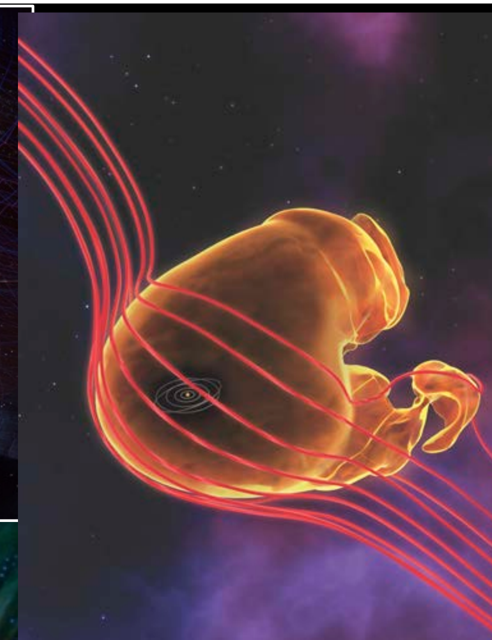
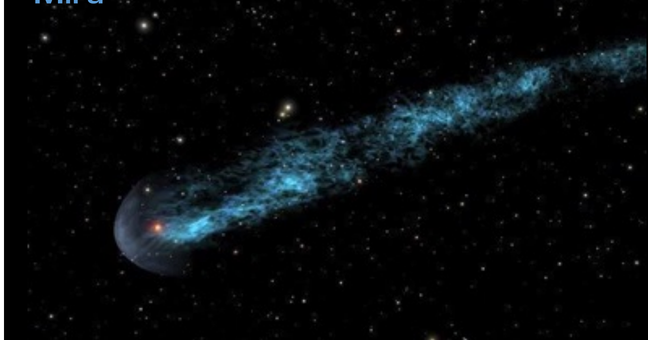
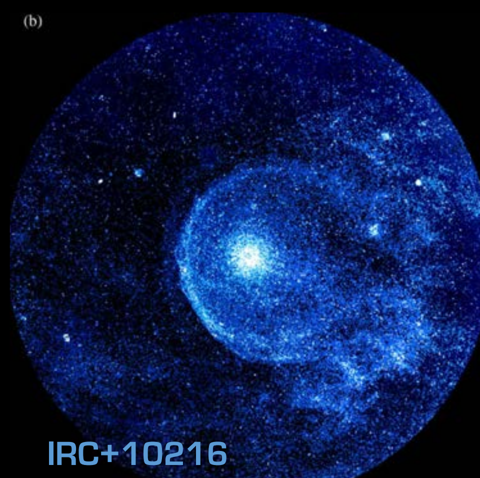
Current Theoretical Challenges In the Outer Heliosphere (Shape of Heliopause)

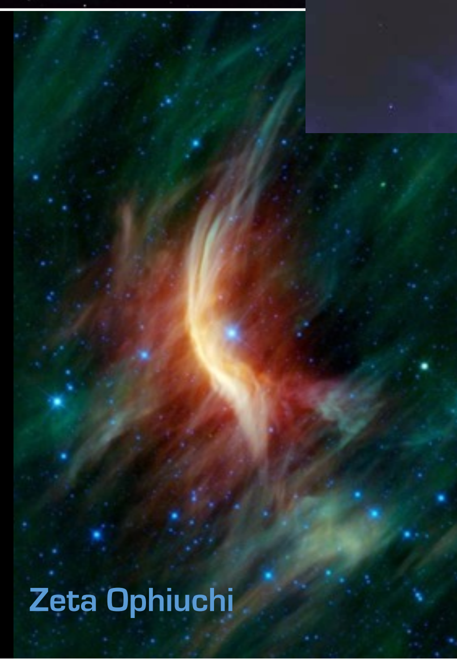
Merav Opher

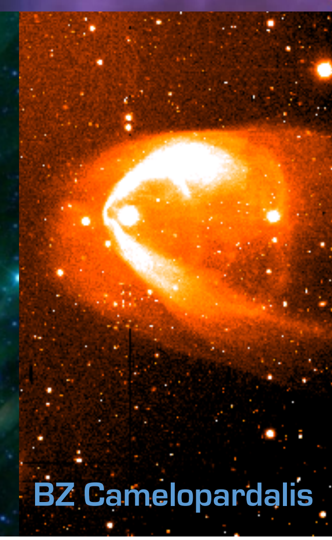


Mira









BOSTON UNIVERSITY

SHIELD Science Questions

- Science Question A:

  What is the global structure of the heliosphere?

- Science Question B:

  How do Pick-Up Ions evolve from “cradle to grave”?

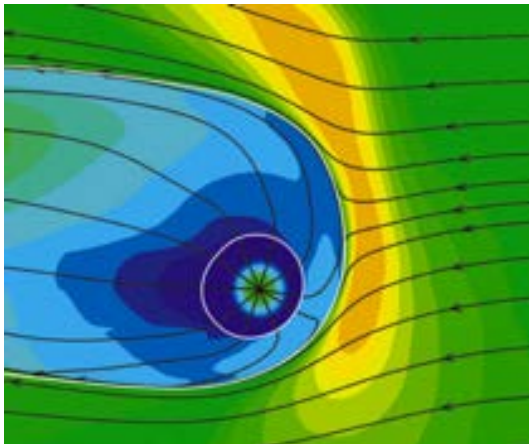
- Science Question C:

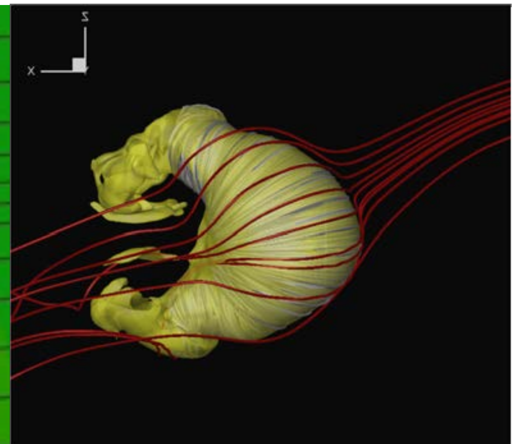
  How does the heliosphere interact with and influence the interstellar medium (ISM)?

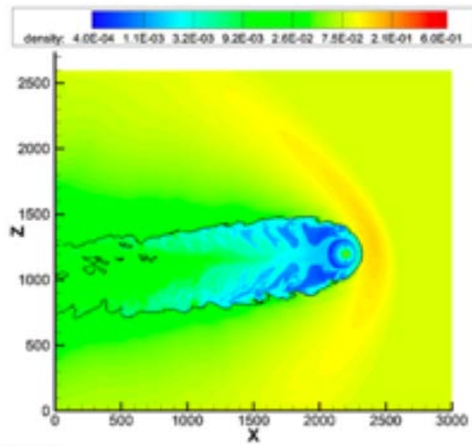
- Science Question D:

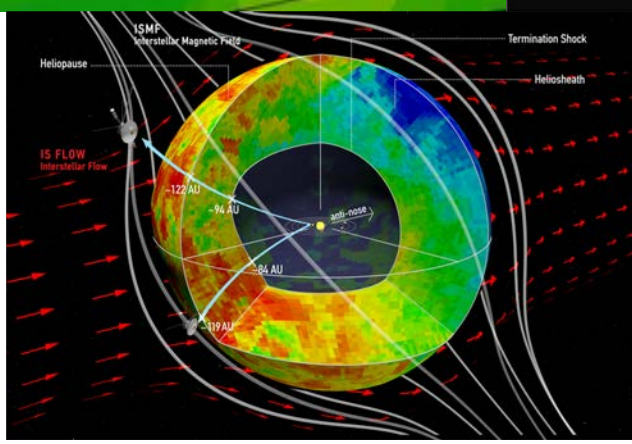
  How do cosmic rays get filtered by and transported through the heliosphere

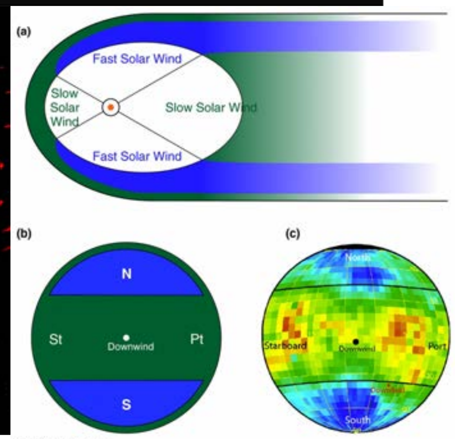
There is a Current Debate on Shape of the Heliosphere





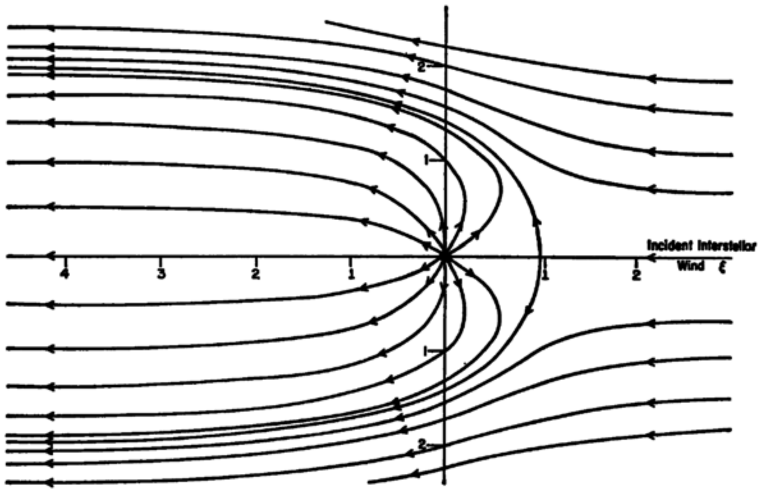




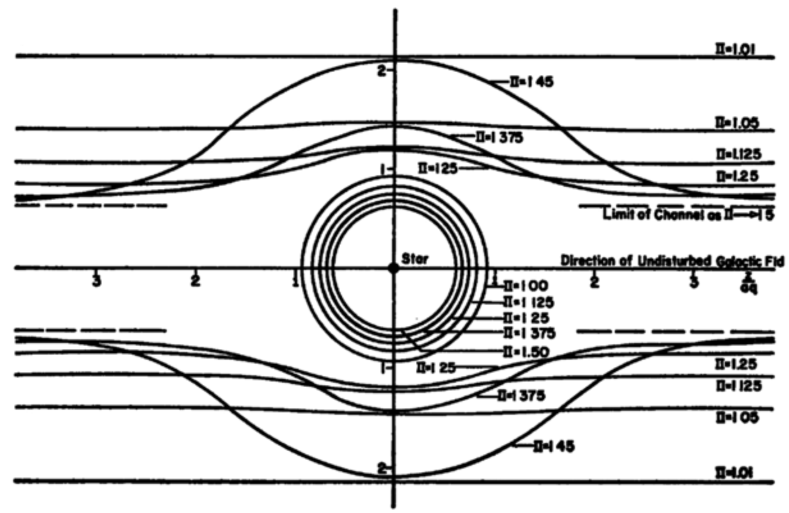


This question is one that will be addressed in SHIELD

Concepts of the Heliosphere: Classic works of 50-60's



Weak Interstellar Magnetic Field



Strong Interstellar Magnetic Field

Parker (1961)

Working Paradigm: Long Comet-like Tail

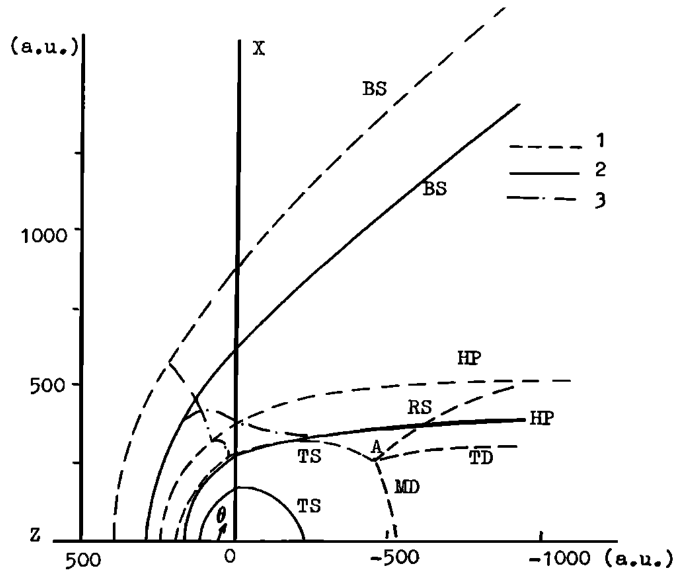
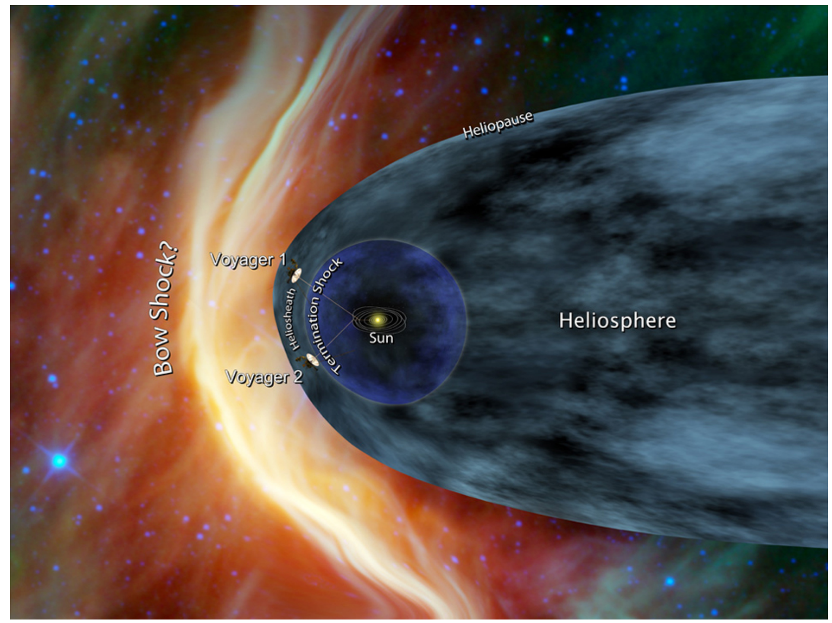
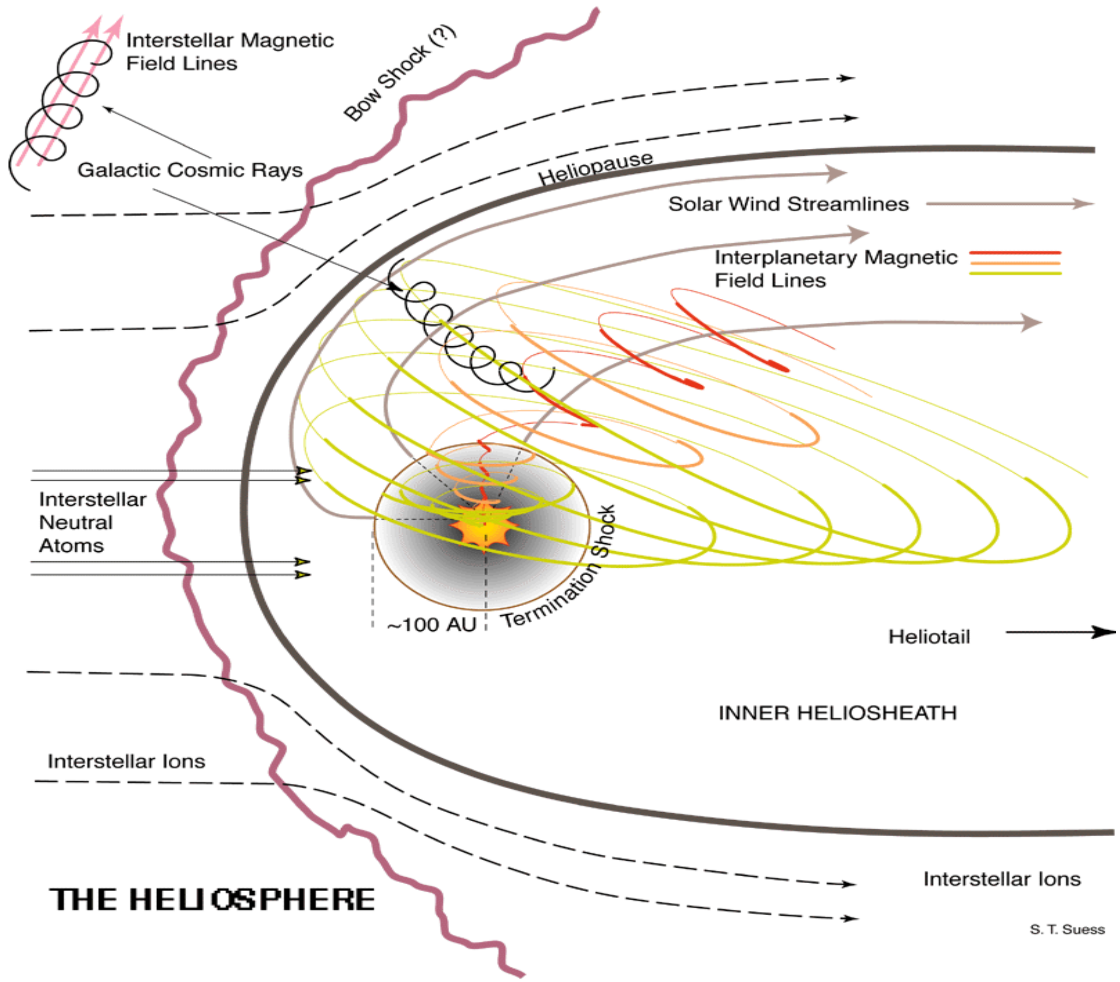


Fig. 2. Geometrical pattern of the interface. Results of the numerical calculations for $n_{H\infty} = 0$ (1) and $n_{H\infty} = 0.14\ cm^{-3}$ (2); curves (3) are the sonic lines. Positions of bow shock (BS), termination shock (TS), heliopause (HP), reflected shock (RS), tangential discontinuity (TD), and Mach disc (MD) are shown.



Baranov & Malama (1993) – Hydrodynamic calculations

ISSUE OF CONFINEMENT by the Solar Magnetic



Assumption is that the solar magnetic field has a negligible role

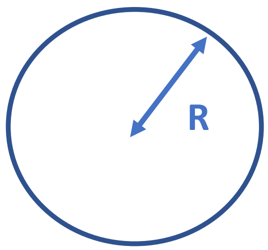
Probably because in the heliosheath, the plasma $\beta = P_T/P_B >> 1$

$$B = B_0\left(\frac{R_0}{r}\right)^2 e_r - B_0\left(\frac{R_0^2}{r}\right)\frac{\Omega \sin\Theta}{v_{SW}} e_\phi,$$

Ω: stellar rotation rate
Θ: polar angle

Interplanetary Magnetic Field

Issue of Confinement: Resistance of the solar magnetic field to being stretched



The tension on a field line with a radius of curvature *R* is
so

$$F_{tension} = |B \cdot \nabla B| / 4\pi \approx \left(B^2 / 8\pi\right)\left(2 / R\right) \qquad F_{tension} \approx 2P_B / R$$

The force stretching the magnetic field due to the flows is

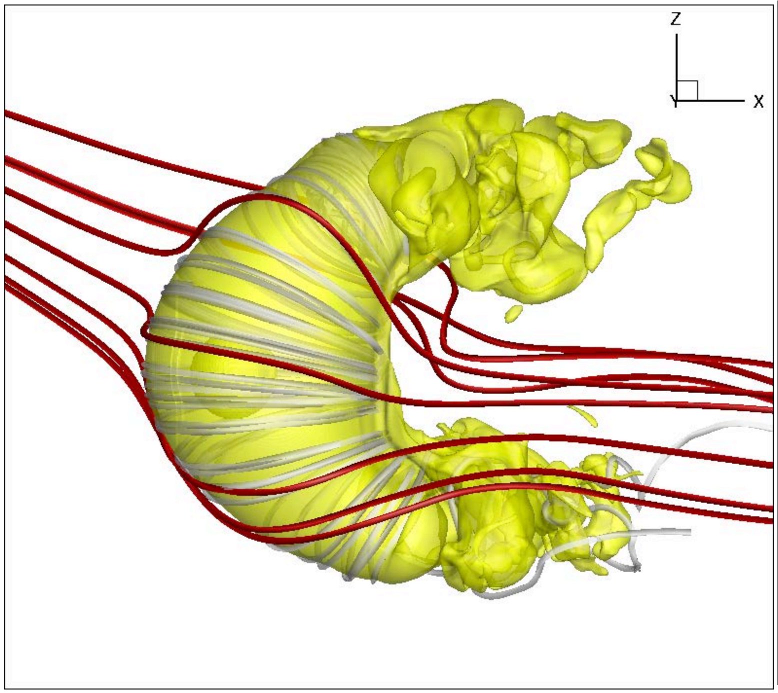
$$F_{streatching} \approx \rho |\mathrm{v} \cdot \nabla \mathrm{v}| / 2 \approx \rho \mathrm{v}^2 \kappa_V / 2 \approx \rho \mathrm{v}^2 / 2R \approx P_{ram} / R$$

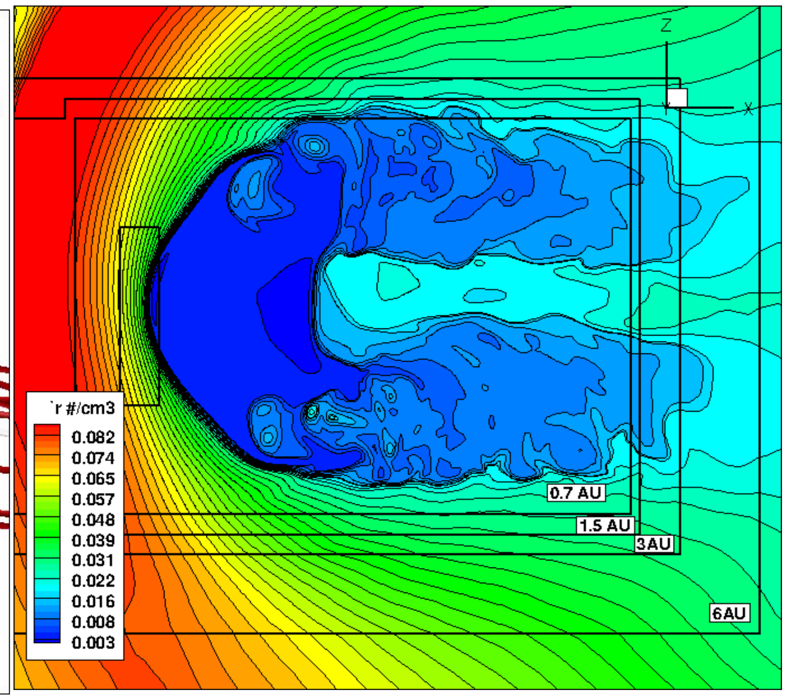
so the ratio between the two forces is

$$F_{streatching} / F_{tension} \approx P_{ram} / 2P_B$$

For the Heliosheath nominal values $F_{streatching}/F_{tension} < 1$

Solar Magnetic Field is the backbone of the heliosphere: “Croissant-Like” Heliosphere



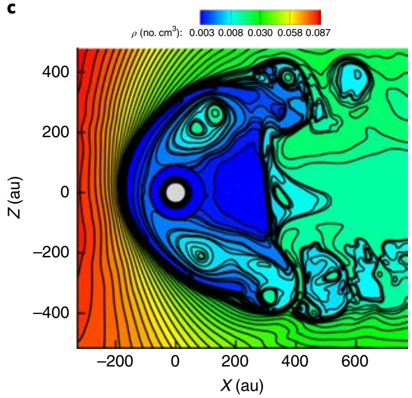


Tension force collimates the heliosheath flow in two jets
(Opher et al. 2015; Drake et al. 2015)

New Global Model: Cold Thermal Solar Wind and PUIs treated separately

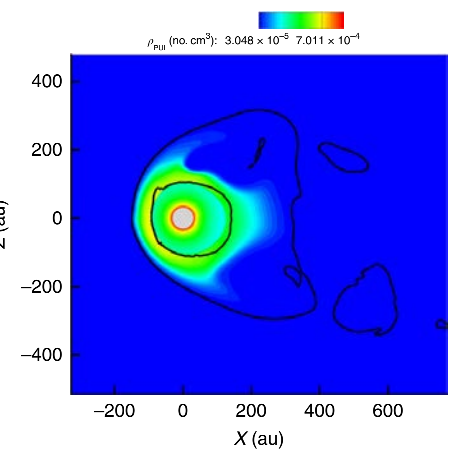
Old Model: Single Ion

c



New Model: Multi Ion

a



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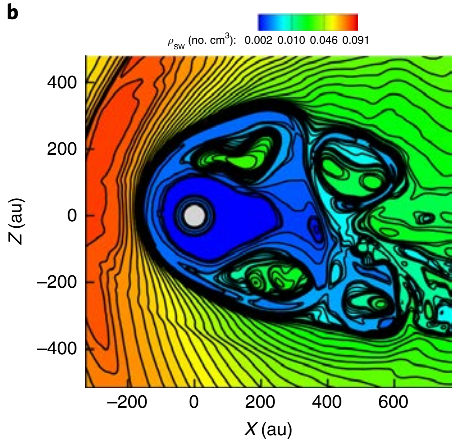
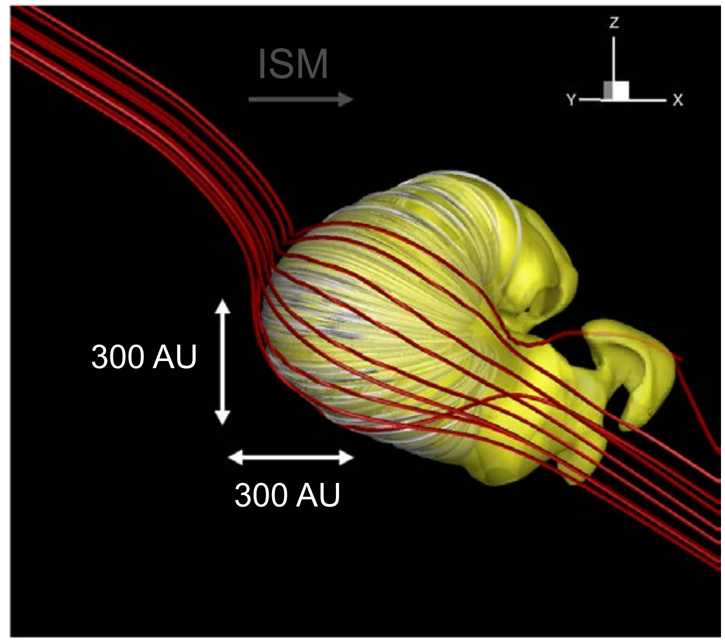
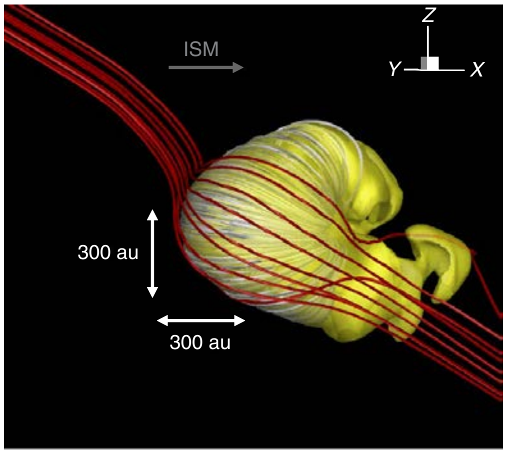




Opher et al. Nature Astronomy 2020

a



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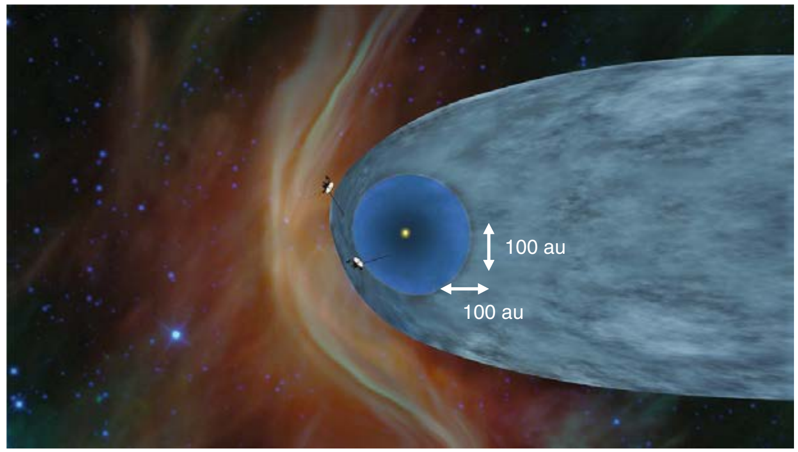
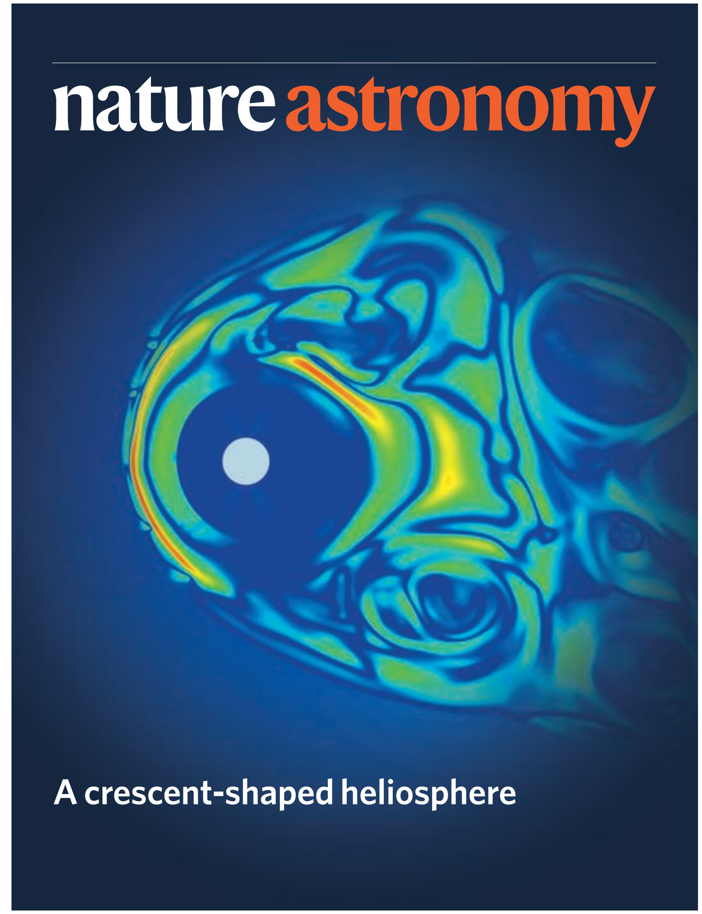


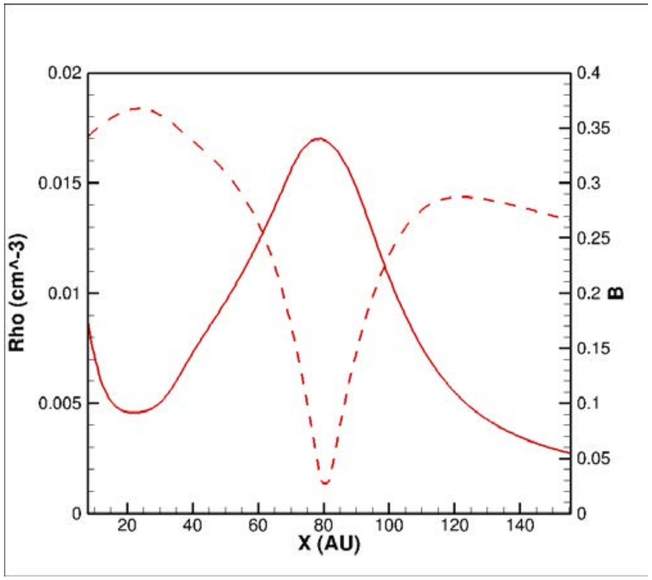


Cover of July issue, 2020

Show the large interest in the community for the question of the shape of the Heliosphere that is one of the questions that SHIELD is addressing

Density Gradient in the Heliosheath

The density gradient is set in the heliosheath due to the magnetic tension from solar magnetic field and is affected as well by the charge exchange

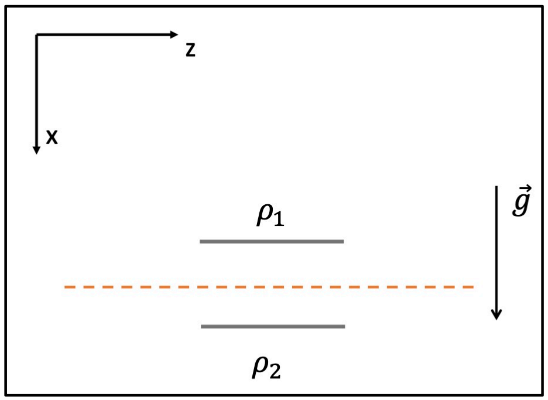


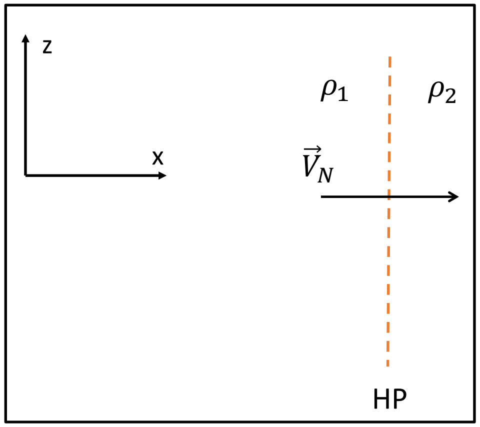
Opher et al. 2021

Density gradient along the axis of the heliospheric jet for the realistic case -

Rayleigh-Taylor instability

Opher et al. 2021





(A)

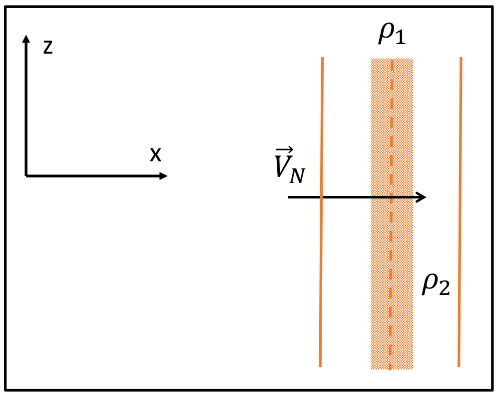
(A) Heavier fluid "1", seating on top of a lighter fluid "2" and the gravity *g* pointing perpendicular to the interface;

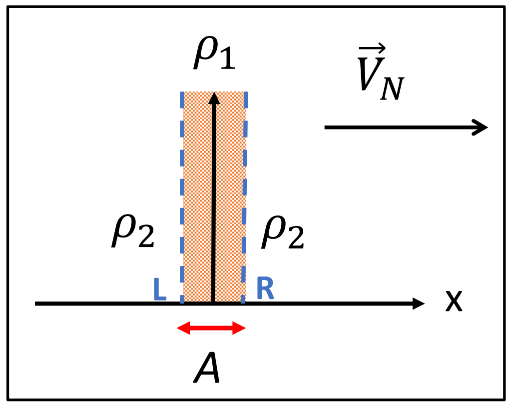
(B) RT at the HP: the streaming of neutrals acts as an effective gravity $\overrightarrow{g^*} \sim \nu_{CN} \overrightarrow{v_N}$

See RT at the HP: Liewer et al. 1996; Zank et al. 1996; Florinski et al. 2004; Avinash et al. 2014

Rayleigh-Taylor instability

Opher et al. 2021

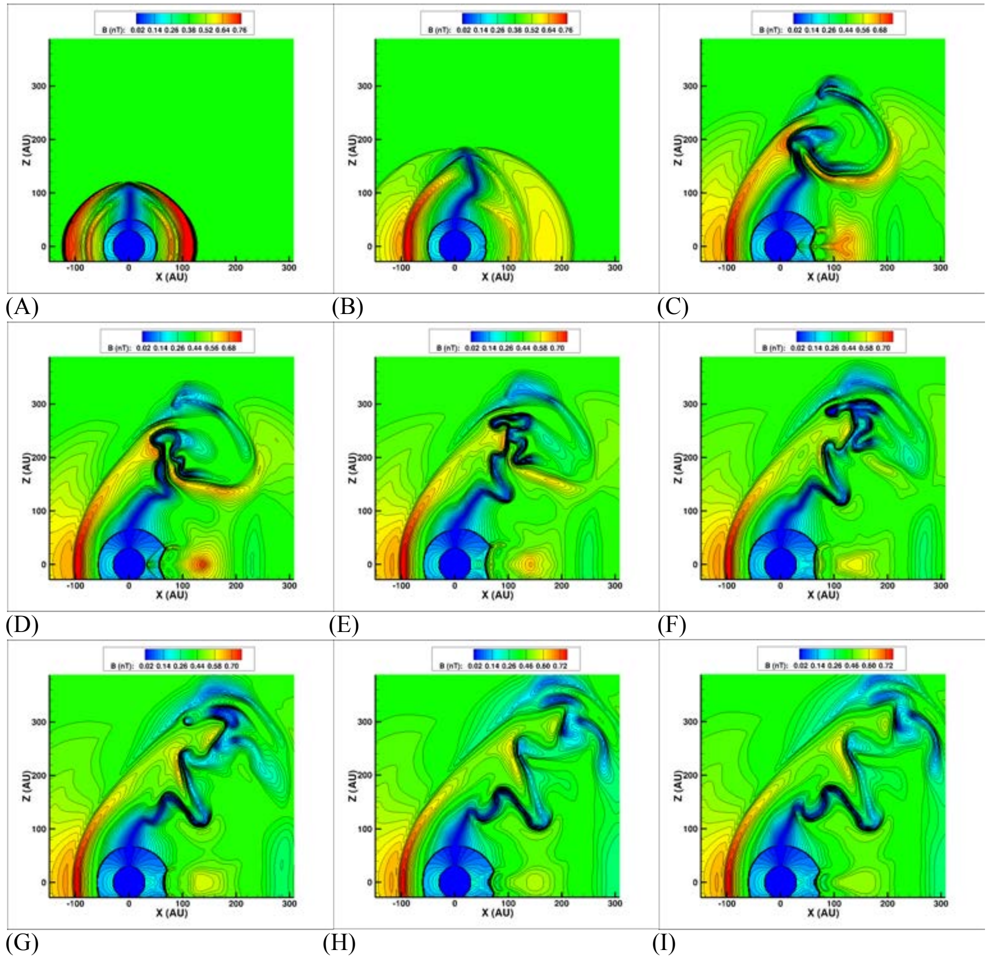




(C) RT along the axis of the heliospheric jets in the situation where there is no motion through the ISM.

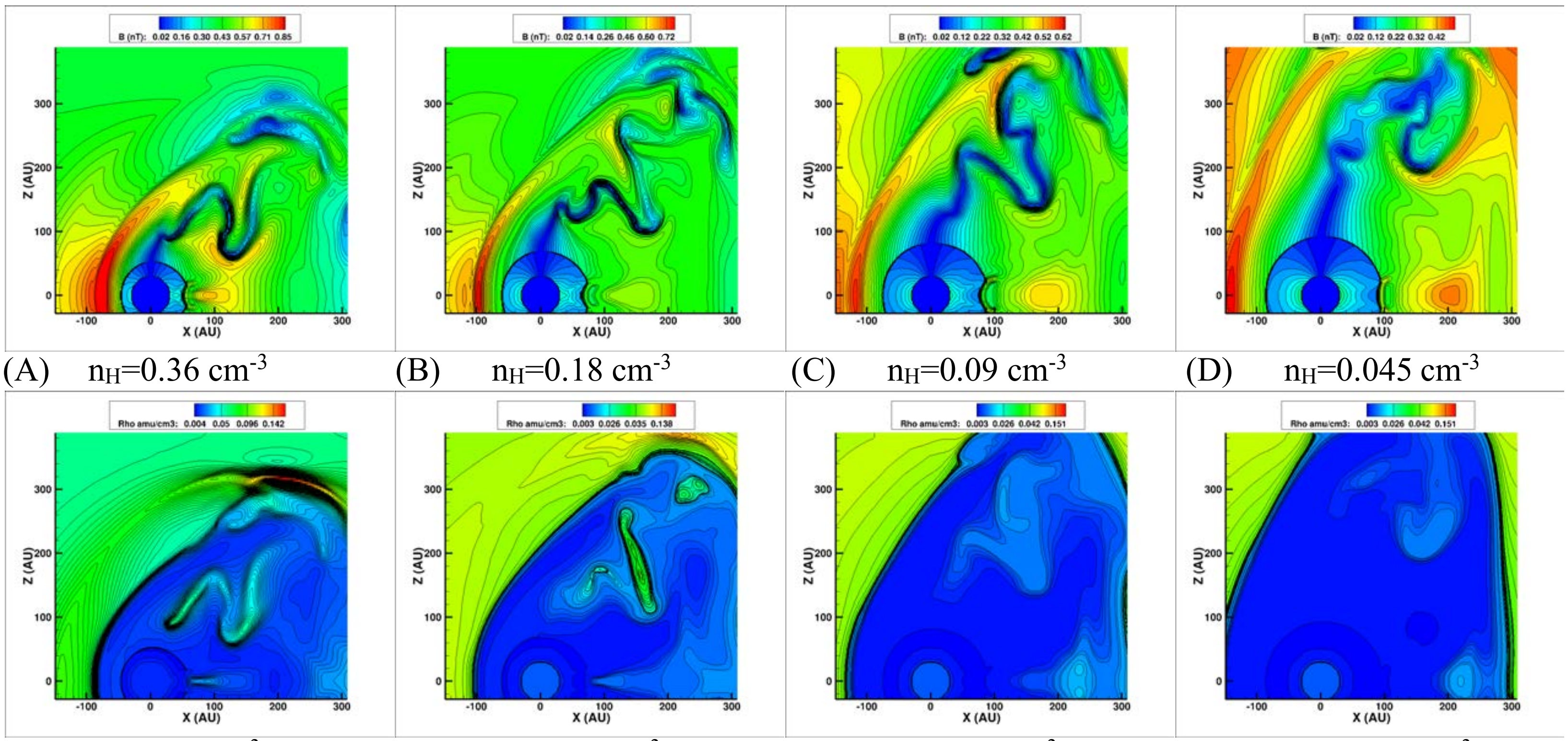
Cartoon of RT in slab geometry. In isolation the left density Jump "L" would be stable while the right interface "R" Will be unstable

A Turbulent Heliosheath Driven by Rayleigh Taylor Instability



Opher et al. 2021

A Turbulent Heliosheath Driven by Rayleigh Taylor Instability



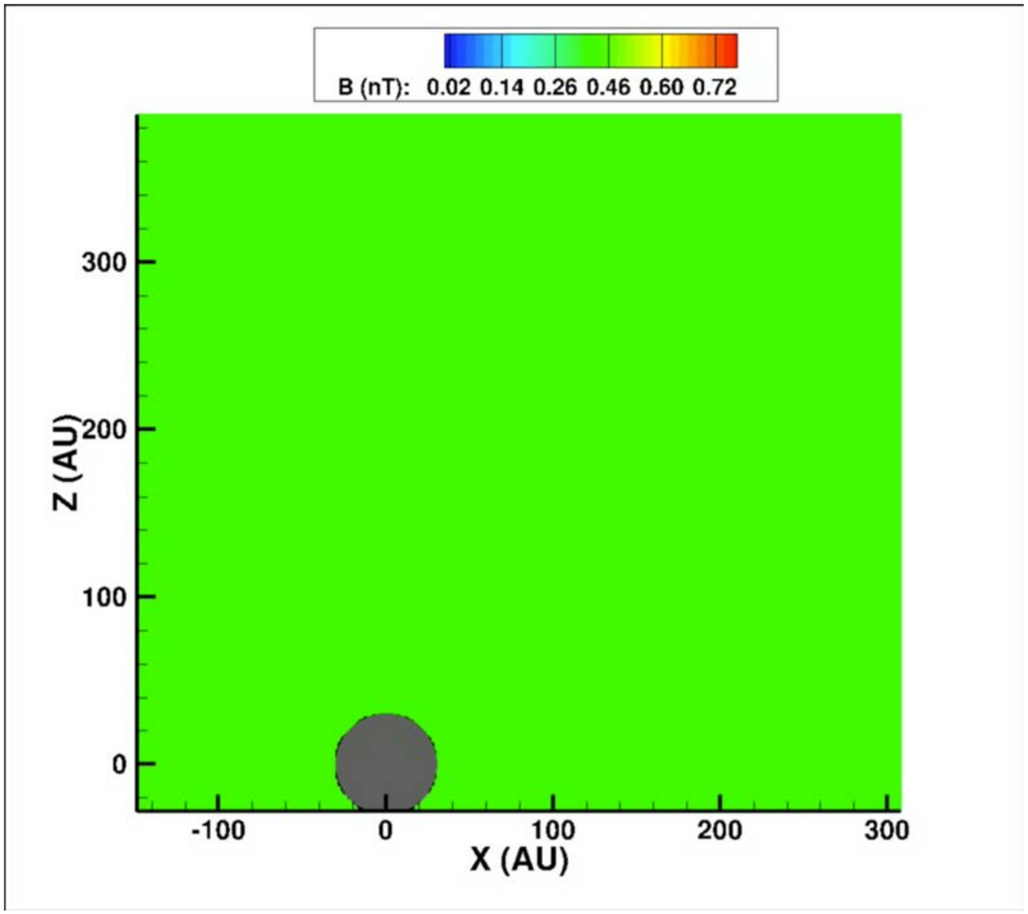
(A) n_H=0.36 cm^{-3} (B) n_H=0.18 cm^{-3} (C) n_H=0.09 cm^{-3} (D) n_H=0.045 cm^{-3}

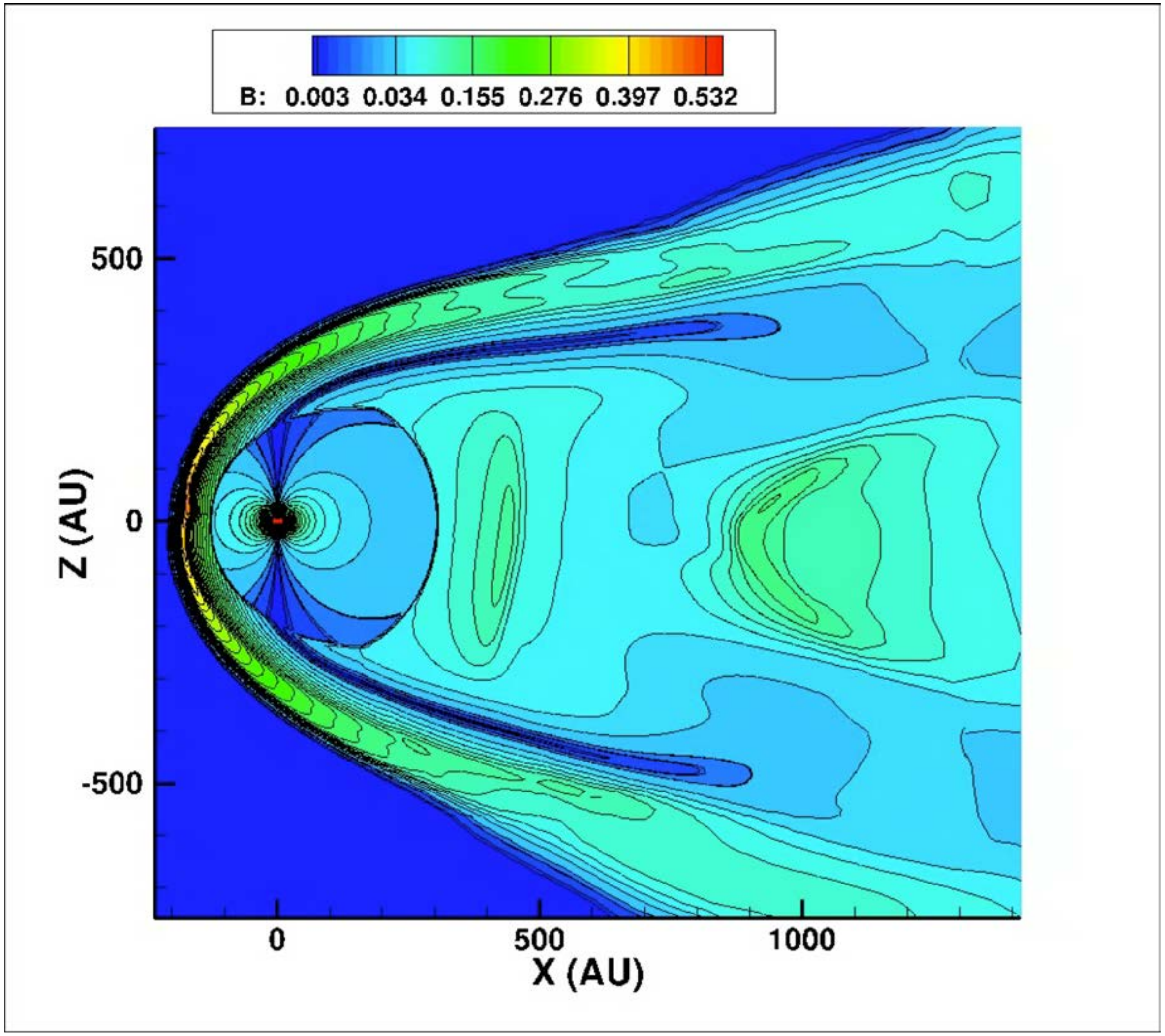
(E) n_H=0.36 cm^{-3} (F) n_H=0.18 cm^{-3} (G) n_H=0.09 cm^{-3} (H) n_H=0.045 cm^{-3}

Fig. 2. The dependence of the instability on neutral H density. Magnetic field (top row) and plasma density (bottom row) are shown at t=41 years for simulations with various ISM neutral H densities.

Opher et al. 2021

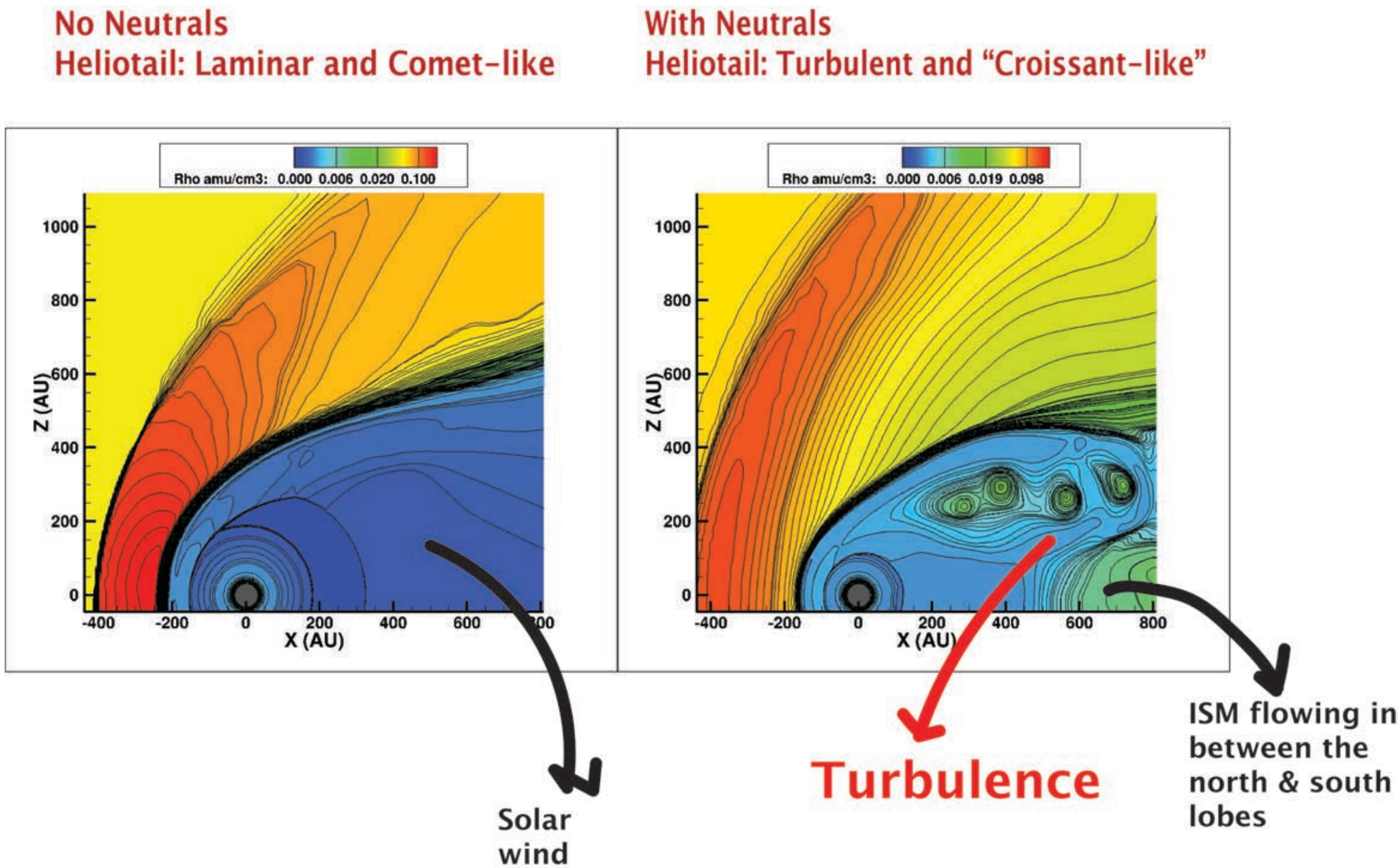
Streaming neutrals in the ISM (n_H=0.18 cm^{-3})





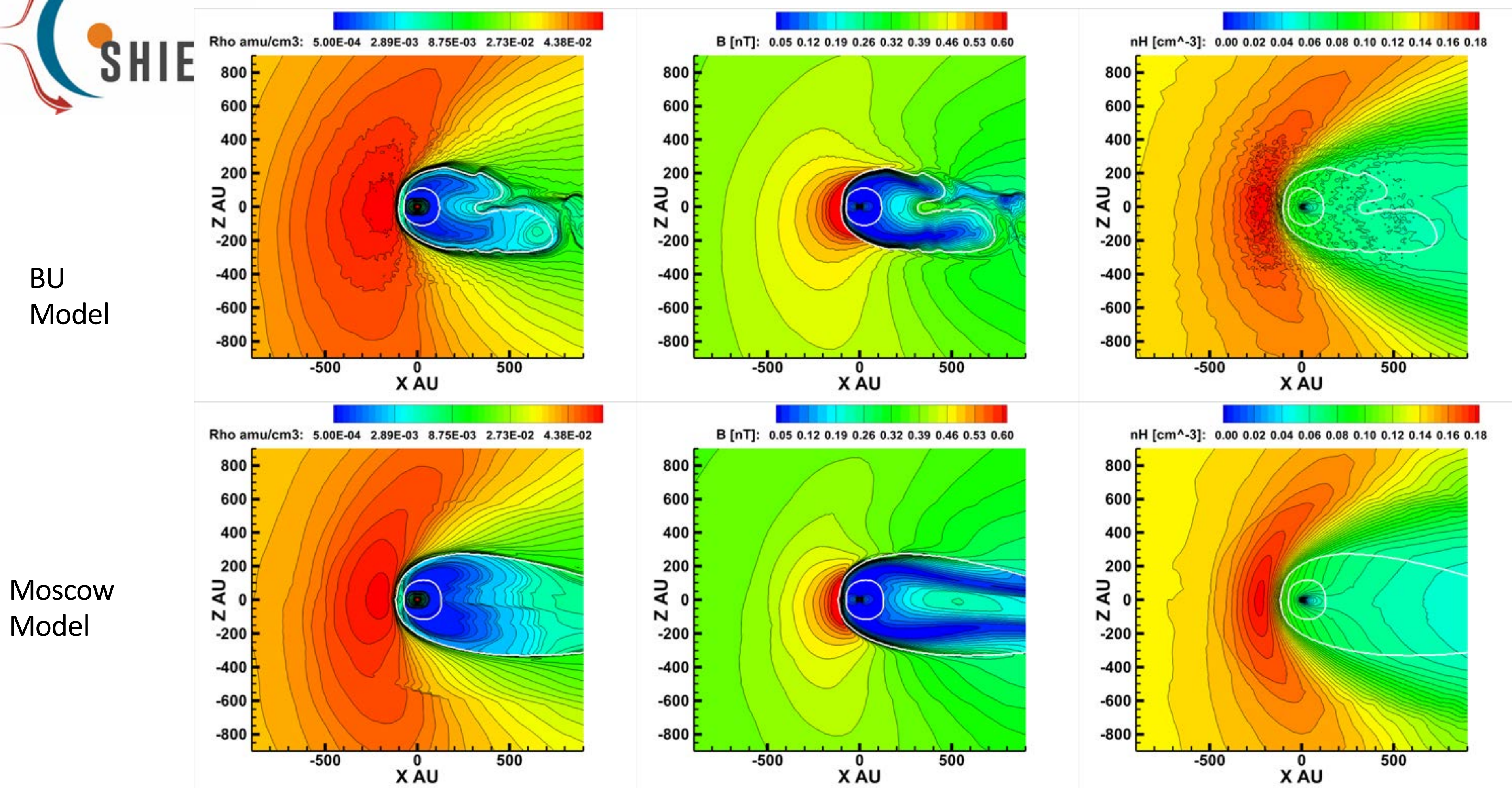
Opher et al. 2021

Discovered an instability in the heliosheath, driven by the neutral H atoms, that is Rayleigh-Taylor-like



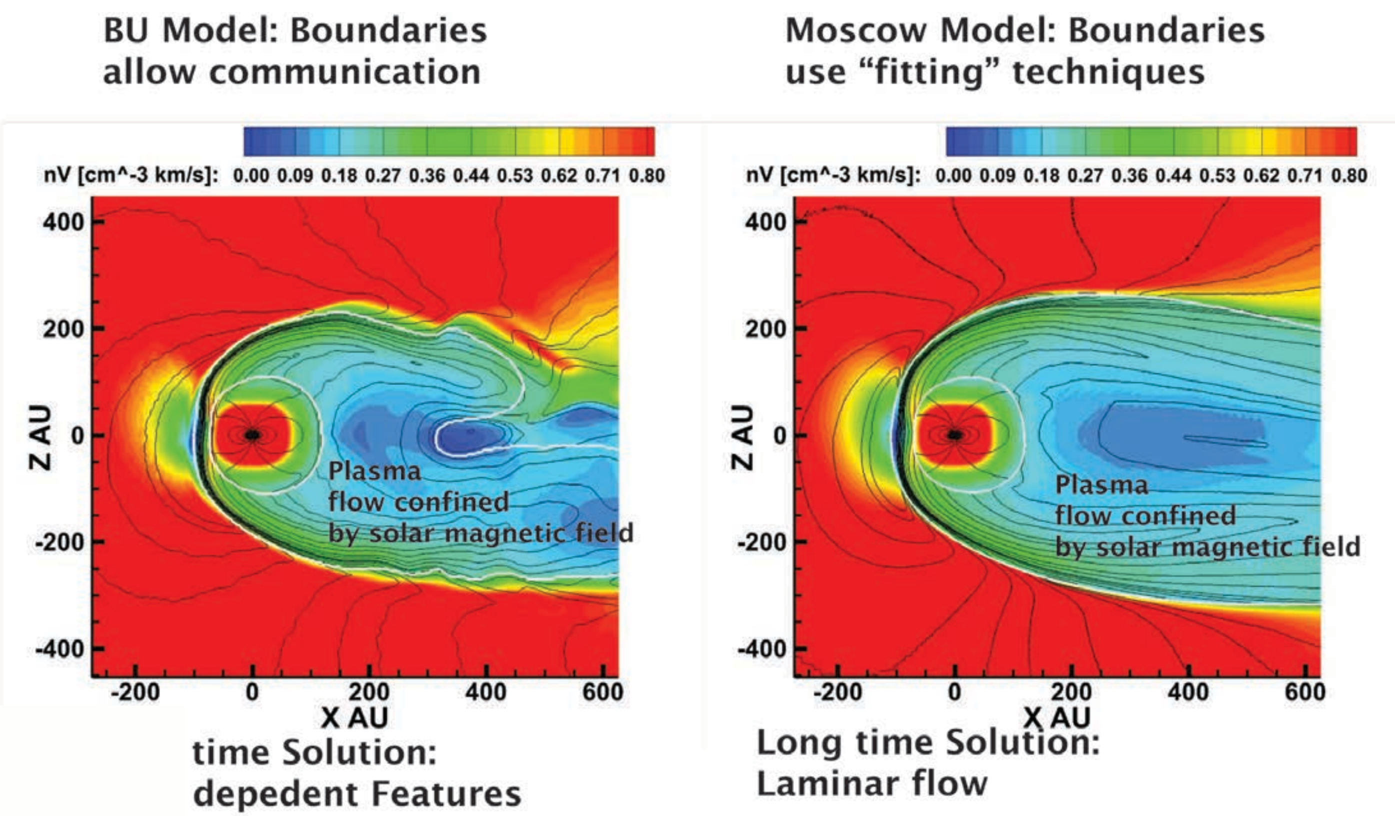
Opher et al. 2021

Next steps: understand the details of the opening of the tail by the instability and consequences for the Heliosheath



Kornbleuth et al. 2021

Conducted first comparison of two different MHD solutions with the same boundary conditions, finding that the plasma in the heliotail is confined by the solar magnetic field



Kornbleuth et al. 2021

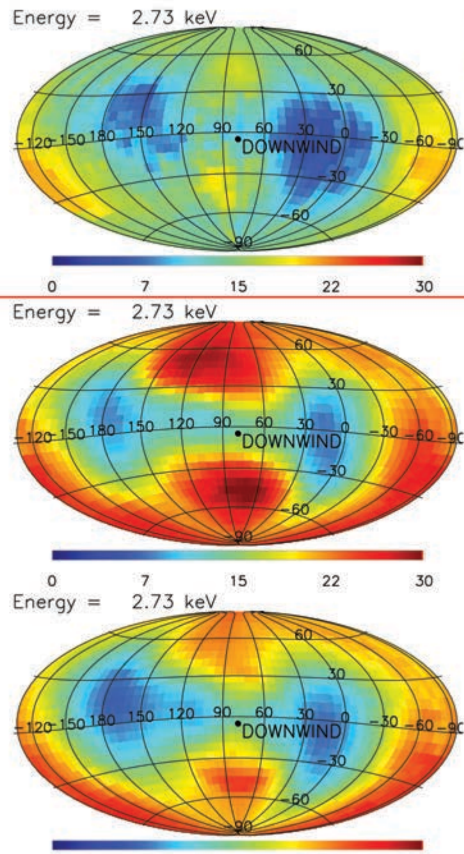
SHIELD

- Conducted first comparison of two different MHD solutions with the same boundary conditions, finding that the plasma in the heliotail is confined by the solar magnetic field (Kornbleuth et al. 2021)

IBEX GDF (2009–2013)

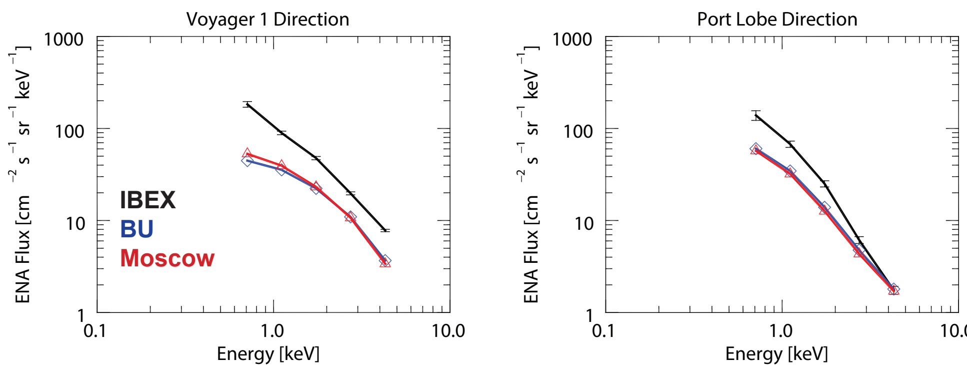
BU Model (x 1.8)

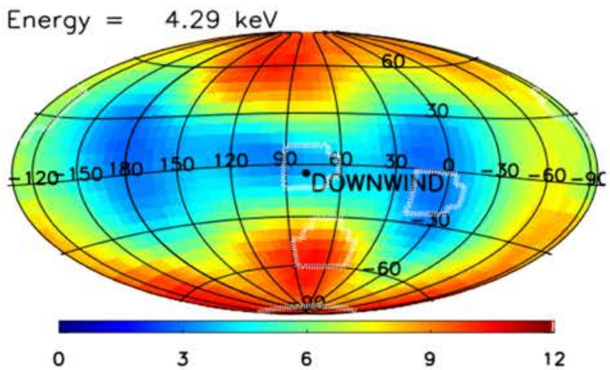
Moscow Model (x 1.8)



Data and models differ

Models reproduce main features of data

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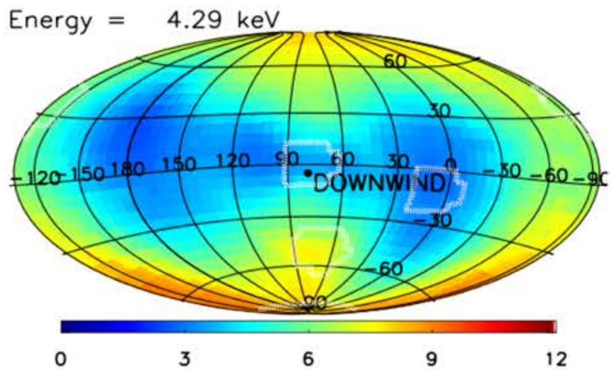
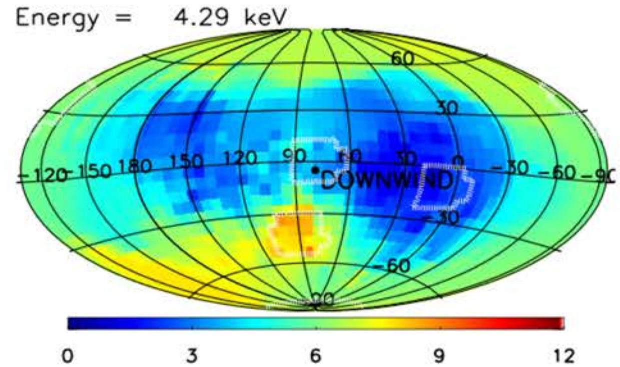
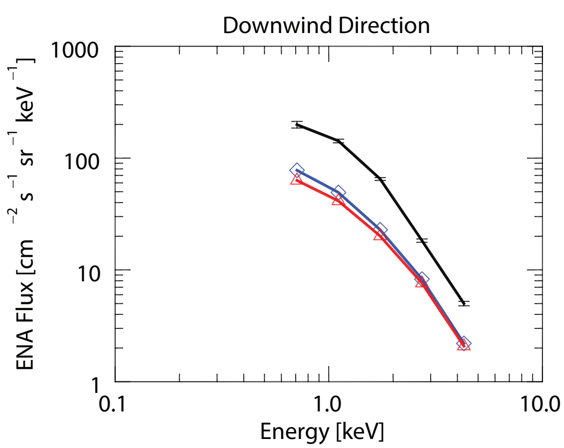
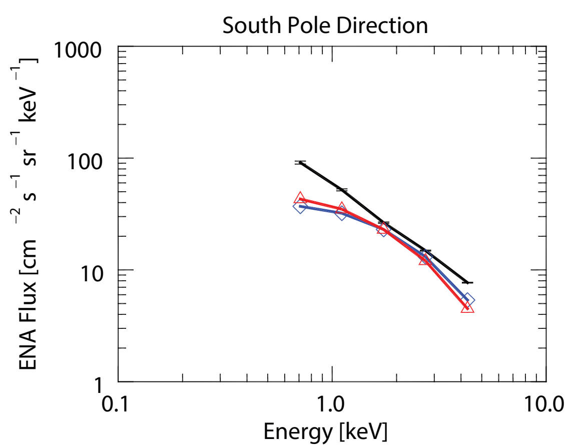
DOWNWIND
0 3 6 9 12


Energy = 4.29 keV
DOWNWIND
0 3 6 9 12


Energy = 4.29 keV
DOWNWIND
0 3 6 9 12


Downwind Direction
ENA Flux [cm⁻² s⁻¹ sr⁻¹ keV⁻¹]
Energy [keV]


South Pole Direction
ENA Flux [cm⁻² s⁻¹ sr⁻¹ keV⁻¹]
Energy [keV]

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Next steps: Understand the details of the opening of the tail by the instability and consequences for the Heliosheath ; in particular for ENA maps

Structure of the tail beyond 200AU: probed by IMAP