alfven Mach no. $\Rightarrow$ MFA, $B(r,t)$

$B(r,t) \Rightarrow V_A(r,t) \Rightarrow q$: power-law slope

$B(r,t) \Rightarrow p_{max,p}$, $p_{max,e}$ (cooling)

FEB & $B(r,t) \Rightarrow$ exponential tail

....

IV. Summary

* Observations of Supernova Remnants

- X-ray ➔ amplified B fields: B_2~ 100-300 μG
- γ-ray ➔ hadronic π^0 emission confirmed

proton spectrum: $N_p(E) \propto E^{-2.2} - E^{-2.3}$ required

* Hybrid/PIC plasma simulations have shown that

- streaming and current driven instabilities ➔ amplify B

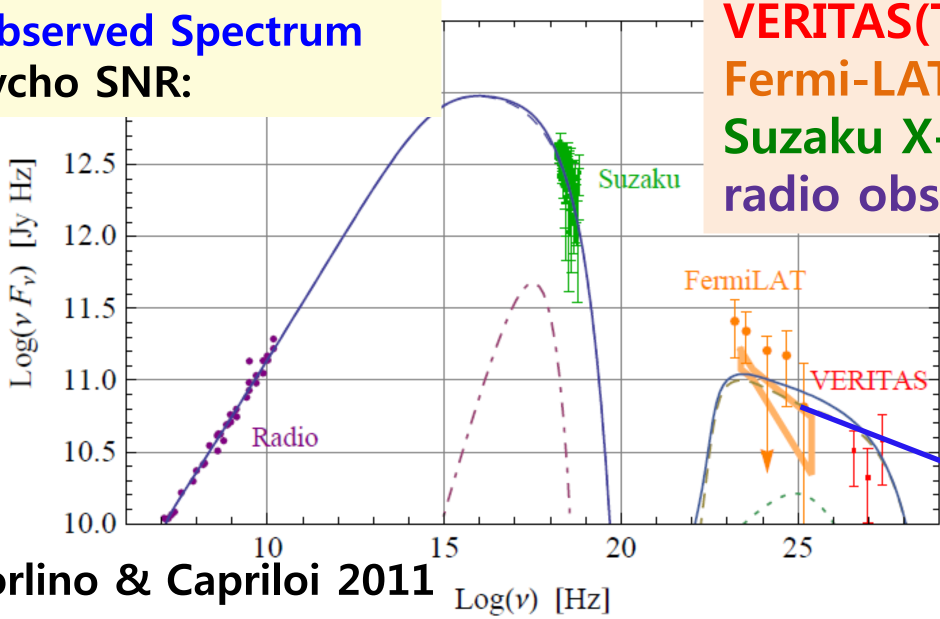
$\delta B / B_o \sim 10 - 30$ is possible

* Wave drift may cause steepening of CR spectrum

- Nonlinear DSA can be consistent with γ-ray observation
- Detail modeling of DSA & time-dependent history are important in predicting non-thermal radiation spectrum

Nonthermal emission from nonlinear DSA vs. multiband observations

Observed Spectrum
Tycho SNR:



VERITAS(TeV), Fermi-LAT (GeV), Suzaku X-ray, radio observation

Morlino & Capriloi 2011

$n_0 = 0.3\,\mathrm{cm}^{-3}$

$T_0 = 10^4\ \mathrm{K}$

$R_s = 3.94\,\mathrm{pc}$

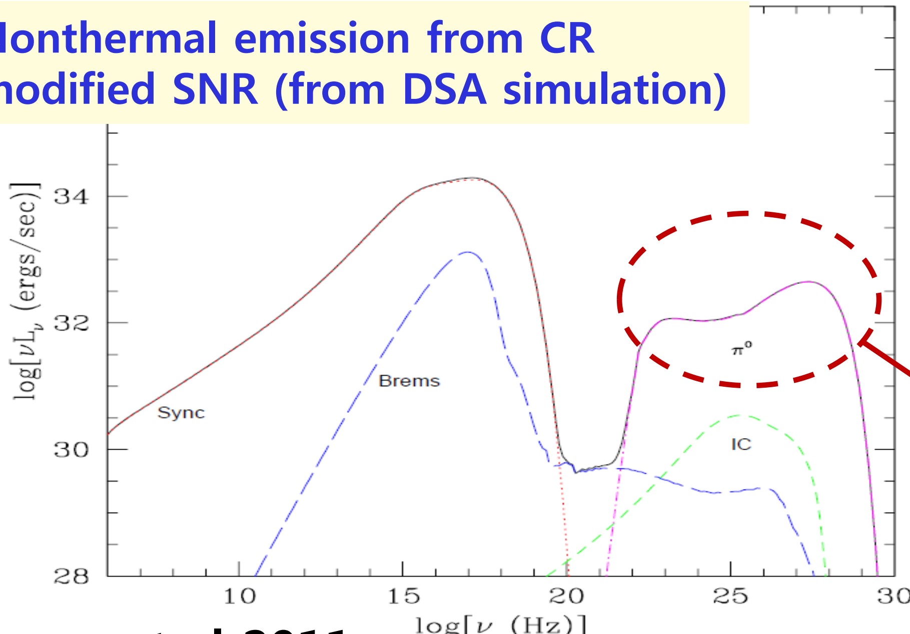
$V_s = 5000\ \mathrm{km/s}$

$B_2 = 300\,\mu\mathrm{G}$

proton spectrum

$$N(E) \propto E^{-2.2} - E^{-2.3}$$

Nonthermal emission from CR modified SNR (from DSA simulation)



Edmon et al 2011

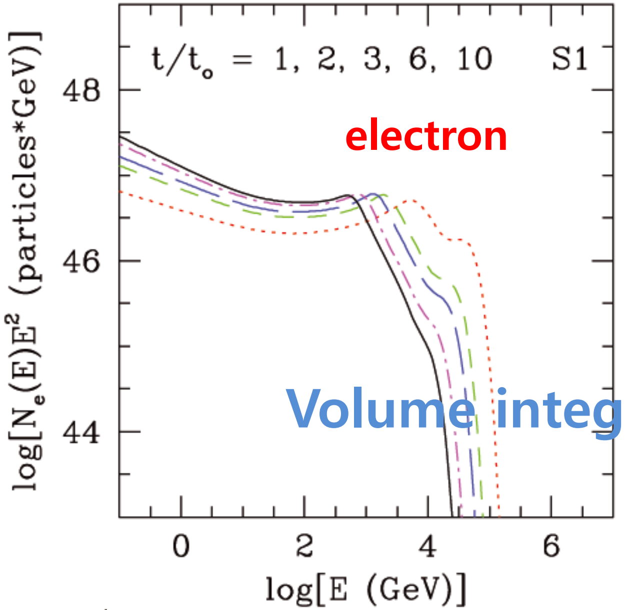
synchrotron (dotted line),
IC (short dashed line)
bremsstrahlung (long dashed line),
π0 decays (dot-dashed line)

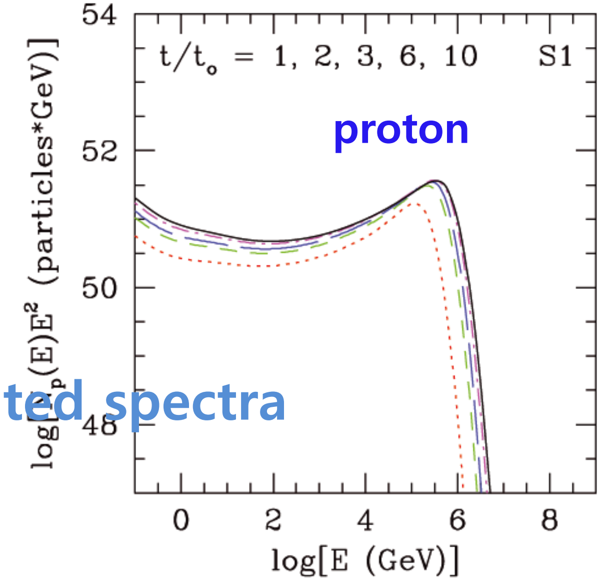
Nonlinear DSA: too efficient ?
- **wave drift**
- **escape of highest energy CRs**
- **damping of turbulent waves**

➔ **Steepening of spectrum**

Nonlinear DSA simulations of Type Ia SNR:

Edmon, Kang, Jones, Ma 2011





Volume integrated spectra

$n_0 = 0.3\,\mathrm{cm}^{-3}$

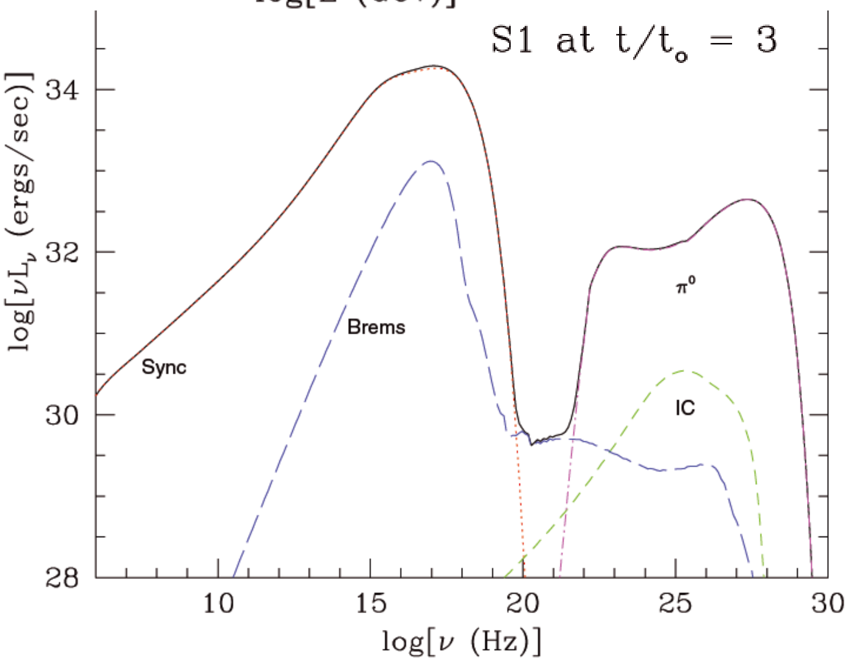
$T_0 = 3\times10^4$ K

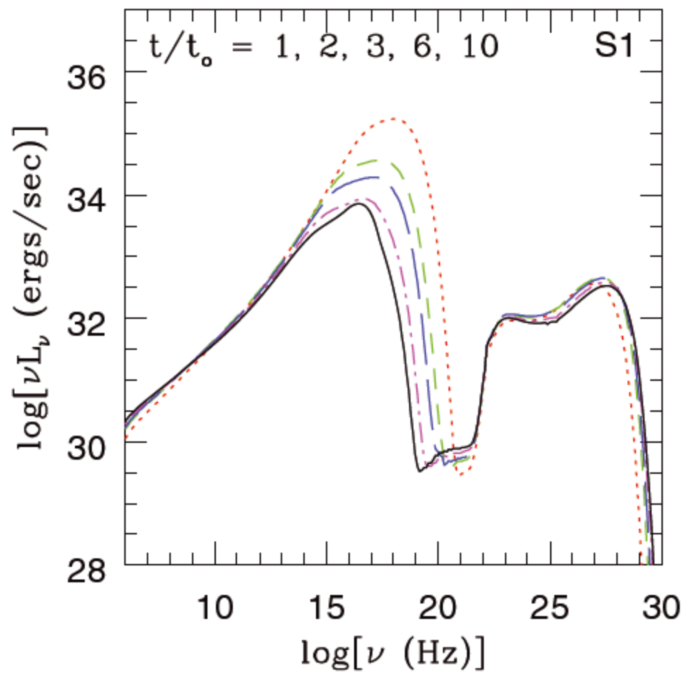
$B_0 = 30\,\mu$G

$B_2 \cong 210\,\mu$G

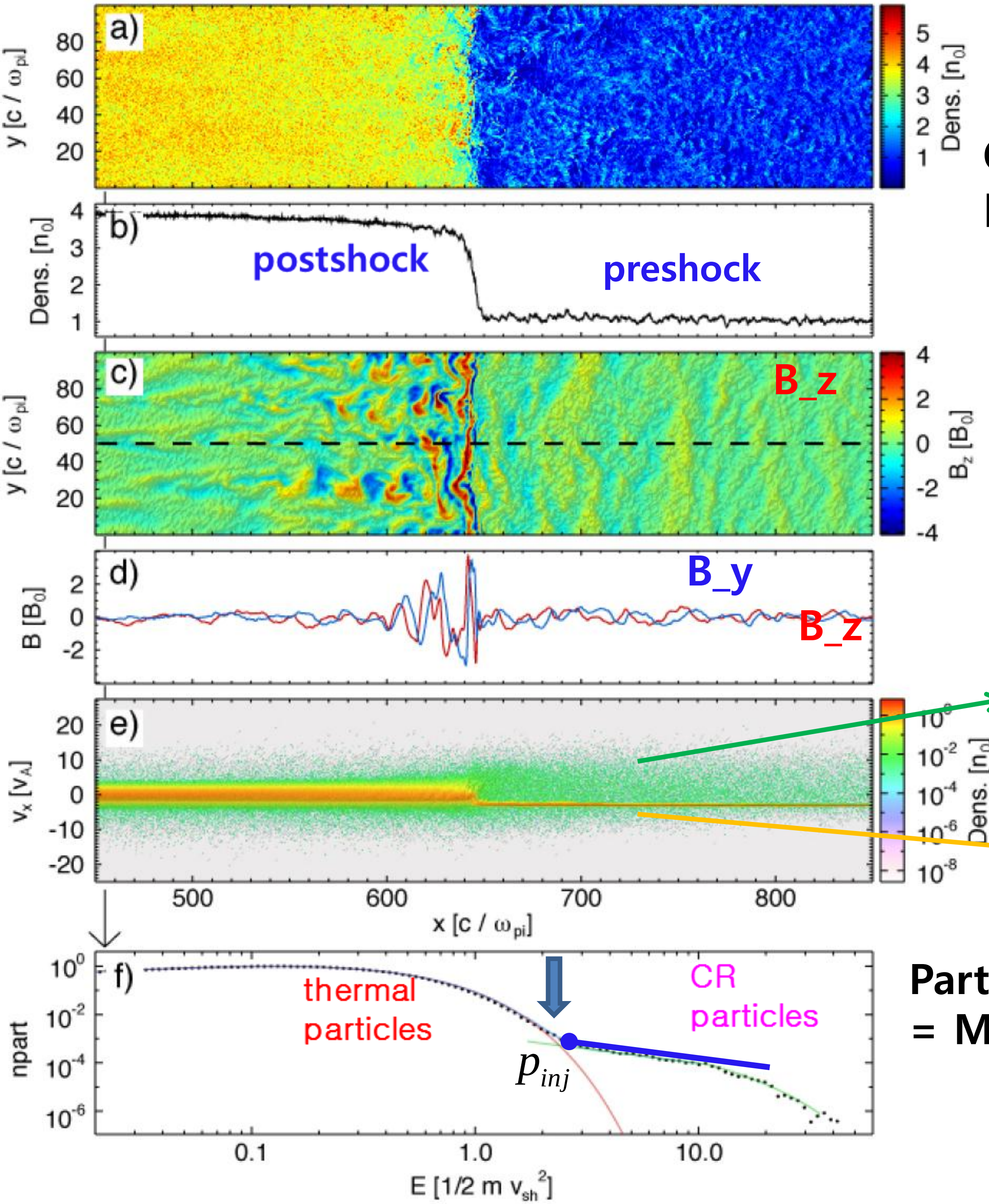
$t_o = 255$ yrs

$K_{e/p} = 10^{-4}$





CR ion injection



Gargate & Spitkovsky 2011
Hybrid simulation in 2D

M_A=3.1, parallel shock

Self-generated resonant waves

Two stream instabilities

Protons streaming upstream

Incoming cold beam

Particle spectrum = Maxwellian + power-law tail

DSAed CR spectrum vs. photon spectrum

CR spectrum in test - particle regime

$$f_{DSA}(p) \propto p^{-q}, \ N(E) \propto E^{-(q-2)},$$

➡ electron synchrotron + IC scattering photon spectrum at shock

$$j_\nu \propto \nu^{-\alpha}, \ \alpha_{\mathrm{syn(IC),shock}} = (q-3)/2, \ \ \alpha_{\mathrm{syn(IC),shock}} \approx 0.5 \ \text{ for } \ q=4$$

volume integrated spectrum of electrons steepenes by +1 in slope

$$F_e(p) = \int f_e(p,x)dx \propto p^{-q-1} \ \text{ (due to cooling) above } p_{break}(t)$$

➡ integrated photon spectrum (unresolved observation)

$$J_\nu \propto \nu^{-\alpha}, \ \alpha_{\mathrm{syn(IC),integ}} = \alpha_{\mathrm{syn(IC),shock}} + 0.5, \ \ \alpha_{\mathrm{integ}} \approx 1.0 \ \text{ for } \ q=4$$

X-ray

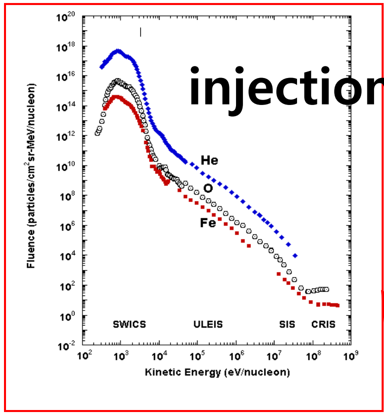
volume integrated spectrum of proton spectrum

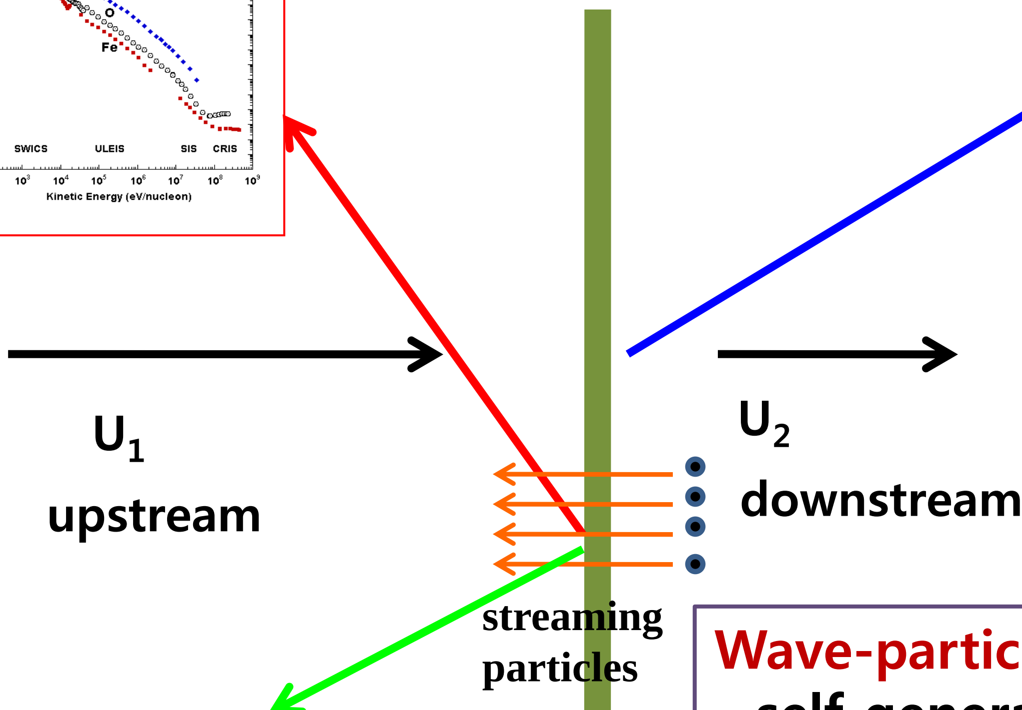
$$\text{proton} + \text{p collision} \Rightarrow \pi^0 \text{ decay } \gamma\text{-ray spectrum}$$

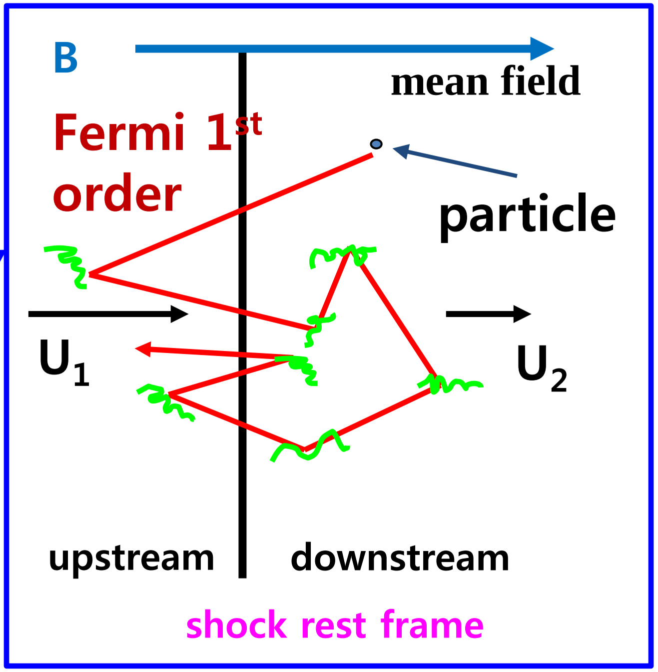
➡ $J_\nu \propto \nu^{-\alpha}, \ \alpha_{\pi^0} \approx (q-2)/2, \ \ \alpha_{\mathrm{shock}} \approx 1 \ \text{ for } \ q=4$

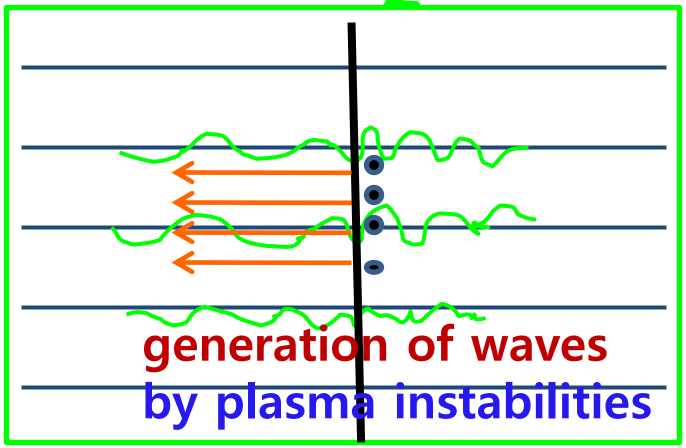
GeV-TeV

Key Physics of DSA









Wave-particle interactions important

- self-generated waves (res. & non-res)
- amplification of B fields
- scattering of particles (diffusion)
- dissipation of waves
- ion injection
- electron heating & injection