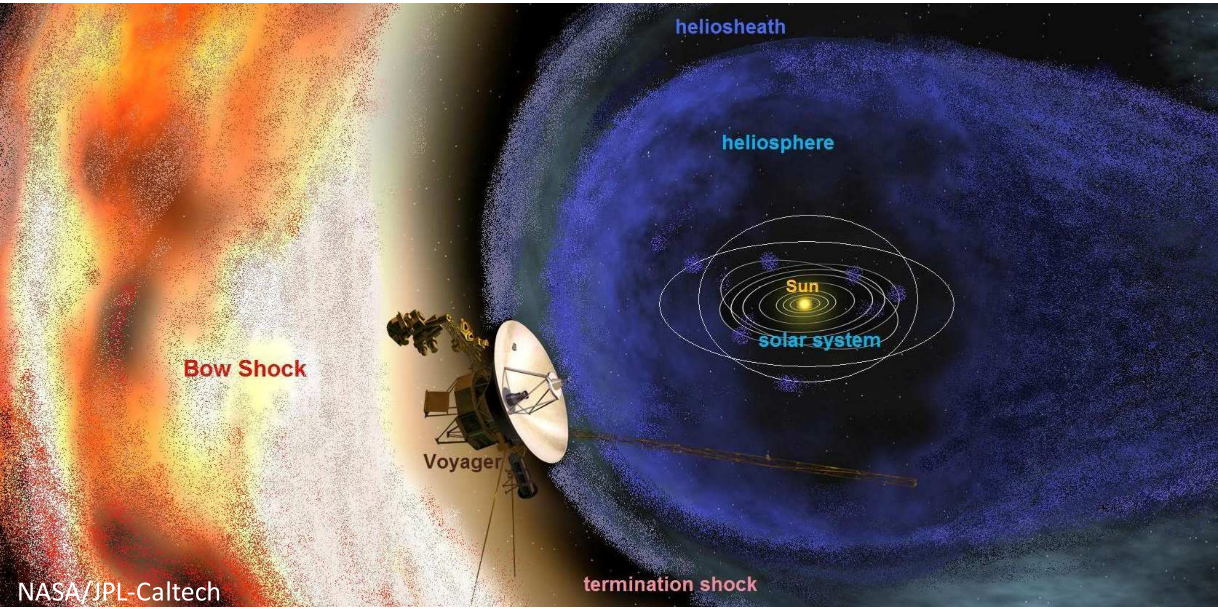

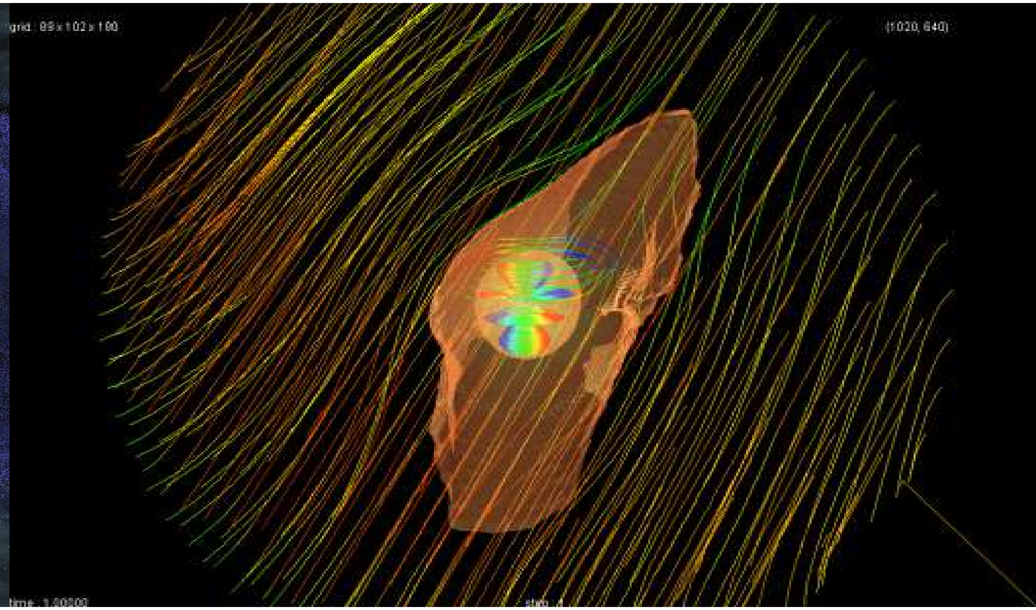

2D PIC simulation of particle acceleration in oblique pickup ion mediated shocks

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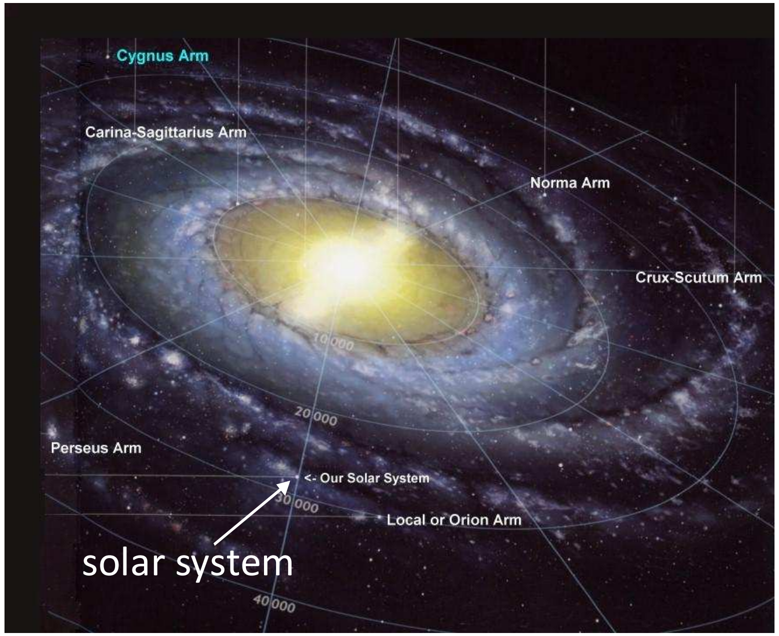
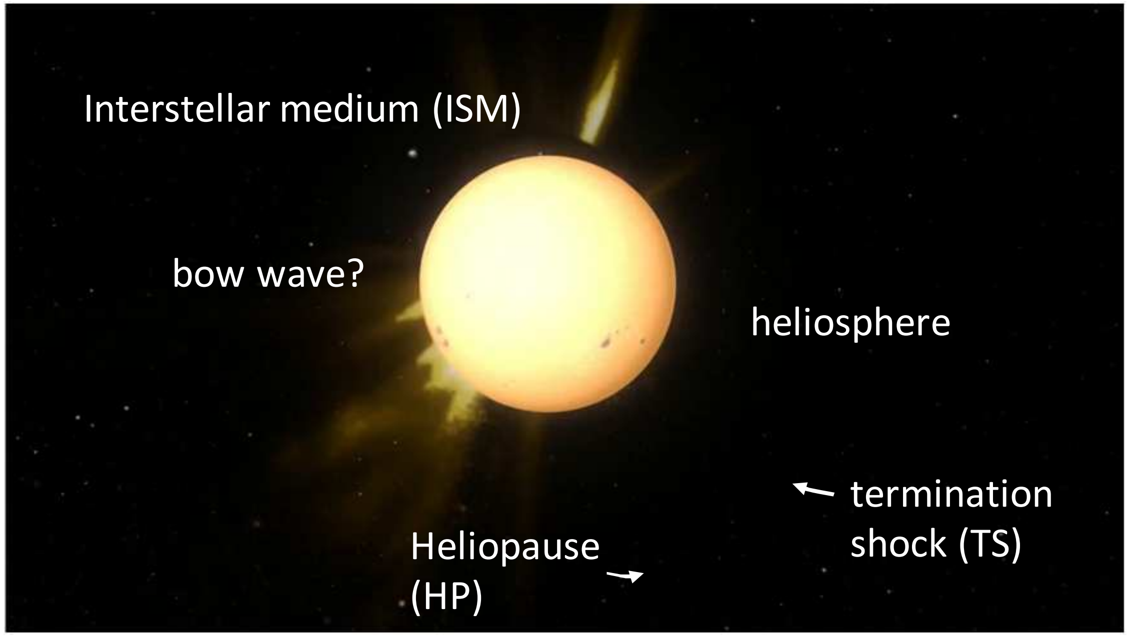
Matsukiyo & Matsumoto, Injection Process of Pickup Ion Acceleration at an Oblique Heliospheric Termination Shock, ApJL, 970, L37 (2024)

Heliosphere

Our galaxy

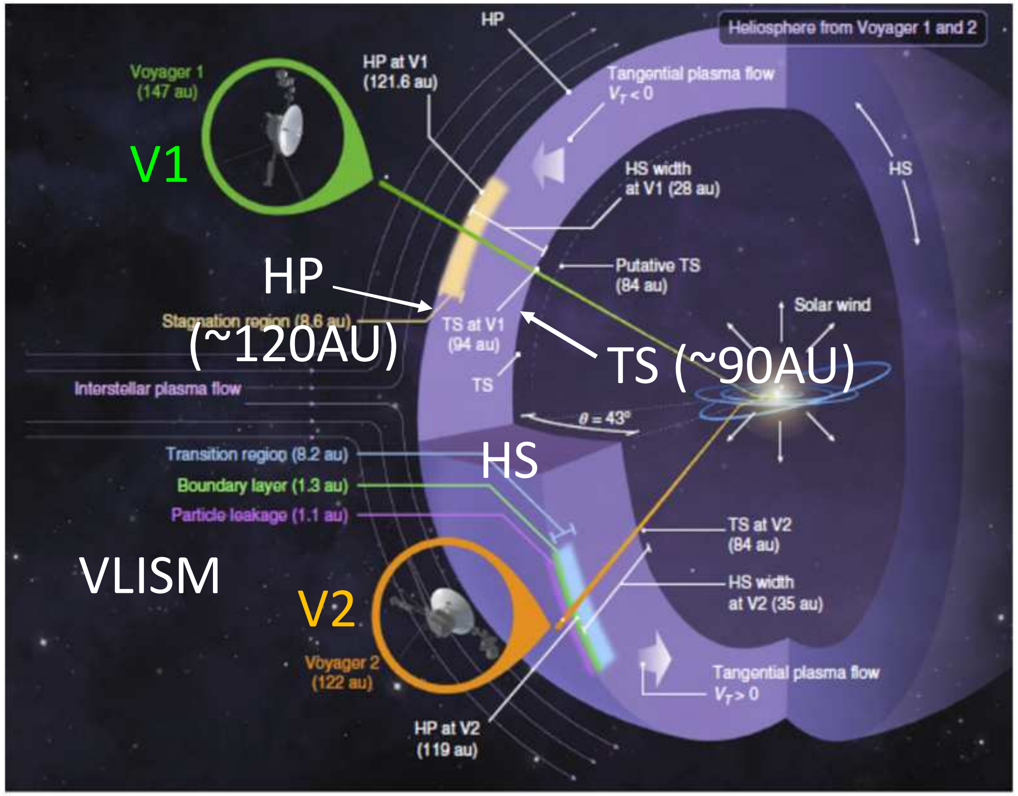


heliosphere



The heliosphere is the region in interstellar space occupied by solar wind plasma. The boundary of the heliosphere is called the heliopause. Inside the heliosphere, there is a termination shock where supersonic solar wind slows down to subsonic speeds.

Structure of the heliospheric boundary



Krimigis et al. [2019]

V1 (V2): Voyager 1 (2)
TS: termination shock, HP: heliopause
HS: heliosheath, VLISM: very local interstellar medium

<u>Typical plasma parameters</u>

		HP		TS
	VLISM	HS		SW
$N[10^{-3}cm^{-3}]$	$40\sim100$	2	2	1
$V[100\,km/s]$	0	$0\sim1$	1.5	3
$T[10^4K]$	$3\sim5$	5	10	1
$B[0.1nT]$	$5\sim7$	$1\sim2$	1	0.6

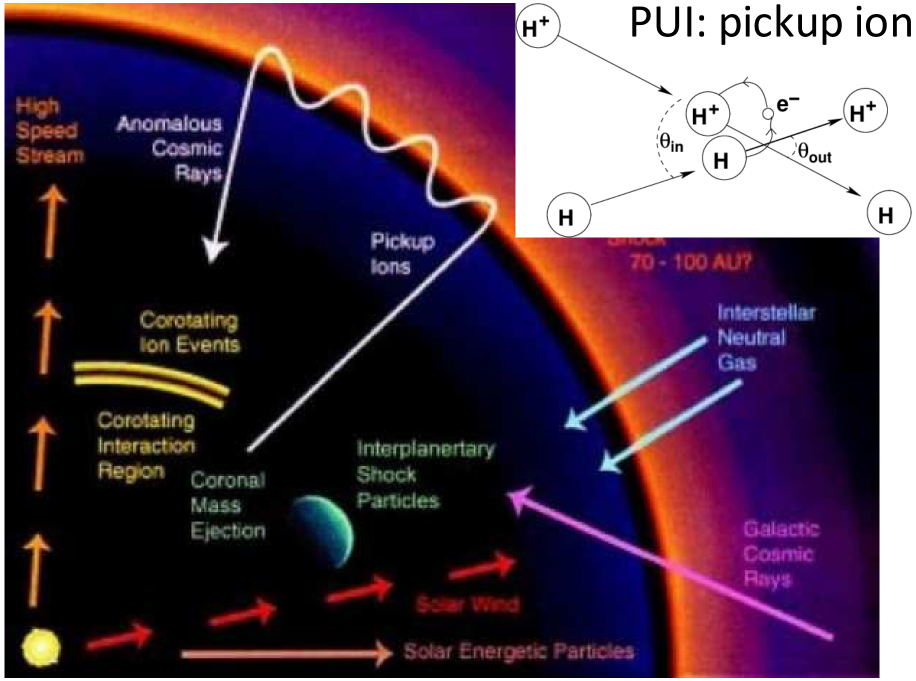
Scientific interests:

- Structure of the boundary region
- Particle acceleration (ACRs, ENAs)
- Solar wind modulation of GCRs
- Properties of the VLISM

Heliospheric termination shock (TS) & ACRs

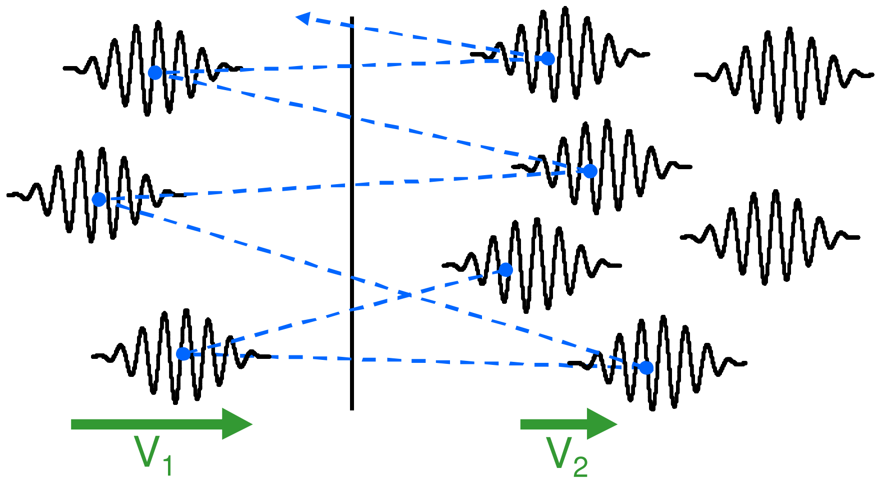
Anomalous CRs (ACRs) are

- accelerated PUIs (~a few 10 MeV)
- believed to be accelerated at TS through diffusive shock acceleration (DSA) process



PUI: pickup ion

DSA model / 1st-order Fermi acc.



- Non-thermal particles scattered by upstream and downstream electromagnetic waves traverse a shock back and forth and are accelerated.

Unresolved injection mechanism to DSA

The DSA model requires the existence of non-thermal particles whose energy is much larger than the thermal energy of the background plasma.

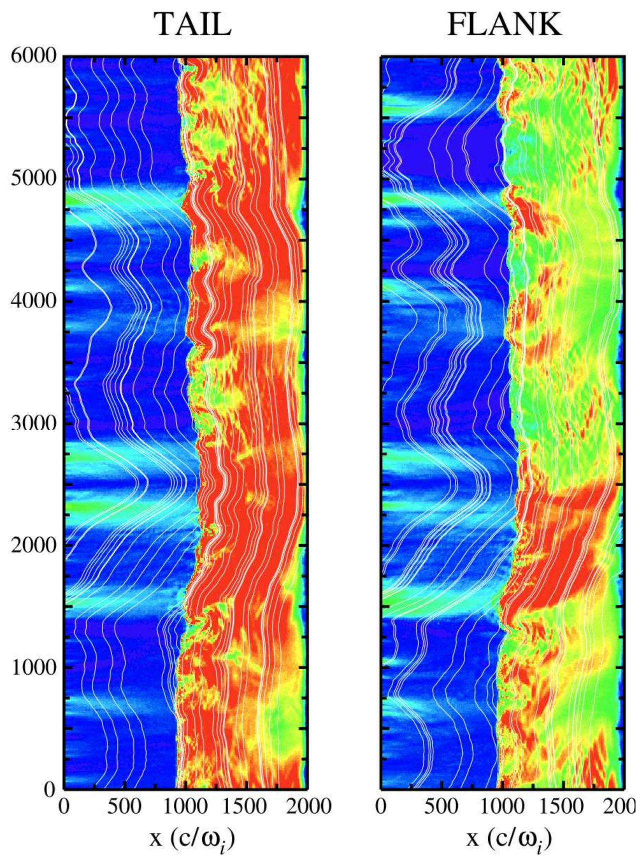
But the mechanism producing the non-thermal particles is unknown. ➔ Injection problem

Giacalone et al. (2021) conducted hybrid simulations and showed that the rate of acceleration for low energy ($\lesssim 50$ keV) PUIs is uniform regardless of the position on the TS.

Upstream turbulence may be essential:

- Non-thermal particles are observed in the region where local B-field is oblique to shock normal.

hybrid sim.



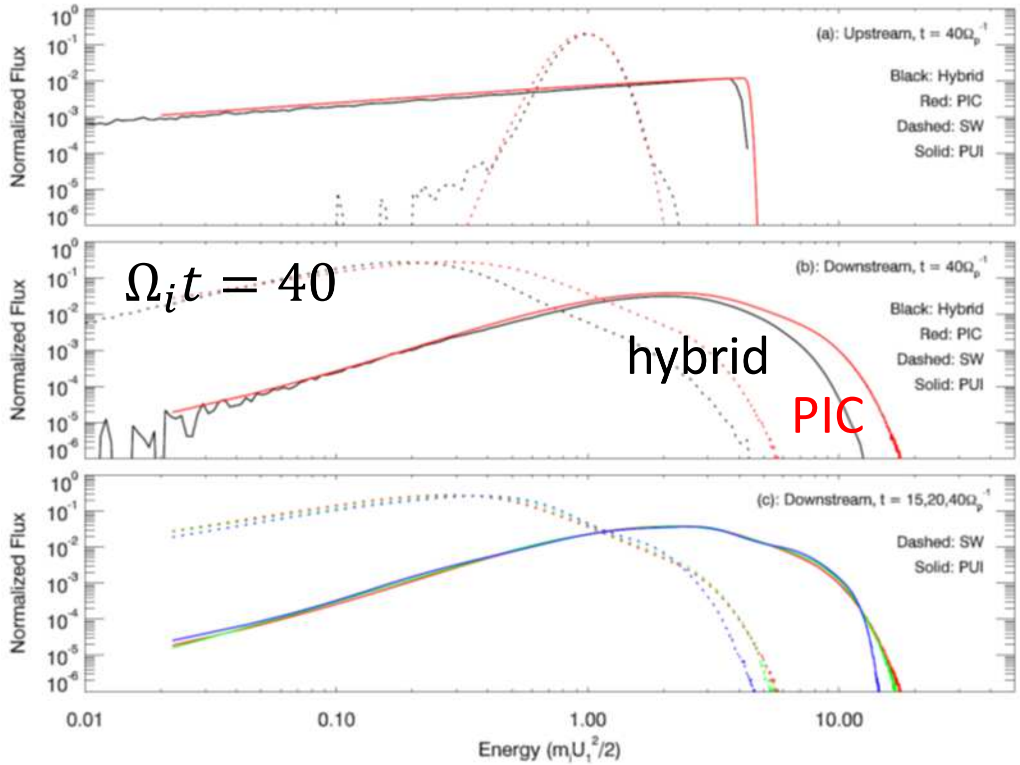
Giacalone et al. [2021]

Unresolved injection mechanism to DSA

Swisdak et al. (2023) compared hybrid simulation and PIC simulation and showed that the rate of acceleration for PUIs is higher in PIC simulation than in hybrid simulation.

They claimed that the difference may be due to the difference of shock potential reproduced in the two types of simulations.

How does the shock potential play a role in the injection?



Swisdak et al. [2023]

Kinetic simulations of PUI mediated shocks

- Kinetic simulation is useful to understand the mechanism of initial stage of acc.
- Shock potential is calculated ab-initio in PIC simulation

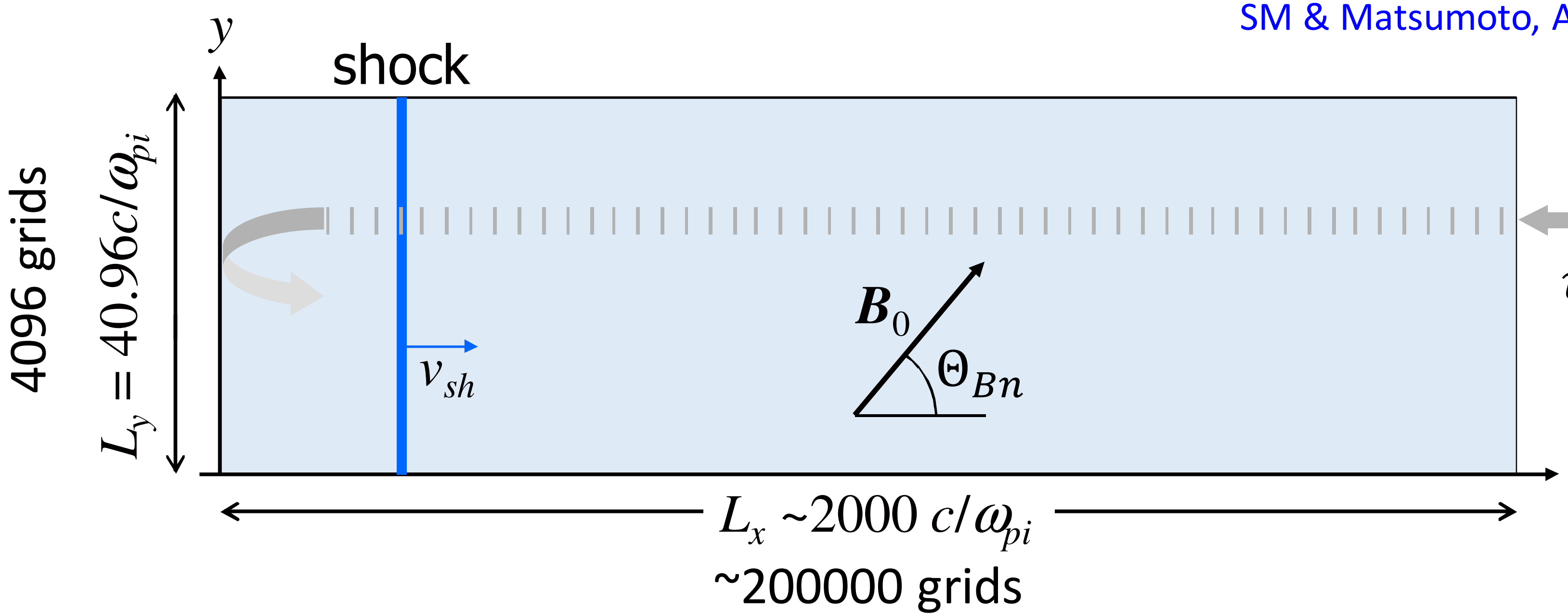
<u>Past kinetic simulations</u>

1D	Θ_{Bn}	n_{PUI}/n_0	2D	Θ_{Bn}	n_{PUI}/n_0	$\Omega_i t$
hybrid			**hybrid**			
Liever+(1993,1995)	40-80	0.1-0.2	Liu+(2010)	90	0.2	60
Kucharek & Scholer(1995)	50-70	0.05-0.3	Giacalone & Decker(2010)	90+turb.	0.25	100
Lipatov & Zank(1999)	72,90	0.001-0.1	Giacalone & Burgess(2010)	90+CS	0.2	100
Wu+(2009,2010)	90	0-0.4	Giacalone+(2021)	80-90+turb.	0.18-0.33	300
			Gkioulidou+(2022)	V2	V2	300
PIC			**PIC**			
Lee+(2005)	90	0.1	Yang+(2015)	90	0-0.25	7
SM+(2007,2011,2014)	60-90	0-0.6	Kumar+(2018)	80	0.25	30
Oka+(2011)	90	0.3,0.01	Swisdak + (2023)	70	0.25	40
Lembege+(2016,2018)	90	0-0.55	**3D**	Θ_{Bn}	n_{PUI}/n_0	
Lembege+(2020)	55	0.04	**PIC**			
			Kumar+(2018)	80	0.25	

1D: wide range of shock angles 2,3D: only the shock angles close to 90°

2D PIC sim. of PUI mediated shock using Fugaku

SM & Matsumoto, ApJL, 970, L37 (2024)



$\boldsymbol{\Theta_{Bn}} = \mathbf{50^\circ}$, $\mathbf{60^\circ}$, $\mathbf{70^\circ}$

$M_A = 5.6$, 5.9, 6.0

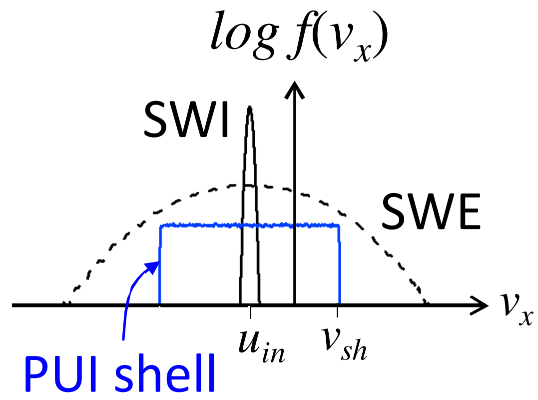
$\beta_e = 0.25\ (T_e = T_{SWI})$

$\boldsymbol{\Omega_i t_{max} = 125}$

$m_i/m_e = 100$

$\omega_{pe}/\Omega_e = 4$

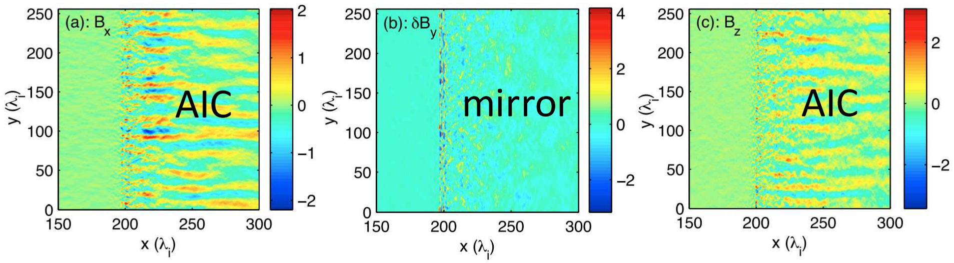
PUI: 25 %



Field structure

- In a perp. shock AIC (Alfven-Ion Cyclotron) and mirror instabilities dominate downstream

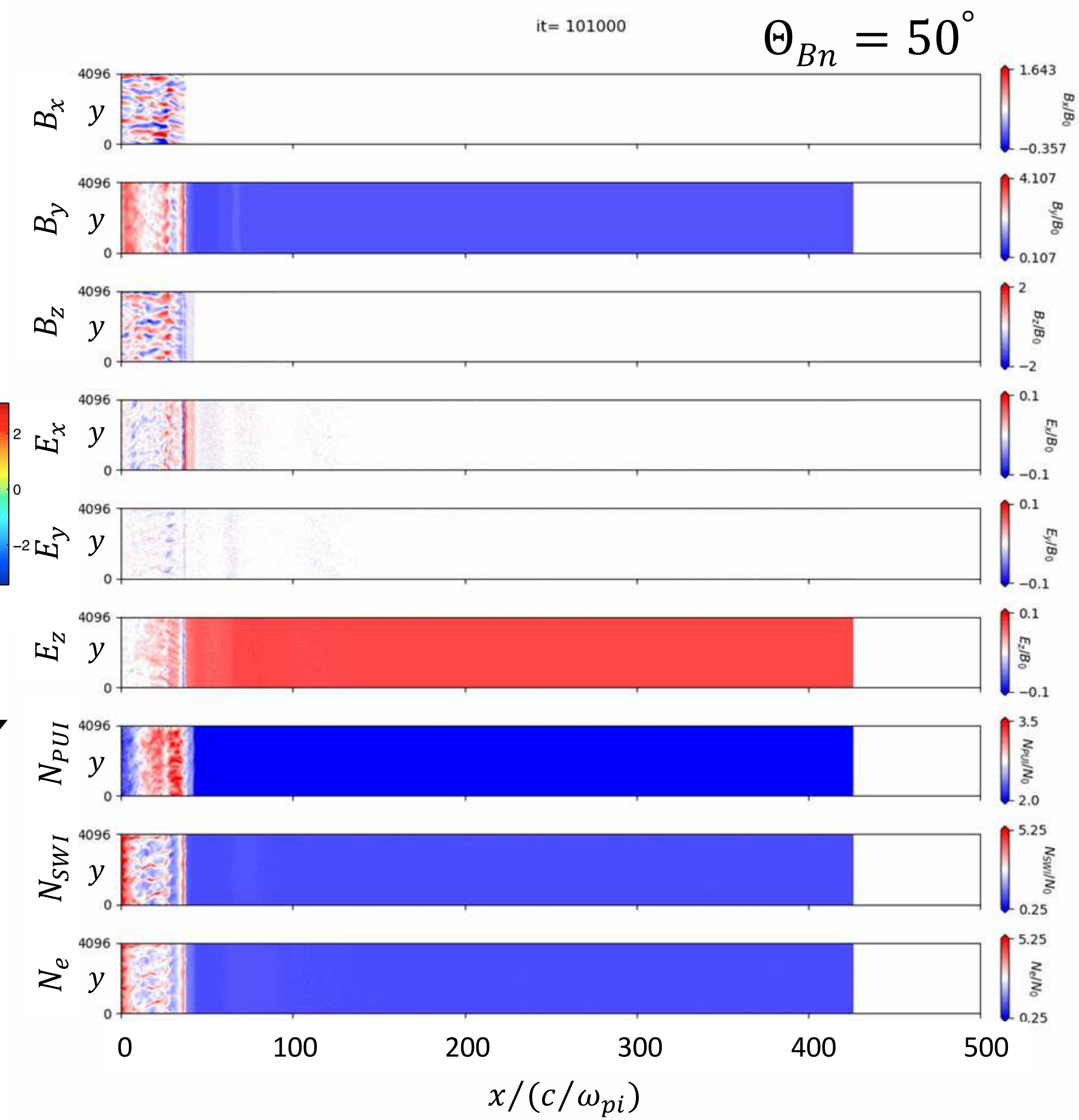
Liu+(2010) $\Theta_{Bn} = 90^{\circ}$



- Large amplitude waves are excited upstream of the shock

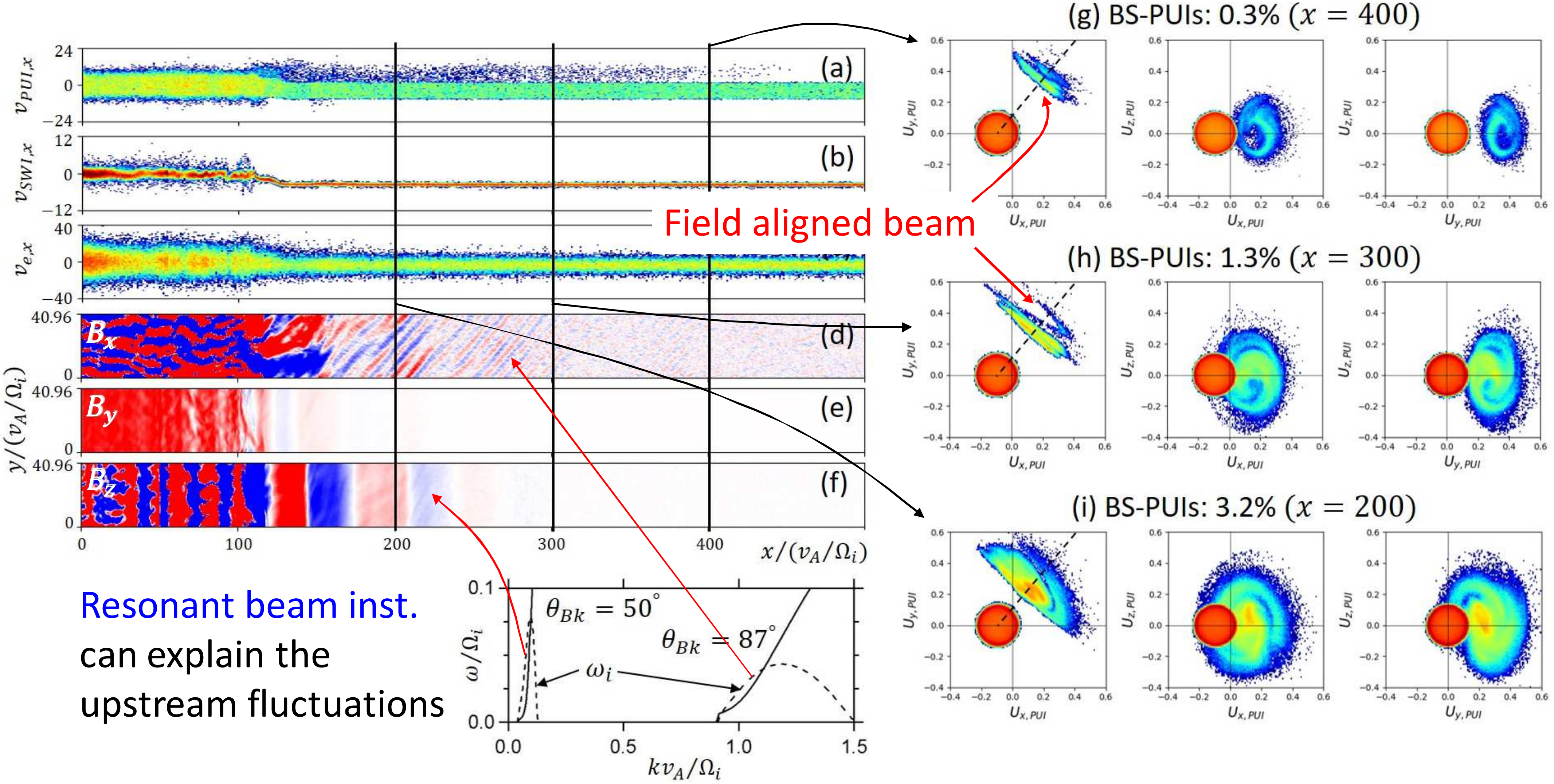
→ shock reformation

→ altering downstream structure for $\Theta_{Bn} = 50^{\circ}$



Back-streaming PUIs

$\Theta_{Bn} = 50^{\circ}$

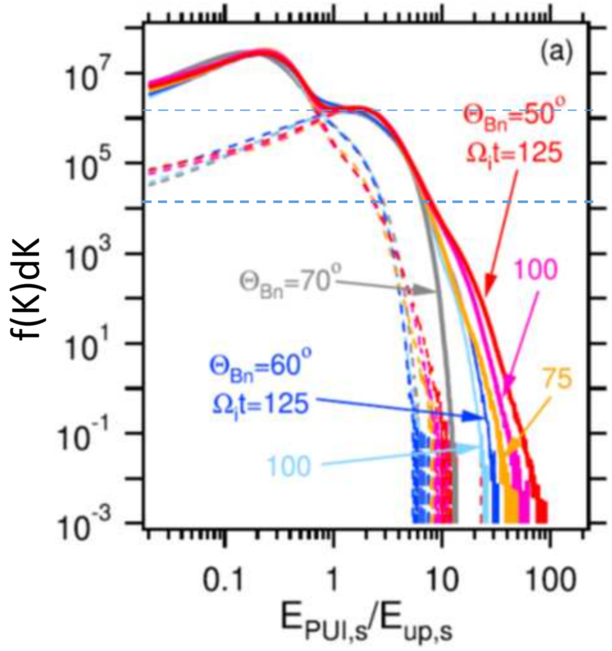


Resonant beam inst.
can explain the
upstream fluctuations

Acceleration of PUIs

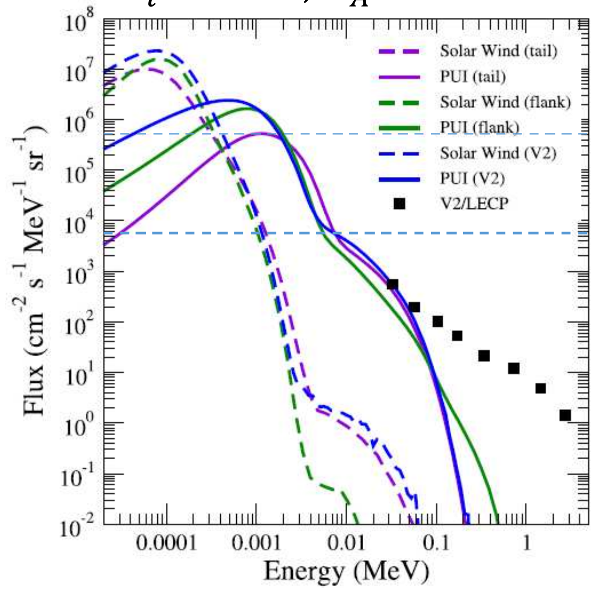
- No accelerated PUIs for $\Theta_{Bn} = 70^{\circ}$
- Energy density of accelerated PUIs at $\Omega_i t = 125$
  - $\Theta_{Bn} = 60^{\circ}$: 6.6%
  - $\Theta_{Bn} = 50^{\circ}$: 13%
- The height of shoulder for accelerated PUIs is about two orders of magnitude lower than the peak of PUIs, which is comparable to Giacalone+(2021)'s results even for smaller M_A and $\Omega_i t$.

PIC sim. $(M_A \lesssim 6)$



Hybrid sim.

$\Omega_i t = 300, M_A \approx 10 - 11$



Giacalone+(2021)

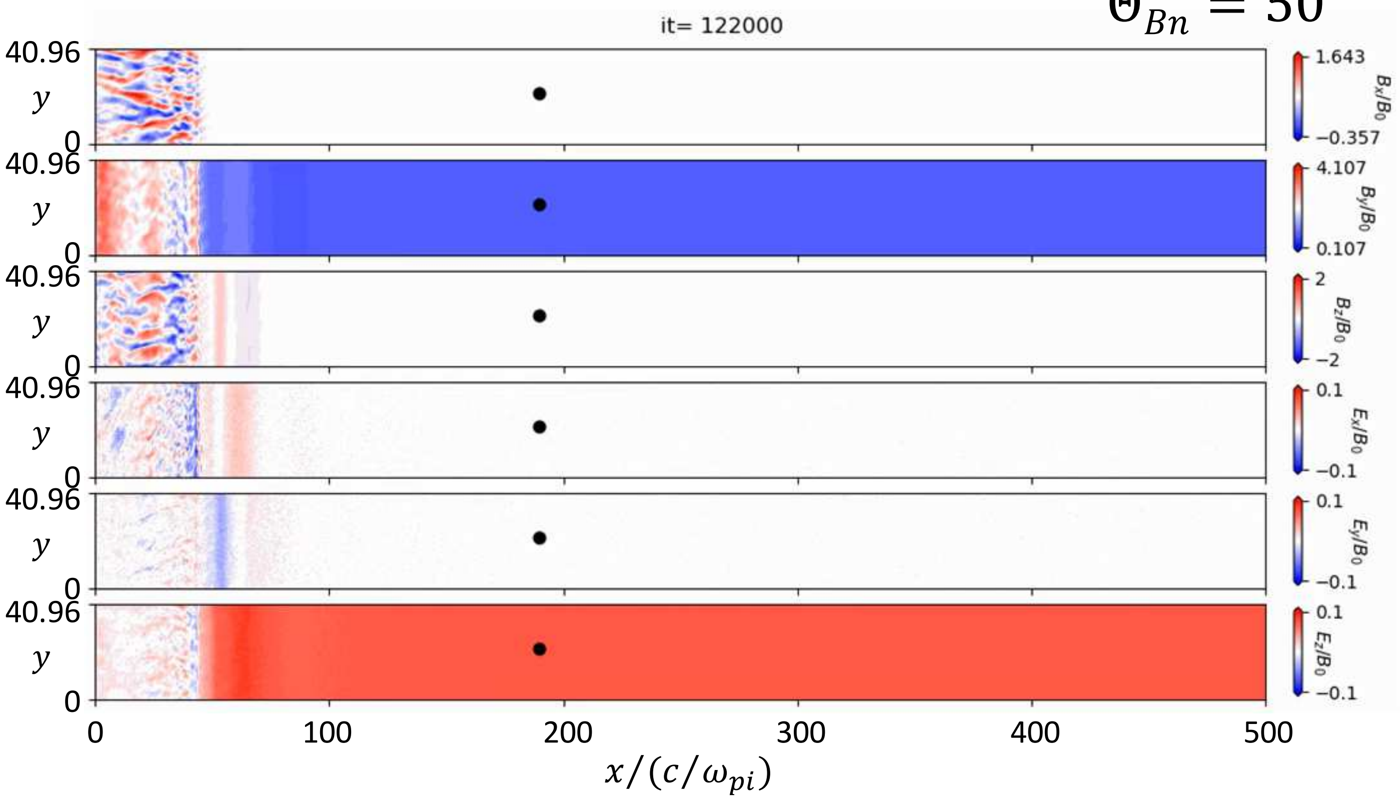
Acceleration of PUIs

Acceleration occurs while a PUI stays near the shock

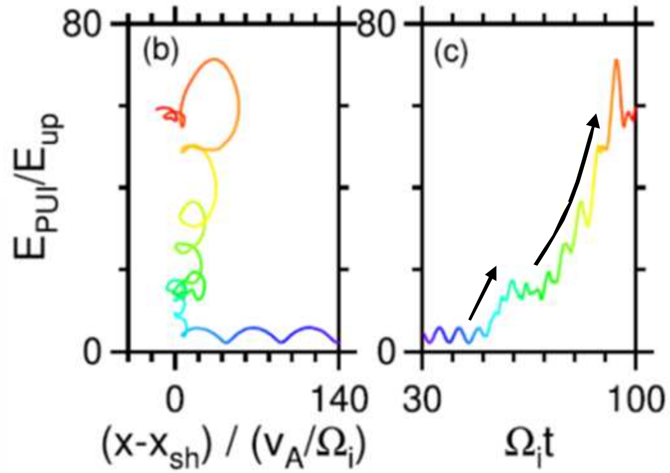
Two acceleration phases

- Later phase: shock drift acc. (SDA)
- Early phase: shock surfing acc. (SSA)

$\Theta_{Bn} = 50^\circ$



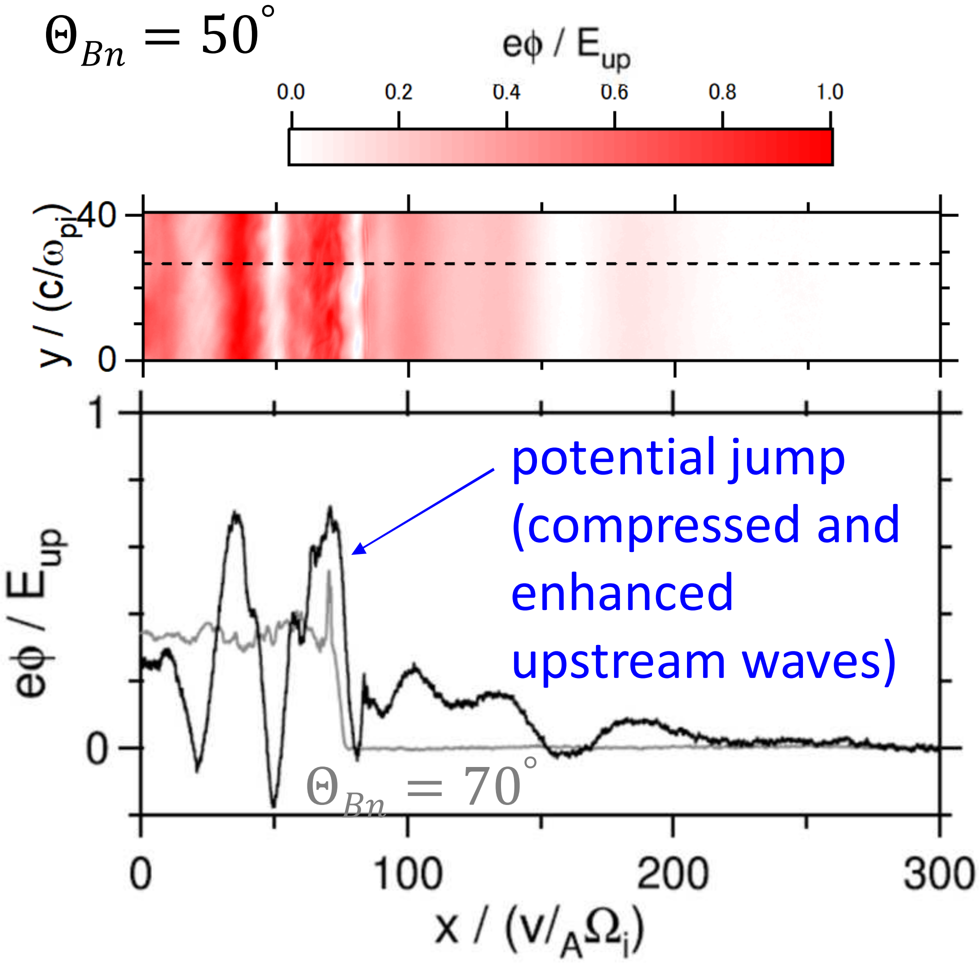
Energy history



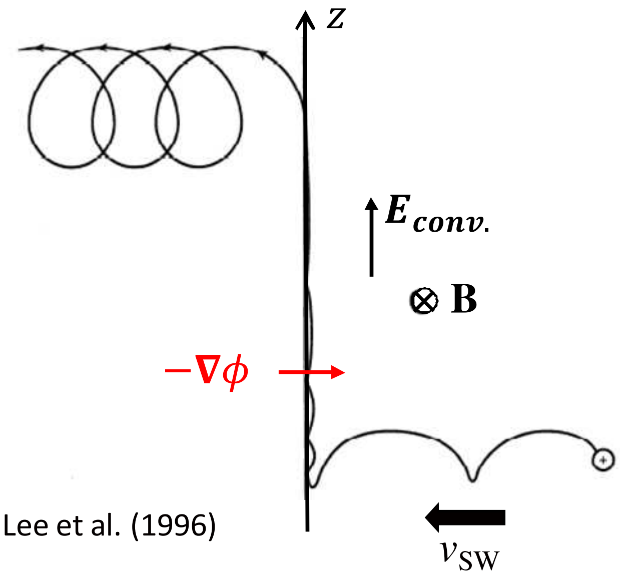
SSA ($\Omega_i t \sim 50 - 60$)

- Multiple reflections with incomplete gyro motion
- Requires a sharp potential jump

SSA through sharp potential



- The upstream fluctuation is compressed and amplified at the shock.
- Large jump at the ramp (~0.7 E_{up}) with ~c/ω_{pi} (or less)
  → SSA



Lee et al. (1996)

Summary

- 2D PIC sim. of PUI mediated oblique ($\Theta_{Bn} = 50^{\circ}, 60^{\circ}, 70^{\circ}$) shock were performed.
- For $\Theta_{Bn} = 50^{\circ}$, large amplitude waves upstream of the shock are generated by the back-streaming PUIs.
- The waves convected by the upstream flow lead not only to shock reformation but also to alter the downstream structure.
- PUIs are accelerated to tens of bulk energy in the shock front.
- Accelerated PUIs experiences SSA followed by SDA.
- ES potential accompanied by the upstream waves is compressed and enhanced, which enables SSA to work.