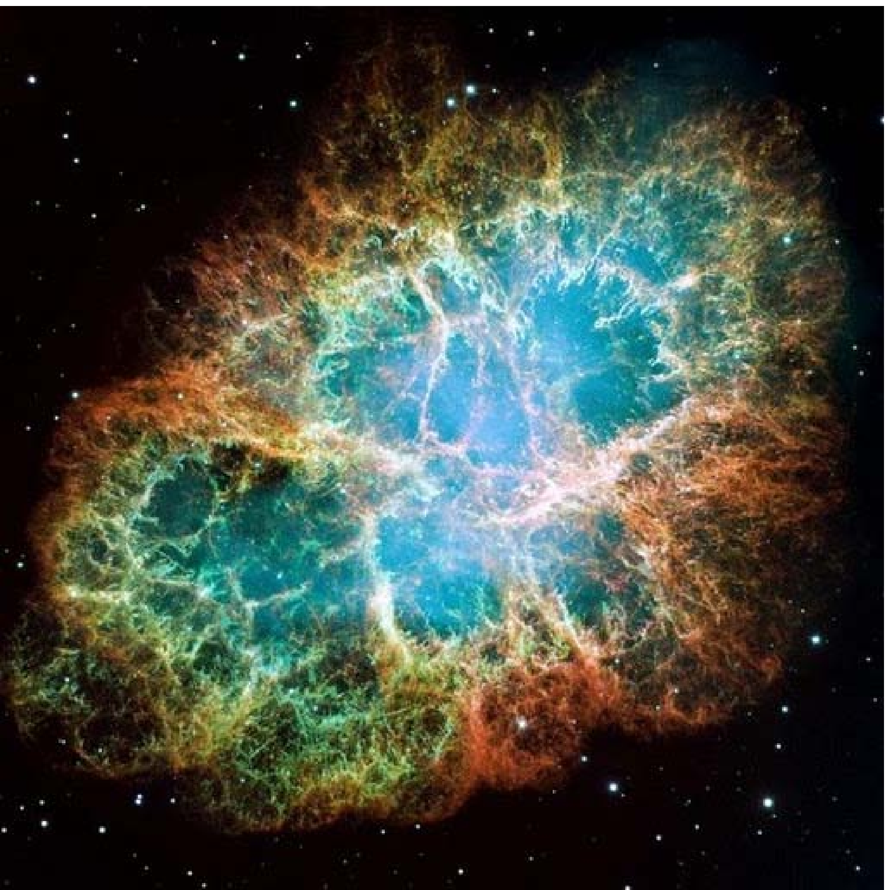
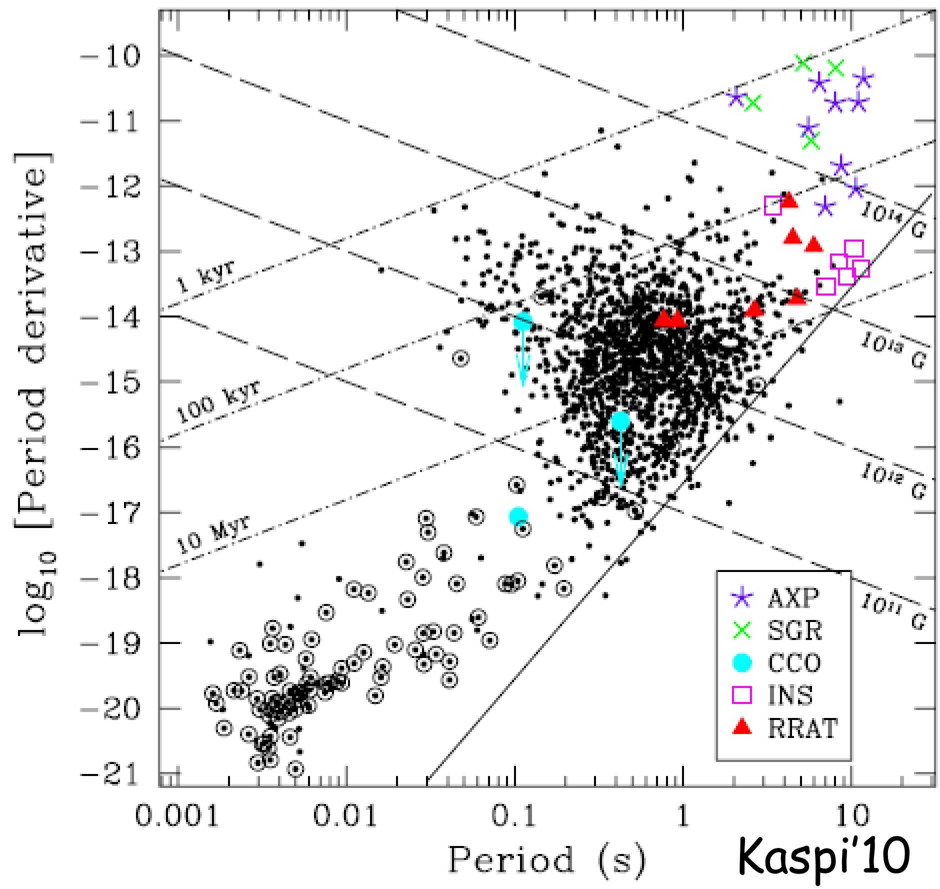
Relativistic Pulsar Wind Termination Shocks Modified by Superluminal Electromagnetic Waves

Takanobu Amano (Univ. Tokyo, Japan)
John Kirk (MPI-K, Germany)

Rotation-powered pulsars

- The energy is fed by the rapid rotation (< 1 s) of a highly magnetized (~10^{12} G) neutron star.





Kaspi'10

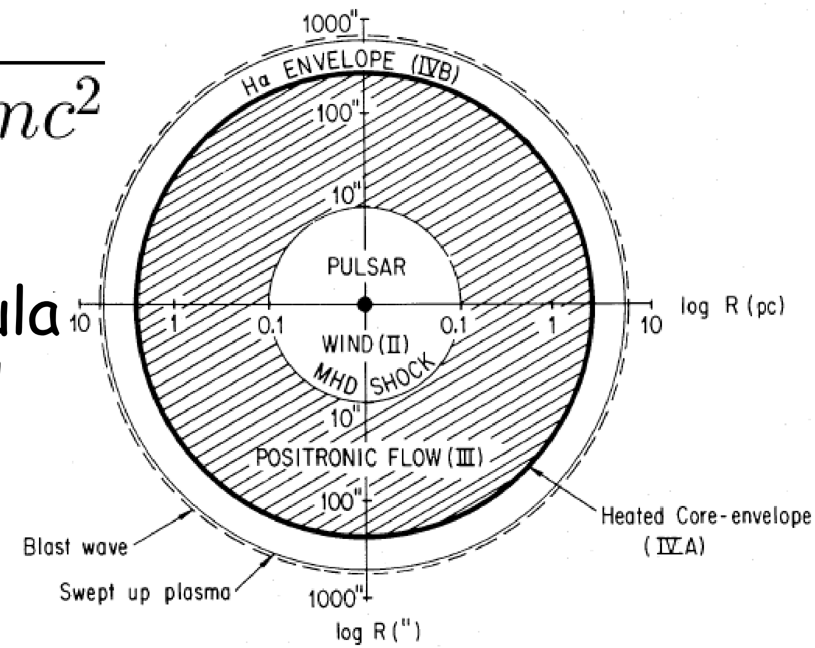
The sigma problem

- The spin-down luminosity of a pulsar is carried away in a form of a relativistic wind.
- It is believed to launch a high-sigma wind, while observations imply the opposite.

$$\sigma = \frac{B^2}{4\pi\gamma^2 nmc^2}$$

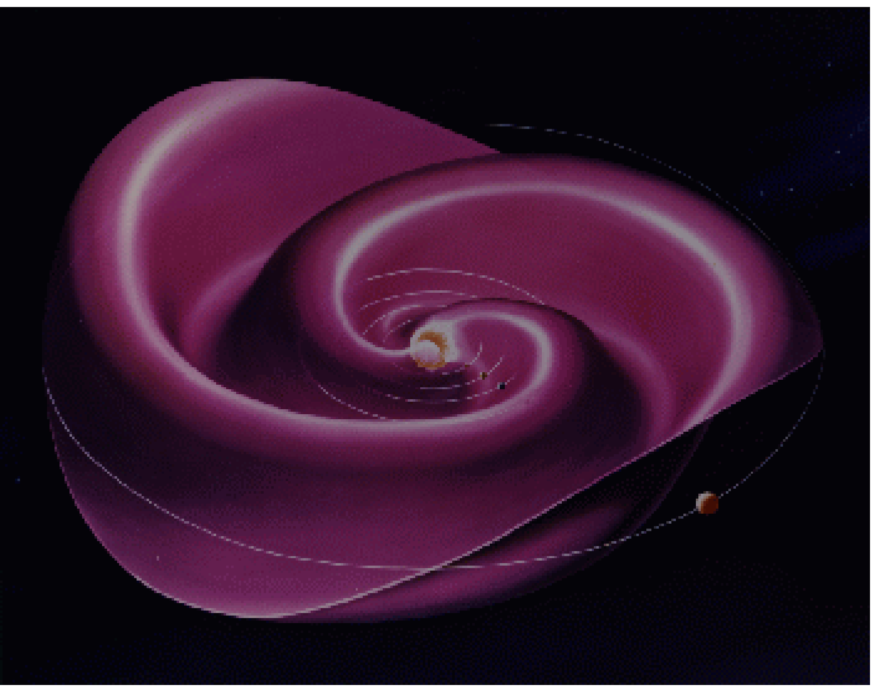
$\sigma \ll 1$ @ nebula
$\sigma \gg 1$ @ wind

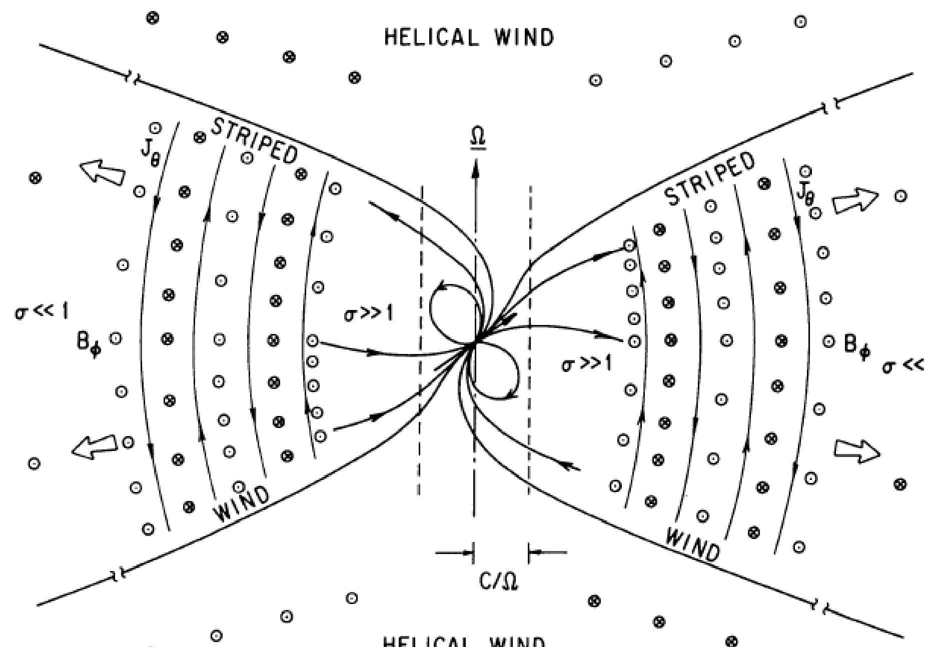
Kennel&Coroniti'84



The striped wind

- Series of current sheets (i.e., MHD waves) are produced by obliquely rotating pulsars.
- Magnetic reconnection has been believed to be important for the required dissipation.



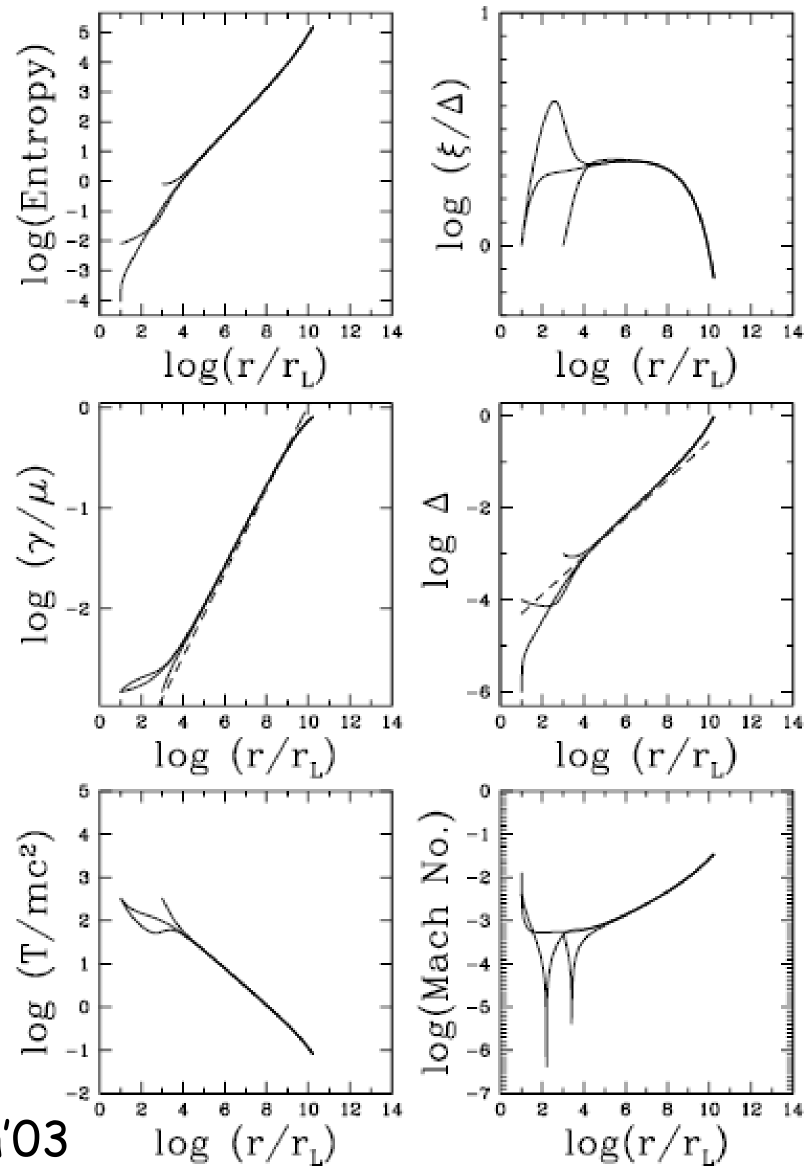


Coroniti'90

Consequence of dissipation in the wind

- Dissipation of Poynting flux in the wind leads to the acceleration of the wind flow.
- Relativistic dilation effect makes the apparent (lab frame) dissipation rate smaller.
- Dissipation may not complete in the wind zone.

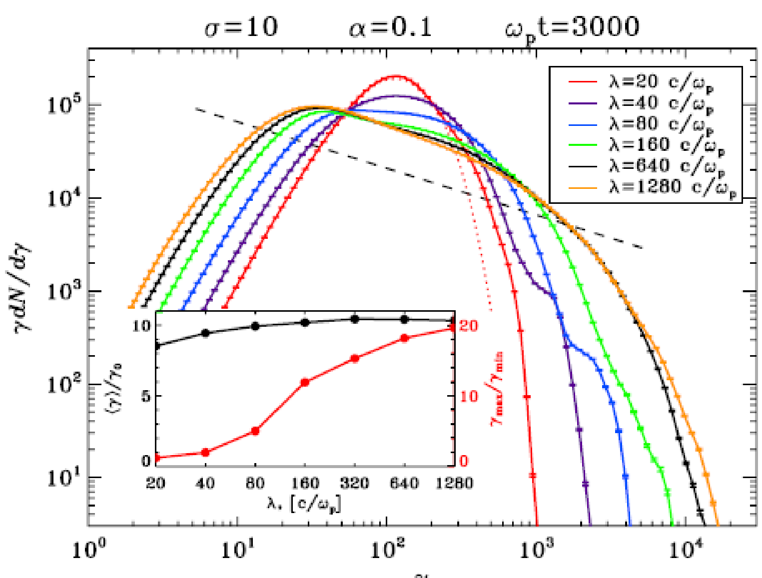
[Lyubarsky&Kirk'01, Kirk&Skjaeraasen'03]

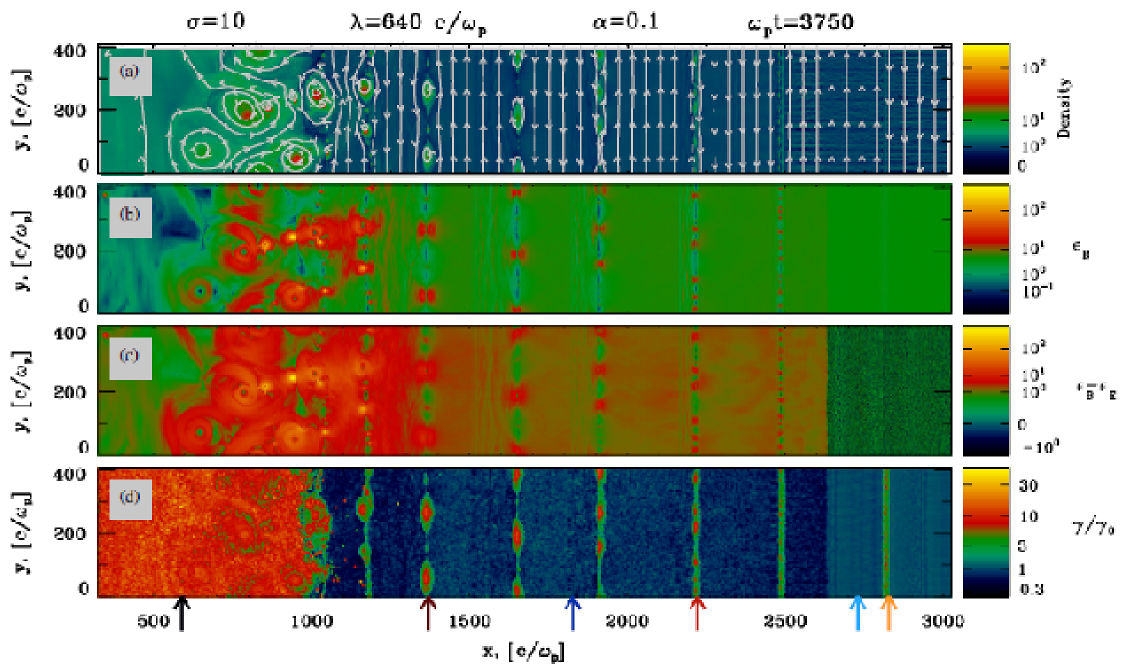


Kirk&Skjaeraasen'03

Interaction with the shock

- The current sheets will eventually interact with the termination shock.
- Magnetic reconnection triggered by the interaction may be responsible for the dissipation as well as the production of non-thermal particles.





Sironi&Spitkovsky'11

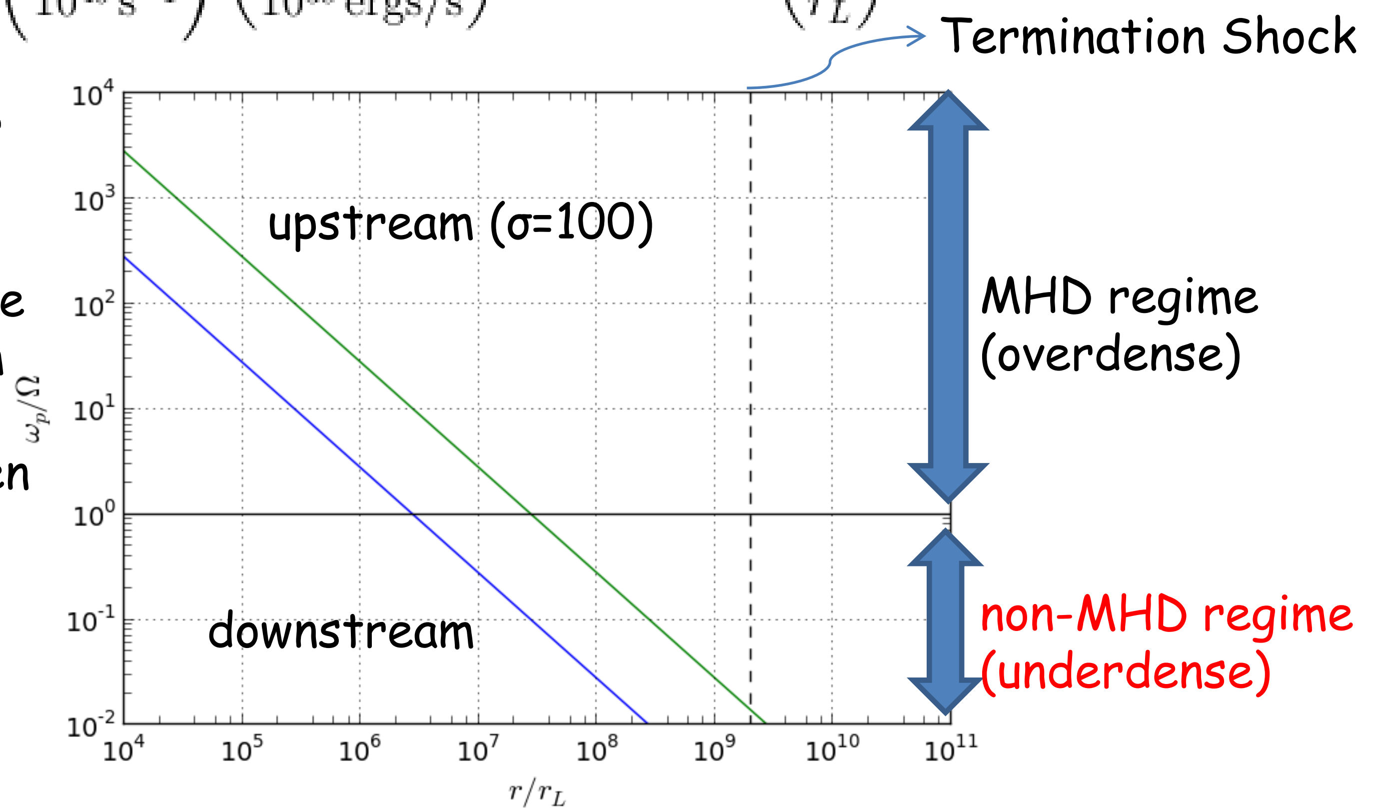
Relevant parameter regime

- The rotation frequency of a young pulsar (measured in the lab. frame) can be higher than the local proper plasma frequency in a far wind zone.

$$\frac{\omega_p}{\Omega} \sim 2.8 \times 10^6 \left(\frac{\dot{N}}{10^{40}\,\mathrm{s}^{-1}}\right)\left(\frac{L}{10^{38}\,\mathrm{ergs/s}}\right)^{-1/2} (1+\sigma)^{1/2} \left(\frac{r}{r_L}\right)^{-1}$$

Fiducial parameters for the Crab.

Interaction between the shock and the upstream waves is likely to occur in non-MHD regime, then what happens ?

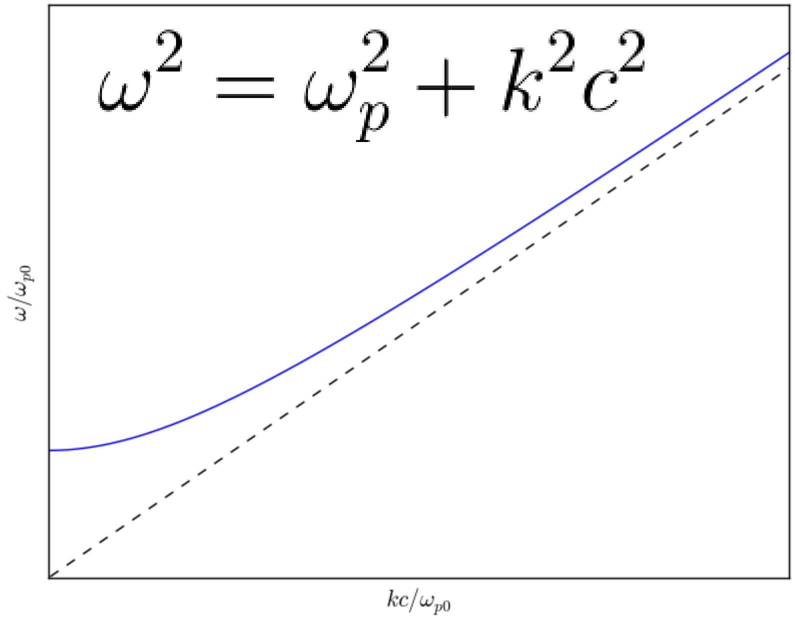


Nonlinear superluminal waves

- Nonlinear counterparts of EM waves, thereby having super-luminal phase speeds (contrary to subluminal MHD waves).
- Relevance to pulsar physics has long been discussed.

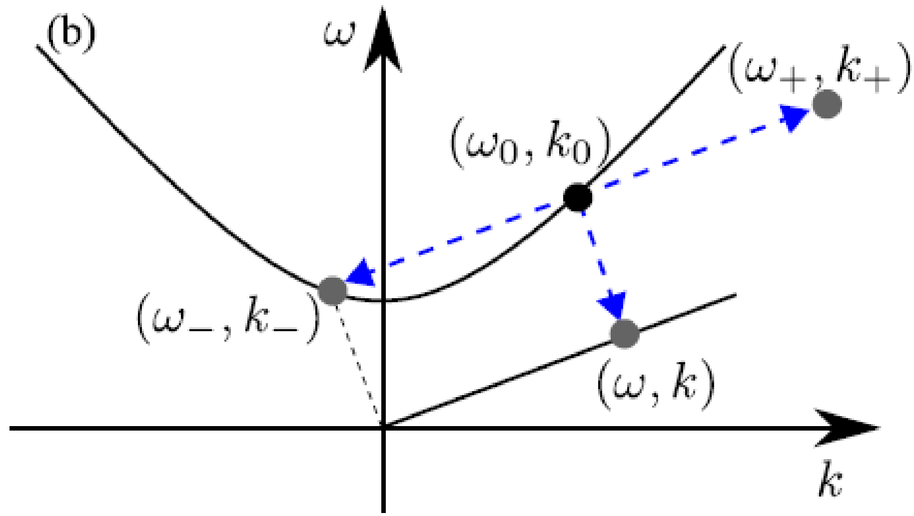
  [c.f., Kennel&Pellat'76, Melatos&Melrose'96, Skjaeraasen+'05, Kirk'10, Arka&Kirk'12]

Nonlinear "dispersion relation" to circularly polarized superluminal waves



The cut-off frequency is determined by the proper plasma frequency.

Parametric instability of EM waves



$$\omega_\pm = \omega_0 \pm \omega \quad k_\pm = k_0 \pm k$$

- The strong pump EM wave can couple to a longitudinal perturbation (sound-like wave) when the matching condition is satisfied. The generated longitudinal waves will eventually dissipate through various processes (formation of shocks, collisionless damping).

Relativistic two-fluid model

- The following system of equations is the simplest model that allows high frequency EM waves to propagate.

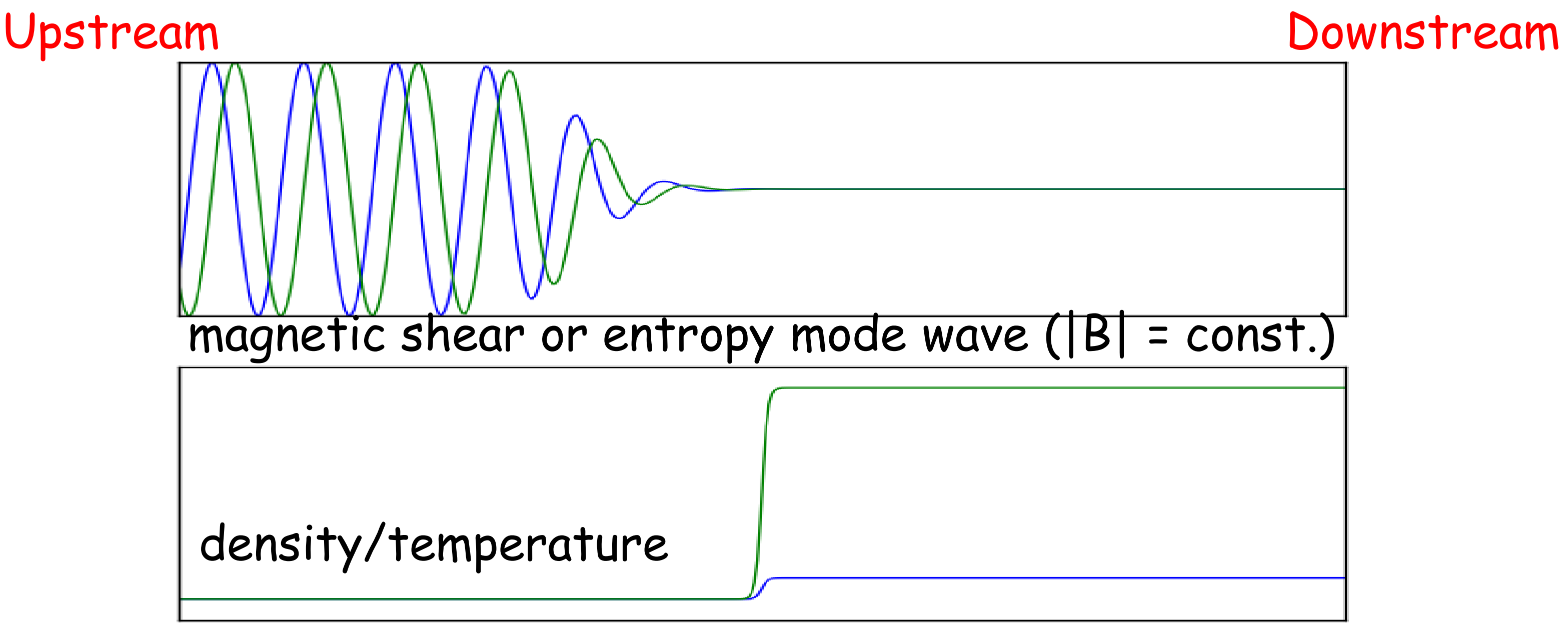
$$
\begin{aligned}
\frac{\partial}{\partial t}(\gamma_s n_s) + \nabla \cdot (n_s \mathbf{u}_s) &= 0, \\
\frac{\partial}{\partial t}\left(\frac{w_s}{c^2}\gamma_s \mathbf{u}_s\right) + \nabla \cdot \left(\frac{w_s}{c^2}\mathbf{u}_s\mathbf{u}_s + \mathbf{I}p_s\right) &= q_s \gamma_s n_s \left(\mathbf{E} + \frac{\mathbf{u}_s}{\gamma_s c} \times \mathbf{B}\right), \\
\frac{\partial}{\partial t}\left(w_s \gamma_s^2 - p_s\right) + \nabla \cdot (w_s \gamma_s \mathbf{u}_s) &= q_s n_s \mathbf{u}_s \cdot \mathbf{E}, \\
\frac{1}{c}\frac{\partial}{\partial t}\mathbf{E} &= \nabla \times \mathbf{B} + \frac{4\pi}{c}\mathbf{J}, \\
\frac{1}{c}\frac{\partial}{\partial t}\mathbf{B} &= -\nabla \times \mathbf{E}, \\
\nabla \cdot \mathbf{E} &= 4\pi\rho, \\
\nabla \cdot \mathbf{B} &= 0,
\end{aligned}
$$

enthalpy density : $w_s = n_s m_s c^2 + \Gamma/(\Gamma - 1)p_s$

* 1D simulations with central scheme with WENO5 + TVD-RK3

Simulation setup

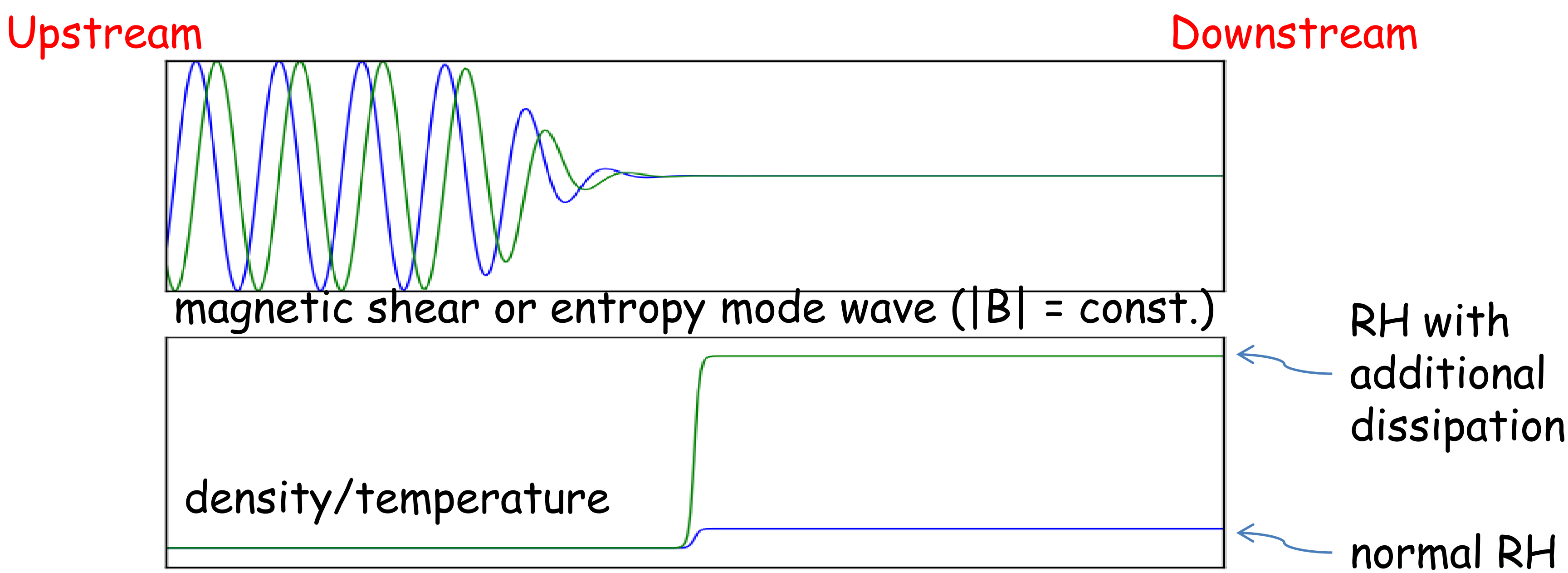
- The pulsar-driven wave is modeled by a circularly polarized magnetic shear wave, which is an equilibrium structure (ω=0) in the comoving frame.
- Phase-averaged magnetic field is zero.



Simulation setup

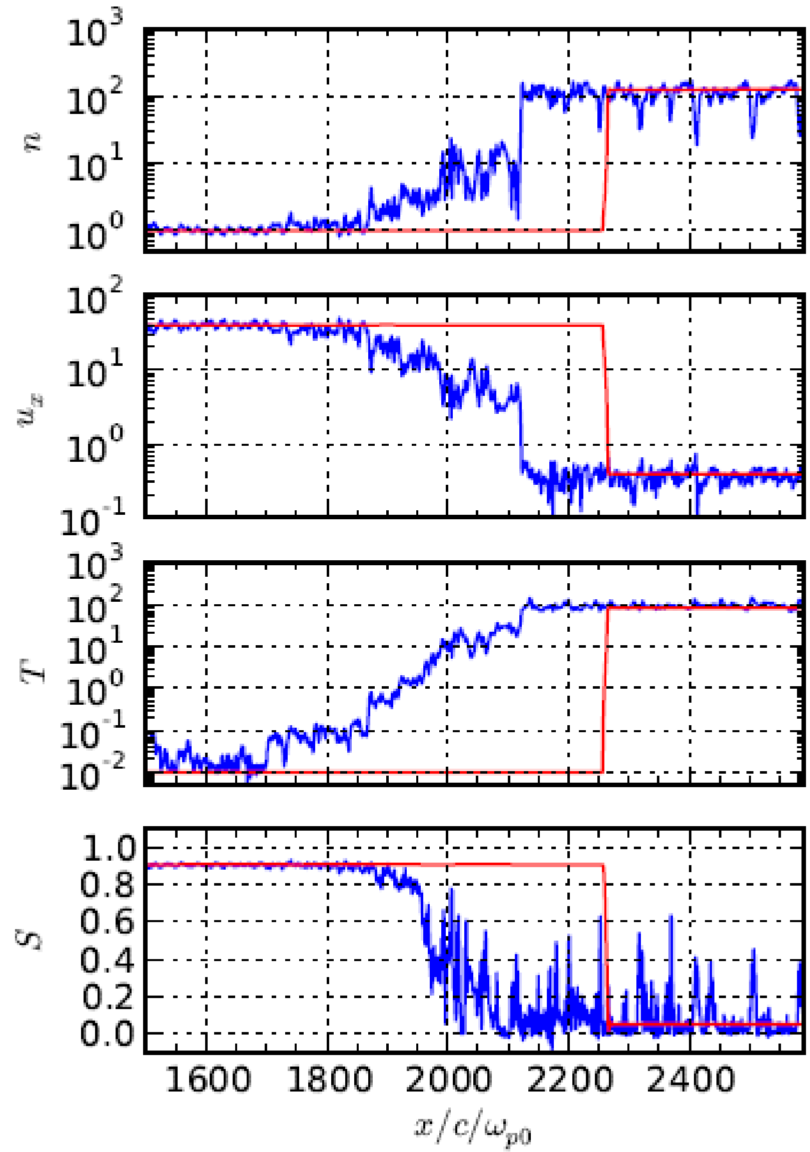
- Complete dissipation of Poynting flux is assumed.

$$
\begin{aligned}
2n_1 u_{x,1} &= 2n_2 u_{x,2} \\
2w_1 \frac{u_{x,1}^2}{c^2} + 2p_1 + \left(1 + \frac{u_{x,1}^2}{\gamma_1^2 c^2}\right)\frac{B_1^2}{8\pi} &= 2w_2 \frac{u_{x,2}^2}{c^2} + 2p_2 \\
2w_1 \gamma_1 u_{x,1} + \frac{u_{x,1}}{\gamma_1}\frac{B_1^2}{4\pi} &= 2w_2 \gamma_2 u_{x,2},
\end{aligned}
$$



High freq. v.s. Low freq.

- Circularly polarized magnetic shear (entropy-mode) waves are injected from upstream.
- Parameters
  - $\sigma = 10$, $\gamma = 40$, $\Omega/\omega_p = 1.2, 0.4$
- An extended precursor ahead of a subshock is found associated with the dissipation.
- The structure remarkably resembles that of a cosmic-ray modified shock [Drury&Völk'81].
- The modification is due to intense EM waves.

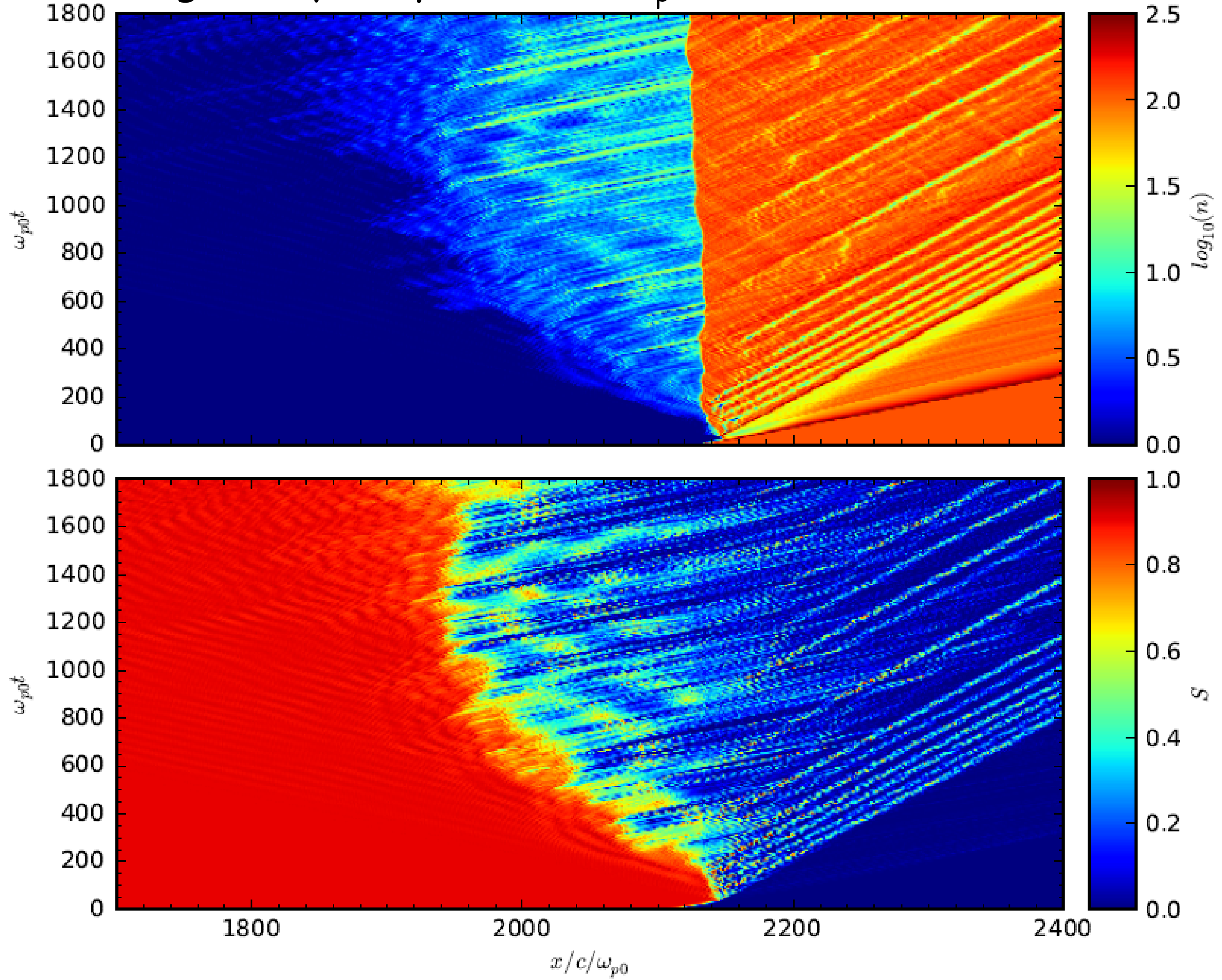


Time evolution

High frequency case: $\Omega/\omega_p = 1.2$

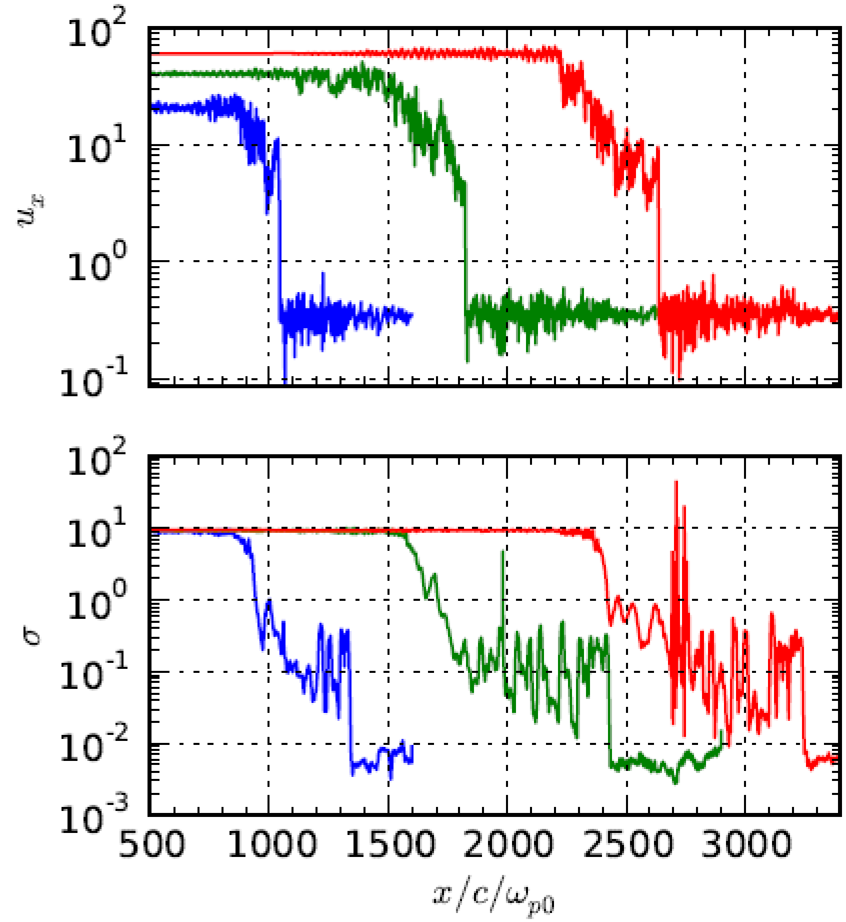
density

Poynting flux

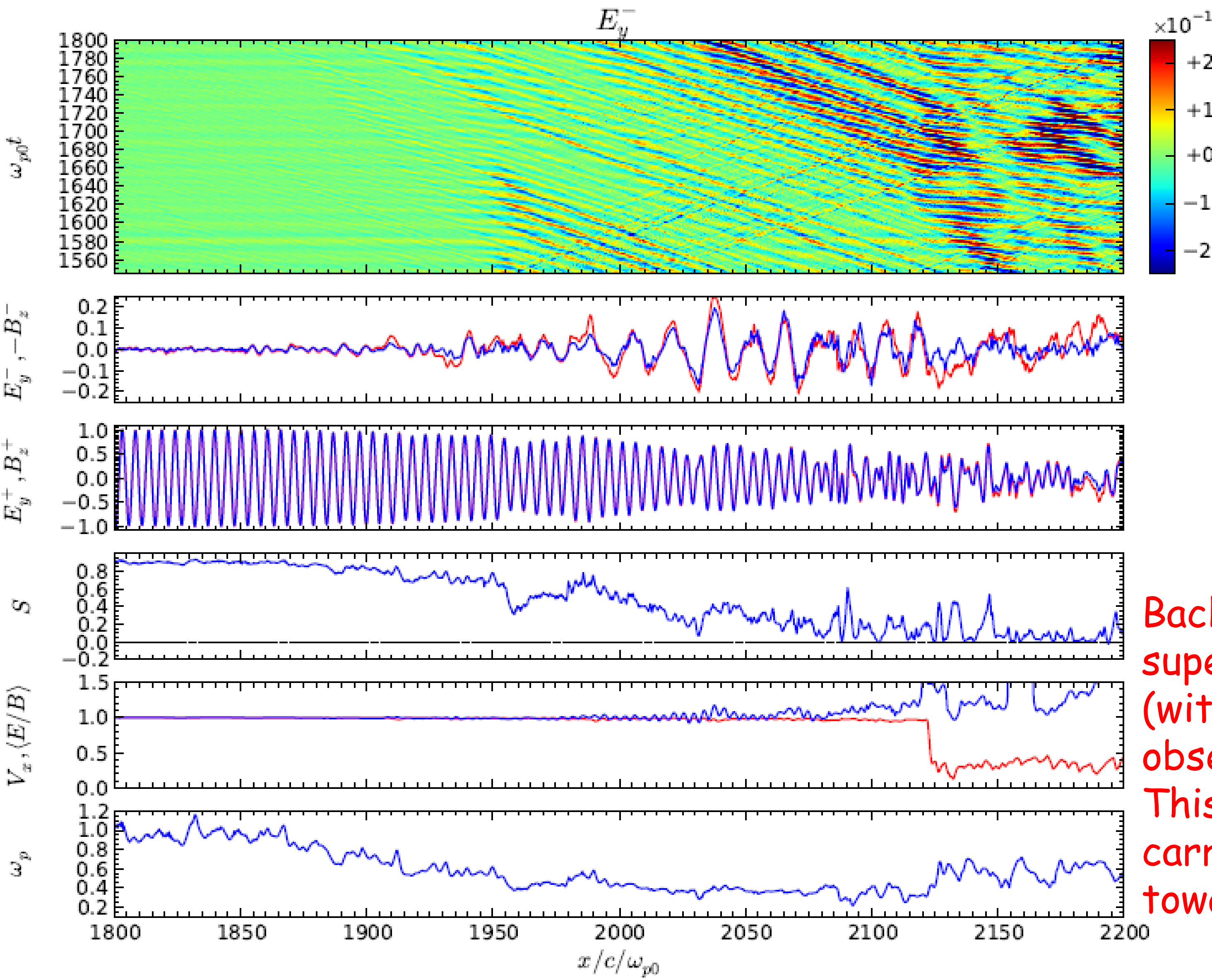


Downstream sigma

- The magnetization parameter sigma substantially decreases through the precursor and subshock.
- The remaining Poynting flux in the downstream is entirely carried by superluminal waves, meaning that the frozen-in condition is completely violated.



Precursor structure



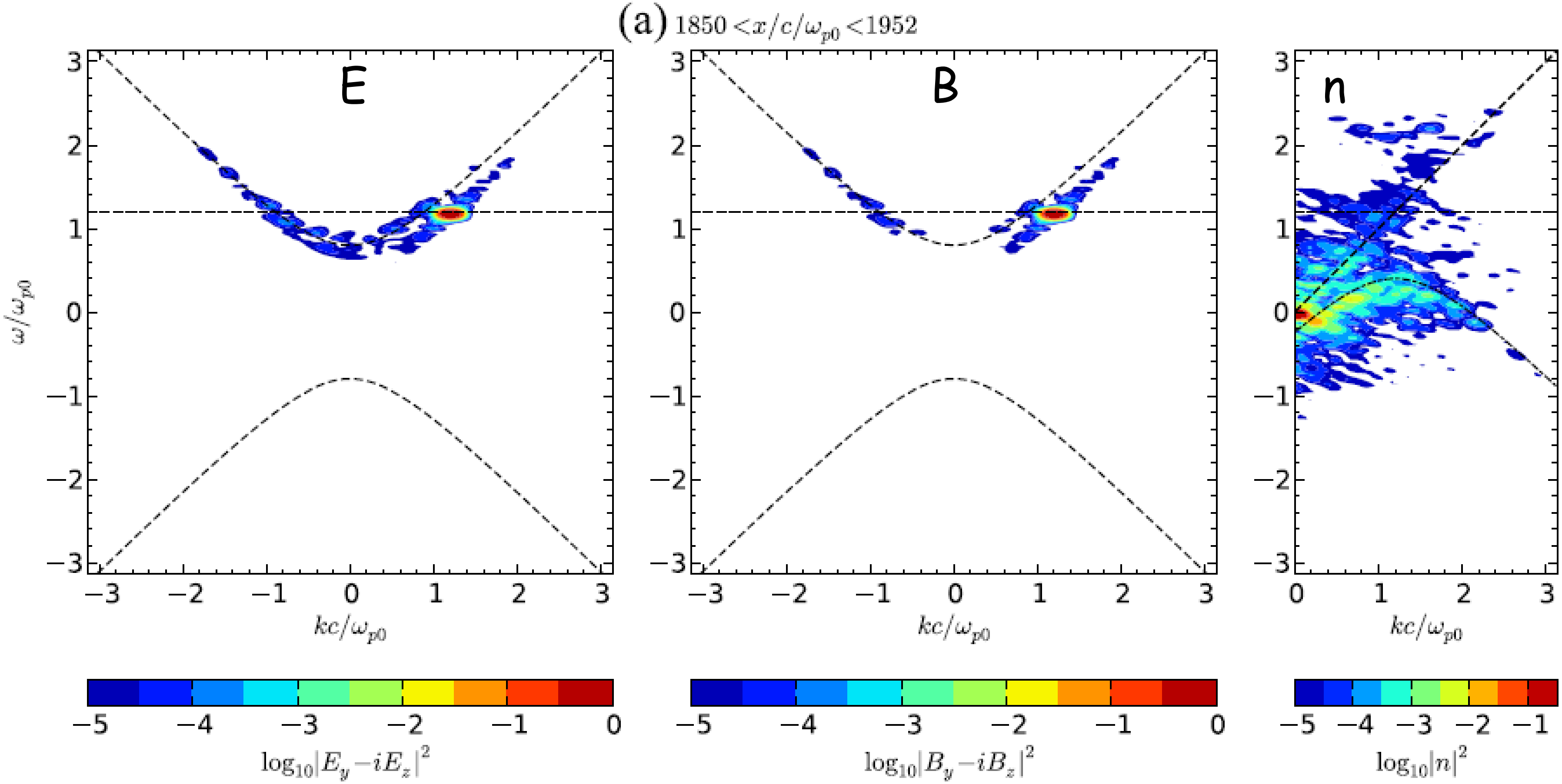
negative helicity

negative helicity

positive helicity

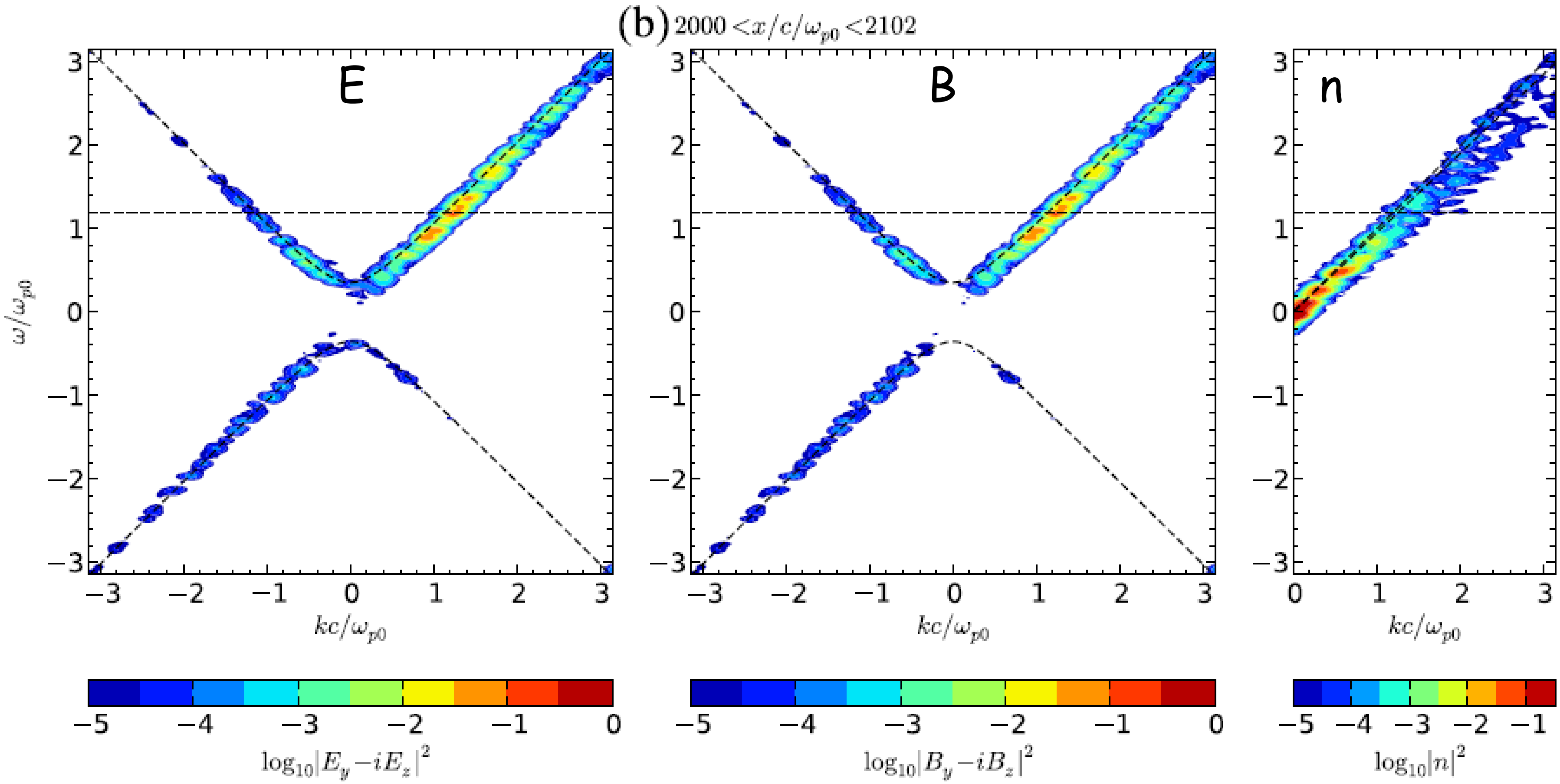
Backward-propagating superluminal waves (with E>B !) are indeed observed.
This is the only agent carrying information toward upstream.

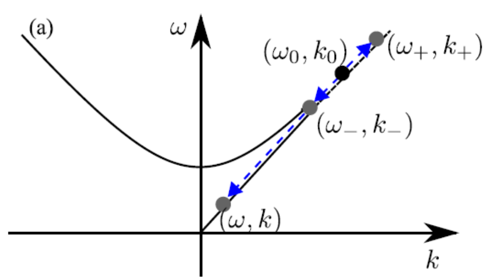
Wave spectra (leading edge)



The density perturbation indicates that the pump wave seems to interact with EM waves, which could be the reason for mode conversion.

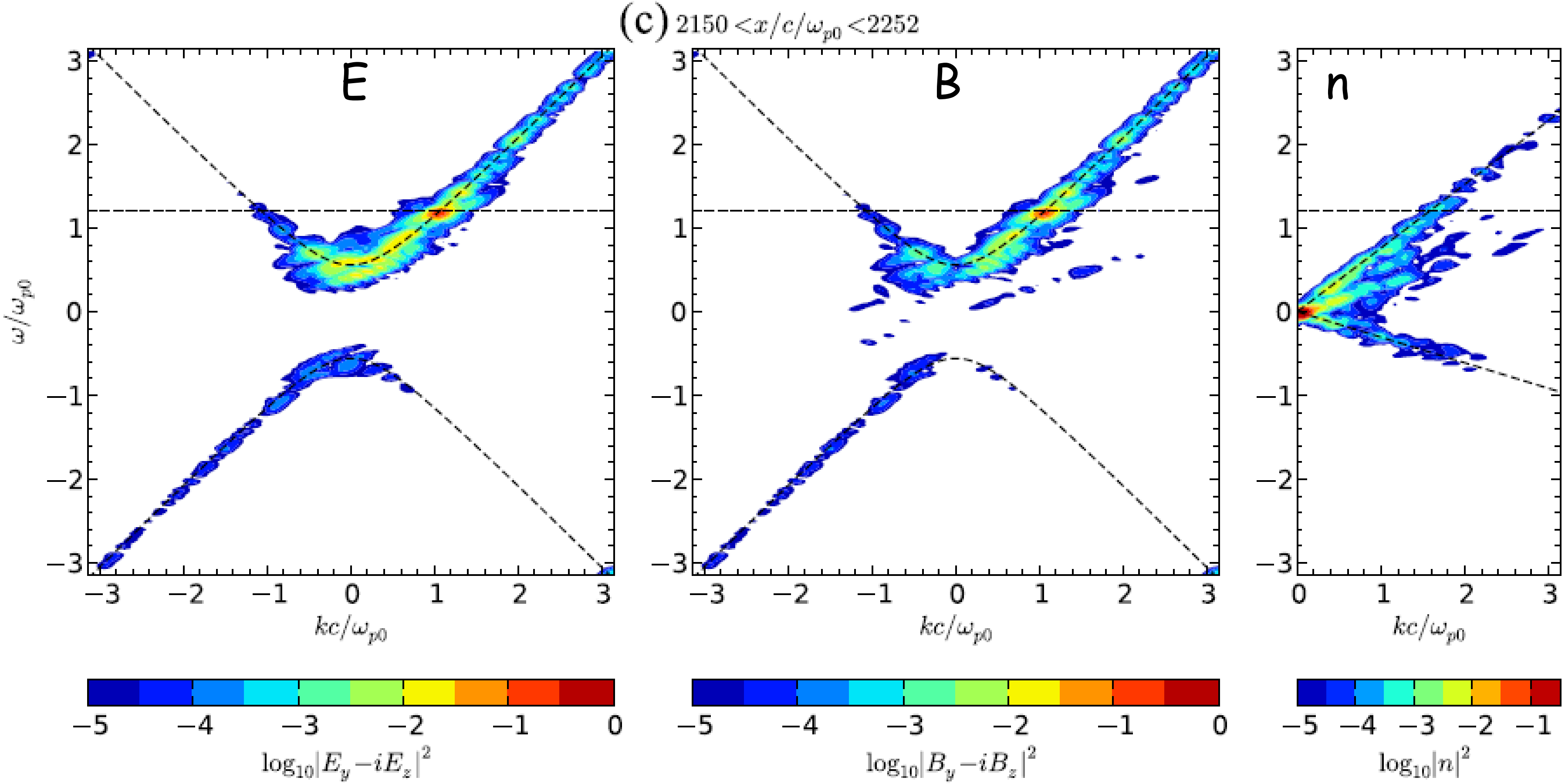
Wave spectra (precursor)

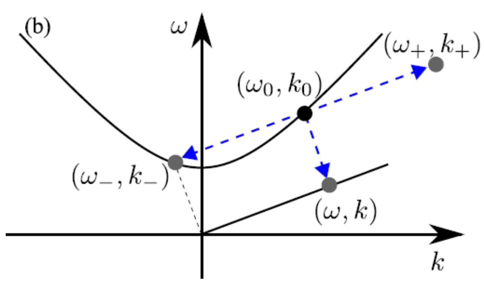




The incoming entropy-mode wave has already been converted into superluminal waves in the precursor, which subsequently decay into sound-like waves.

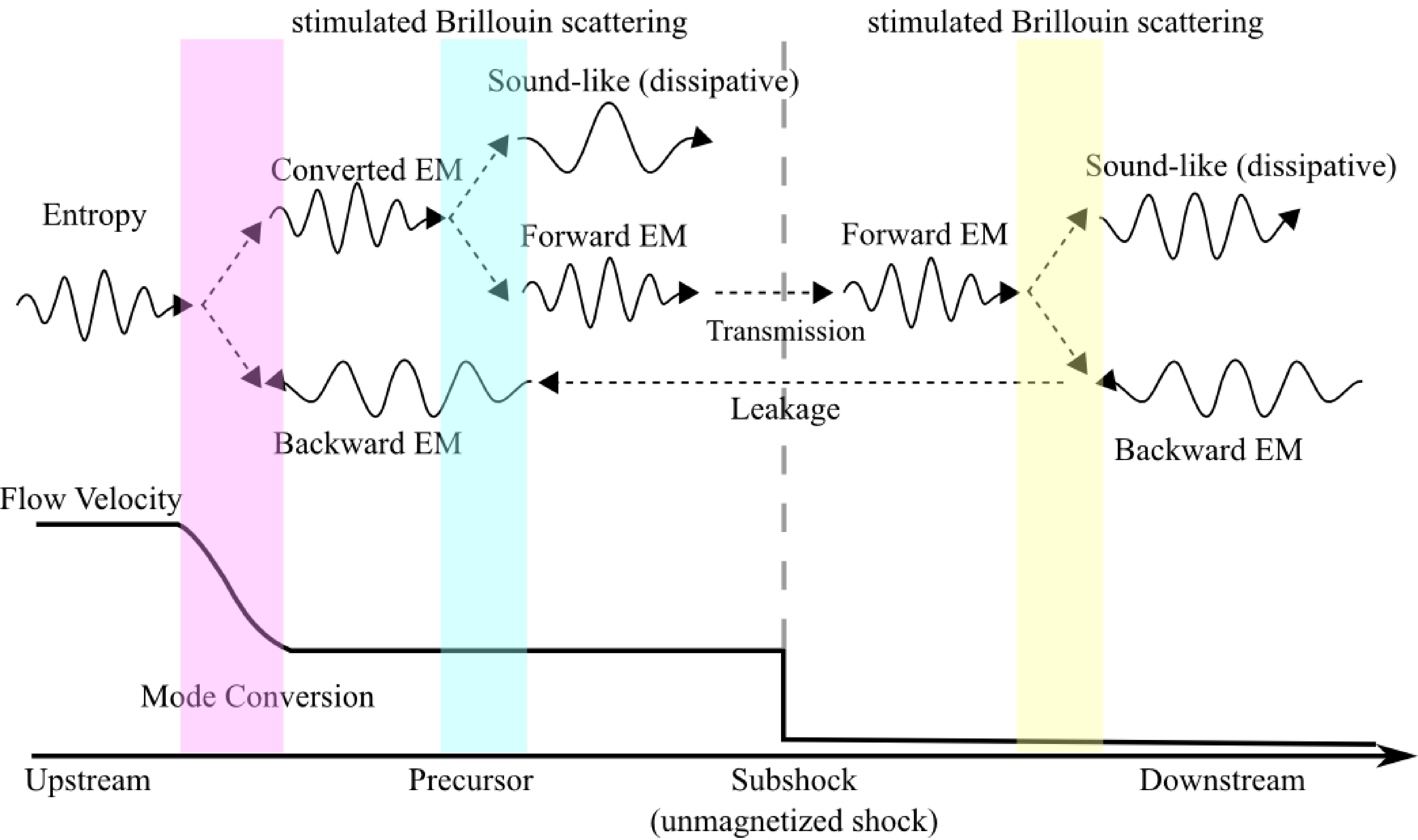
Wave spectra (downstream)





Backward propagating EM waves are generated in the downstream, which eventually leak out toward the precursor region.

Schematic view



Conclusions

- MHD (or entropy-mode) waves driven by an oblique rotator may be converted into superluminal EM waves of relativistic intensity through the interaction with a standing relativistic termination shock.
- The superluminal waves rapidly decay and lead to substantial dissipation of Poynting flux, which modifies the overall shock structure.
- The downstream flow becomes essentially un-magnetized by passing through the modified shock, as required to explain observations of PWNe.

Reference: Amano, T., Kirk, J. G., The Role of Superluminal Electromagnetic Waves in Pulsar Wind Termination Shocks, Astrophys. J., 770, 18, 2013