IBEX

Interstellar Boundary Explorer

Imaging the edge of out solar system and beyond — Discovering the global interaction between the solar wind and the interstellar medium

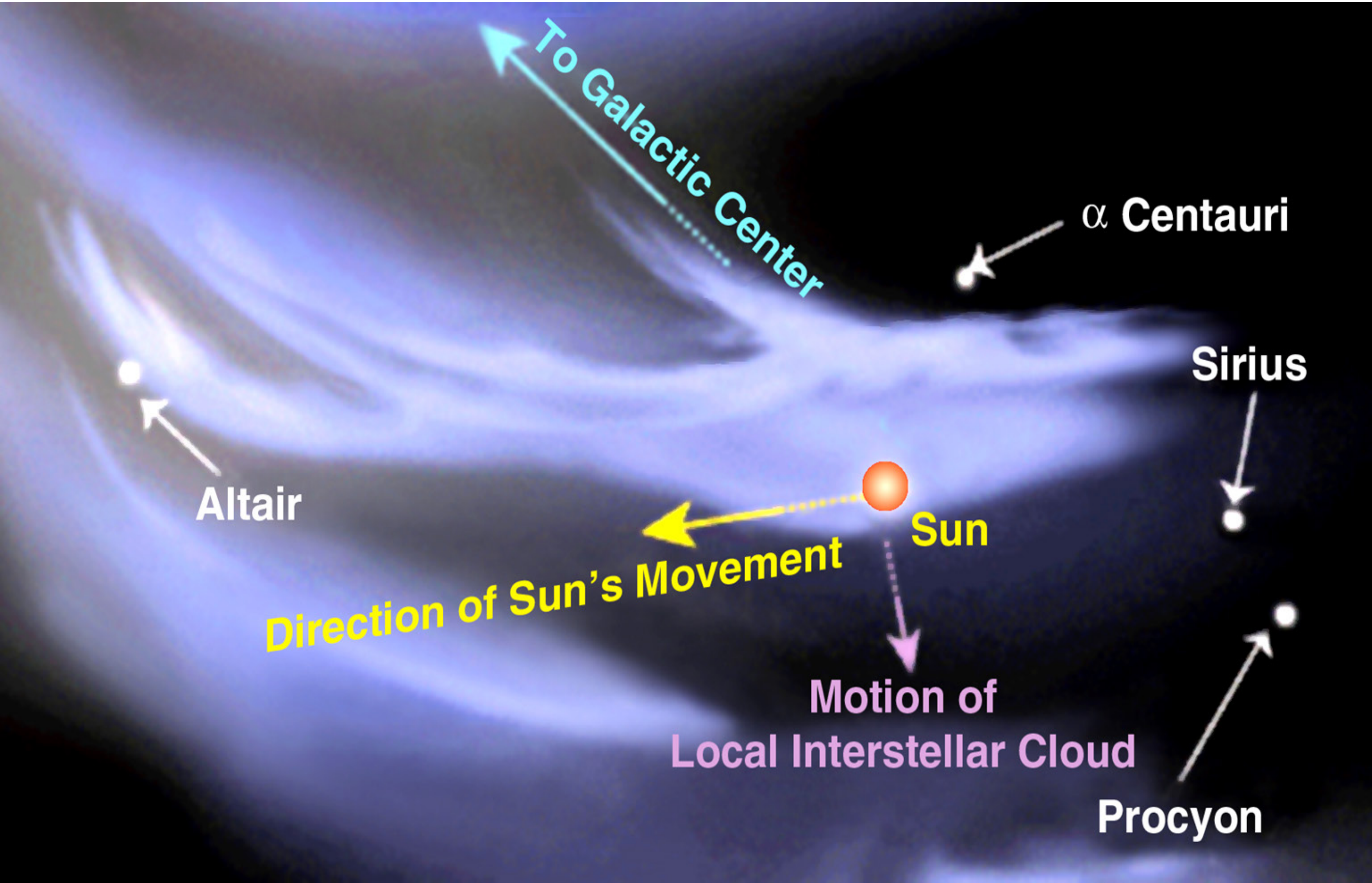
Opening a New Window on Our Global Heliosphere
… IBEX
… the Voyagers
… and the next steps (IMAP)

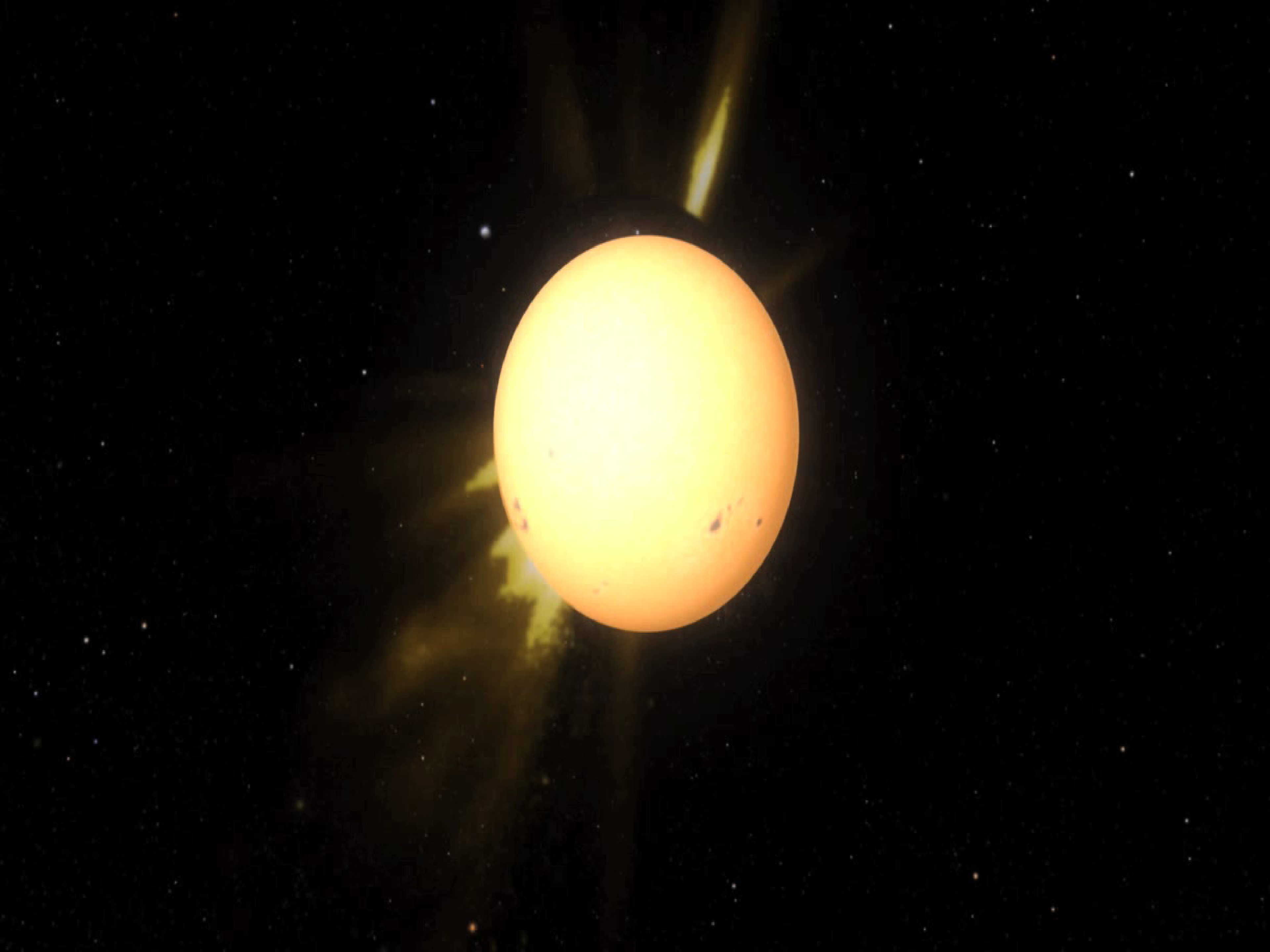
N. Schwadron

University of New Hampshire

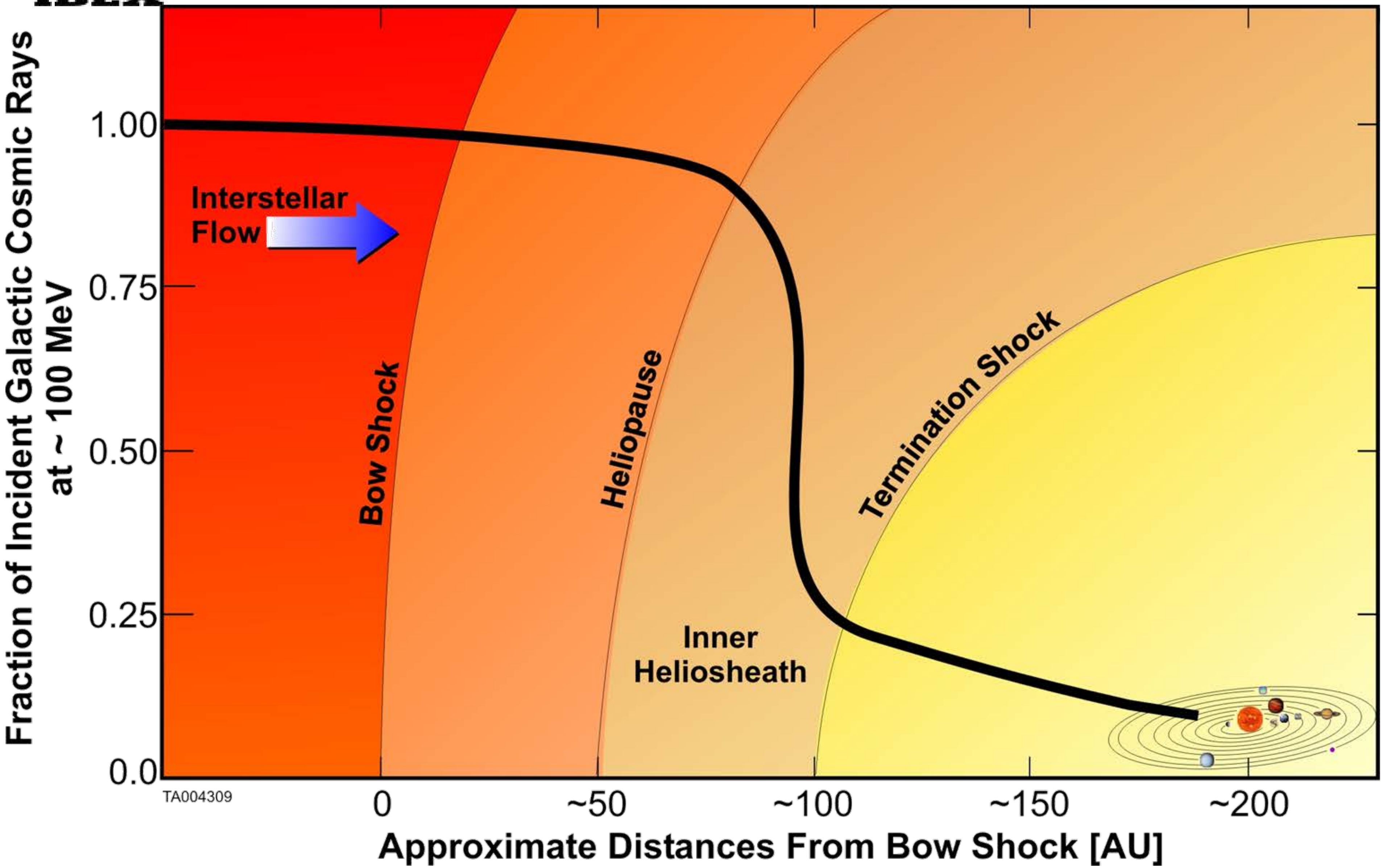
NEROC– Nov 2018

The Sun and Local Interstellar Medium (LISM)

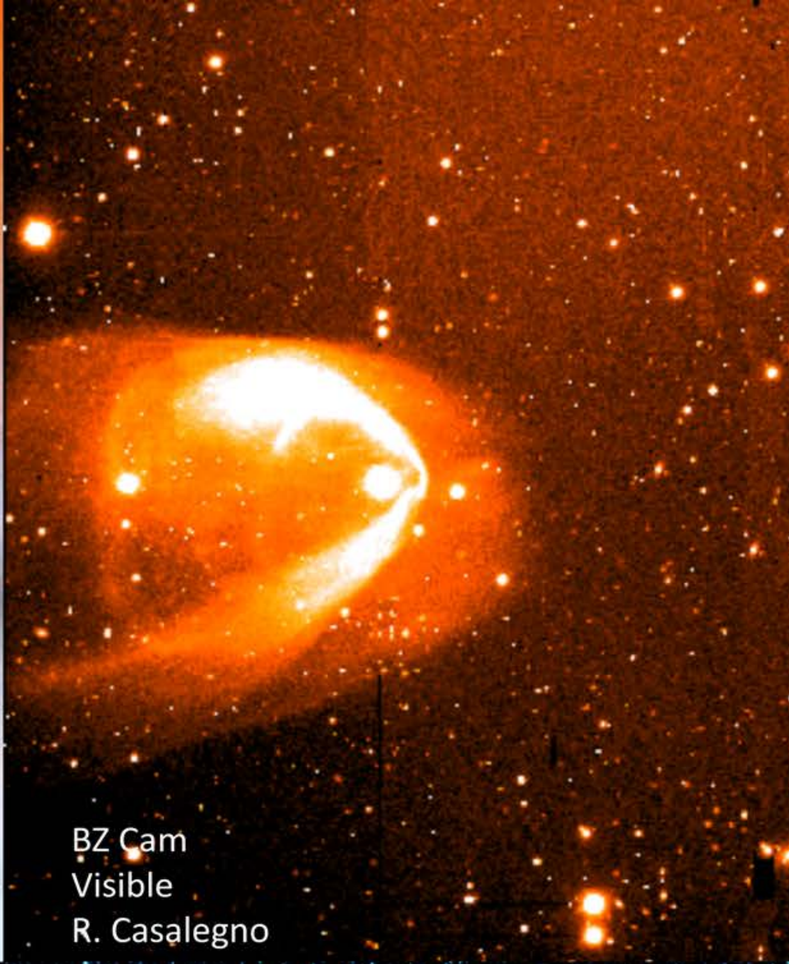


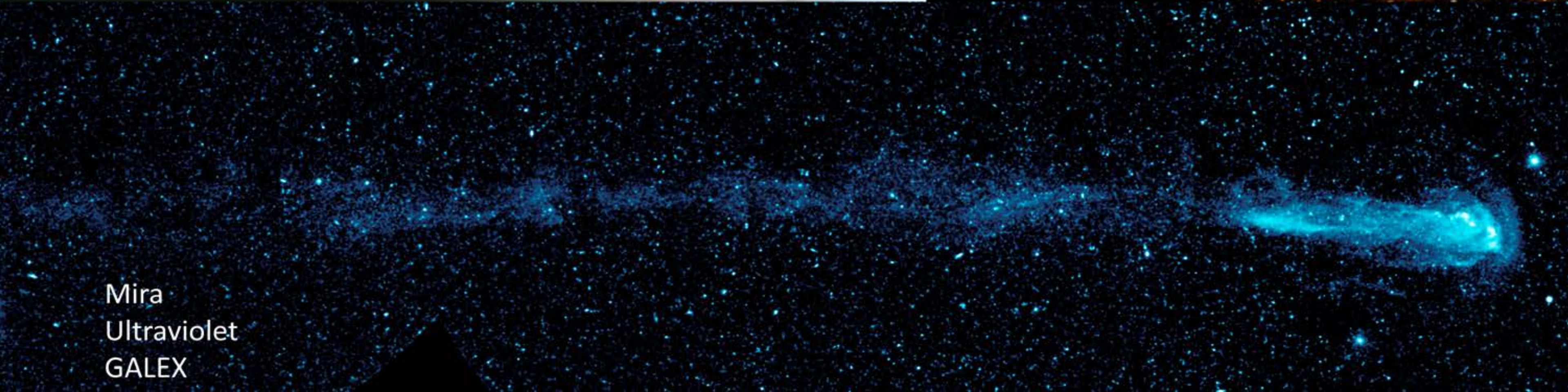


Relevant to Exploration: GCR Shielding

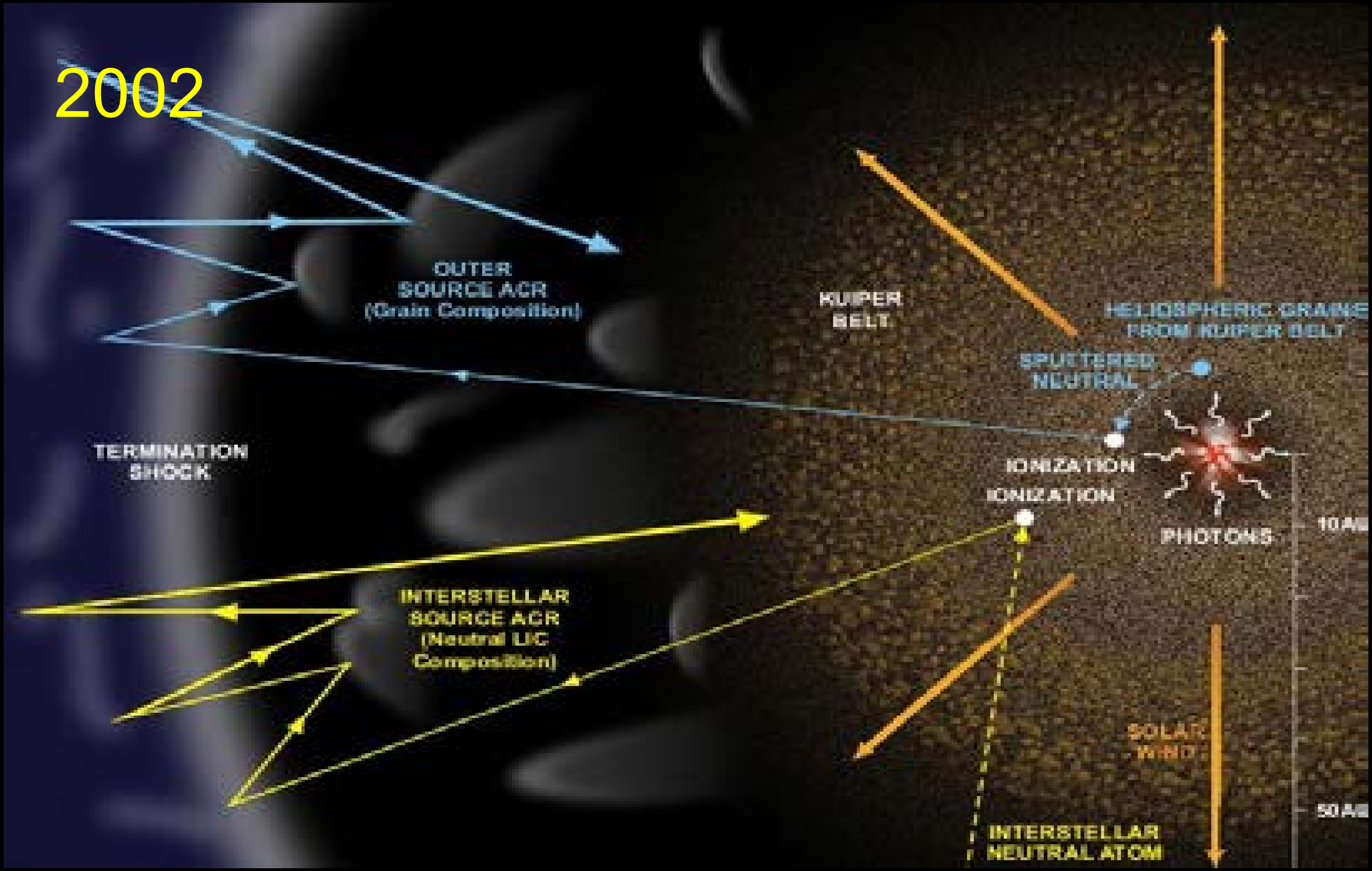


ASTROSPHERES





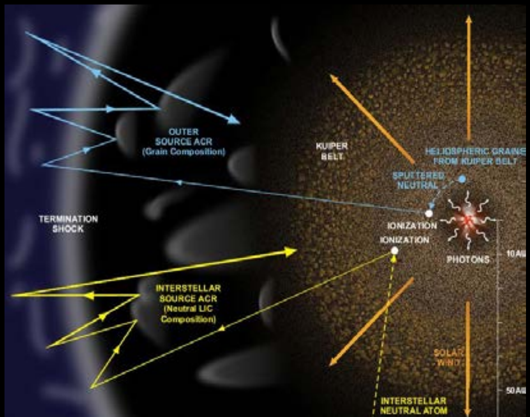
Timeline of the Interstellar Discovery



Schwadron et al., GRL, 2002

Timeline of the Interstellar Discovery

2002



Voyager 1 and Voyager 2 remain inside the termination shock

Distance to TS **unknown**

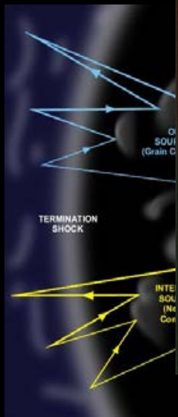
Heliosheath **unmeasured**

Global properties of heliosphere **unknown**

Only indirect evidence from Anomalous Cosmic Rays, radio emissions, neutral populations and lyman alpha

Timeline of the Interstellar Discovery

2002



Dec 2004

Voyager 1's first crossing of the termination shock

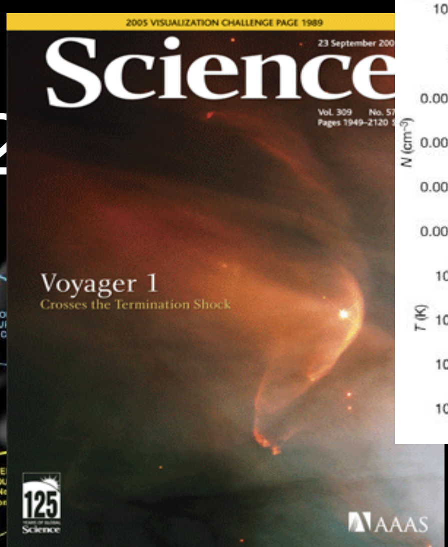
Distance, properties known at one location and at one time

Exploration of Heliosheath begins

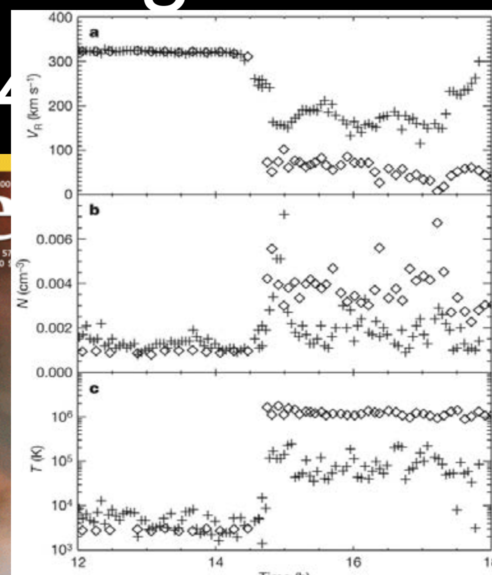
Timeline of the Interstellar Discovery

2002

Dec 2004



Aug 2007



Richardson et al., 2008

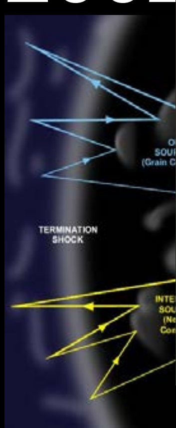
Voyager 2's second crossing of the termination shock

Distance, properties known at <u>two</u> locations and at two times

Discovery of termination shock (and heliosphere) asymmetries

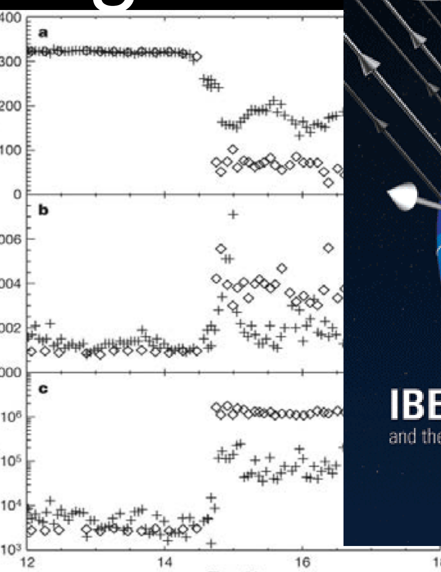
Timeline of the Interstellar Discovery

2002



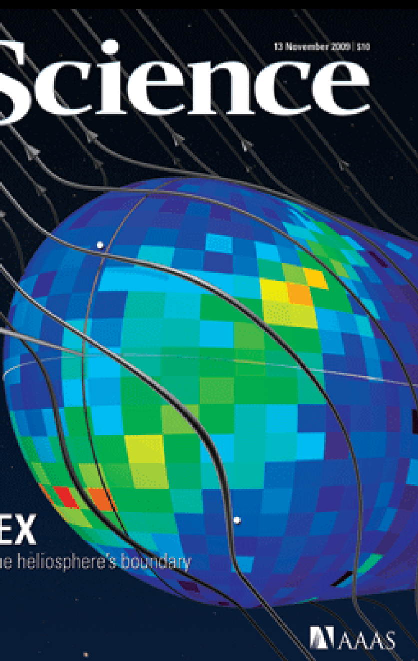
Dec 2004

Aug 2007



Richardson et al., 2008

Dec 2009



Global structure of Heliosheath, termination shock

Properties of LISM

Existence of Bow Wave

Pickup ions, Suprathermal population critical to plasma pressure

Discovery of IBEX ribbon

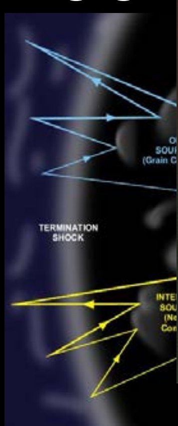
Possible link between Ribbon and interstellar magnetic field

Timeline of the Interstellar Discovery

Voyager 1 enters the local galactic medium

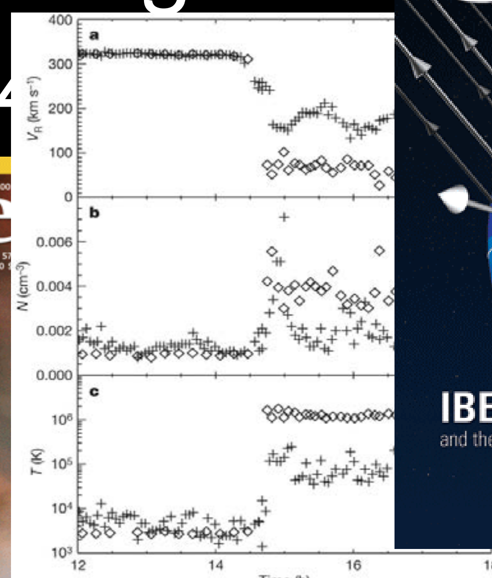
In situ galactic exploration begins

2002



Dec 2004

Aug 2007



Richardson et al., 2008

Dec 2009

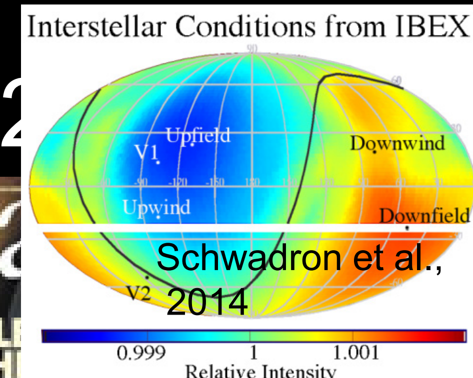
Aug 2012

Timeline of the Interstellar Discovery

Ribbon Ordering by LISM Magnetic Field confirmed by TeV anisotropies

Journey continues

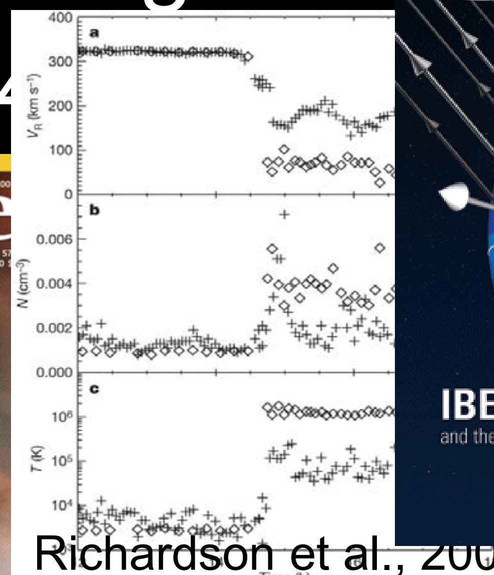
2014-2016



Aug 2012

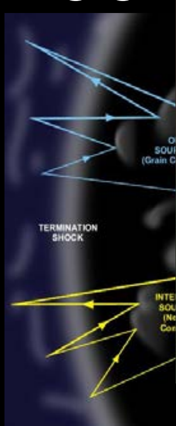
Dec 2009

Aug 2007



Dec 2004

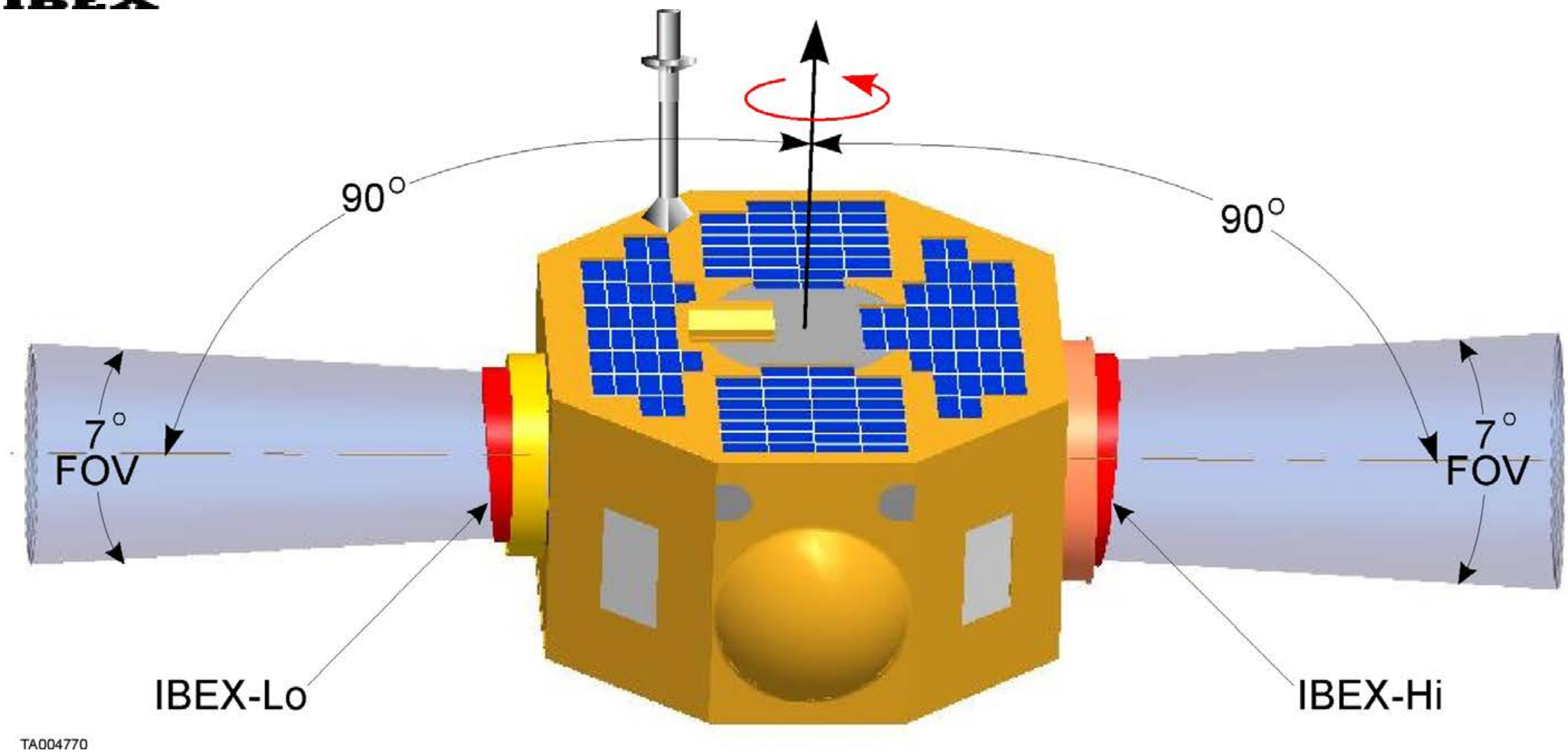
2002



Examples: Opher et al., Science, 2007; Schwadron et al., ApJ, 2016; Opher et al., ApJ, 2017; Zirnstein et al, ApJ, 2016; Schwadron et al., ApJ, 2015

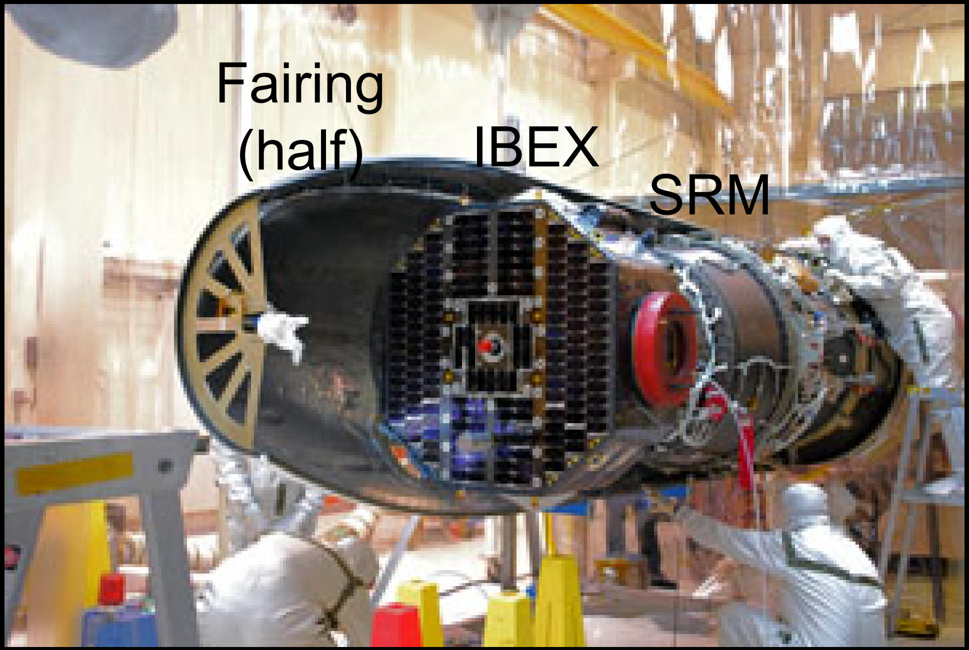
Effects of interstellar magnetic field on global heliosphere, plasma and neutral populations

IBEX Spacecraft



- Two huge aperture single pixel ENA cameras:
  - IBEX-Lo (~10 eV to 2 keV)
  - IBEX-Hi (~300 eV to 6 keV)
- Simple sun-pointed spinner (4 rpm)

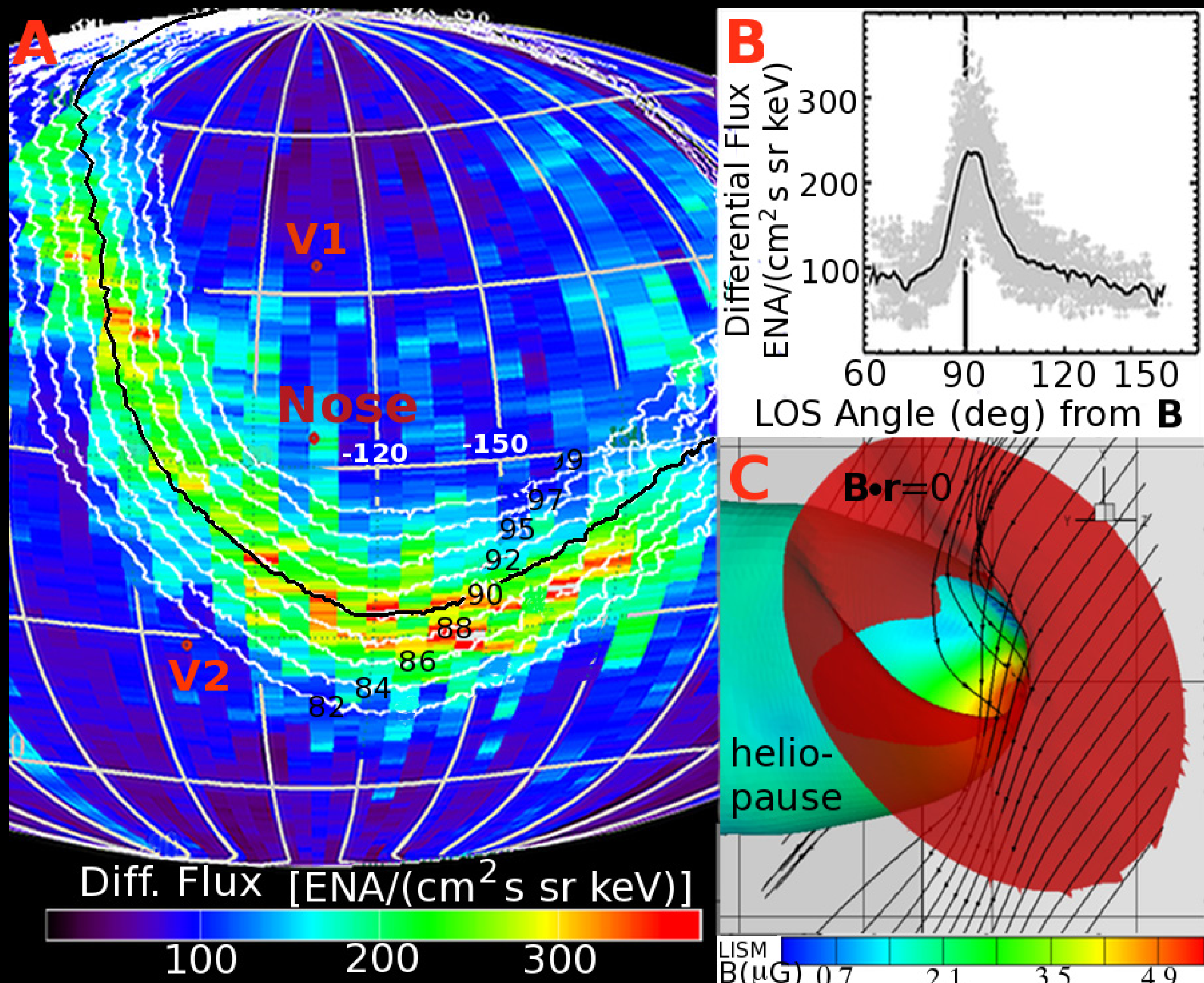
IBEX Orbit Raising Approach



- No mission has ever used a Pegasus LV to achieve orbit higher than LEO (few hundred km)!
- IBEX apogee ~50 R_E
- New approach combines 3 orbit-raising methods
  - Pegasus launch vehicle
  - IBEX-supplied Solid Rocket Motor (SRM)
  - Hydrazine Propulsion System finishes orbit raising and trims out delta-V dispersions from solid rocket motors

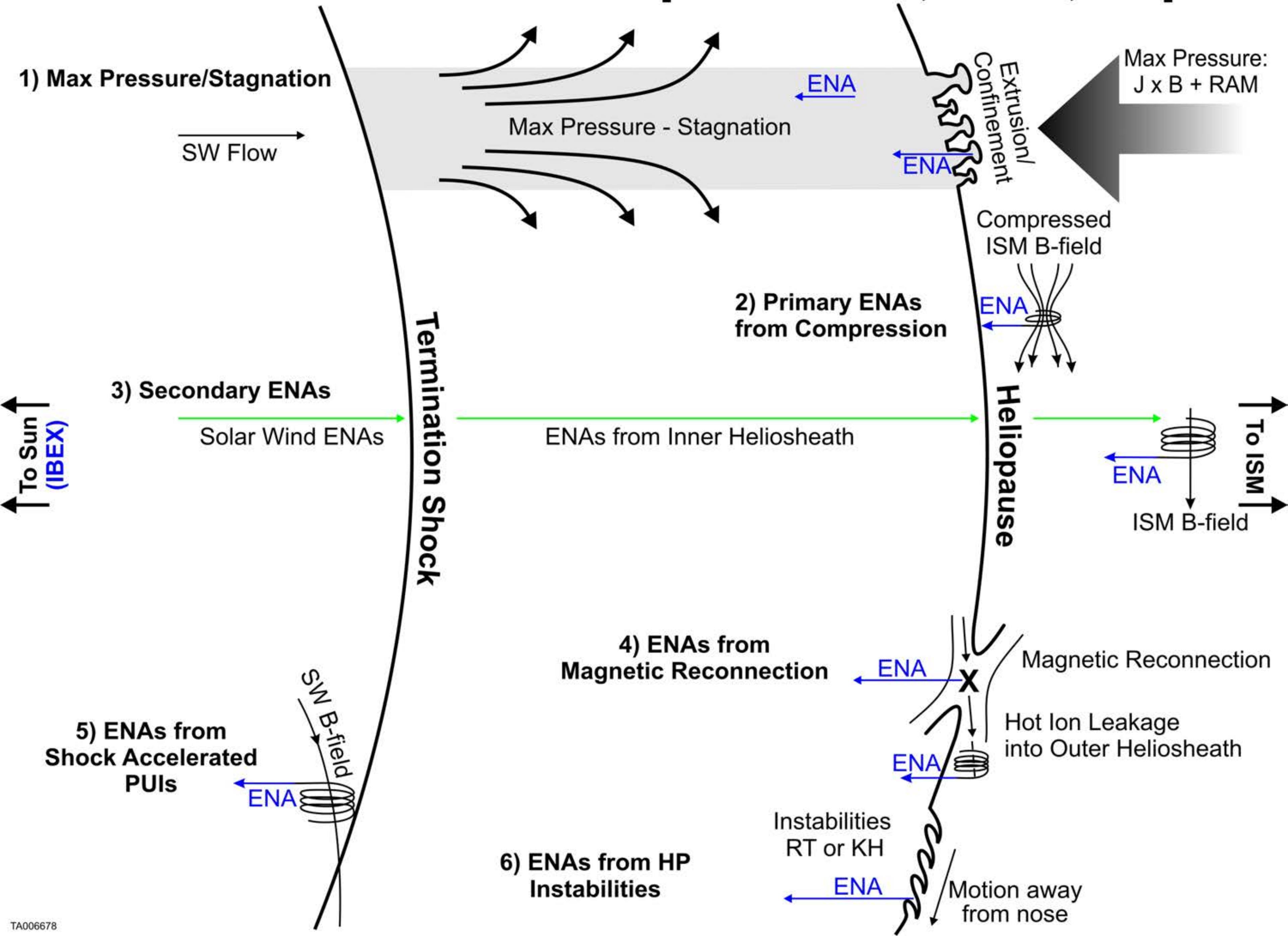
Ribbon Correlates with **B•r**=0

- A: 1.1 keV Map with contours **B•r** angle from Model 2 and the LOS over 10 AU outside heliopause
- B: Flux as function of LOS angle from **B**
- C: Global structure of heliopause and **B•r**=0 surface



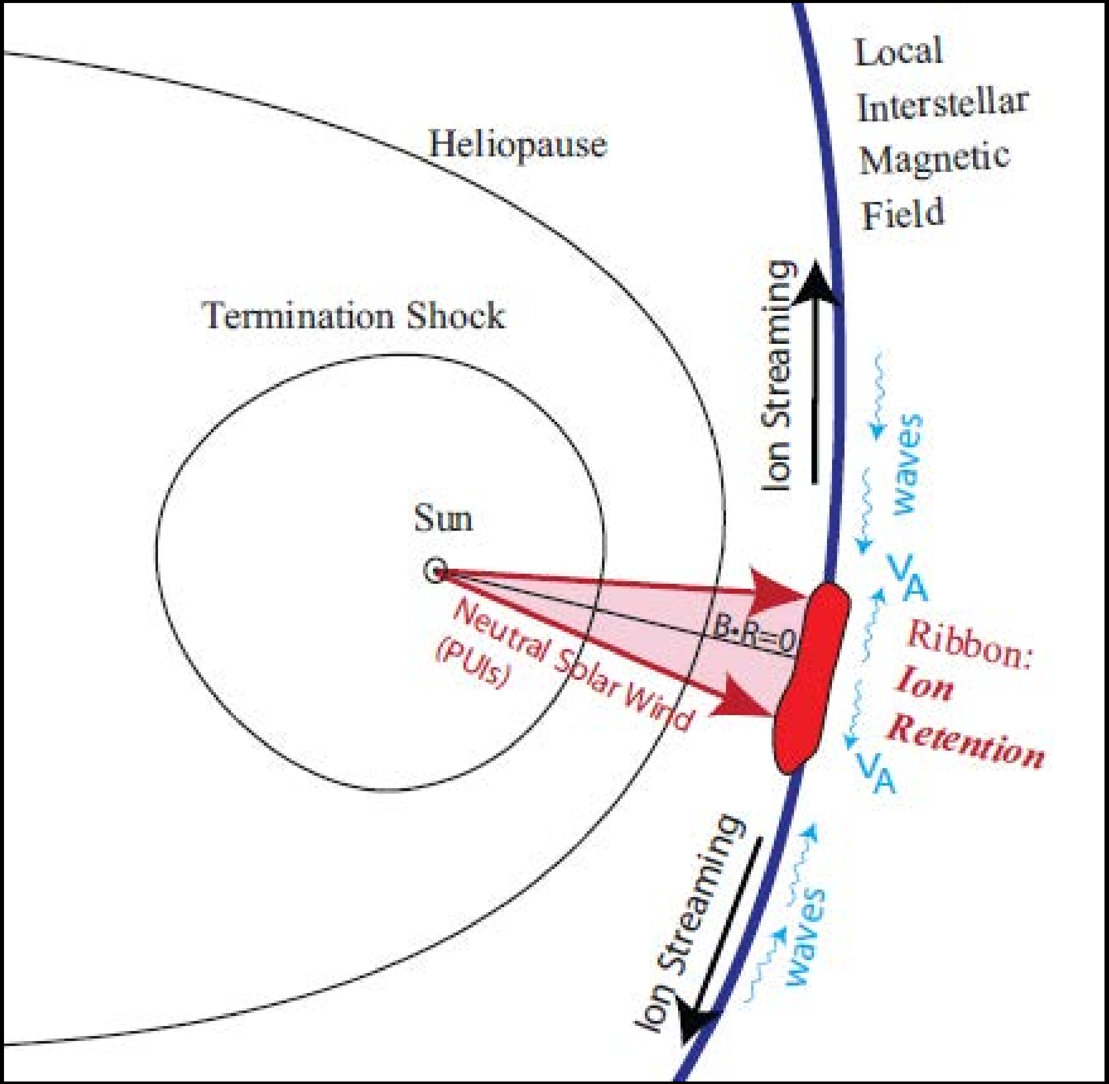
Schwadron et al., Science, 2009

Possible Sources of IBEX Ribbon [McComas et al., *Science*, 2009]

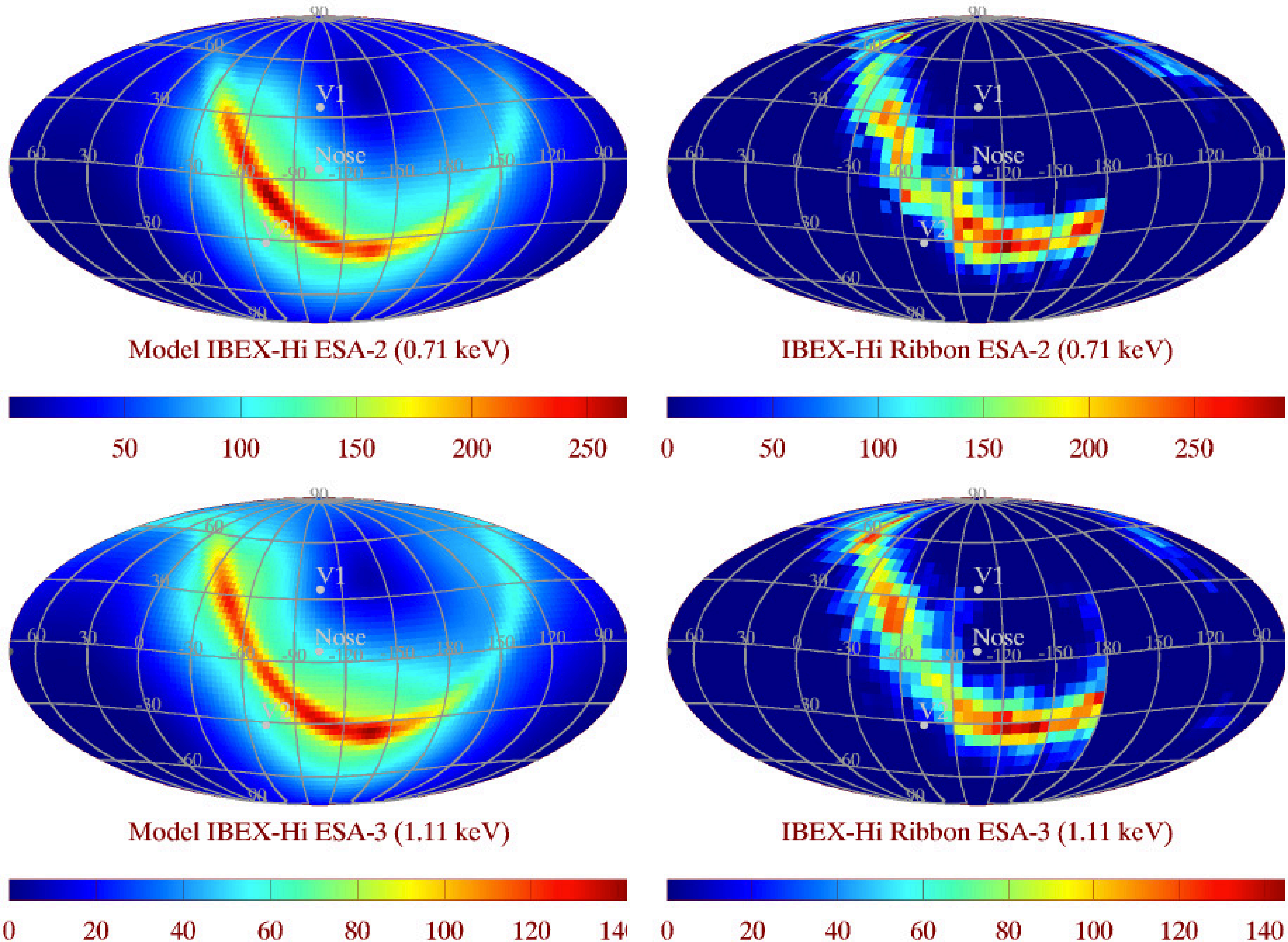


Spatial Retention Region

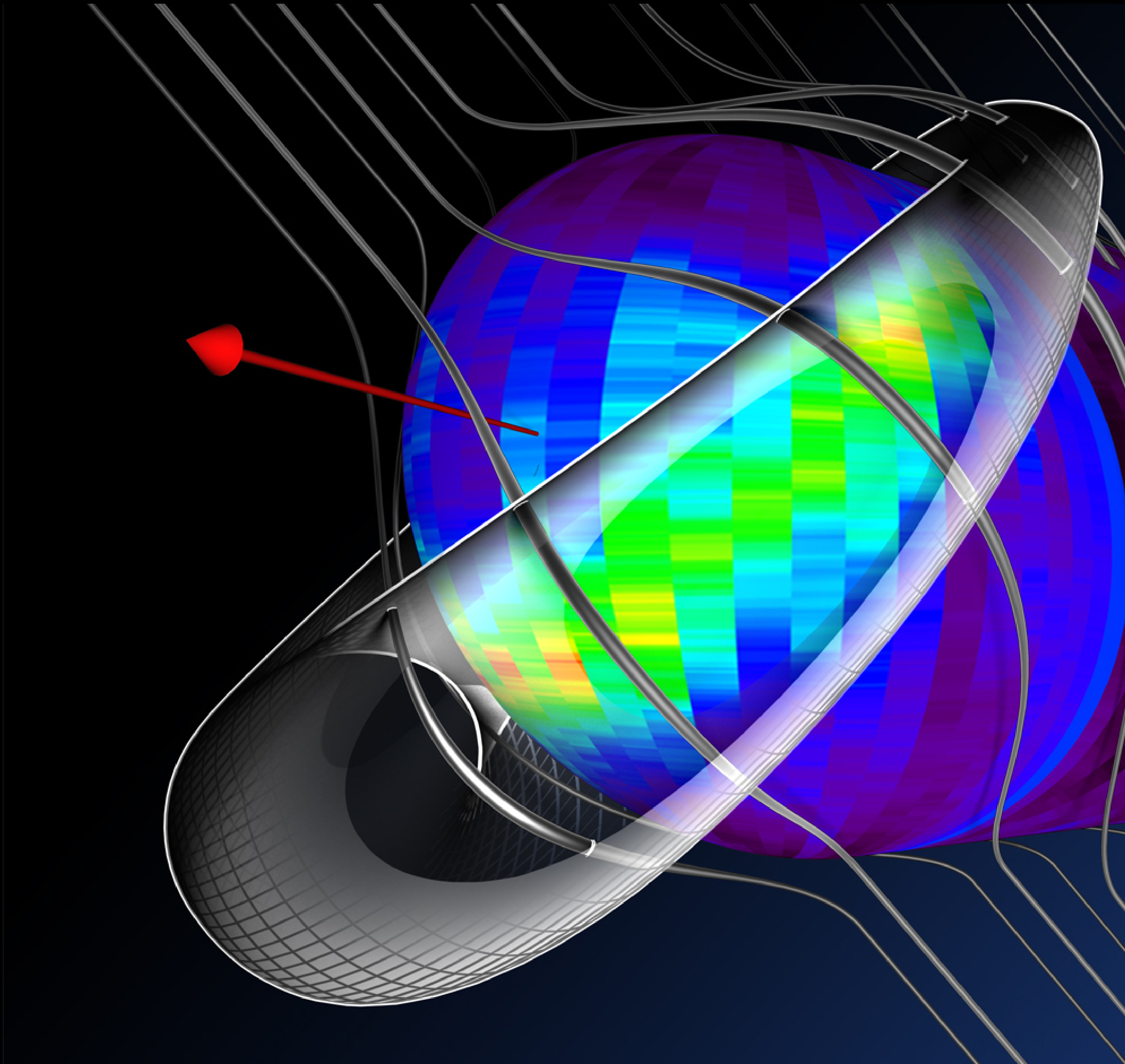
- Instability within retention region
  - Stronger isotropization of distribution functions
  - Reduced ion mobility
- Ion streaming outside retention region
  - waves propagate toward retention region



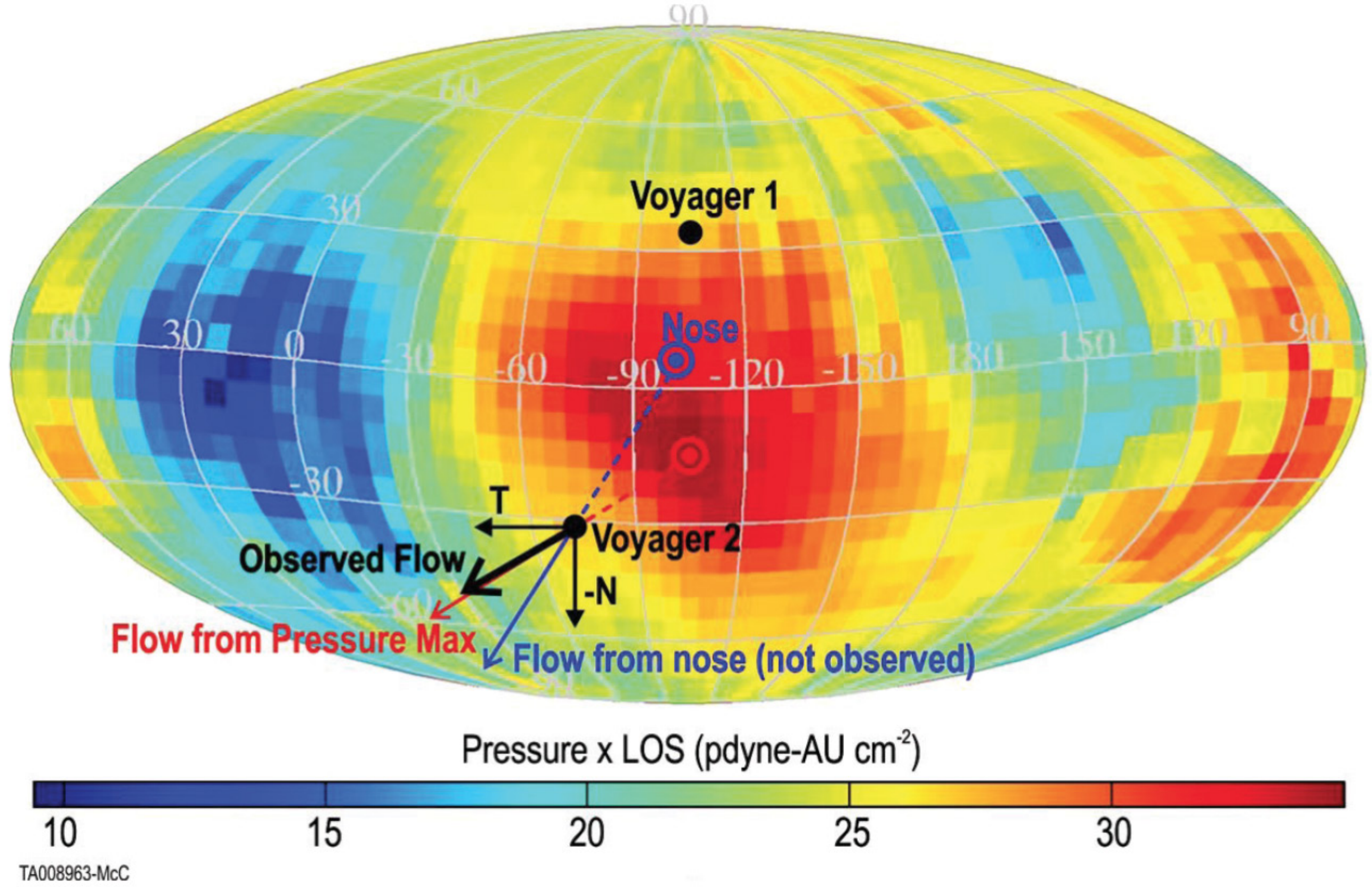
Schwadron and McComas, *ApJ*, 2013

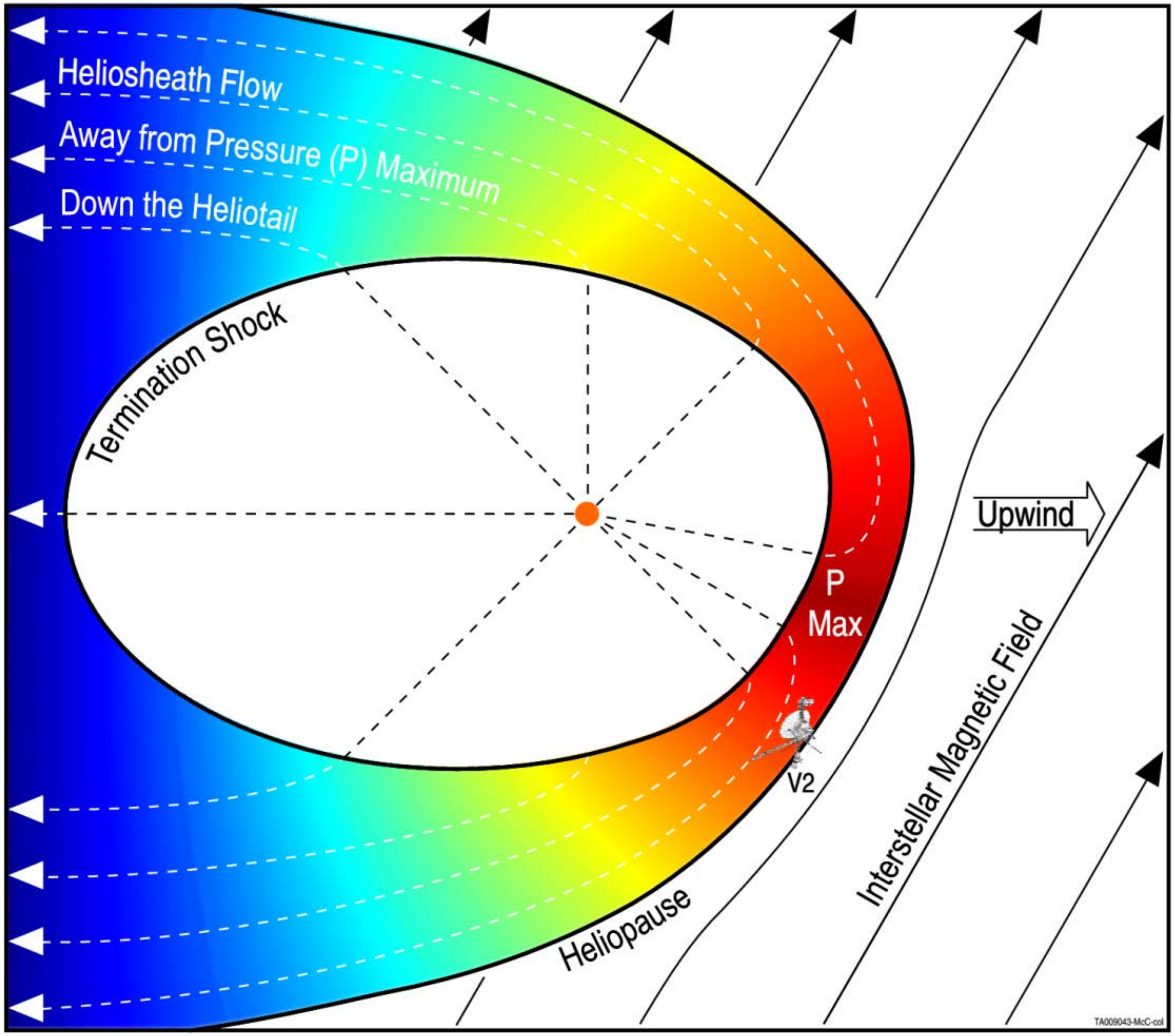


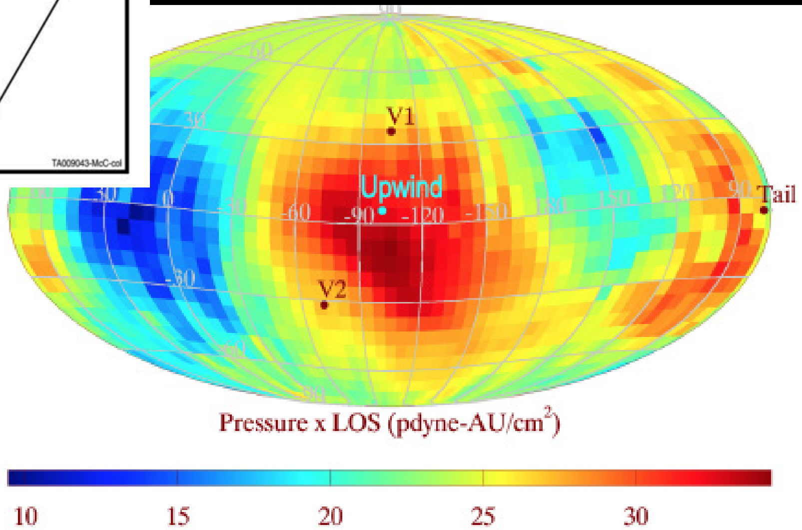
Schwadron and McComas, ApJ 2013



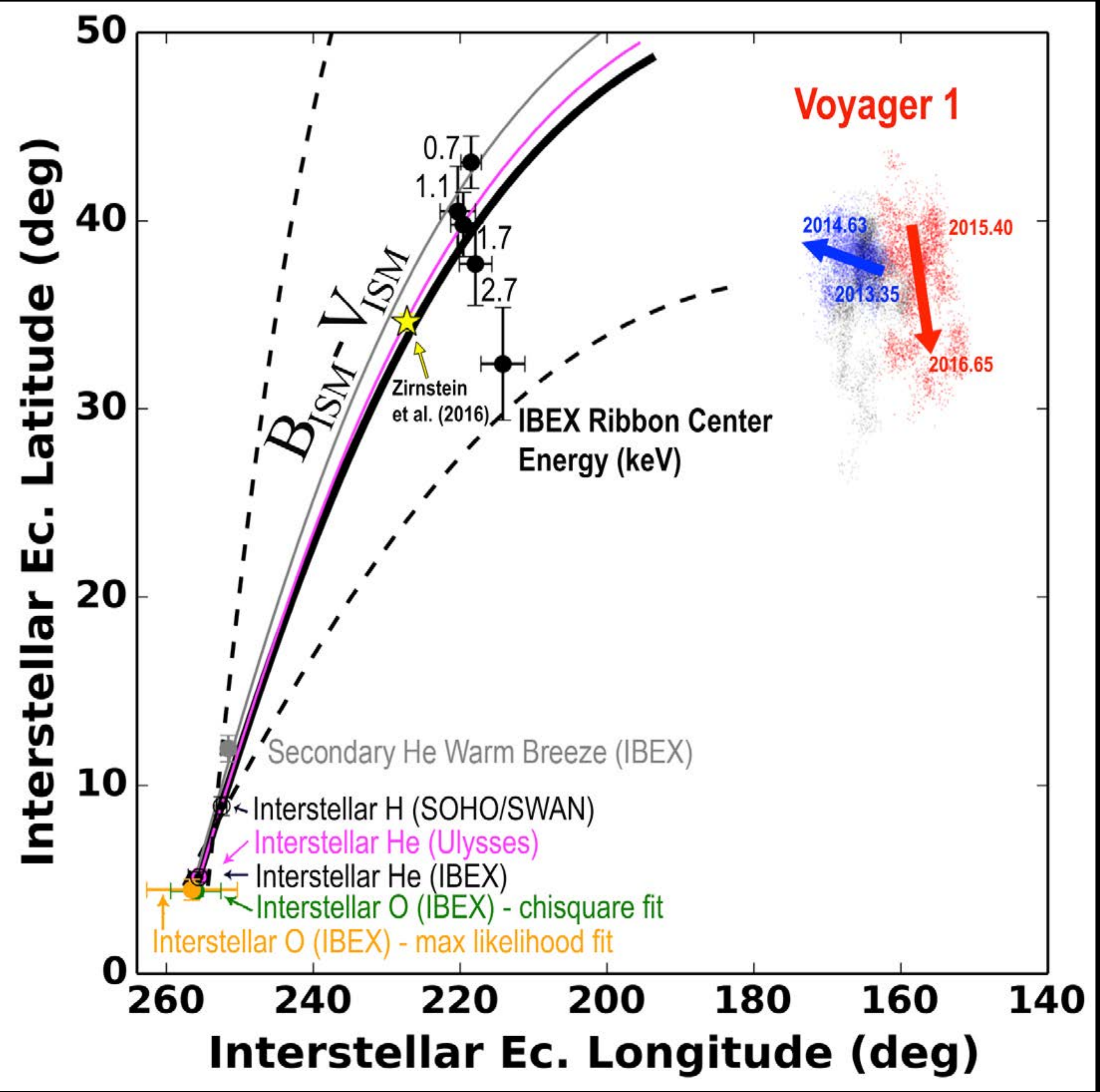
Schwadron and McComas, 2013


Voyager 1
Nose
Voyager 2
T
-N
Observed Flow
Flow from Pressure Max
Flow from nose (not observed)
Pressure x LOS (pdyne-AU cm^{-2})
10
15
20
25
30
TA008963-McC

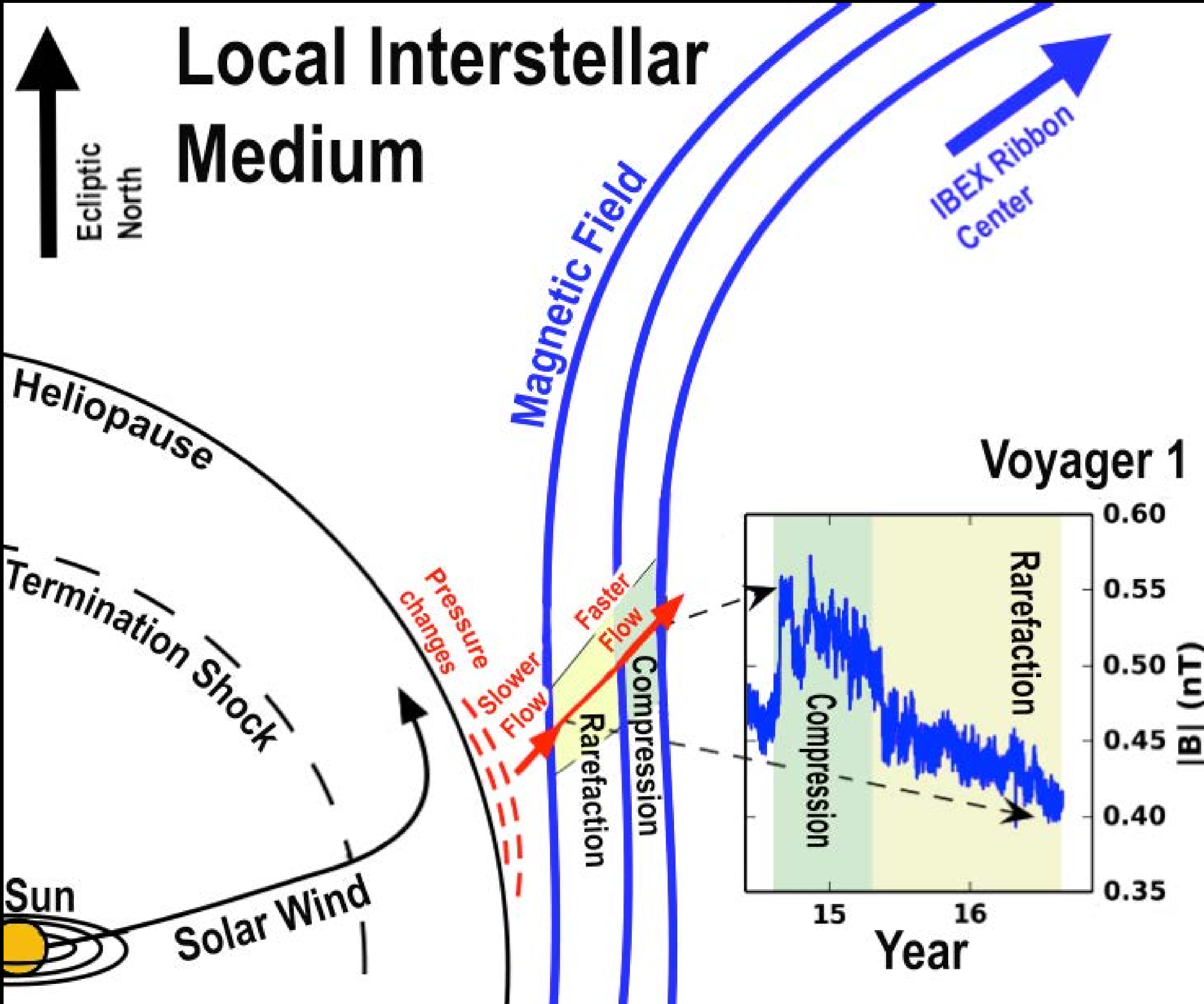




Schwadron et al., ApJ, 828, 81 2016

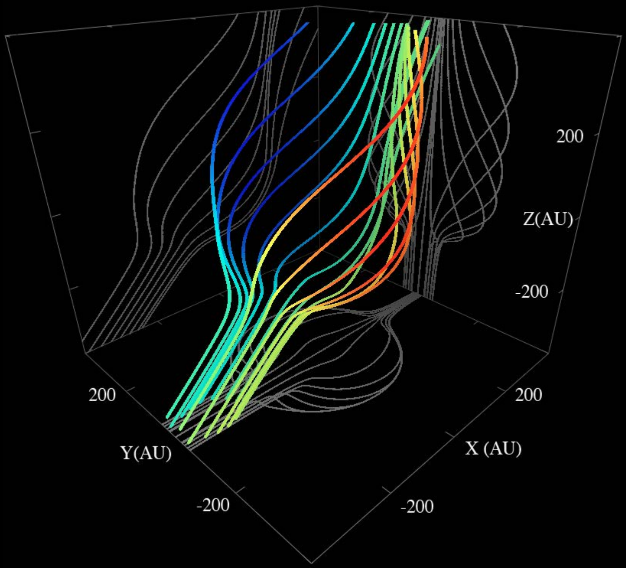


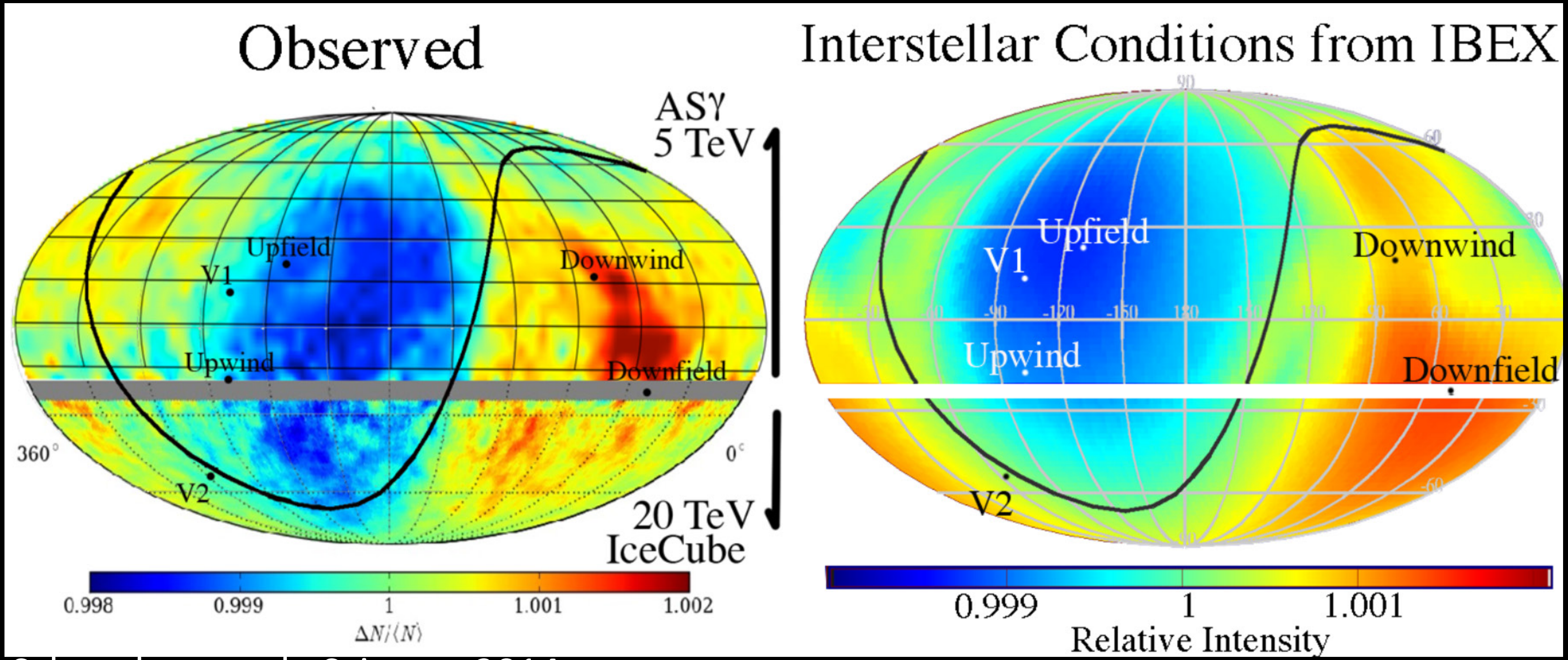
Schwadron and McComas, ApJ, 849, 2017



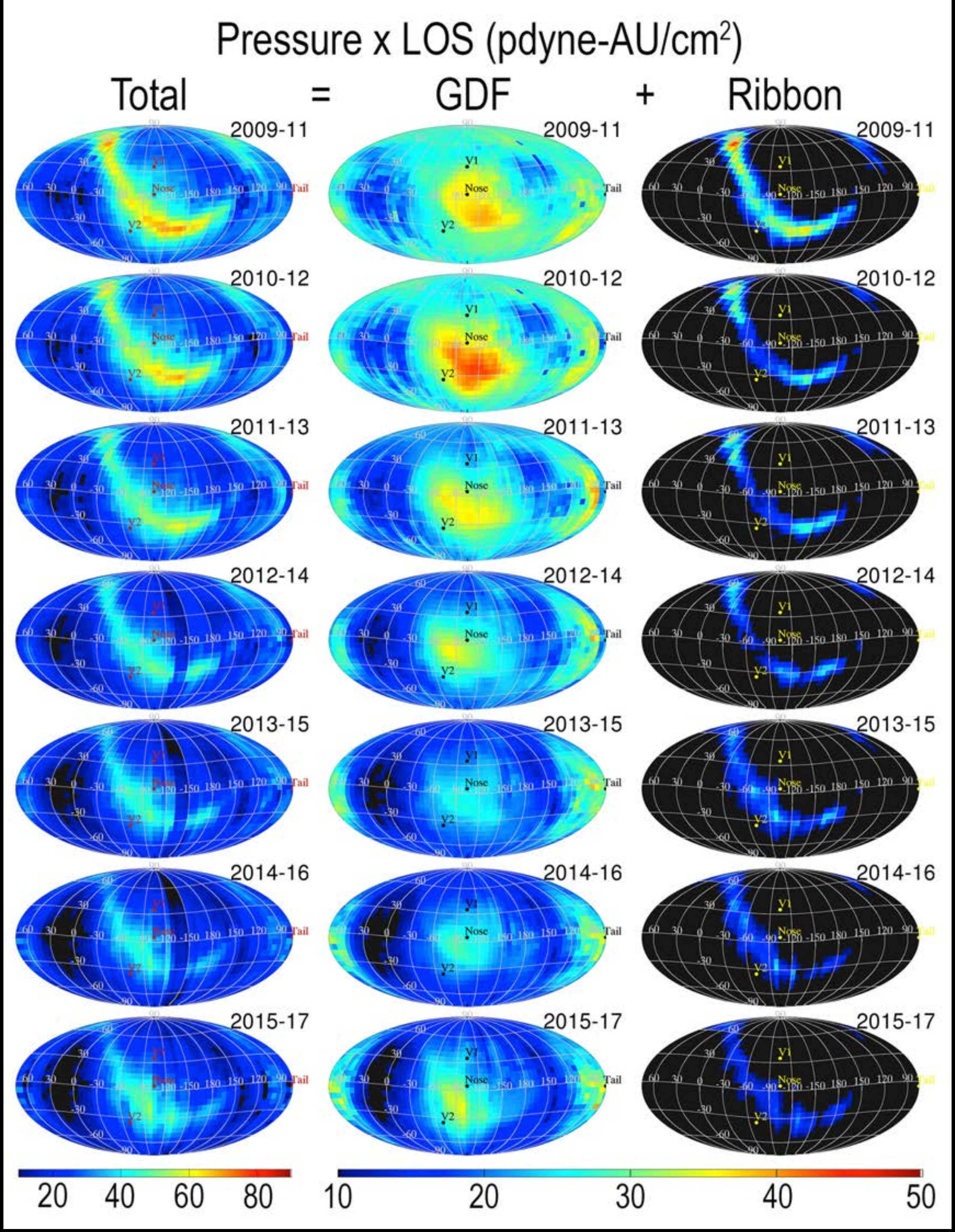
Schwadron and McComas, ApJ, 849, 2017

Comparison of Observed TeV Anisotropies

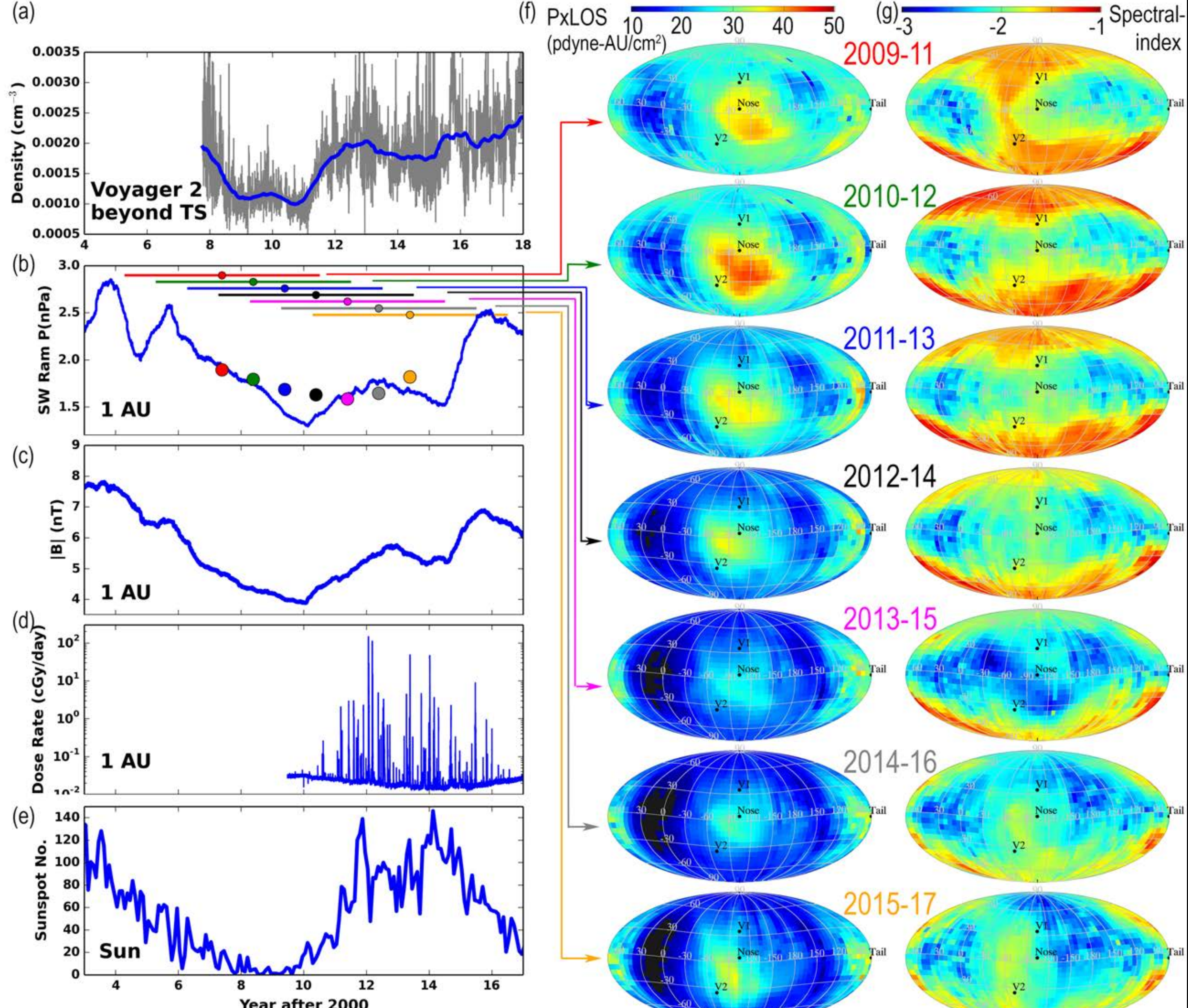




Schwadron et al., Science, 2014



Schwadron et al., ApJS, 2018

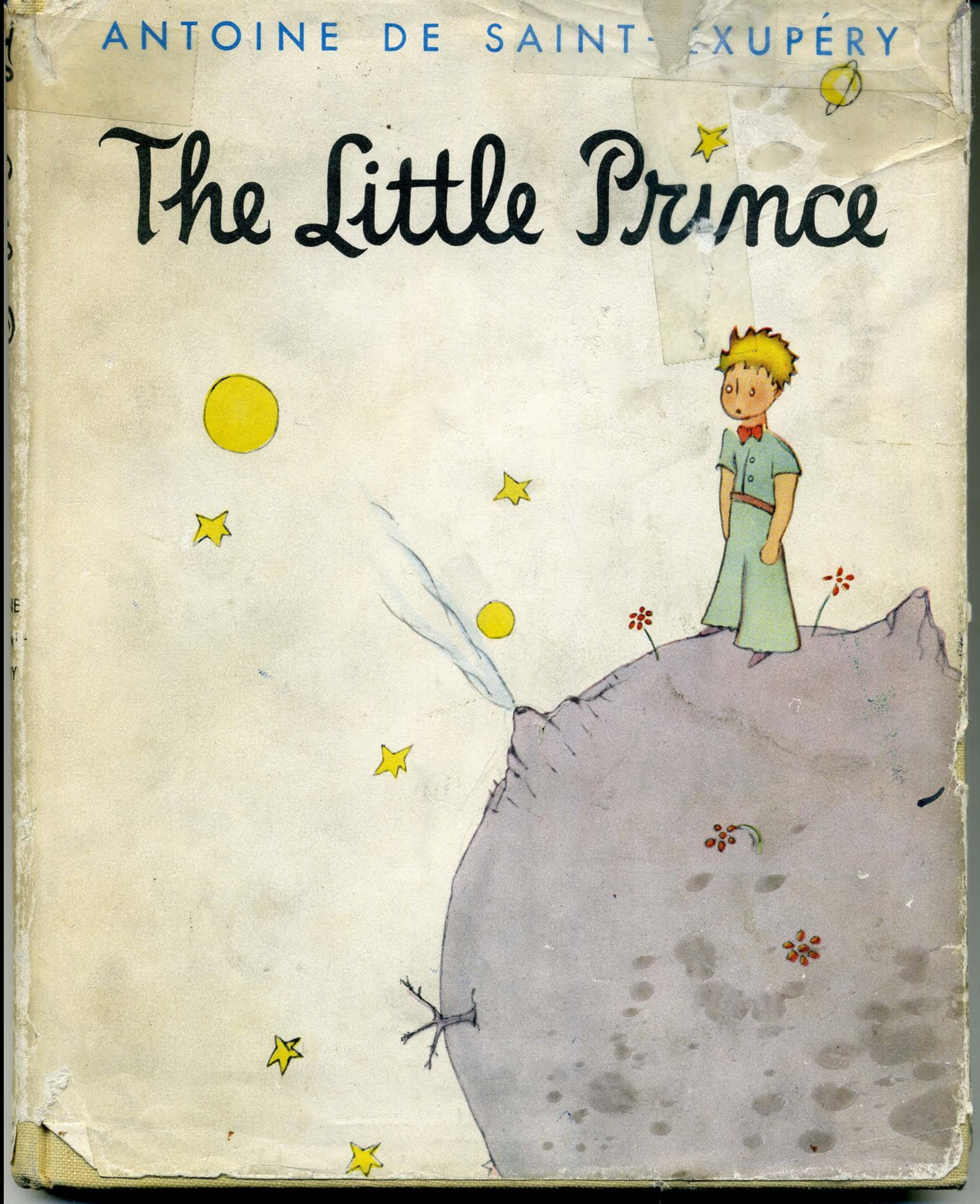


Schwadron et al., ApJS, 2018

"L'essential est invisible pour les yuex"

Advancement requires that we understand and move beyond hidden boundaries

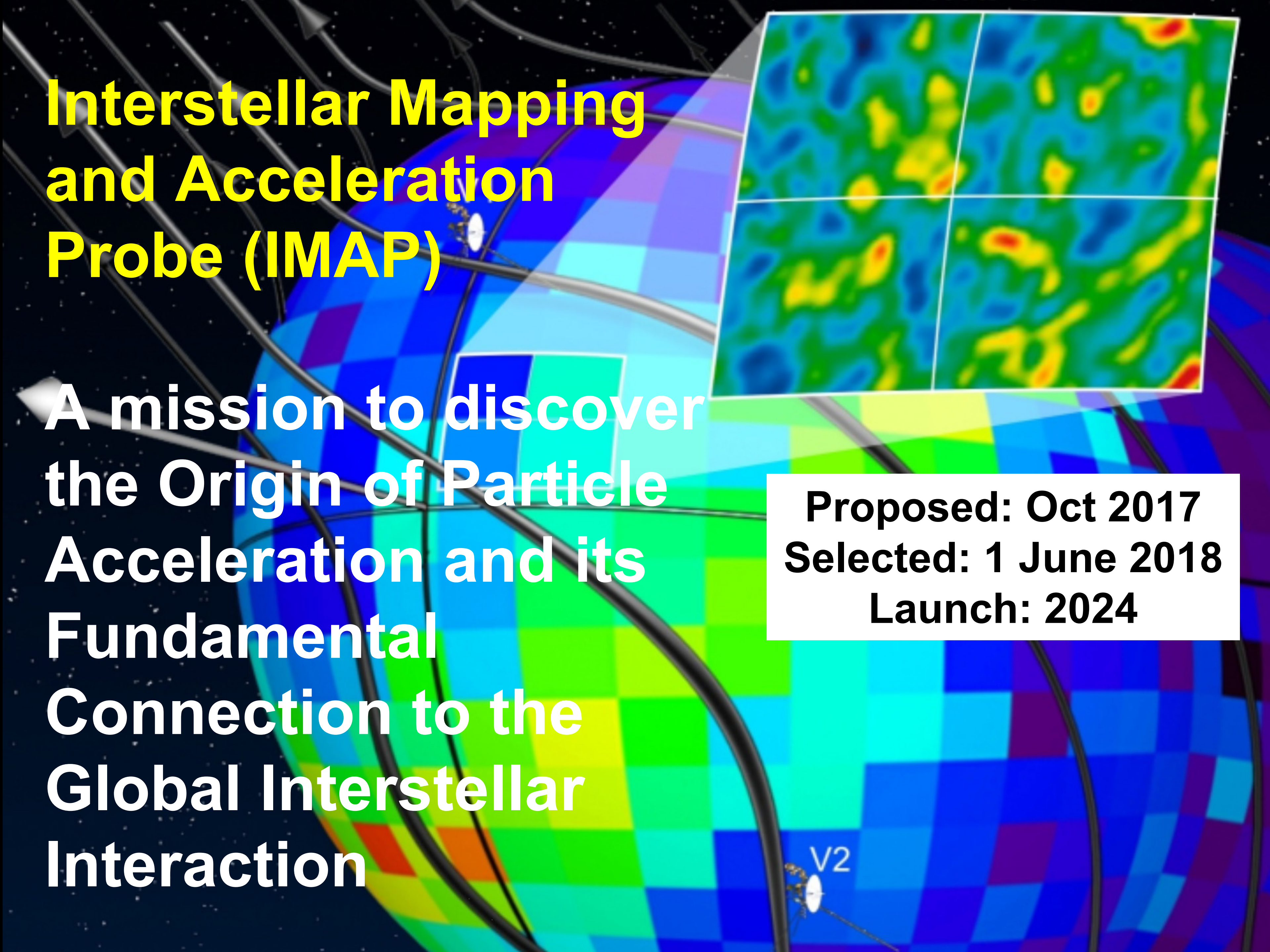
Entering a new realm of galactic exploration



Interstellar Mapping and Acceleration Probe (IMAP)

A mission to discover the Origin of Particle Acceleration and its Fundamental Connection to the Global Interstellar Interaction

Proposed: Oct 2017
Selected: 1 June 2018
Launch: 2024



PRINCETON UNIVERSITY

JOHNS HOPKINS APPLIED PHYSICS LABORATORY

Goddard SPACE FLIGHT CENTER

SwRI

University of New Hampshire

MIT

Los Alamos NATIONAL LABORATORY EST.1943

LASP Laboratory for Atmospheric and Space Physics University of Colorado **Boulder**

Smithsonian Astrophysical Observatory

THE UNIVERSITY OF ARIZONA

CBK PAN

UNIVERSITÄT BONN

JPL Jet Propulsion Laboratory California Institute of Technology

UNIVERSITÄT BERN

THE UNIVERSITY OF ALABAMA IN HUNTSVILLE

Caltech

名古屋大学 NAGOYA UNIVERSITY

Berkeley UNIVERSITY OF CALIFORNIA

UCLA

RUHR UNIVERSITÄT BOCHUM RUB

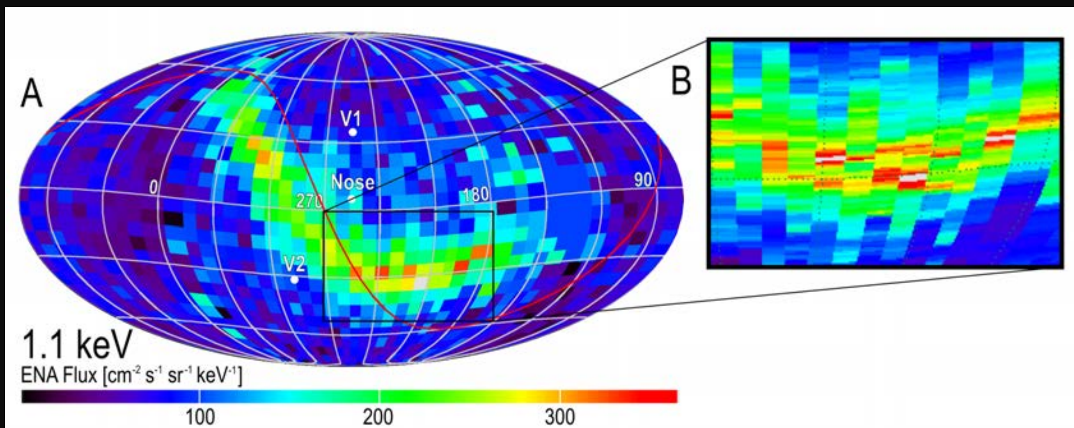
NOAA NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION U.S. DEPARTMENT OF COMMERCE

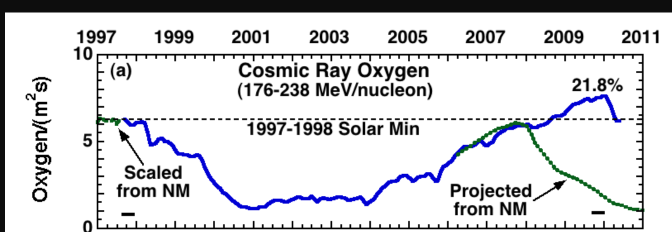
AEROSPACE

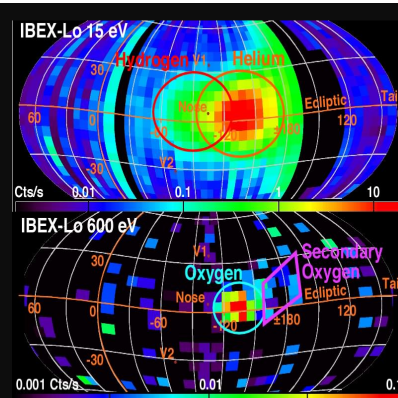
THE UNIVERSITY OF CHICAGO

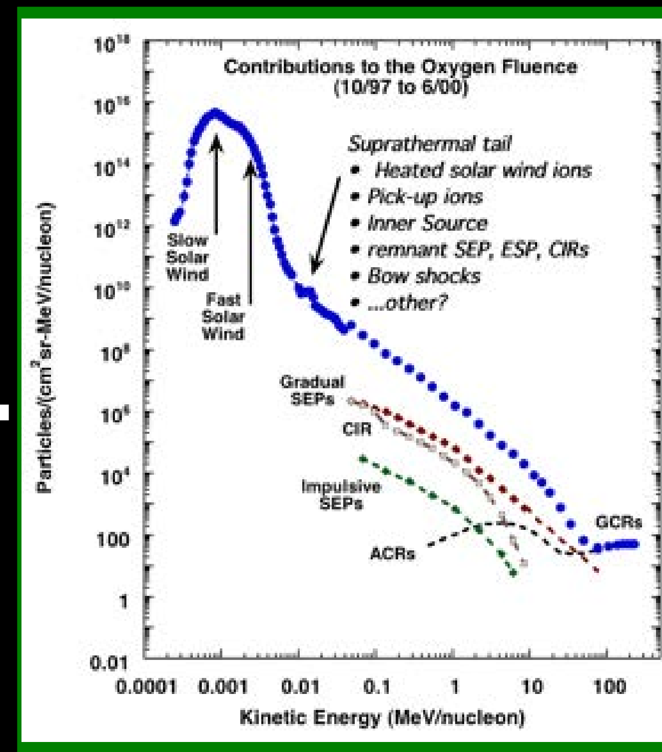
UNIVERSITY OF DELAWARE

Interstellar Mapping & Acceleration Probe





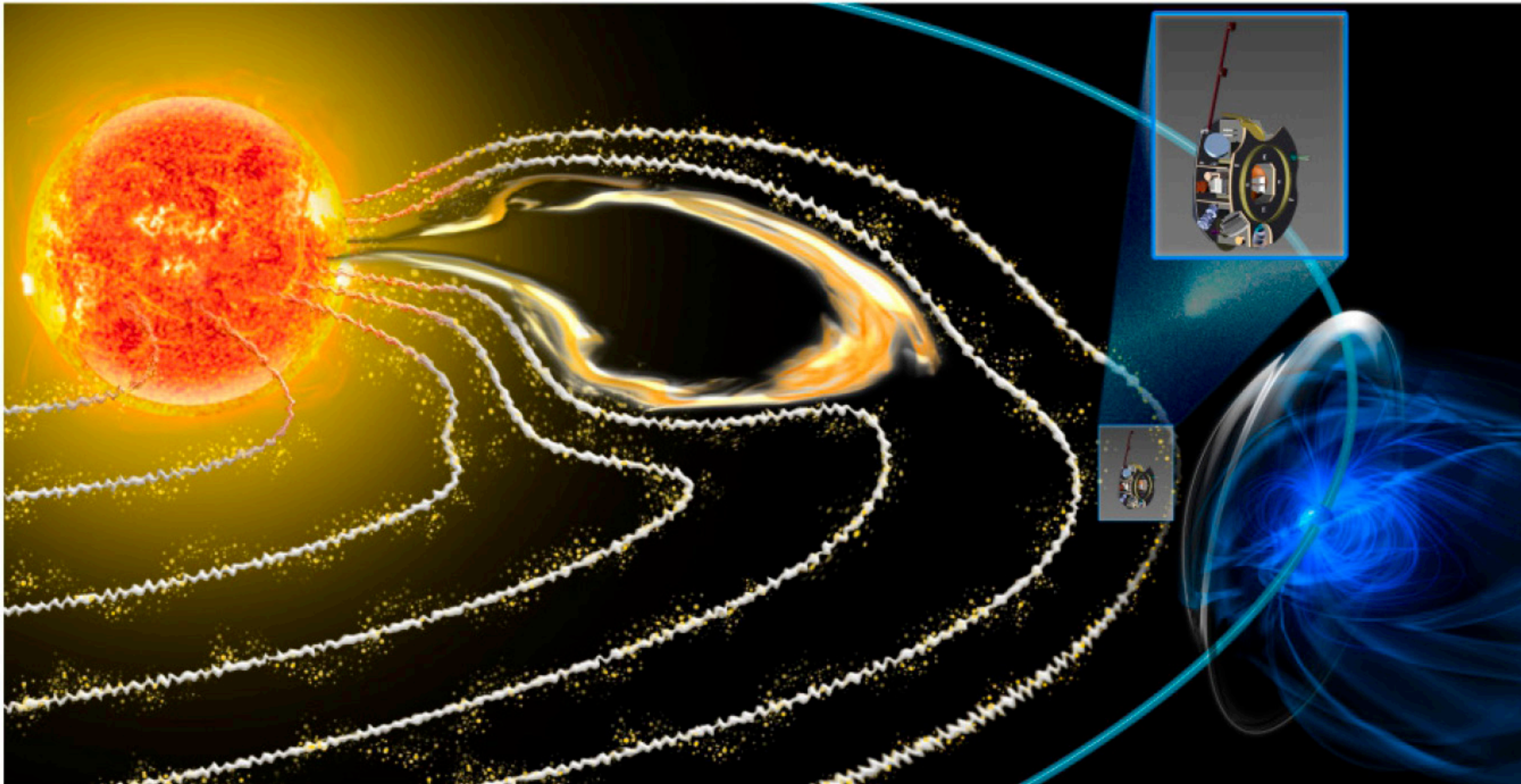




+

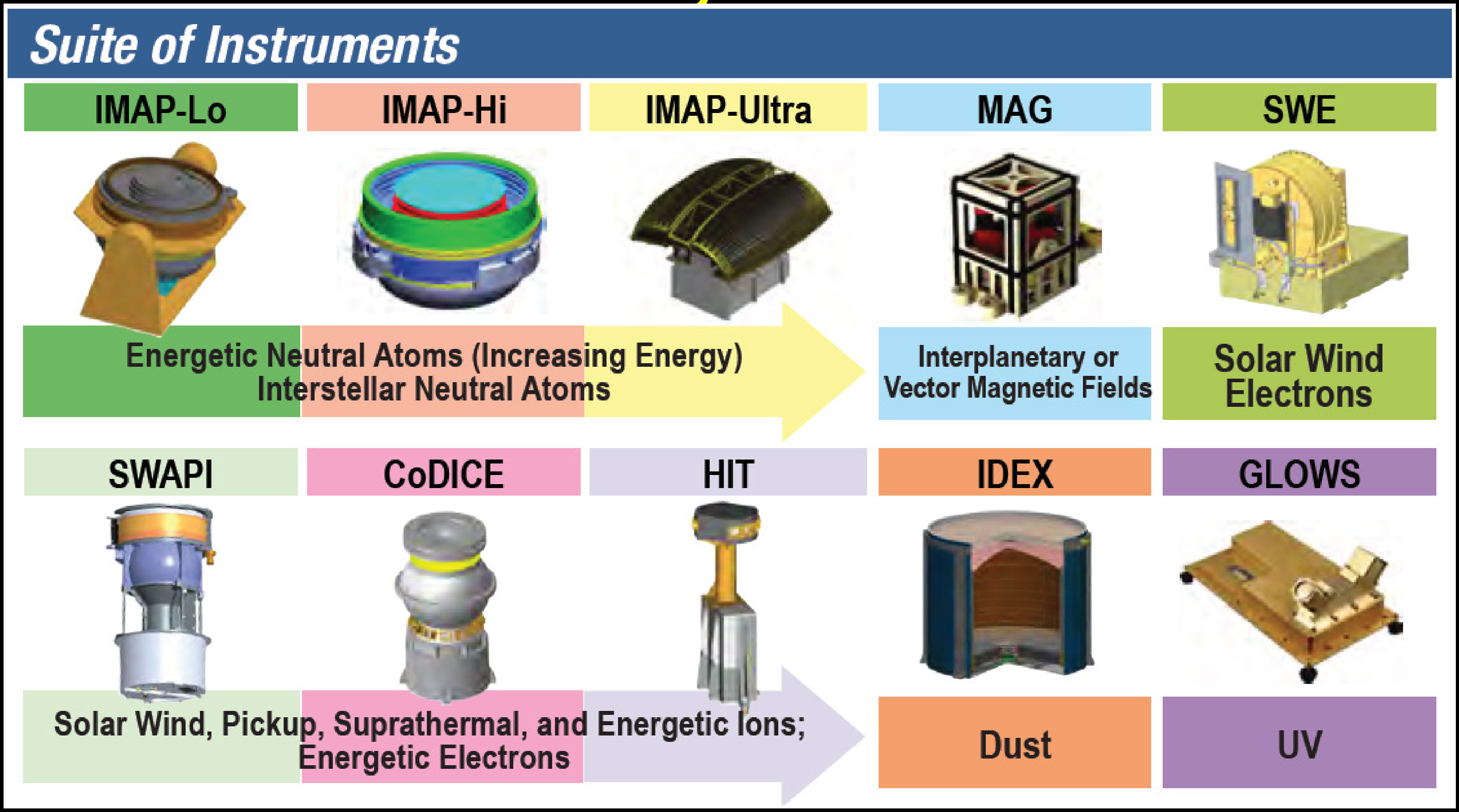
Hi-Resolution ENA Images of the Heliosphere Boundary
Detailed Analysis of the ISM Flow for H, D, He, O & Ne with Neutral Atoms and Pickup Ions
Study Interstellar Dust Flow and its Composition

Study Source Populations for SEPs Including Suprathermal Tails as well as Acceleration at Hi-Res
Monitor Space Weather from L1

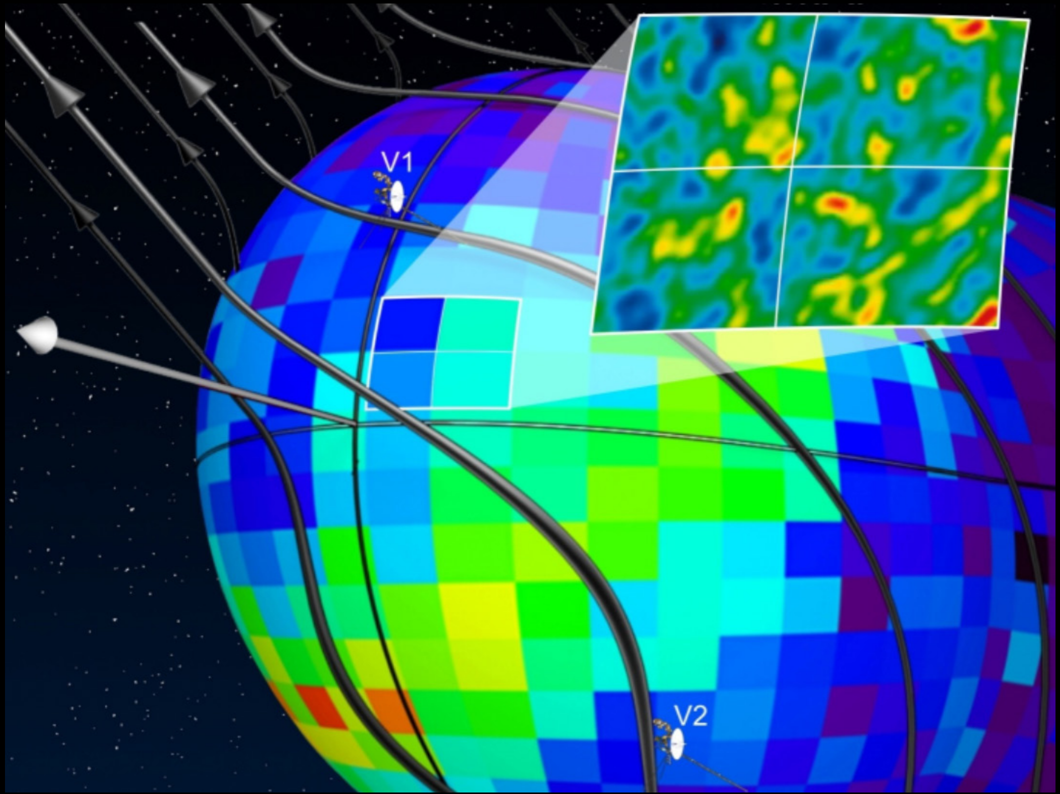


Ta010525-IMAP

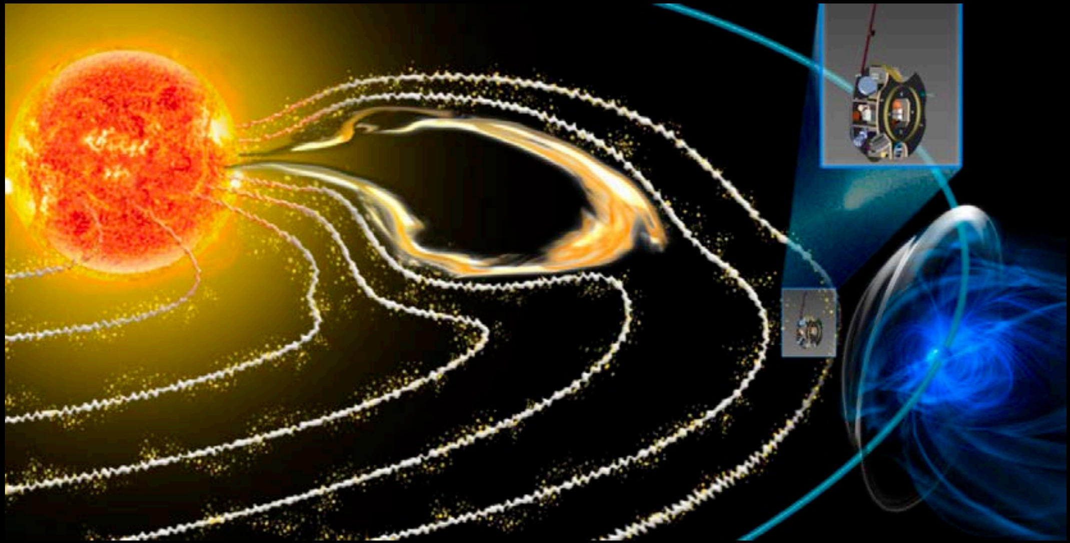
Comprehensive Science Payload



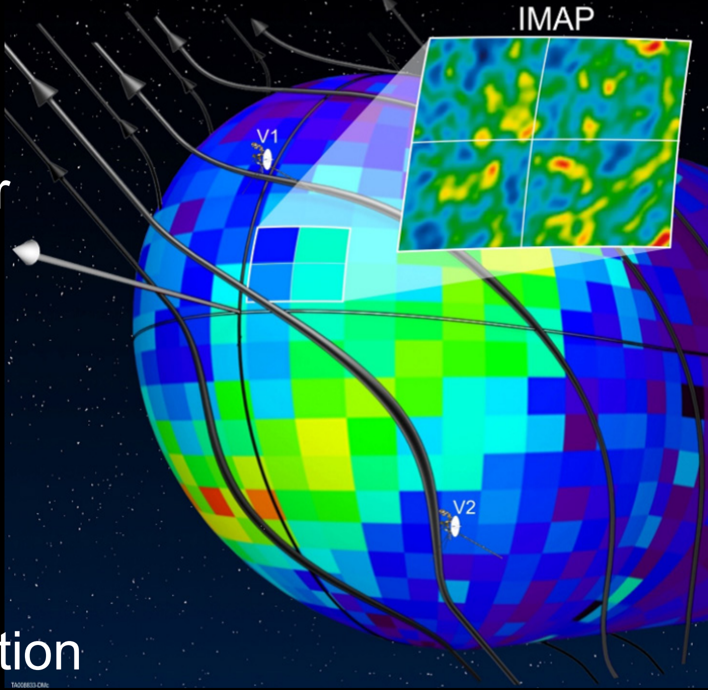
Interstellar Mapping and Acceleration Probe (IMAP)



.. Civilizations next step into Galactic Exploration

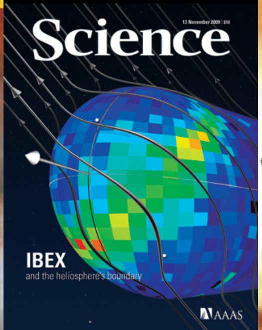


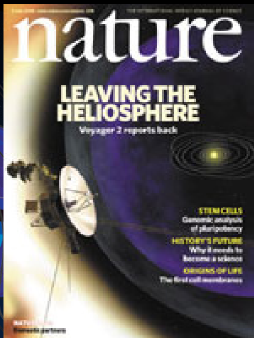
Summary



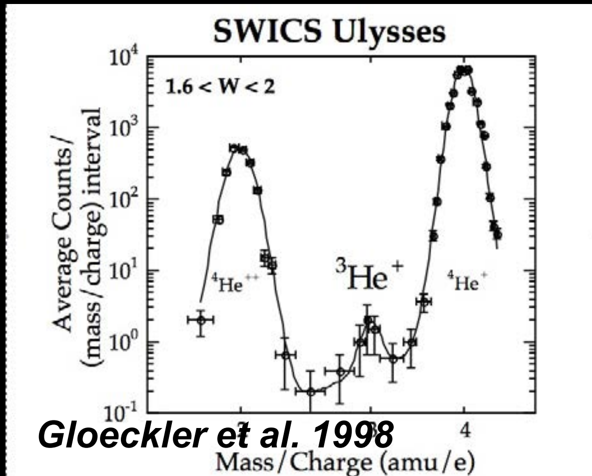
- IBEX + Voyagers provide a new paradigm of our Magnetically Influenced Heliosphere
- Interstellar O + He Warm Breeze add new dimensions to understanding of filtration + B-V orientation
- 7 Year study underway in our time-evolving heliosphere

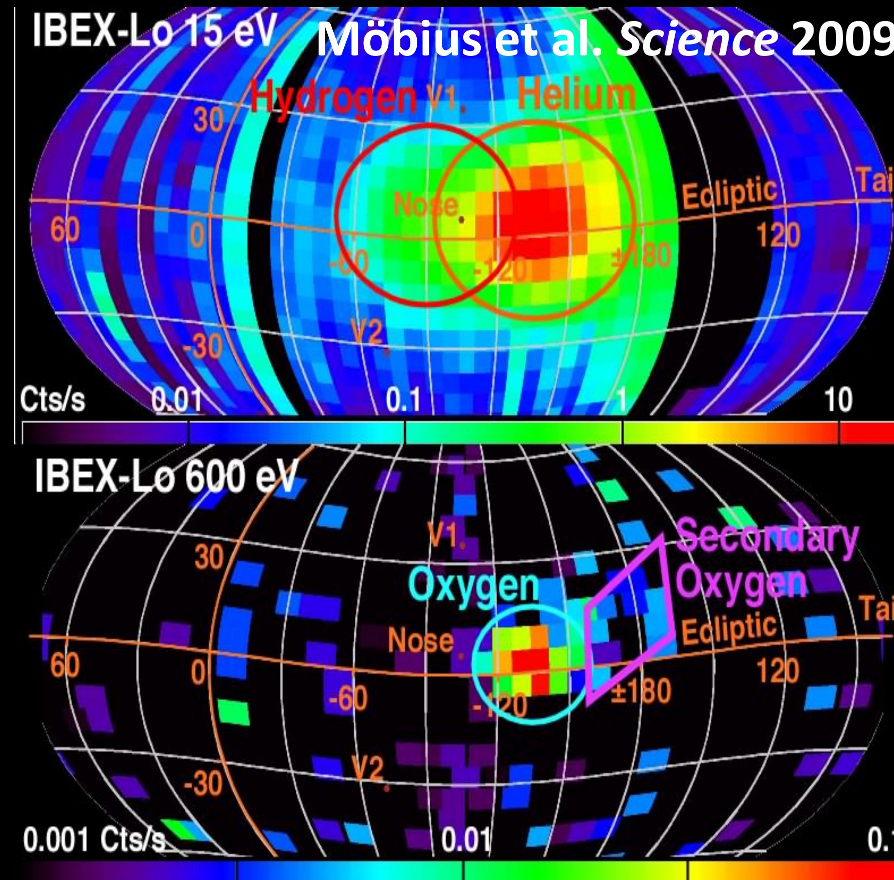
- Preparing IMAP, next step in Ed Stone's Expedition
  - IMAP Fundamental and highly relevant scientific questions
    - *Interstellar Interactions – Heliospheric Frontier*
    - *Acceleration of energetic particles and propagation of cosmic rays*
    - *Interstellar Conditions*
    - *L1 Science – Geospace Inputs and Responses*
  - Societally critical and urgent
    - *Voyager synergy*
    - *Most unique solar conditions in 80 years*
  - Broad scientific engagement
  - IMAP Low cost and ready for implementation!





What are the Physical Properties and the Composition of the ISM?



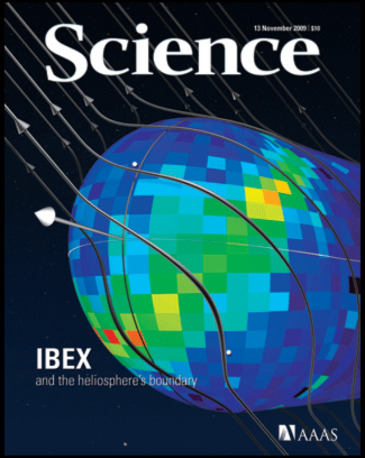


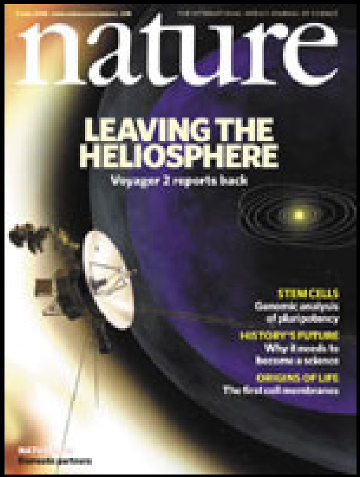
- IMAP provides ISM Composition
  - First direct measurements of interstellar Deuterium with ISM neutrals (Implications for Big Bang Cosmology)
  - High-precision observations of ISM $^{3}He/^{4}He$ & $^{22}Ne/^{20}Ne$ ratio with pickup ions to better than 5% accuracy
- IMAP enables detailed study
  - H, He, O, and Ne ISM flow
  - Outer heliosheath with O and He secondary flow

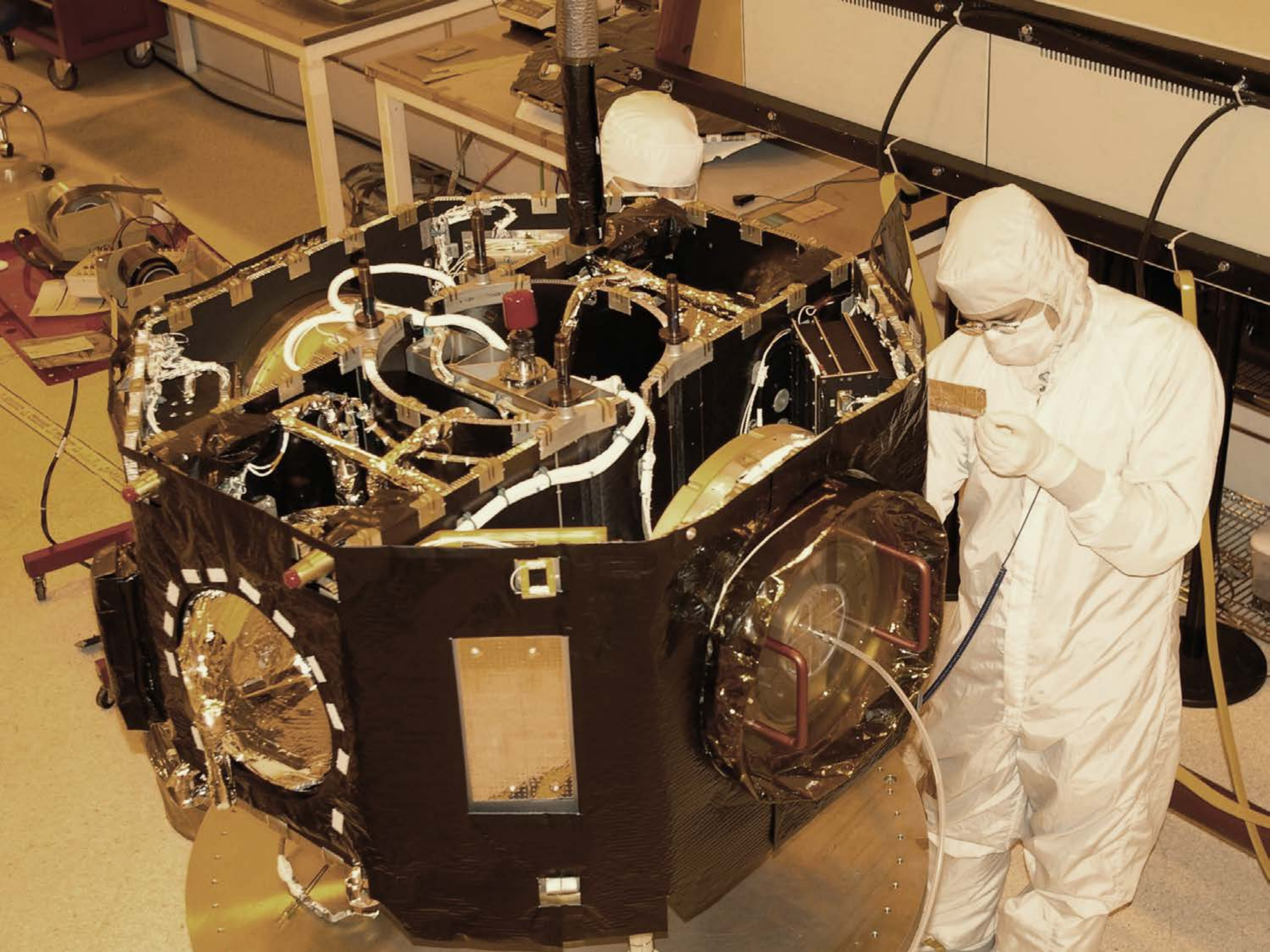
- Simultaneous Global properties of Ly-α backscatter, evolution of neutral H inflow
- Composition and properties of interstellar grains

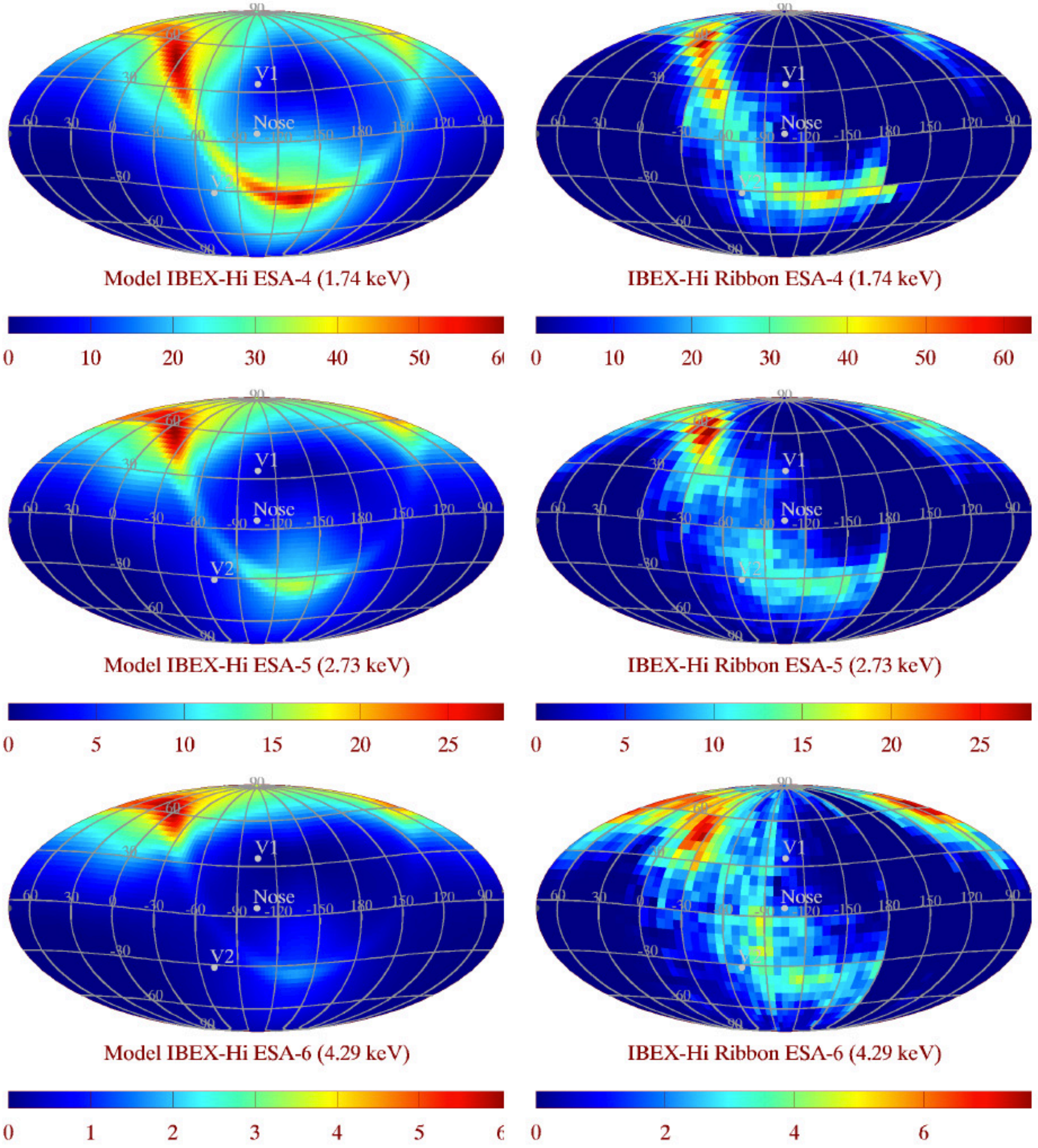
Criteria: IMAP Answers Vital and Urgent Scientific Problems

- Area of rapid discovery and progress at the Outer Frontier
  - Discovering our evolving home in the local galactic environs
- Urgency
  - Synergy with Voyager 1 and 2
  - Changes in the space environment allow extremely good imaging, time dependence of interstellar boundaries and changes in cosmic rays
- Fundamental Scientific Discovery of the Composition and Properties of Local Interstellar Medium
  - IMAP/Voyager co-temporal observations fundamentally enabling
- Discovery of the Fundamental Physical Processes that Control Particle Acceleration throughout the Cosmos
  - Underlying variations and sources of ubiquitous suprathermal ions
  - Injection of seed populations into particle acceleration
  - Particle injection and acceleration in TS and heliosheath
- Fundamental Scientific Implications for Exoplanetary Habitability and Future of our World
  - History and future within our galaxy key to understanding the conditions on our evolving planet over time and as prerequisite for future expansion across the solar system
  - Understanding our global heliosphere, physical interactions
  - Understanding of interstellar interactions that influence exoplanetary habitability







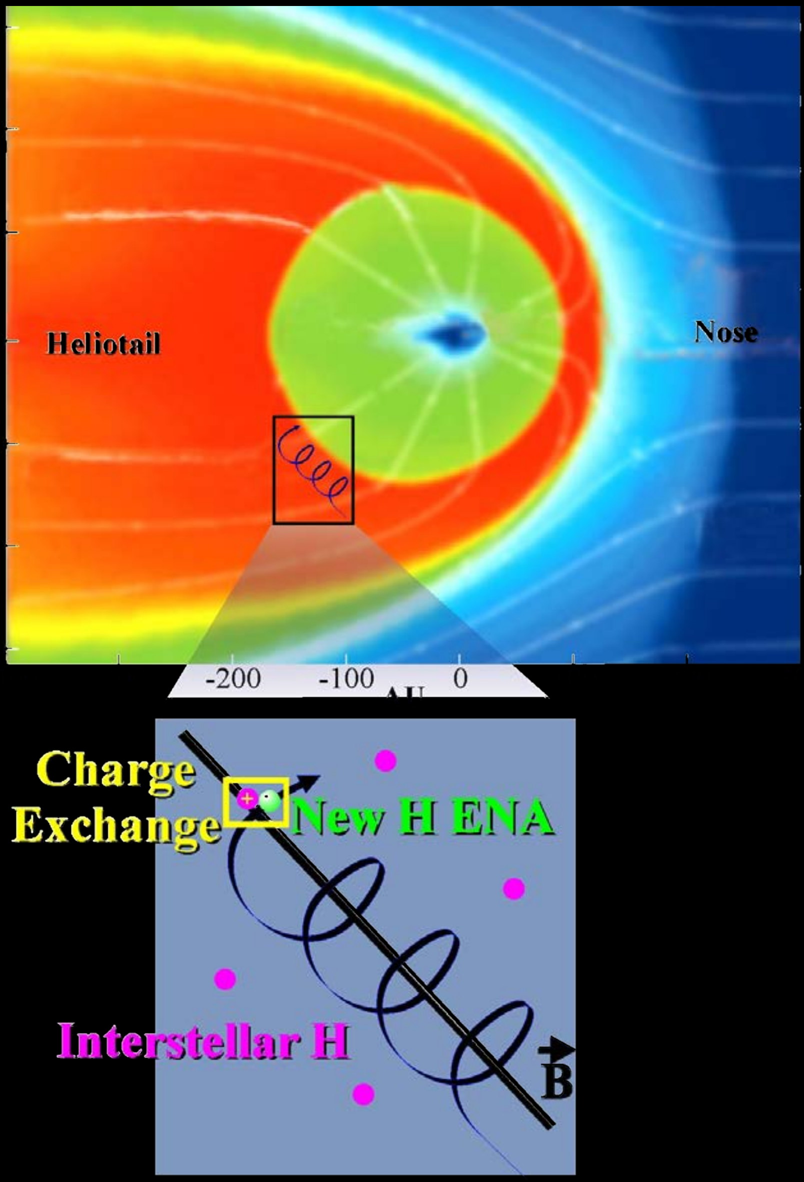


Schwadron and McComas, ApJ, 2013

IBEX Mission

- Small Explorer
  - Smallest and cheapest type of full NASA mission
  - Foreign contributions: Swiss (hardware) and many country (science) contributions
- Fast Track Schedule
  - Selected: January 2005
  - Mission PDR: January 2006
  - Confirmation Rev: March 2006
  - Mission CDR: September 2006
  - Payload Delivery: September 2007
  - VAFB Delivery: July 2008
  - Launch: 19 October 2008

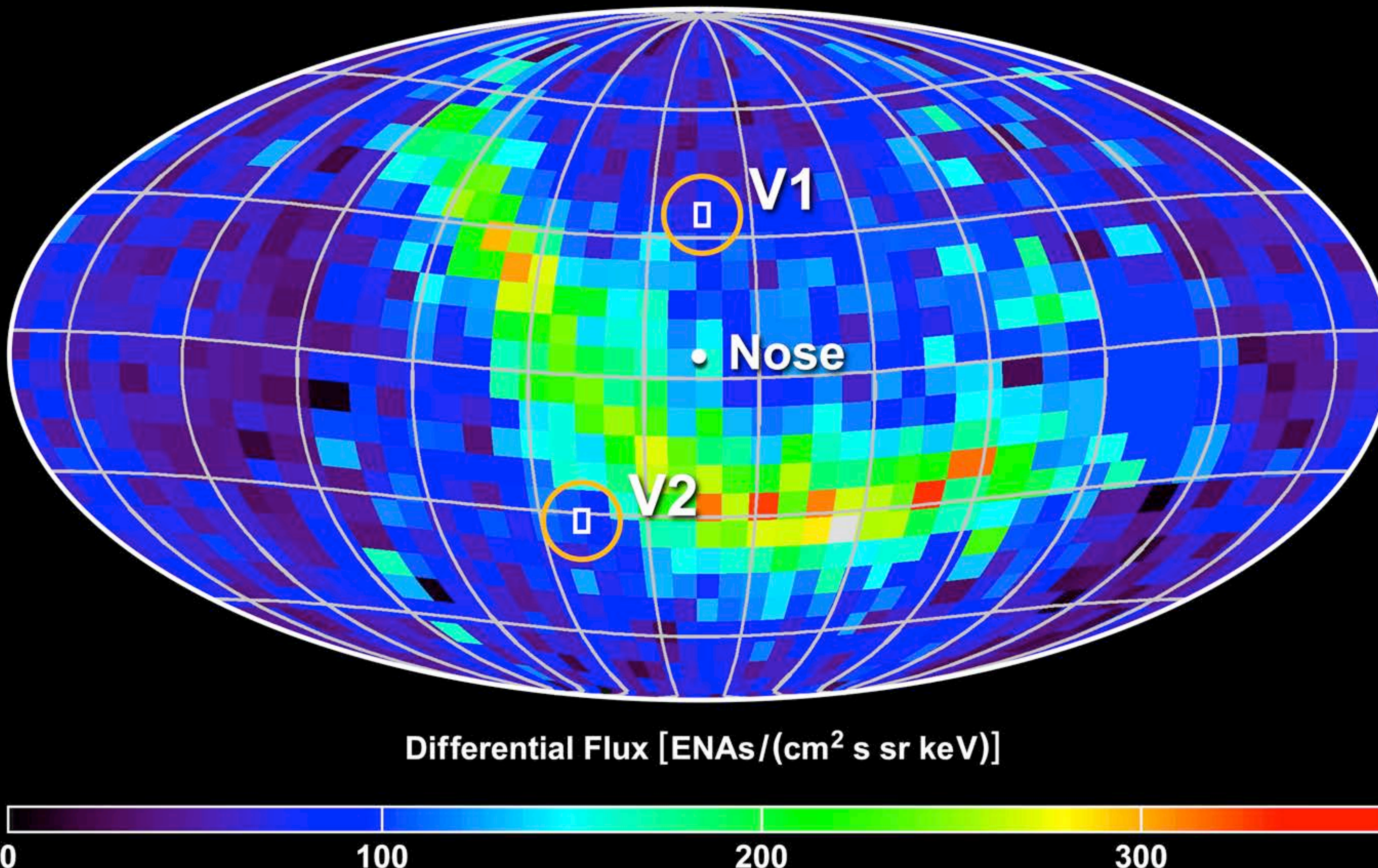
ENAs Illuminate the Heliosheath



- Supersonic SW must slow down and heat before it reaches the interstellar medium
- Large numbers of interstellar neutrals drift into heliosphere
  - Ly-α backscatter
  - interstellar pickup ions
- Hot SW charge exchanges with interstellar neutrals to produce ENAs
- Substantial ENA signal from outside the TS guaranteed from first principles

$$J_{ENA} = \int dx\, n_H\, J_{ION}\, \sigma$$

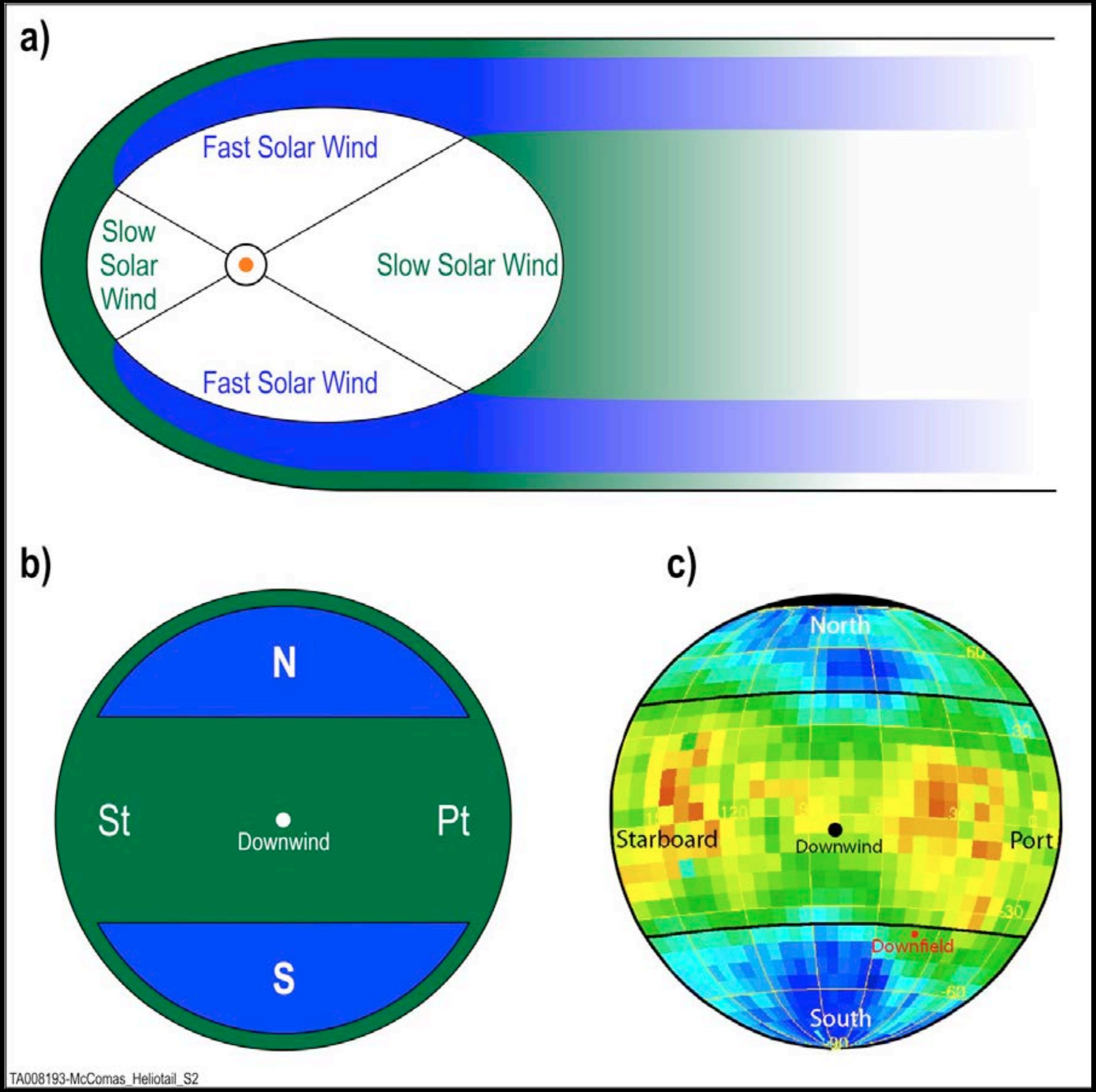
IBEX-Hi (0.9-1.5 keV)



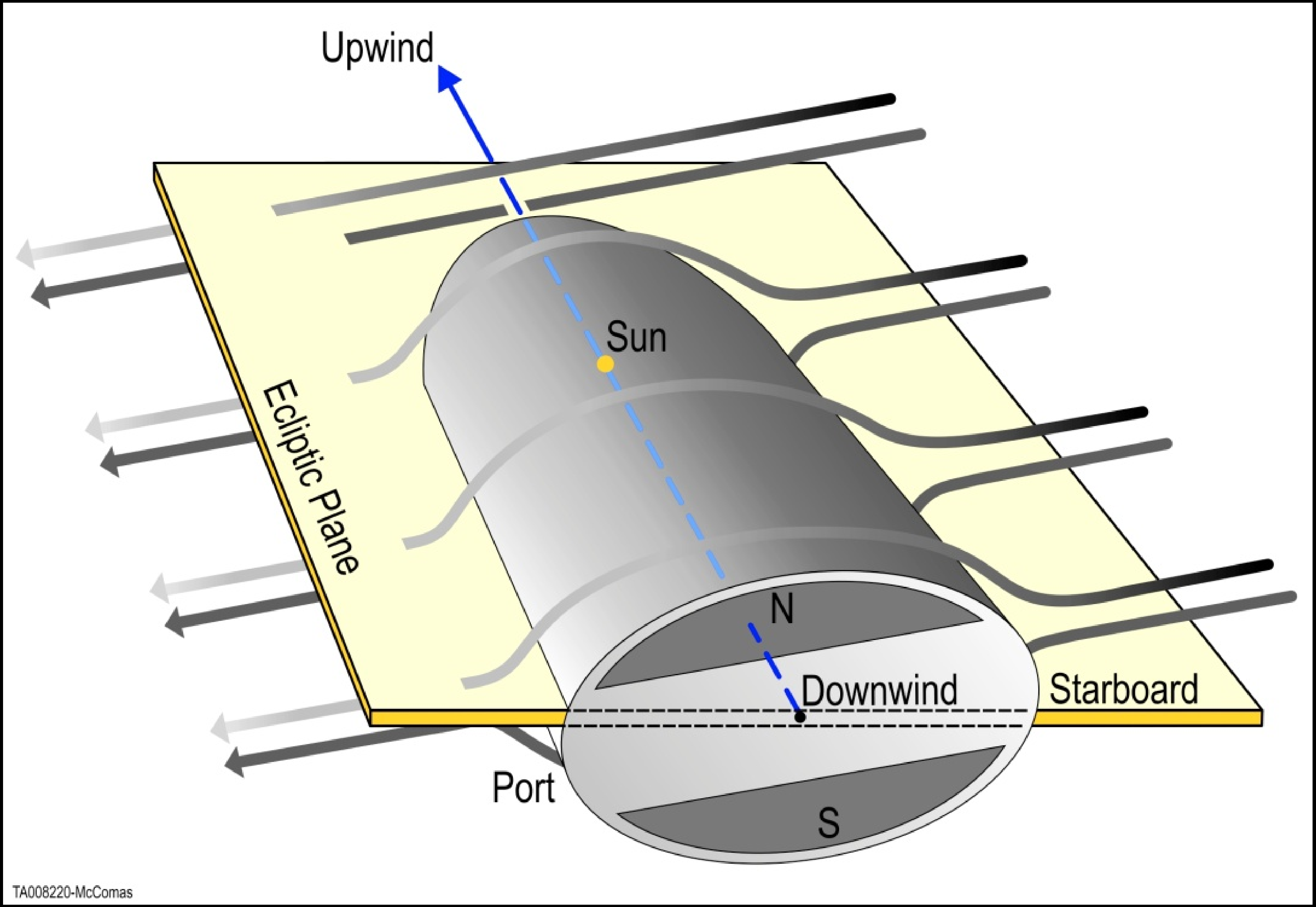

Science
13 November 2009 | $10
IBEX
and the heliosphere's boundary
AAAS

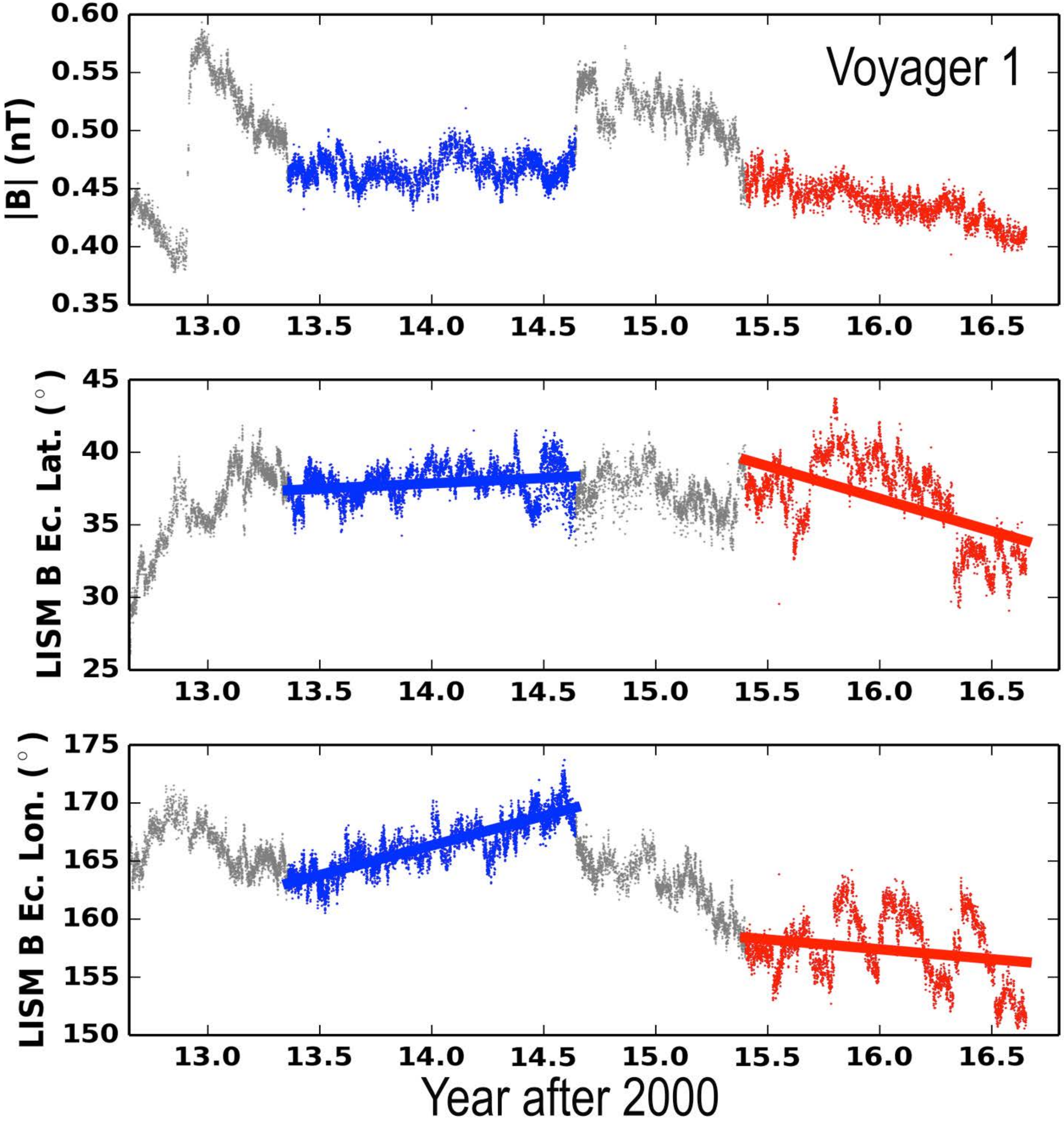
Heliotail Observed

- Influence of Solar Wind
- Port and Tail Lobes
- Twisting by external field influence

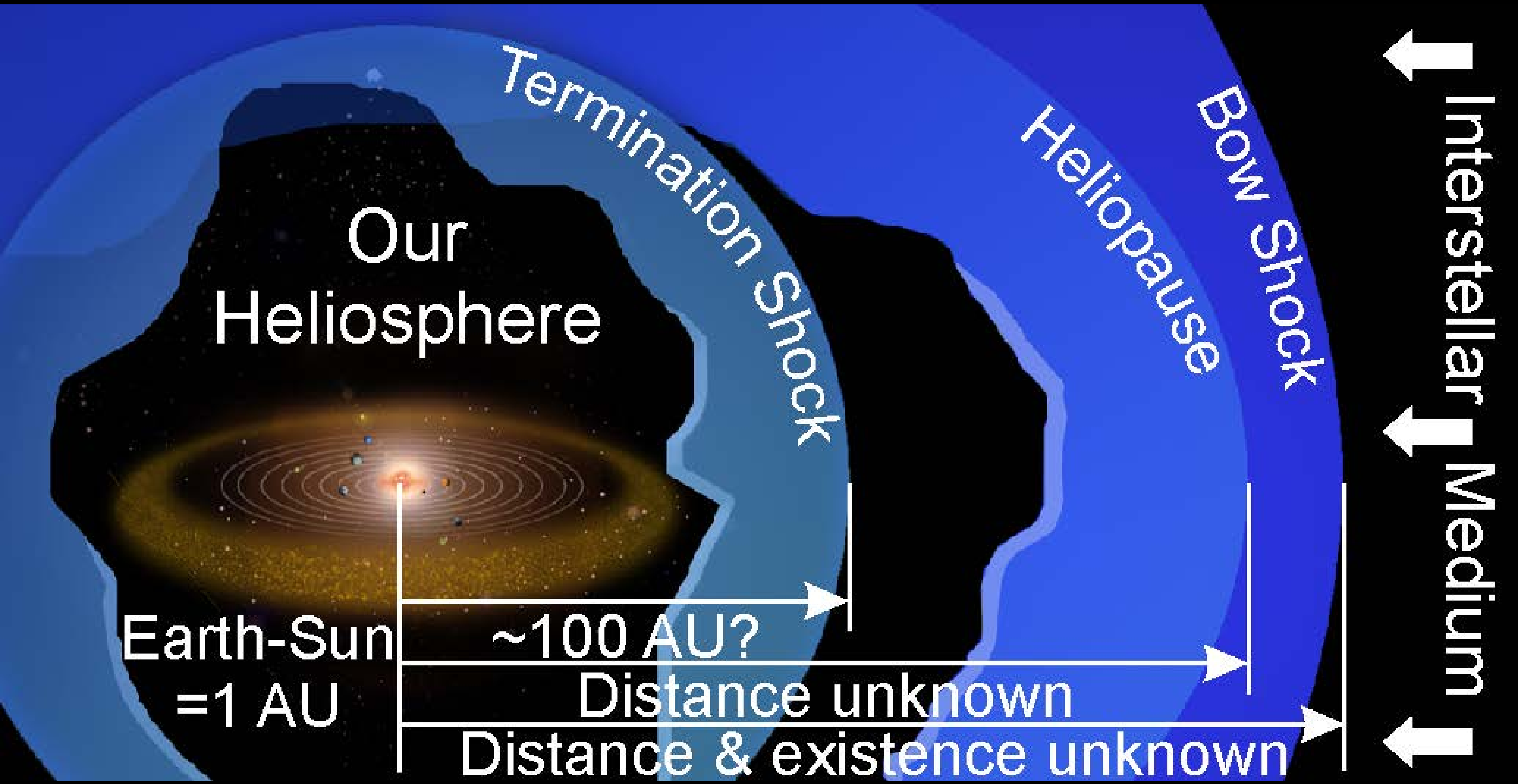


LISMF Twists Heliotail



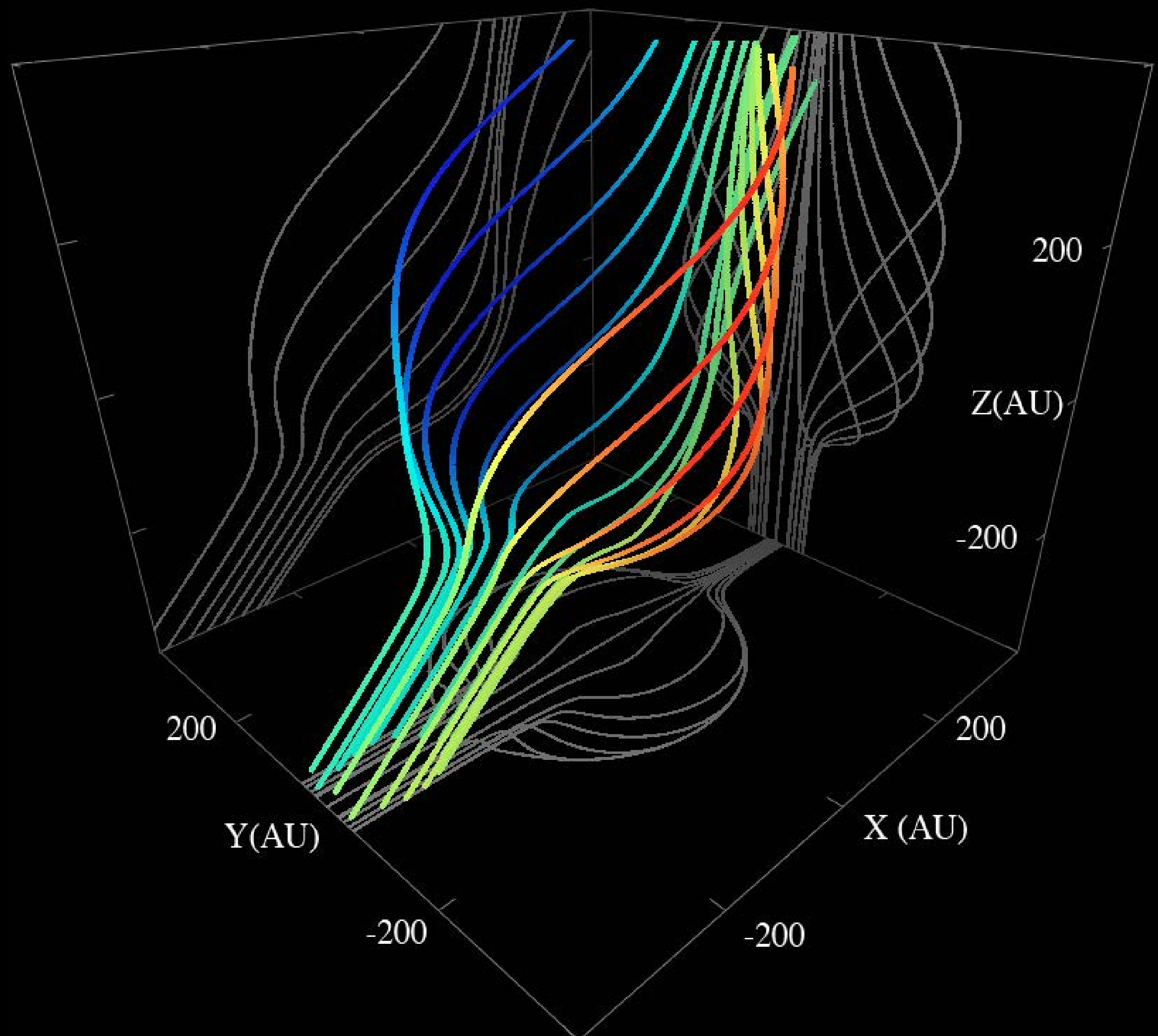


Schwadron and McComas, ApJ, 849, 2017


Our
Heliosphere
Termination Shock
Heliopause
Bow Shock
Interstellar Medium
Earth-Sun
=1 AU
~100 AU?
Distance unknown
Distance & existence unknown

Interstellar Magnetic Field Influence

- Interstellar magnntic field deflected around our heliosphere
- Affects TeV cosmic rays with ~100 AU gyroradii
- Controls structure of the IBEX ribbon



Schwadron et al., 2014, 2015

Solar and Space Physics 2013 Decadal Survey

- Interstellar Mapping & Acceleration Probe