Electron-beam instabilities in the foreshock of oblique high-Mach-number shocks

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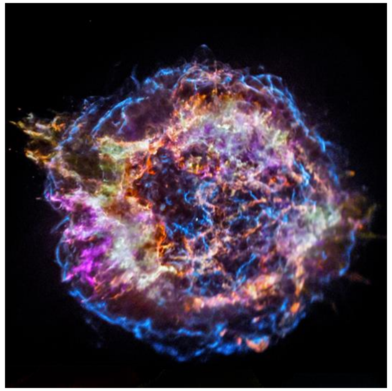
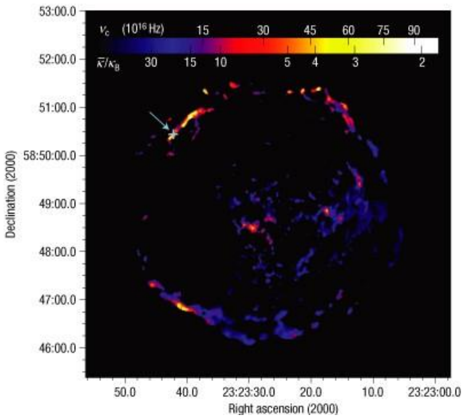
International Cosmic-Ray Conference 2021

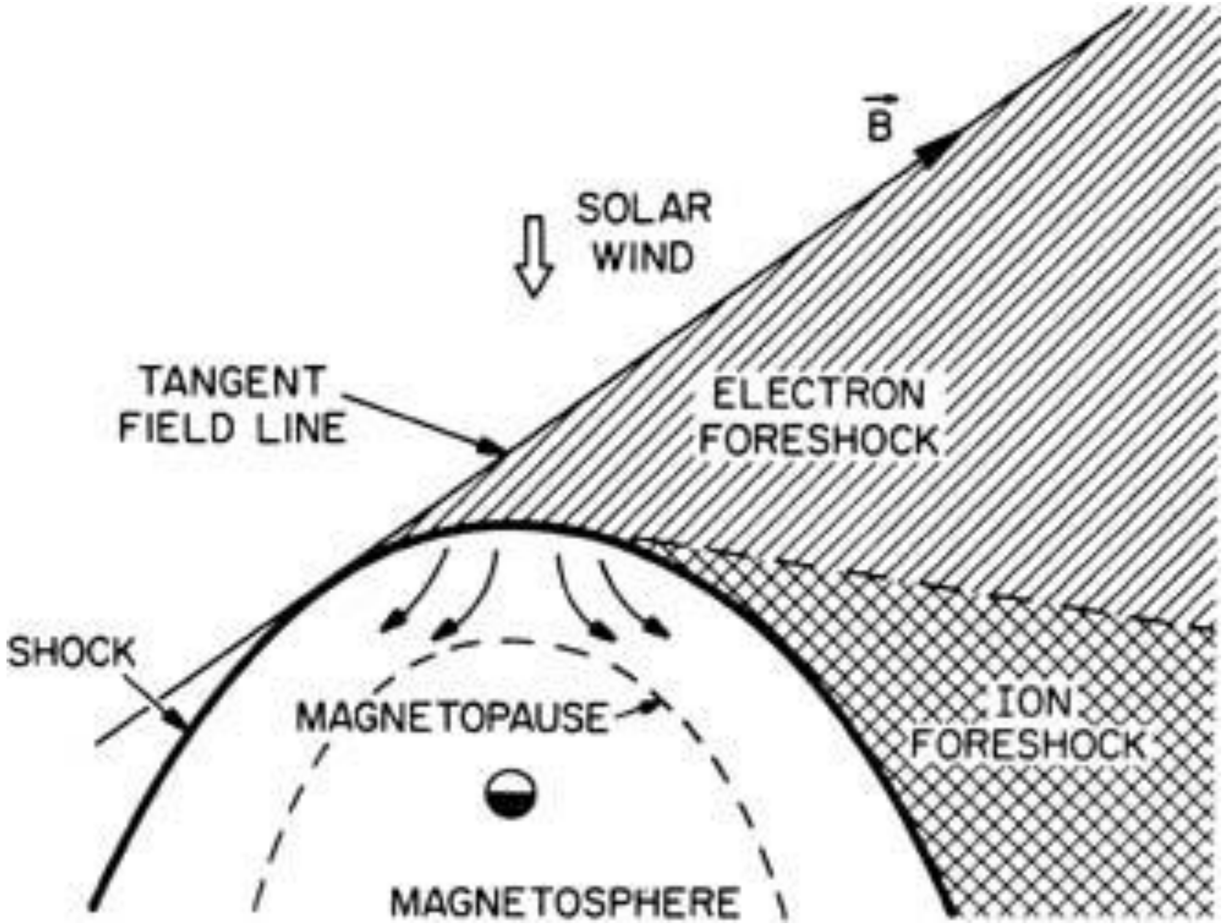


[NASA/CXC/SAO]



[Stage et al 2006]

Foreshock geometry at oblique shocks



[D. A. Gurnett]

Typical electron-foreshock waves

Alfvén waves
Electron-beam firehose instability
[Gary 85]

Langmuir waves
2-stream instability

Quasiparallel whistler waves
Whistler heat-flux instability
[Gary 85]

Oblique whistler waves
[Sentman et al 83]

Left-hand polarised

Electrostatic

Right-hand polarised

Periodic PIC simulations with solar-wind parameters

Borda de Agua et al, JGR 1996

2D3V simulation of electron beam with $T_\perp \gg T_\parallel$
Parallel Langmuir waves
Oblique whistler waves forward and backward

Fu et al, PoP 2014

2D3V simulation of electron beam with $T_\perp > T_\parallel$
Electrostatic instability, then **quasiparallel whistler** instability
Only weak oblique whistlers

Micera et al, ApJ 2020

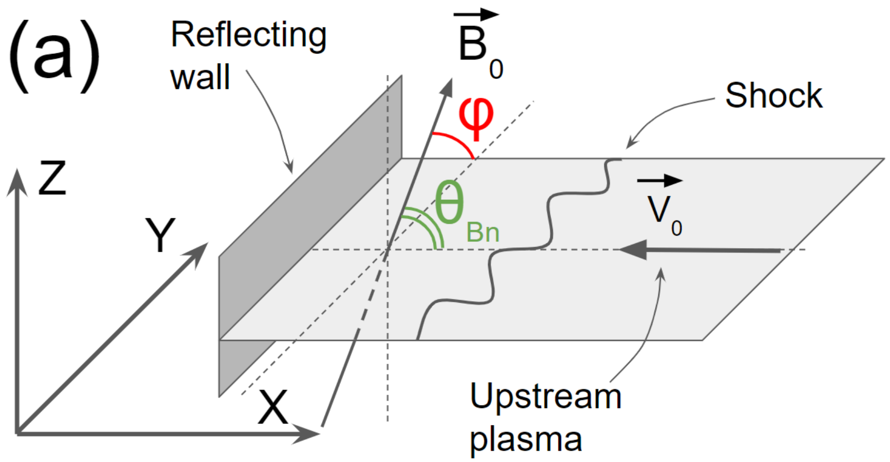
2D3V simulation of electron strahl with $T_\parallel > T_\perp$
Fast-growing **oblique whistlers** scatter strahl perpendicularly
Then susceptible to **quasiparallel whistlers**

Shock simulation with Mach number 63

Xu et al, ApJ 2020

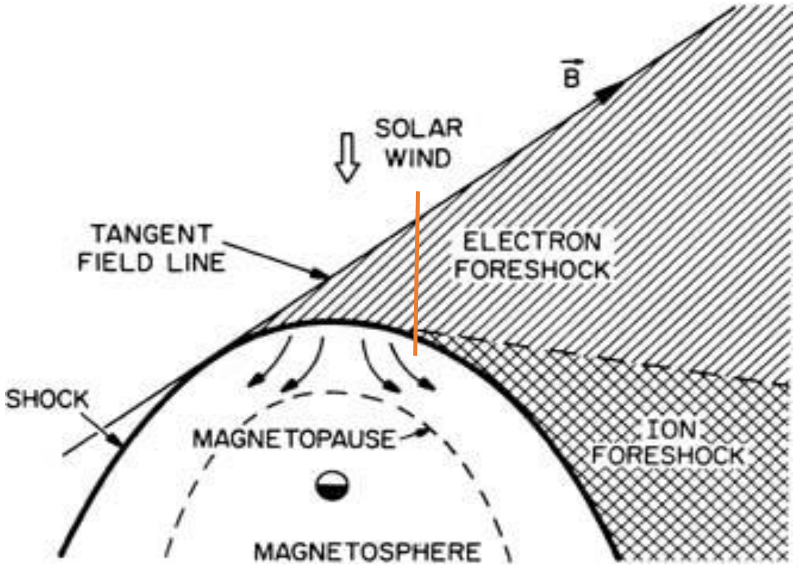
1D3V simulation of oblique shock with shock-mirrored electrons
Strong **LCP waves** in foreshock
Electrons undergo SDA in shock, then escape and **perform DSA**

Shock-reflected electrons and the foreshock instabilities they excite

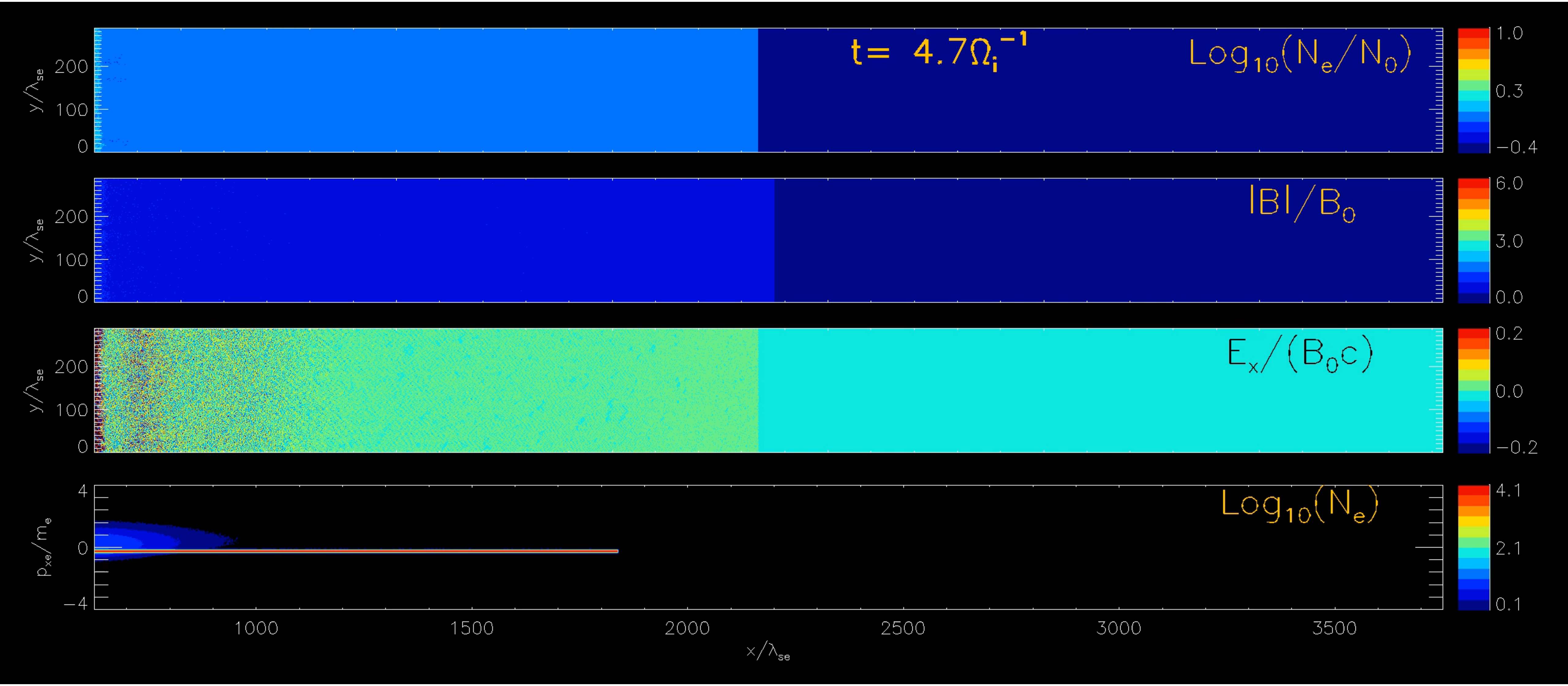


(a) Retrieve properties of shock-reflected electrons from 2D3V shock simulation

(b) Determine unstable wave modes from linear analysis and periodic PIC simulations



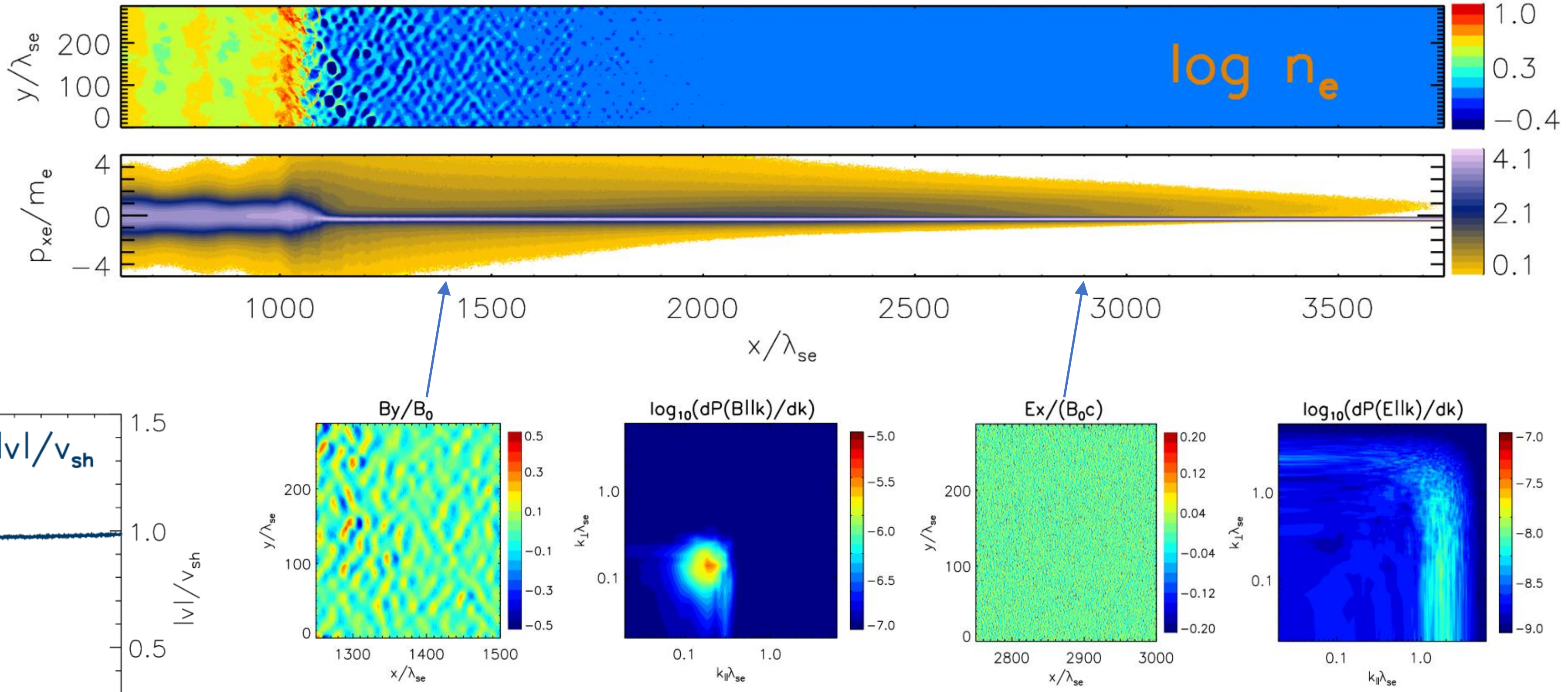
$M_A = 30;\ \theta_{Bn} = 60°$

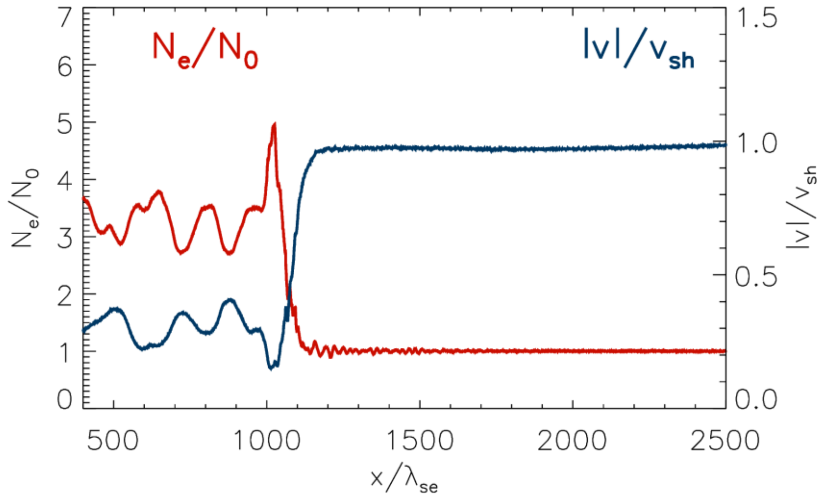


Movie – see video

Near vs far upstream in the electron foreshock

$$M_A = 30$$
$$\theta_{Bn} = 60°$$
$$m_p = 50$$



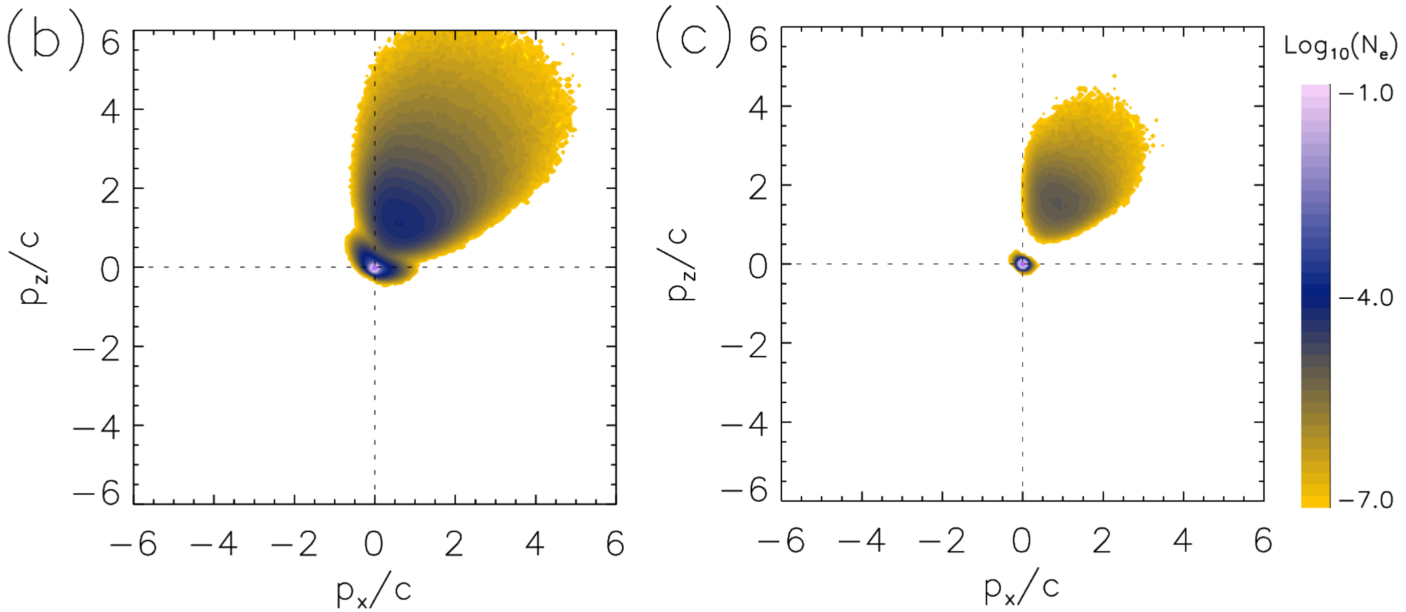


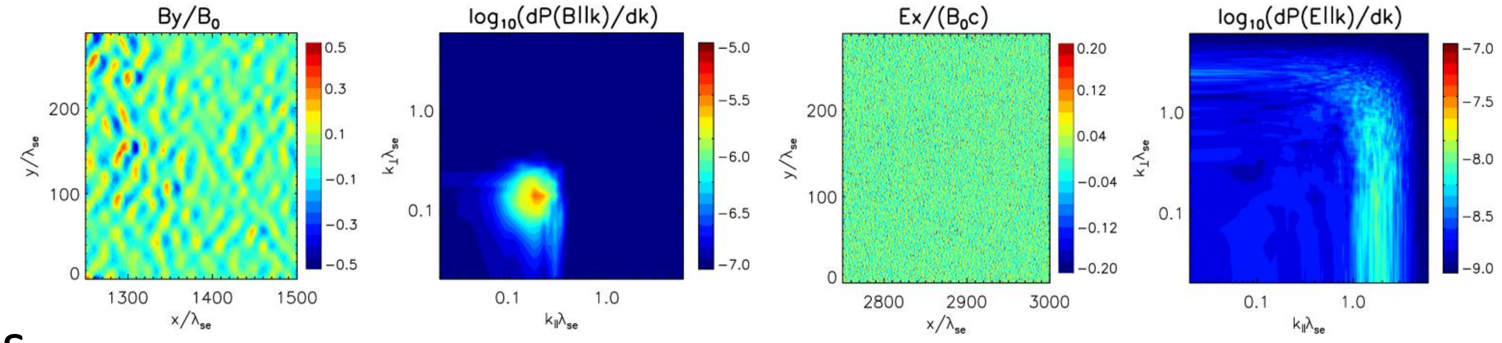
Near upstream:
Oblique whistlers

Far upstream:
Parallel electrostatic waves

Electron distributions

	Near upstrm	Far upstrm
n_{beam}	$0.025\ n_0$	$0.0027\ n_0$
β_{beam}	0.89	0.91
γ_{beam}	2.2	2.4
v_{th}	0.46c	0.40c
$(v_{th,\perp}/v_{th,\parallel})$	0.8	0.8





Reflection by Buneman-driven waves at the shock creates relativistic foreshock electrons

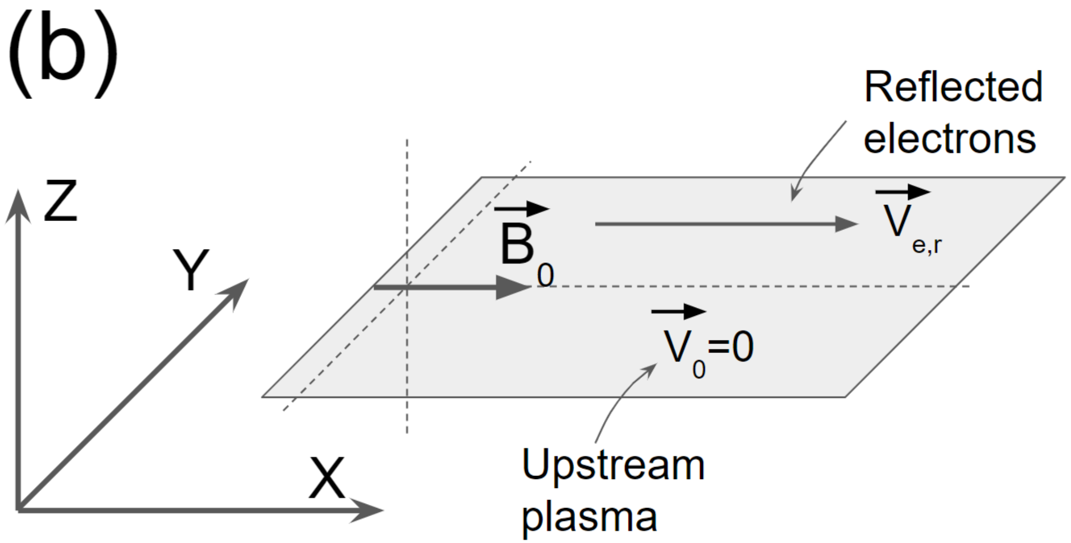
Near upstream:
Oblique whistlers

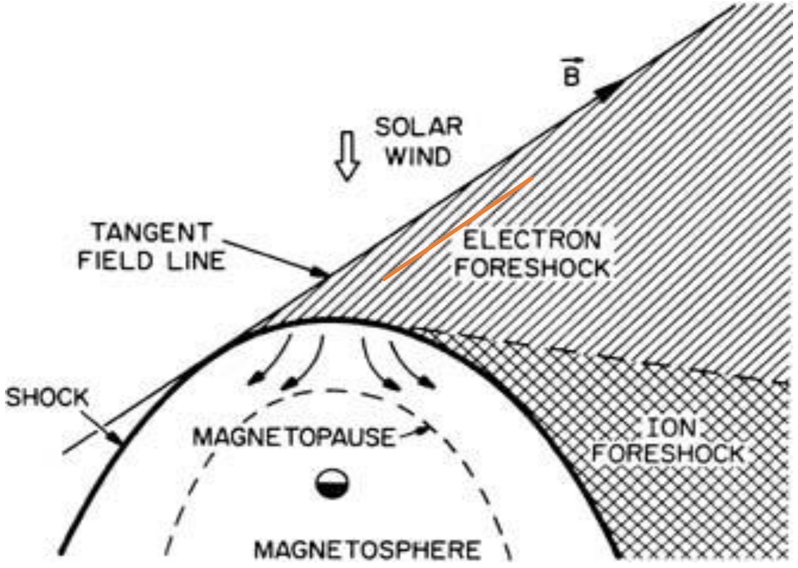
Far upstream:
Parallel electrostatic waves

See Paul Morris' talk...

Periodic simulations: far upstream

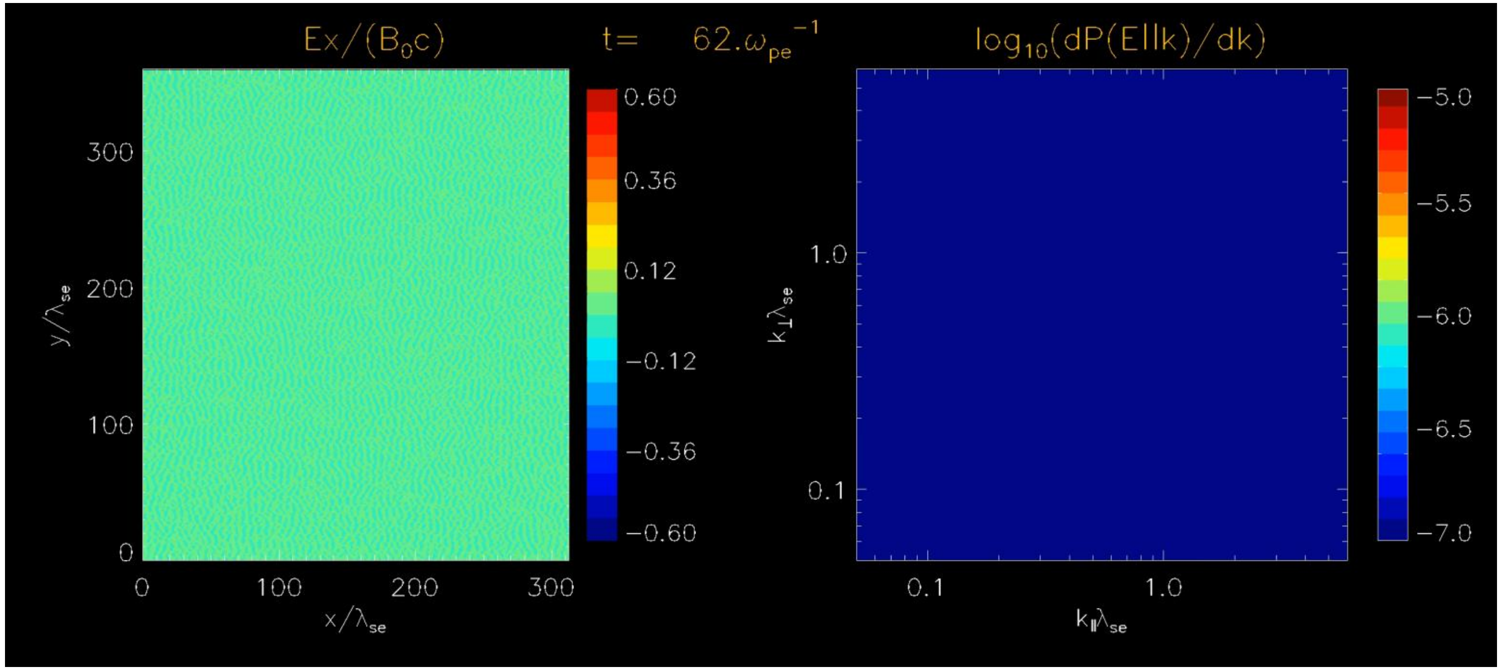
	Far upstrm
n_{beam}	0.0027 n_0
β_{beam}	0.91
γ_{beam}	2.4
v_{th}	0.40c
$(v_{th,\perp}/v_{th,\parallel})$	0.8

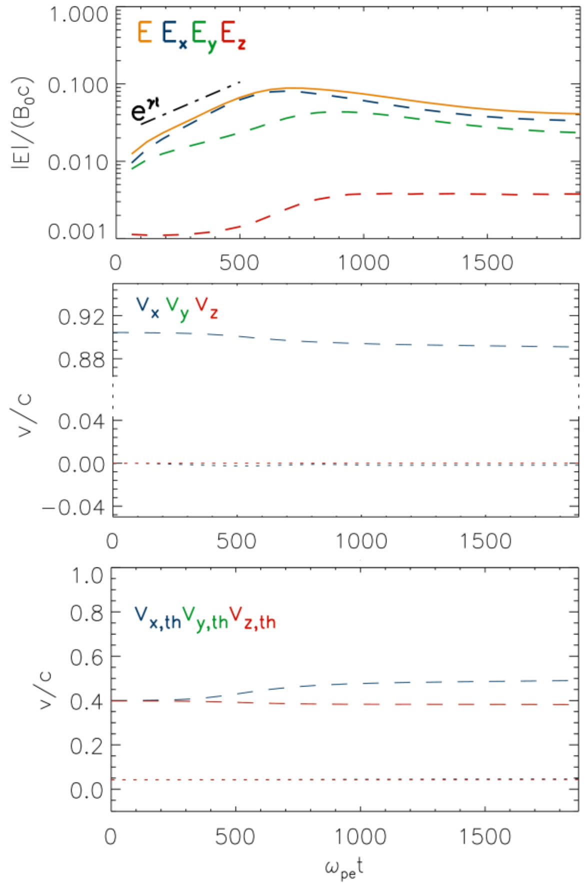




(b) Determine unstable wave modes from linear analysis and periodic PIC simulations

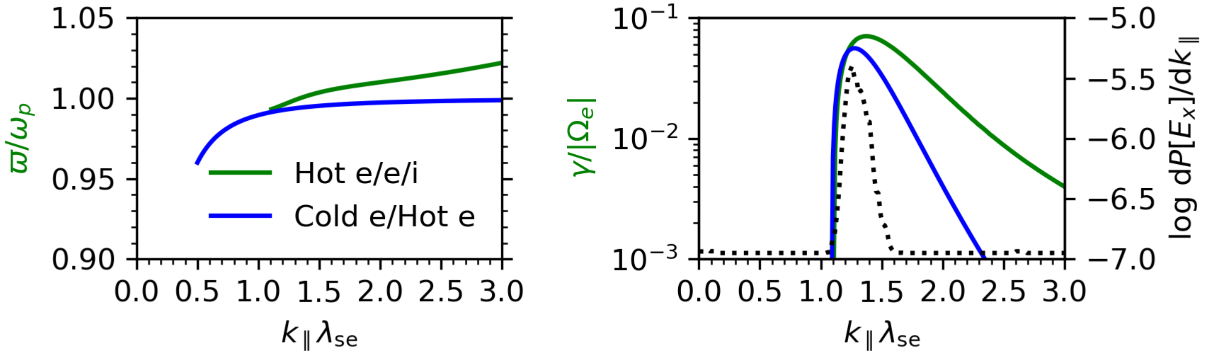
Far upstream: electron-acoustic instability

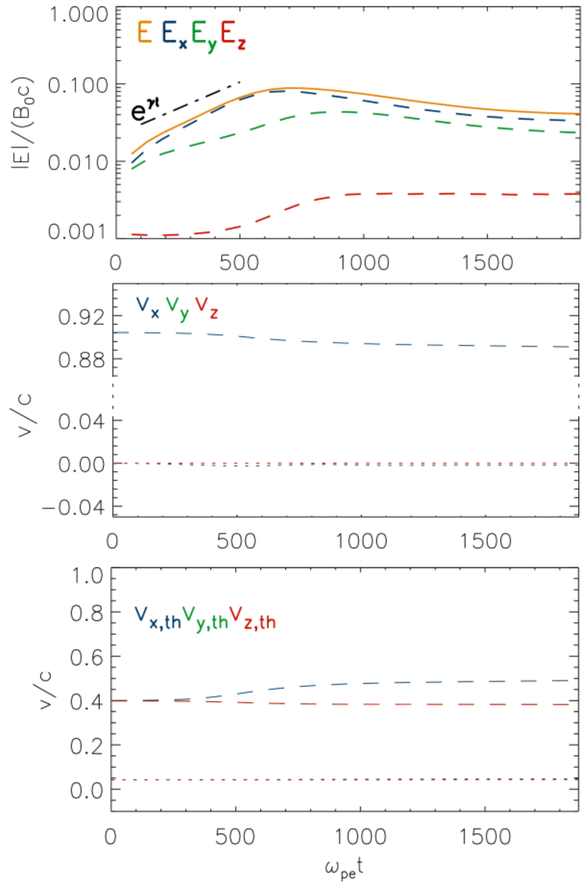




Movie – see video

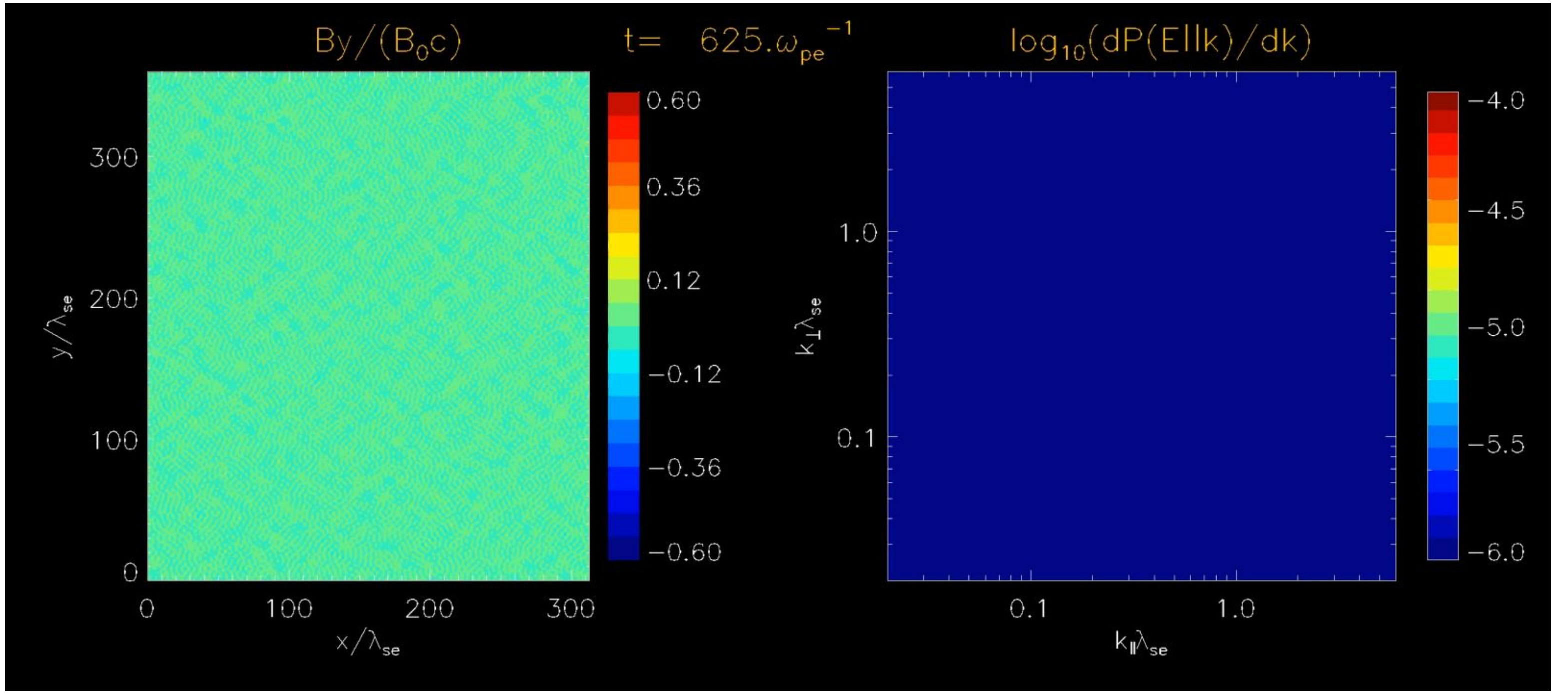
Far upstream: electron-acoustic instability

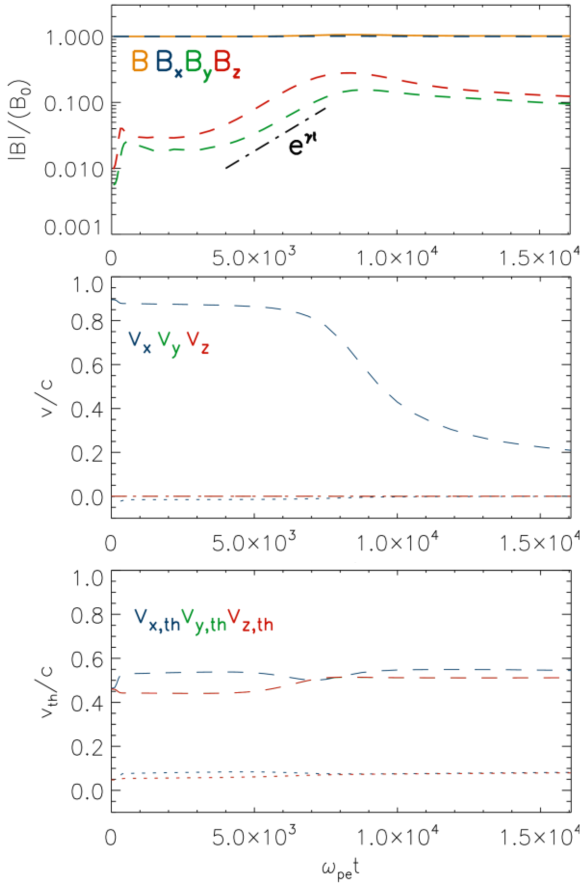




Blue lines: Electron-acoustic instability (e/e 2-stream w/ hot beam)
Green lines: WHAMP (linear dispersion solver)
Both calculations assume **isotropic Gaussians** with **relativistic beam-electron mass** $m_{beam} = \gamma_{beam} m_e$

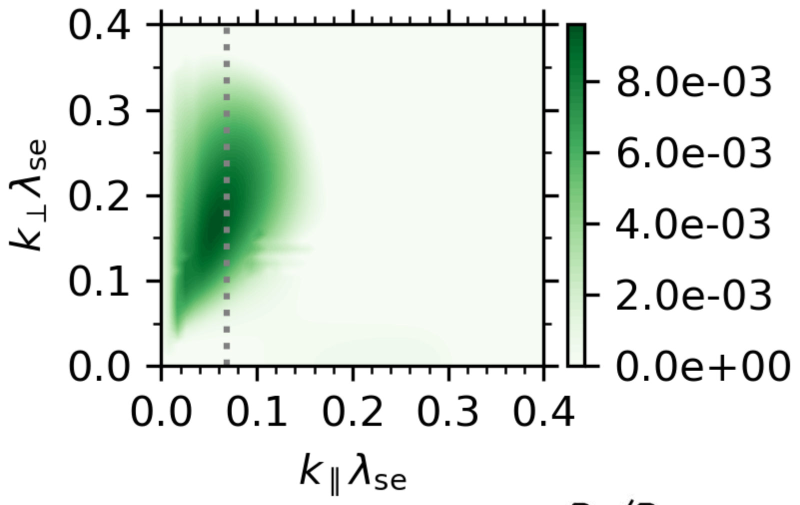
Near upstream: oblique-whistler instability





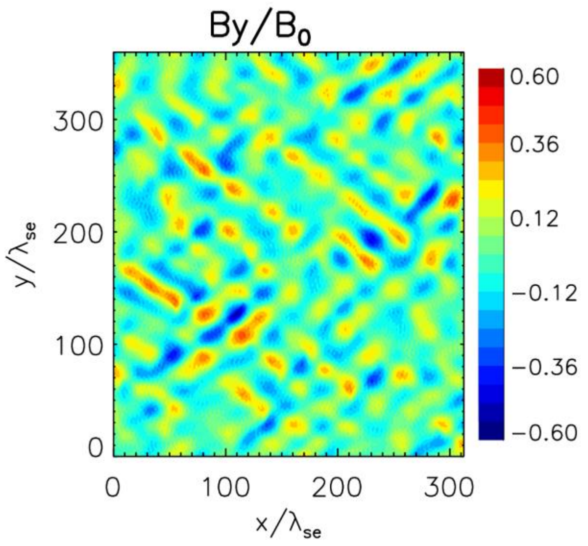
Movie – see video

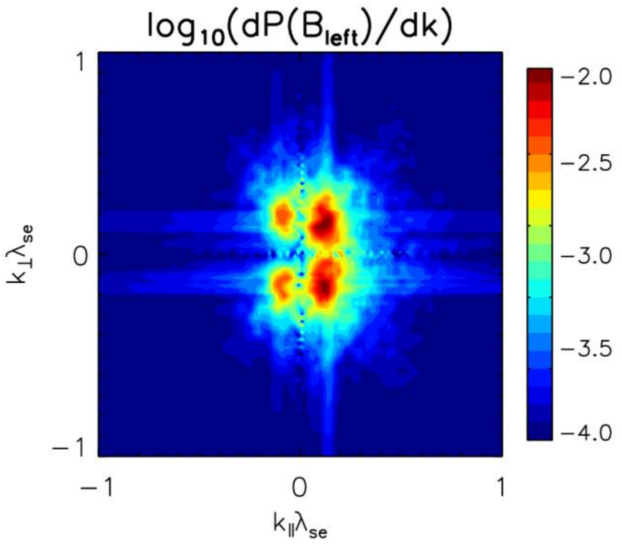
Near upstream: oblique-whistler instability

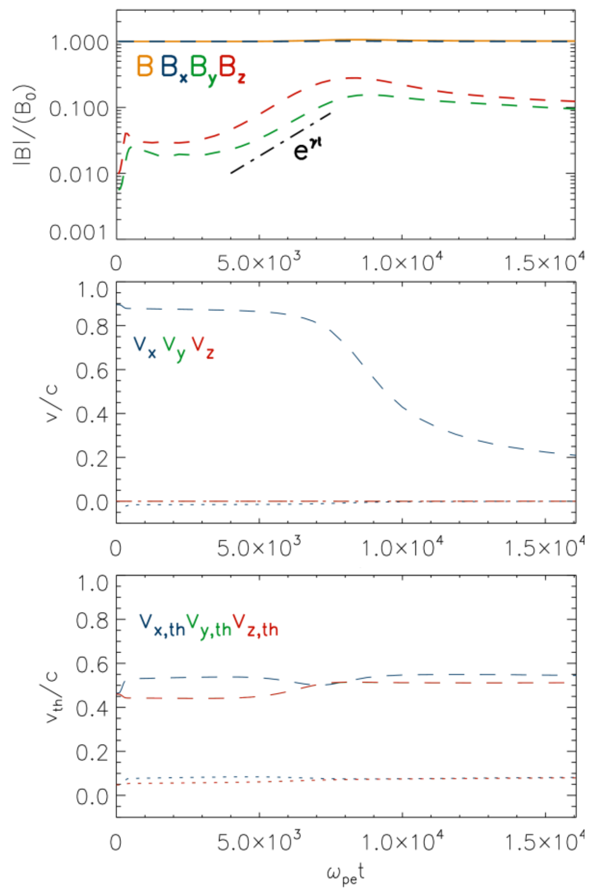


Left: Lin. dispersion solution
Bottom: Magnetic field in simulation and its helicity decomposition

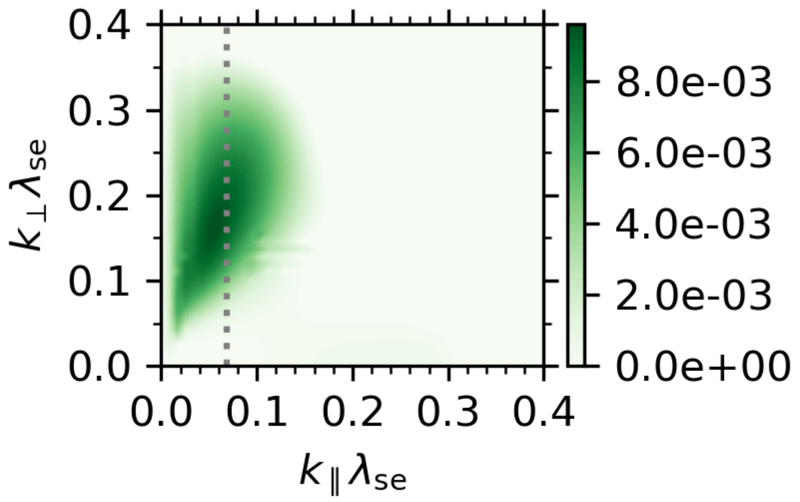
Right-hand polarised waves







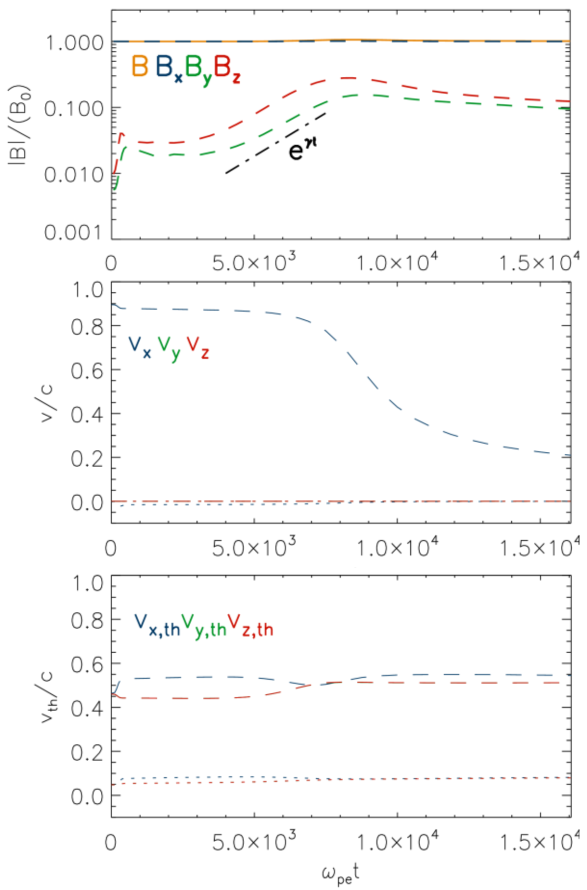
Near upstream: oblique-whistler instability

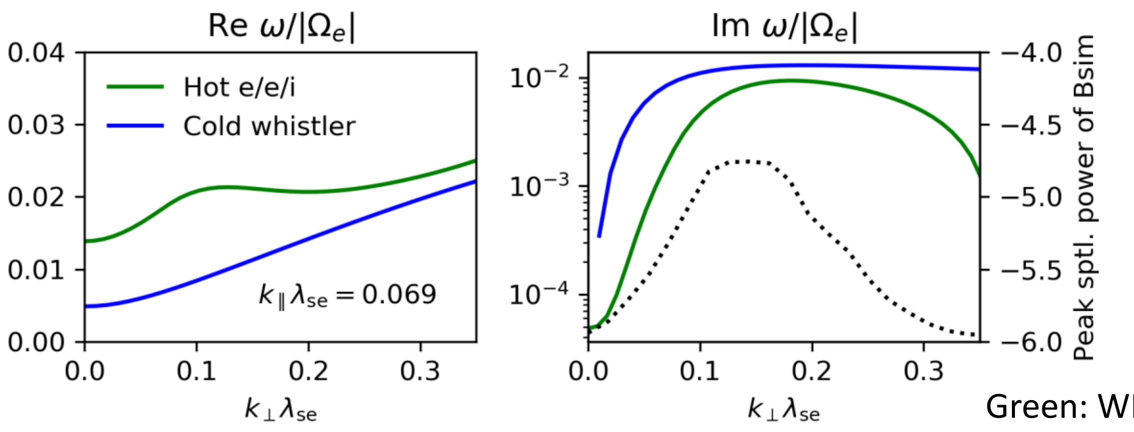


$$\varpi - k_\parallel v_\parallel = 0.9944\ |\Omega_e|$$

(electron gyroresonance)

Right-hand polarised waves





Green: WHAMP

Blue lines: cold-whistler dispersion (left), Stepanov/Kitsenko 1961 (right)

Summary

- Shock-reflected electron beams tend to have a fairly isotropic distribution ($T_\perp < T_\parallel < 2\,T_\perp$)
- In the **far upstream**, the electrostatic **electron-acoustic** instability excites parallel Langmuir waves
- In the **near upstream**, the denser reflected-electron beam is able to excite gyroresonant **oblique whistlers** before the shock arrives
- We observe no whistler heat-flux or electron-beam firehose instabilities