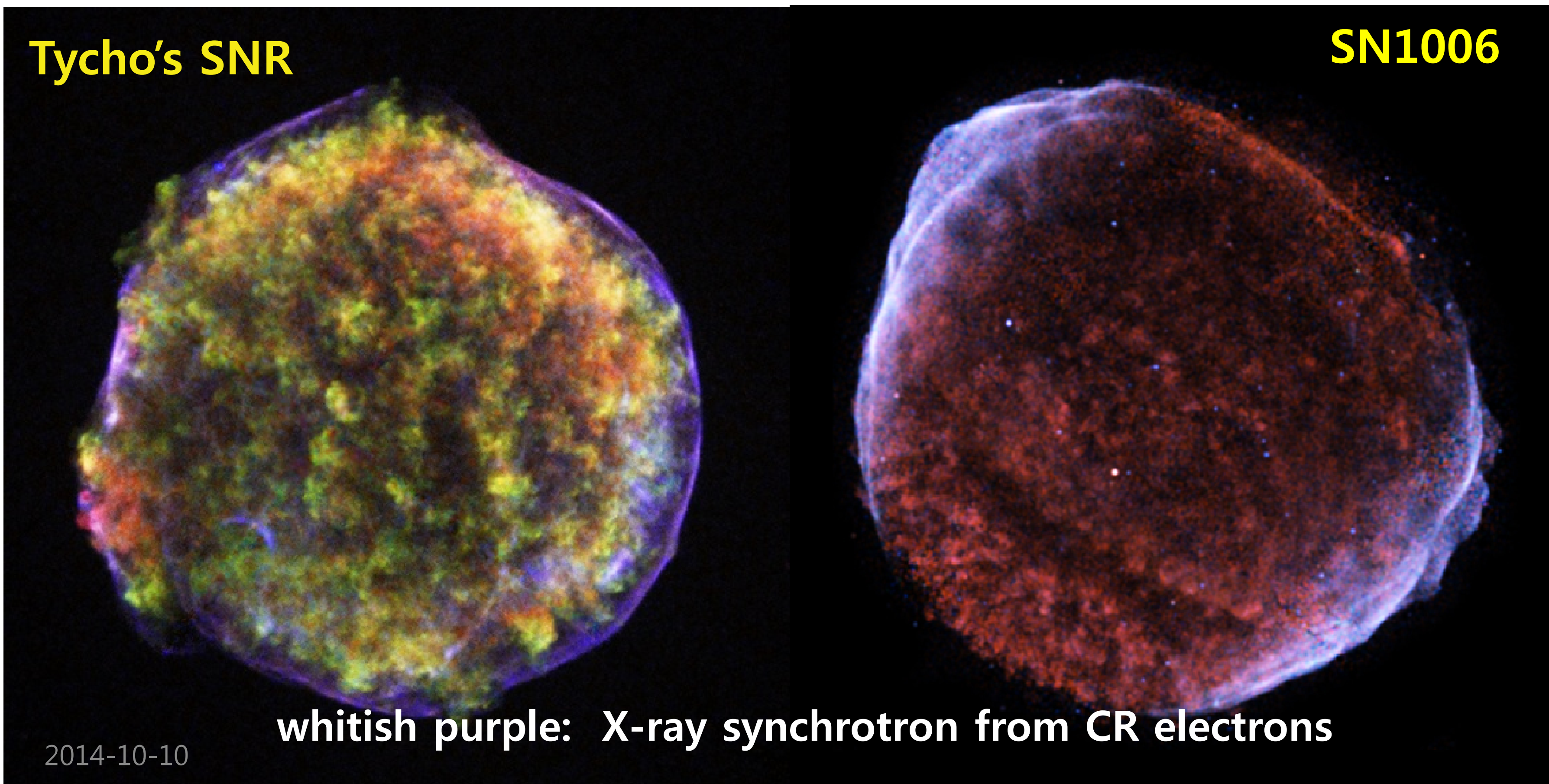
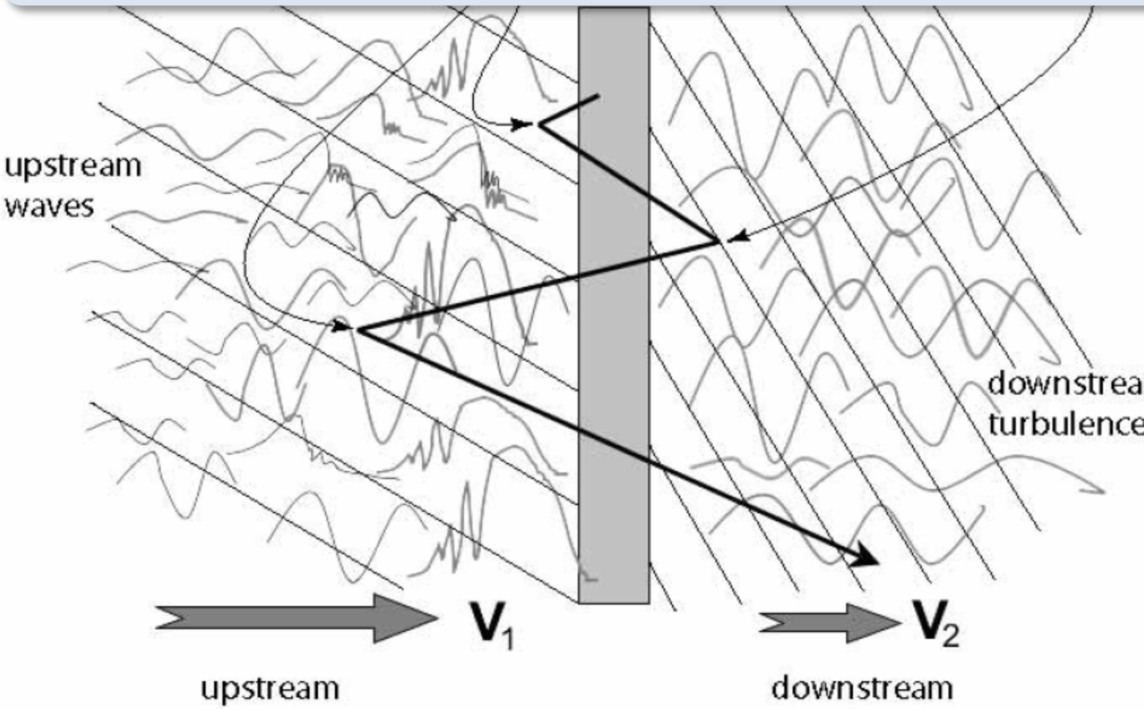
Kinetic Plasma Processes in Diffusive Shock Acceleration

Hyesung Kang

Pusan National University, Pusan, Korea



H.E. Particles are accelerated at shocks by Fermi 1st order process



Collisionless shock

test - particle solution

$$f_{test}(p) \propto p^{-q_{test}}$$

$$q_{test} = \frac{3u_1}{(u_1 - u_2)}$$

$\rightarrow 4$ for large M

(strong shocks)

$$\Rightarrow N(E) \propto E^{-2}$$

MHD waves in a converging flow act as converging mirrors

→ particles are scattered by MHD 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

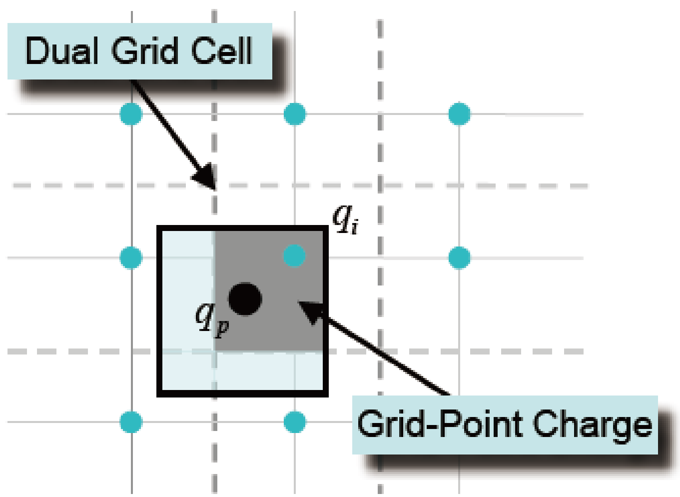
Kinetic Plasma Simulations: PIC (Particle In Cell)/ Hybrid

PIC Approach to Vlasov Equation

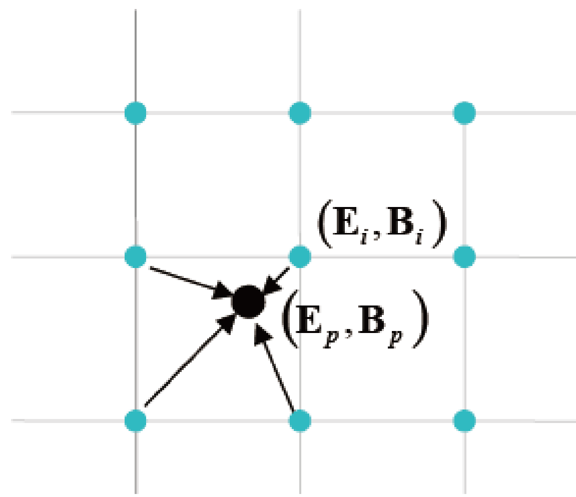
(Slide from Spitkovsky)

- Lorentz-Force: $\mathbf{F}_p = q\mathbf{E}_p + \frac{q}{m}\left(\mathbf{p}_p \times \mathbf{B}_p\right)$
- Solve Maxwell Equations on grid
- "Grid aliasing" (Birdsall et al.)

-can follow kinetic plasma processes:
e.g. wave-particle interactions
-provide the most complete pictures,
but very expensive



Charge Assignment



Force Interpolation

PIC (Amano & Hoshino 2012; Riquelme & Spitkovsky 2011, Guo + 2014, Kato 2014)

Hybrid (Giacalone 2013; Gargate & Spitkovsky 2011, Caprioli & Spitkovsky 2014): Ion PIC + Electron fluid

Collisionless Boltzman Eqn (Vlaso - Maxwell): $f(\vec{x}, \vec{p}, t)$ in 6D phase space

$$\frac{\partial f}{\partial t} + \frac{\vec{p}}{m}\cdot\vec{\nabla} f + \vec{F}\cdot\frac{\partial f}{\partial \vec{p}} = 0 \qquad \left(\text{where } \vec{F} = q[\vec{E} + \frac{1}{c}(\vec{\upsilon}\times\vec{B})]\right)$$

Fokker - Planck Eqn for collisionless plasma in quasi - linear limit:

gyro - phase averged $f(x, p, \mu, t)$ in 3D phase space

$$\frac{\partial f}{\partial t} + \mathrm{v}\cdot\frac{\partial f}{\partial x} = \frac{\partial}{\partial \mu}\left(D_{\mu\mu}\frac{\partial f}{\partial \mu}\right) + \frac{\partial}{\partial \mu}\left(D_{\mu p}\frac{\partial f}{\partial p}\right) + \frac{1}{p^2}\frac{\partial}{\partial p}\left(p^2 D_{p\mu}\frac{\partial f}{\partial \mu}\right)$$
$$+ \frac{1}{p^2}\frac{\partial}{\partial p}\left(p^2 D_{pp}\frac{\partial f}{\partial p}\right)$$

e.g. Schlickeiser 1989

where $D_{\mu\mu}, D_{\mu p}, D_{p\mu}, D_{pp}$: wave - particle interations due to turbulence

Diffusion - Convection Eqn (with Alfven waves)

pitch - angle averaged $f(x, p, t)$: isotropic part

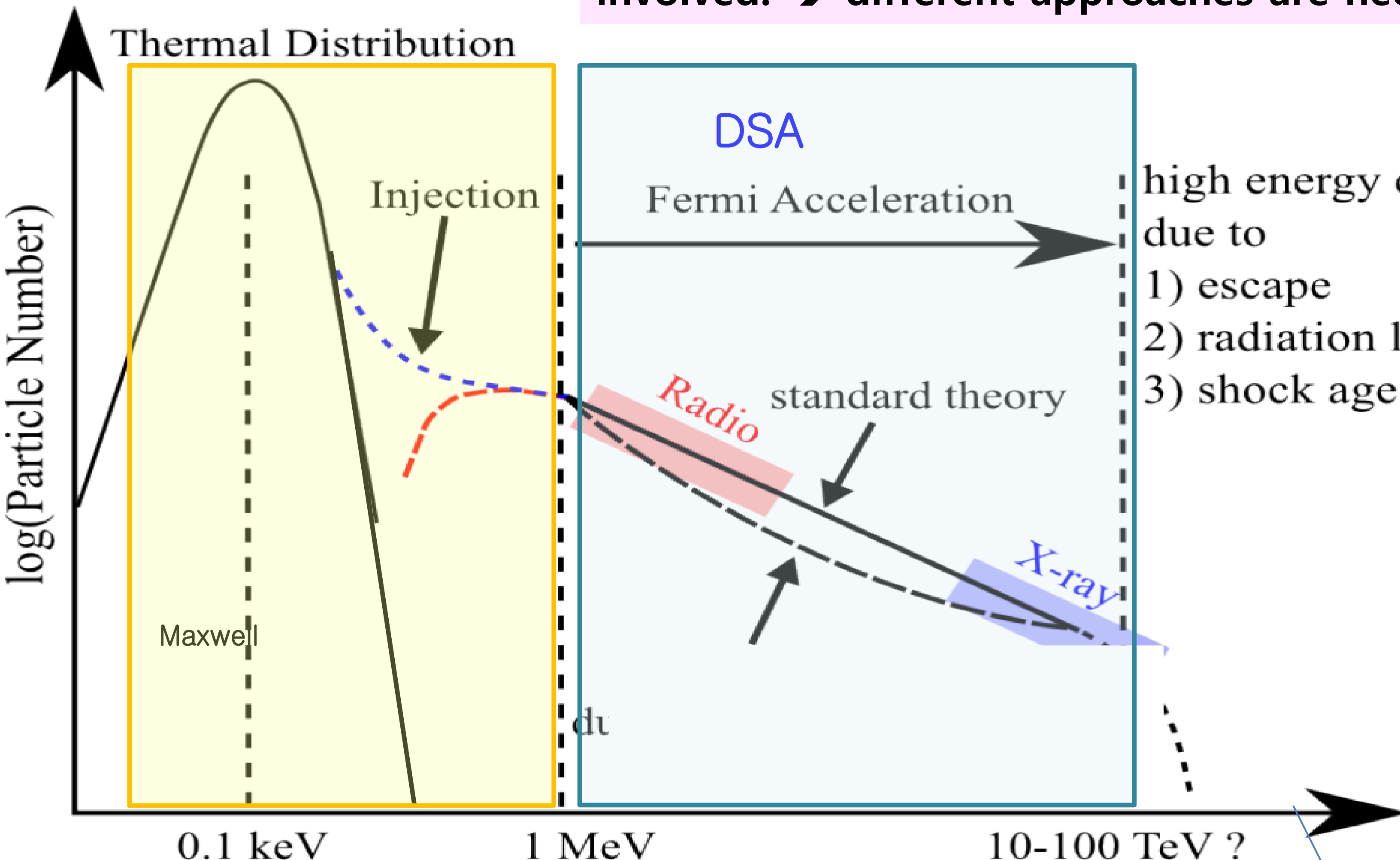
e.g. Skilling 1975

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

2nd order: small in DSA

$f(x, p, t)$: isotropic part

Wide ranges of space, time, energy scales are involved. ➔ different approaches are needed.



PIC/Hybrid simulations
wave-particle interactions
Injection, pre-heating via plasma instabilities

Diffusion Convection Eqn
phenomenological models
for injection, diffusion, wave drifts...

from Amano 2009

Time-dependent DSA simulations (Kang, Jones,..)

Diffusion Convection Equation with Phenomenological recipes

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

$$u_w \approx \text{wave drift speed} \approx V_A(x) = B(x)/\sqrt{4\pi\rho}: \quad \text{MFA}$$

$$\kappa(x,p) \approx \kappa^* p \propto B(x)^{-1} \quad : \text{Bohm-like diffusion}$$

$$Q(x,p) = \text{ injection of suprathermal ptls into Fermi process}$$

ordinary gasdynamics EQs + P_c terms

(1D plane quasi-parallel shock)

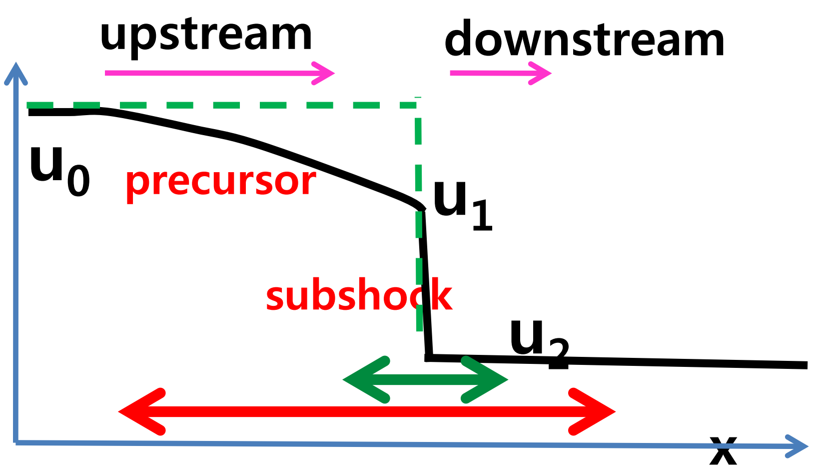
$$\frac{\partial \rho}{\partial t} + \frac{\partial (u\rho)}{\partial x} = 0$$

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

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

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

Nonlinear DSA effects: CR pressure feedback
CR modified shock with high Mach no.

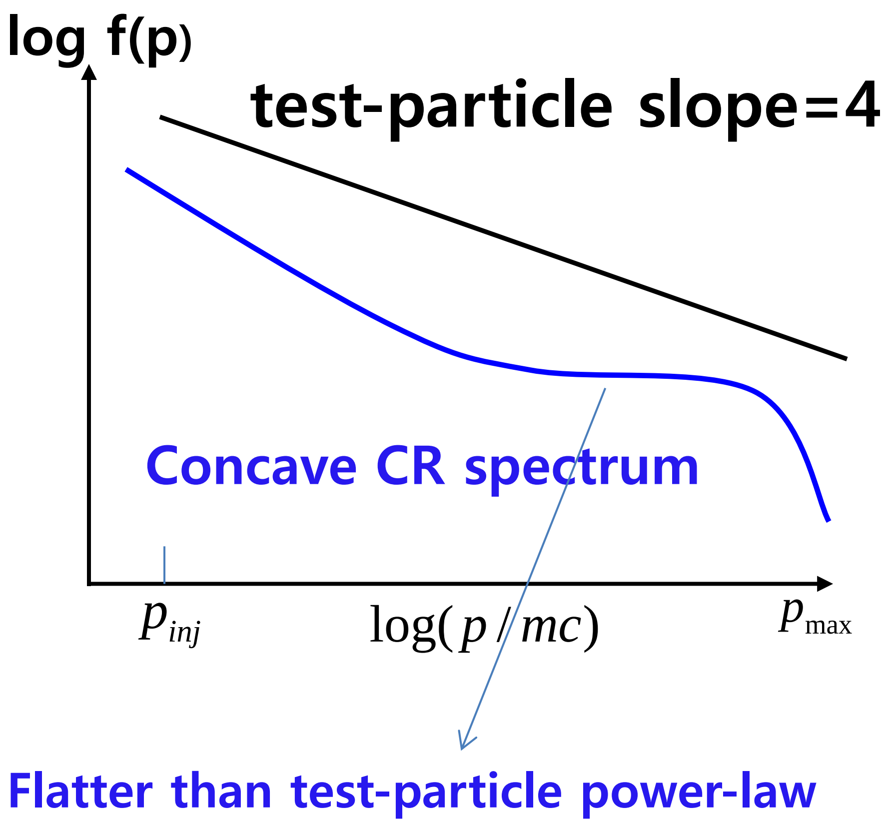


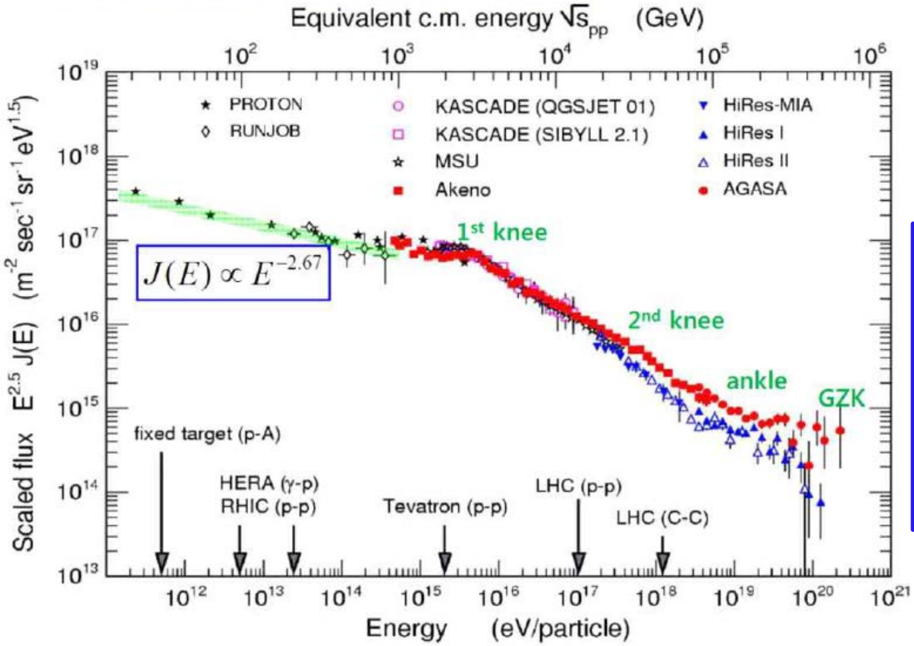
across the subshock

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

across the total shock

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





Observed CR spectrum at Earth: J(E)

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

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

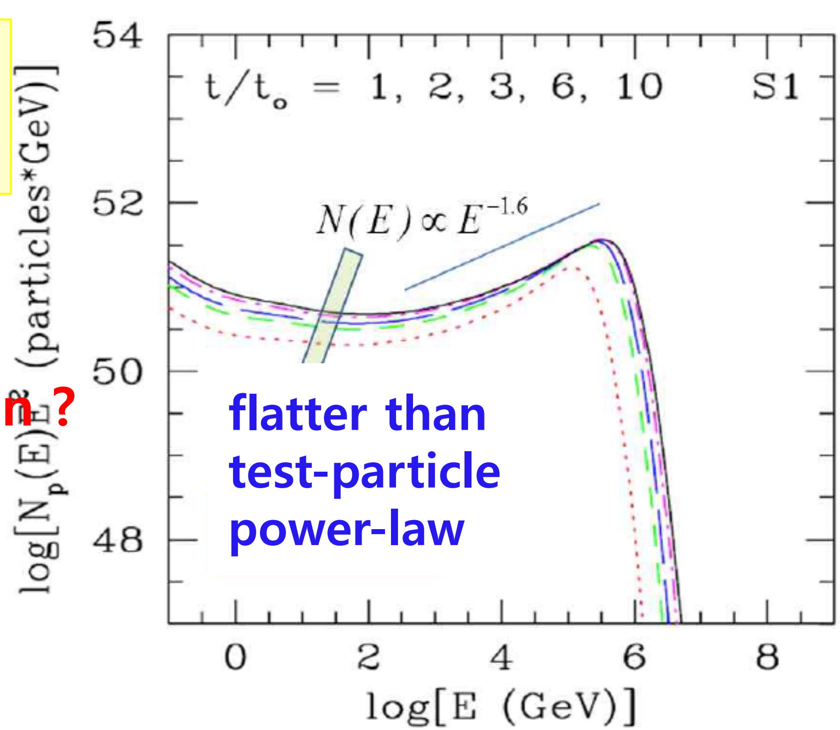
$\Rightarrow N(E) \propto E^{-2.2}$ at sources

Nonliner DSA simulations

➔ CR spectrum at source: N(E)

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

Nonlinear DSA simulation of SNR



Discrepancy bwn theory and observation ?

➔ possible solutions

1) MFA and

2) Alfvenic drift :

Wave-Particle Interactions: CR streaming Instabilities

streaming CR protons upstream of parallel shocks

→ excite resonant Alfven waves (i.e. ion/ion streaming instability)

→ amplify B field (Bell 1978, Lucek & Bell 2000)

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

resonant waves

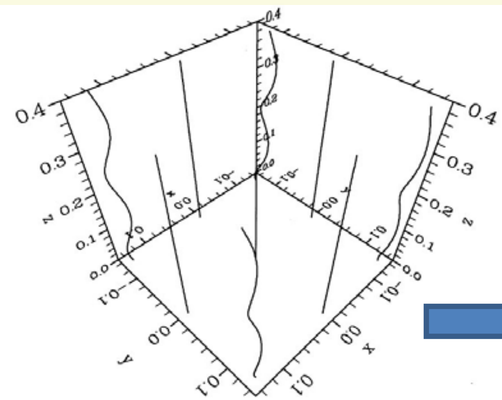


Figure 8. Magnetic field lines at $t = 0$ for the three-dimensional run.

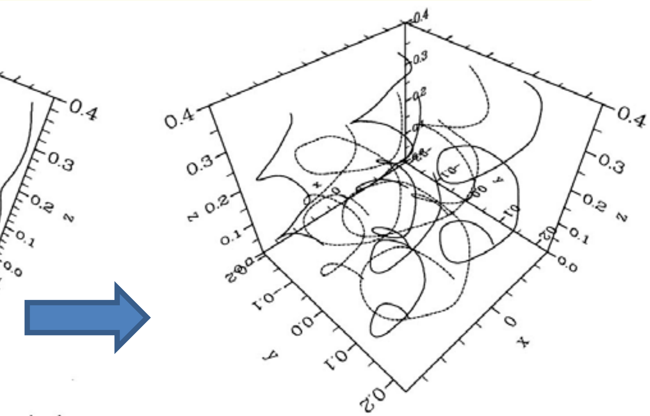
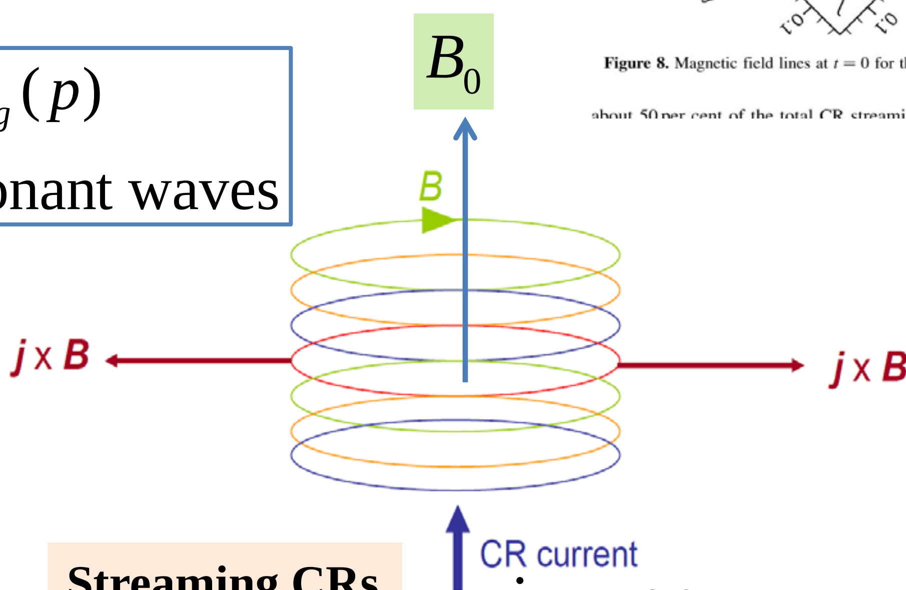


Figure 9. Magnetic field lines after 1.5 CR gyrations for the three-dimensional run.

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

nonresonant waves



Streaming CRs

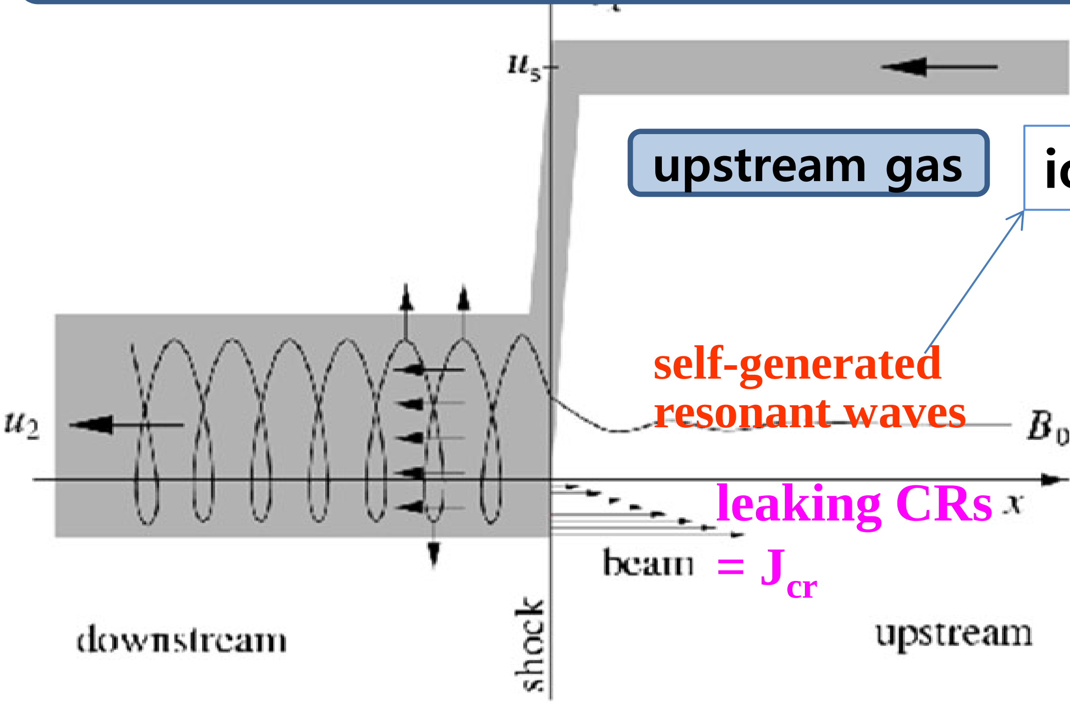
$$j_{cr} = en_{cr}u_s$$

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

$$\frac{B_\perp}{B_0} \sim \frac{B_\parallel}{B_0} \sim 10$$

Riquelme & Spitkovsky 2009

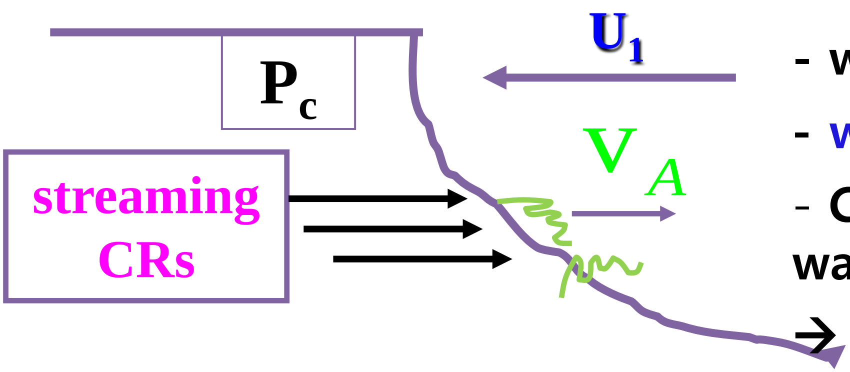
Alfvenic Drift: leads to steepening of N(E)



$$V_A(x) \sim \frac{B(x)}{\sqrt{4\pi\rho}}$$ on amplified field

➔ **Faster Alfvenic drift**

➔ **Softer CR spectrum**



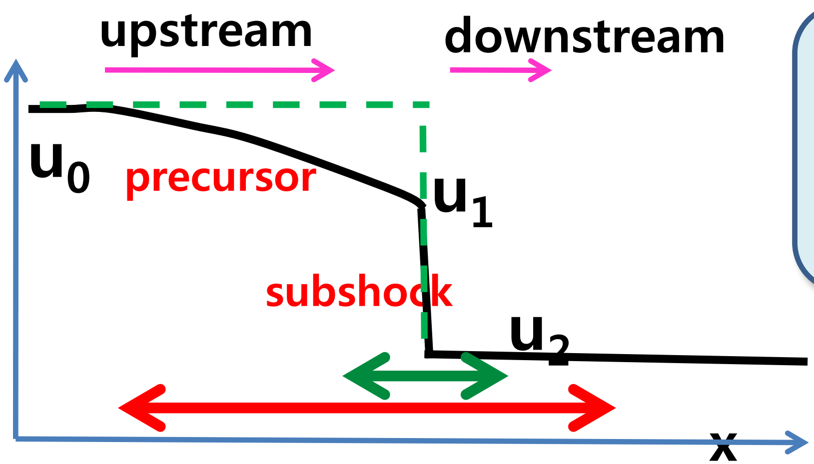
- waves are generated by streaming instability.
- waves drift upstream with $u_w \approx V_A$
- CRs are scattered and isotropized in the wave frame (instead of fluid frame)

→ Experience smaller Δu $\Rightarrow u - V_A$

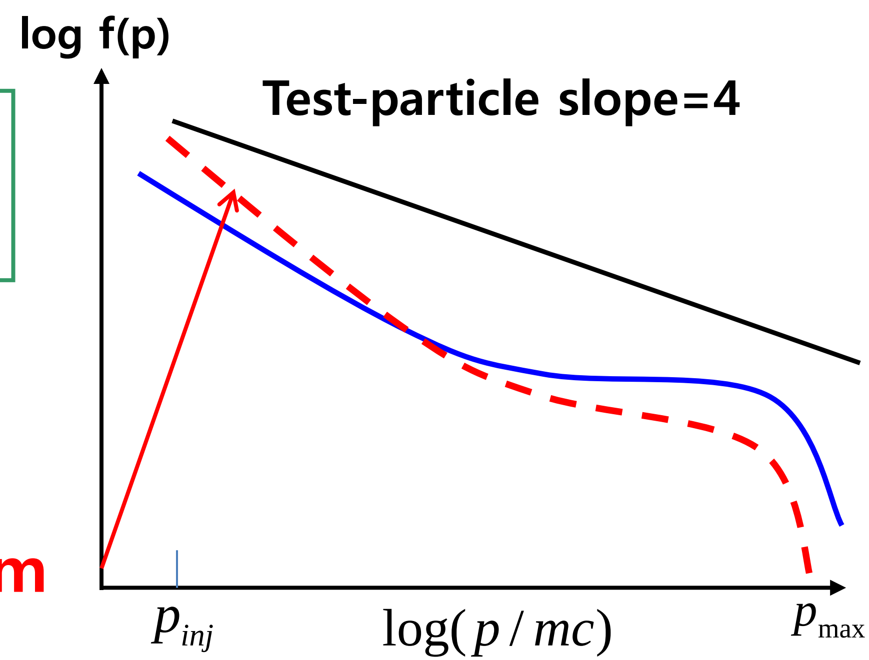
→ less efficient acceleration

→ Steepening of CR spectrum

Bell 1978



CR modified shock
+ Magnetic Field Amplification
+ fast Alfvenic Drift



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 $\Rightarrow$ MFA

$\Rightarrow$ larger B_1 & B_2 $\Rightarrow$ larger V_A

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

Highly nonlinear problem !

DSA simulations of SNRs with MFA & Alfvenic Drift

in a co-expanding frame which expands with the forward shock.

ordinary gasdynamics EQs + P_c terms

$$\frac{\partial\tilde{\rho}}{\partial t} + \frac{1}{a}\frac{\partial(\upsilon\tilde{\rho})}{\partial x} = -\frac{2}{ax}\tilde{\rho}\upsilon$$

$$\frac{\partial(\tilde{\rho}\upsilon)}{\partial t} + \frac{1}{a}\frac{\partial(\tilde{\rho}\upsilon^2 + \tilde{P}_g + \tilde{P}_c)}{\partial x} = -\frac{2}{ax}\tilde{\rho}\upsilon^2 - \frac{\dot{a}}{a}\tilde{\rho}\upsilon - \ddot{a}x\tilde{\rho}$$

$$\frac{\partial(\tilde{\rho}\tilde{e}_g)}{\partial t} + \frac{1}{a}\frac{\partial(\tilde{\rho}\tilde{e}_g\upsilon + \tilde{P}_g\upsilon + \tilde{P}_c\upsilon)}{\partial x} = -\frac{\upsilon}{a}\frac{\partial\tilde{P}_c}{\partial x} - \frac{2}{ax}(\tilde{\rho}\tilde{e}_g\upsilon + \tilde{P}_g\upsilon) - 2\frac{\dot{a}}{a}\tilde{\rho}\tilde{e}_g - \ddot{a}x\tilde{\rho}\upsilon - \tilde{L}(x,t)$$

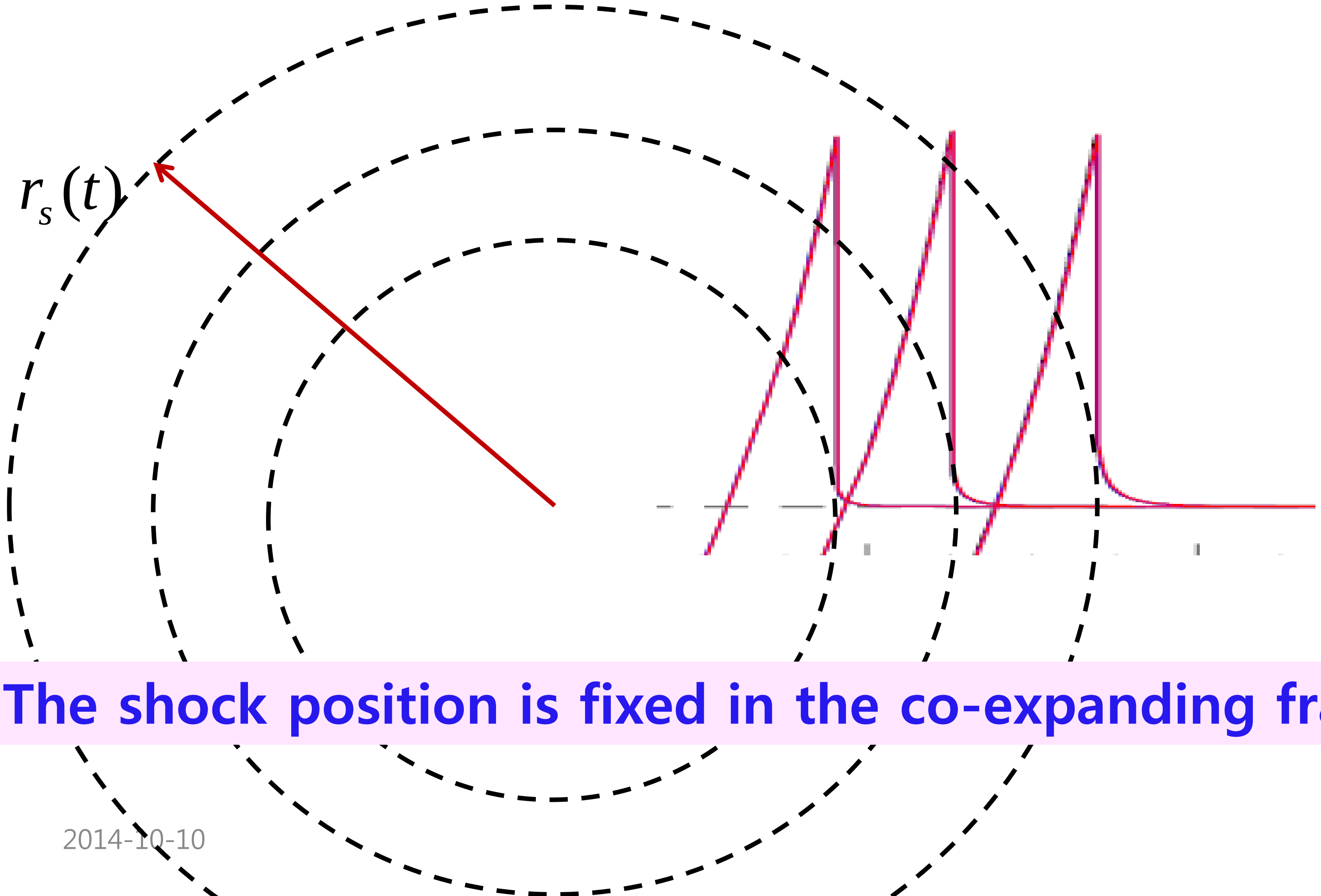
Diffusion Convection Equation for $g = f(r,p,t)p^4$ **for protons and electrons**

$$\frac{\partial\tilde{g}}{\partial t} + \frac{(\upsilon - u_w)}{a}\frac{\partial\tilde{g}}{\partial x} = [\frac{1}{3ax}\frac{\partial}{\partial x}(x^2(\upsilon - u_w)) + \frac{\dot{a}}{a}](\frac{\partial\tilde{g}}{\partial y} - 4\tilde{g}) + 3\frac{\dot{a}}{a}\tilde{g} + \frac{1}{a^2x^2}\frac{\partial}{\partial x}(x^2\kappa\frac{\partial\tilde{g}}{\partial x})$$

$x = r/a$: co-expanding coordinate, a = expansion factor, $y = \ln p$

CRASH code in 1D spherical geometry: **Kang et al. 2013**

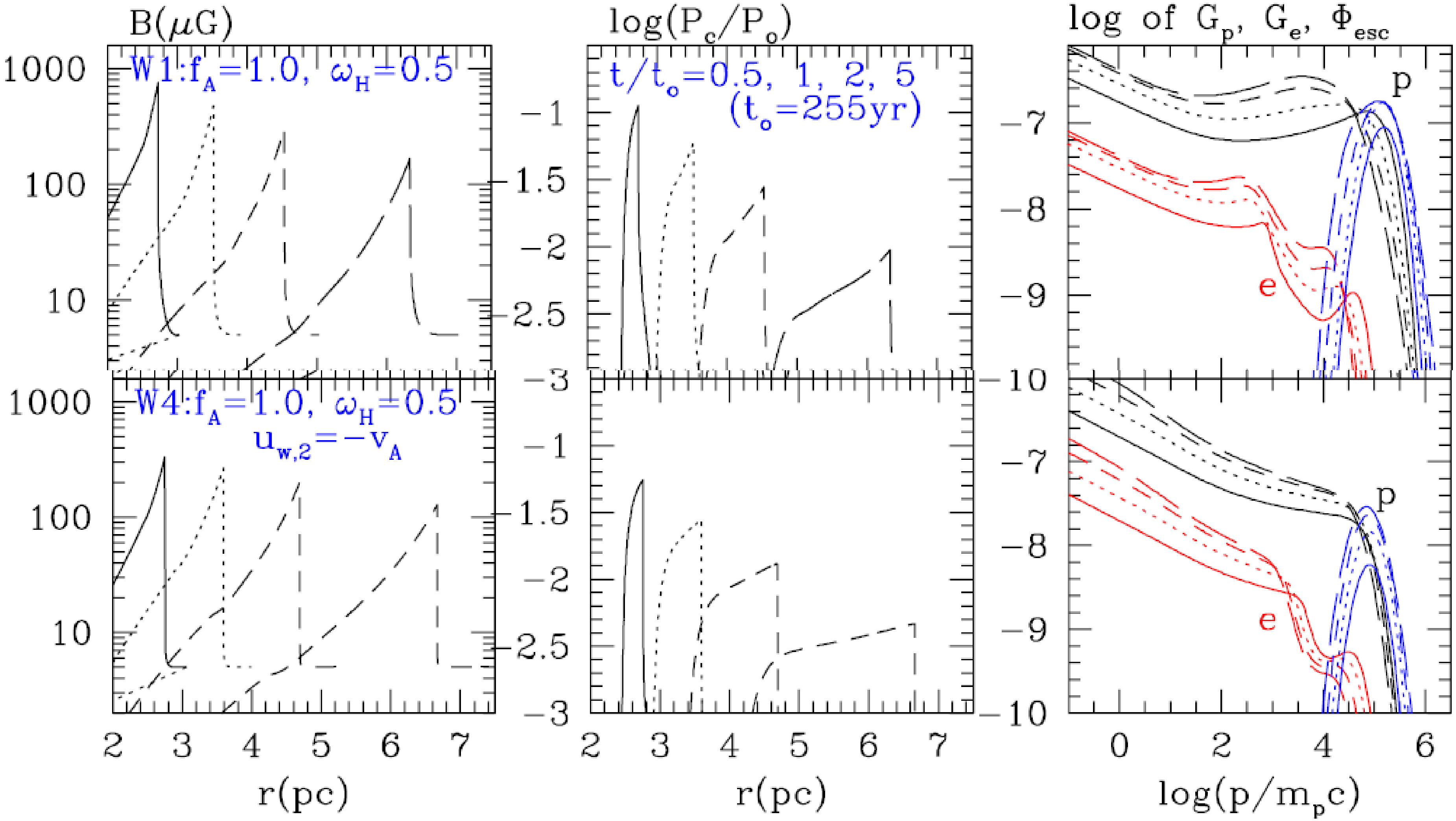
The expansion factor, $a(t)$, is defined so that the shock position, $x_s = \text{constant}$, in co-expanding coordinate, while $r_s(t) \equiv a(t) \cdot x_s$ expands in physical coordiate



The shock position is fixed in the co-expanding frame.

Type Ia SNR Model： 1D spherical CRASH

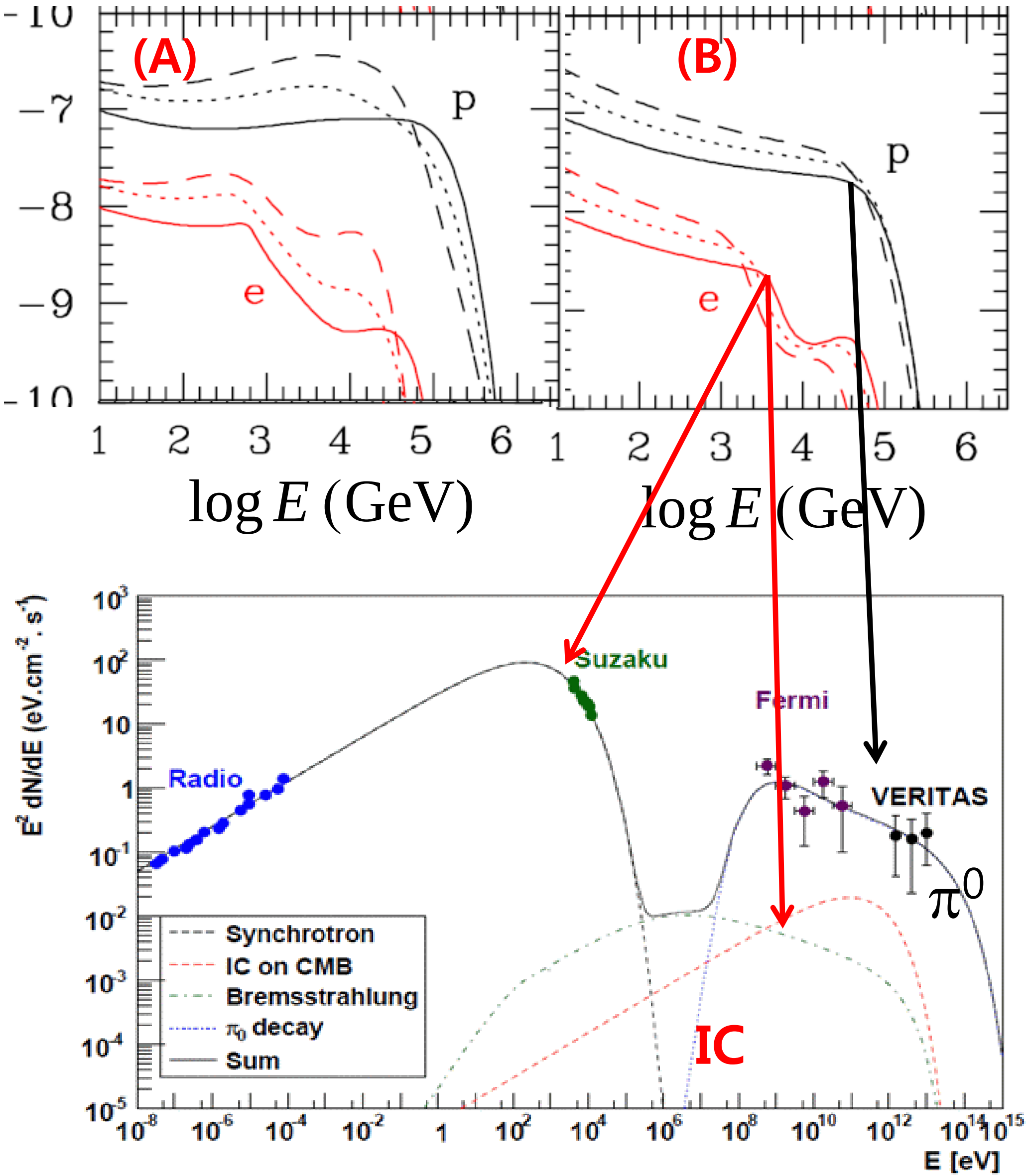
$M_{ej} = 1.4\,M_{\Theta}, \quad E_o = 10^{51}\ \text{ergs}, \ n_{ISM} = 0.3\,\text{cm}^{-3}, \ T_0 = 3\times10^4\ \text{K}, \ B_0 = 5\mu\text{G}$



Two different models for B(x) and AD

$$G(p) = \int_{r_i}^{r_s} 4\pi \cdot f(p)\,p^4 \cdot r^2 dr$$

$E^2 N(E)$: volume integrated CR spectrum depends on $B(r)$ model.

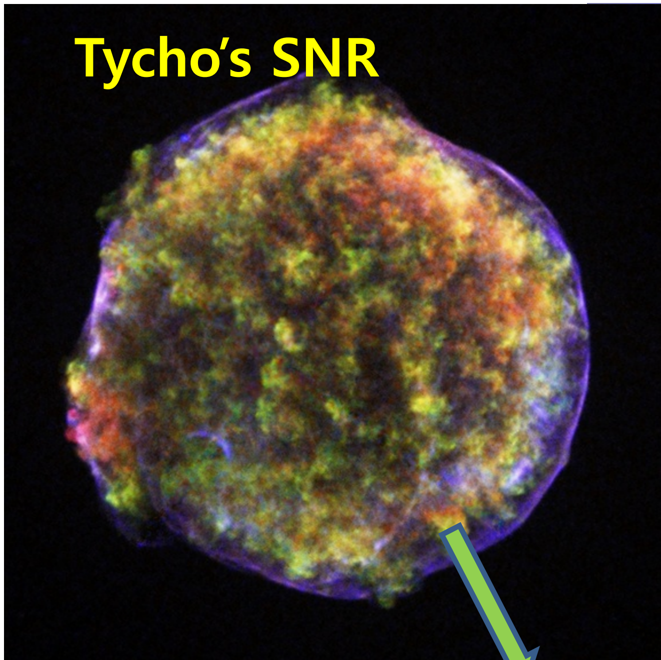


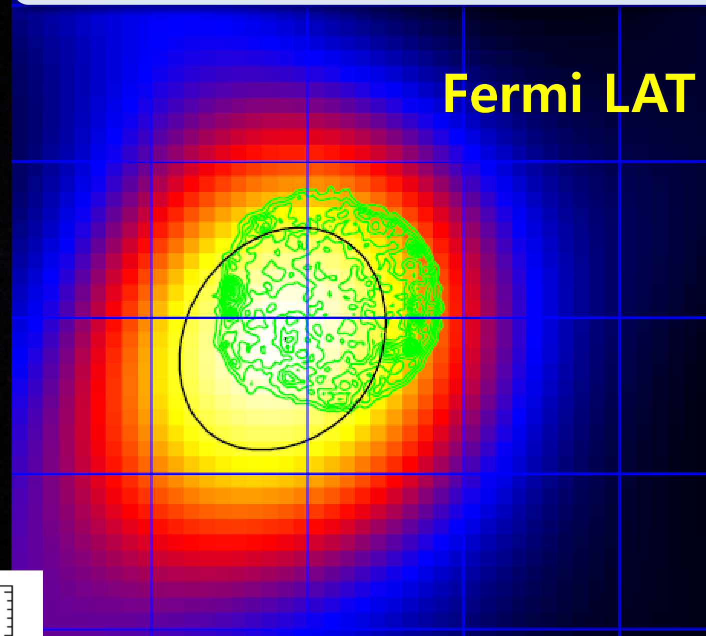
time - dependent evolution of
$B(r,t) \Rightarrow V_A(r,t) \,\&\, \kappa(p,r,t)$
$\Rightarrow q$: slope
$\& \; E_{\max,p}, \;\; E_{\max,e}$ (cooling)

So details of DSA modeling are important in predicting nonthermal emission from SNRs.

Highest energy end of CR spectra determines keV, GeV-TeV emission.

Nonthermal emission from Tycho's SNRs



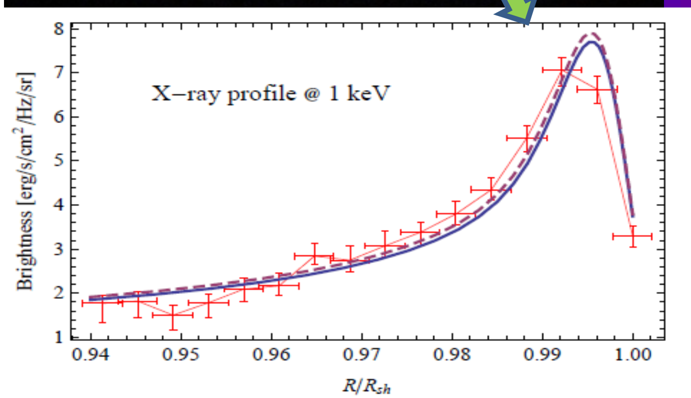


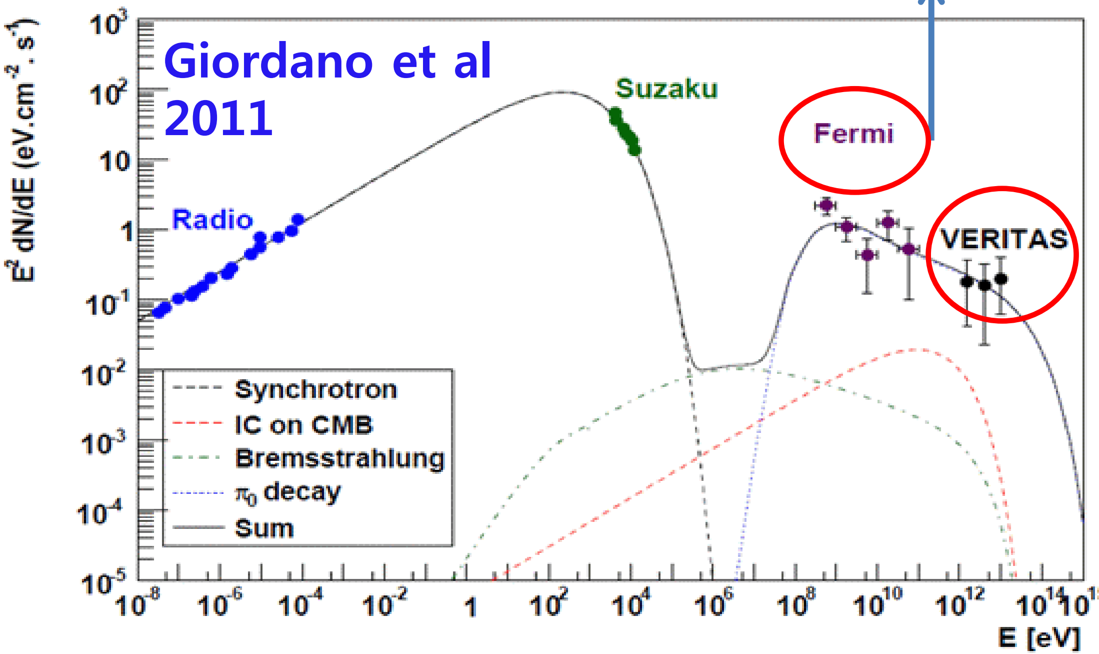
Proton spectrum

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

$$B_2 \sim 200\mu G$$

π^0 decay emission





Projected X-ray emission

➔ B_2=100-500 μG

➔ Magnetic Field Amplification at shocks

Summary: Take-home messages

-Wave-particle interactions are important in DSA theory:
So Various plasma instabilities, MFA, Alfvenic drift, pre-heating of protons/electrons should be studied further by plasma simulations.

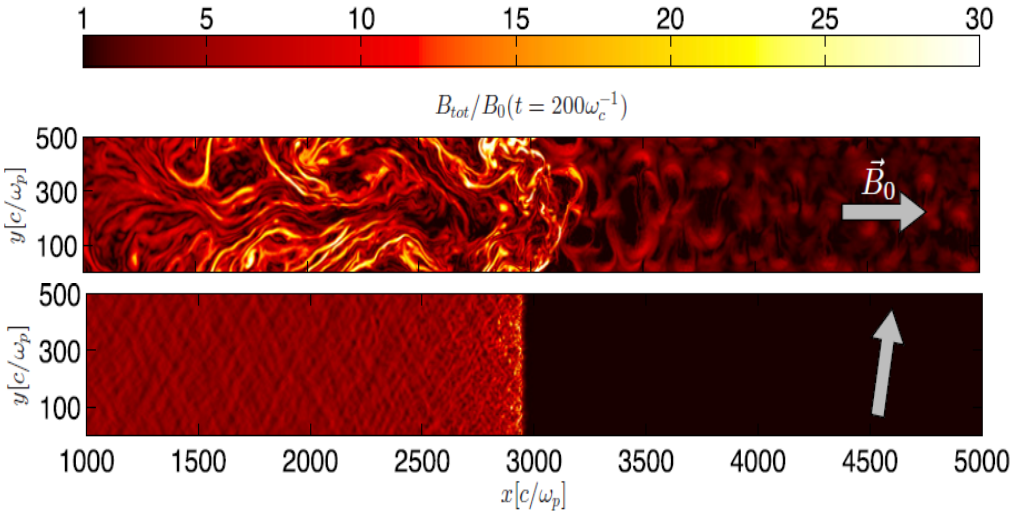
➔ provide phenomenological models for DSA simulations

-Detailed plasma physics of DSA are important in predicting nonthermal emission from SNRs.

➔ Testing "SNR hypothesis for the origin of Galactic CRs"

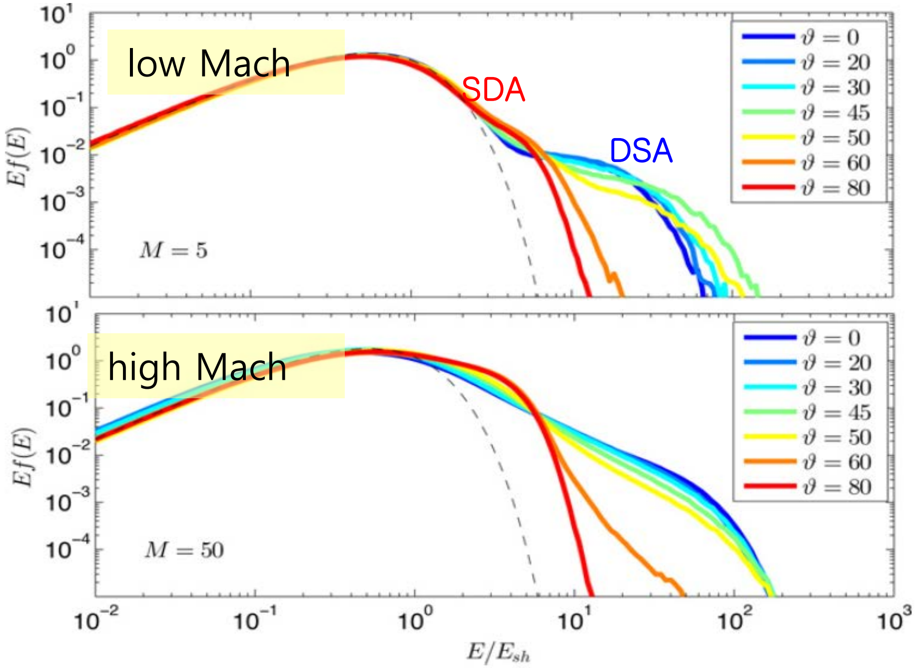
Proton acceleration at shocks: 2D Hybrid simulation

Caprioli & Sptikovsky 2014



At parallel shocks, stream of accelerated protons into upstream
→self-generated waves
→Turbulent B amplification

At perpendicular shocks
No accelerated protons into upstream
→No turbulent waves



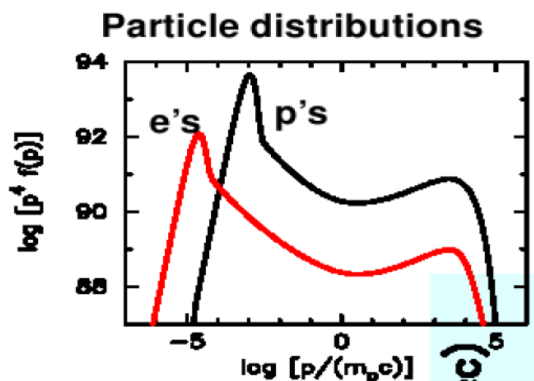
DSA=Diffusive Shock Acceleration at quasi-parallel shocks $(\theta_B < 45^\circ)$

SDA=Shock Drift Acceleration at quasi-perpendicular shocks $(\theta_B > 45^\circ)$

At quasi-parallel shocks
-CR acceleration efficiency
~10-20% in energy
-CR injection efficiency
~10^{-3} in number

Nonthermal radiation from CRs accelerated at SNR shocks
➔ provide observational evidence and constraints for CR acceleration.

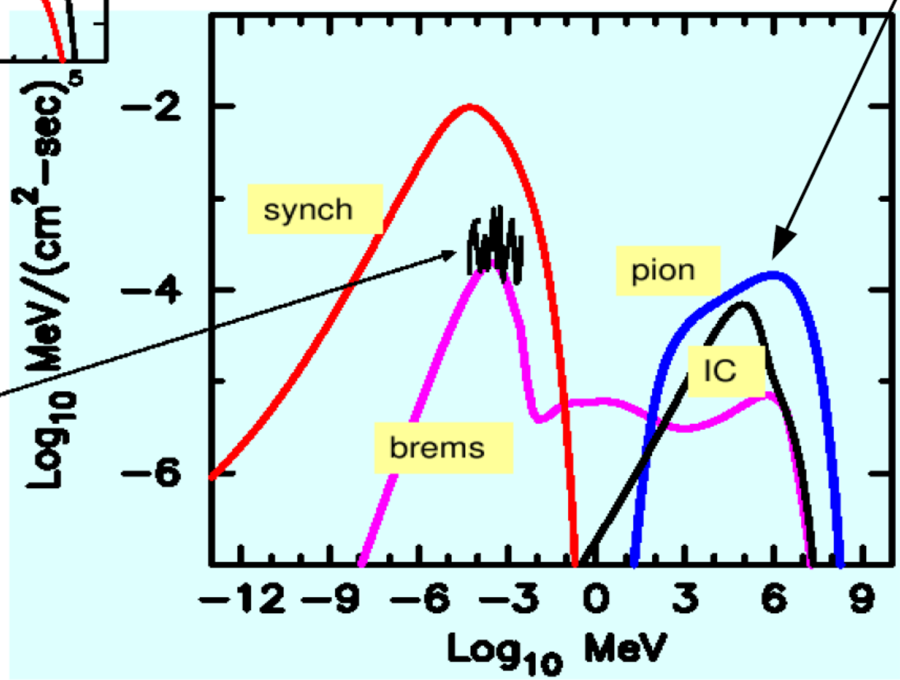
- -CR e + B field → Synchrotron (radio – X-ray)
- -thermal & non-thermal bremsstrahlung
- -CR e + CMBR → Inverse Compton scattering →TeV γ-ray
- -CR p + p→ π^0 decay → 100 GeV γ-ray



(nonlinear DSA)

continuum emission

Pion decay and IC are competitive mechanisms



In addition, emission lines in thermal X-rays

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

From Ellison's talk

Numerical Methods to study Particle Acceleration

***Monte Carlo Simulations with a scattering model:**

$$\lambda \propto \frac{R^\alpha}{\rho} = \lambda_0 \left(\frac{A}{Q}\right)^\alpha \left(\frac{v}{u_2}\right)^\alpha \left[\frac{\rho_2}{\rho(x)}\right],$$

- scattered with a prescribed scattering model,
- assume a steady-state shock structure with FEB

e.g. Ellison, Baring, Jones, Vladimirov +

***Semi-analytic approach**

- analytical solution of the stationary diffusion–convection equation
  + gasdynamic conservation equations

e.g. Blasi, Amato, Caprioli, Molino +

***Time-dependent diffusion-convection Simulations**

- diffusion approximation based on isotropy of particle distribution
- follow time dependent evolution of *f(x,p,t)* + gasdynamics Eqs

e.g. Berezhko et al., Kang & Jones

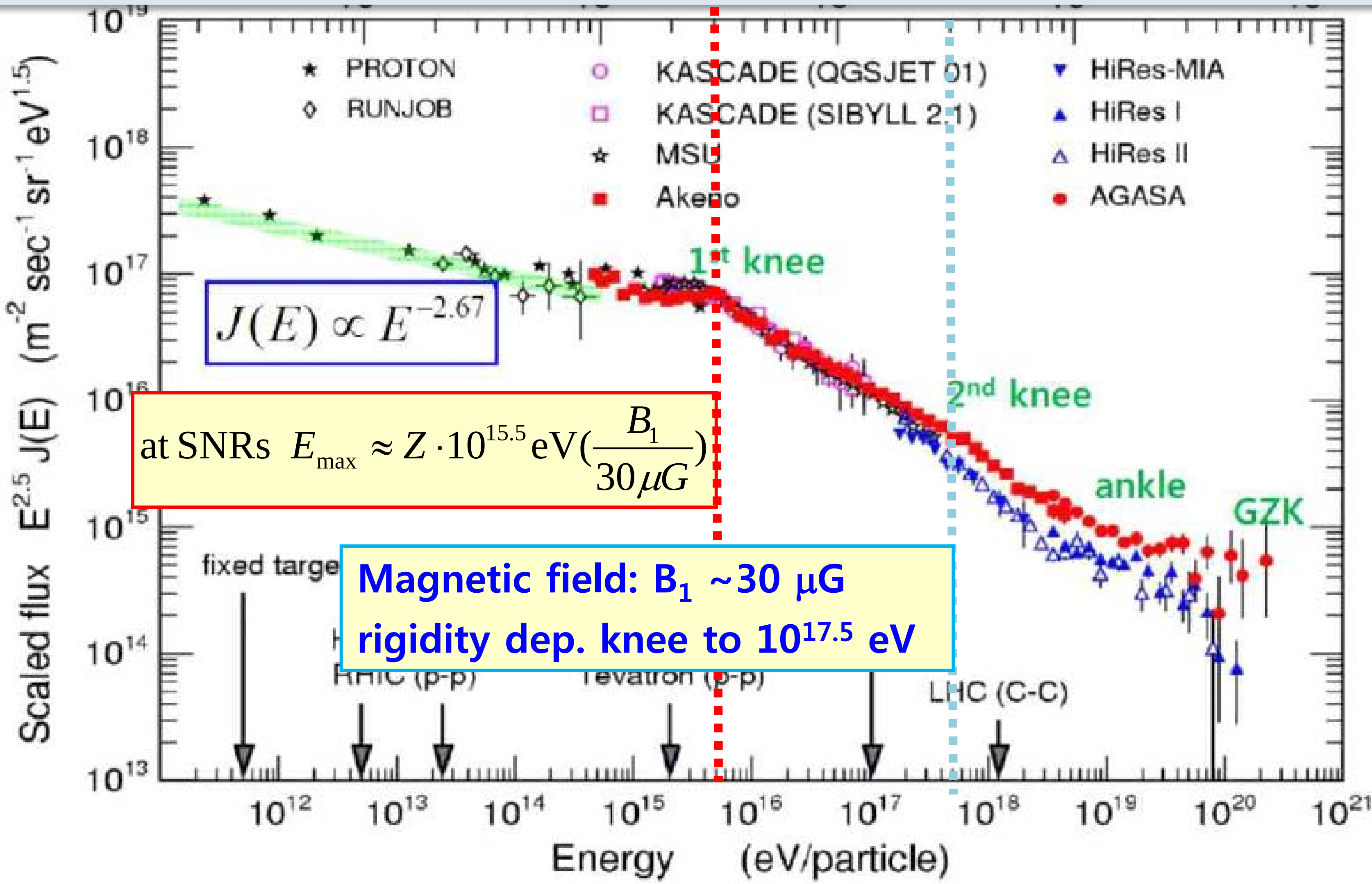
***Full PIC & Hybrid plasma simulations: 3D is required, non-relativistic**

- follow individual particles and magnetic fields
- provide the most complete pictures, but very expensive

PIC (Amano & Hoshino 2012; Riquelme & Spitkovsky 2011, Guo + 2014, Kato 2014)

hybrid (Giacalone 2013; Gargate & Spitkovsky 2011, Caprioli & Spitkovsky 2014)

Energy Spectrum of Cosmic Rays are power-law of $\sim E^{-3}$



Below~$10^{17.5}$ eV: Galactic CRs are nuclei accelerated in SNRs
if magnetic fields are amplified to B_1 ~30 μG at the shock.