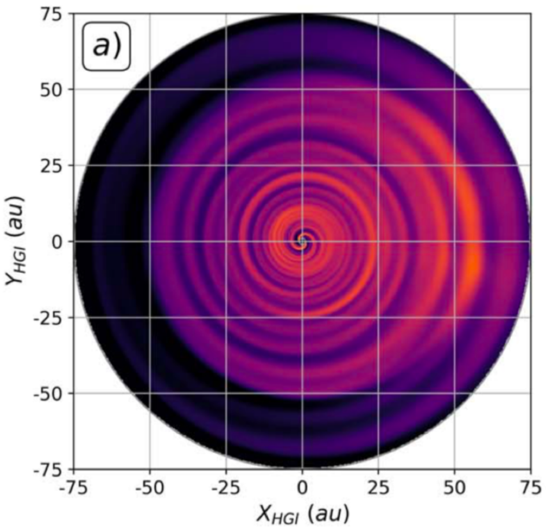
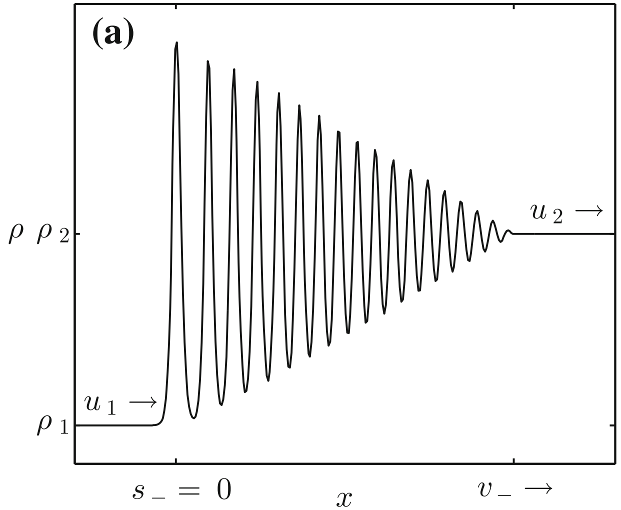
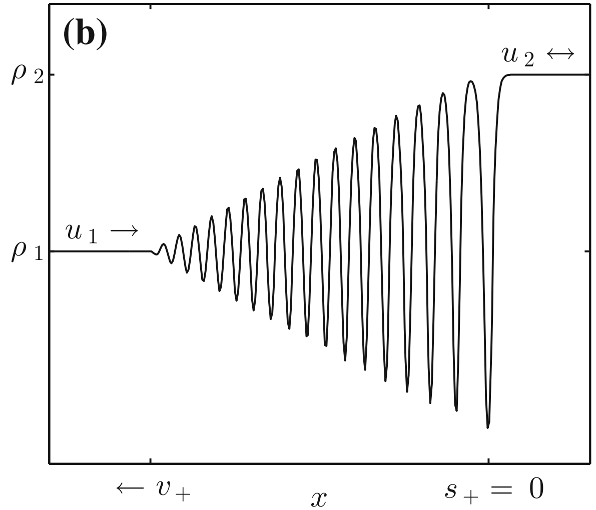






Multi-fluid Simulation of Interplanetary Shocks With Pickup Ions

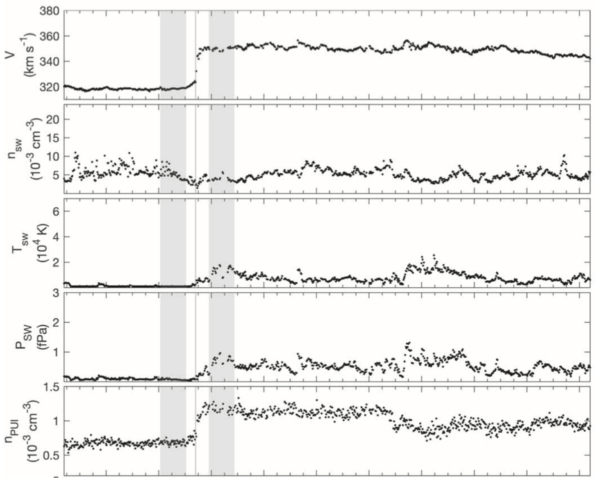
Bertalan Zieger

Center for Space Physics, Boston University

BOSTON UNIVERSITY

SHIELD

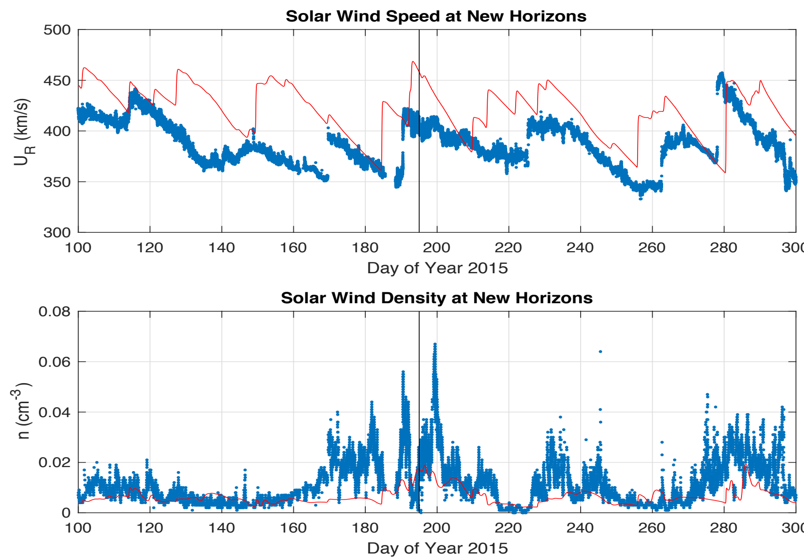
Motivation & Outline



PUI shock observed by New Horizons (*McComas et al.*, 2022)

- Oblique shocks introduce differential flow between solar wind ions and pickup ions (PUI), as demonstrated by multi-fluid simulations.
- New Horizons data indicate inconsistency with the assumption of a single bulk velocity. The mass flux should be conserved across shocks for all the ion species.
- Solar wind ions and PUI need to be treated as separate fluids with different velocities.

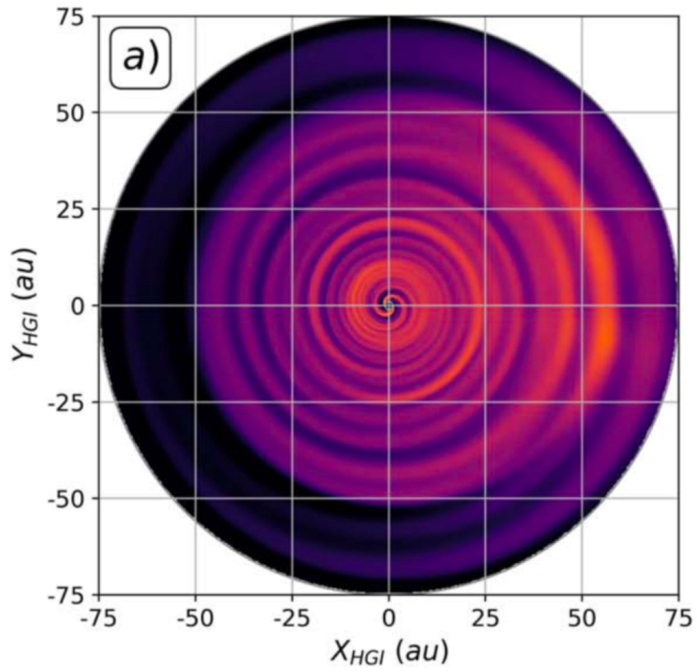
- High-resolution multi-fluid reconstruction of an interplanetary shock observed by New Horizons at 50 AU
- Multi-fluid, hybrid, and PIC simulation of the termination shock
- 2D solar wind propagation model (MSWIM2D) to predict magnetic field at New Horizons



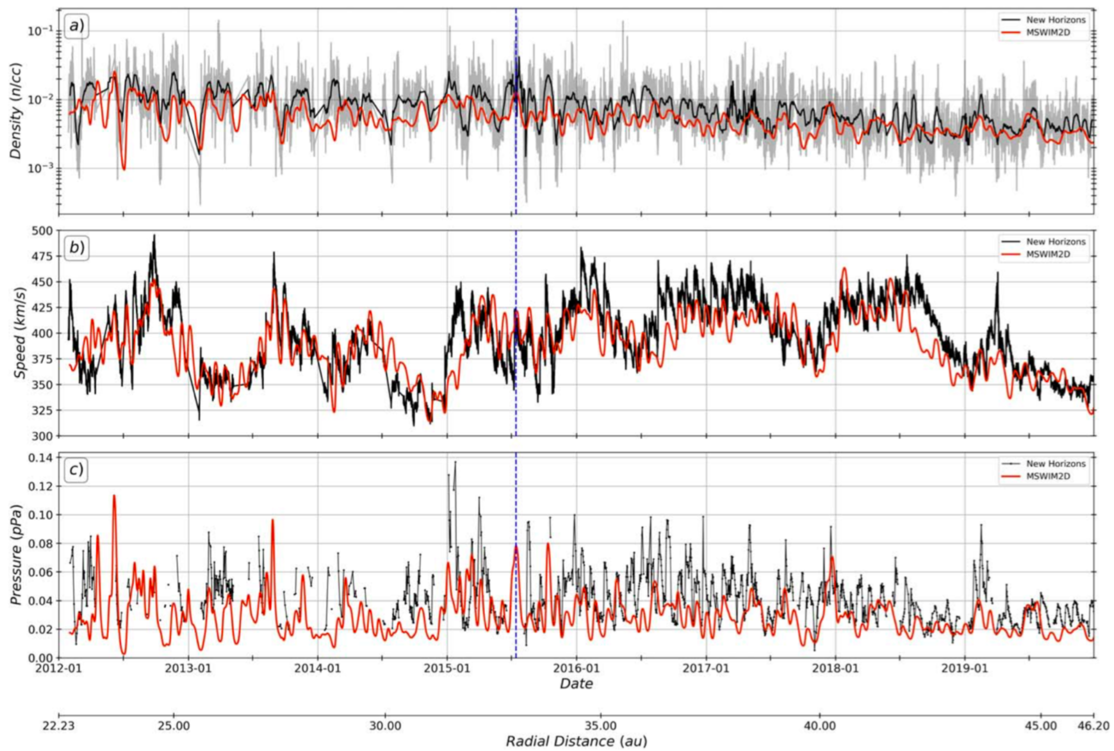
MHD reconstruction of the New Horizons Pluto flyby

Solar Wind Propagation from 1 AU to the Outer Heliosphere: The MSWIM2D model

- 2D MHD model of the solar wind with interstellar neutrals, using ACE, WIND, and STEREO data as input at the inner boundary at 1 AU
- Predict radial trends in the solar wind in the ecliptic plane from 1 AU to 75 AU

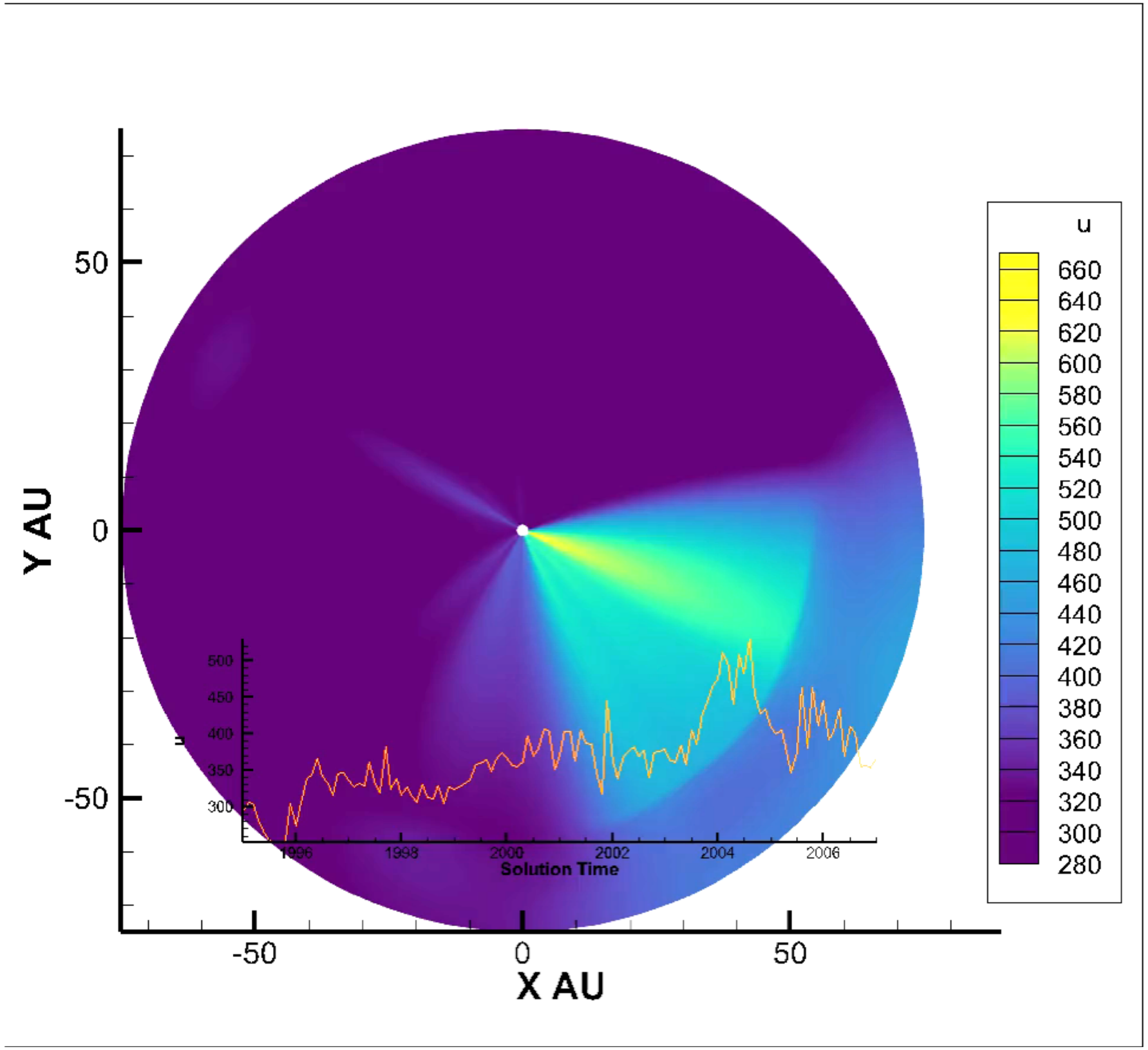


Solar wind speed in the ecliptic plane (*Keebler et al.*, 2022)



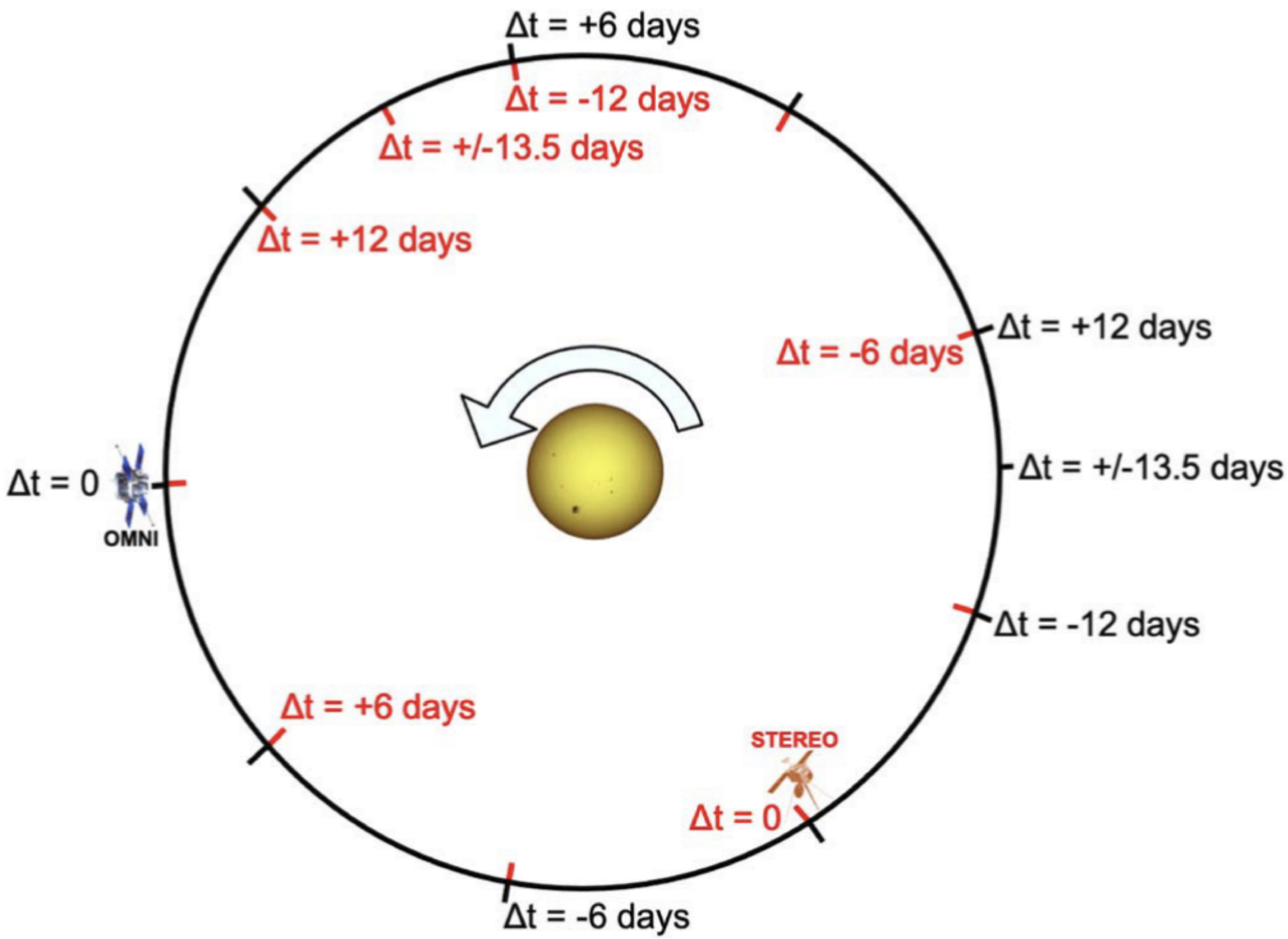
Model validation with New Horizons SWAP data (*Keebler et al.*, 2022)

MSWIM2D Simulation of Solar Wind Speed 1995 - 2007



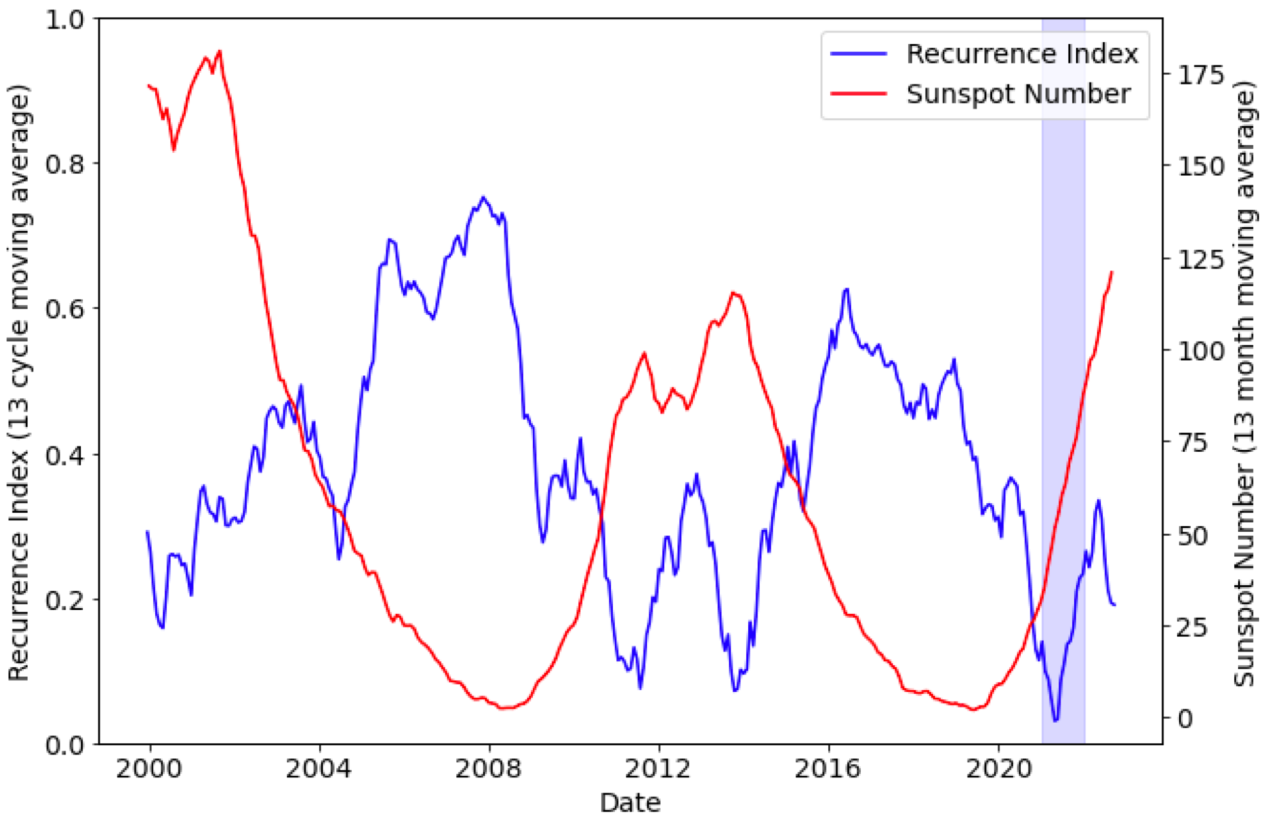
Courtesy of *Anna Nica*

Inner Boundary Conditions at 1 AU from Earth (OMNI) and STEREO



(*Keebler et al*., 2022)

Solar Cycle Variation of the Solar Wind Recurrence Index



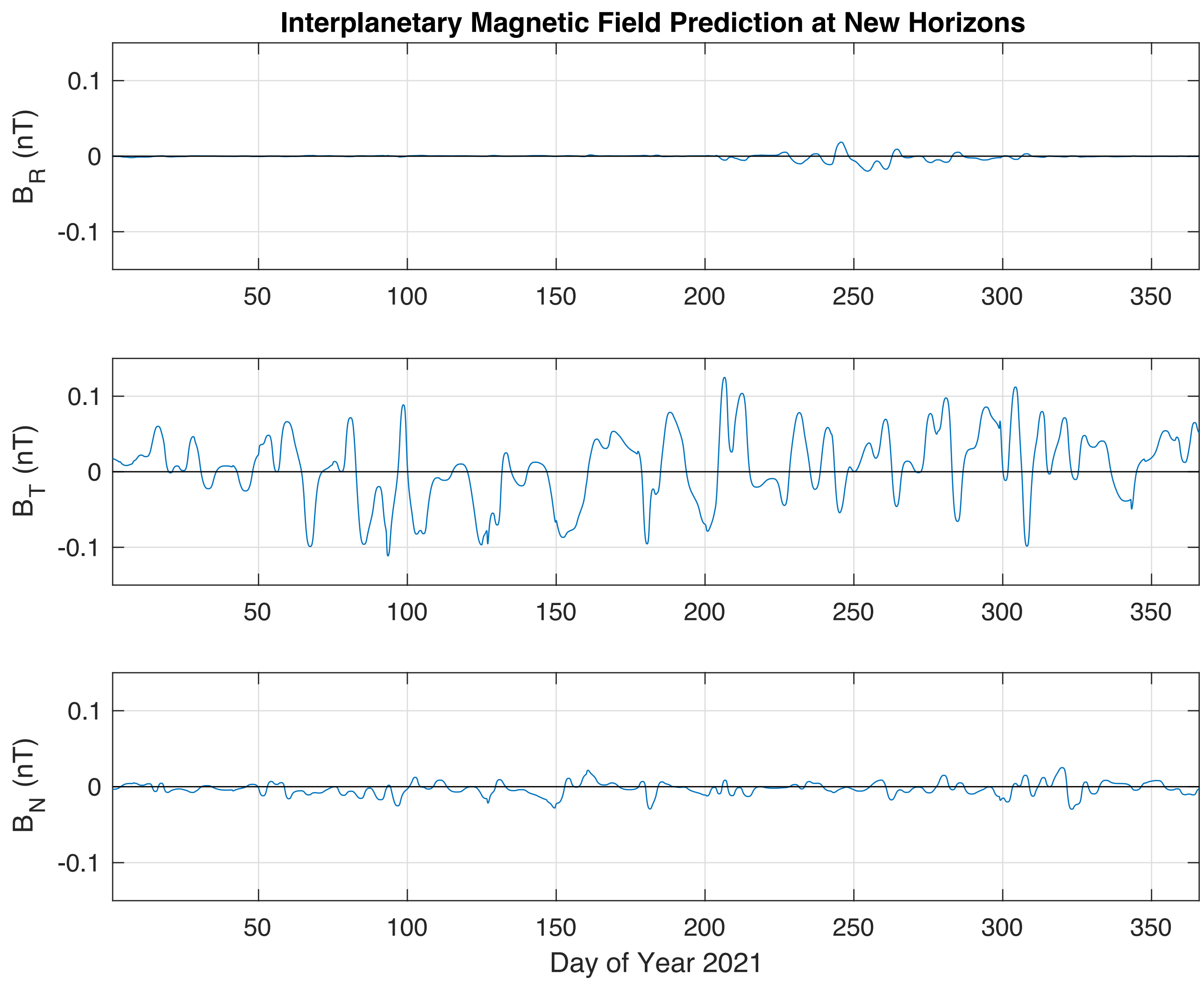
Recurrence index:

Correlation of hourly solar wind speed data between successive solar rotations (27 days)

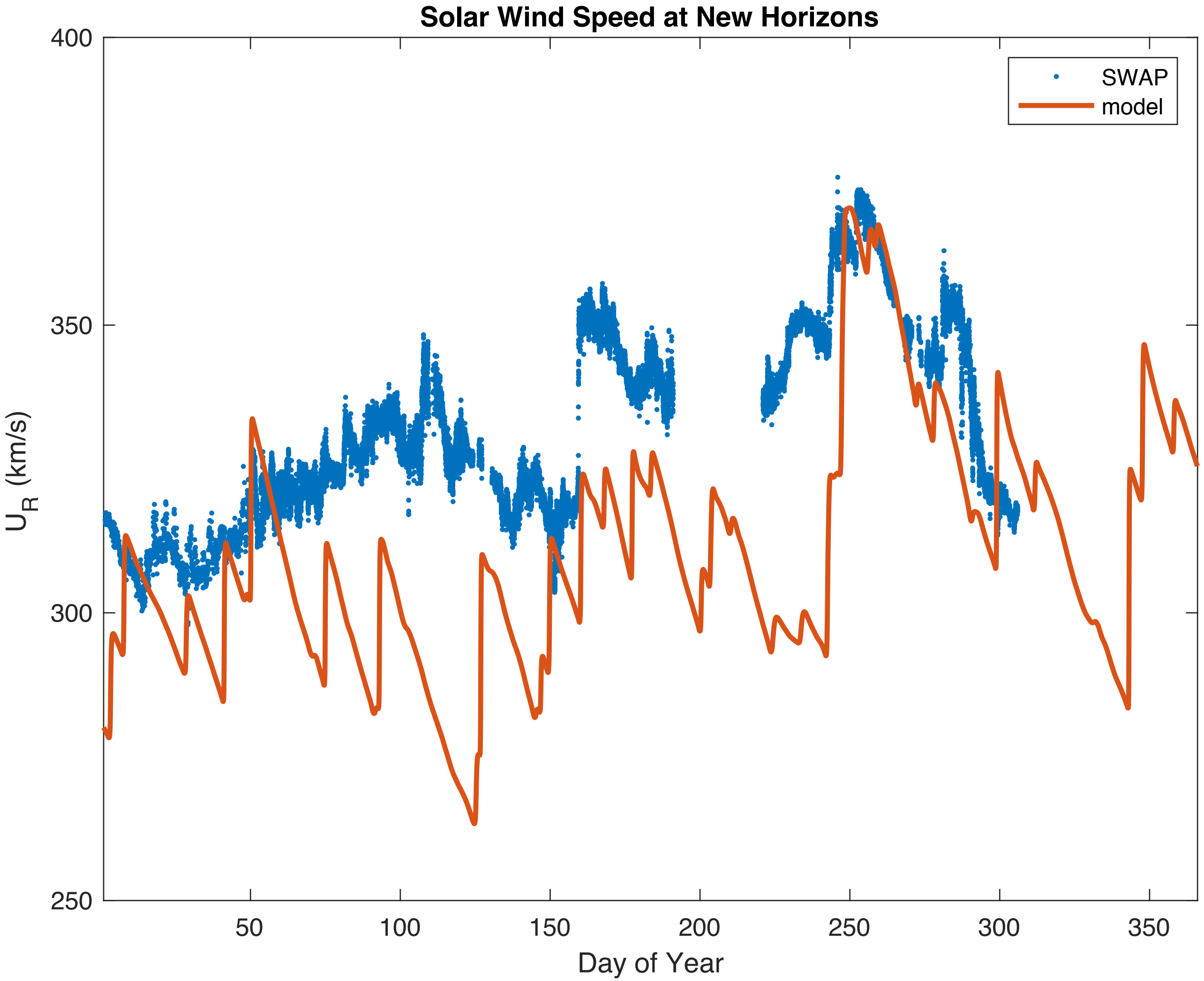
Highest in the late declining phase of the solar cycle due to recurrent high-speed solar wind streams

Courtesy of *Sammy Siegel*

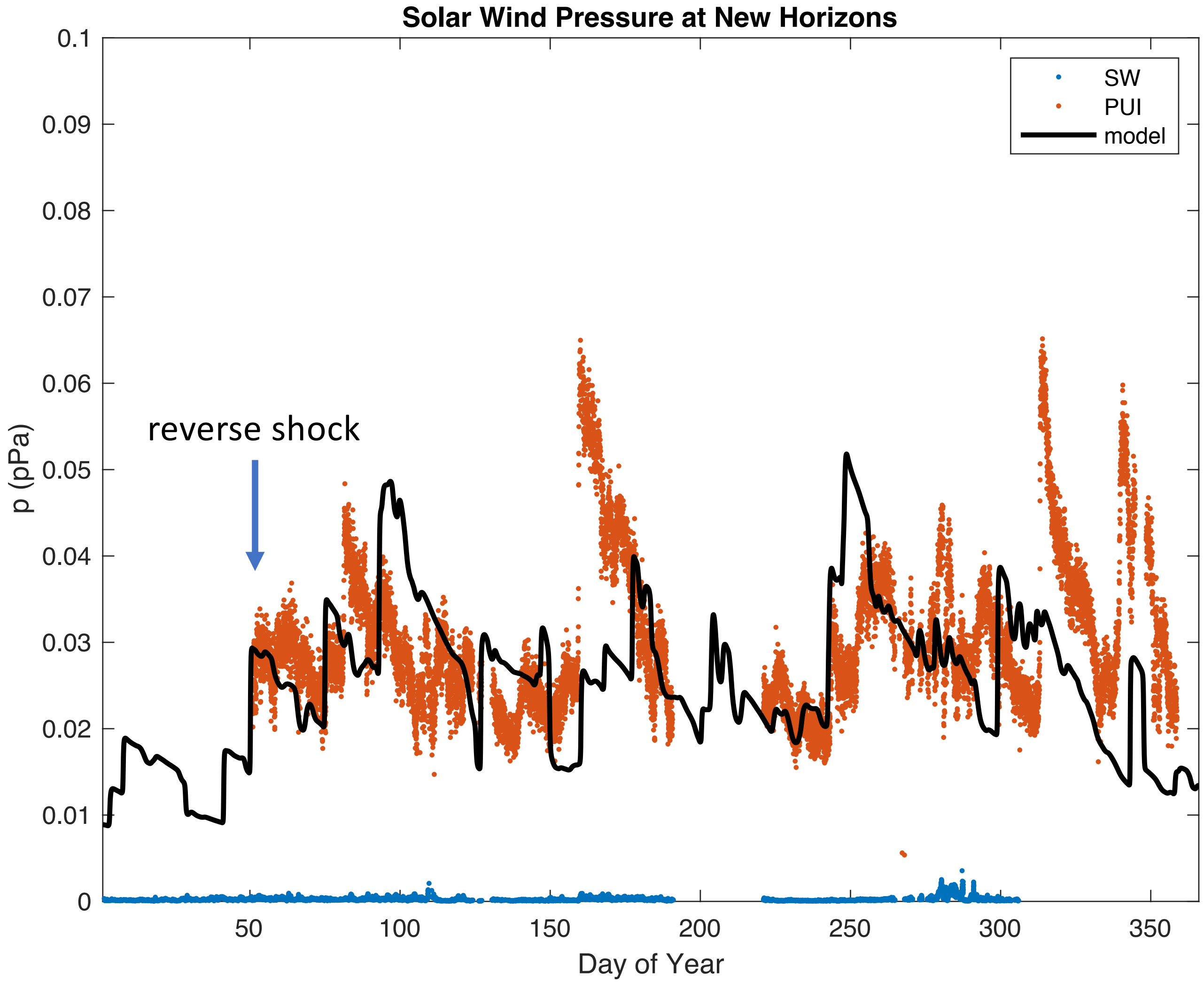
Interplanetary Magnetic Field Prediction at New Horizons



Solar Wind Speed at New Horizons in 2021



Solar Wind Pressure at New Horizons in 2021

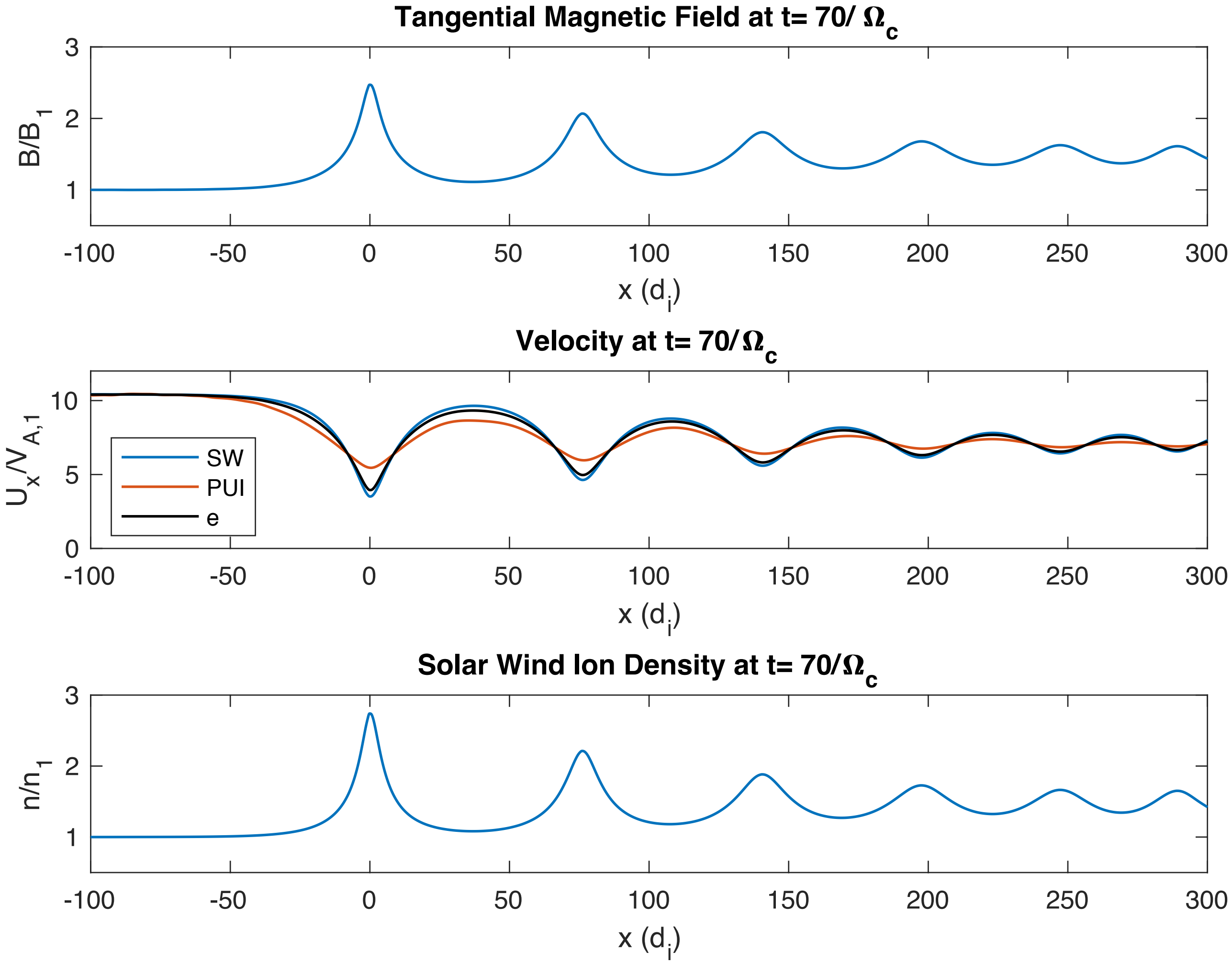


Multi-fluid Simulation of an Interplanetary Shock Observed by New Horizons on DOY 50 in 2021

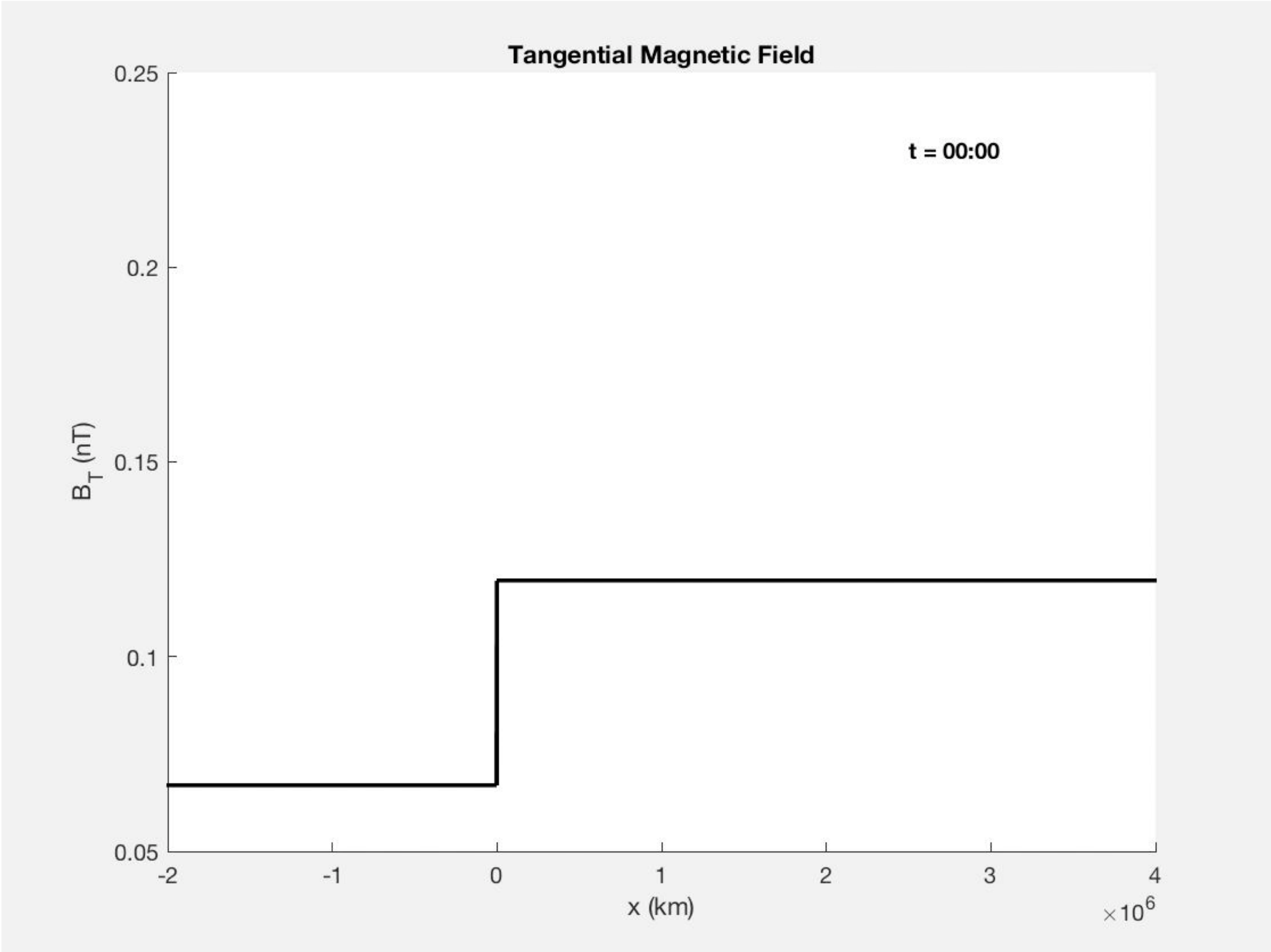
PUI abundance = 30%
T_{PUI}/T_{SW} = 400

	TS3
Compression ratio = 1.5	(1.8)
Mach number = 1.3	(1.6)
Plasma β = 73	(60)

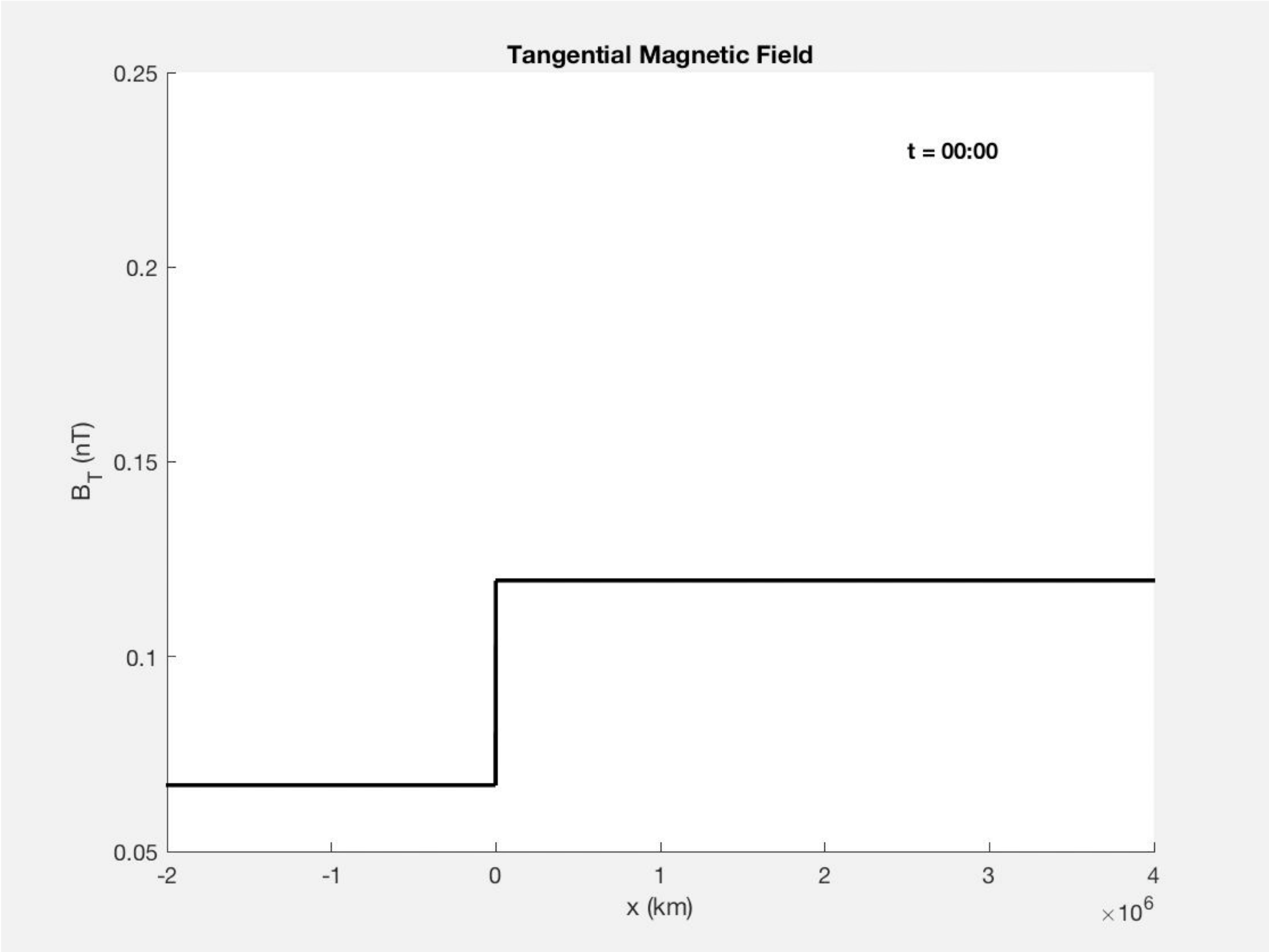
Low Mach number subcritical dispersive shock wave



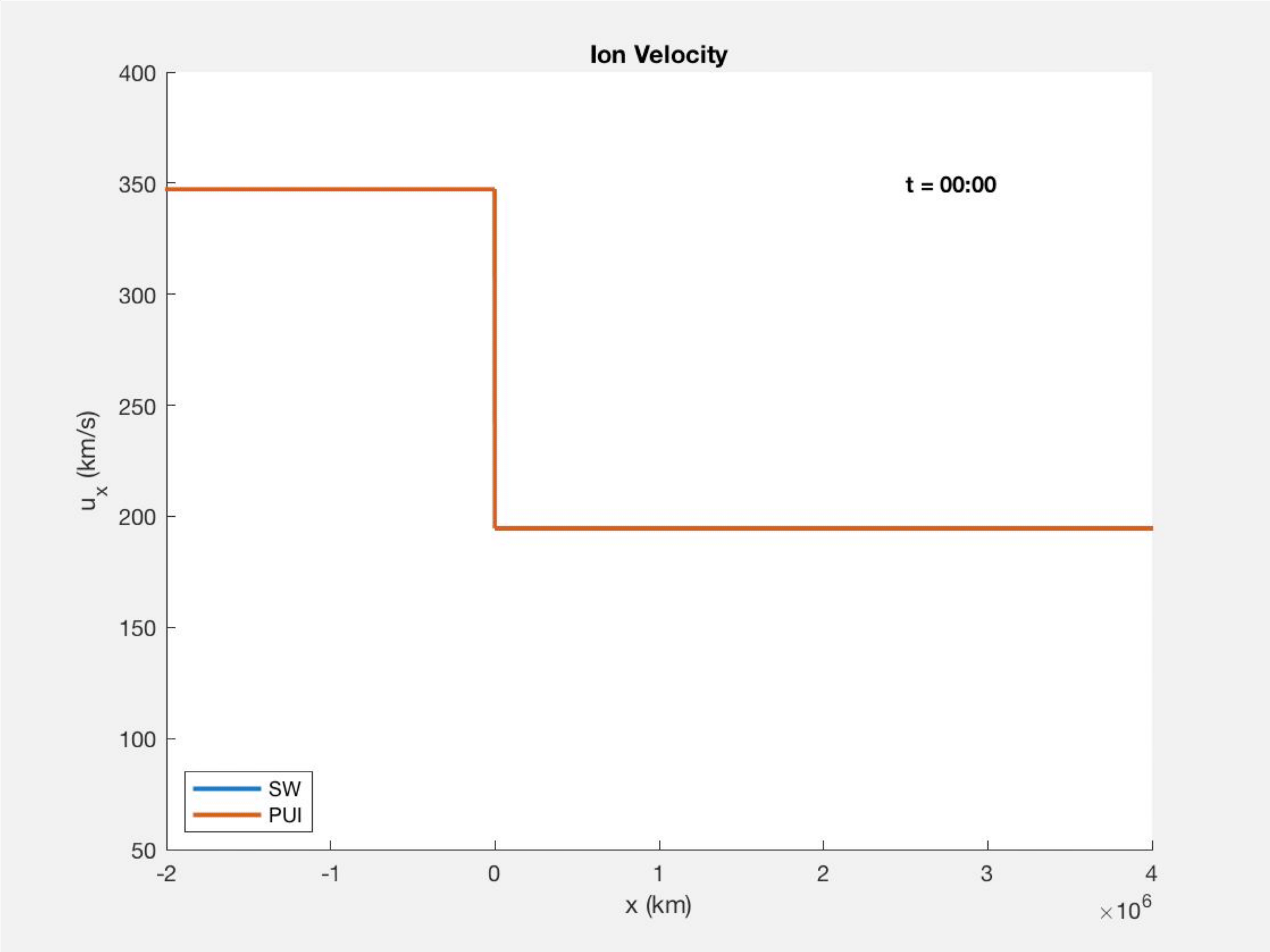
Multi-species MHD Simulation of the Termination Shock



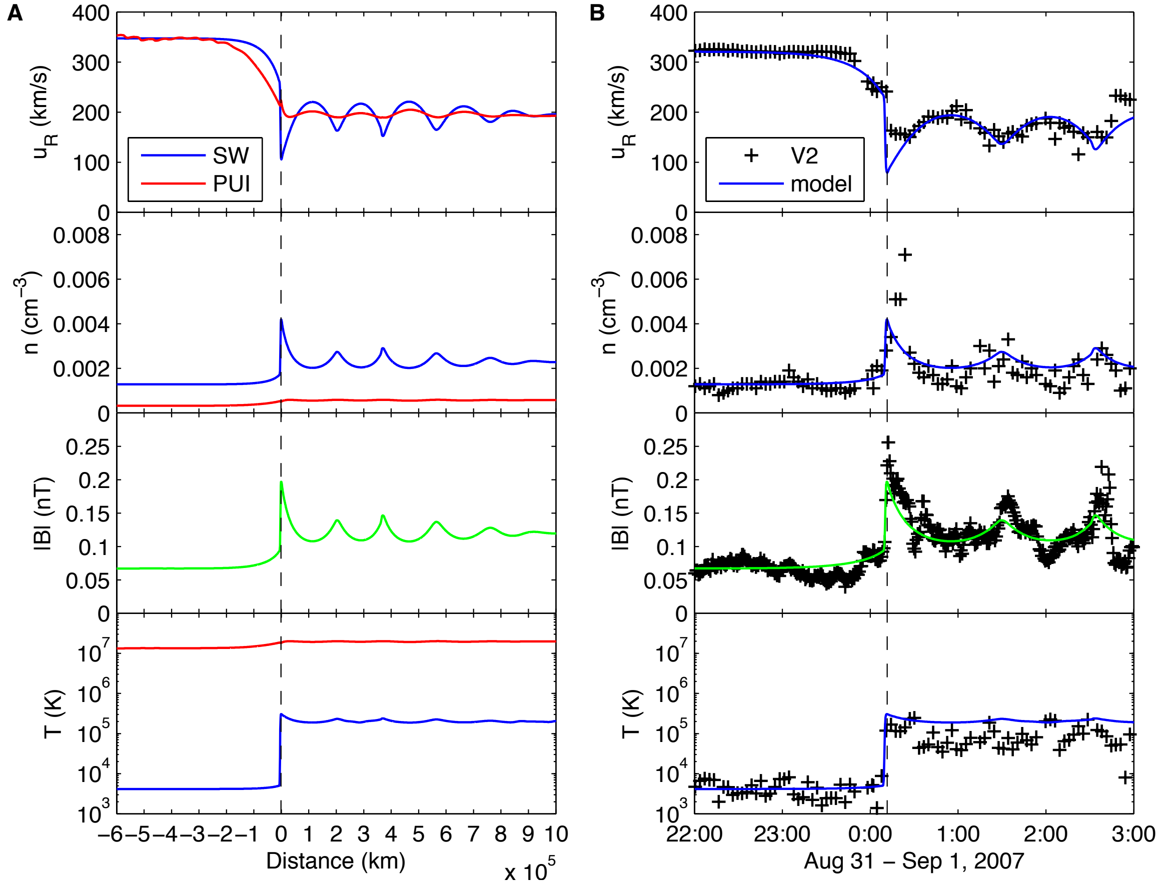
Three-Fluid Simulation of the Termination Shock



Three-Fluid Simulation of the Termination Shock



Model Validation With Voyager 2 Data, TS3

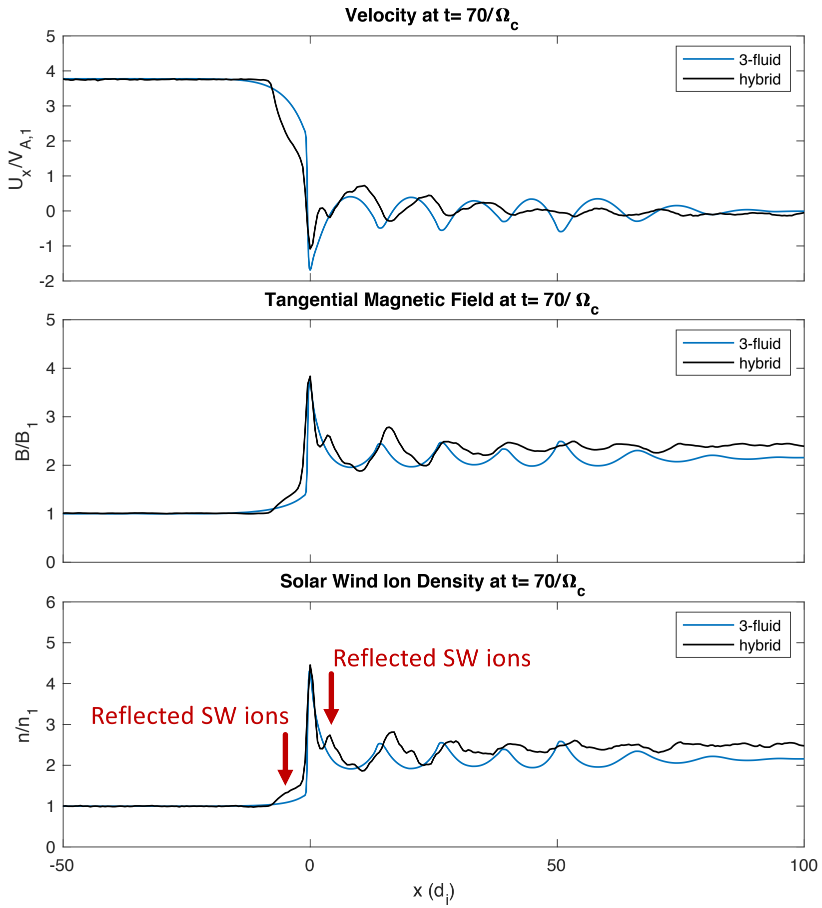


The pickup ion temperature can be constrained by fitting the simulated shock structure to Voyager 2 observations.

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

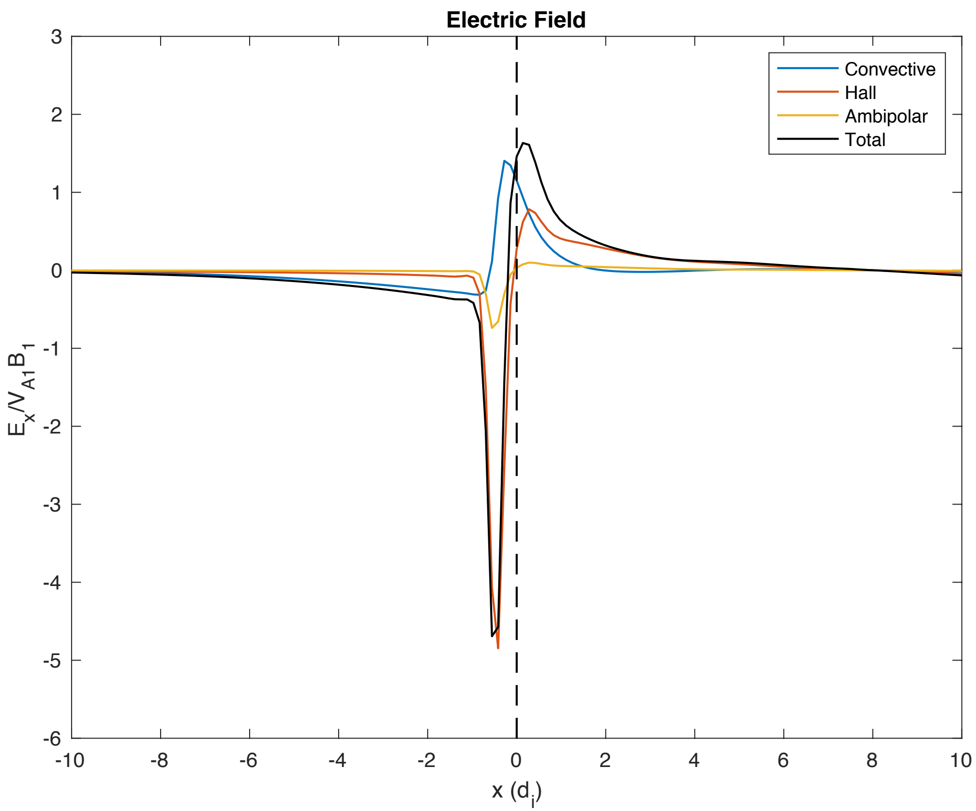
Three-Fluid and Hybrid Simulations of TS2



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

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

Cross-Shock Electric Field, TS2



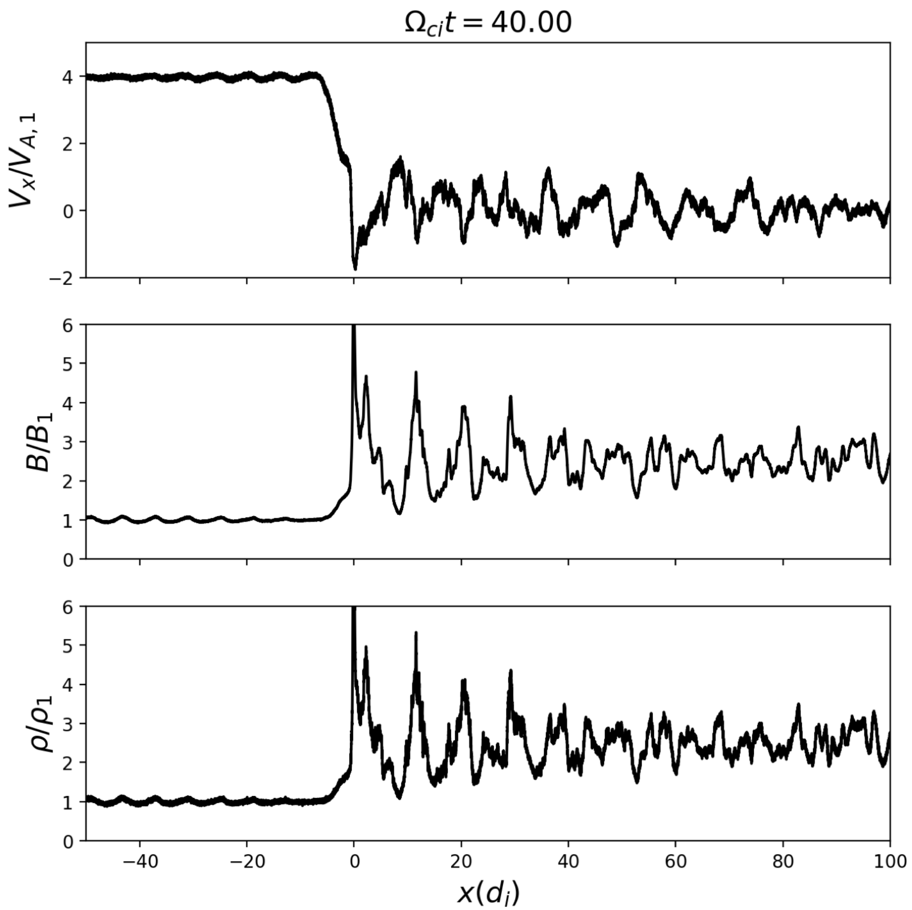
The Hall term dominates in the cross-shock electric field.

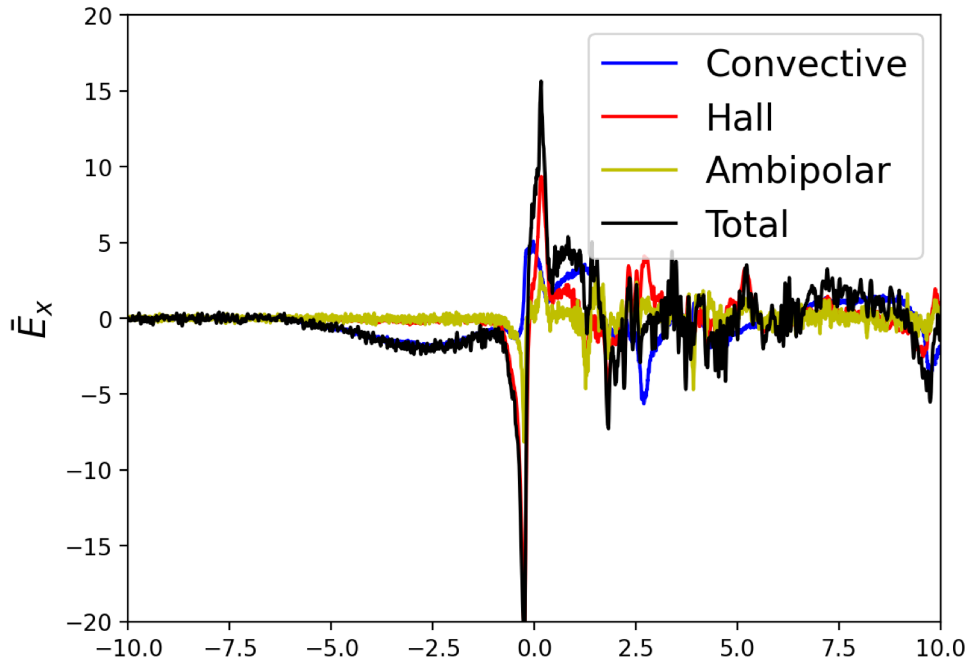
The convective and ambipolar terms more or less compensate each other.

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

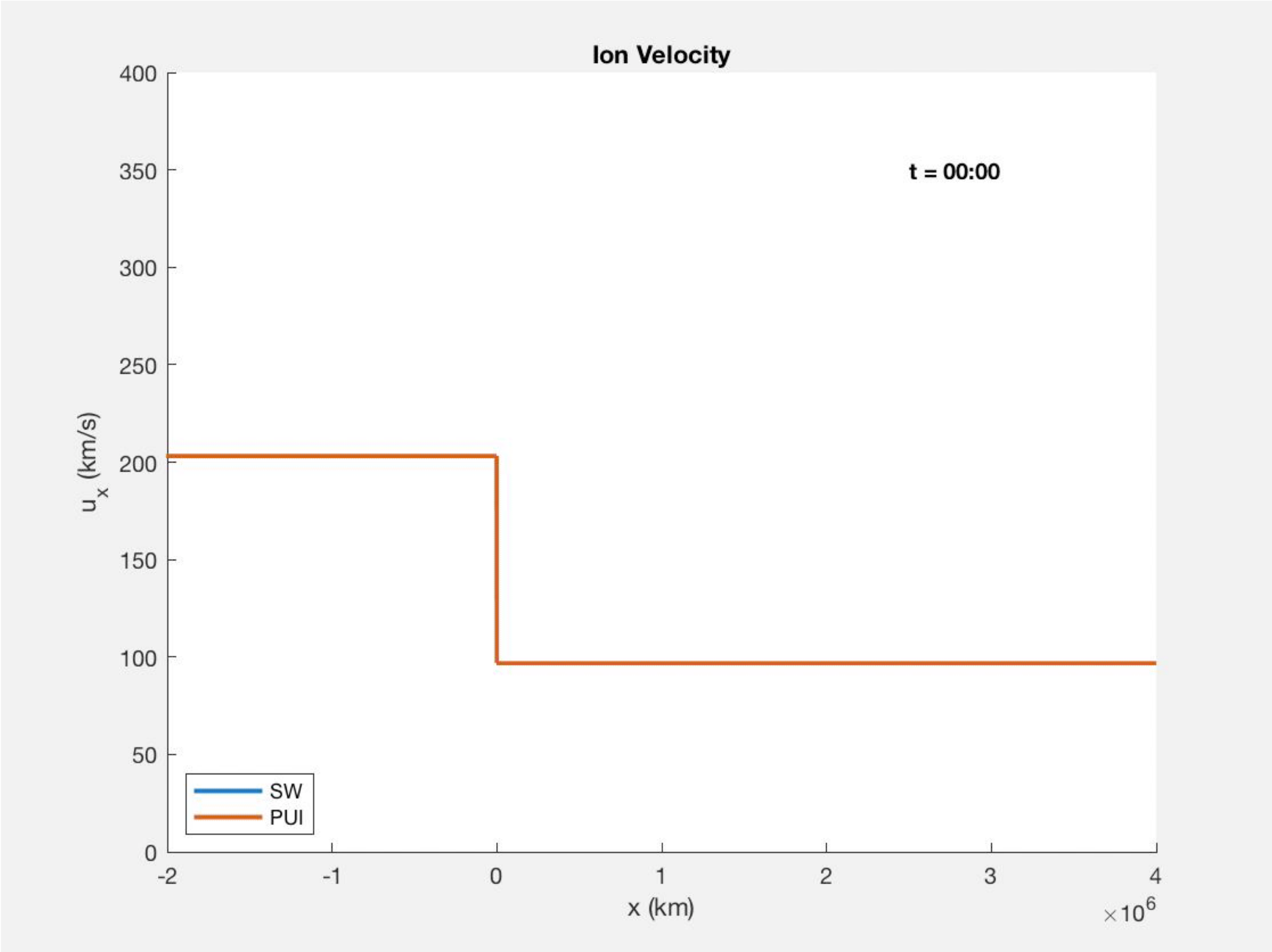
PIC Simulation of TS2



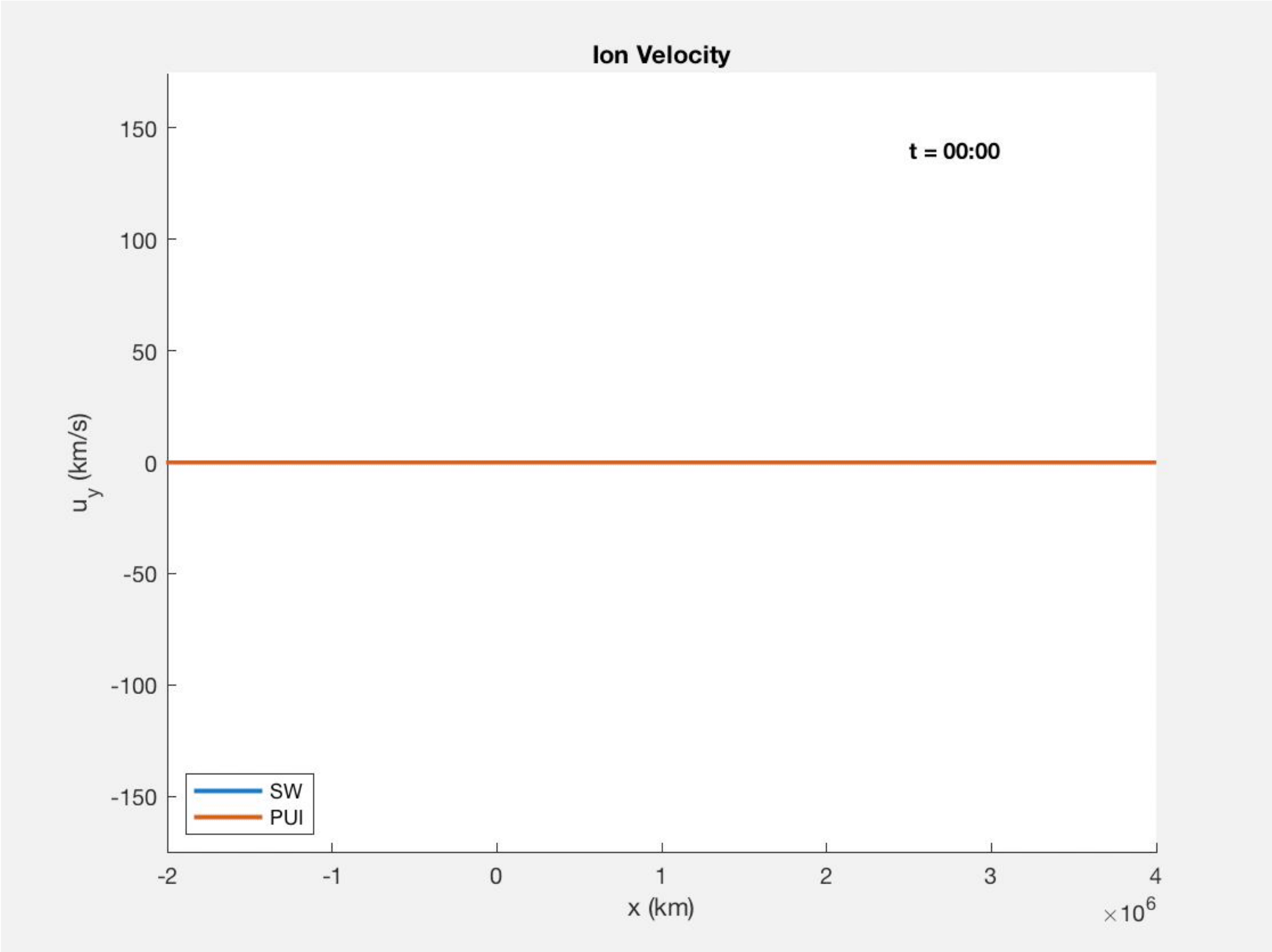


Courtesy of *Senbei Du*

Three-Fluid Simulation of an Oblique Termination Shock, $\theta_{Bn} = 70°$
Radial Velocity



Three-Fluid Simulation of an Oblique Termination Shock, $\theta_{Bn} = 70°$
Tangential Velocity



Conclusions

- **Pickup ions should be treated as a separate fluid in the outer heliosphere**
- **The magnetic field at New Horizons can be predicted by a 2D solar wind propagation model (MSWIM2D).**
- **The prediction is best in the declining phase of the solar cycle when the solar wind recurrence index is high.**
- **The shock observed by New Horizons at 50 AU on DOY 50 in 2021 is a subcritical dispersive shock wave.**
- **Multi-fluid simulation with pickup ions can reproduce the microstructure of the termination shock observed by Voyager 2.**
- **The multi-fluid approach is validated by hybrid and PIC simulations.**
- **Oblique multi-ion shocks introduce differential ion flows in the downstream region.**