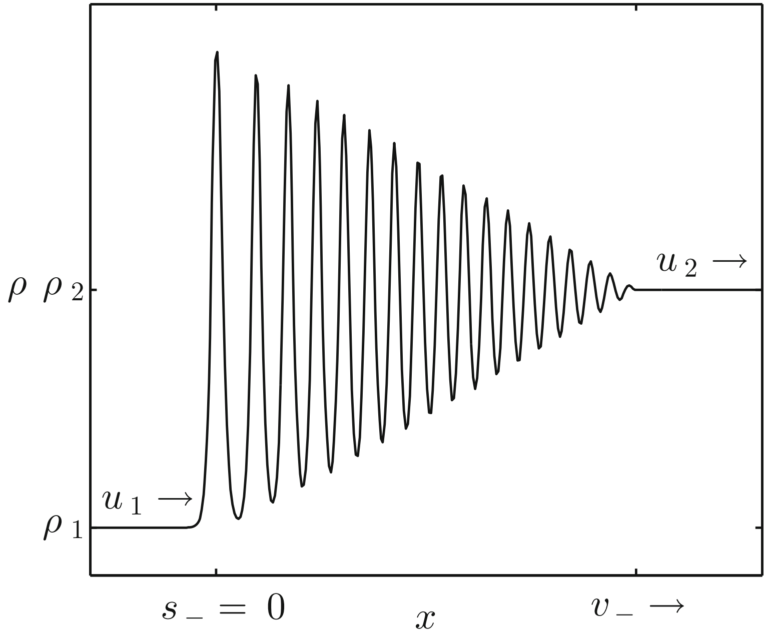


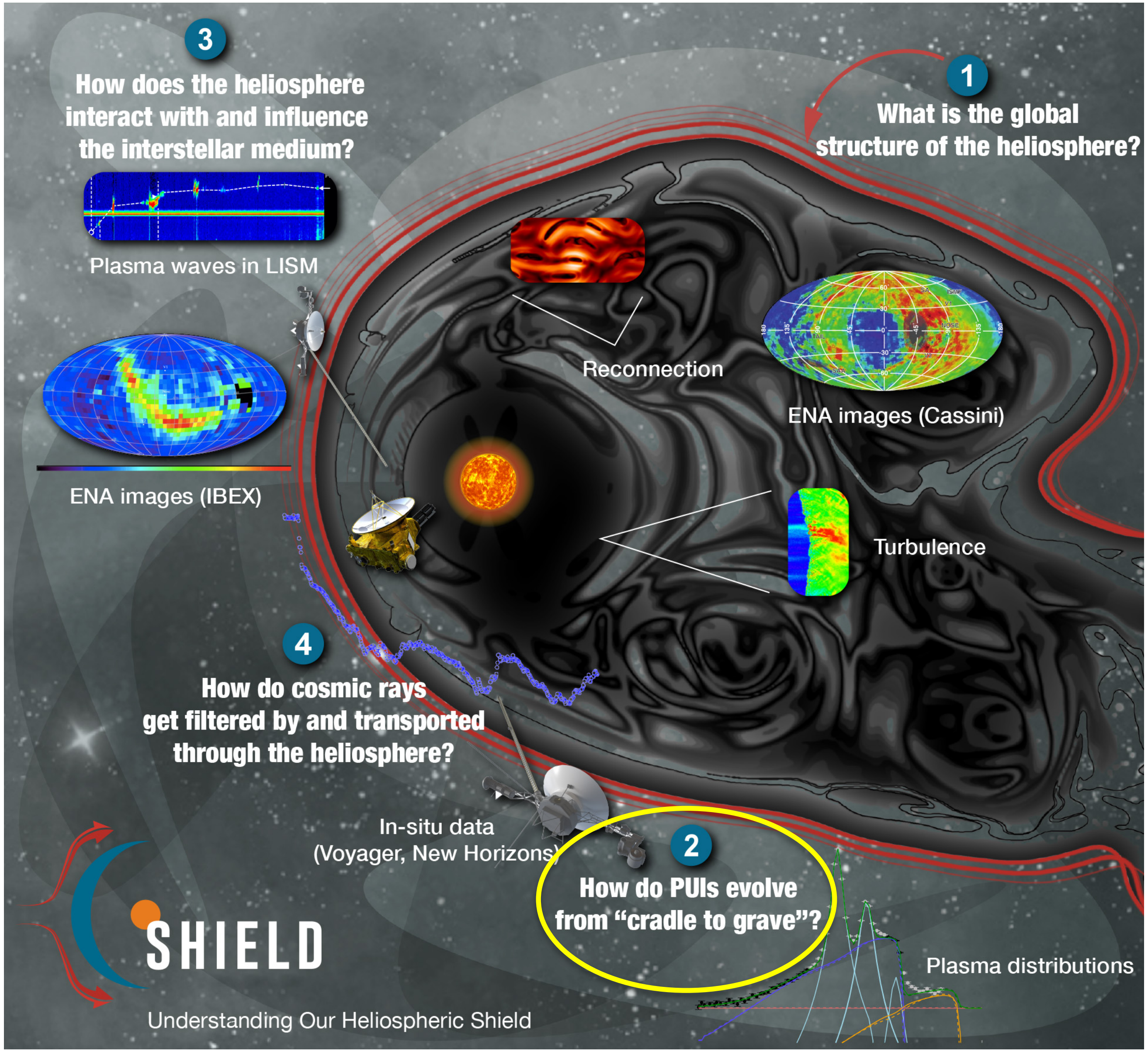
The Dispersive Nature of the Heliospheric Termination Shock

Bertalan Zieger, Joe Giacalone, Marc Swisdak, Gary Zank, and Merav Opher

BOSTON UNIVERSITY

SHIELD

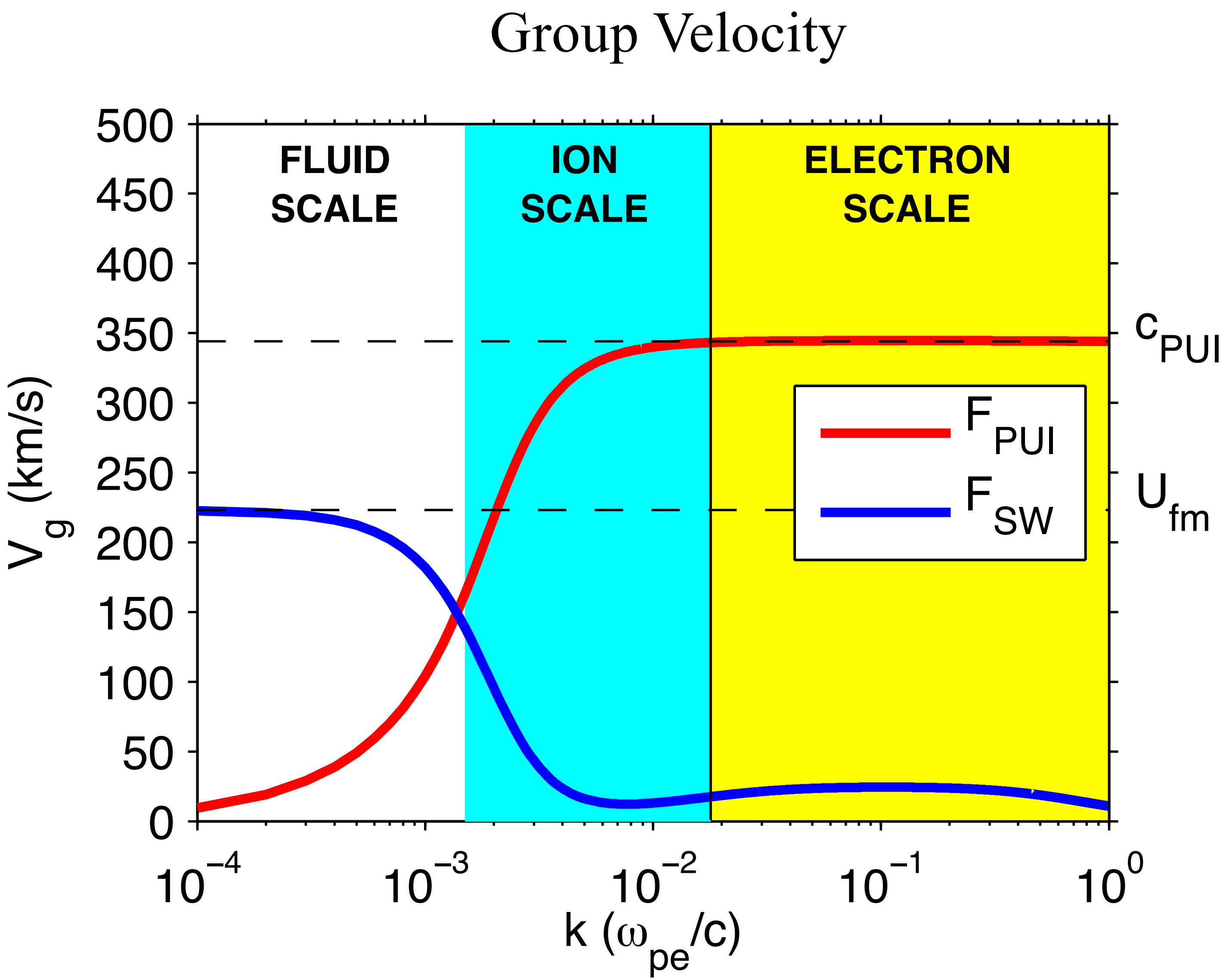
SHIELD DRIVE Science Center



Overview

- Three-fluid, hybrid, and particle-in-cells (PIC) simulations of the heliospheric termination shock
- Validation with Voyager 2 termination shock crossings (TS2, TS3)
- Cross-shock electric field for the three types of simulations
- Conclusions

Dispersive Fast Magnetosonic Modes in the Three-Fluid Solar Wind Model



The presence of hot pickup ions results in a **low-frequency fast mode** (F_{SW}) and a **high-frequency fast mode** (F_{PUI}).

Both fast modes are dispersive on fluid scale.

F_{PUI} corresponds to the **fundamental ion Bernstein mode** in the kinetic description.

Zieger et al., 2015

Fast Magnetosonic Mach Number of the Termination Shock

Shock adiabatic equation for perpendicular shocks

$$2(2-\gamma)q^2 + \gamma\left[2(1+\beta_1) + (\gamma-1)\beta_1 M_1^2\right]q - \gamma(\gamma+1)\beta_1 M_1^2 = 0,$$

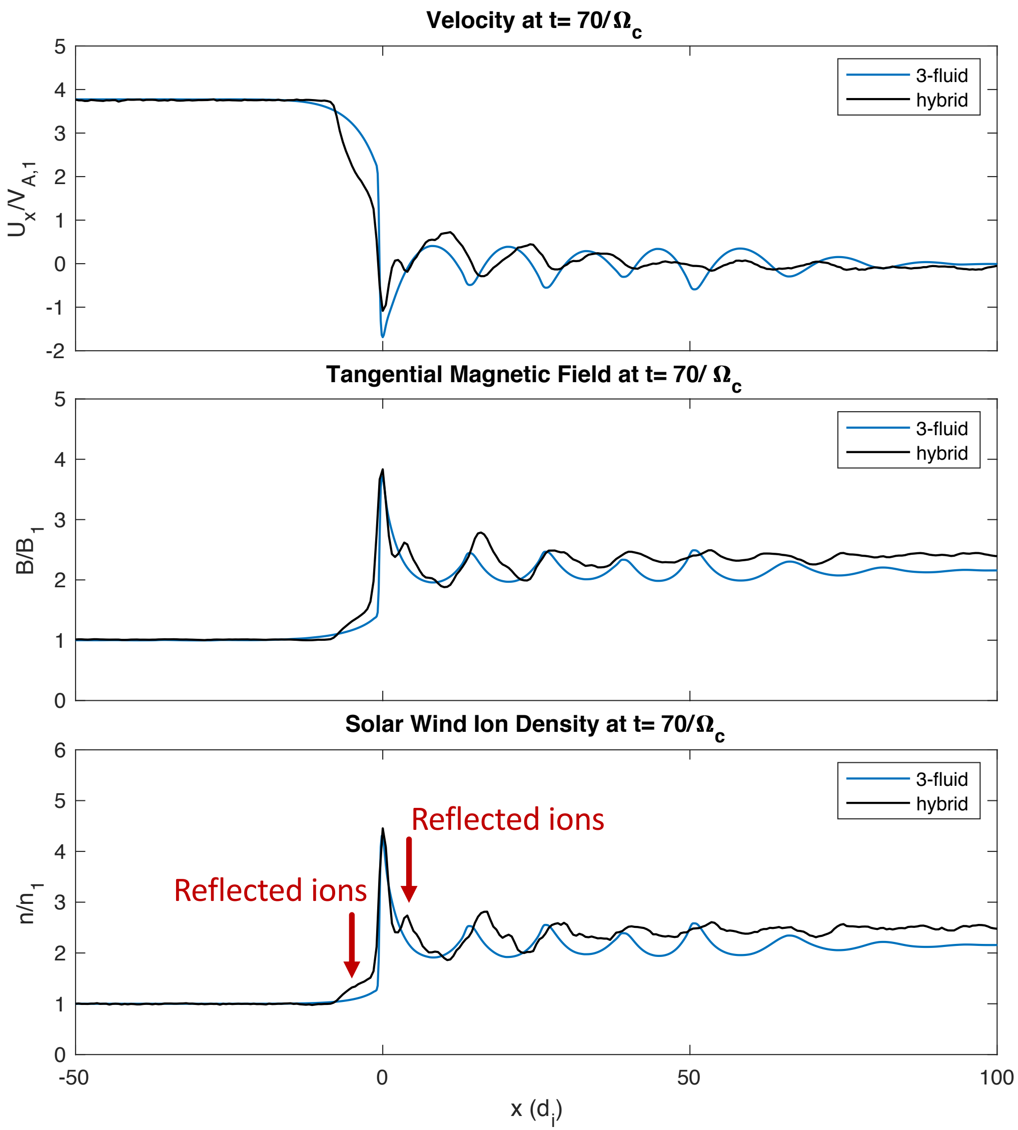
$$\beta_1 = \frac{2}{\gamma}\frac{c_{s,1}^2}{V_{A,1}^2} \qquad M_1 = \frac{u_{n,1} - V_s}{c_{s,1}} \qquad M_{fm,1} = \frac{u_{n,1} - V_s}{\sqrt{c_{s,1}^2 + V_{A,1}^2}}$$

The shock adiabatic equation can be solved for the upstream sound speed of the total fluid ($c_{s,1}$).

	Compression Ratio	**Mach Number**
TS2	q=2.2	$M_{fm,1} = 1.86$
TS3	q=1.6	$M_{fm,1} = 1.40$

Both termination shock crossings of Voyager 2 were low-Mach number subcritical shocks ($M_{crit} = 2.76$ for high-β perpendicular shocks).

Three-Fluid and Hybrid Simulations of TS2

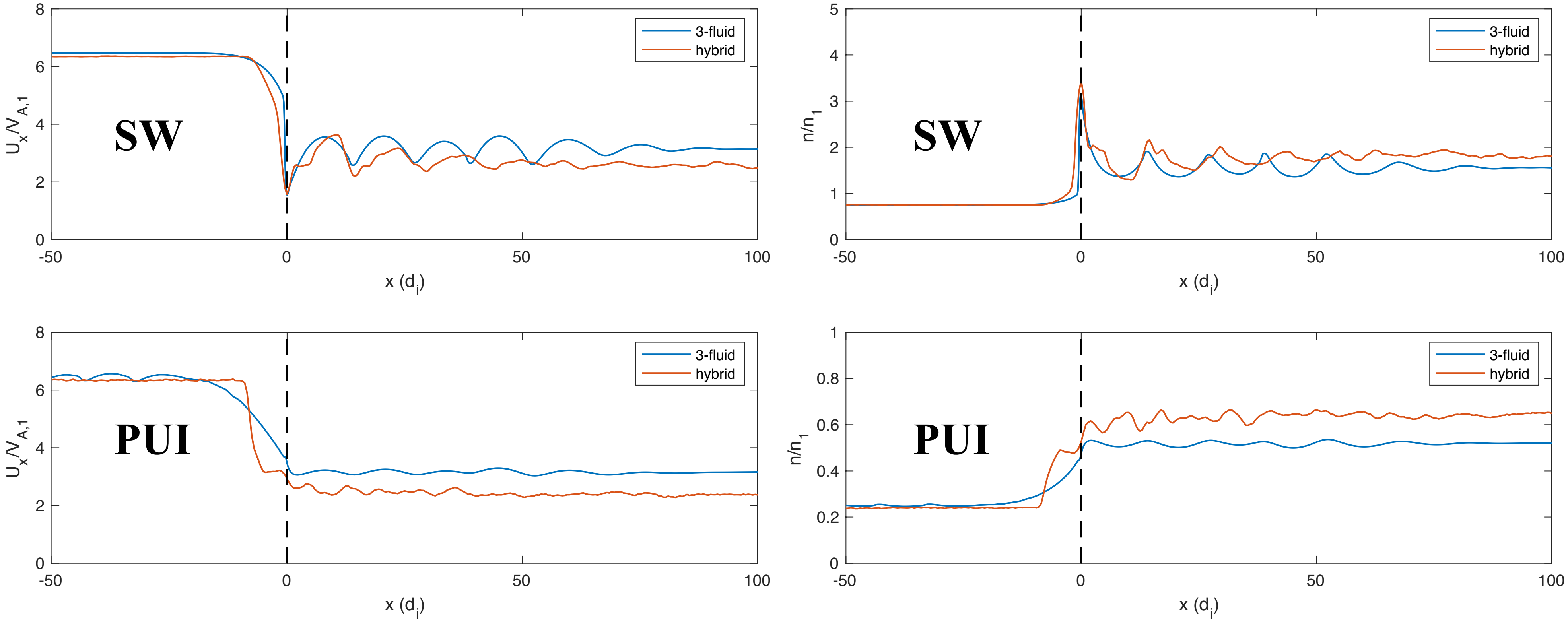


The shock structure is dominated by dispersion rather than ion reflection.

The secondary peaks in the ion density are produced by reflected solar wind and pickup ions.

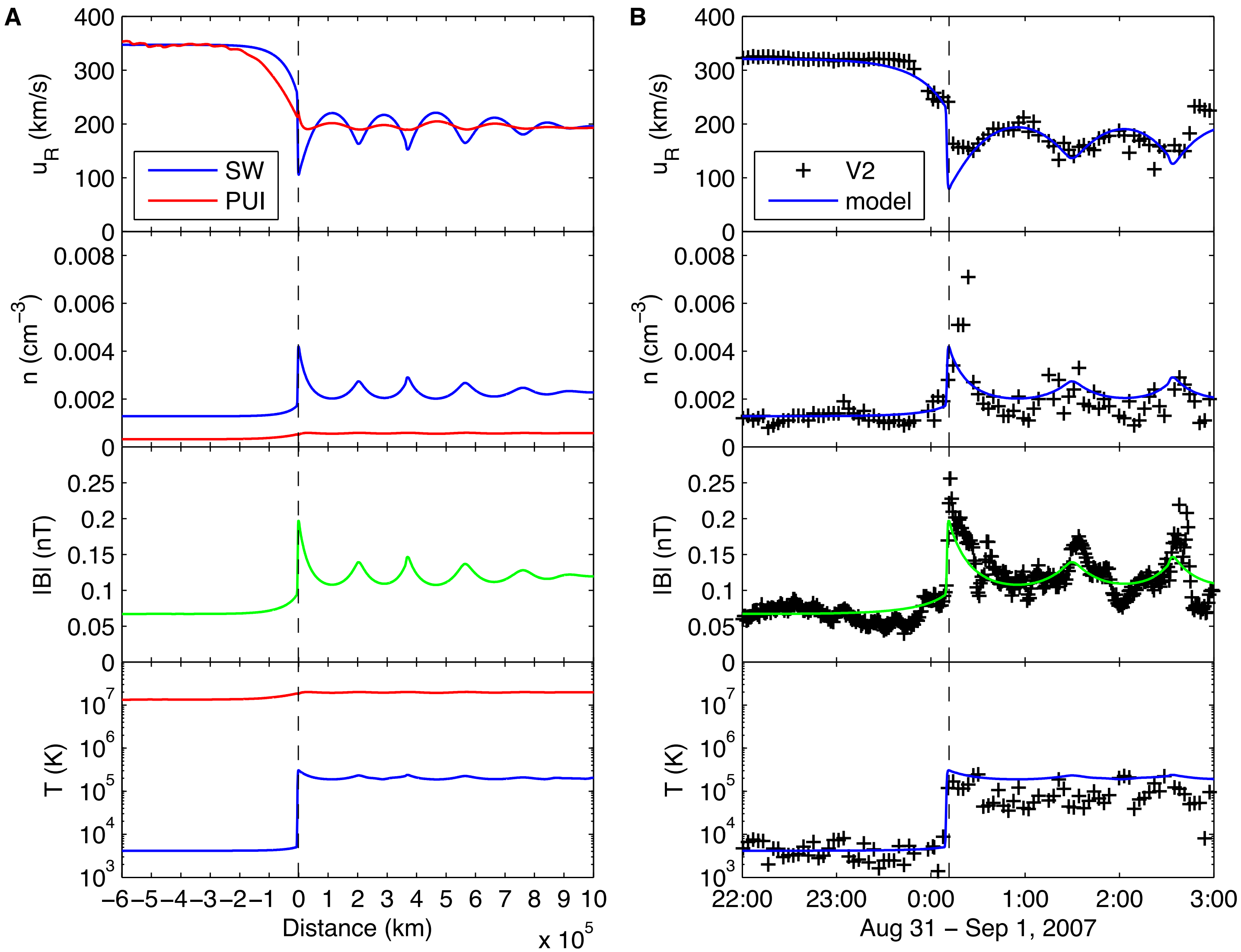
Ion Reflection at the Termination Shock

Velocity **Density**



Decreased ion velocities and increased ion densities upstream of the termination shock indicate reflected ion populations in the hybrid simulation.

Model Validation With Voyager 2 Data, TS3



The pickup ion temperature can be constrained by fitting the simulated shock structure to Voyager 2 observations.

n_{SW}= 0.0013 cm^{-3}

T_{SW}= 4200 K

B= 0.067 nT

n_{PUI}= 0.25 n_{SW}

A_{PUI}= 0.2

T_{PUI}= 13.4 MK

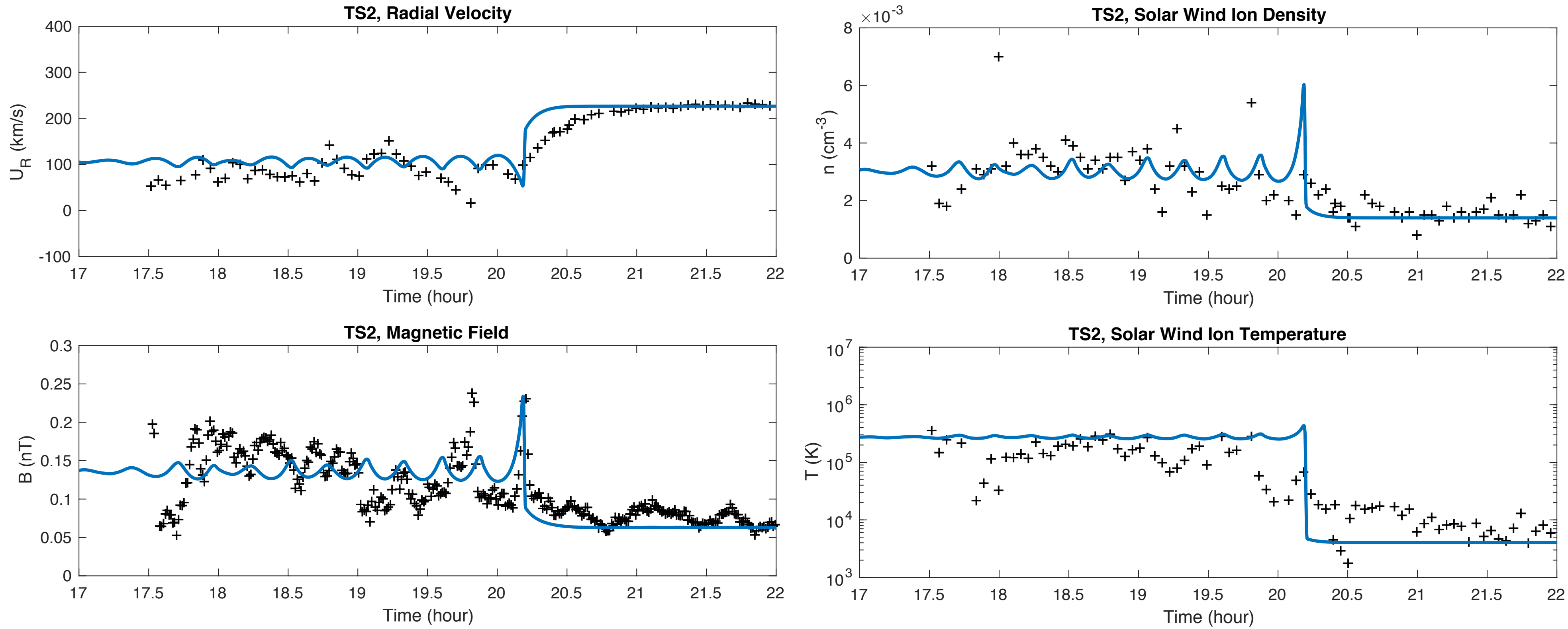
T_e= 0.83 MK

p_e= 0.0173 pPa

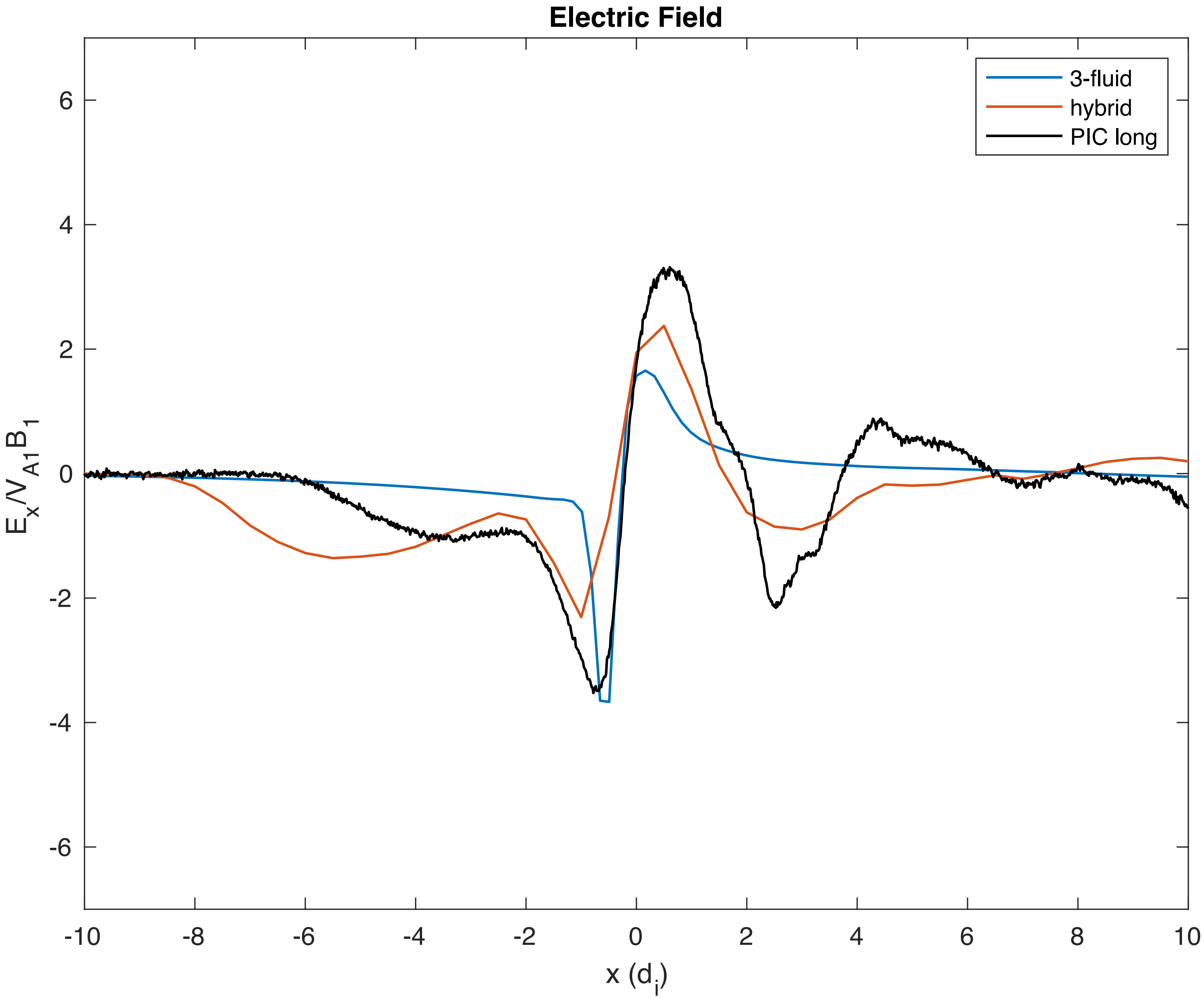
Zieger et al., 2015

Model Validation With Voyager 2 Data, TS2

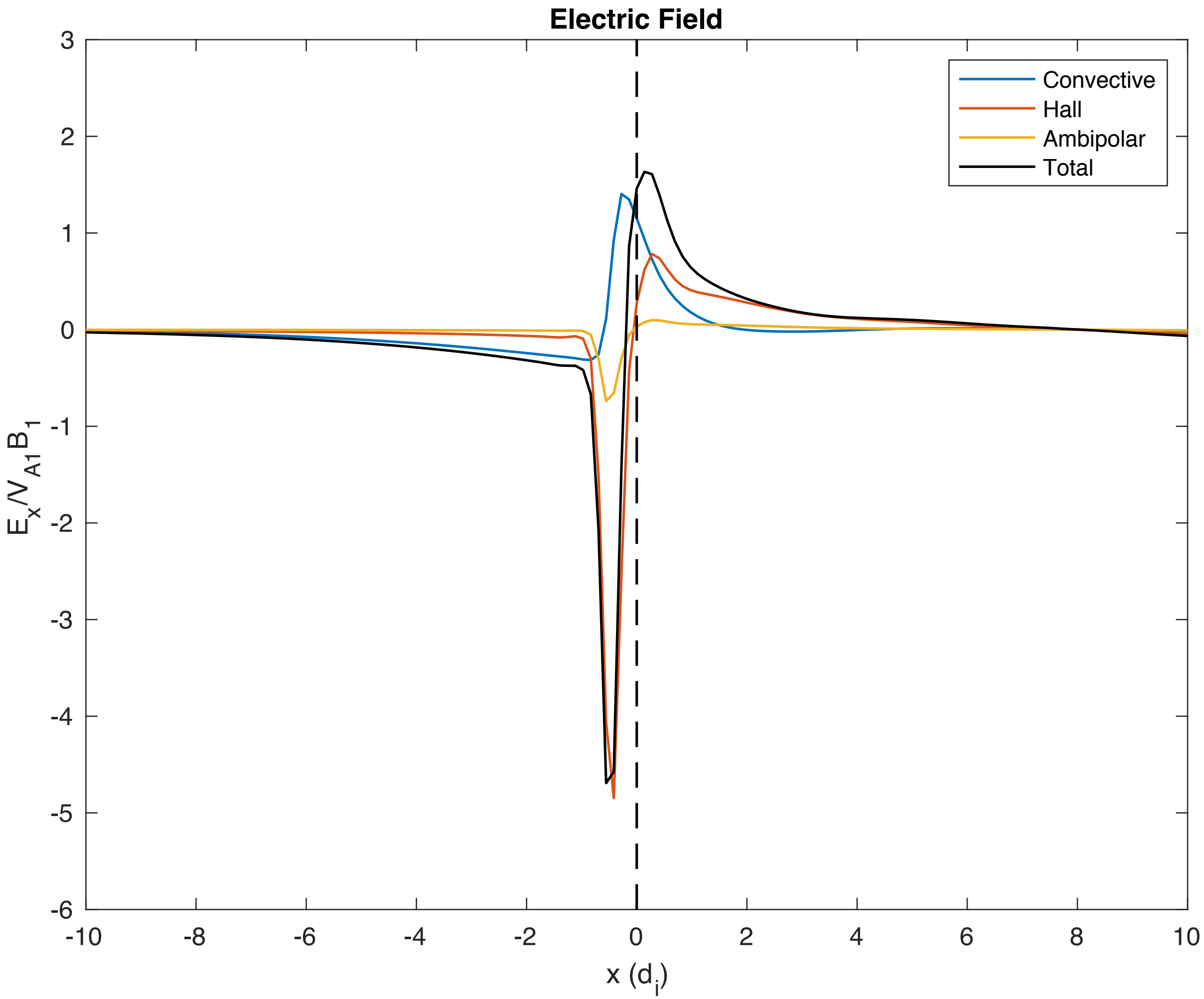
Shock parameters from Li et al. [2008]



Cross-Shock Electric Field, TS2



Cross-Shock Electric Field, TS2



The Hall term dominates in the cross-shock electric field.

The convective and ambipolar terms more or less compensate each other.

Generalized Ohm's Law: $$\mathbf{E} = -\mathbf{u}_+ \times \mathbf{B} + \frac{1}{en_e}\mathbf{J}\times\mathbf{B} - \frac{1}{en_e}\nabla p_e + \eta\mathbf{J}$$

convective Hall ambipolar ohmic

Conclusions

- The termination shock is a **low-Mach number dispersive shock wave** with a soliton edge and a quasi-stationary trailing wave train.
- Both termination shock crossings of Voyager 2 (TS2, TS3) are **subcritical shocks**, where dispersion dominates over ion reflection.
- **General agreement** among the three-fluid, hybrid, and PIC simulations of the termination shock.
- **Kinetic effects** (reflected solar wind ions) only slightly modify the shock structure.
- The simulations closely **reproduce the Voyager 2 termination shock crossings**.
- The cross-shock electric field is **dominated by the Hall term**.