Cosmic ray acceleration in supernova remnants

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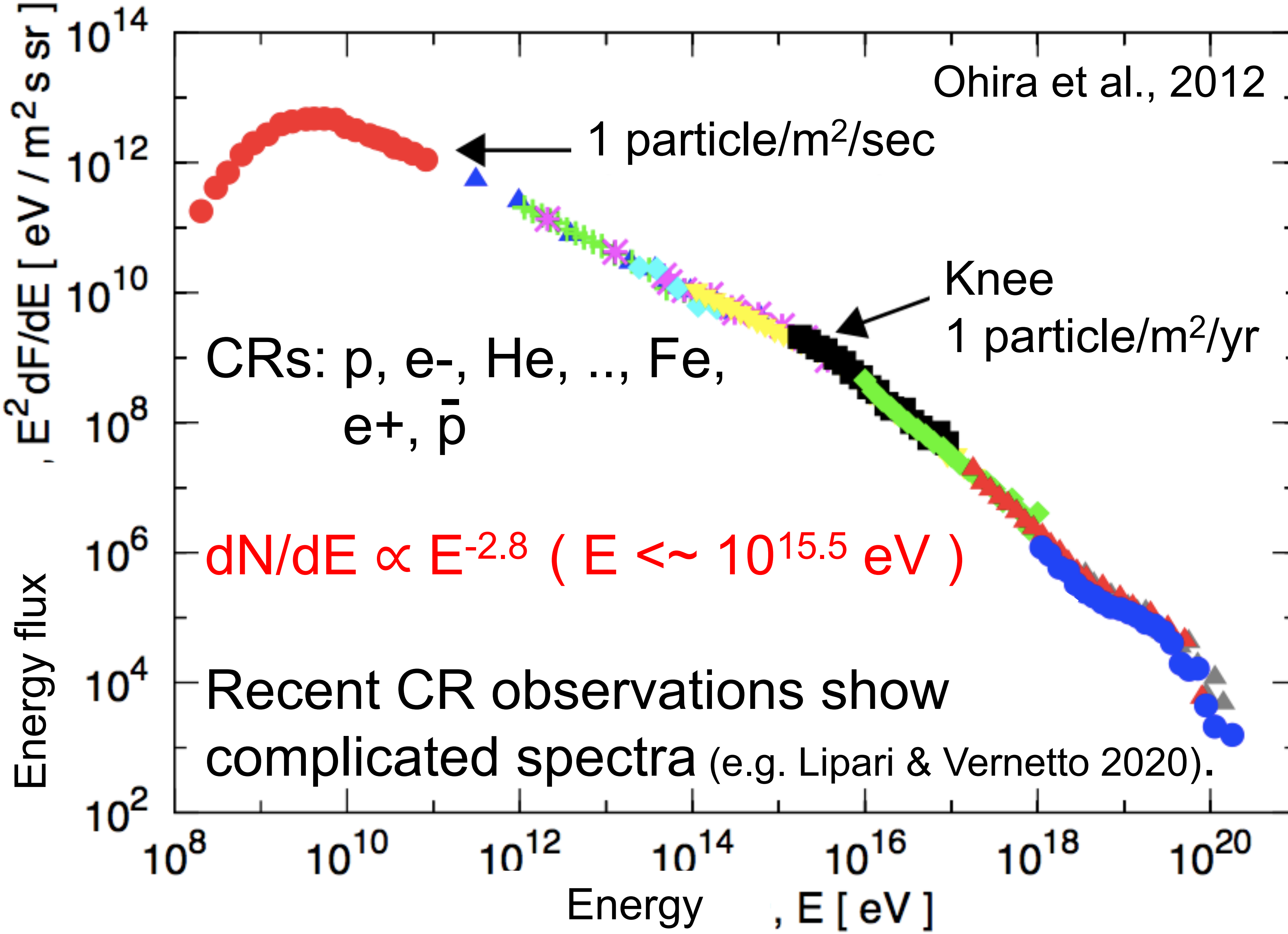
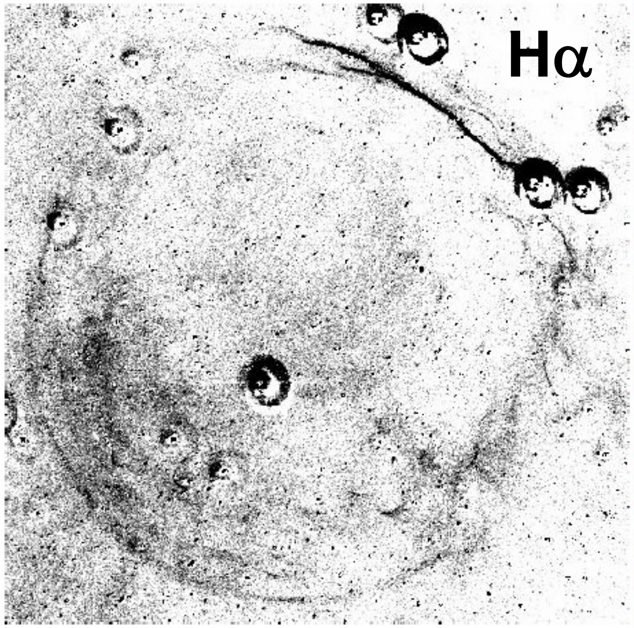
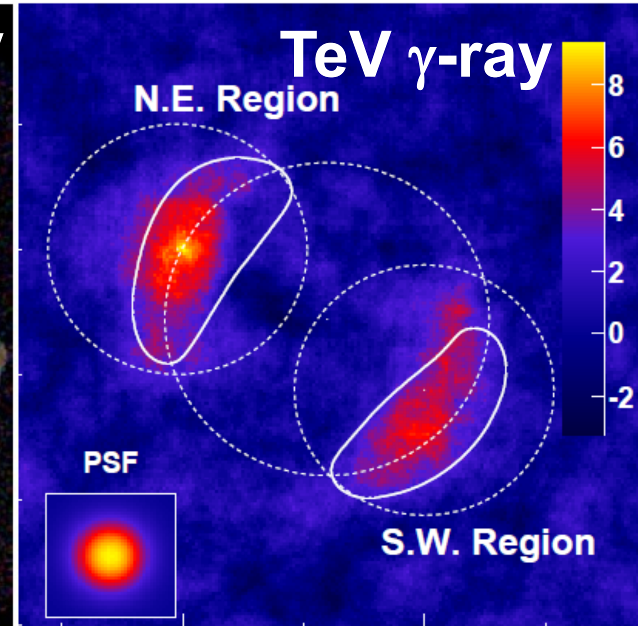
Cosmic-ray spectrum in the current universe



SuperNova Remnant (SNR) and Diffusive Shock Acceleration (DSA)

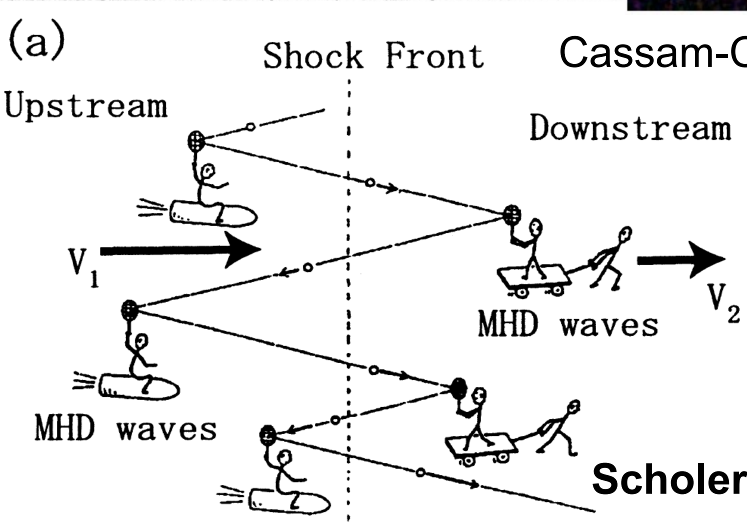
SNRs are remnants of the explosion of a star.





Cassam-Chenai et al. 2008

Acero et al. 2010



Diffusive Shock Acceleration (DSA)

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

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

Origin of Galactic cosmic rays

SNR shocks are thought to be the accelerator of GCRs.

However, we don't know

What type of SN accelerate GCRs,

type Ia, Ib/c, IIp, IIb, ... , all?

Is it isolated or in a superbubble?

Which shock accelerates GCRs,

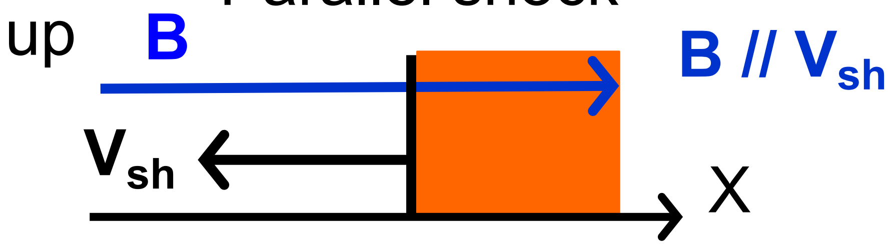
forward shock or reverse shock?

Which shock accelerates GCR,

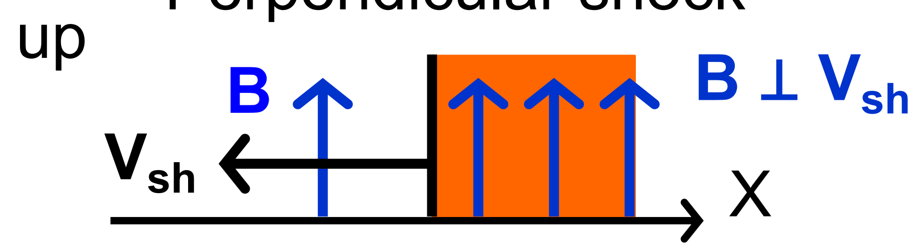
parallel shock or perpendicular shock?

DSA at parallel and perpendicular shocks

Parallel shock



Perpendicular shock



Injection

Parallel shock: Particles can easily go back to upstream region.

Perpendicular shock: Low energy particles cannot go back to upstream region (Jokipii1987).

H atoms help the injection. (Ohira2012,2013,2016)

Spectral index

Parallel shock: For $U_{CR} << \rho V_{sh}^2$, s = 2.

For $U_{CR} >\sim 0.1\rho V_{sh}^2$, ??? ?

Perpendicular shock: For $\delta B_{down} << B_0$, s >> 2. (Takamoto & Kirk 2015)

For $\delta B_{down} >> B_0$, s = 2. (Kamijima, Ohira, Yamazaki 2020)

E_{max}

Parallel shock: For $\delta B \sim B_0 \sim 3\mu G$, $E_{max} << 1PeV$. (Lagage & Cesarsky 1983)

$\delta B_{up} > 100\ \mu G$ is needed. ?

Perpendicular shock: For $\delta B << B_0 \sim 3\mu G$, $E_{max} \sim 1PeV$. (Jokipii1987)

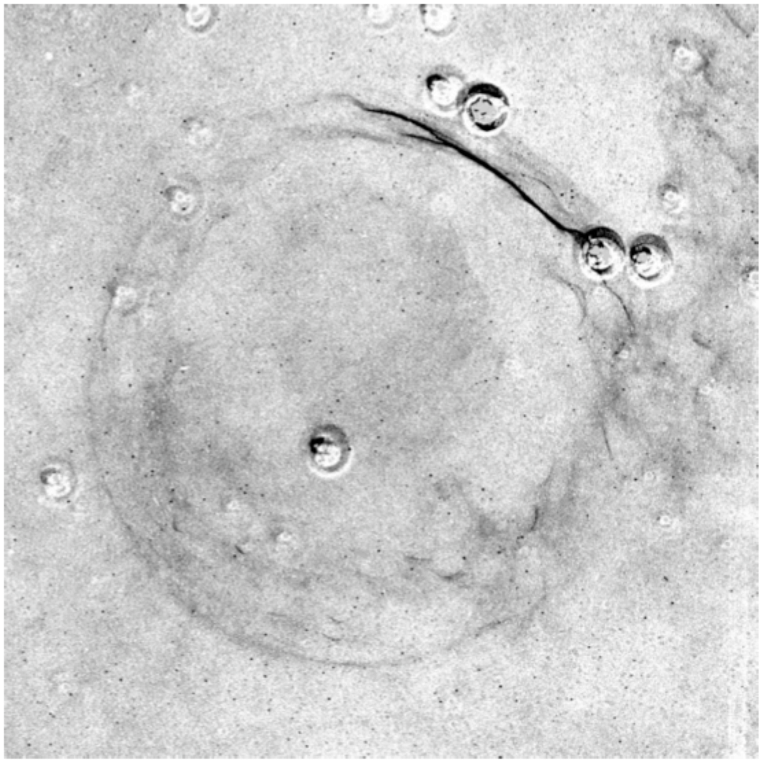
Escape of CRs makes E_{max} small.

$\delta B_{up,subluminal} \sim 10\ \mu G$ is needed.

(Kamijima & Ohira, in preparation)

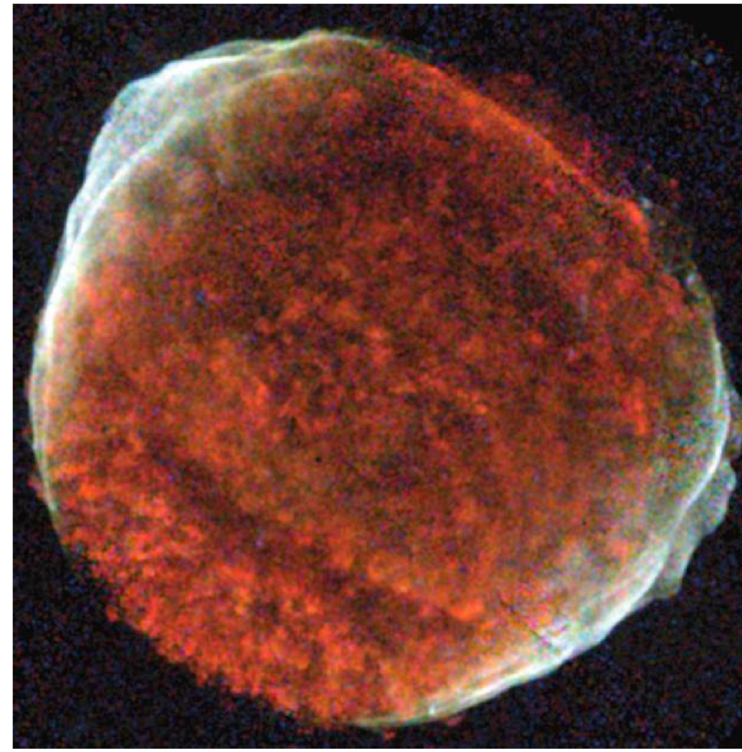
Hydrogen atom around SNRs

Hα



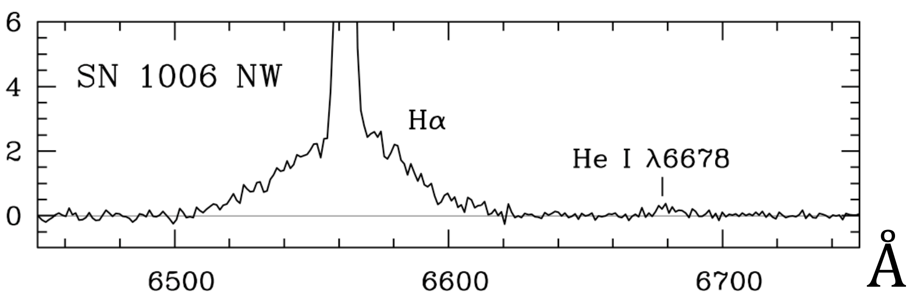
Winkler et al. ApJ 2003

X ray



Cassam-Chenai et al. ApJ 2008

SN1006



$n_H / (n_p + n_H) \sim 0.5$

Ghavamian et al. ApJ 2000, 2002

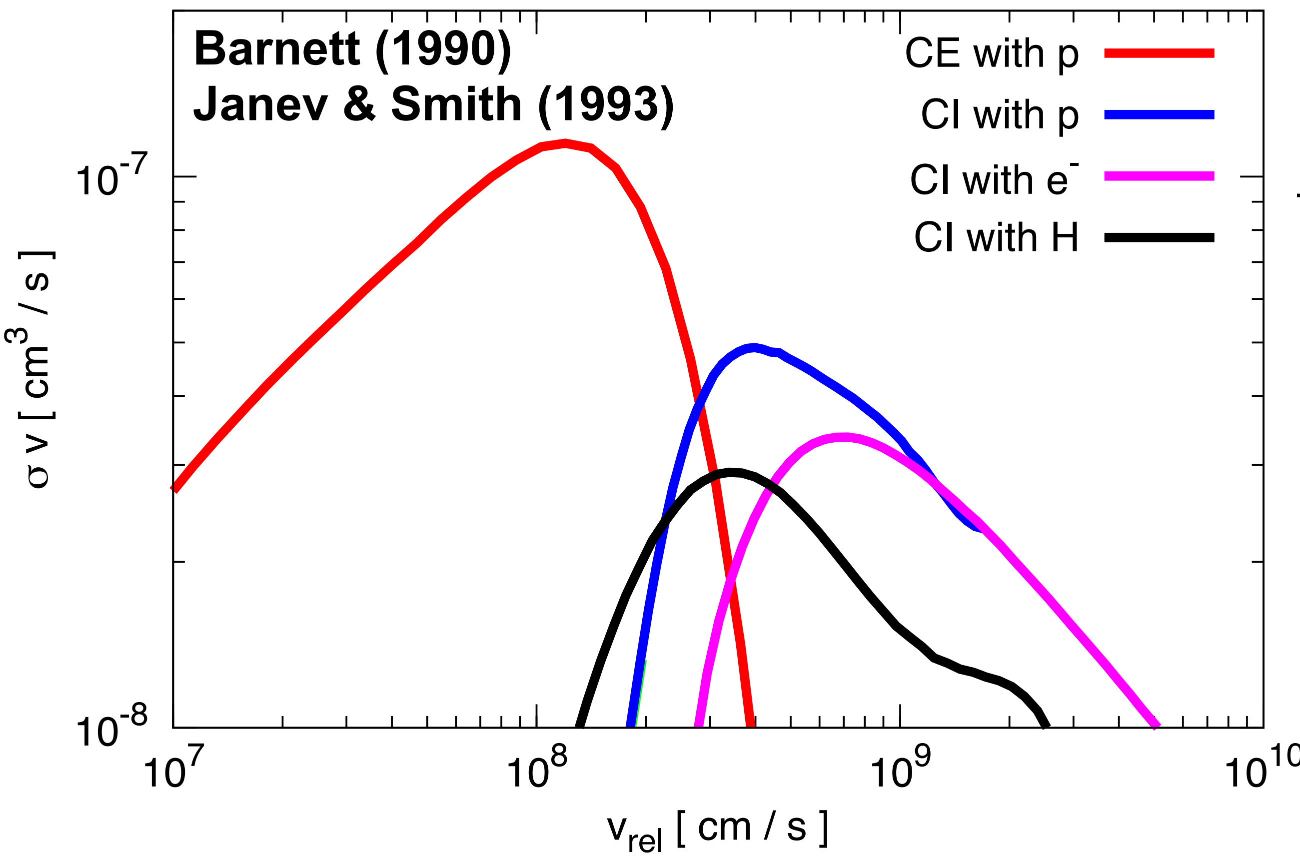
Ionization of Hydrogen atom

Charge exchange with proton $H + p \rightarrow p + H$

Collisional ionization with proton $H + p \rightarrow p + e^- + p$

Collisional ionization with electron $H + e^- \rightarrow p + e^- + e^-$

Collisional ionization with hydrogen atom $H + H \rightarrow p + e^- + H$

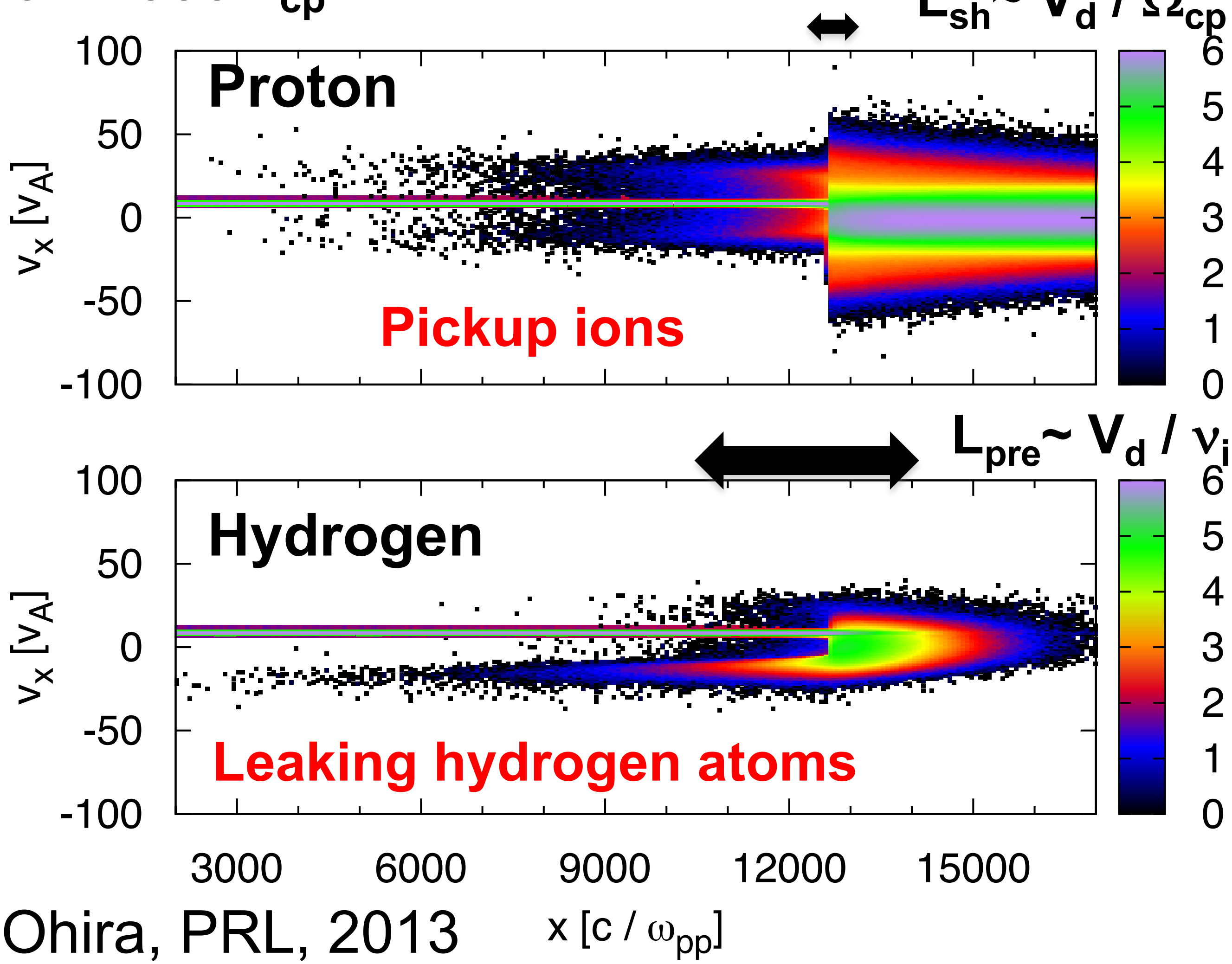


$$\frac{\nu_{ce}}{\Omega_{cp}} \approx 10^{-5} \times \left(\frac{\sigma v}{10^{-7} \mathrm{cm}^3 / \mathrm{s}} \right) \times \left(\frac{n}{1 \mathrm{cm}^{-3}} \right) \left(\frac{B}{3 \mu G} \right)^{-1}$$

Phase space plots ($V_d = 10 V_A = 2000$ km/s)

There are leaking hydrogen atoms and pickup ions in the upstream region.

$t = 2000 \Omega_{cp}^{-1}$



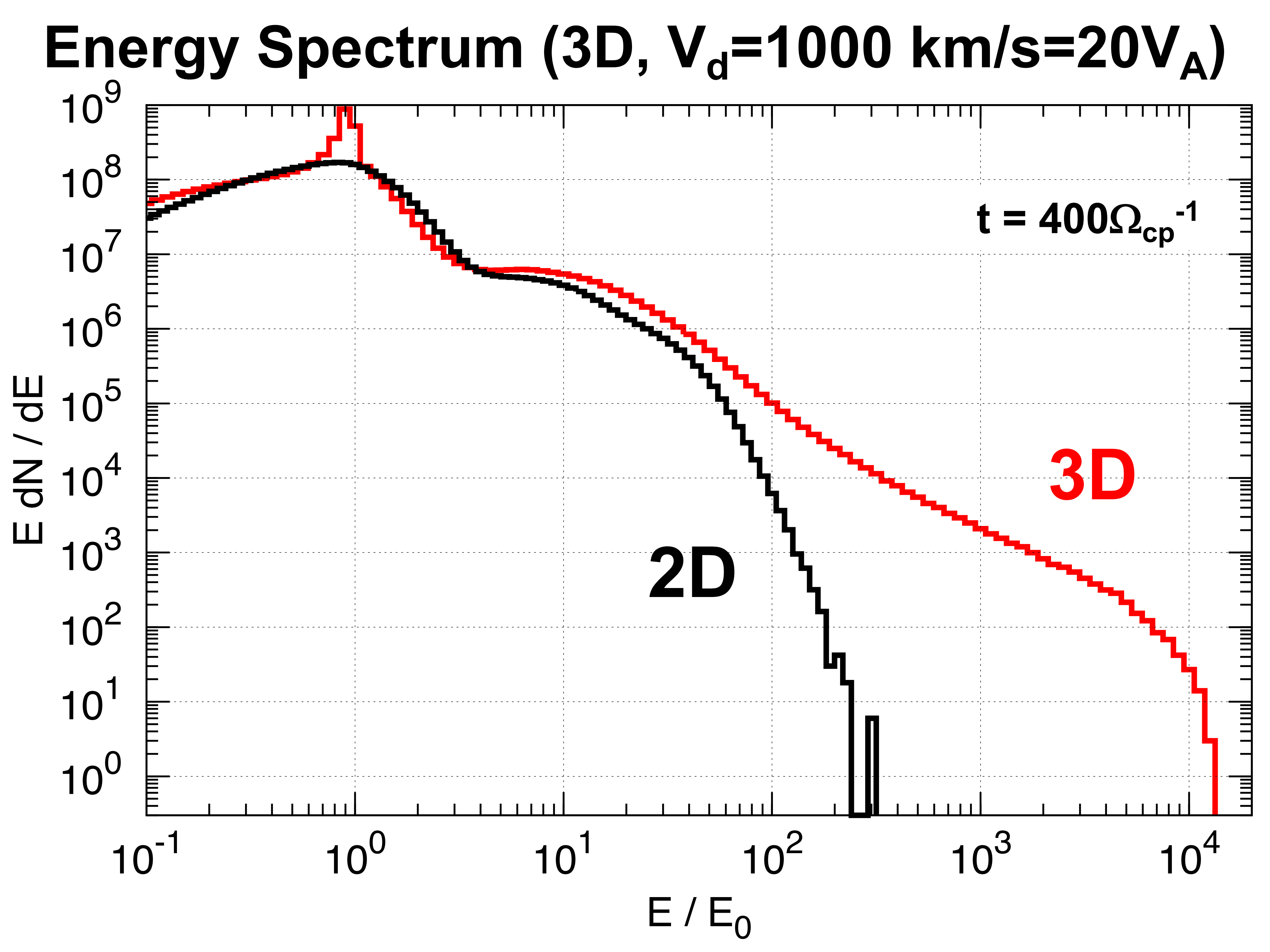
$V_{sh} \sim 13.6 V_A$
~ 2700 km/s
in the upstream frame

$n_{leak}/n_H \sim 0.07$
at the shock front

$u_{leak} / V_{sh} \sim 0.23$
in the shock rest frame

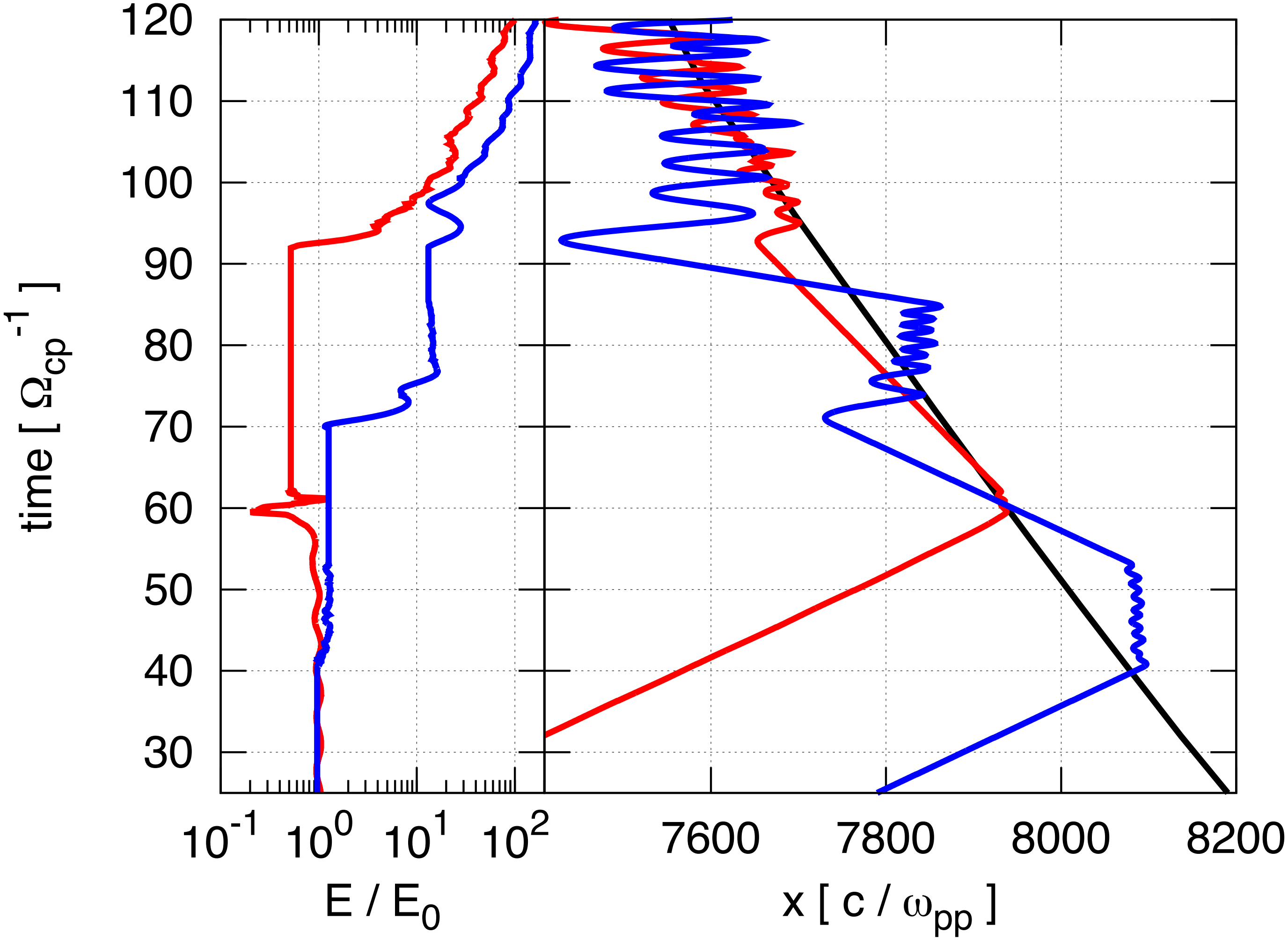
$(nu)_{leak}/(nu)_{up} \sim 0.016$
in the shock rest frame

Ohira, PRL, 2013



Energy Spectrum (3D, V_d=1000 km/s=20V_A)
$t = 400\Omega_{cp}^{-1}$
3D
2D
E dN / dE
E / E_0
10^9
10^8
10^7
10^6
10^5
10^4
10^3
10^2
10^1
10^0
10^{-1}
10^0
10^1
10^2
10^3
10^4

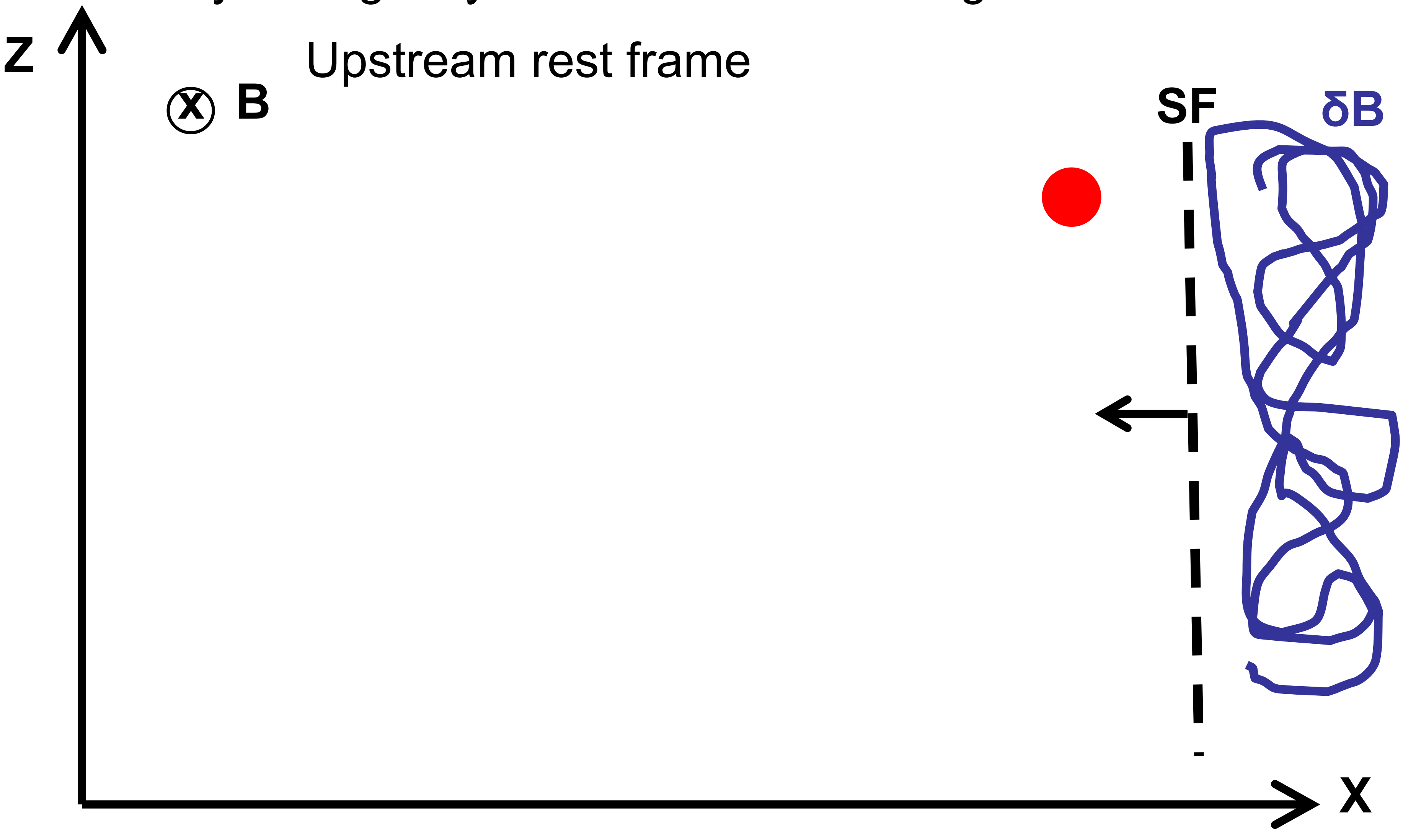
Trajectories of accelerated particles (3D)



Leaking particles are accelerated by the pickup process in the upstream region and the second shock heating. The pre-accelerated particles are injected to DSA at the perpendicular shock.

New picture of DSA at the perpendicular shock

Our simulation shows that the magnetic field fluctuation is very strong only in the downstream region.



New model of DSA at perpendicular shocks

Original model of DSA at perpendicular shocks (Jokipii 1987)

Particles move diffusively both in the upstream and downstream.

To make the acceleration time small, magnetic field fluctuations have to be small both in the upstream and downstream.
Then, the CR spectrum becomes very steep. (Takamoto & Kirk 2015)

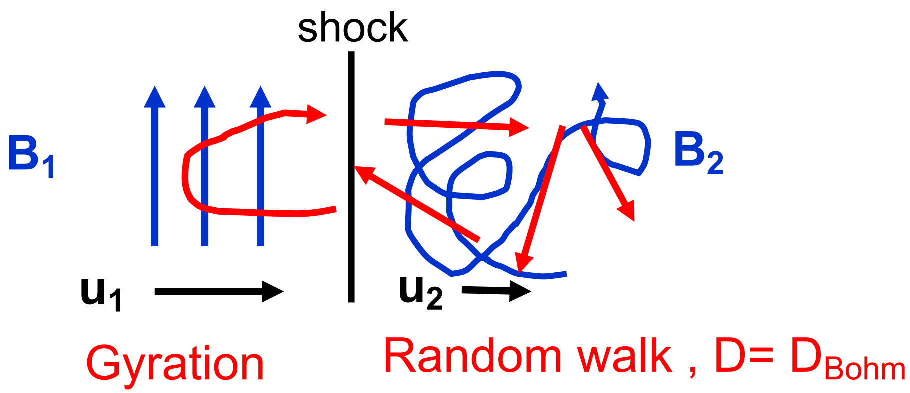
Our new model of DSA at perpendicular shocks (Kamijima et al. 2020)

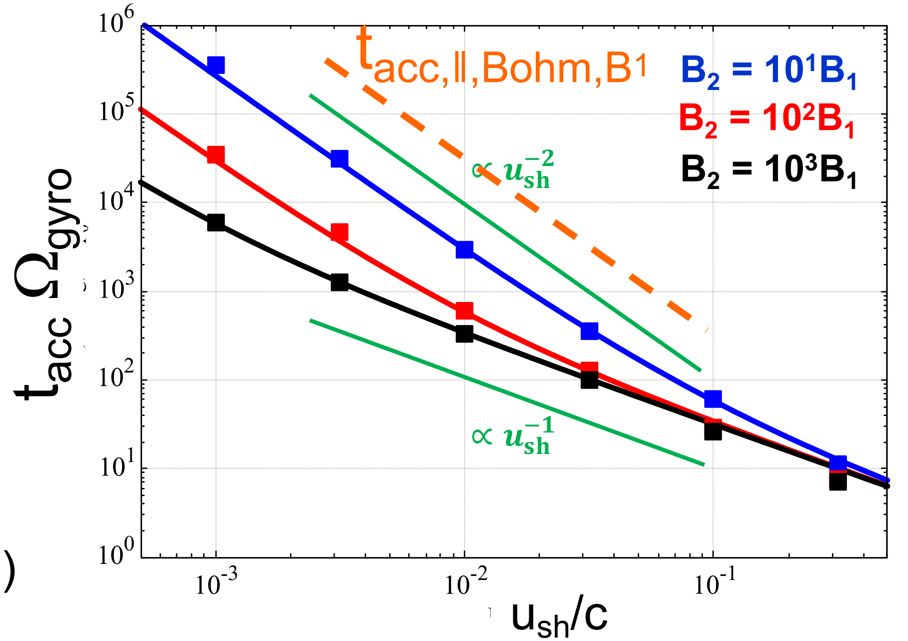
In the upstream, particles gyrate in the uniform magnetic field.

In the downstream, particles move diffusively in the strongly amplified magnetic field.

$t_{acc} << t_{acc,para}$? $dN/dE \propto E^{-2}$?

Test particle simulation in plane shocks



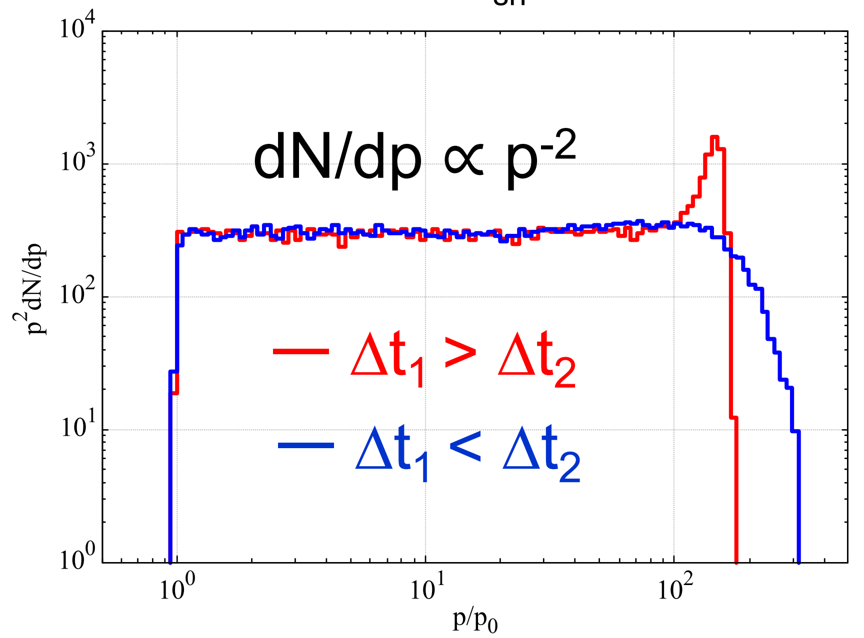


Residence time

$$\Delta t_1 = \pi \Omega_{\mathrm{g},1}^{-1} \qquad \Delta t_2 = \frac{4D_2}{u_2 v} \quad \text{(Drury 1983)}$$

$t_{acc} = (\Delta t_1 + \Delta t_2)p / \Delta p$, $\Delta p = u_1 / v$

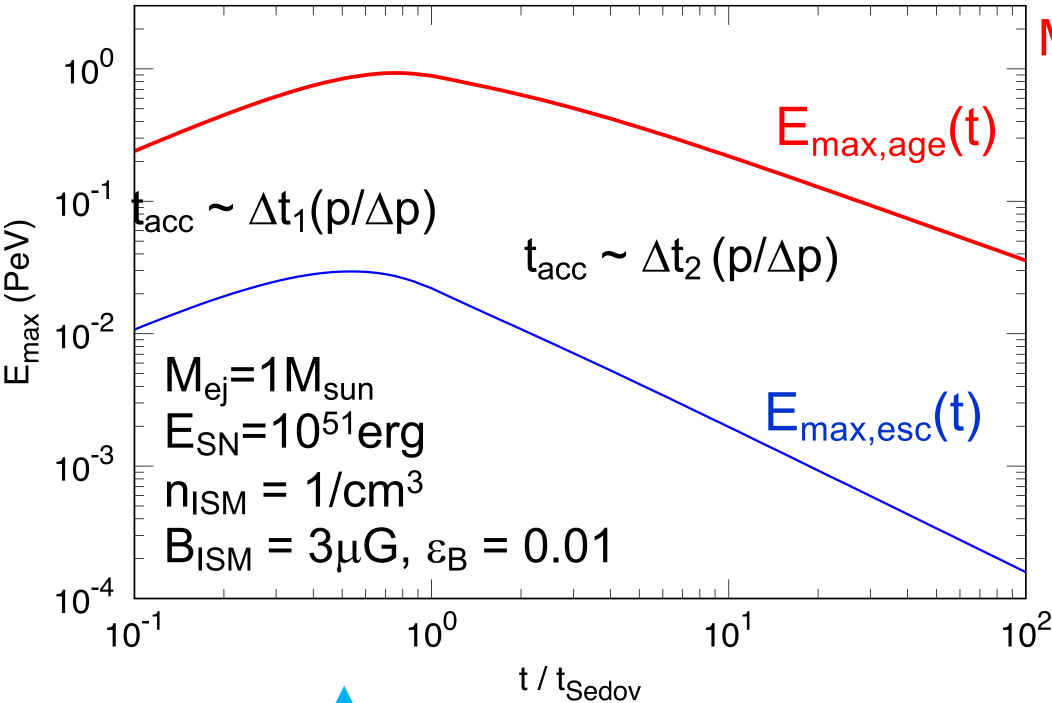
$$t_{\mathrm{acc},\perp} = \pi \left(\frac{u_{\mathrm{sh}}}{v}\right)^{-1} \Omega_{\mathrm{g},1}^{-1} + \frac{16}{3}\left(\frac{B_2}{B_1}\right)^{-1}\left(\frac{u_{\mathrm{sh}}}{v}\right)^{-2}\Omega_{\mathrm{g},1}^{-1}$$



Our model simultaneously realizes the rapid acceleration and the canonical spectrum, $dN/dp \propto p^{-2}$, even if there is no upstream magnetic field amplification.

Kamijima, Ohira, Yamazaki (2020)

E_{max} at the perpendicular shock in SNRs



Maximum energy limited by the age

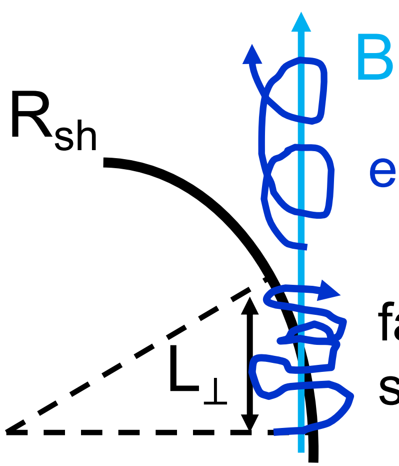
$t_{acc} = t_{age}$

$u_{sh} = u_{sh}(t)$ → $E_{max,age}(t)$

$B_{down}^2/8\pi = \varepsilon_B \times (\rho u_{sh}^2 / 2)$

For type Ia SNe,

$E_{max,age}(t_{Sedov}) \sim E_{knee}$



escape along the B line

fast acceleration in the superluminal region

Diffusion coefficient along the B line = $D_{Bohm,B1}$

Maximum energy limited by escape

$t_{acc} = t_{esc}$

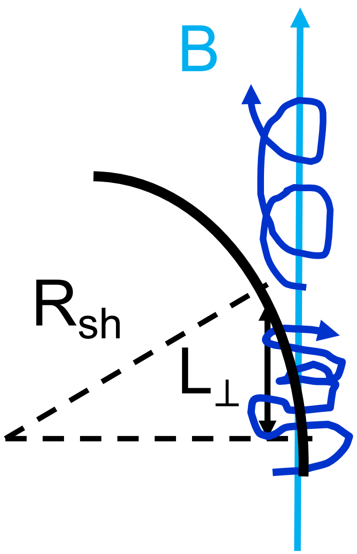
$t_{esc} = L_\perp^2/D_{Bohm,B1}$ → $E_{max,esc}(t)$

$L_\perp = R_{sh} \times (u_{sh}/c)$

$E_{max,esc}(t) << E_{knee}$

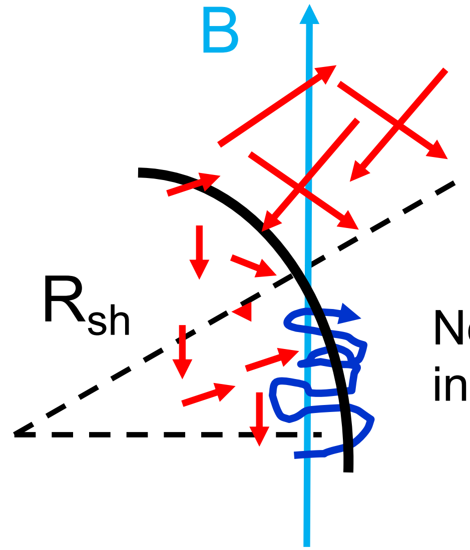
Kamijima & Ohira (in preparation)

Self confinement by streaming instability



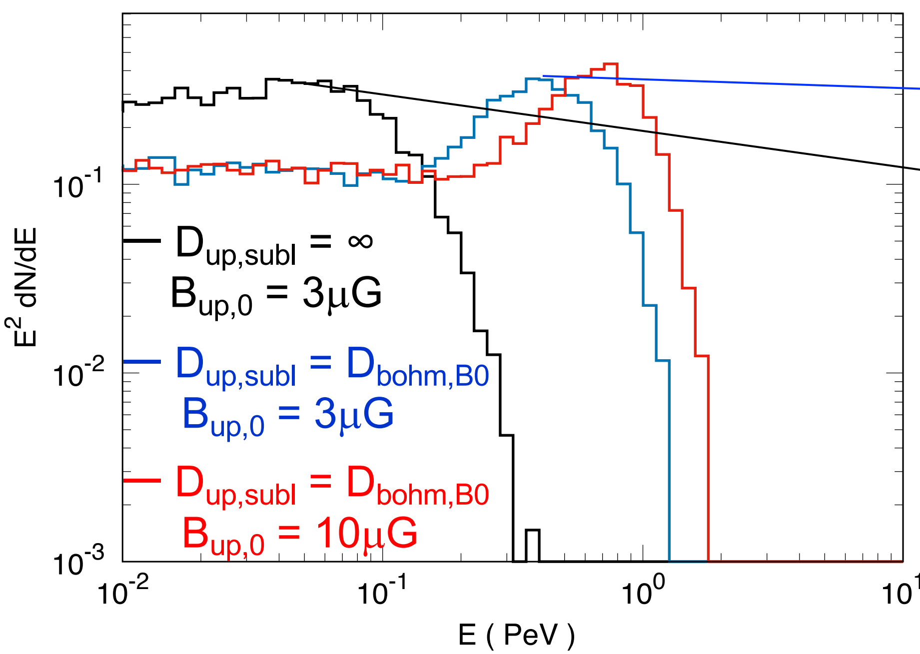
CR streaming instabilities amplify magnetic field fluctuations in the subluminal region.

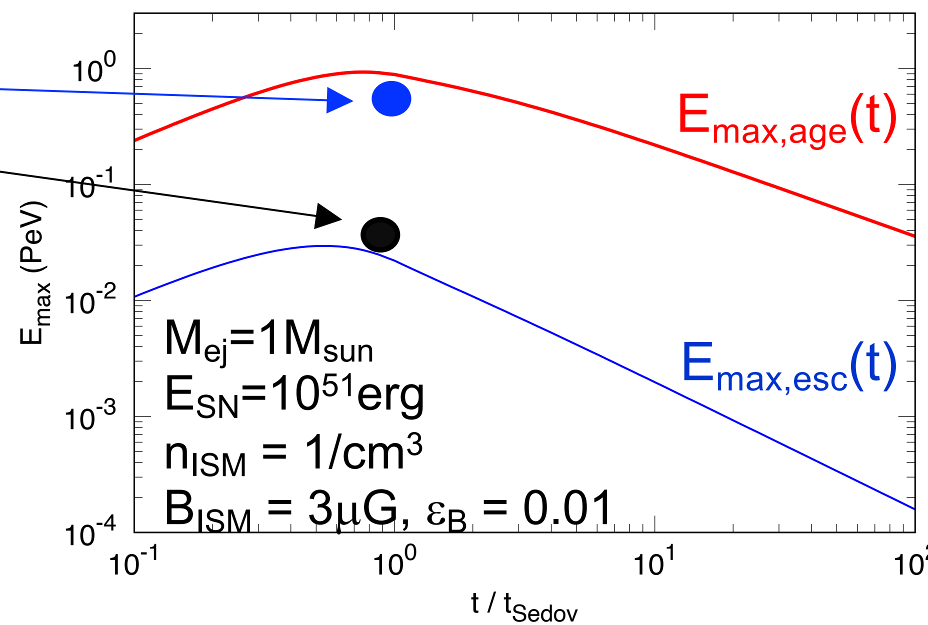
fast acceleration in the superluminal region



Random walk in the subluminal upstream region

No streaming instability





Summary

Perpendicular shocks of SNRs have been thought to be the PeVatron.

However, DSA at the perpendicular shock has the injection problem and spectral problem (Jokipii 1987, Takamoto & Kirk 2015).

We showed that the perpendicular shock in partially ionized plasma can inject particles to DSA (Ohira 2016).

We proposed a new model of DSA at the perpendicular shock, which simultaneously realizes the rapid acceleration and the canonical spectrum, $dN/dp \propto p^{-2}$, even if there is no upstream magnetic field amplification (Kamijima, Ohira, Yamazaki 2020).

We first investigated the escape process of CRs from the perpendicular shock. The escape process reduces E_{max} to 0.03PeV, but if a self confinement by a CR streaming instability works, E_{max} can be the PeV scale even though the upstream magnetic field is smaller than 100 μG (Kamijima & Ohira, in preparation).

What's your targeted physics in next decades?

Constructing a more specific acceleration theory
which includes information of the CR source

Understanding the injection and acceleration site for CR nuclei,
Dust injection?, reverse shock?

What we need to accomplish?

Deep observations of Gamma ray and neutrino at $E > 100$TeV

Precise measurement of CR nuclei at $E \sim 1$PeV

Precise identification of SNR type

Gamma-ray observation with a higher angular resolution $\Delta\theta<0.01^\circ$