Particle Acceleration at Astrophysical Shocks

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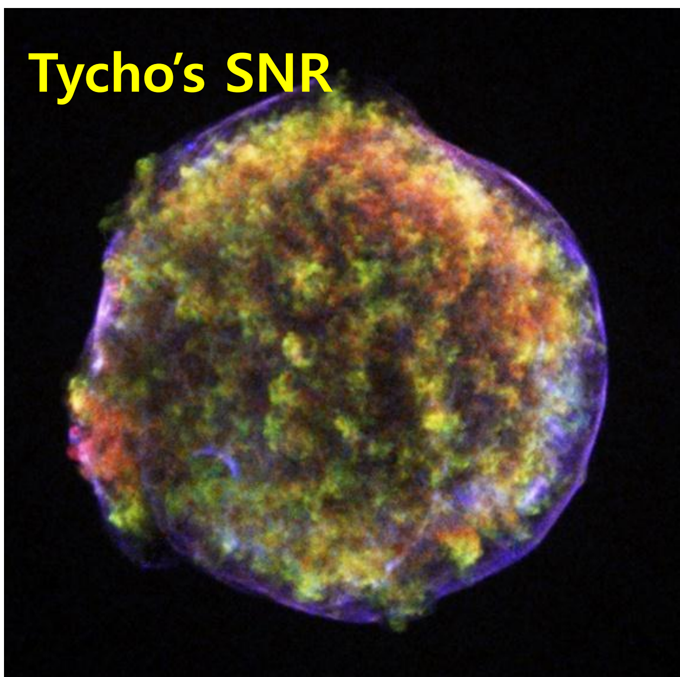
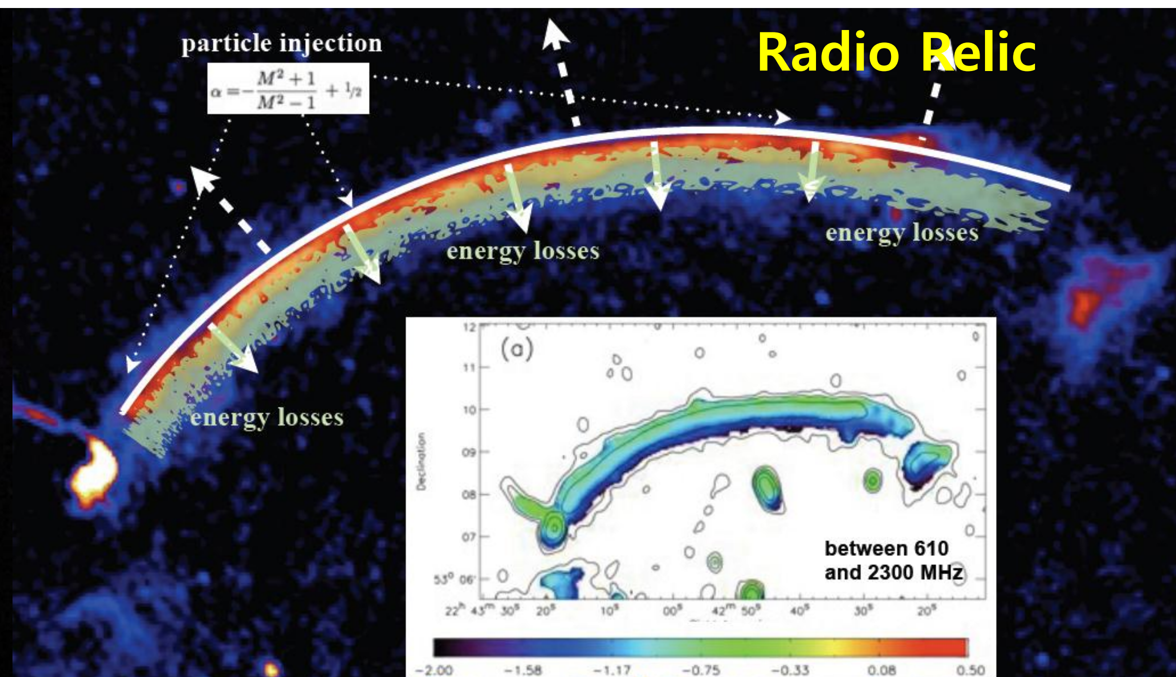




Outline

I. Introduction

- Diffusive Shock Acceleration (DSA)
- magnetic field amplification (MFA) and Alfvenic drift (AD)

II. DSA simulations including MFA & AD

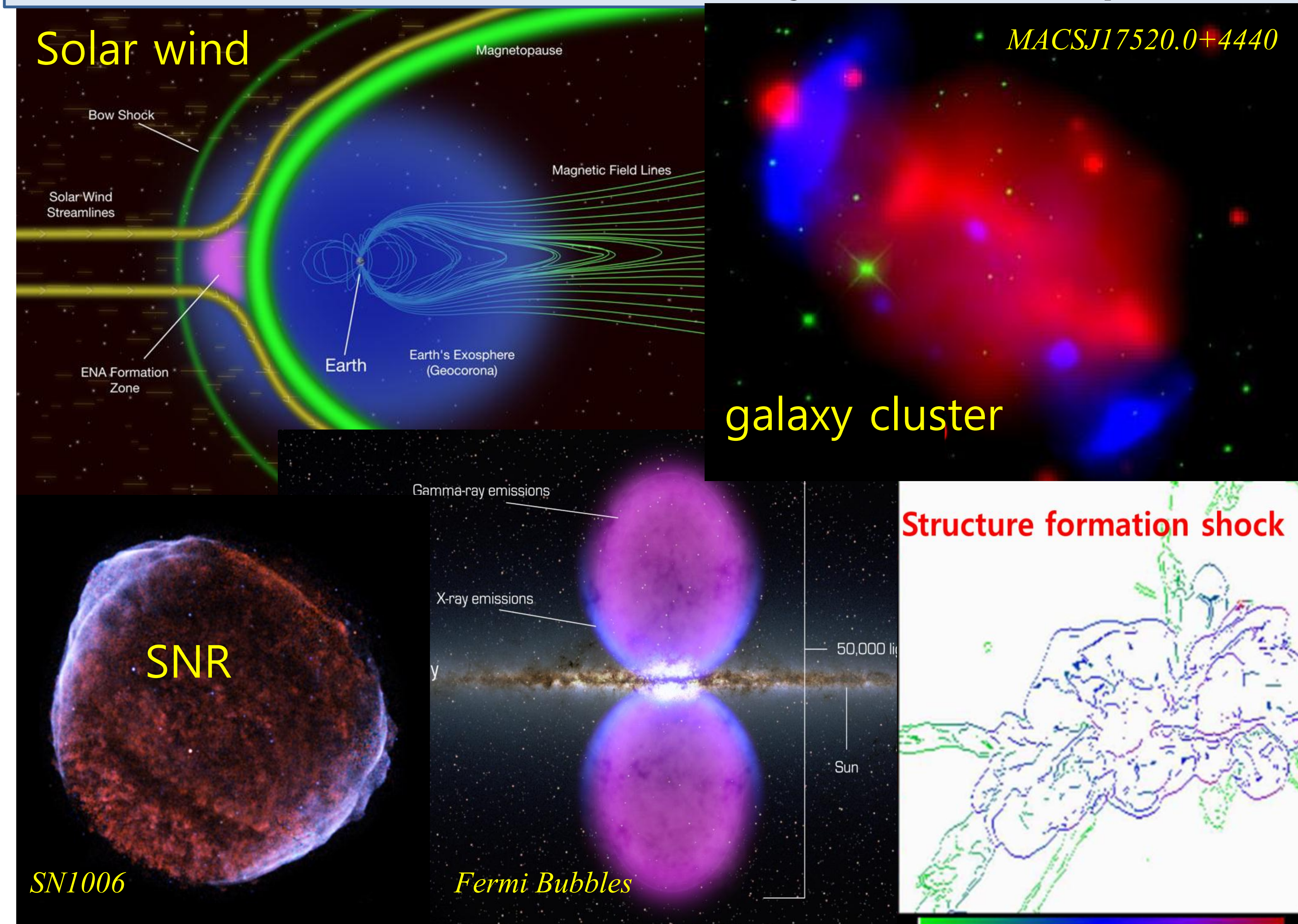
- CR acceleration efficiency at cosmological shocks
- Nonthermal emission from Supernova Remnants (SNRs)

III. Shocks in Structure Formation Simulations

- Radio Relics (shocks) around galaxy clusters

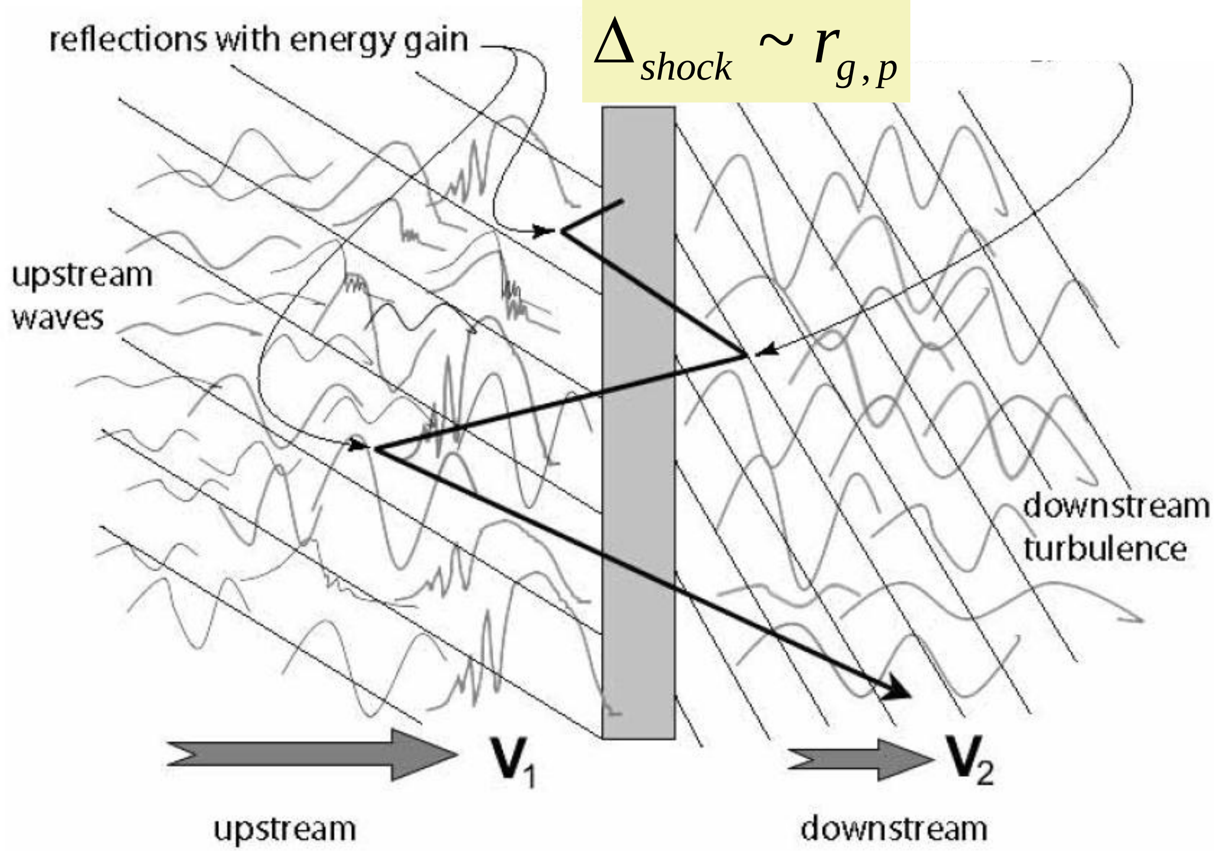
IV. Summary

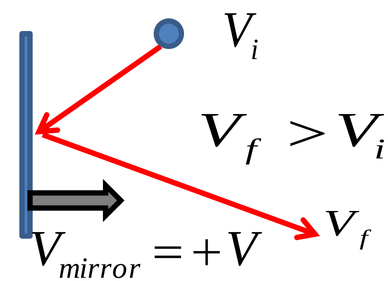
Nonrelativistic Shocks & Cosmic Rays (relativistic particles)



Particle Acceleration at Shocks: Fermi 1st order

$\Delta_{shock} \sim r_{g,p}$





Collision with approaching mirrors → gain energy

MHD waves = scattering centers = mirrors

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

$$\frac{\Delta p}{p} \sim \frac{u_1 - u_2}{v} \text{ at each shock crossing}$$

DSA= Diffusive Shock Acceleration

$$\langle \Delta p / p \rangle = \frac{2}{3}\frac{u_1 - u_2}{\upsilon} \text{ at each crossing, } \upsilon = \text{part. speed}$$

$$\text{after 2n crossings: } p_n \sim \prod_{i=i}^{n}(1+\frac{4}{3}\frac{u_1 - u_2}{\upsilon_i}) p_0$$

$$\ln(p_n / p_0) \sim \frac{4}{3}(u_1 - u_2)\sum_{i=1}^{n}\frac{1}{\upsilon_i}$$

$$\text{advection fraction: } \frac{nu_2}{n\upsilon/4} = \frac{4u_2}{\upsilon}, \text{ returning prob.: } (1-\frac{4u_2}{\upsilon})$$

$$\text{probability of 2n crossings: } P_n \sim \prod_{i=i}^{n}(1-\frac{4u_2}{\upsilon_i})$$

$$\ln P_n \sim 4u_2 \sum_{i=1}^{n}\frac{1}{\upsilon_i} = -3\frac{u_2}{u_1 - u_2}\ln(p_n / p_0)$$

Test-particle spectrum

$$P_n = (p_n / p_0)^{-3u_2/(u_1 - u_2)}$$

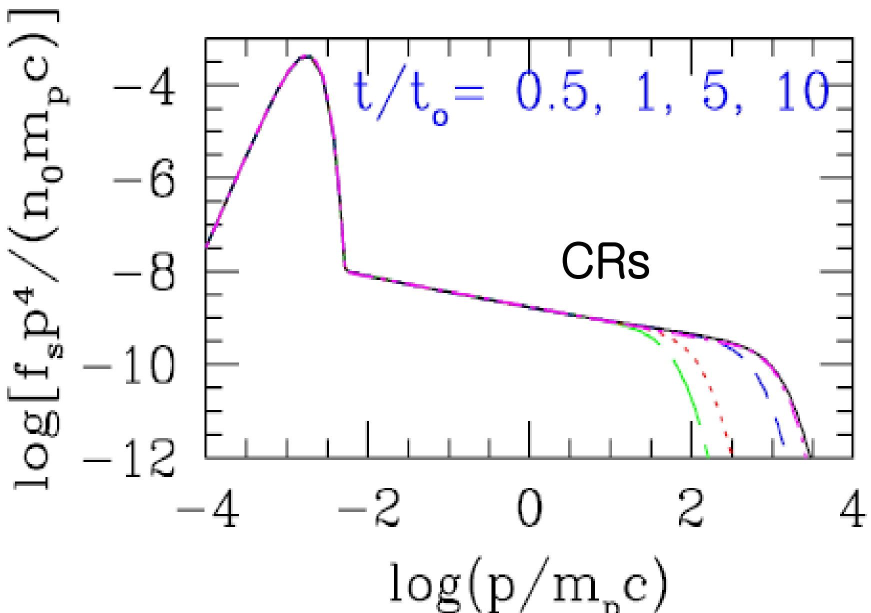
$$f(p) \propto p^{-q} \quad \text{: power-law}$$

$$q = \frac{3u_2}{u_1 - u_2} = \frac{3r}{r-1}$$

r = compression ratio

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

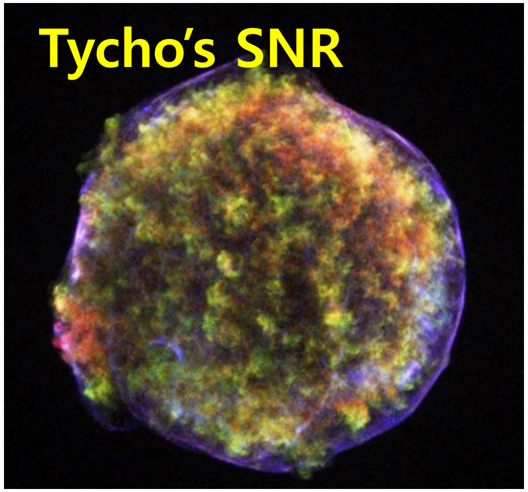
$$N(E) \propto E^{-\gamma} \qquad \gamma = q - 2 = 2$$



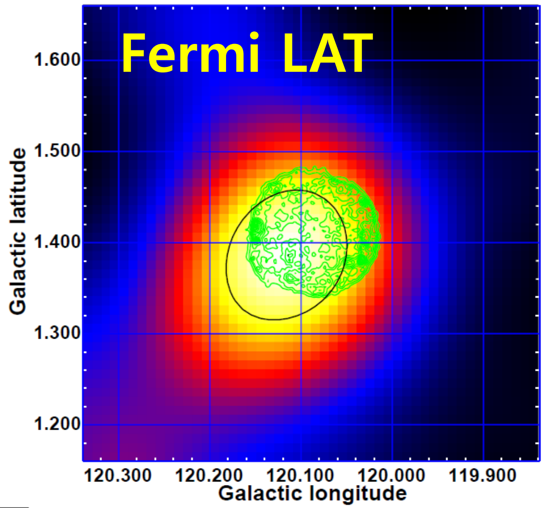
$f(p)$: isotropic part of momentum distribution function

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

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



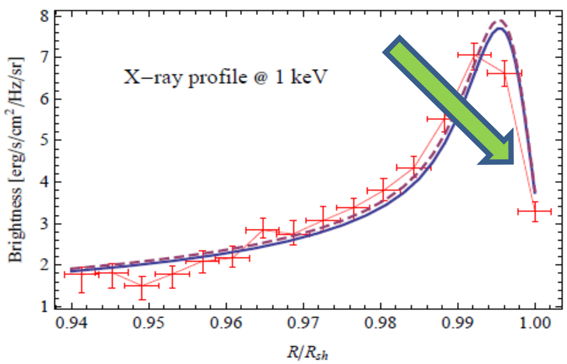
Giordano et al 2011



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

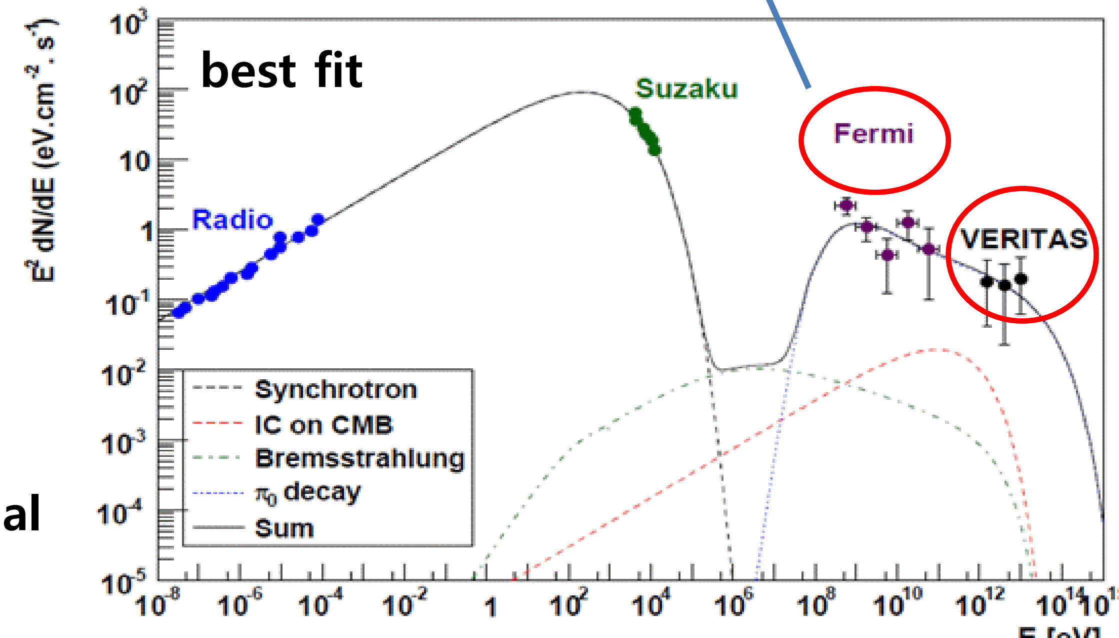
$$B_2 \sim 200\mu G$$

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

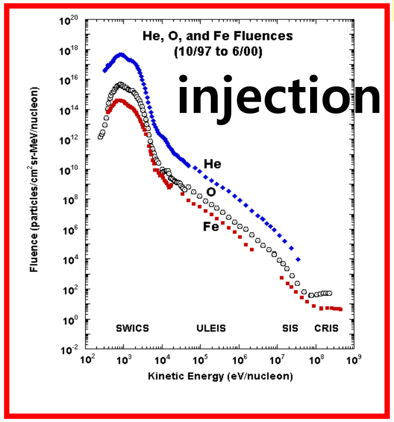


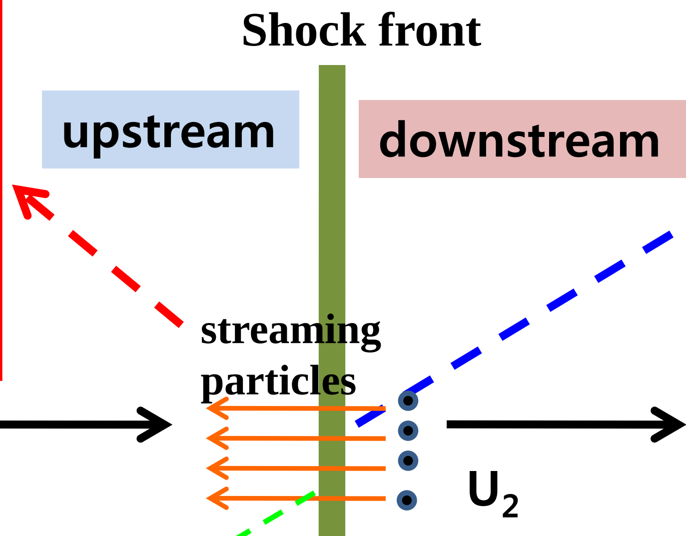
Projected X-ray emission (B_2=300 μG)
Chandra X-ray data at 1 keV.

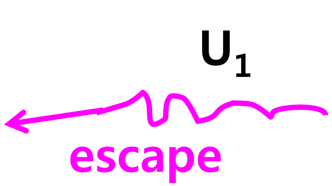
- thin filaments of nonthermal X-ray indicating fast synchrotron cooling

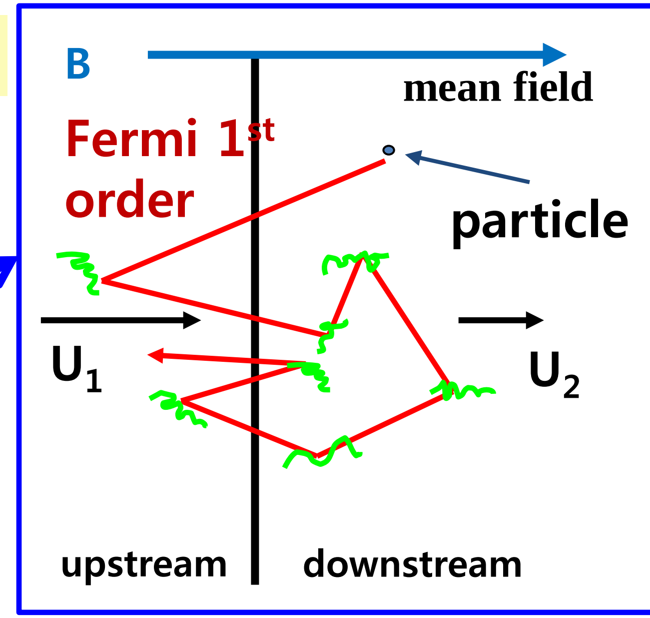


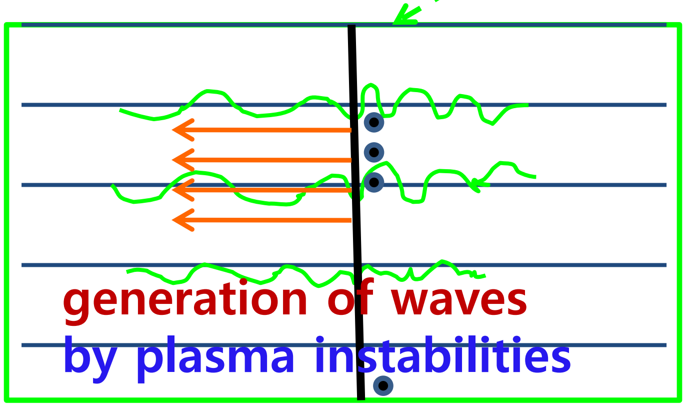
Physics of collisionless shock











Wave-particle plasma interactions
- self-generated waves (res. & non-res)
- amplification of B fields
- scattering of particles (diffusion)
- dissipation of waves
- particle escape
- ion injection
- electron pre-heating & injection
- ...

They are not understood well especially at weak non-relativistic shocks.

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

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

nonresonant waves

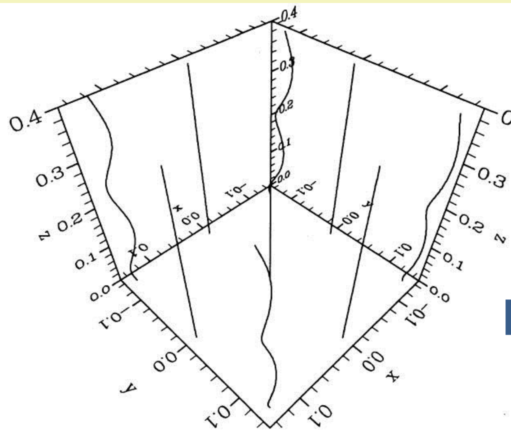


Figure 8. Magnetic field lines at $t = 0$ for the three-dimensional run.

B field lines, t = 1.5

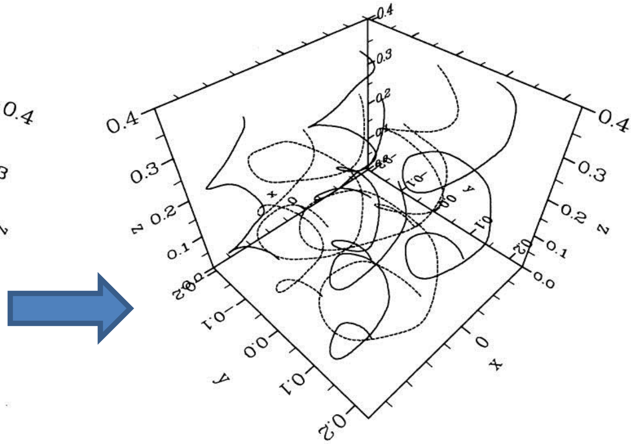
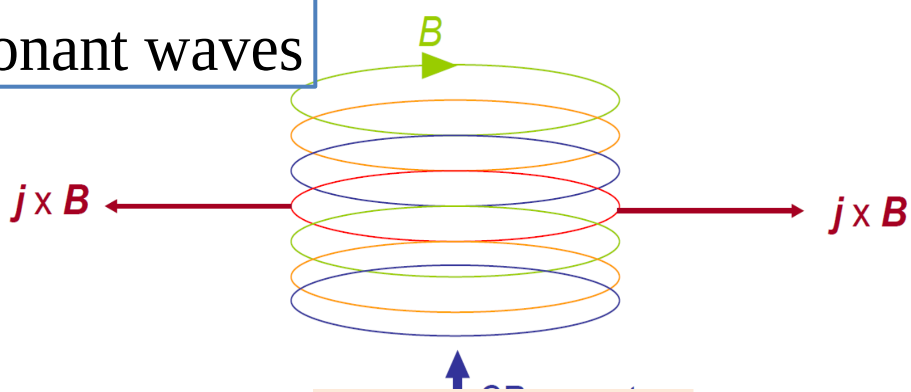


Figure 9. Magnetic field lines after 1.5 CR gyrations for the three-dimensional run.



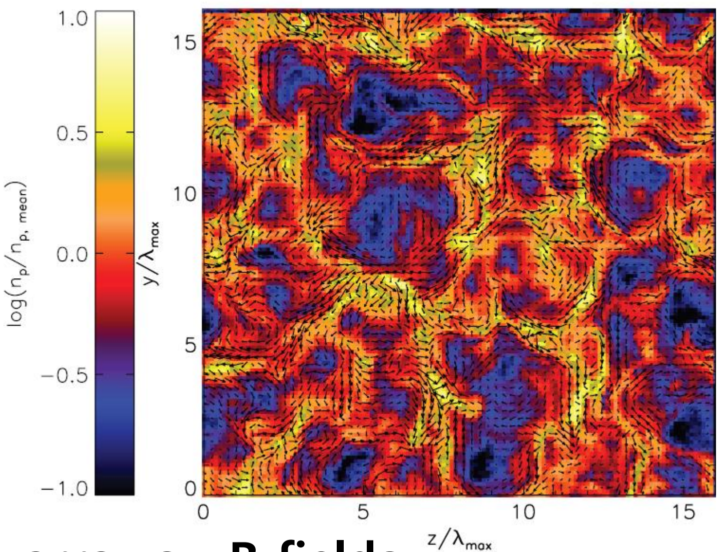
Streaming CRs

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

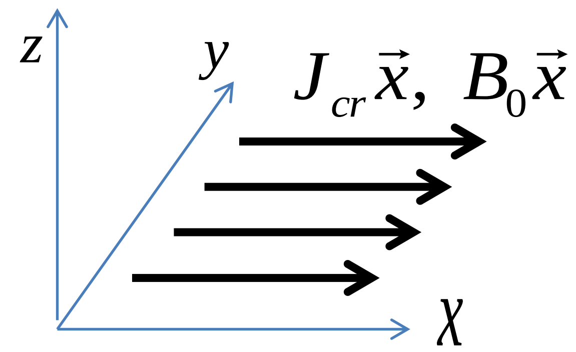
Bell's CR current driven instability

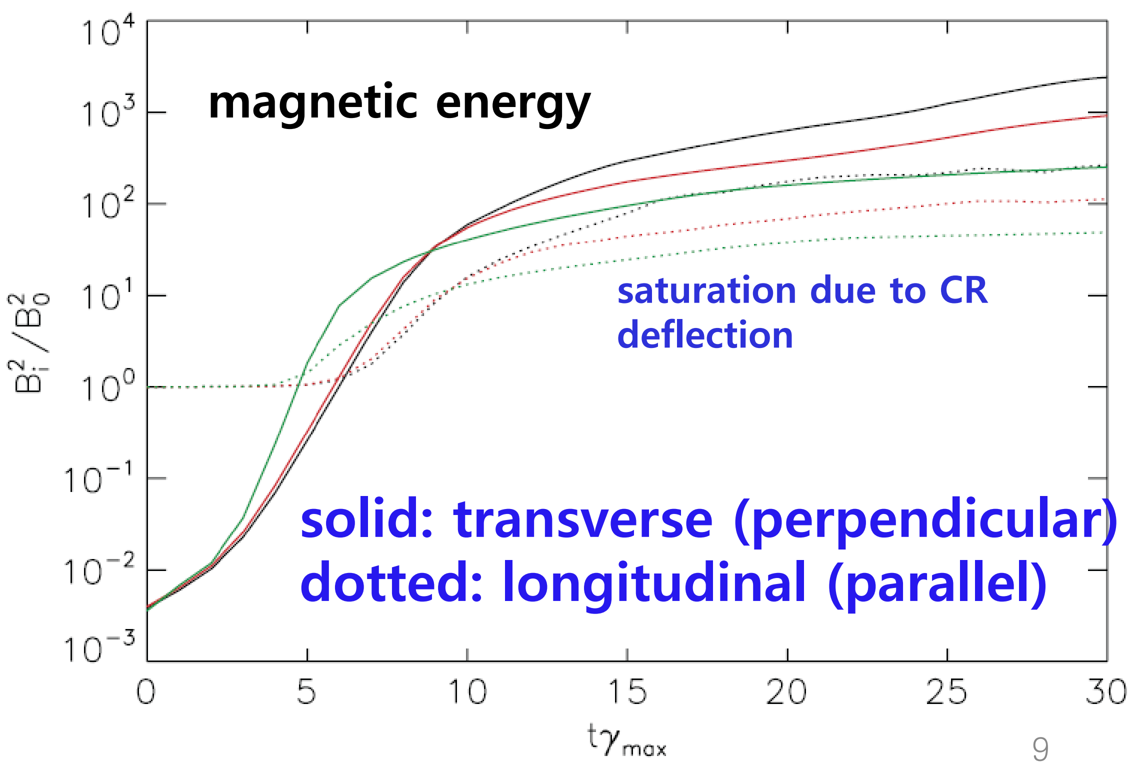
Riquelme & Spitkovsky 2009 PIC (Particle in Cell) simulation

$y - z$ plane



arrows= B fields





Confirmation of Bell's CR current driven instability

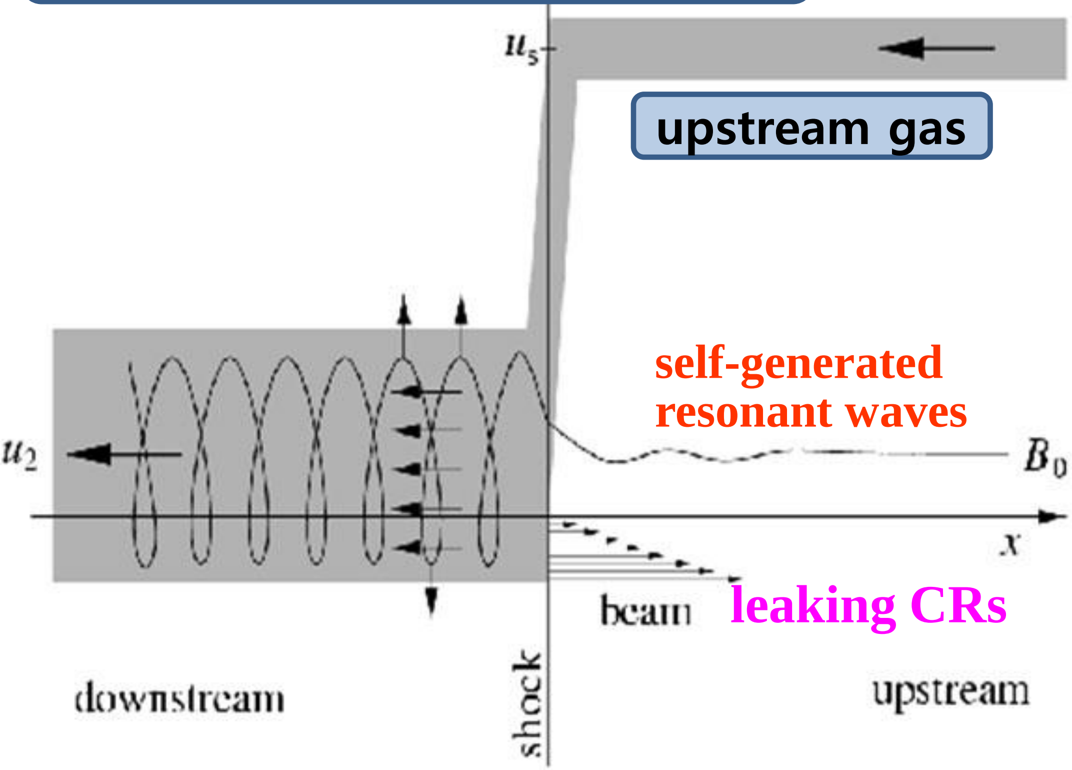
$$\frac{B_x}{B_0} \sim 10$$

(parallel)

$$\frac{B_{y(z)}}{B_0} \sim 30$$

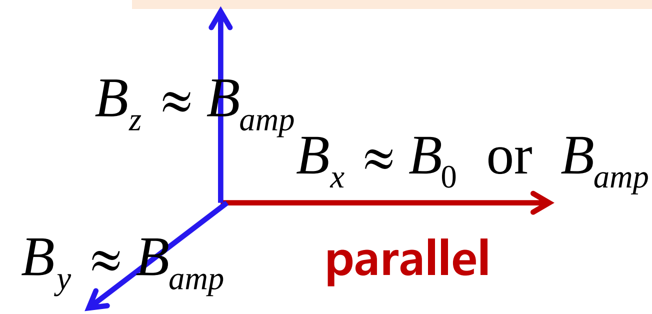
(perpendicular)

Wave excitation & drift

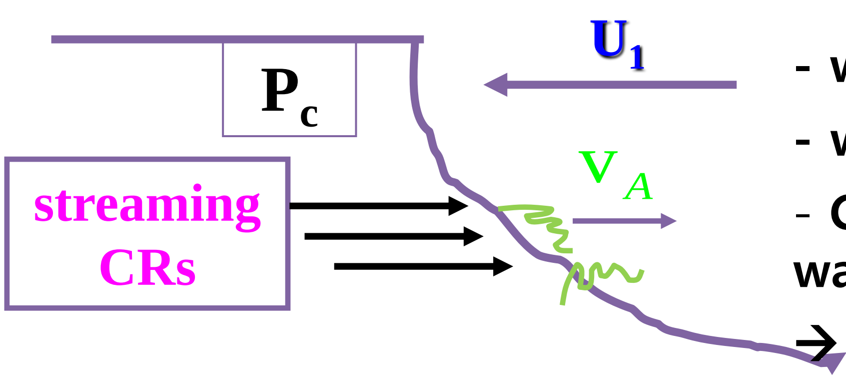


$$V_A = \frac{B_0}{\sqrt{4\pi\rho}} \quad \text{background field}$$

$$V_A = \frac{B}{\sqrt{4\pi\rho}} \quad \text{amplified field}$$



Resonant & nonresonant waves



- waves are generated by streaming instability.
- waves drift upstream with $u_w \approx V_A$
- CRs are scattered and isotropized in the wave frame

→ Experience smaller Δu $\Rightarrow u - V_A$

→ less efficient acceleration

Bell 1978

II. DSA simulations including MFA & AD

Basic Equations for DSA Simulations in diffusion approximation

(1D plane quasi-parallel shock)

$$\frac{\partial \rho}{\partial t} + \frac{\partial (u\rho)}{\partial x} = 0$$

$$\frac{\partial (\rho u)}{\partial t} + \frac{\partial}{\partial x}(\rho u^2 + P_g + P_c) = 0$$

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

ordinary gasdynamics EQs + P_c terms

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

Diffusion Convection Eq. with wave drift effect

$$\frac{\partial f}{\partial t} + (u + u_w)\frac{\partial f}{\partial x} = \frac{1}{3}\frac{\partial}{\partial x}(u + u_w) \cdot p \frac{\partial f}{\partial p} + \frac{\partial}{\partial x}\left[\kappa(x,p)\frac{\partial f}{\partial x}\right] + Q(x,p)$$

$u_w \approx$ wave drift speed

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

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

Phenomenological models for MFA & Alfvenic Drift

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

- B field amplification via plasma instabilities :

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

in TP regime: $U(x)=1$ ➔**no MFA**

$$\frac{B_2}{B_1} = \sqrt{\frac{1}{3} + \frac{2}{3}\left(\frac{\rho_2}{\rho_1}\right)^2} \quad \text{(isotropic fields) in downstream } (x \le x_s)$$

where $U(x) = [V_s - u(x)]/V_s$, $M_{A,0} = V_s / V_{A,0}$: Alfvenic Mach no., $V_{A,0} = B_0 / \sqrt{4\pi\rho_0}$

- wave speed :

$$u_w \approx \frac{B(x)}{\sqrt{4\pi\rho(x)}}$$

in amplified fields
➔ maximize the AD effect
➔ reduce CR efficiency at strong shocks

- Free Escape Boundary: $f(p, x_{\rm FEB}) = 0$ at $x_{\rm FEB} = 0.5 \cdot x_s$

Diffusion-Convection Eq. for CR protons with Alfvenic drift

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

a heuristic model

our phenominological model:

$u_w \approx V_A$ in upstream, $u_w \approx 0$ in downstream,

$V_A = B(x)/\sqrt{4\pi\rho(x)}$ is Alfven speed.

Test-particle solution: injected population: $f_2(p) = f_{inj}(\frac{p}{p_{inj}})^{-q}$

thermal leakage injection at $p_{inj} \approx 6.6 \cdot m_p u_2 \approx 3.7 \cdot p_{th}$

Modified Power-law slope: steepening due to smaller velocity jump

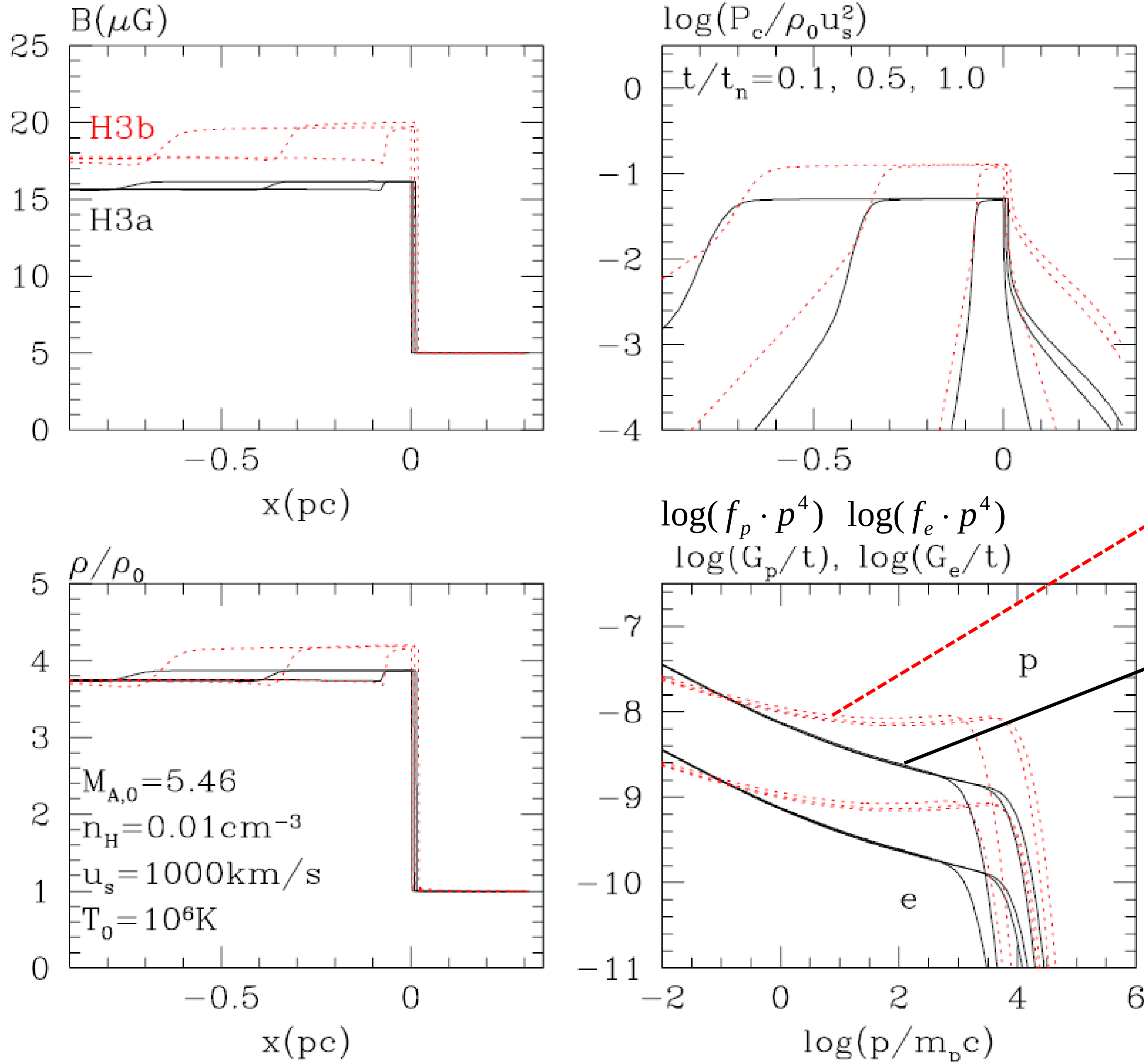
$$q = \frac{3 \cdot (u_1 - V_A)}{(u_1 - V_A) - u_2} = \frac{3r \cdot (1 - M_A^{-1})}{r - 1 - r \cdot M_A^{-1}}$$

$$M_A = \frac{u_s}{V_A}$$

where $r = \frac{\rho_2}{\rho_1}$: shock compression ratio

Plane Parallel Shock with MFA & AD

M_s=6.7



$$V_A = \frac{B_0}{\sqrt{4\pi\rho}}$$

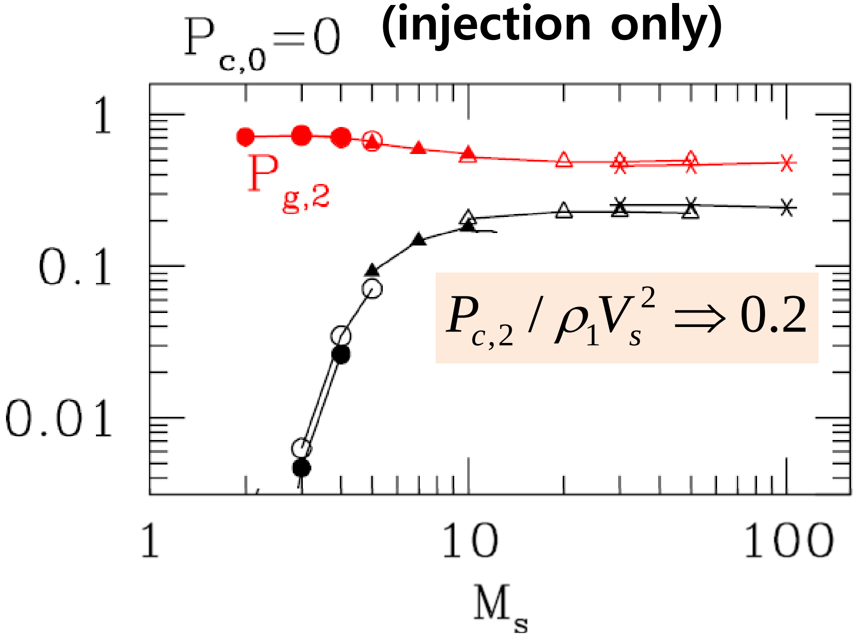
$$V_A = \frac{B(x)}{\sqrt{4\pi\rho}}$$

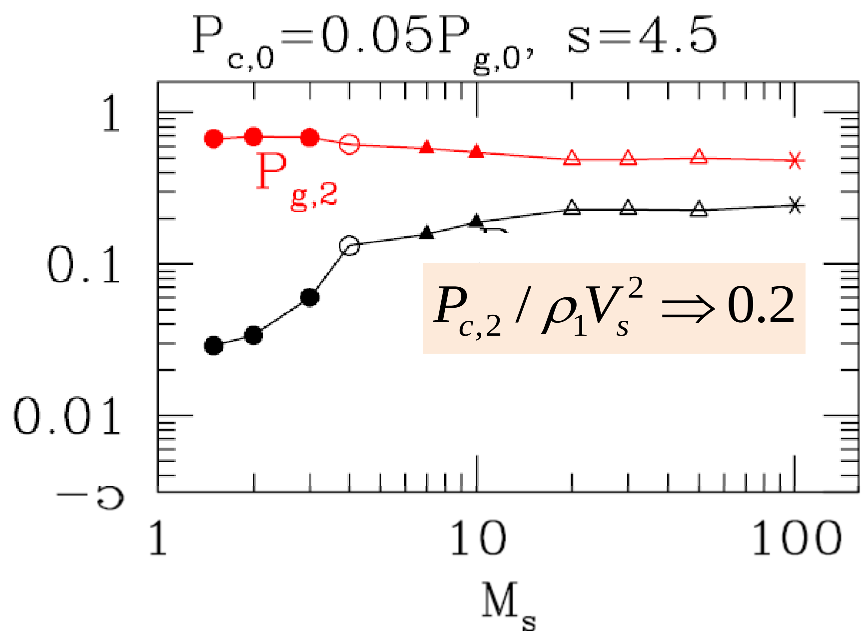
Steepening due to AD

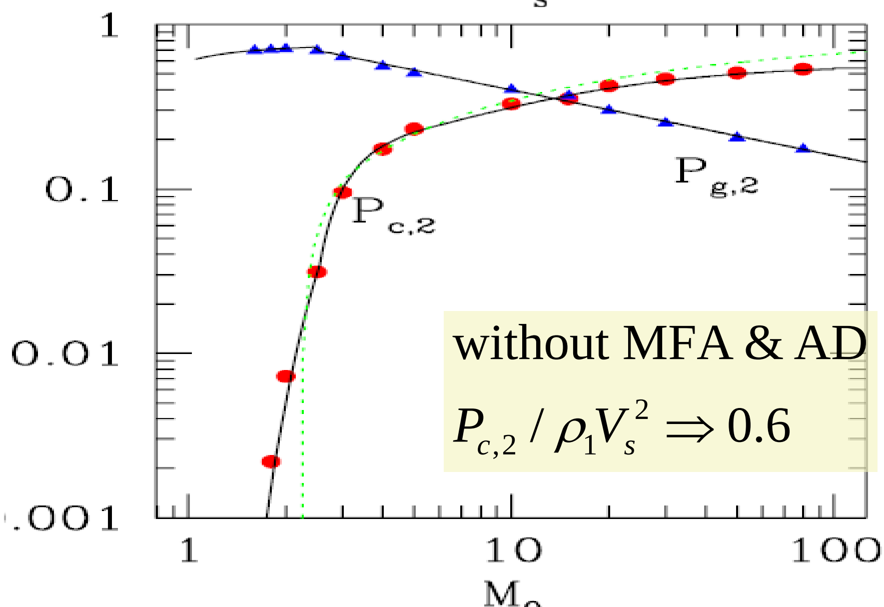
CR acceleration efficiency with MFA & AD

Kang & Ryu 2012

(injection only)







CR efficiency depends on M_s, not on T_0

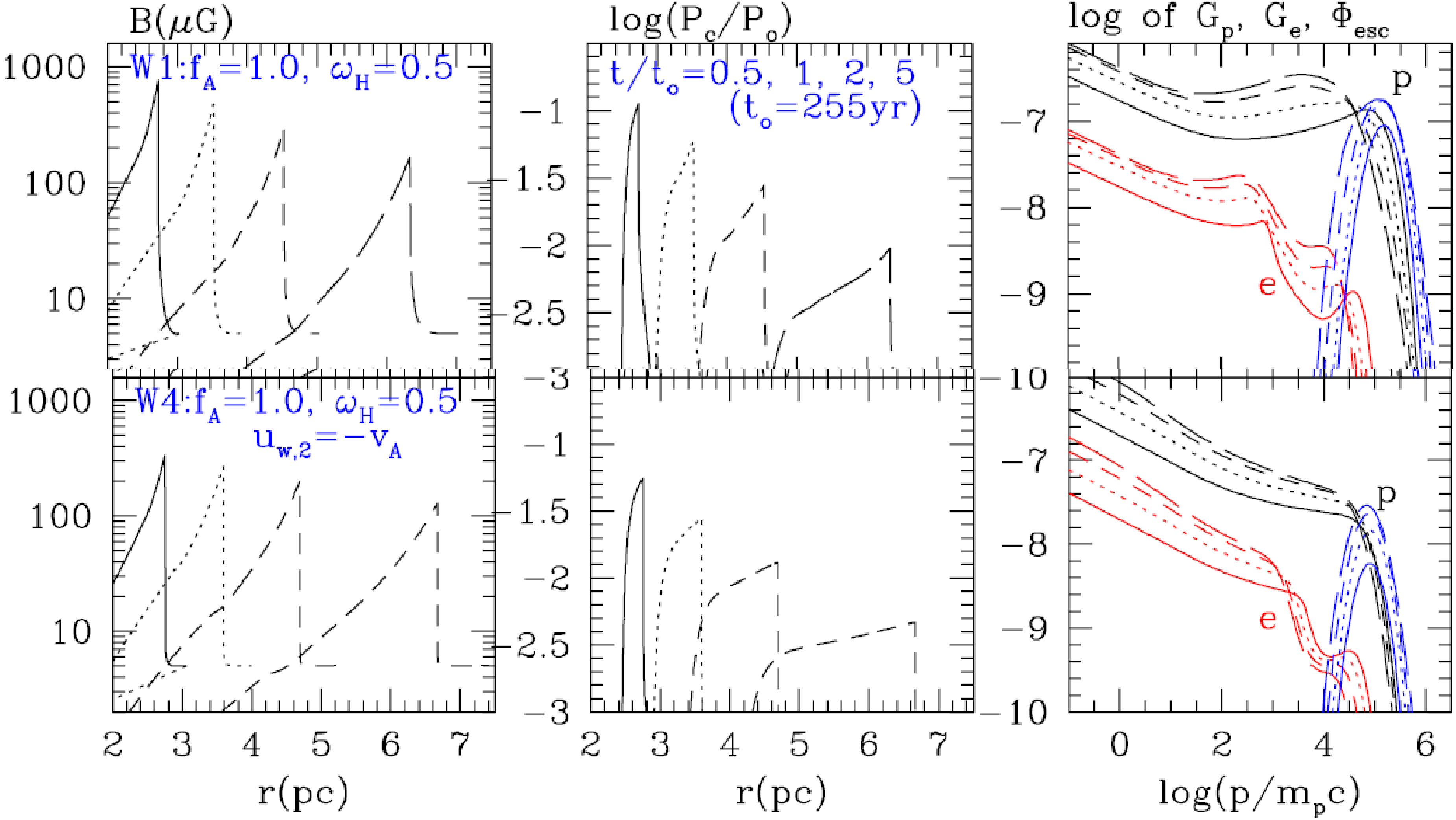
Plane parallel cosmological shocks

Kang + 2007

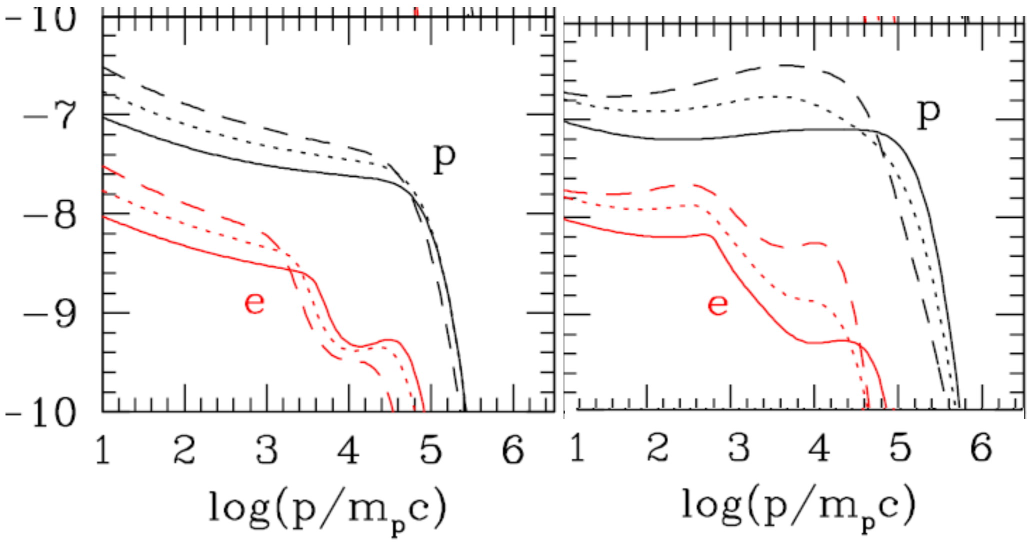
Type Ia SNR Model : 1D spherical CRASH

$M_{ej} = 1.4\,M_{\Theta}$, $E_o = 10^{51}$ ergs, $n_{ISM} = 0.3\,cm^{-3}$, $T_0 = 3\times10^4$ K, $B_0 = 5\mu G$

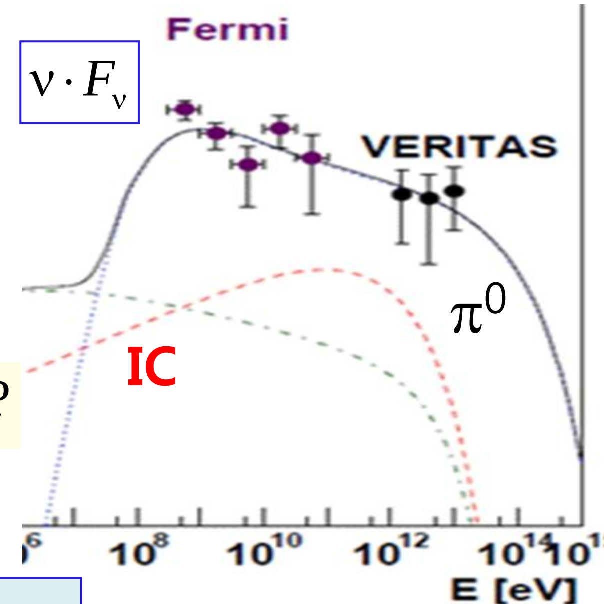
$r_o = 3.18$pc, $t_o = 255$ yrs



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



$K_{e/p} = ?$



time-dependent evolution of $u_s(t)$

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

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

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

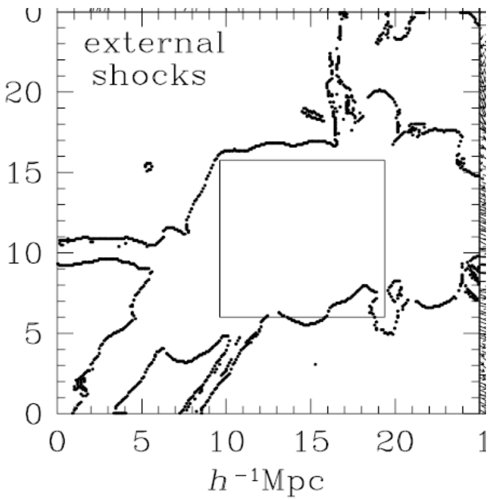
$B(r,t) \Rightarrow p_{\max,p},\ p_{\max,e}$ (cooling)

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

....

III. Shocks in Structure Formation Simulations

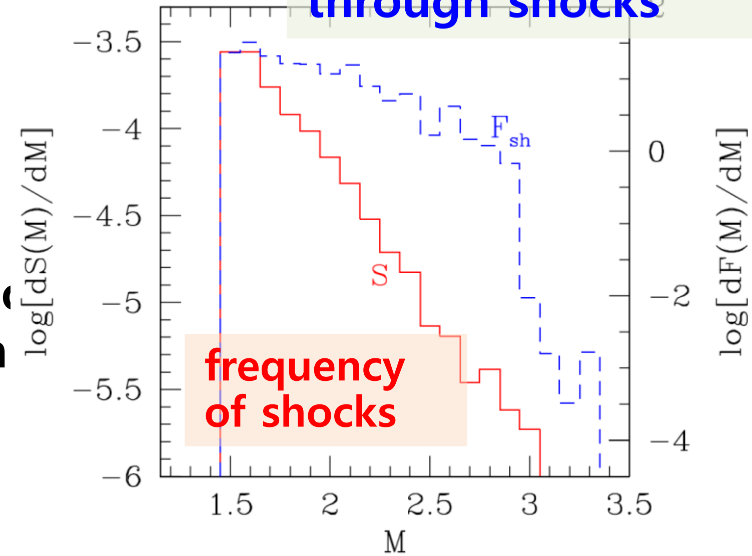
Accretion Shocks



strong shocks with Vs~1000-3000 km/s.

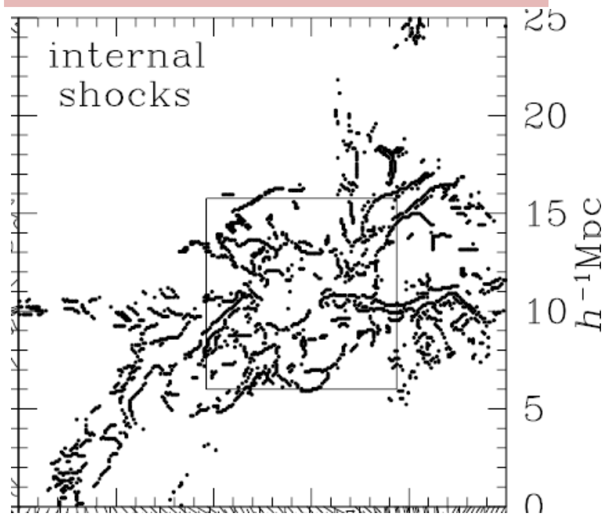
At accretion shocks DSA injection/accelerati efficiency could be high as in SNRs.

kinetic E. flux through shocks



frequency of shocks

Shocks inside ICM



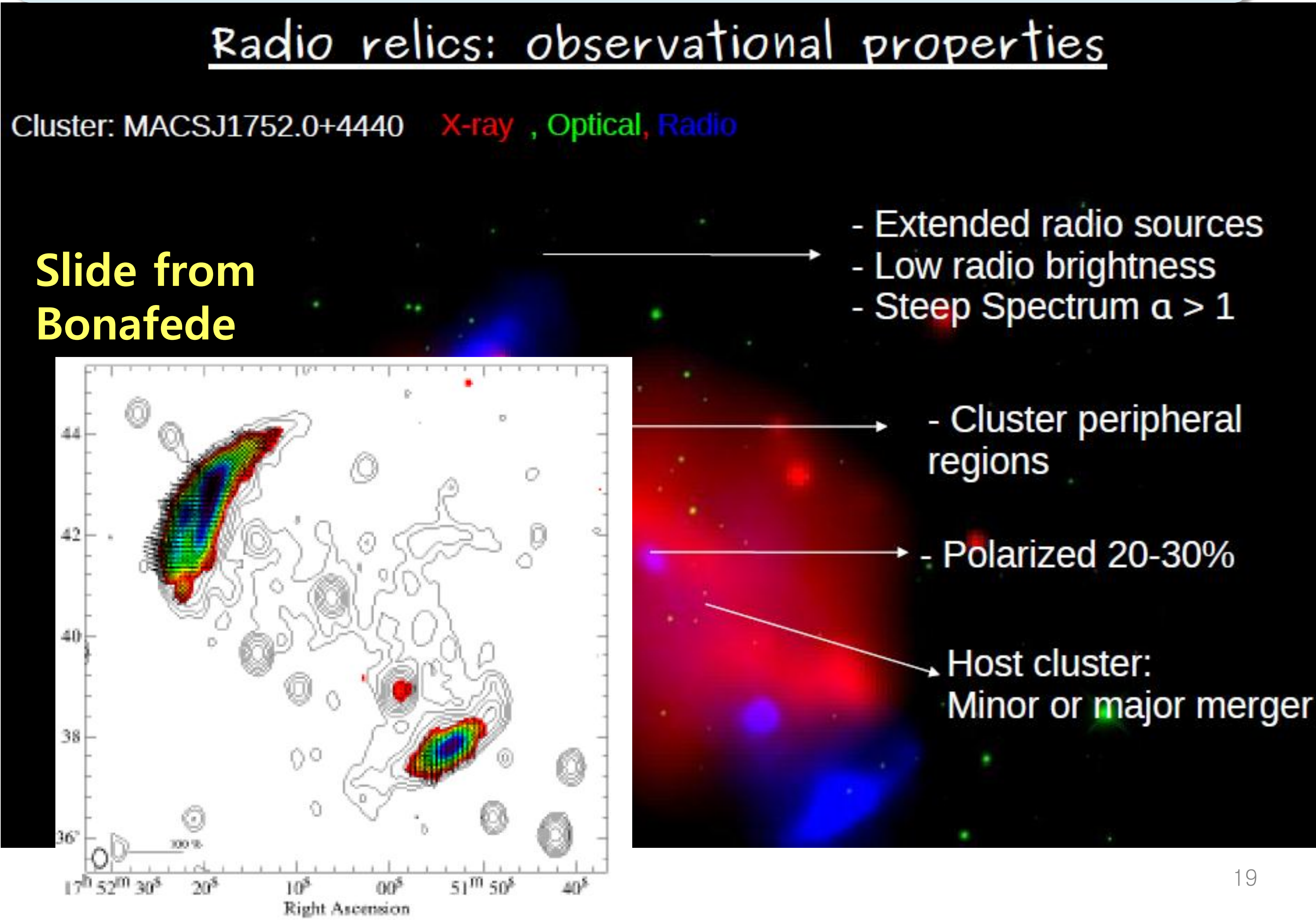
Weak shocks with M<3 are dominant inside ICM (T>10^7K).

They are energetically important. ($F_{KE}=0.5\rho V_s^3$)

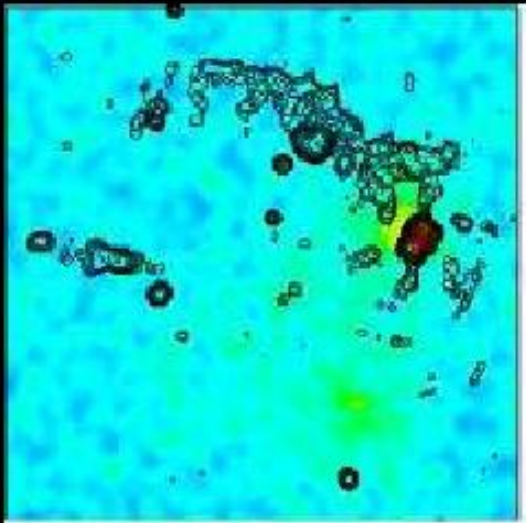
At weak merger shocks DSA CR injection/acceleration efficiency is low.

➔ re-acceleration of pre-existing CRs can be important

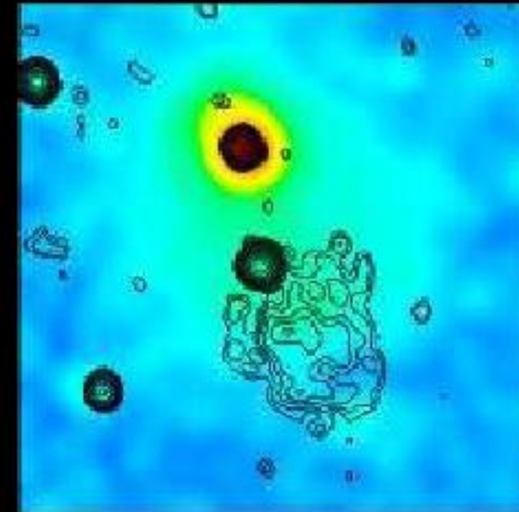
Radio Relics of clusters: Diffuse Synchrotron Emission



Radio relics: morphologies

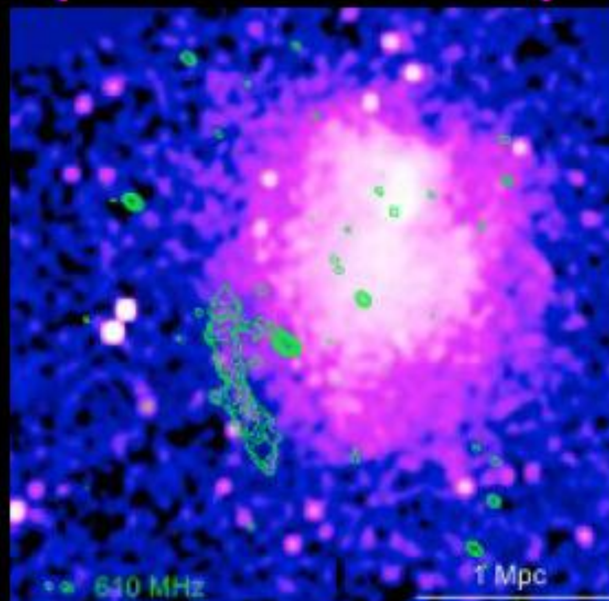


Abell 115
(Govoni et al. 2001)

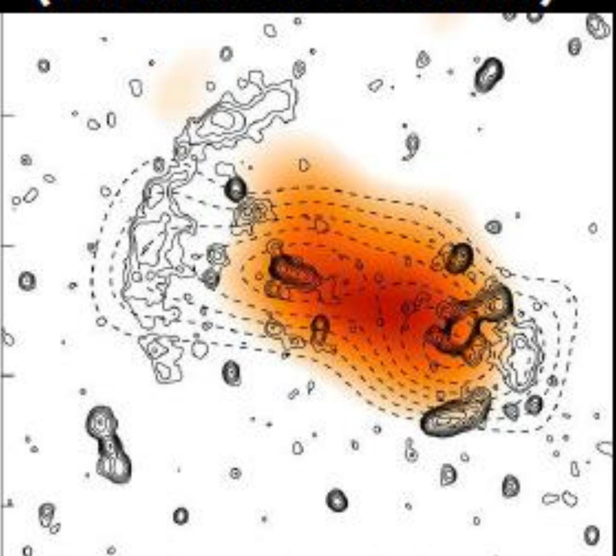


Abell 1664
(Govoni et al. 2001)

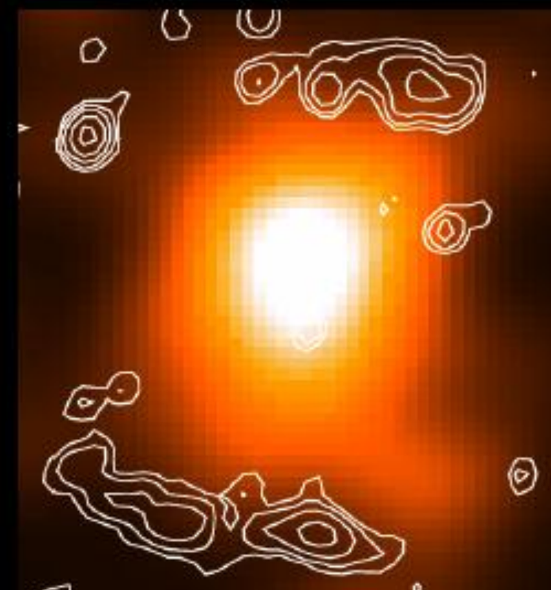
Abell 521
(Giacintucci et al. 2008)



ZwCl 0008.8+5215
(van Weeren et al. 2011)



Slide from Bonafede



Abell 1240
(Bonafede et al. 2009)

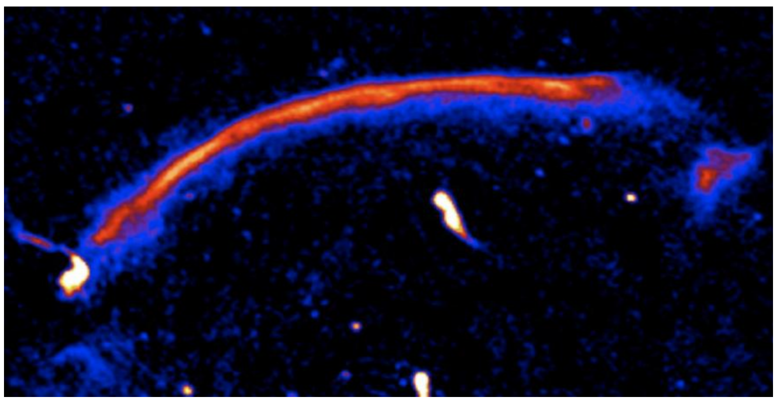
Injection versus Re-acceleration at Radio Shocks ?

$$\alpha_{shock} \approx (q-3)/2 \;\text{ or }\; (s-3)/2$$

$s =$ "pre-exisiting slope"

$$q = \frac{3r}{r-1} = \text{"shock accelerated slope"}$$

$$\text{pre-existing}: \; f_0(p) = f_{pre}\left(\frac{p}{p_{inj}}\right)^{-s}$$

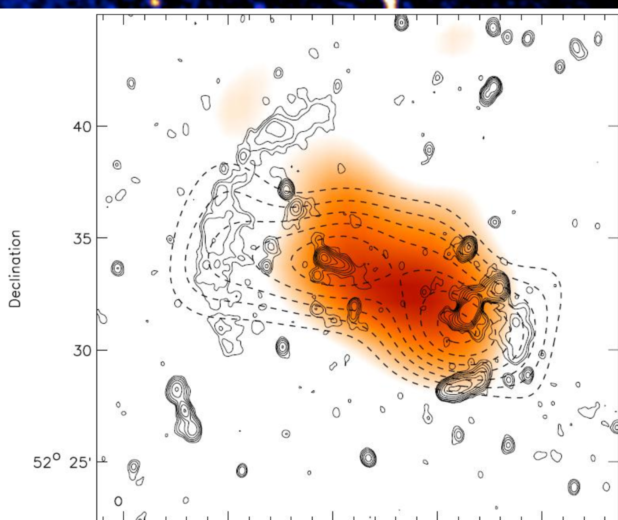


"Sausage" Radio relic in CIZA J2242.8+5301

$$\text{observed slope}: \; \alpha_{shock} \approx 0.6, \quad \alpha_{\text{integrated}} \approx 1.08$$

$$\Rightarrow q \approx 4.2, \quad M \approx 4.6: \quad \text{injection}$$

$$\text{or} \quad \Rightarrow s \approx 4.2, \quad M \sim 2-3: \; \text{re-acceleration}$$



Double relics in ZwCl 0008.8+5215

$$\text{observed}: 1.1 \le \alpha_{shock} \le 1.2, \quad 1.5 \le \alpha_{\text{integrated}} \le 1.6$$

$$\Rightarrow \text{injection}: \quad 2.2 \le M \le 2.4$$

$$\text{or} \; \Rightarrow \text{re-acceleration}: \quad s = 5.4$$

DSA simulations for planar shocks: Electrons only

- Diffuse Shock Acceleration : "CRASH" code
- Test-particle regime (CR feedback off): M= 2-4.5

$$T_{ICM} \sim 10^8\,\mathrm{K},\ c_s = 1500\ \mathrm{km/s},\ M = 2-4.5,\ B_1 = 1\mu G$$

- Diffusion convection Eq. for CR electrons with cooling

$$\frac{\partial f_e}{\partial t} + u\frac{\partial f_e}{\partial x} = \frac{1}{3}\frac{\partial u}{\partial x}\,p\frac{\partial f_e}{\partial p} + \boxed{\frac{1}{p^2}\frac{\partial}{\partial p}\left[p^2 b(p) f_e\right]} + \frac{\partial}{\partial x}\left[\kappa(x,p)\frac{\partial f_e}{\partial x}\right] + Q(x,p)$$

$f_e(x,p,t) = \text{isotropic part of electron distribution function}$

$b(p) = -dp/dt = DB_e^2 p^2 = \text{synchrotron} + \text{IC cooling}$

$Q = \text{injection from thermal pool}$

- Injection only vs. (Injection + Re-acceleration) models

$$\text{pre-existing CR electrons:}\quad f_e(p) \propto \left(p/p_{\rm inj}\right)^{-s}$$

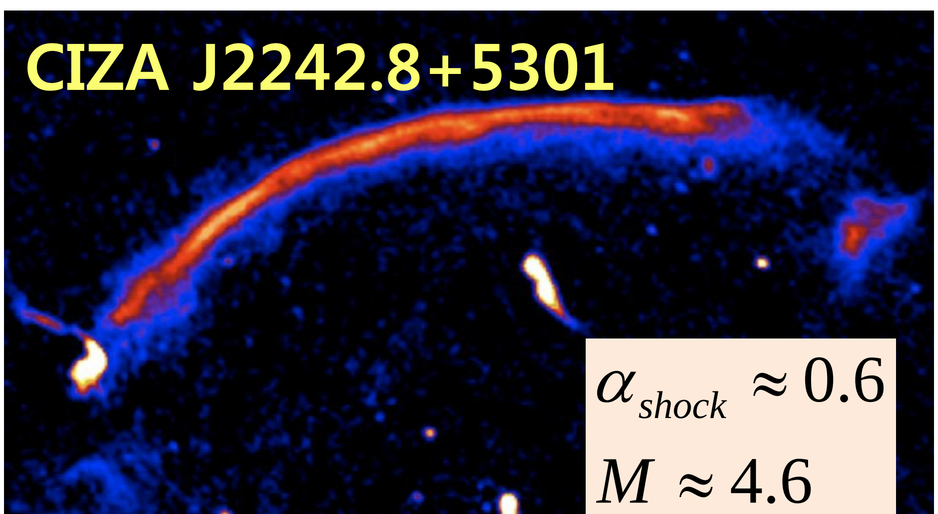
$$\boxed{p_{\rm inj}/m_p c \sim 1.5\times10^{-2},\quad \gamma_{\rm e,inj} \sim 30}$$

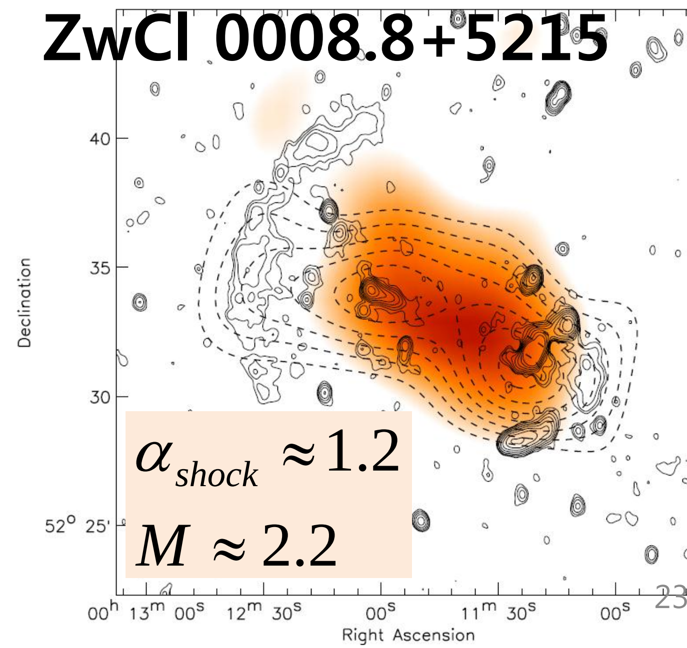
Table 1. Parameters for Plane-Parallel Shock Simulations

Model Name	z	$c_{s,1}$ (km s^{-1})	M	u_2 (km s^{-1})	s	B_2 (μG)	Cluster
M4.5B3.5I	0.1921	6.0×10^2	4.5	7.7×10^2	-	3.5	CIZA J2242.8+5301
M2B7S4.2	0.1921	1.25×10^3	2.0	1.1×10^3	4.2	7.0	CIZA J2242.8+5301
M2B2.3I	0.103	1.25×10^3	2.0	1.1×10^3	-	2.3	ZwCl0008.8+5215
M2B2.3S5.4	0.103	1.25×10^3	2.0	1.1×10^3	5.4	2.3	ZwCl0008.8+5215

$$\text{pre-existing}: \quad f_0(p) = f_{pre}\left(\frac{p}{p_{inj}}\right)^{-s}$$

Inject. vs. re-accel.

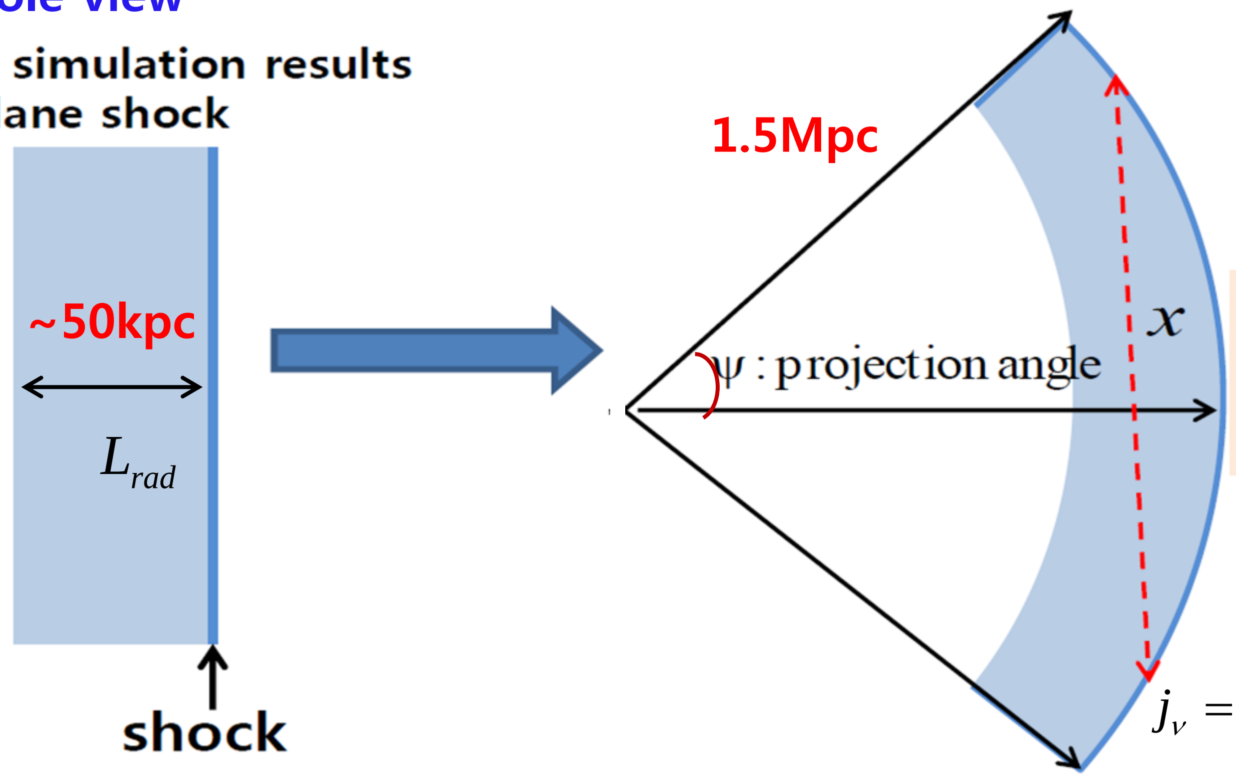




pole view

DSA simulation results at plane shock

mapping onto a spherical shell



Synchrotron emissivity

$$I_\nu = \int j_\nu(x)dx$$

integration along lines of sight

$$j_\nu = \text{synchrotron emissivity}$$

$$I_\nu = \int j_\nu \, dx = \text{intensity}$$

$$S_\nu = I_\nu \cdot \pi \cdot (\theta_1 \times \theta_2)(1+z)^{-3}$$

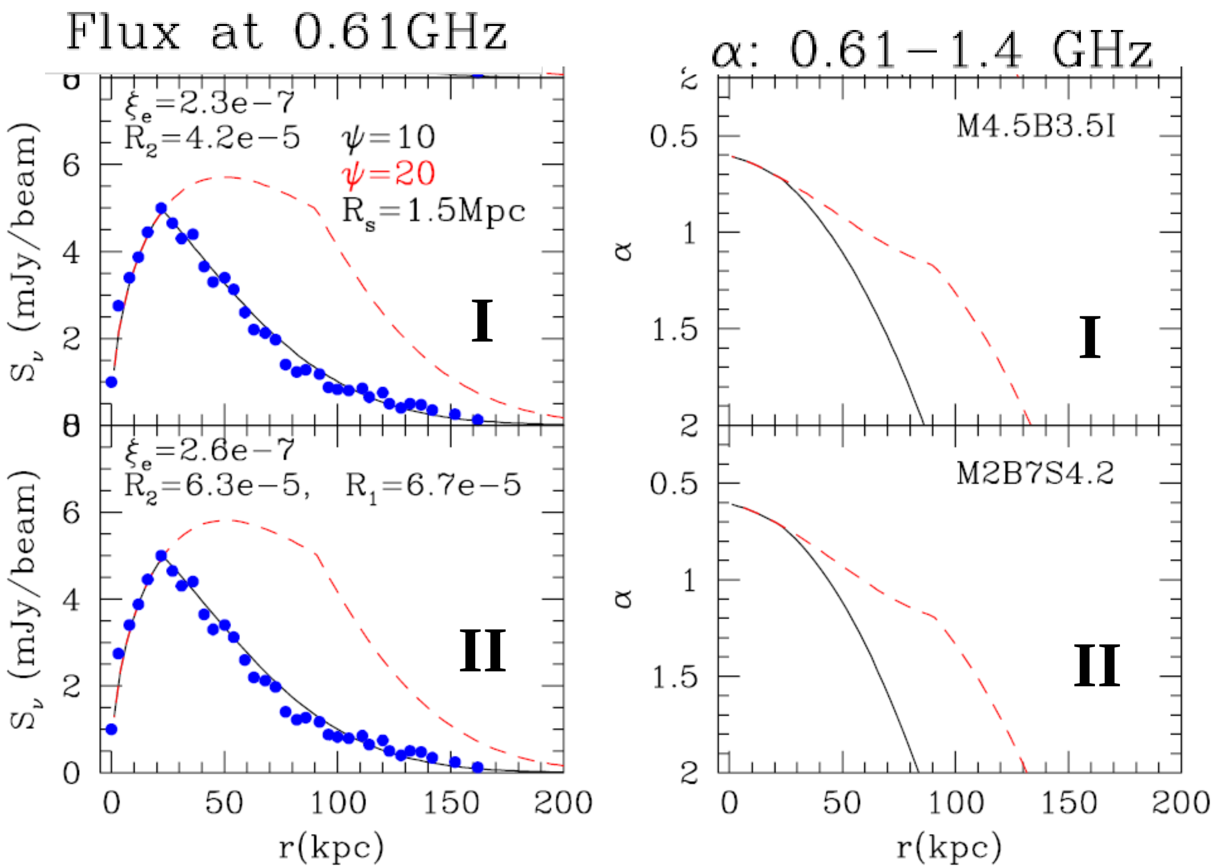
$$\nu_s = \nu_o(1+z), \quad \frac{I_{\nu,o}}{\nu_o^3} = \frac{I_{\nu,s}}{\nu_s^3}$$

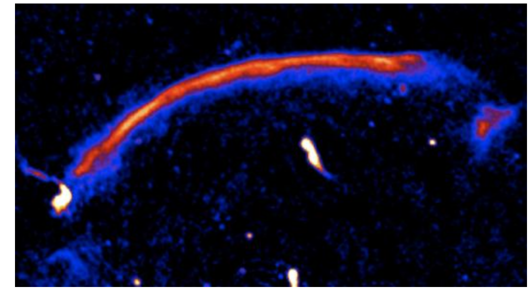
Thin shell approximation

$$L_{rad} \approx 890\text{kpc} \cdot \left(\frac{u_2}{10^3\,\text{km/s}}\right) \frac{B_2^{1/2}}{B_2^2 + B_{CBR}^2} \left(\frac{\nu_{obs}}{1\text{GHz}}\right)^{-1/2} (1+z)^{-1/2}$$

Gaussian Beam of $\theta_1 x \theta_2$

Simulation Result I: CIZA J2242.8+5301





Blue dots: data from van Weeren et al 2010 the flux is re-scaled to fit each model.

Best fit to radio profile, $S_{0.61}(r)$

$\psi \approx 10^\circ$: projection angle

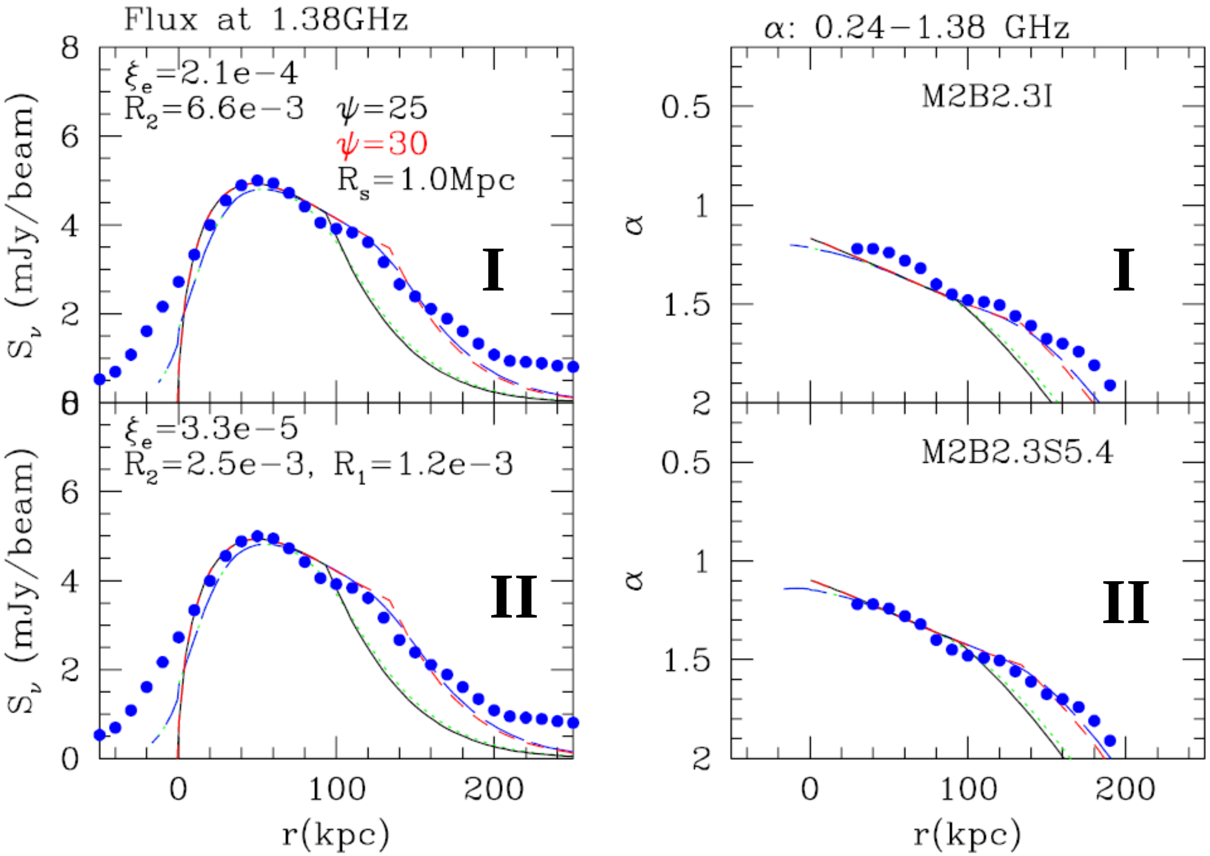
I. $M = 4.5$, $B_2 = 3.5\mu$G, injection only $\Rightarrow \xi_e \sim 10^{-7}$

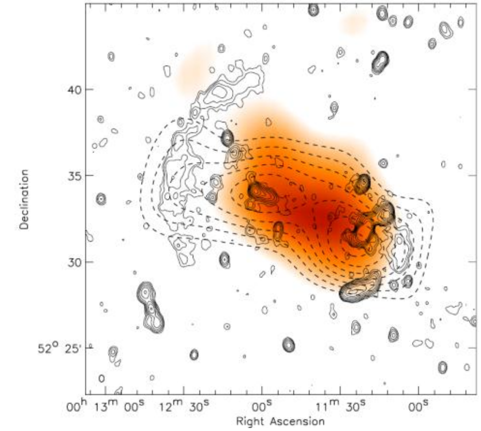
II. $M = 2$, $B_2 = 7.0\mu$G, $s = 4.2$ $\Rightarrow P_{CRe,1} / P_{g,1} \sim 10^{-4}$

Both models can explain the observation.

Kang, Ryu, Jones 2012

Simulation Result II: ZwCl 0008.8+5215





Blue dots: data from van Weeren et al 2011. the flux is re-scaled to fit each model.

Best fit to radio profile, $S_{1.38}(r)$

$\psi \approx 30^\circ$: projection angle

I. $M = 2,\ B_2 = 2.3\mu\mathrm{G}$, injection only

II. $M = 2,\ B_2 = 2.3\mu\mathrm{G}$, $s = 5.4$

$\xi_e \sim 10^{-4}$: injection rate is too high ??

$P_{cr,e} / P_{gas} \sim 10^{-3}$: pre-existing CR

due to turbulent acceleration ?

Kang, Ryu, Jones 2012

IV. Summary

* Plasma simulations of nonrelativistic collisionless shocks

- CR streaming and current instabilities ➔ amplify B fields

* Magnetic field amplification and Alfvenic drift in upstream region may reduce the DSA efficiency at strong modified shocks.

$$\text{so } P_{c,2}/\rho_1 V_s^2 \Rightarrow 0.2 \quad \text{for } M > 10 \quad (\beta_{\rm p} = \frac{P_g}{P_B} \sim 100 \text{ in ICMs})$$

* Nonthermal radiation from Supernova Remnants (SNRs)

- X-ray obs: amplified B fields ~ 100-300 μG
- γ-ray obs: proton spectrums $N(E) \propto E^{-2.3}$ required

Details of DSA modeling control the highest end of CR spectrum

* Radio shocks (relics) around merging clusters
CR injection/acceleration are inefficient at weak shocks.
Reacceleration of pre-exisiting CRs could be important.

We need to understand better wave-particle interactions at weak shocks.