# Particle acceleration by ion-acoustic solitons in plasma in a magnetic field

K. Matsuno[1], H. Ishihara[1], M. Takahashi[2], Y. Masada[2]

[1]Osaka City University

[2]Aichi University of Education

# Introduction

High energy phenomena in the Universe ⇒ Cosmic rays

Non-thermal energy spectrum: $N(E) \propto E^{-s}$ ( $s$=2〜3 )

✓ Fermi acceleration by shock wave is a major candidate.

➢ We propose a new acceleration mechanism:

***Particle acceleration by***

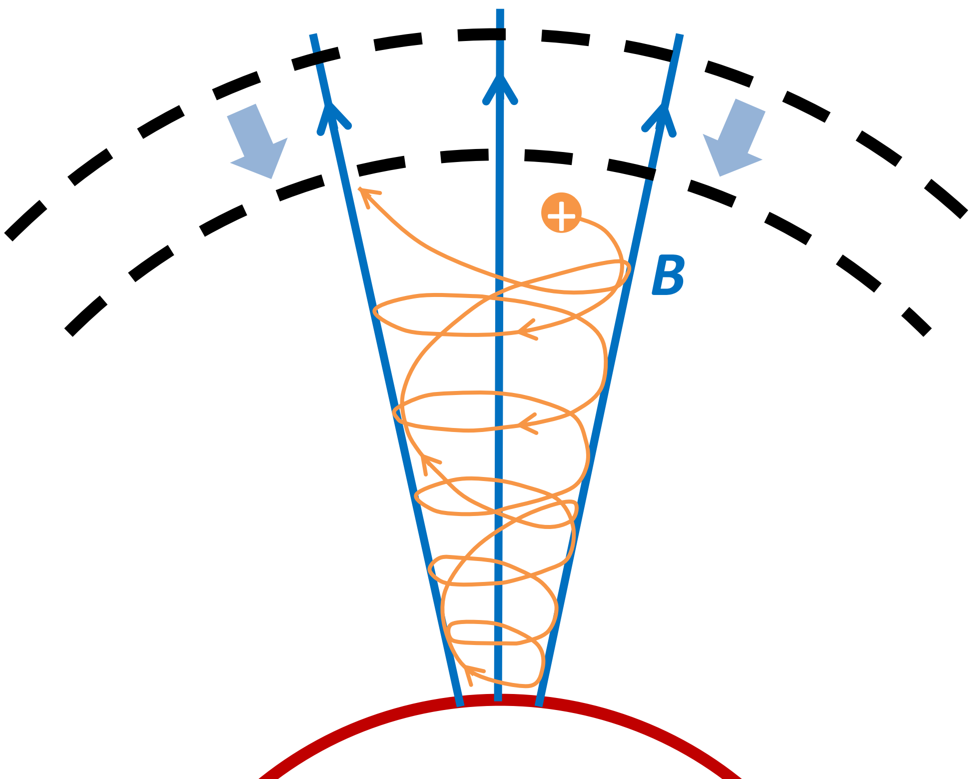
***spherical ion-acoustic solitons in plasma in radial magnetic field***

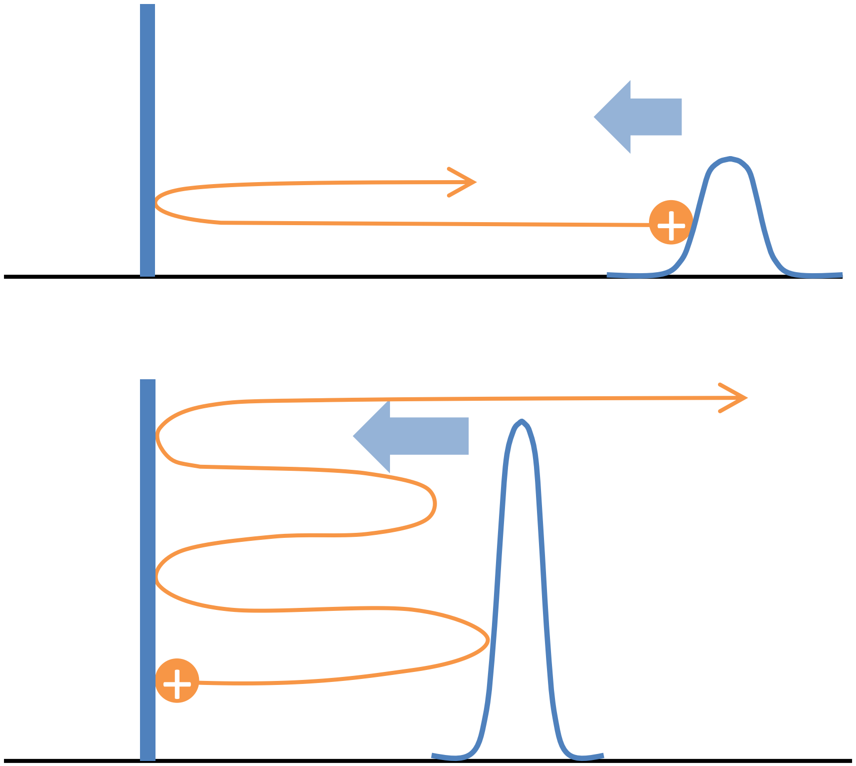
| | Fermi acceleration | Soliton acceleration |
|---|---|---|
| reflected by | magnetic cloud | electric potential |
| power law | stochastic | growth of potential |

# Particle acceleration by ion-acoustic soliton

- ✓ Acoustic soliton wave, described by spherical Kortweg-de Vries equation, grows in its wave height as wave shrinks to the center.

- ➢ Charged particles confined between magnetic mirror and electric potential accompanied with the shrinking wave get energy by reflections.



# Ion-electron plasma system

$$M^{(j)}n^{(j)}\left(\frac{\partial \boldsymbol{v}^{(j)}}{\partial t}+\left(\boldsymbol{v}^{(j)}\cdot\nabla\right)\boldsymbol{v}^{(j)}\right)=en^{(j)}\left(\boldsymbol{E}+\boldsymbol{v}^{(j)}\times\boldsymbol{B}\right)-\nabla P^{(j)}$$

$$\frac{\partial n^{(j)}}{\partial t}+\nabla\cdot\left(n^{(j)}\boldsymbol{v}^{(j)}\right)=0,\quad \nabla\times\boldsymbol{E}=-\frac{\partial \boldsymbol{B}}{\partial t},\quad \nabla\times\boldsymbol{B}=\boldsymbol{J}+\frac{\partial \boldsymbol{E}}{\partial t}$$

$M^{(j)}$, $n^{(j)}$, $\boldsymbol{v}^{(j)}$, $P^{(j)}$ ($j = i, e$): mass, number density, velocity, pressure of ion ($i$)/electron ($e$) fluid

✓ Assumption : Wavefront is perpendicular to radial magnetic field

Cold ion and hot electron fluids with spherical symmetry

✓ new variables :

$$\xi=\frac{\epsilon^{1/2}}{\lambda_D}(r+c_0t)\,,\qquad \tau=\frac{\epsilon^{3/2}}{\lambda_D}c_0t$$

Debye length $\lambda_D$

sound velocity $c_0$

✓ reductive perturbation :

$$\frac{e\phi}{k_BT^{(e)}}=\epsilon\phi_1+\epsilon^2\phi_2+\cdots\,,\qquad \frac{v^{(i)}}{c_0}=\epsilon v_1+\epsilon^2v_2+\cdots$$

$$\frac{n^{(i)}}{n_0}=1+\epsilon n_1+\epsilon^2 n_2+\cdots$$

➢ We obtain $\Phi := \phi_1 = -v_1 = n_1$

and Korteweg-de Vries (KdV) equation

# Korteweg-de Vries equation

$$\frac{\partial \Phi}{\partial \tau} - \Phi\frac{\partial \Phi}{\partial \xi} - \frac{1}{2}\frac{\partial^3 \Phi}{\partial \xi^3} + \gamma\frac{\Phi}{\tau} = 0$$

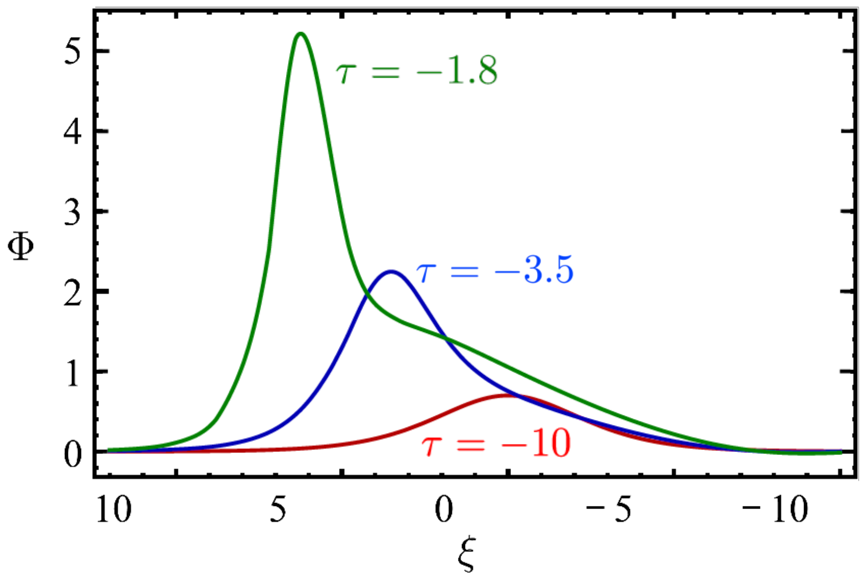
$$\gamma = \begin{cases} 0 & \text{(planar)} \\ 1 & \text{(spherical)} \end{cases}$$

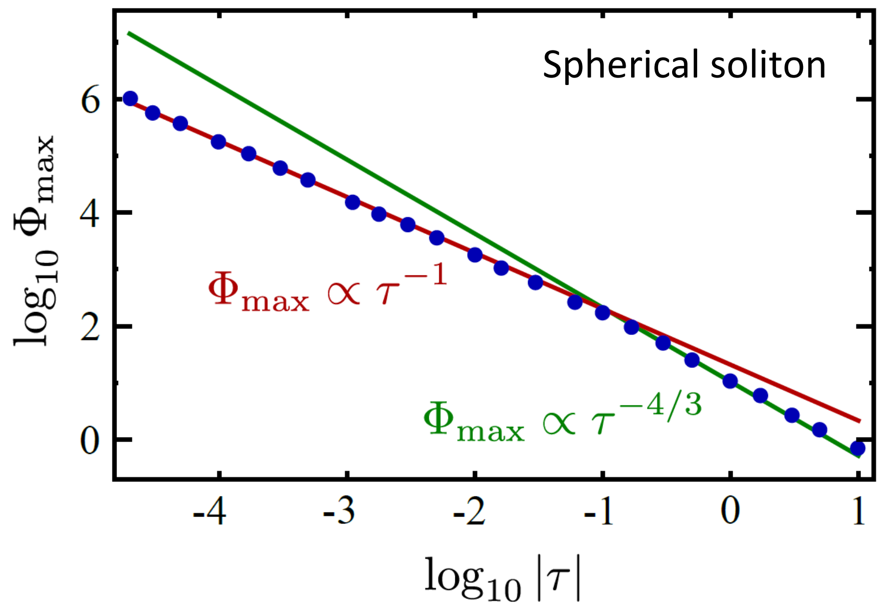
$$\tau = \tau_0 \quad \longrightarrow \quad \tau = \tau_f \ (r = r_f)$$

- Early time (large radius and τ ): planar soliton like
- Late time (small radius and τ): the last term on l.h.s. becomes important

✓ Spherical soliton wave height grows in time

# Time evolution of soliton wave form and height




✓ growth rate of wave height is power law in time

- In order to simplify the system, we make a model where spherical soliton is replaced by a <u>thin shell wall</u>

- We calculate test particle motion confined between magnetic mirror and shrinking thin shell, and obtain <u>energy spectra of accelerated particles</u>

# Thin shell wall models

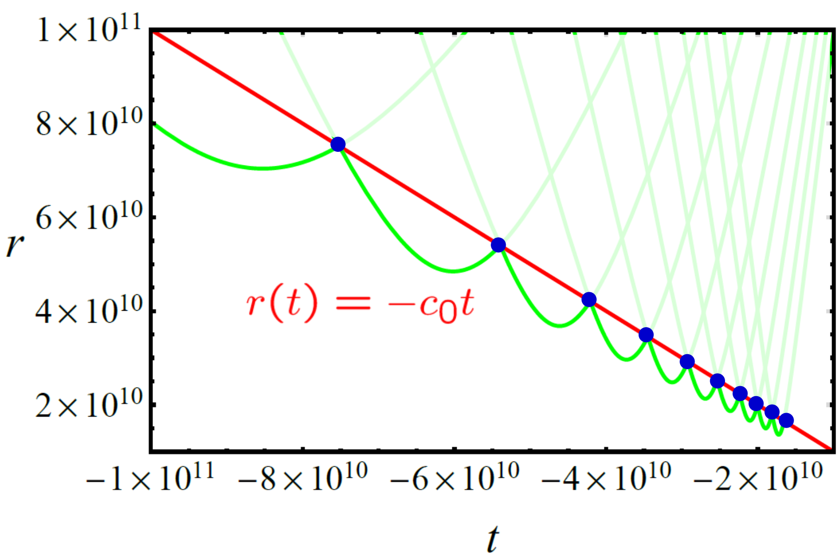
1. Shell wall: Initial radius $r_0$ of shell at initial time $t_0$ (<0), moves with sound velocity $c_0$ $\Rightarrow$ $r(t) = -c_0\, t$
2. Electric potential : $\Phi(t) = \Phi_0\,(t/t_0)^{-\alpha}$ ($\alpha = 1$ , 4/3)
3. Final time: (Shell radius) = (Polar region size) acceleration stops

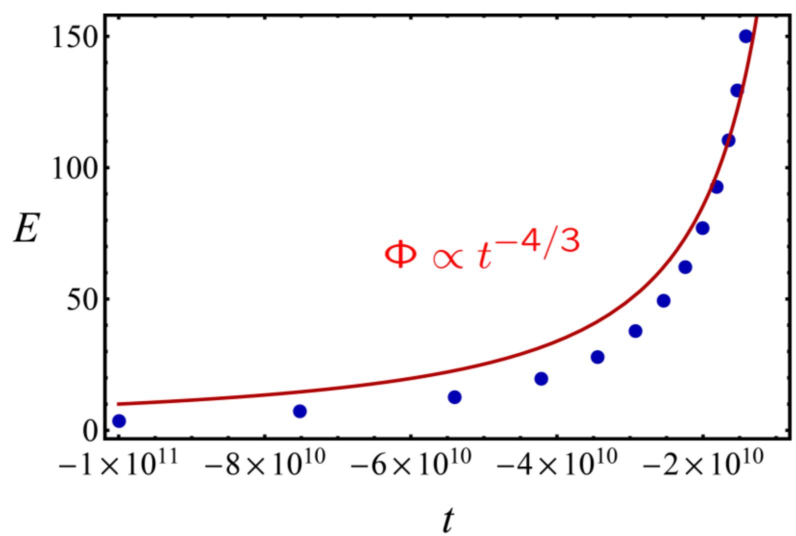
A. Test charged particles: Elastic reflection by the moving shell wall

$\Rightarrow$ Particle velocity: $\boldsymbol{v} = (v_\perp,\ v_\parallel) \longrightarrow (-v_\perp - 2c_0,\ v_\parallel)$

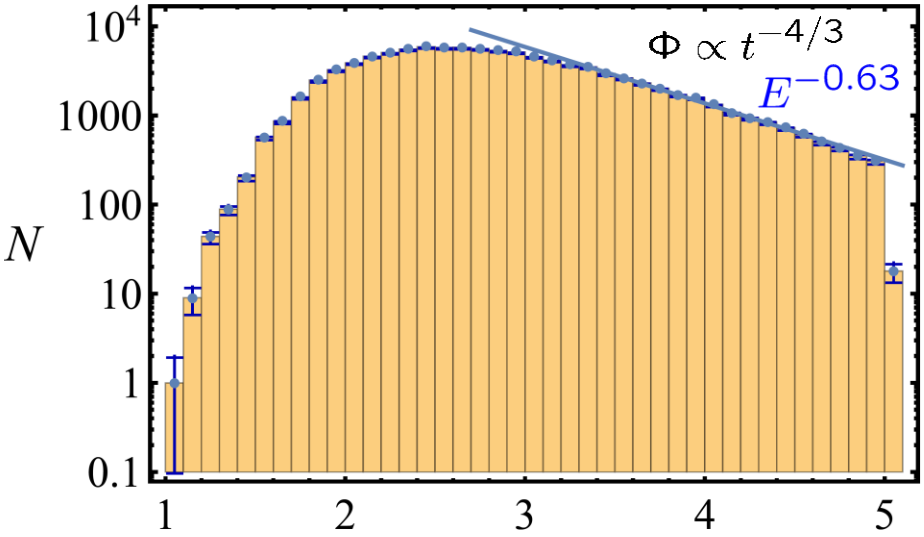
B. Escaping particles: (Particle energy) > $\Phi(t)$

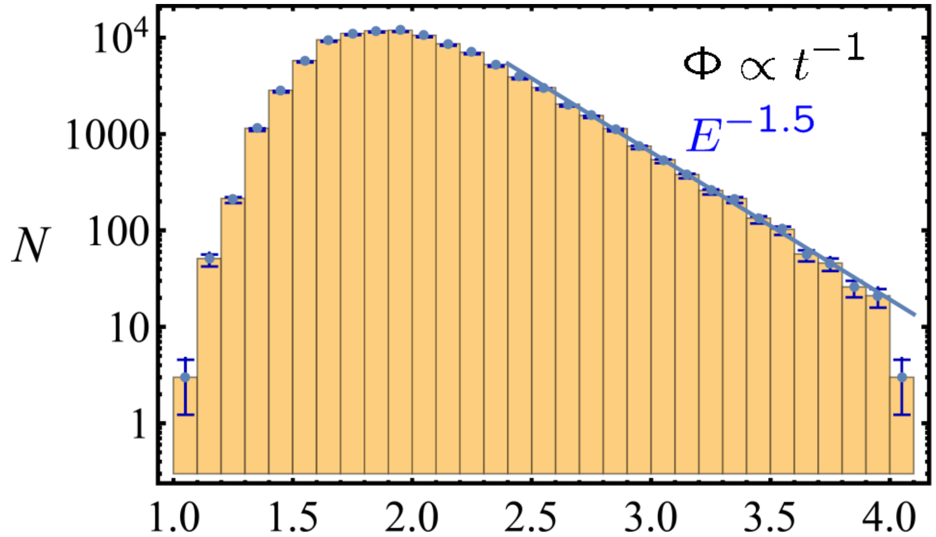
$\Rightarrow$ Particles escape to infinity



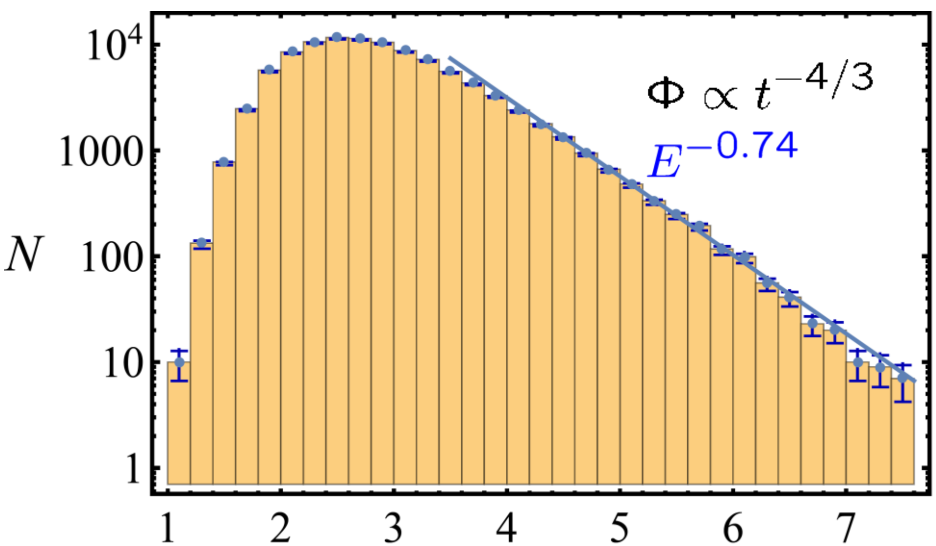



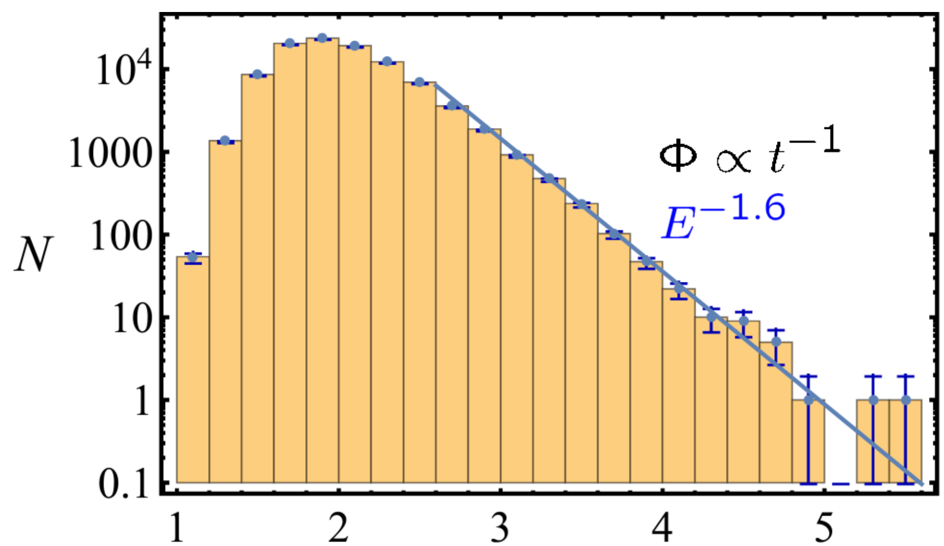
# Energy spectra of output particles




($r_0 = 10^9$ m, $r_f = 10^6$ m)




($r_0 = 10^{11}$ m, $r_f = 10^6$ m)

# Summary

We propose a new acceleration mechanism for charged particles by using spherical ion-acoustic solitons propagating in ion-electron plasma in radial magnetic field.

Electric potential grows with a power law in time as waves shrink.

⇩

We obtain power law spectra of energy for accelerated particles.

- We expect that acceleration mechanism by solitons would be applicable to heating of atmosphere of compact objects, energy transfer between waves and particles, etc.