Particle Acceleration by Sound Waves Generated in the Shock Downstream Region

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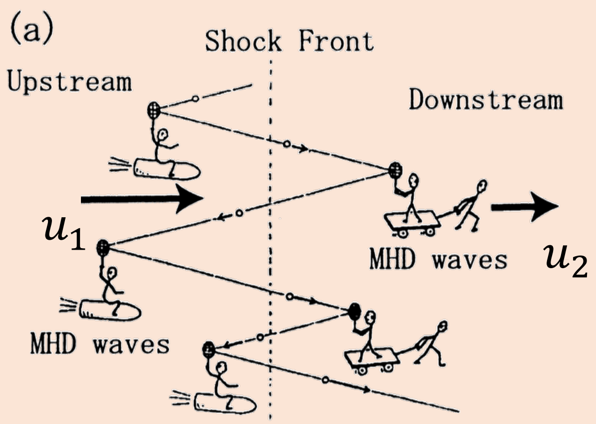
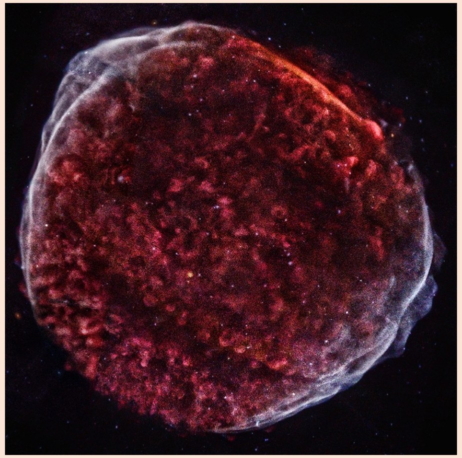
Diffusive Shock Acceleration (DSA)

- Diffusive shock acceleration (DSA) in supernova remnants (SNRs) is recognized as the standard explanation for generation of galactic cosmic rays (CRs) below the knee.
- In DSA, particles gain energy proportional to the velocity difference between upstream and downstream.

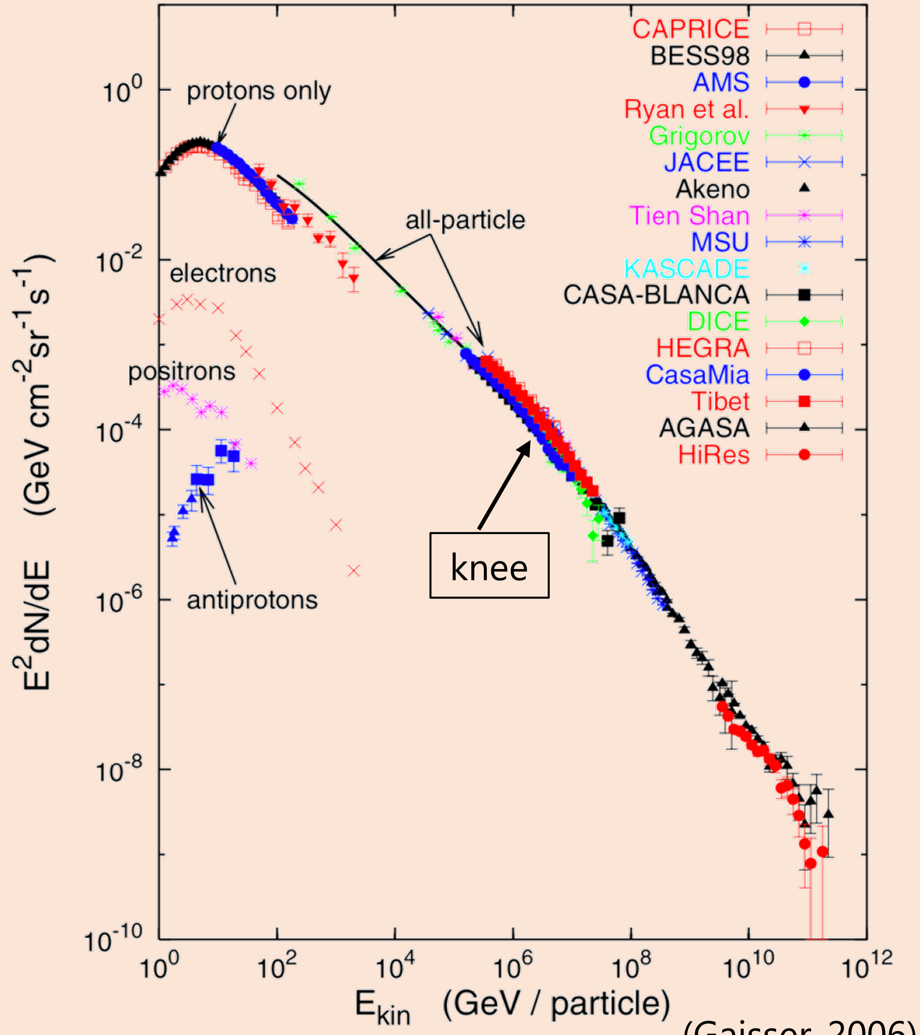
$$\langle \Delta p \rangle = \frac{4}{3}\frac{u_1 - u_2}{v}\, p$$



(Scholer)



(SN1006, NASA)



(Gaisser, 2006)

Problems of DSA

- Although DSA can naturally explain the power-law energy spectrum of CRs with a few reasonable assumptions, several problems are pointed out (e.g. Kirk & Dendy, 2001).
  - ✓ Maximum attainable energy

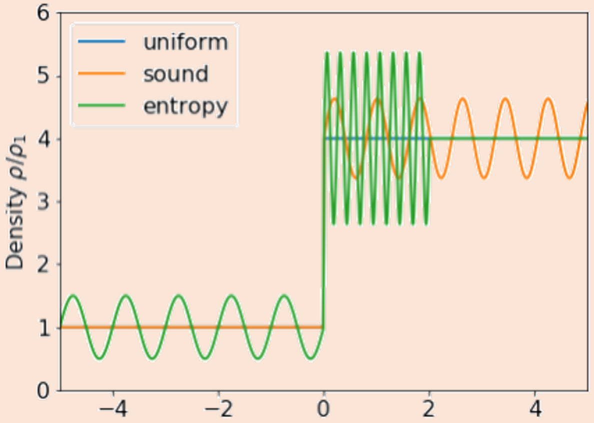
    The maximum energy achieved in typical supernova remnants does not reach the highest energy of galactic CRs (knee energy, $10^{15.5}\mathrm{eV}$).
  - ✓ Spectral index

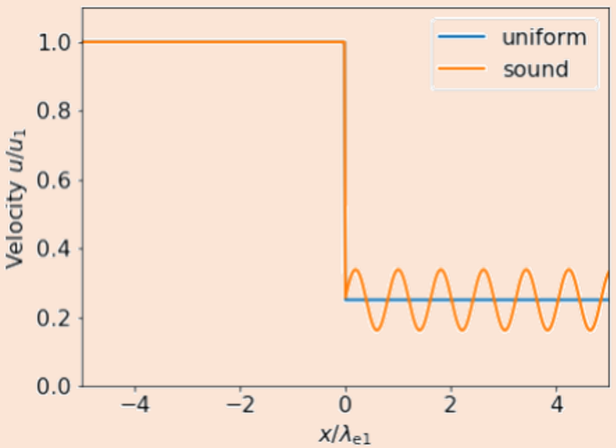
    Although DSA uniquely predicts the spectral index to be $s = 2$, it is not always consistent with that observed on the Earth ($s \sim 2.7$) and those estimated from radiation from supernova remnants.
  - ✓ Injection problem

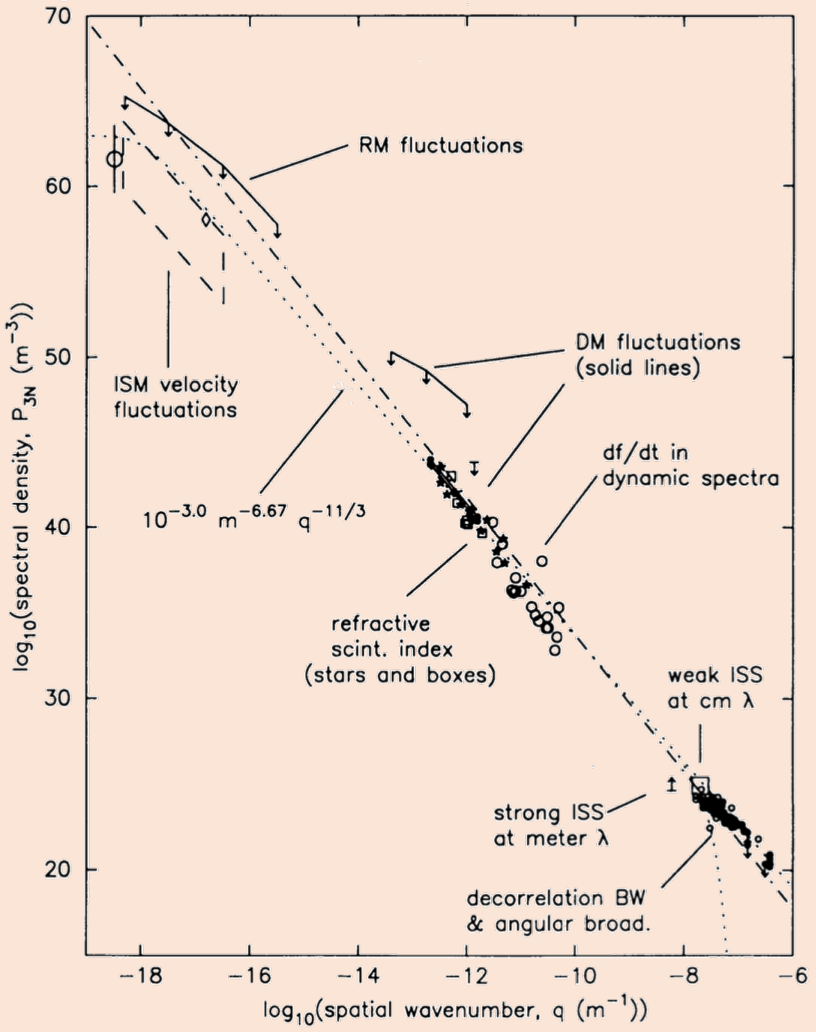
    DSA assumes the existence seed high-energy particles which freely cross the shock transition region. Pre-acceleration of such seed particles is not fully understood.
- We need some modifications to resolve these problems.

Medium inhomogeneity

- Inhomogeneity in the medium is not included in the standard DSA, although its existence is confirmed by observations (e.g. Ferrière, 2020)
- In our previous work, we investigated the influence of medium inhomogeneity on particle acceleration (Yokoyama & Ohira, 2020).
- We made test-particle simulations for cosmic rays, while linear analytical solutions are used for the description of background plasma.
- When the shock wave propagates through an inhomogeneous medium, **sound waves** are generated behind the shock.







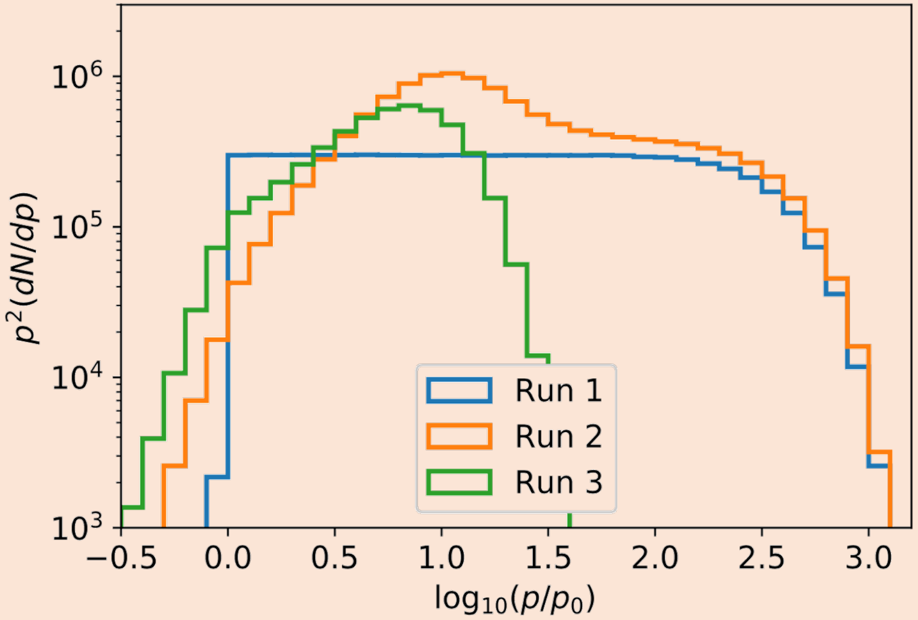
(Armstrong et al., 1995)

Particle acceleration by sound waves

- Spectrum of DSA is significantly modified when there are density fluctuations in the shock upstream (orange spectrum)
- Particles are accelerated by downstream sound waves even when they cannot cross the shock (green spectrum).
- Acceleration mechanism in the shock downstream is identified as second-order acceleration, where particles are stochastically accelerated by local velocity difference δu_2.

$$\frac{\langle \Delta p \rangle}{p} \propto \left(\frac{\delta u_2}{v}\right)^2$$

- This work does not include the nonlinear evolution of sound waves.



(Yokoyama & Ohira, 2020, ApJ)

$$u_{\rm sh} = 0.01\,c,$$
$$M_1 = 100,$$
$$\delta\rho_1 = 0.5\,\rho_1,$$
$$\lambda_{\delta u_2} = 200\,\lambda_{\rm mfp}(p_0)$$

Simulations in this work

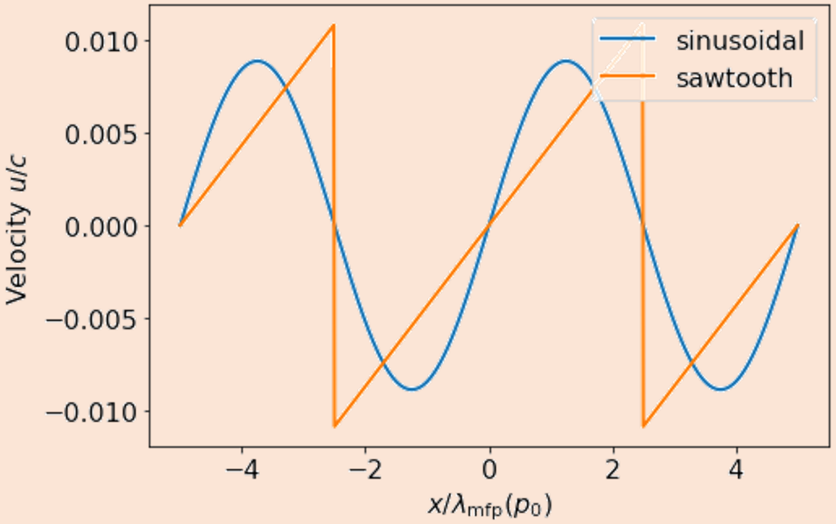
- In our previous simulations, nonlinear evolution of sound waves is not included.
- **Steepening** into weak shock waves and **dissipation** can influence particle acceleration in the shock downstream region.
- We investigate the effects of nonlinear evolution of sound waves by the following simulations:

1. Test-particle simulations which solve particle diffusion under sawtooth waves.

   Weak shock waves generated by steepening are imitated by analytical sawtooth velocity field (The right figure).

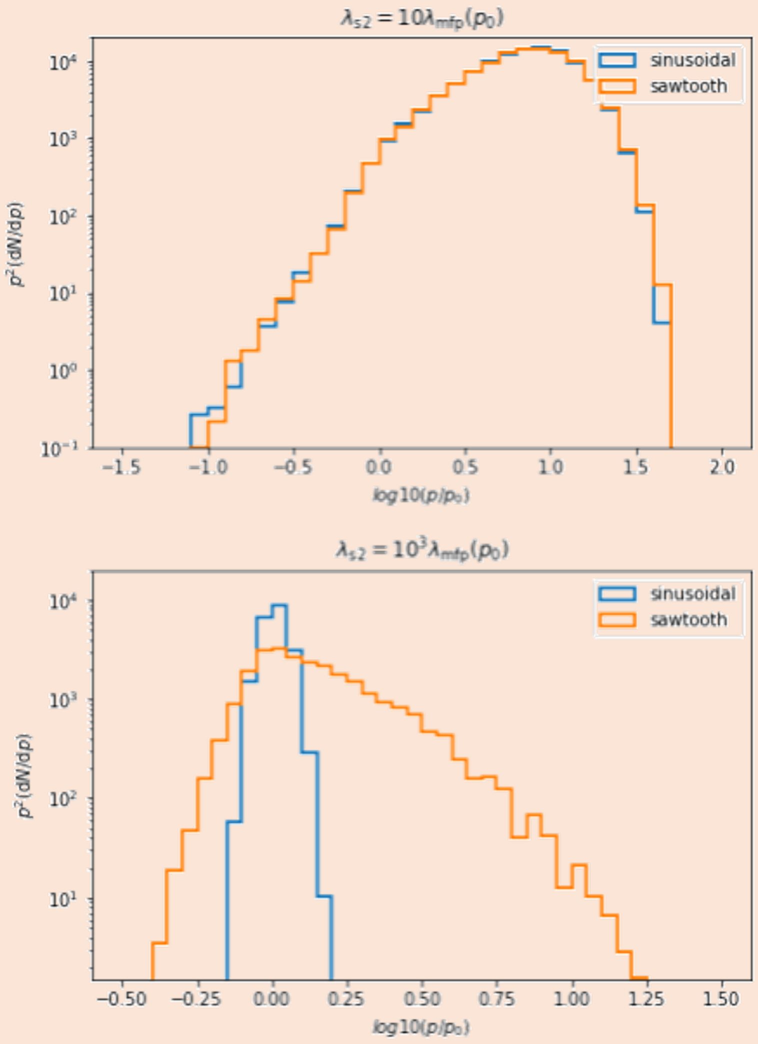
2. Test-particle simulations which numerically solve both particle diffusion and shock propagation into an inhomogeneous medium.

   Fluid equations which describe the evolution of the background plasma are also solved numerically.



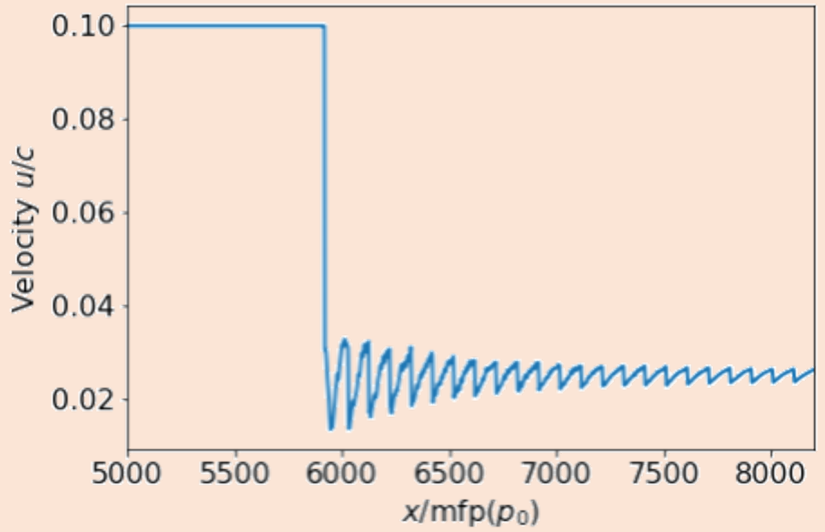
Results of simulation 1

- Parameters: $u_{sh} = 0.1c$, $\delta\rho_1 = 0.5\,\rho_1$, $\lambda_{\delta u_2} = 10, 10^3\lambda_{\rm mfp}$.
- Figures are spectra at $t = 10^5\tau_{sc}$ after first particle injection.
- When the wavelength is relatively short ($\lambda_{\delta u_2} = 10\,\lambda_{\rm mfp}$), sawtooth waves act for particles in the similar way as purely sinusoidal sound waves.
- When the wavelength is long ($\lambda_{\delta u_2} = 10^3\,\lambda_{\rm mfp}$), sawtooth waves still efficiently accelerate particles, while acceleration by sinusoidal waves becomes inefficient.
- Because dissipation time $t_{\rm dis}$ of sound waves is longer than $10^5\tau_{sc}$ for longer wavelength ($\lambda_{\delta u_2} \geq 10^3\,\lambda_{\rm mfp}$), efficient acceleration is expected to occur thanks to the steepening.

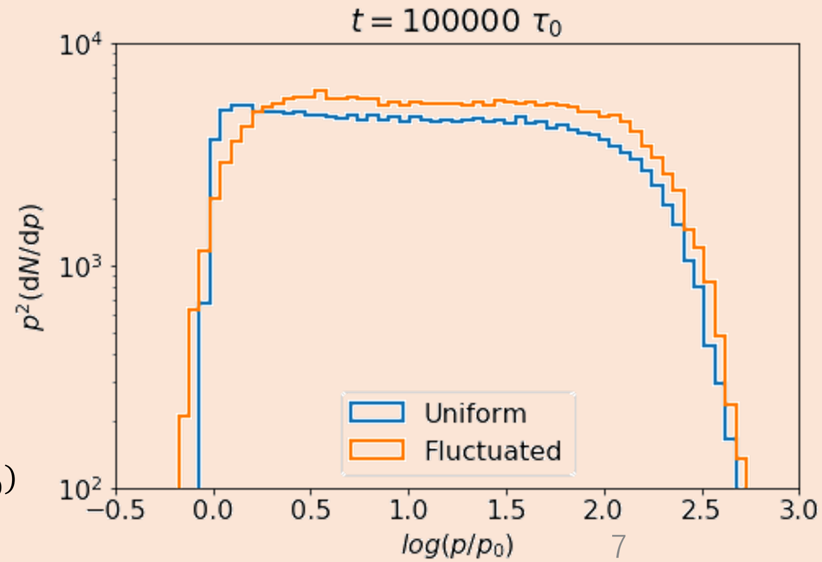


Results of simulation 2

- Steepening and dissipation of sound waves are confirmed (in the top figure).
- The number of high-energy particles is increased (orange spectrum in the bottom figure) compared to the uniform case (blue spectrum).
- Although dissipation time is less than or comparable to the simulation time for this wavelength ($\lambda_{\delta u_2} = 10^2\ \lambda_{\rm mfp}$), modification of spectrum by medium inhomogeneity is confirmed.
- We expect more remarkable modification for longer wavelength and slower shock velocity.
- We met numerical difficulty in doing simulations for other parameters and we are still working on.



$u_{\rm sh} = 0.1\ c,$
$M_1 = 100,$
$\delta\rho_1 = 0.5\ \rho_1,$
$\lambda_{\delta u_2} = 100\ \lambda_{\rm mfp}(p_0)$



Summary

- We investigate the influence of **medium inhomogeneity** on particle acceleration.
- Modification of the spectrum is confirmed even when we include nonlinear evolution of sound waves.
- Particles are additionally accelerated in the shock downstream region by sound waves and weak shock waves originated from the upstream inhomogeneity.

[Future works]

- Simulations for other parameters
- Simulations in more realistic (3-D, multi-wavelength) turbulence and comparison with observations
- Inclusion of back-reactions of accelerated particles

  Plasma instabilities may amplify turbulence or magnetic field and promote downstream acceleration.

Considering medium inhomogeneity is important for particle acceleration.