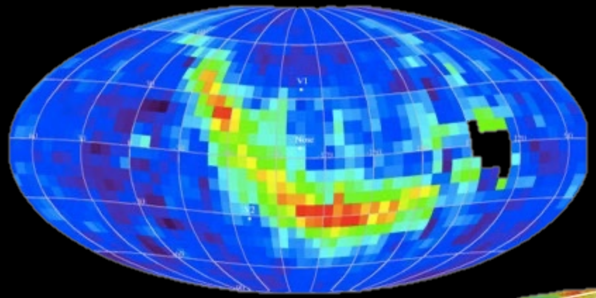
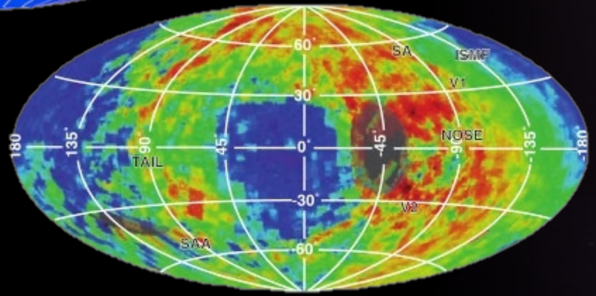
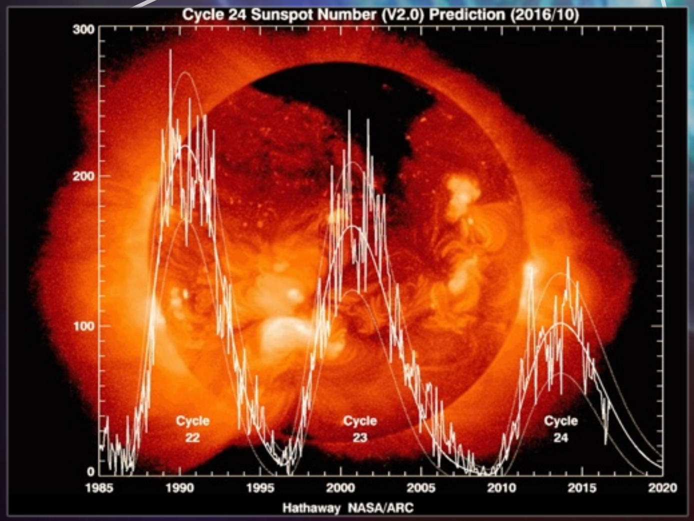
Heliosphere Fundamentals

SHIELD Summer School
June 2, 2025

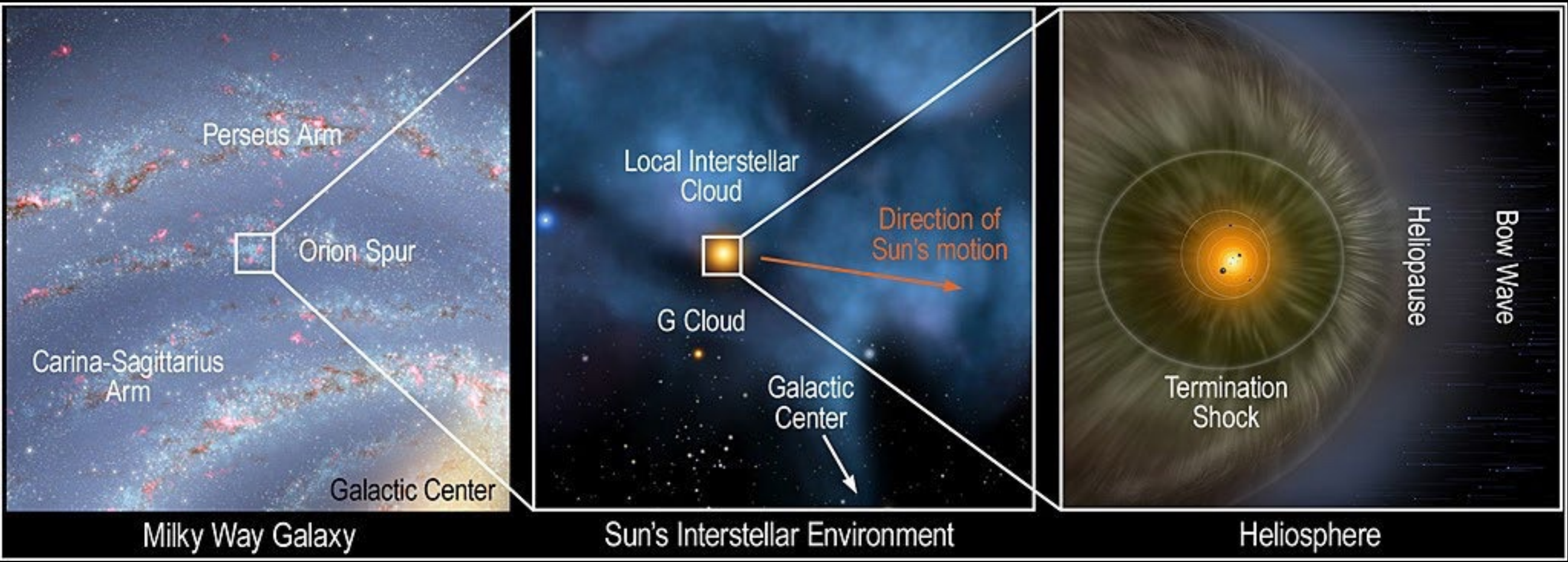
Chika Onubogu, SHEILD, Boston University



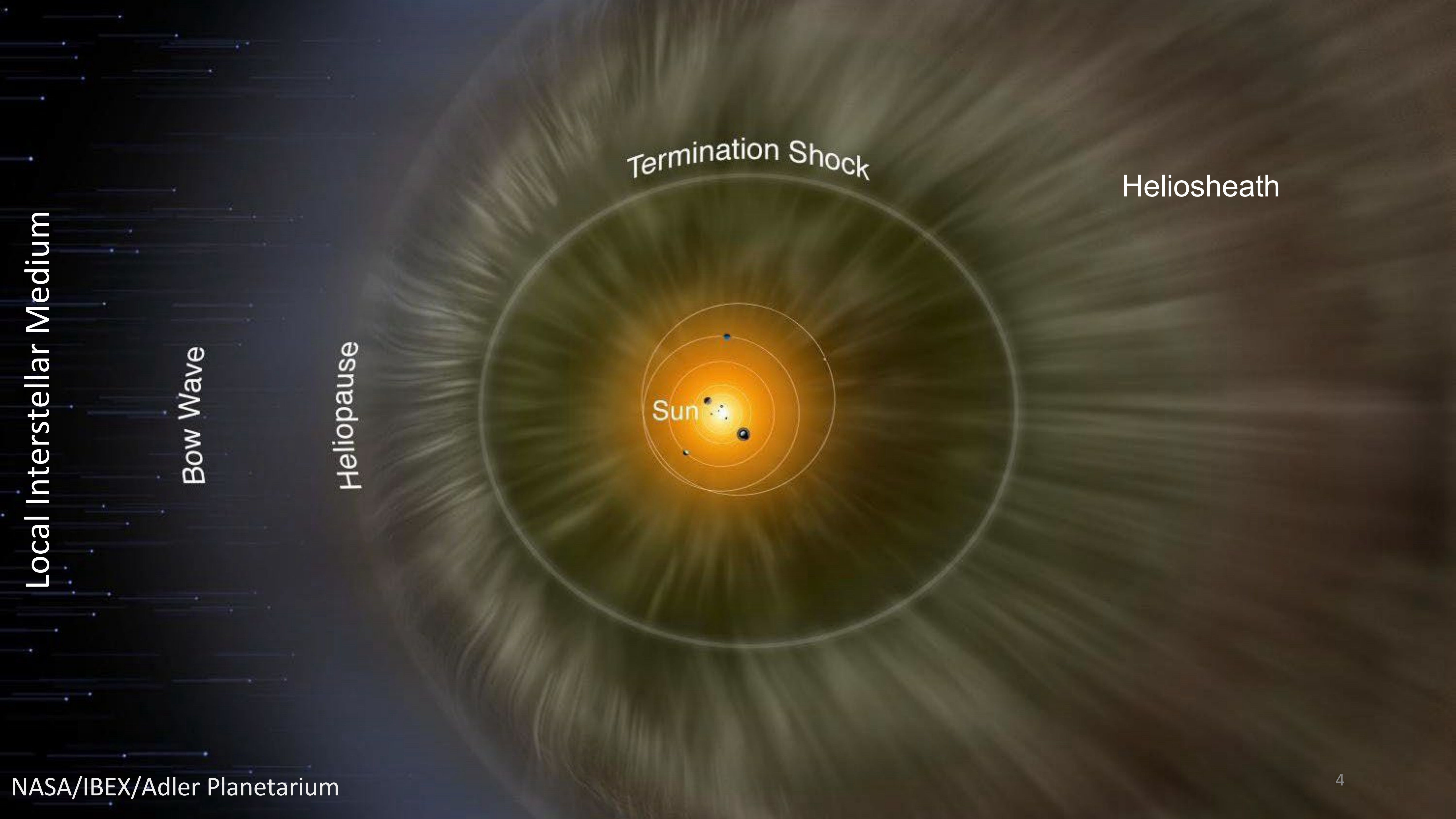




Our place in the Milky Way



McComas et al. (2014)


Termination Shock
Heliosheath
Local Interstellar Medium
Bow Wave
Heliopause
Sun
NASA/IBEX/Adler Planetarium

Building Up the Inner Heliosphere

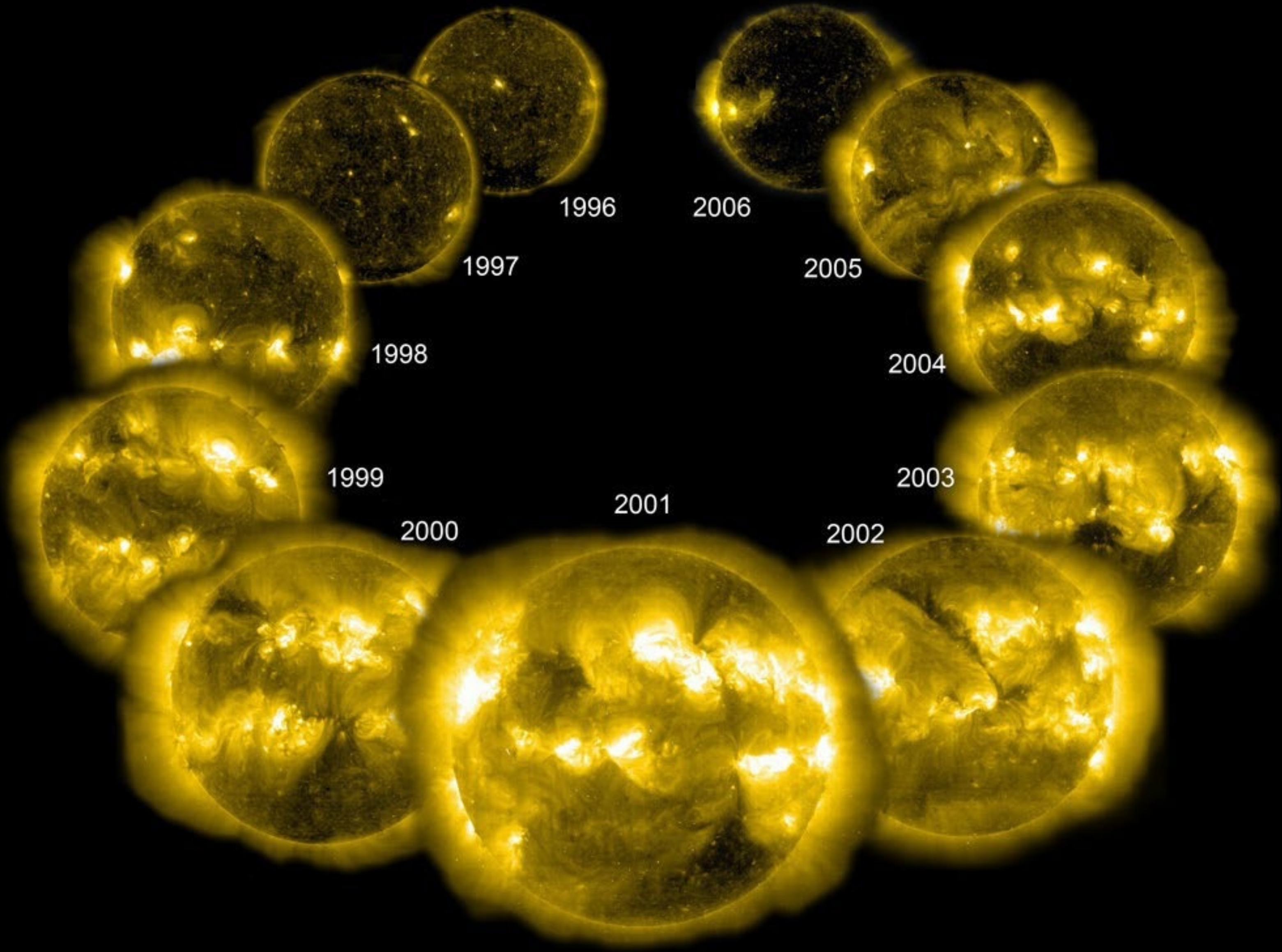
(R < 10 au)

NASA/Solar Dynamics Observatory

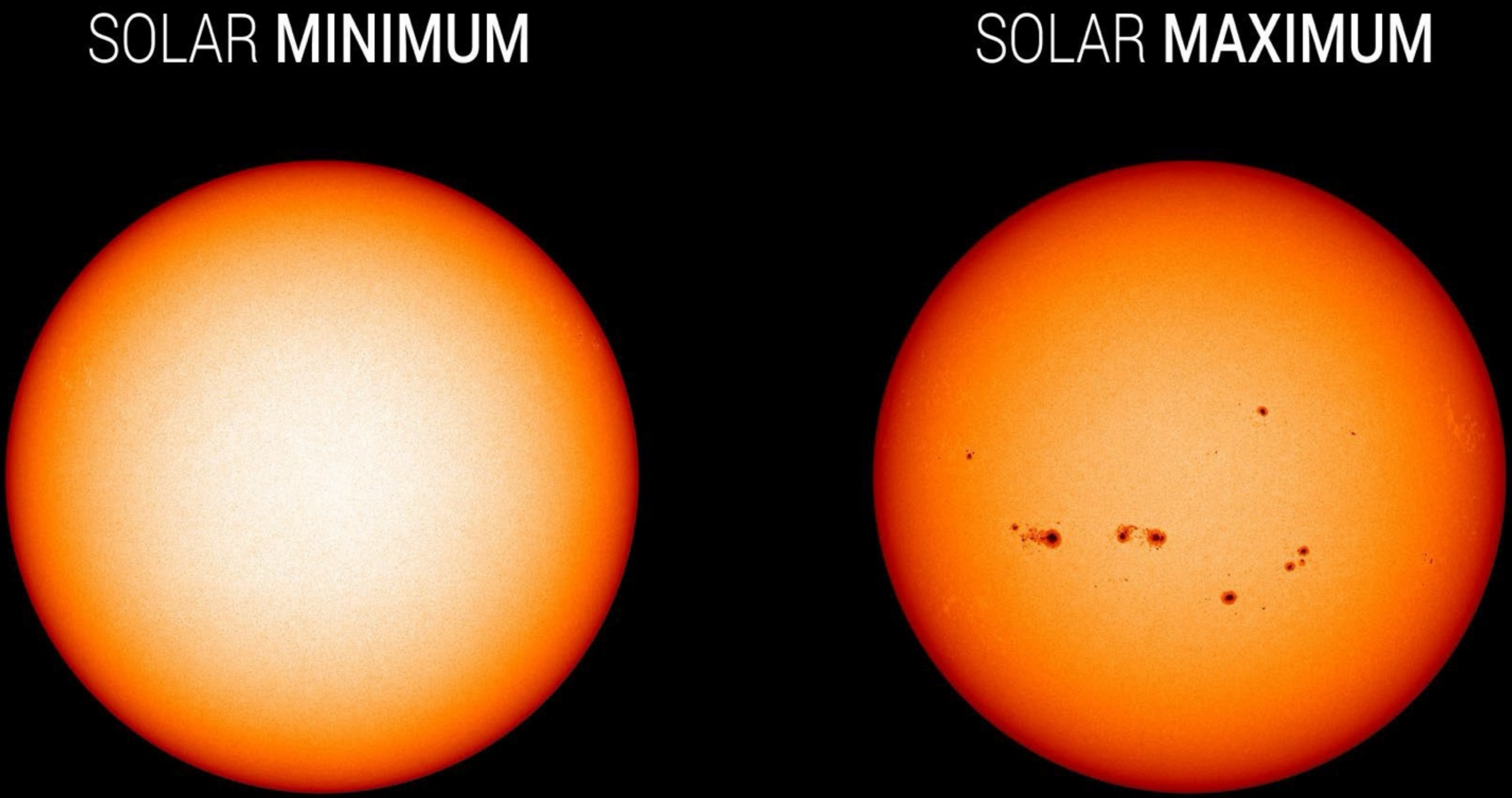
The Sun

the heart of the heliosphere

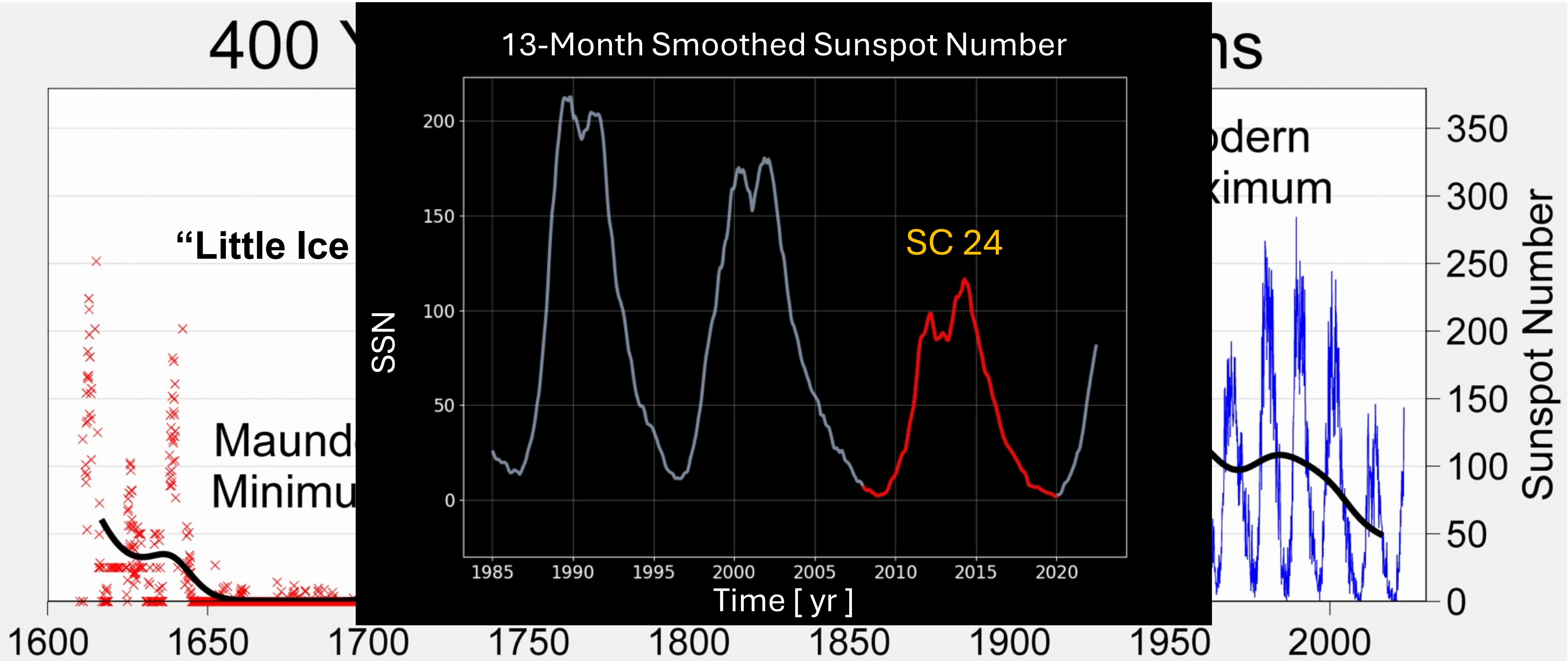
The 11-year Solar Activity Cycle



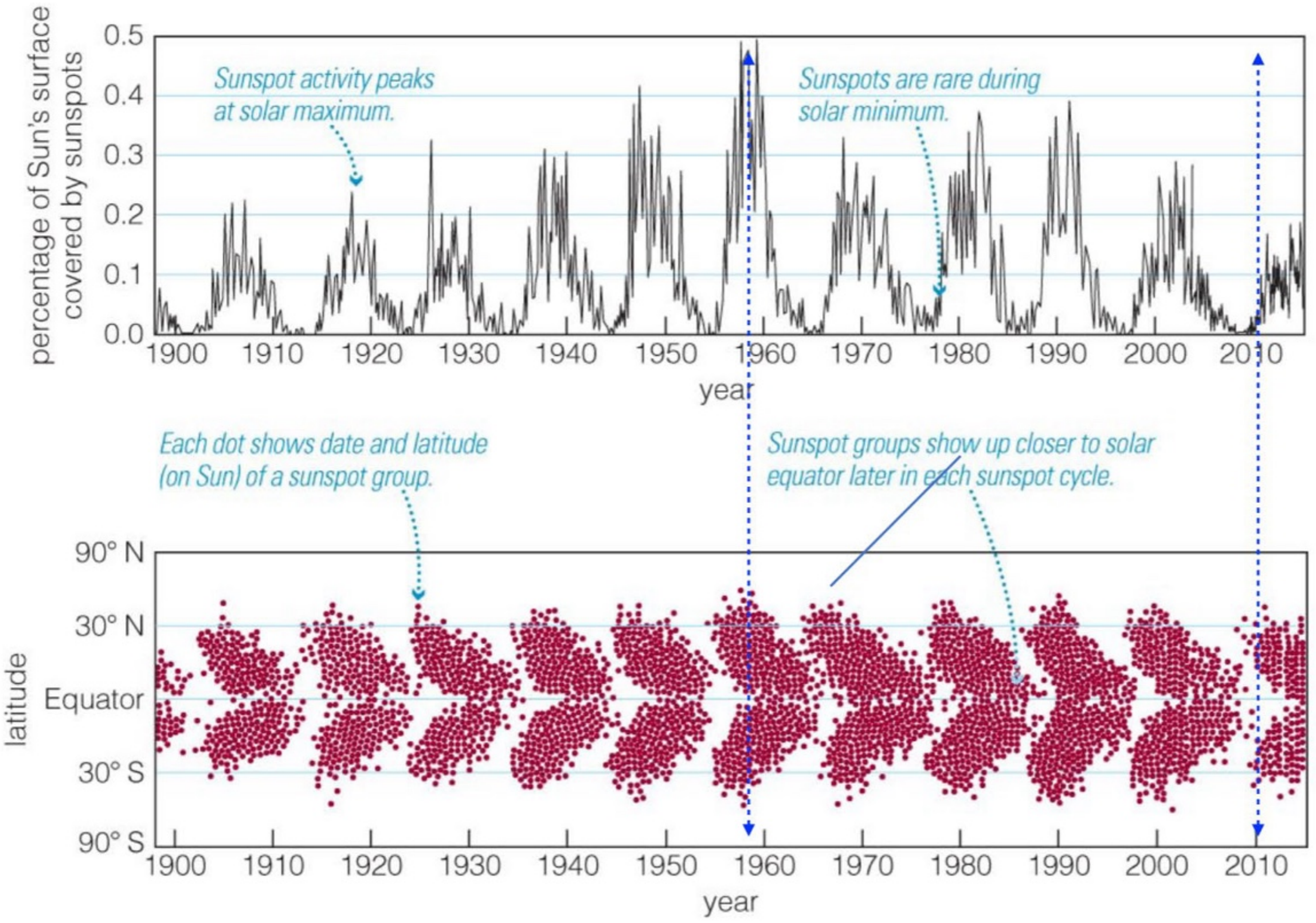
Sunspot Numbers Keep Track of the Solar Cycle



History of Sunspot Records



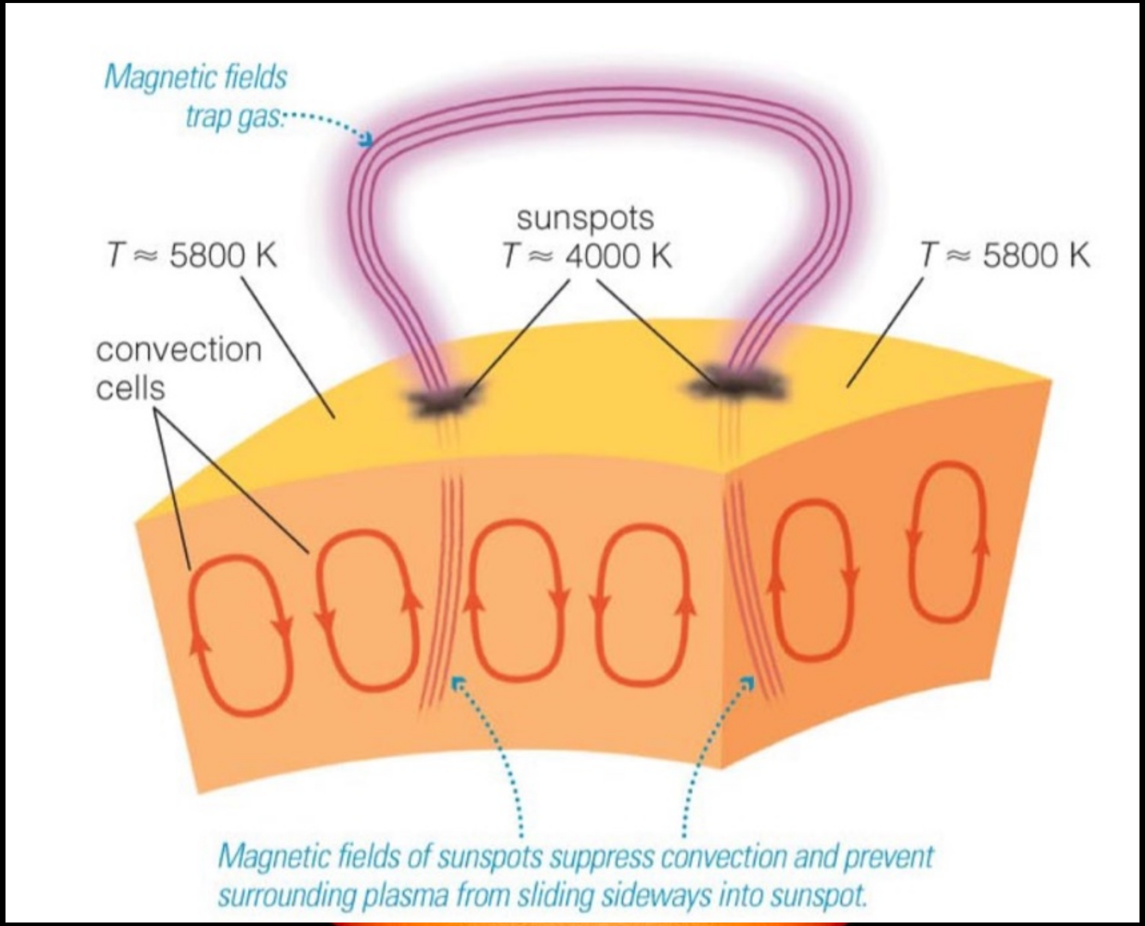
Sunspots Trends with the Solar Cycle

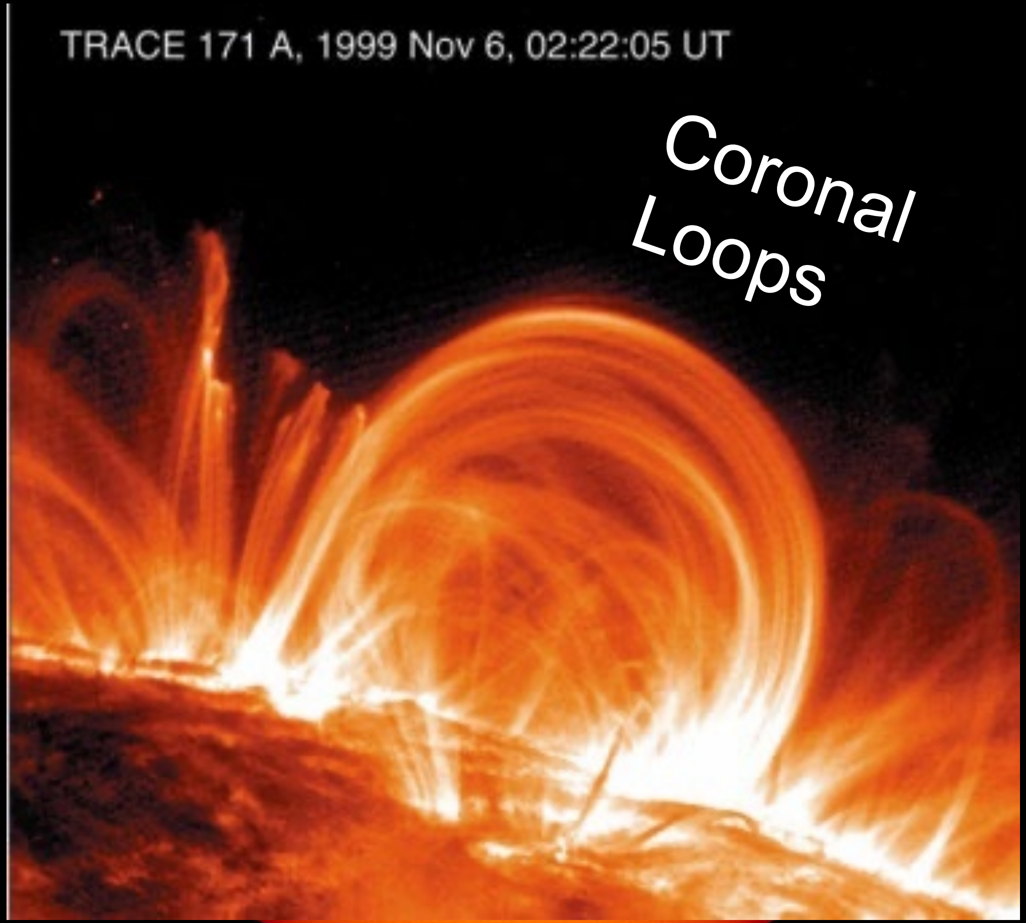


a This graph shows how the number of sunspots on the Sun changes with time. The vertical axis shows the percentage of the Sun's surface covered by sunspots. The cycle has a period of approximately 11 years.

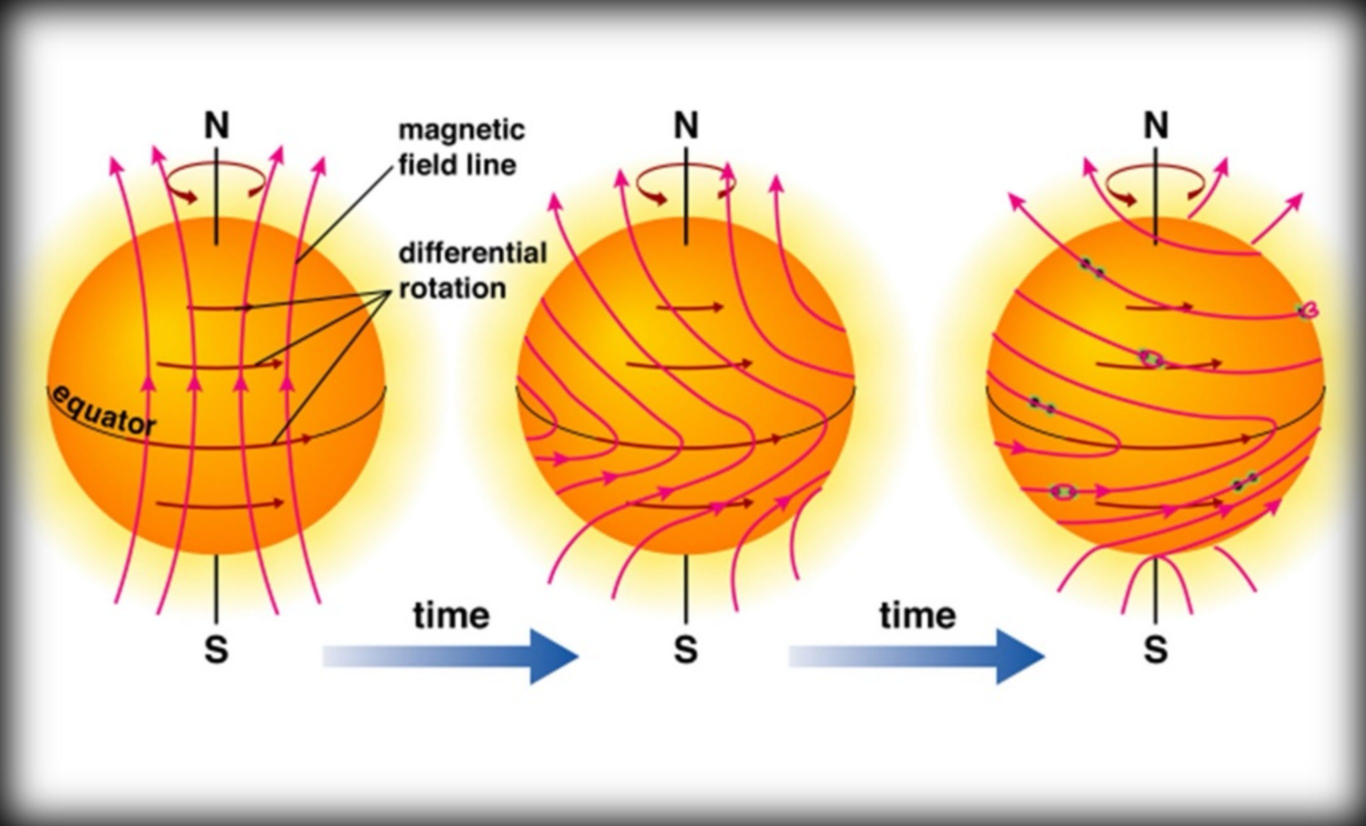
b This graph shows how the latitudes at which sunspot groups appear tend to shift during a single sunspot cycle.

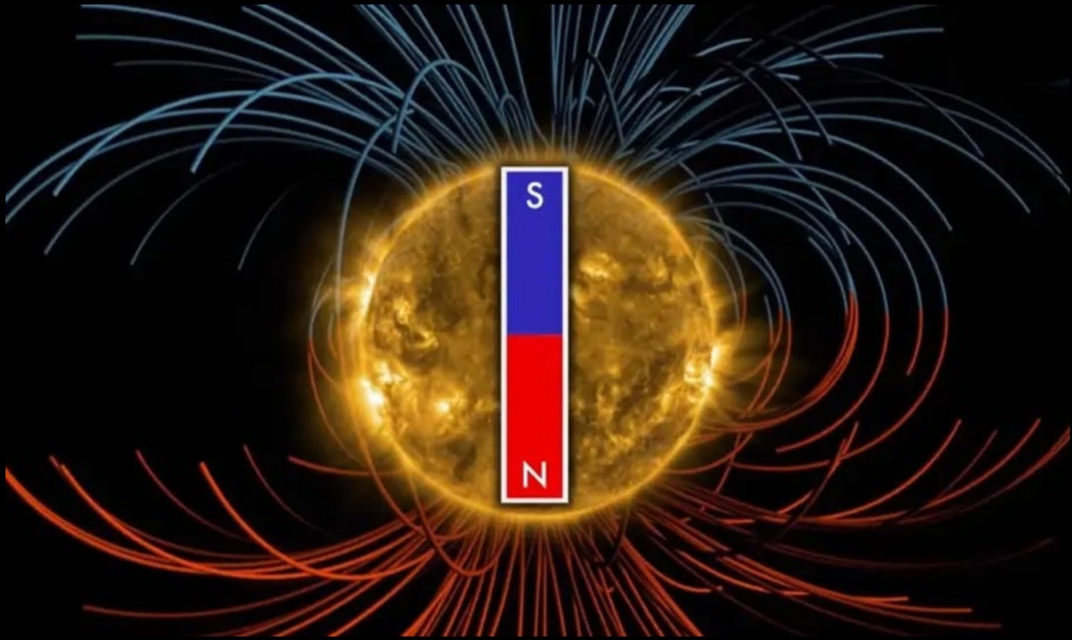
What Causes Sunspots to Form?



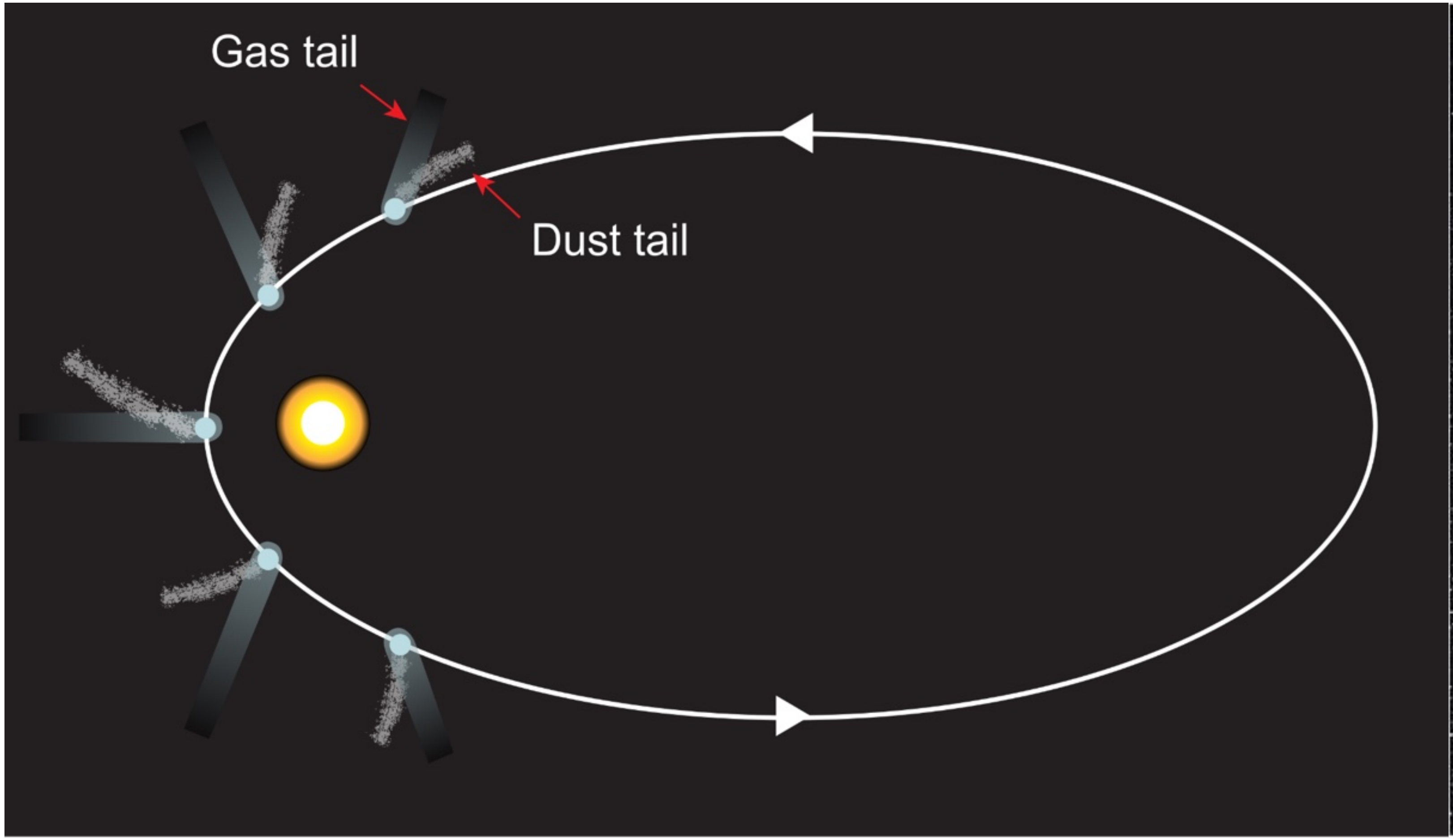


What Causes Sunspots to Form?





- Large-scale magnetic field structure is dipolar.
- Polarity flips every 11 years in time with the solar cycle.
- Twisted magnetic fields during polarity changes produces magnetic loops.



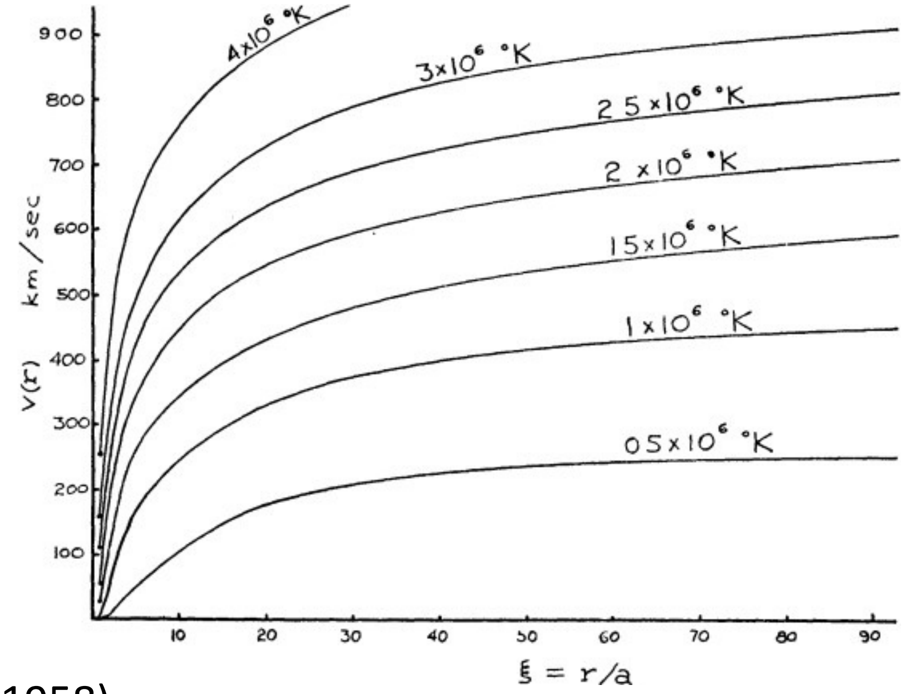
The Solar Wind

the flesh of the heliosphere

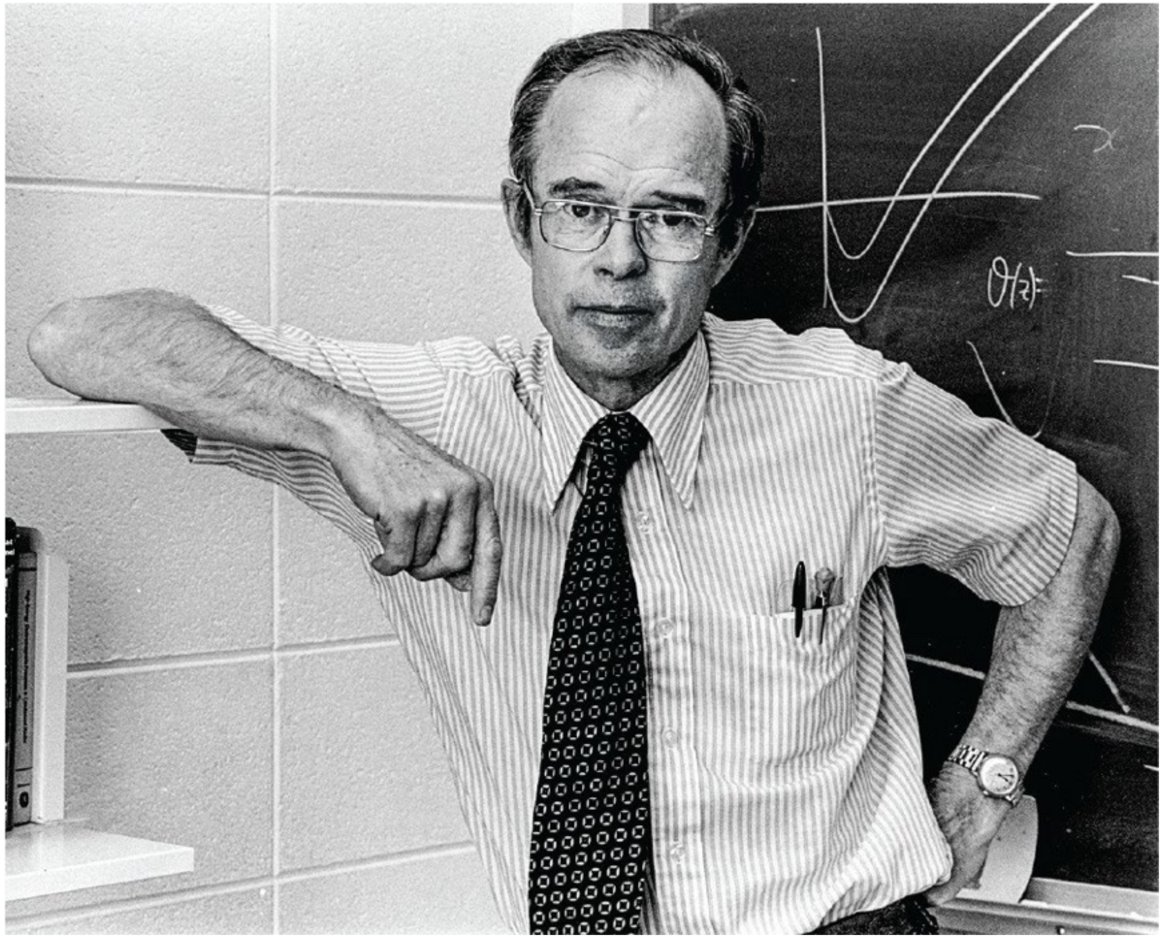
- Separated comet tails give evidence of an ionized component of plasma that expands far beyond the Sun.

1958: Eugene Parker suggested the expanding solar corona – aka the solar wind!

- Assumed spherically symmetric, hydrodynamic expansion of an isothermal solar corona



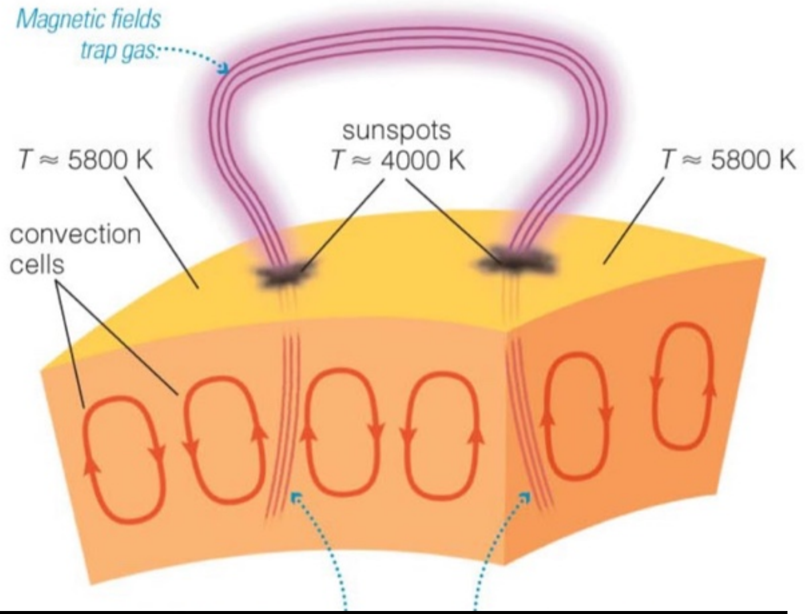
Parker (1958)



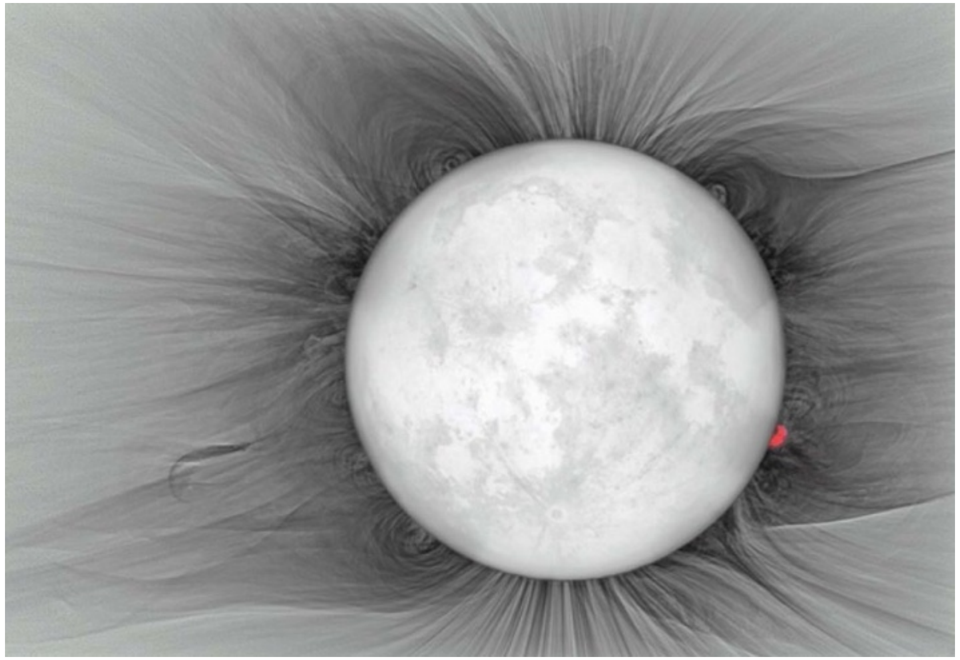
- Plasma and magnetic field are connected.

- Hot, **expanding** coronal plasma is confined into arcs above the photosphere along bipolar, magnetic field loops.

- What if the magnetic field is not a closed loop?

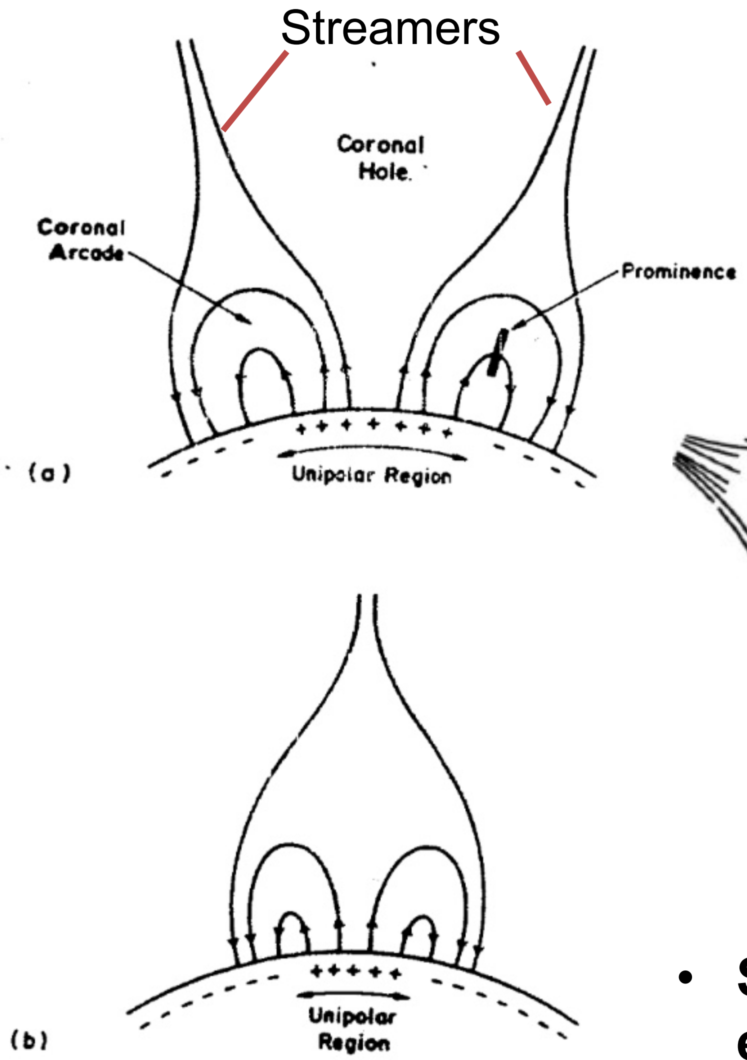


Open Magnetic Field and Coronal Holes

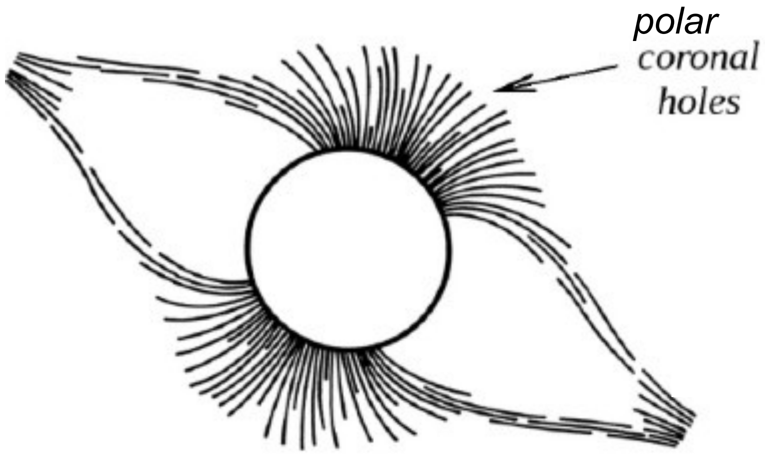


D. Rabin, NASA Goddard

- Striated features show the coronal plasma along magnetic field lines

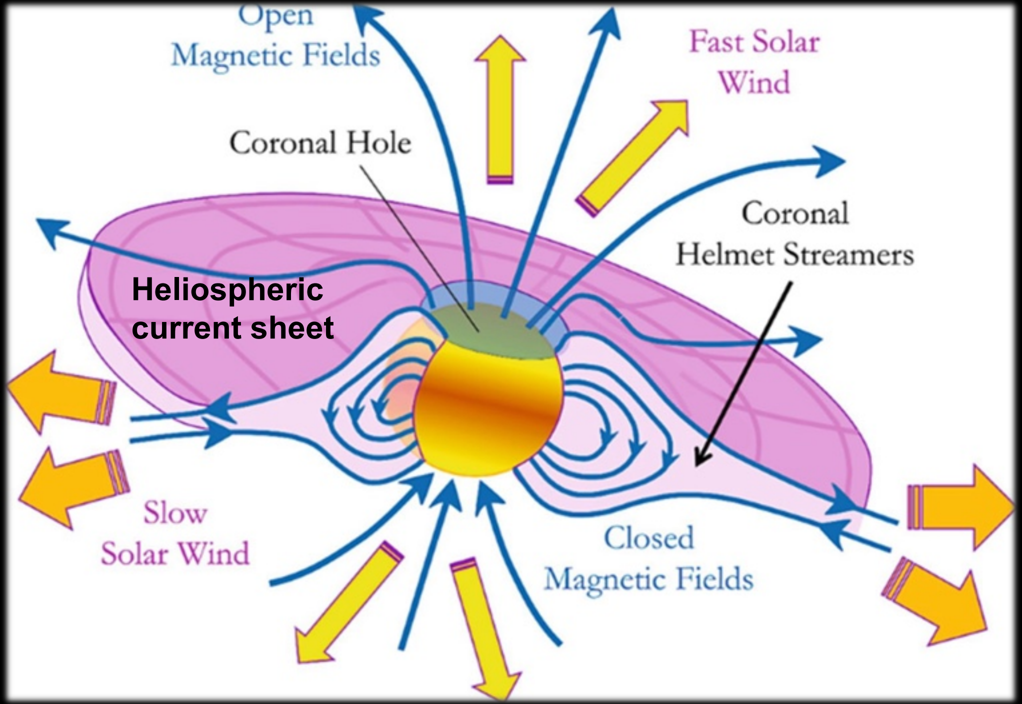


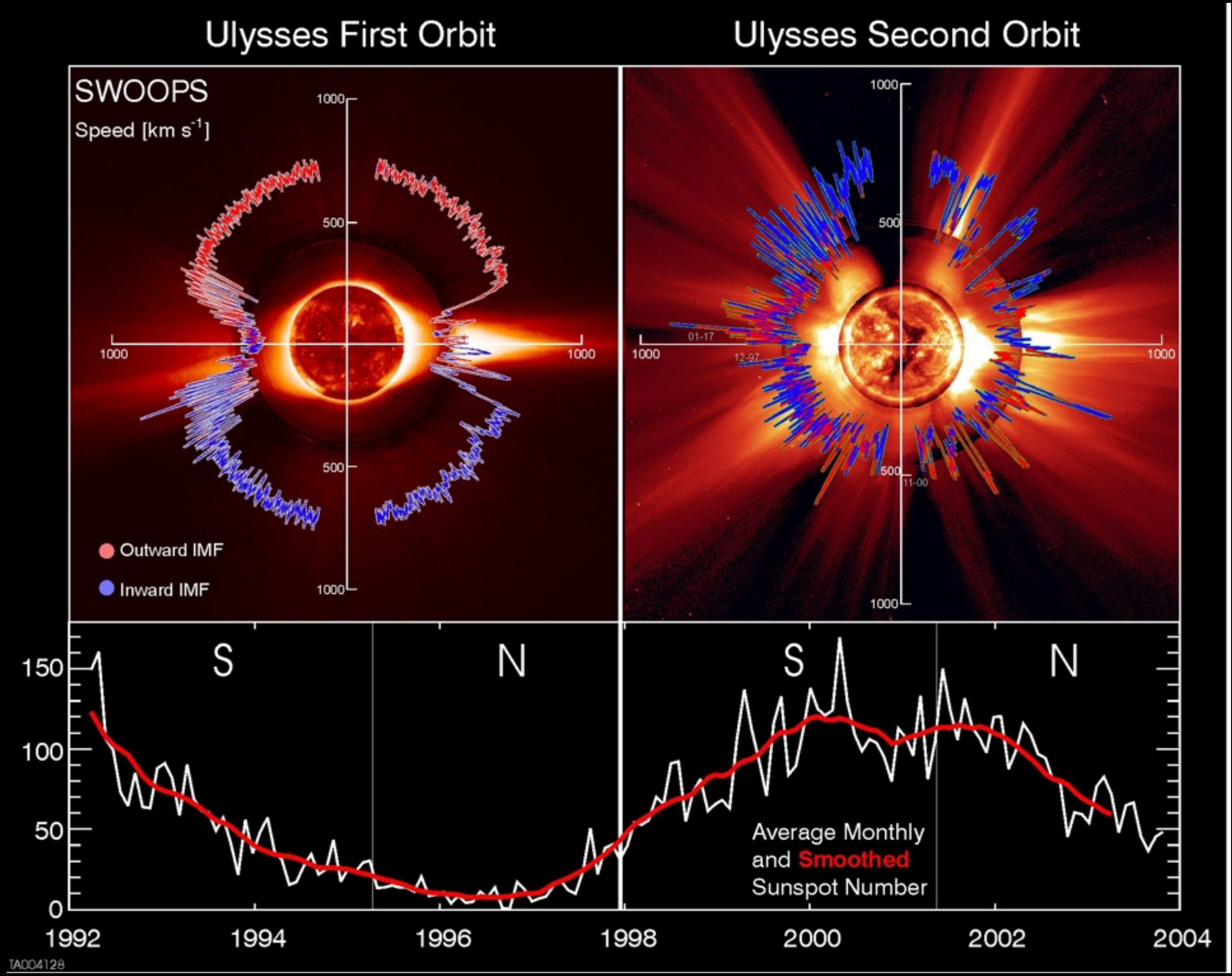
- Certain magnetic field configurations allow coronal plasma to expand past the corona.



- **Solar wind is plasma that escapes from the corona!**

Solar Wind Escapes with Varying Speeds





Properties of the Solar Wind

Fast Solar Wind:

Stable streams over long time periods.

Flow speeds 400-800 km/s

Average ion density ~3 cm^{-3} at 1au (H/protons)

4% Helium nuclei (alpha particles)

Mostly confined to polar coronal holes during **solar min**

Forms at lower latitudes during **solar max**

Proton temperature ~2.5×10^5 K

Electron temperature ~1×10^5 K

Slow Solar Wind:

Less organized pattern with heliolatitude

Flow speeds 250-400 km/s

Average ion density ~8 cm^{-3} at 1au (H/protons)

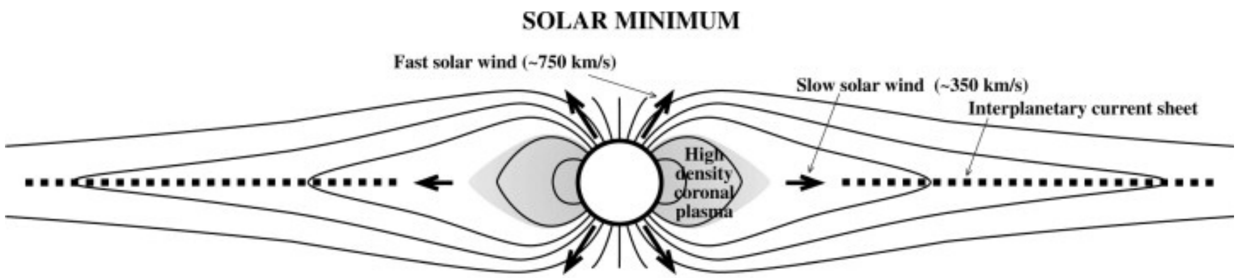
Source from current sheet and streamers

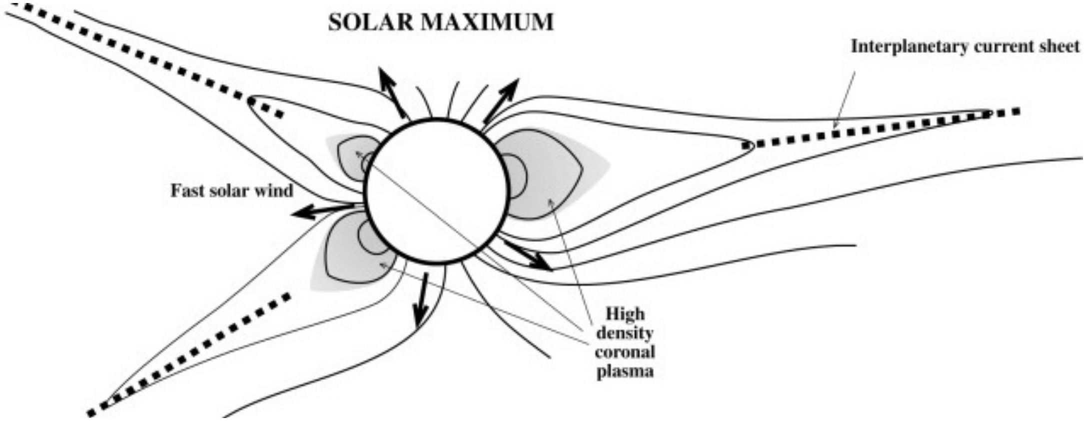
More prevalent during **solar max**

Highly variable and turbulent

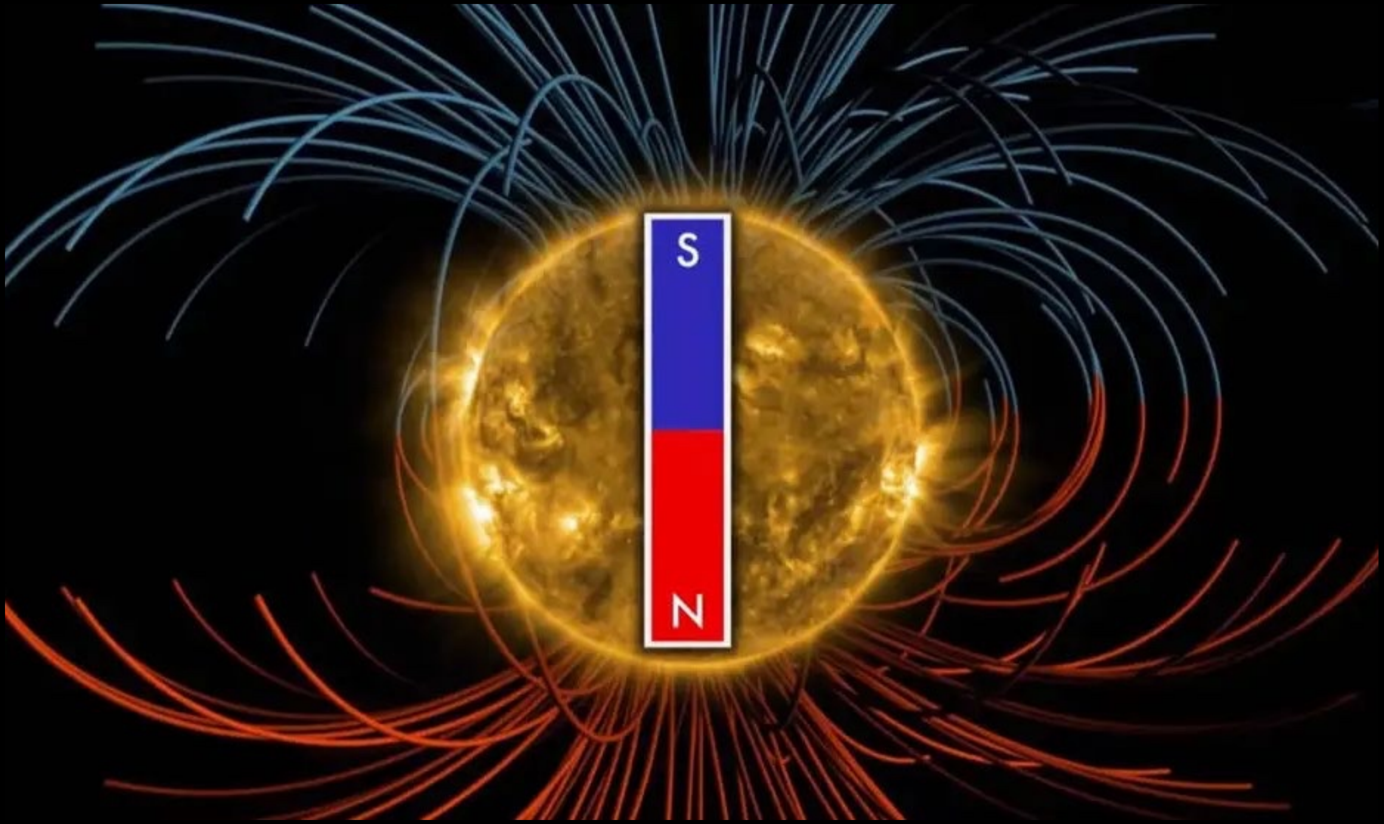
Proton temperature ~4×10^4 K

Electron temperature similar to fast wind





The Solar Magnetic Field



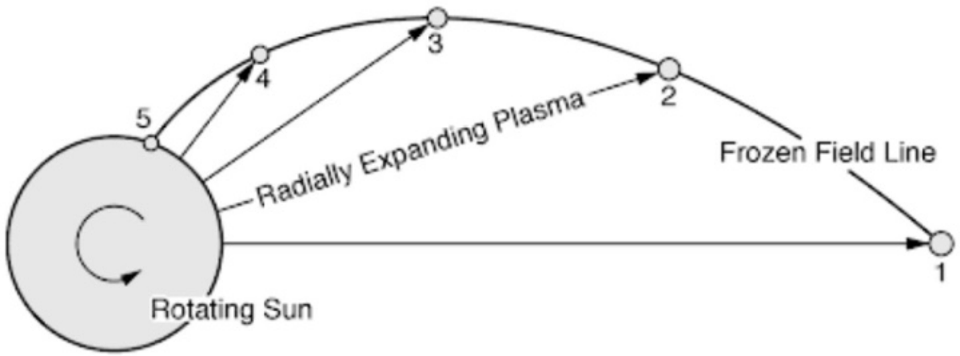
Dipole field, but what about at larger scales?

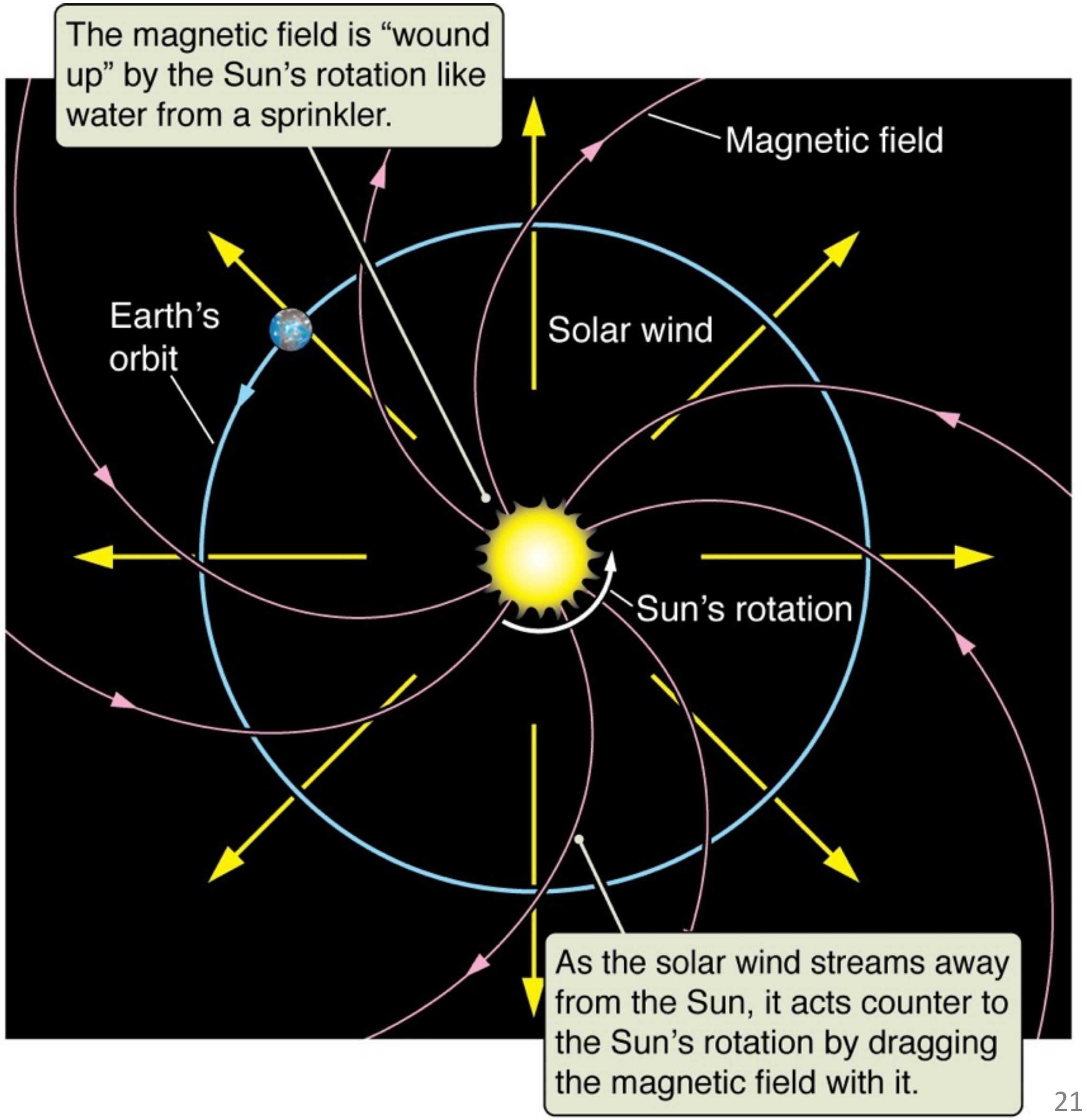
The Solar Magnetic Field is "**Frozen-in**" with the Plasma

- Frozen-in property of the magnetic field dictates that it moves with the solar wind plasma.

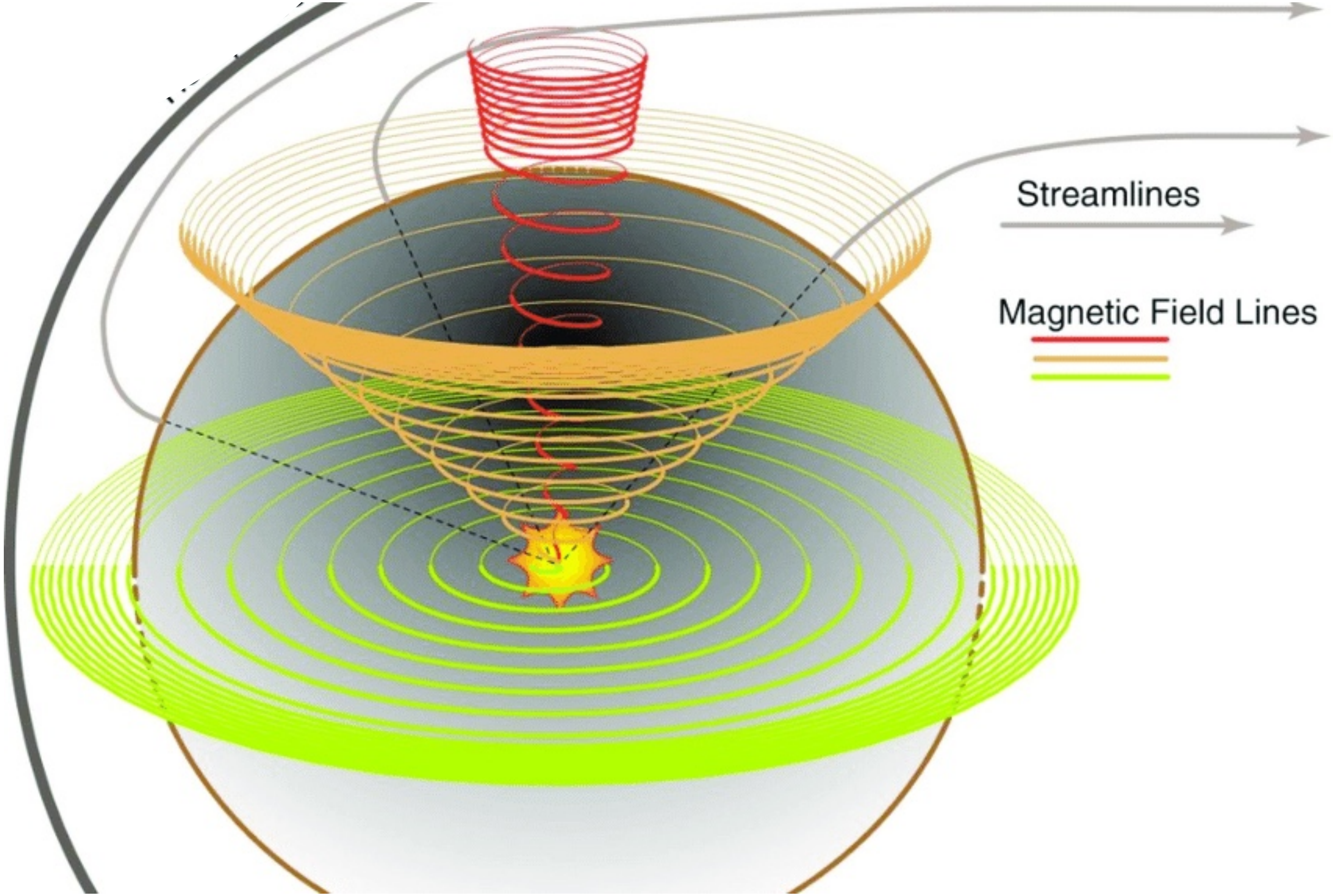
- Superposition of nearly constant solar wind speed v along a line rotating with constant angular speed ω.

- **Parker Spiral**

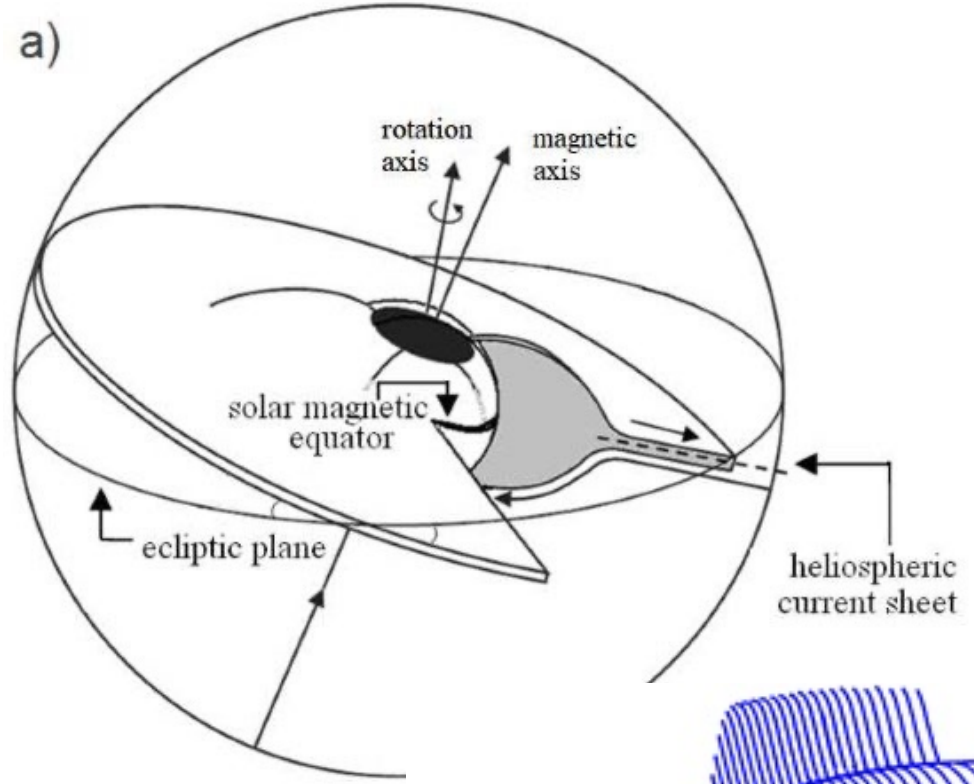




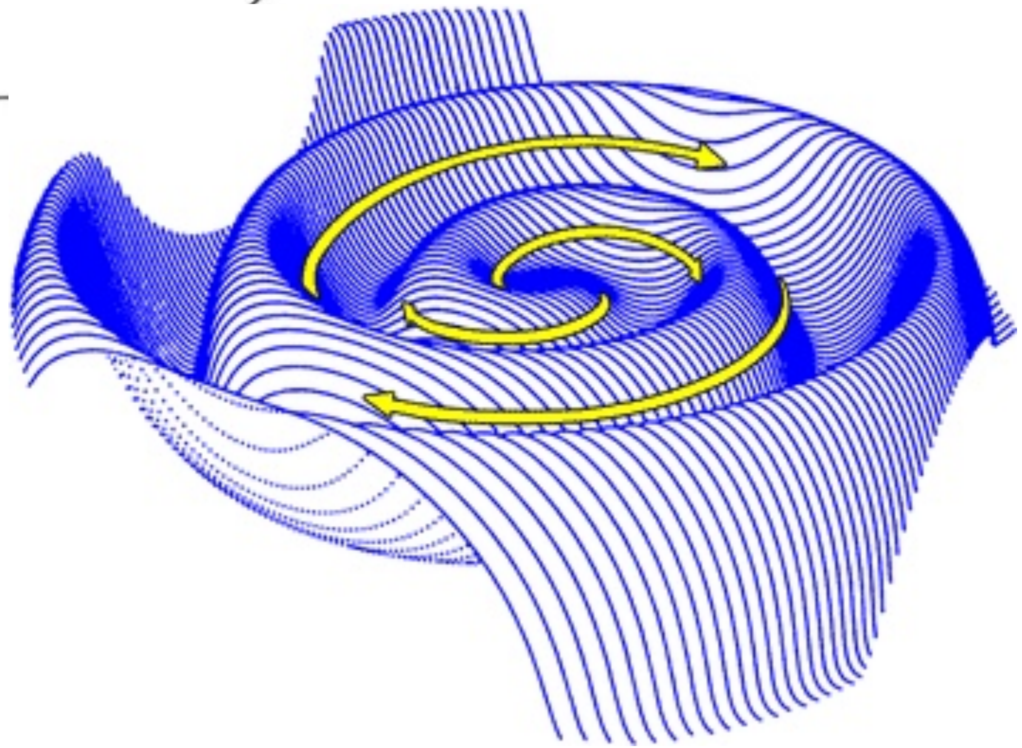
Parker Spiral Magnetic Field



The Heliospheric Current Sheet

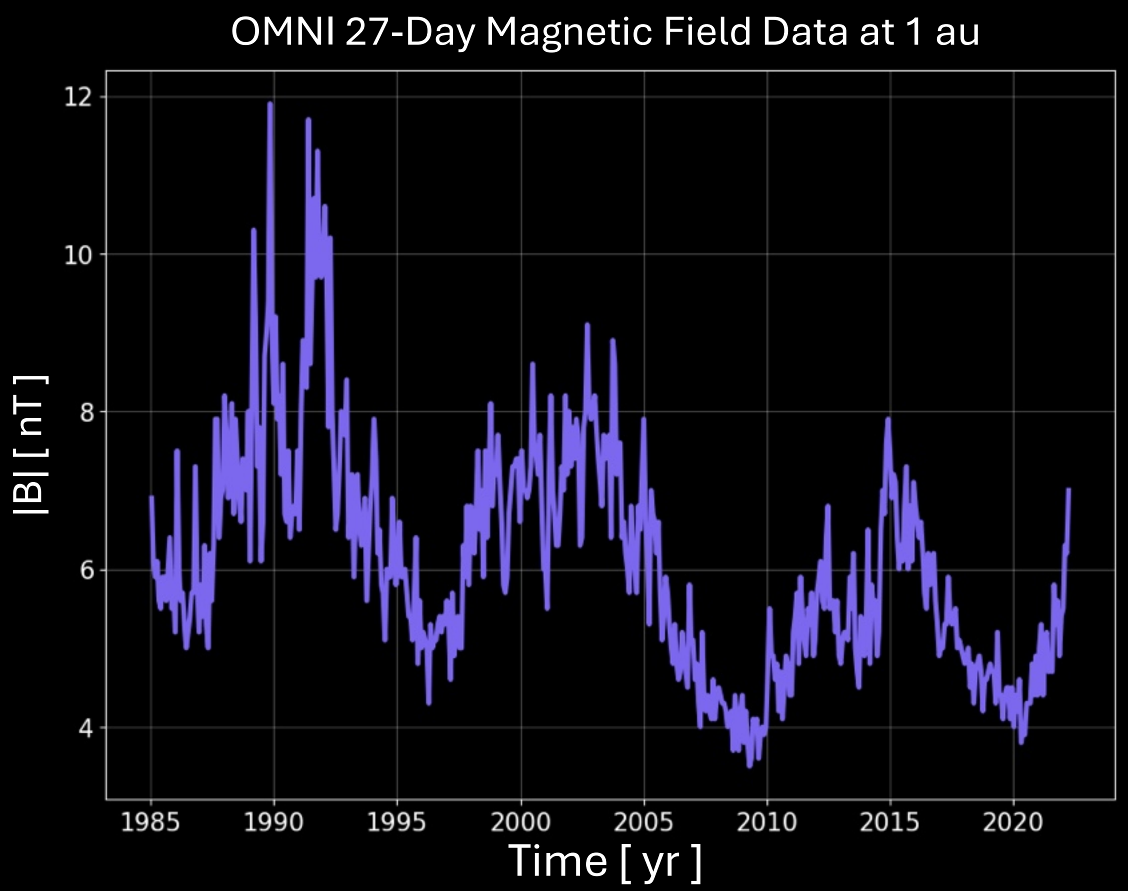


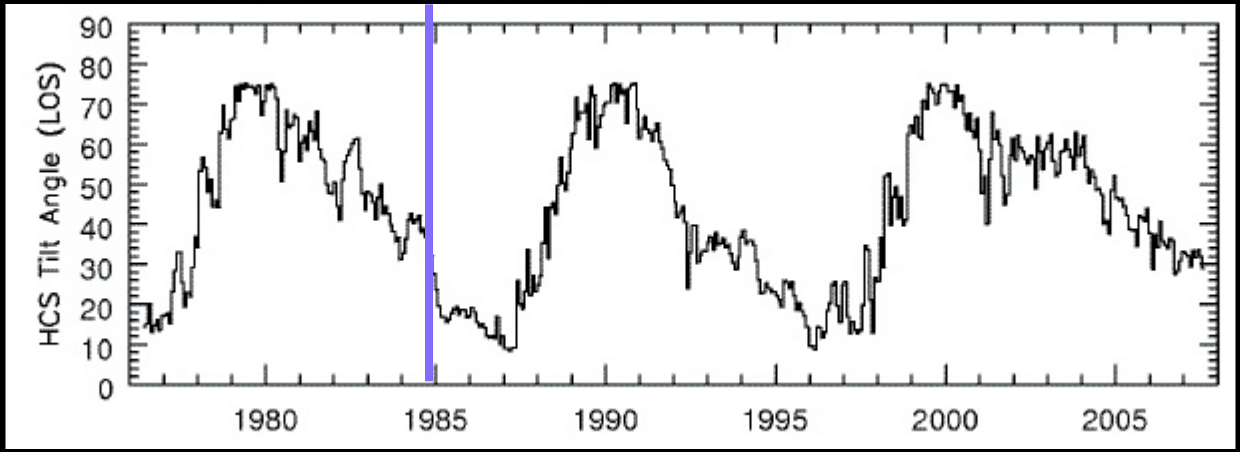
- Regions where opposite polarized magnetic field meet (or reconnect) develop a current sheet reminiscent of a ballerina skirt.



- Current sheet also “flaps” due to solar-cycle dependent variation in the magnetic axis tilt.

Solar Magnetic Field Also Changes with Solar Cycle





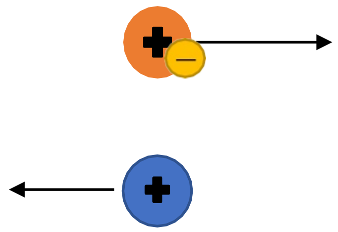
Pick-up Ions (PUIs)

The other charged component of the solar wind

Charge Exchange in the Heliosphere

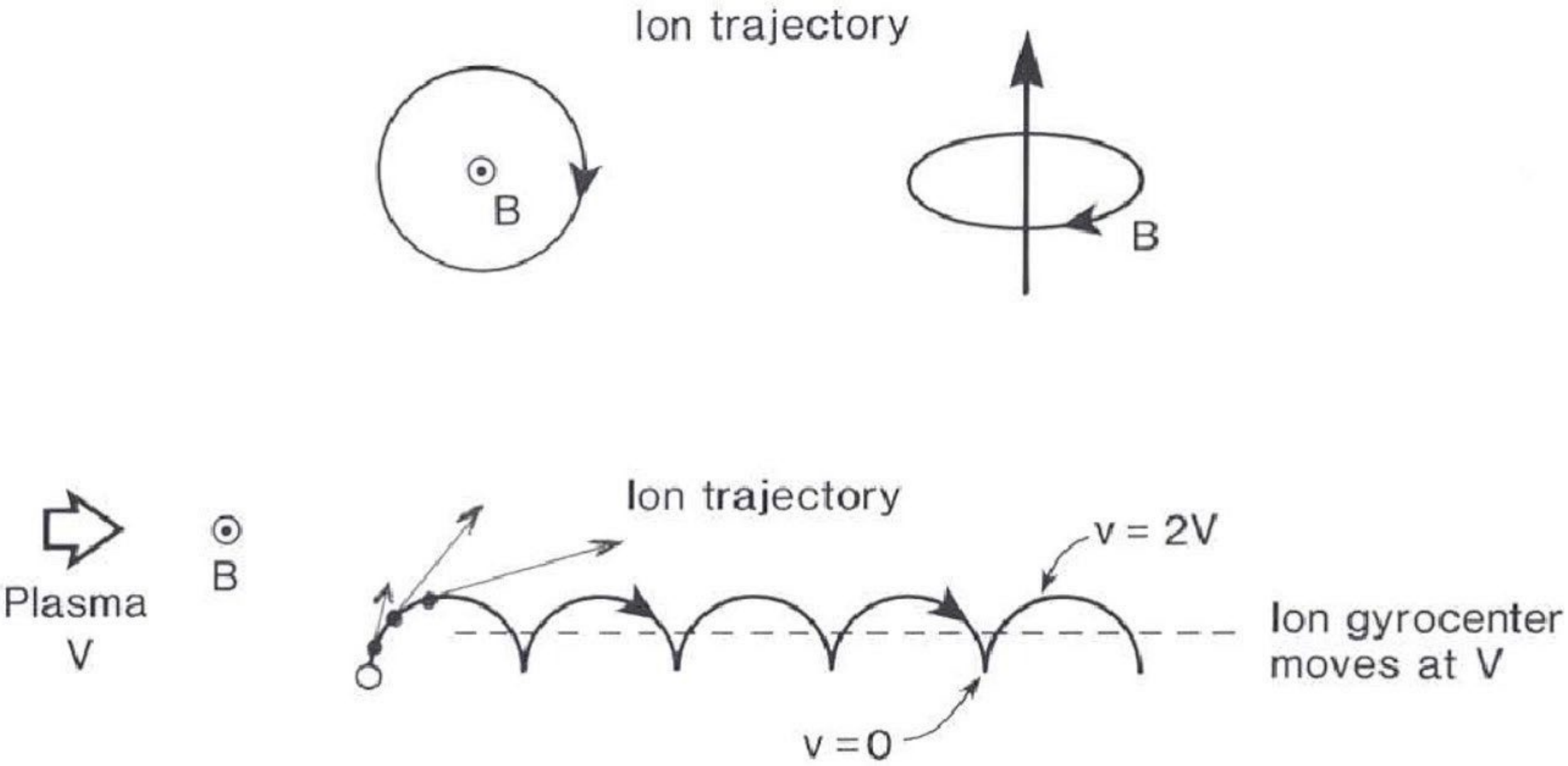
Charge Exchange in the Heliosphere

Energetic Neutral Atom
ENA (400 km/s)



Pick-up Ion (25 km/s)

Pick-up Ions (PUIs) are "picked up" by the solar magnetic field



Luhmann (2003)

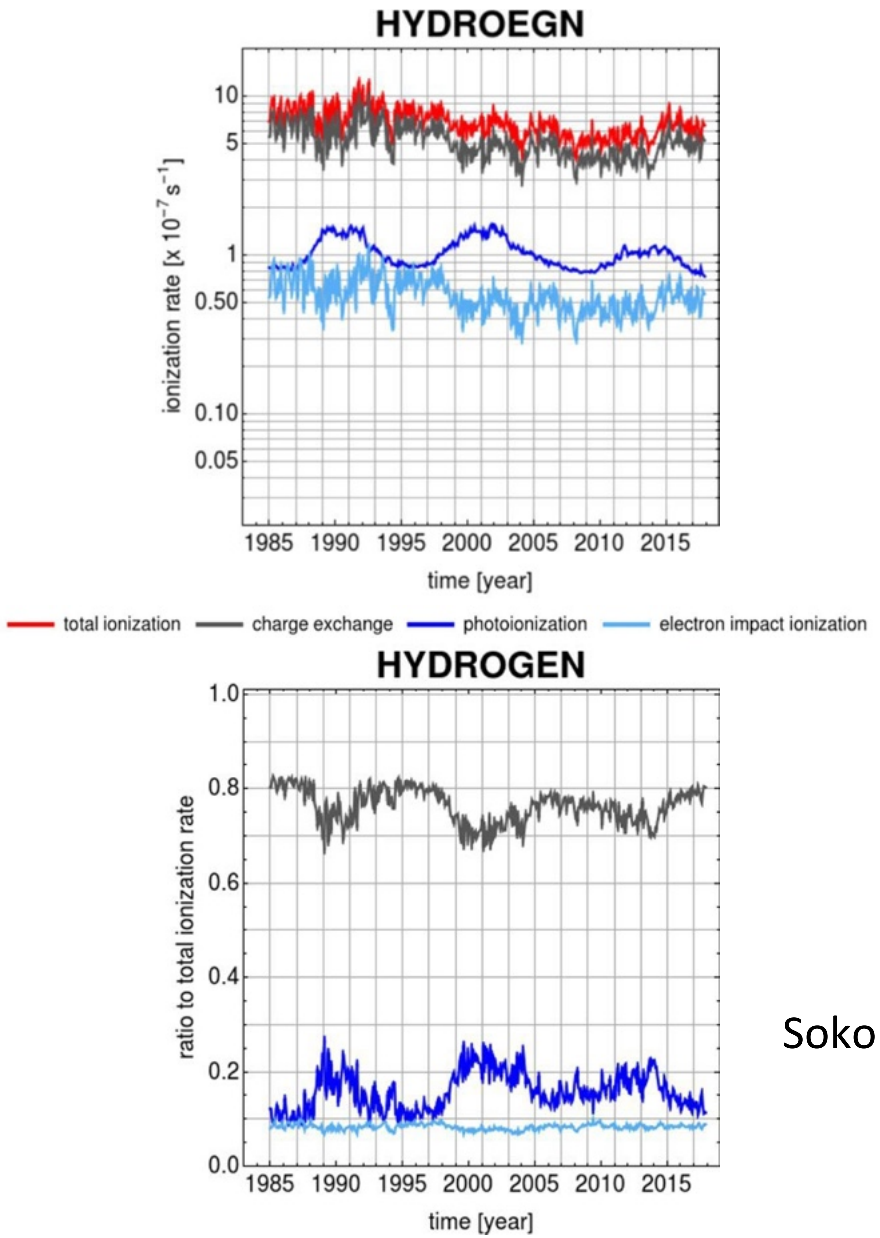
Charge exchange is the dominant source of PUIs in the Heliosphere

Aside from charge exchange, also have **electron impact ionization** and **photoionization** of neutrals to create PUIs

Around 1 au, charge exchange is the dominant source of ionization

Most PUIs are therefore created through charge exchange, leading to creation of energetic neutral atoms (ENAs) through this same process

In photoionization and electron impact ionization, no ENAs are created



Sokol et al. (2019)

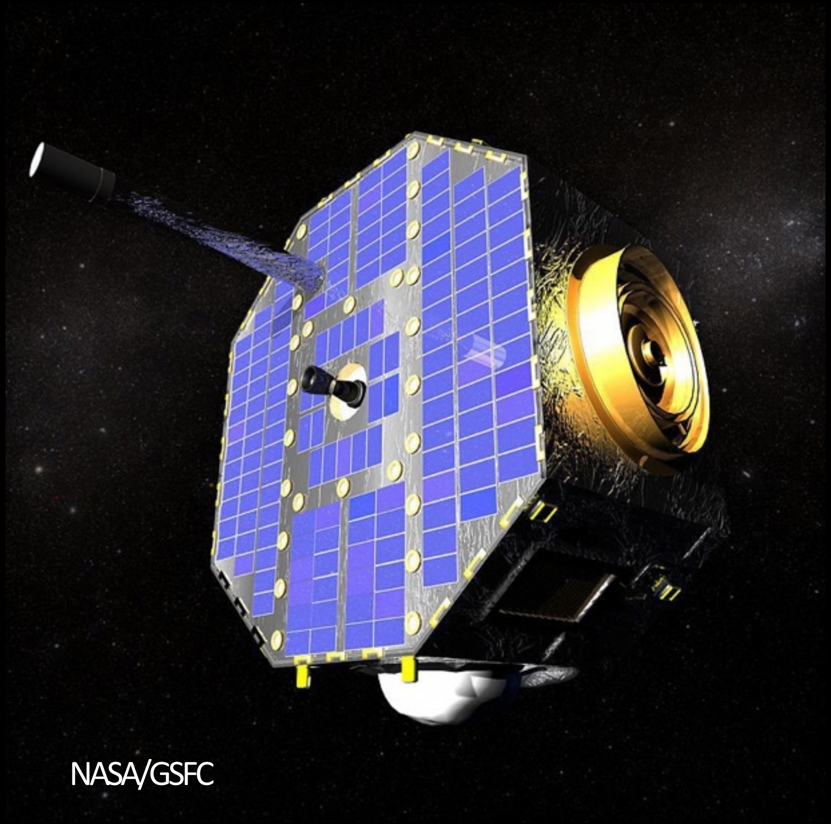
Observing the Outer Heliosphere

(R > 10 au)

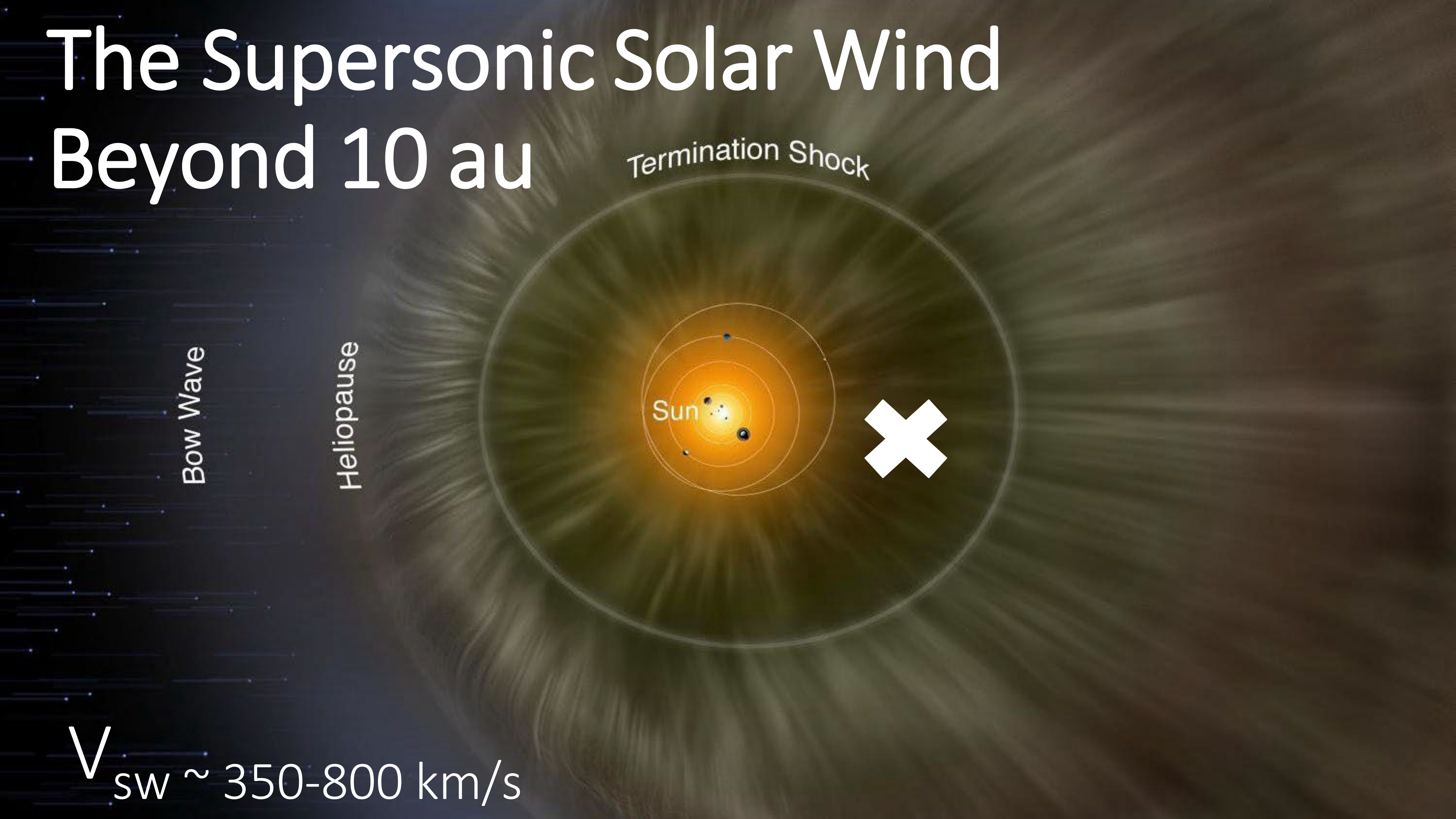
Methods for Observing the Heliosphere

In-situ Measurements (e.g. Voyager 1 & 2, New Horizons, Ulysses, etc.)
-Direct observations of plasma environment
-Limited to properties along lines-of-sight

ENA Observations (e.g. IBEX, Cassini)
-Indirect observations of the heliosphere
-Provide global perspective

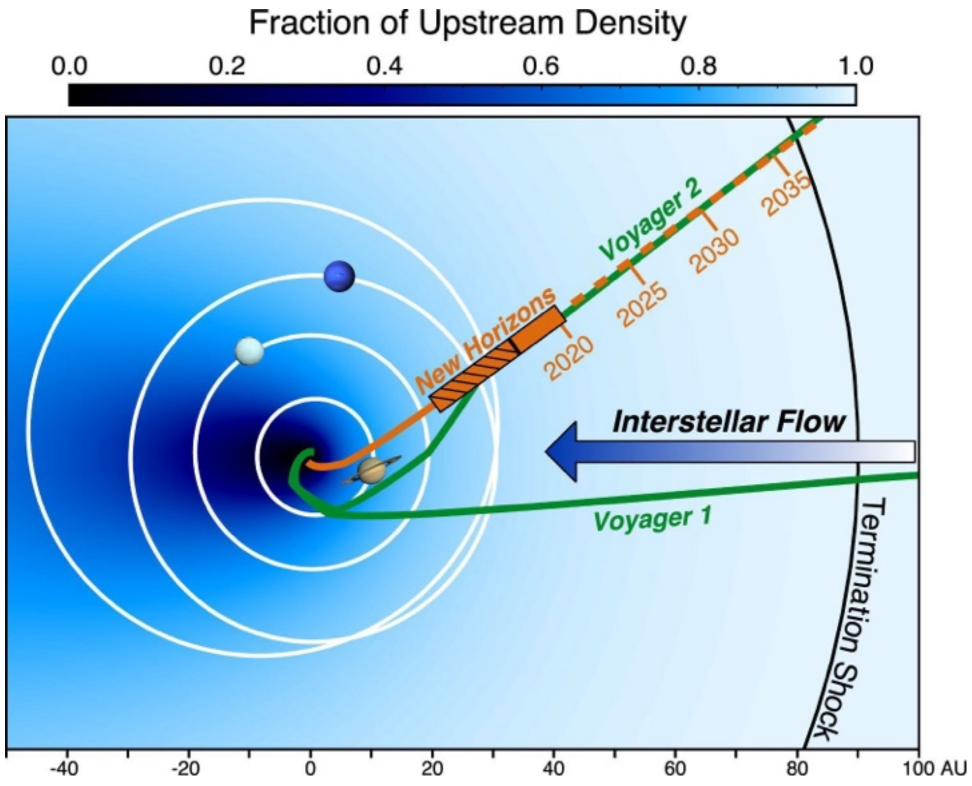


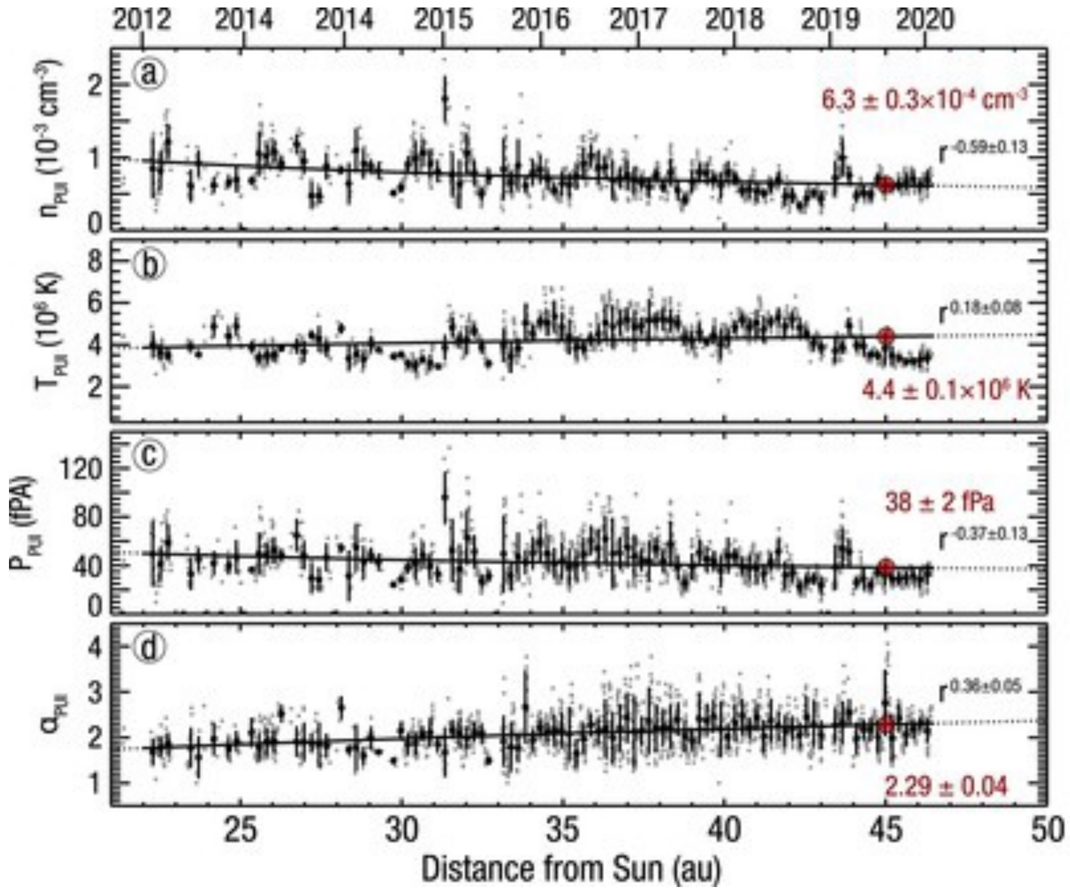
The Supersonic Solar Wind Beyond 10 au



$V_{sw} \sim 350\text{-}800$ km/s

New Horizons Observes PUIs in the Supersonic Solar Wind

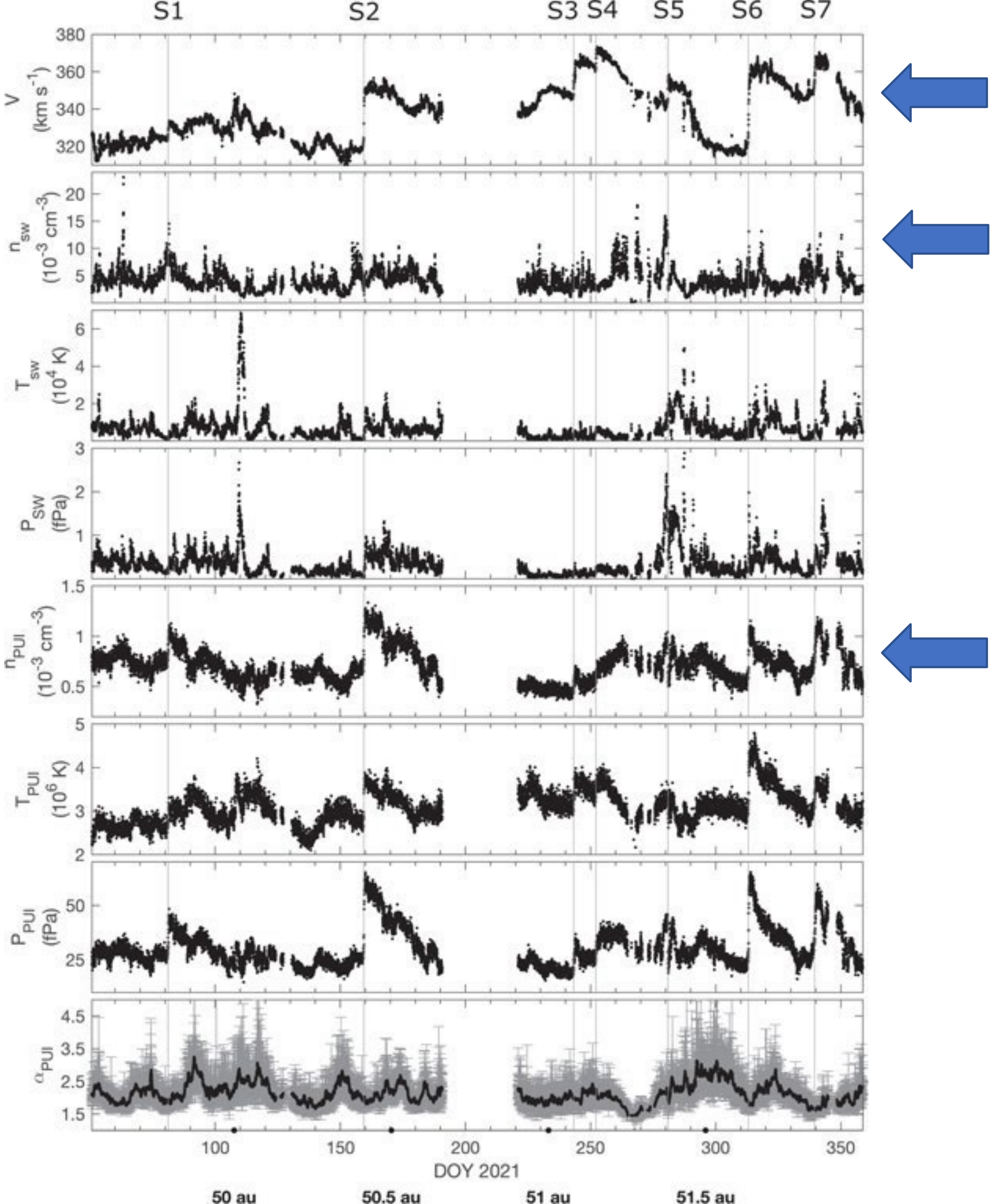




McComas et al. (2021)

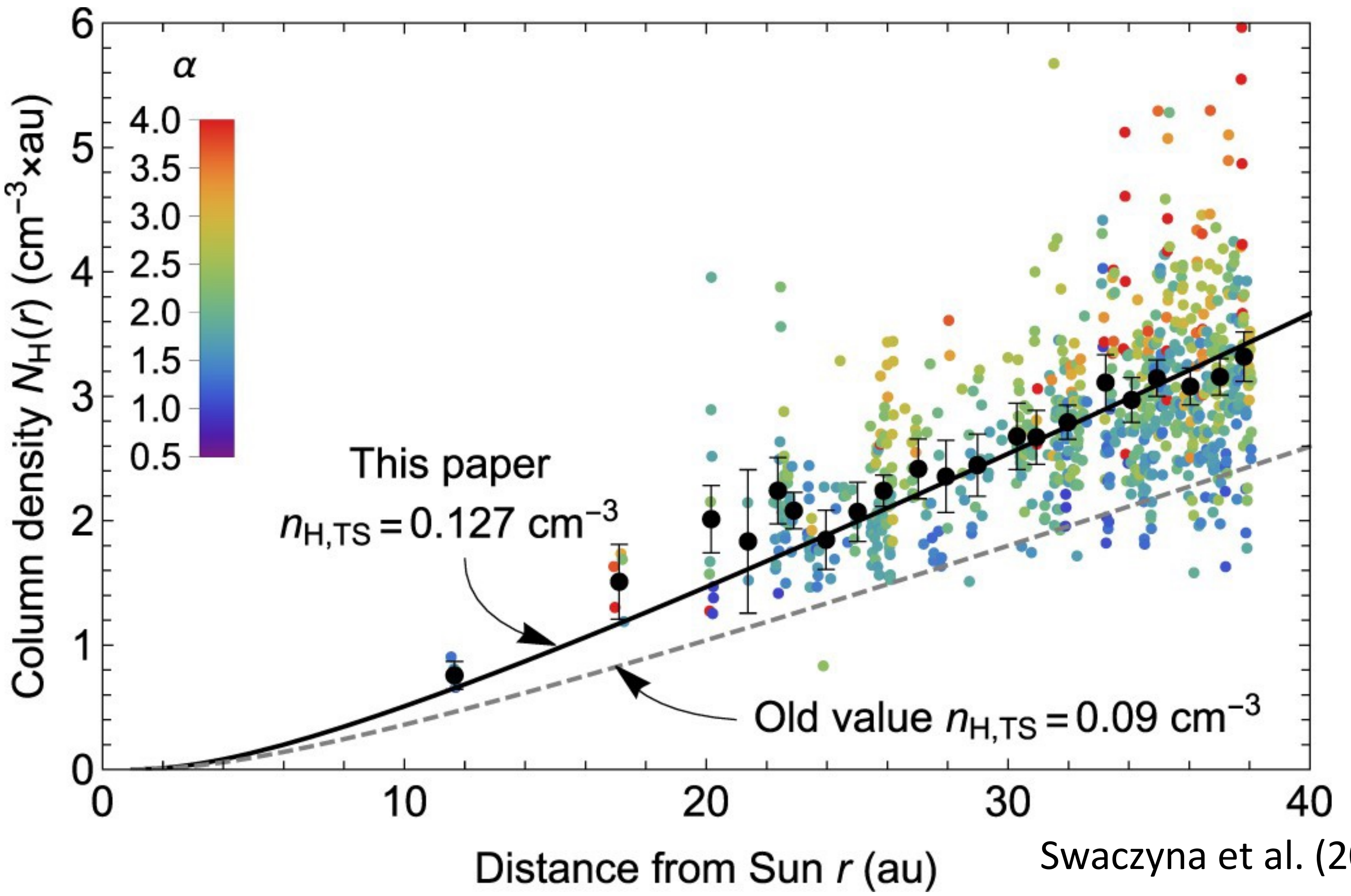
PUI Mediated Shocks

- **<u>Shocks</u> refer to sharp jumps or discontinuities in associated quantities like velocity or density**.
- PUIs are found to be preferentially compressed and heated across the shocks.
- Measurements suggest thermal or "cold" solar wind ions participate little in the large-scale fluid-like interactions of the outer heliosphere.



McComas et al. (2022)

Can Use New Horizons PUI Observations to Infer the Neutral Hydrogen Density at the Termination Shock (and beyond)



Swaczyna et al. (2020)

What is the mean free path of interstellar neutrals through the heliosphere?

Assume charge exchange cross-section of neutral-proton charge exchange in the heliosphere is about 2e-15 cm^2

Assume average proton density in
th

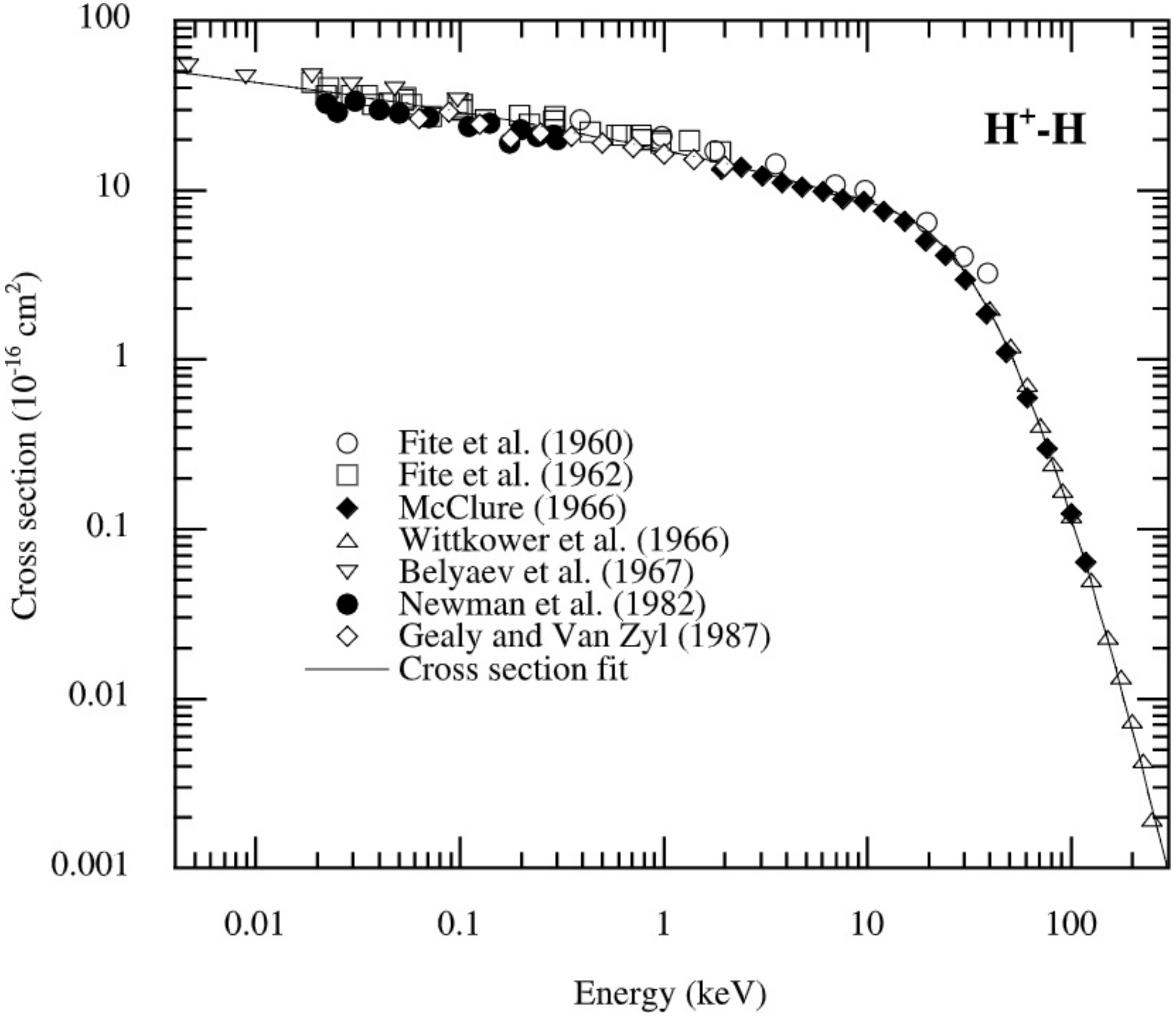
Roughly 3000 au !

1 au = 1.5e13 cm

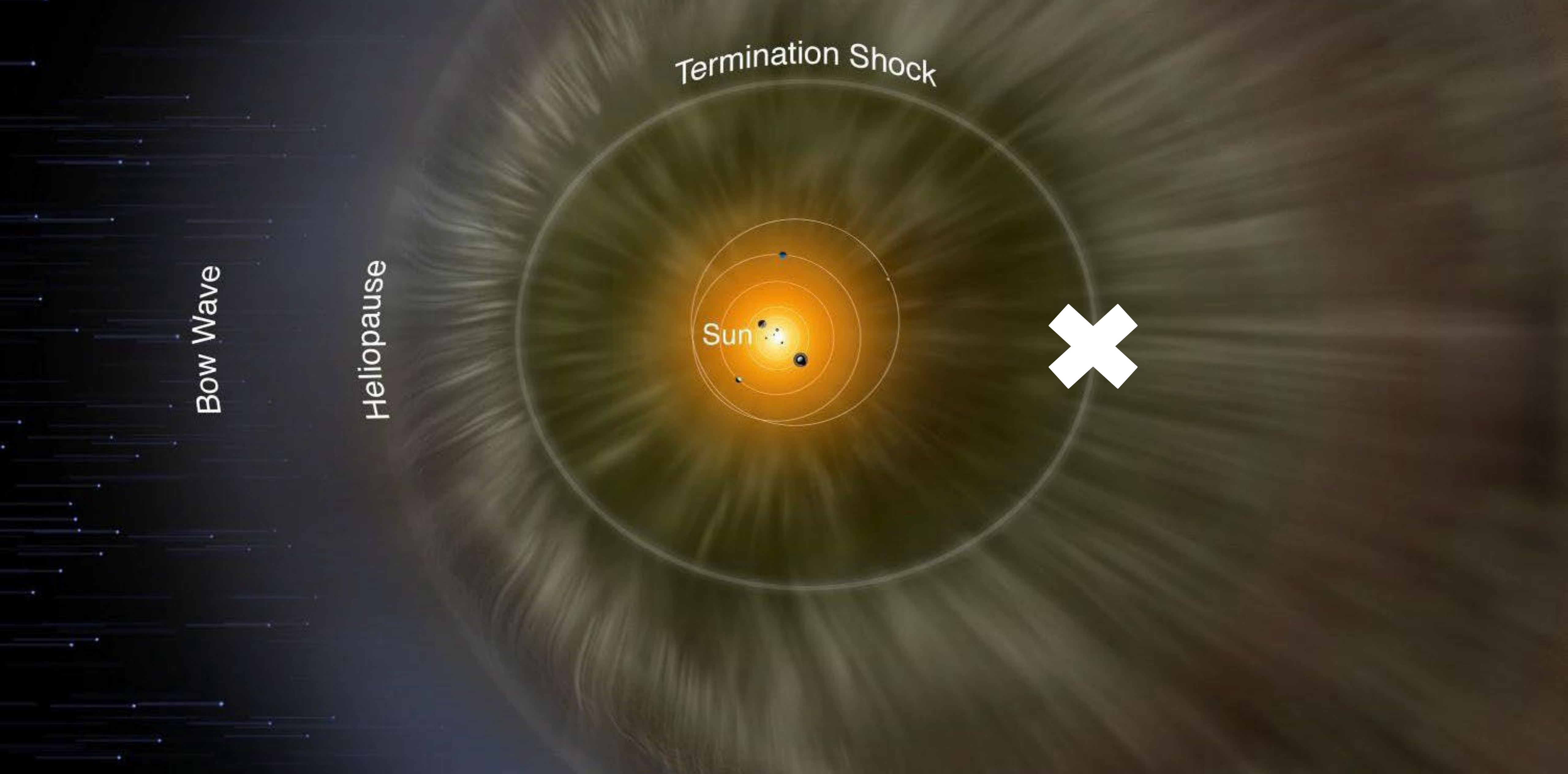
On average, how far will a neutral travel through the heliosphere before charge exchanging?

(Hint: if you do not remember the equation for mean free path, follow the units!)

Lindsay & Stebbings (2005)



The Termination Shock



The Mystery of the Termination Shock

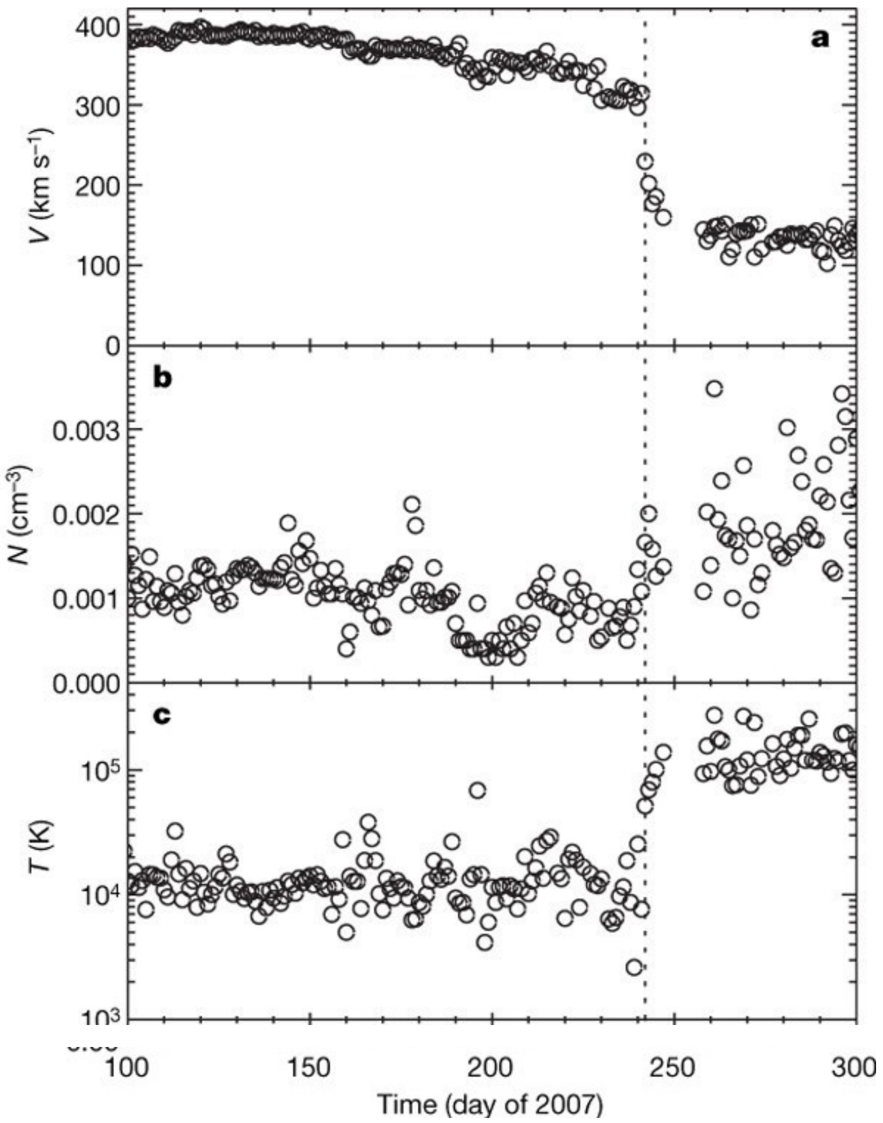
- In crossing the termination shock along Voyager 2, the ram/dynamic pressure of the solar wind plasma is converted to thermal pressure (i.e. pressure due to moving/friction is converted in heat)

- The thermal solar wind ion velocity showed a clear crossing of the termination shock.

- Not all of the pressure was accounted for.

(We will revisit this in the afternoon lab!)

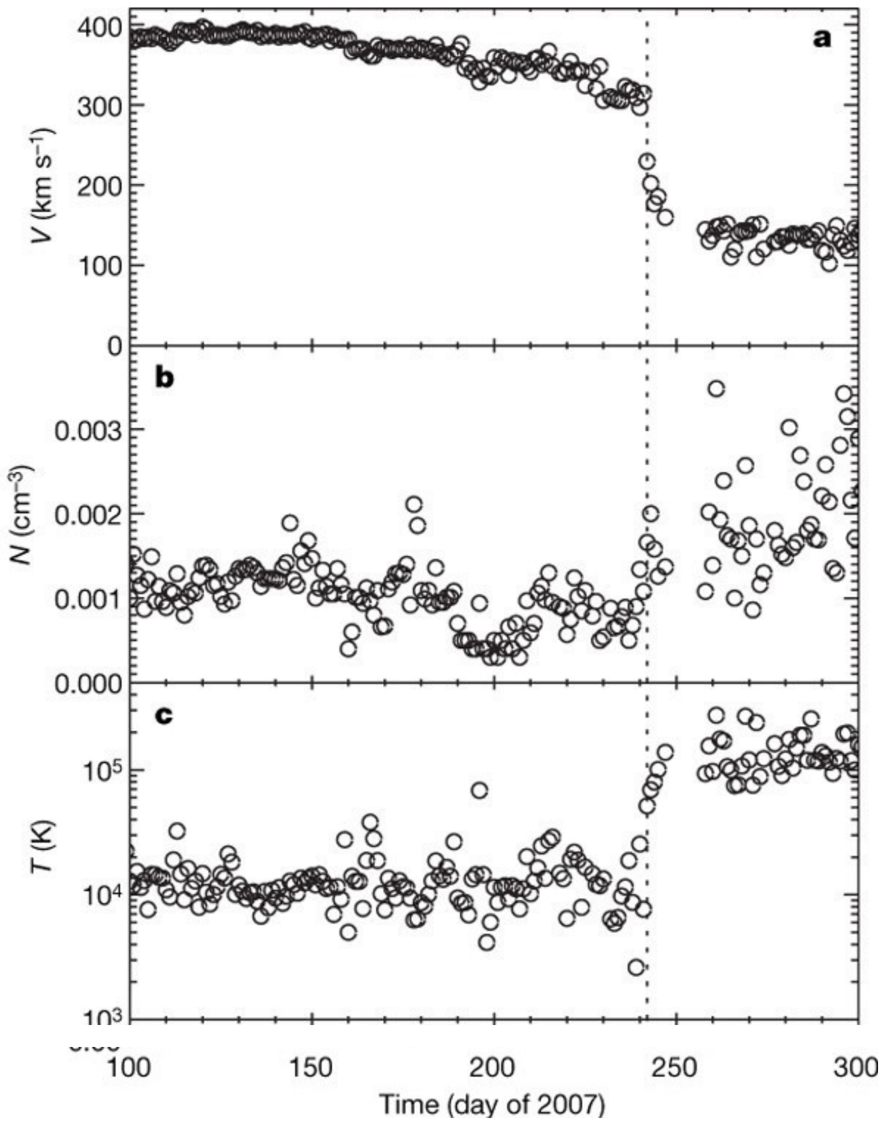
Richardson et al. (2008)



The Mystery of the Termination Shock

- Predictions of the Voyager TS crossing also anticipated a strong shock.
- Compression ratio (γ) = 4
- What Voyager actually observed was a weak shock γ ~ 2

Richardson et al. (2008)

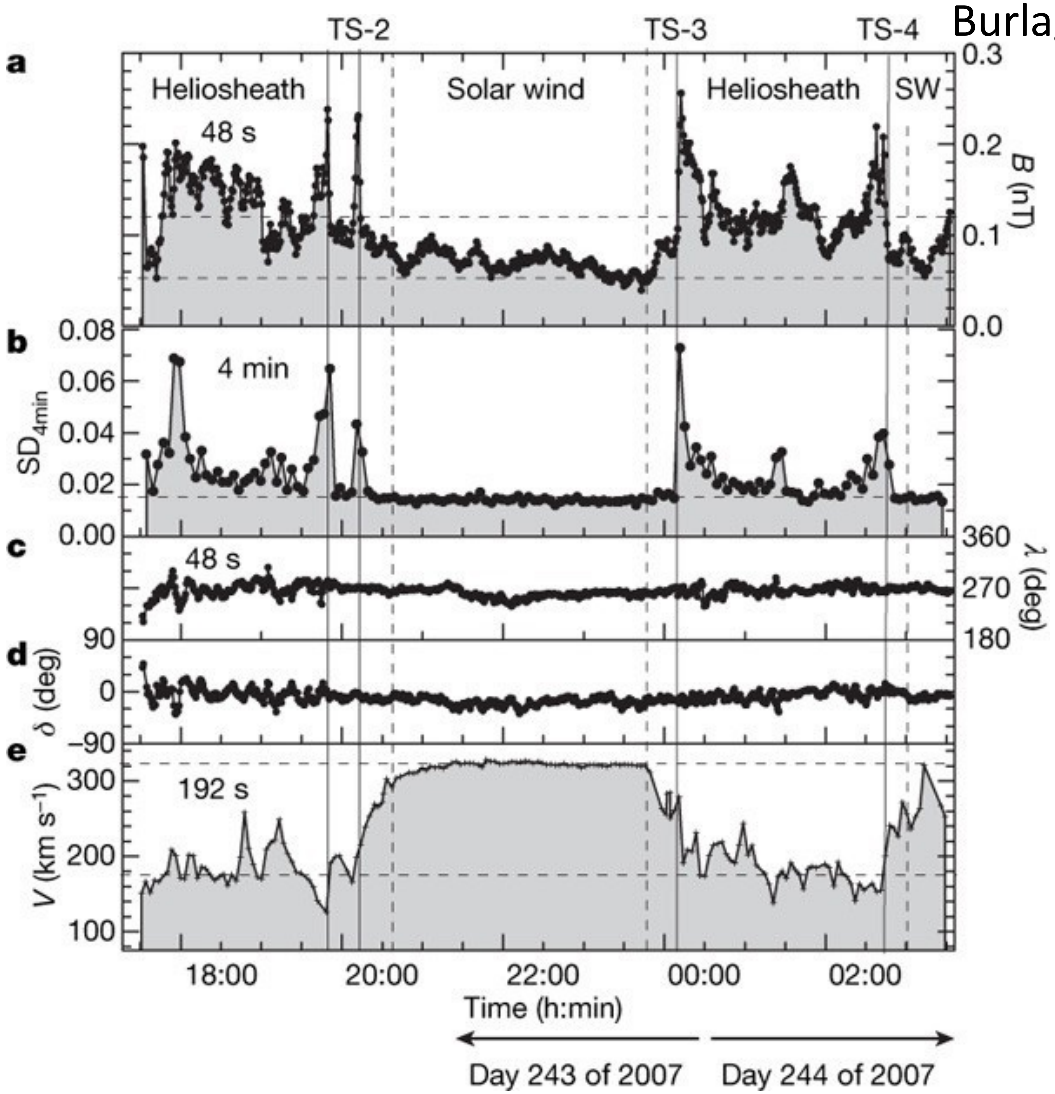


Multiple Crossings of the Termination Shock Observed by Voyager 2

Voyager 2 crossed the termination shock **5 times (!)** before finally remaining in the heliosheath

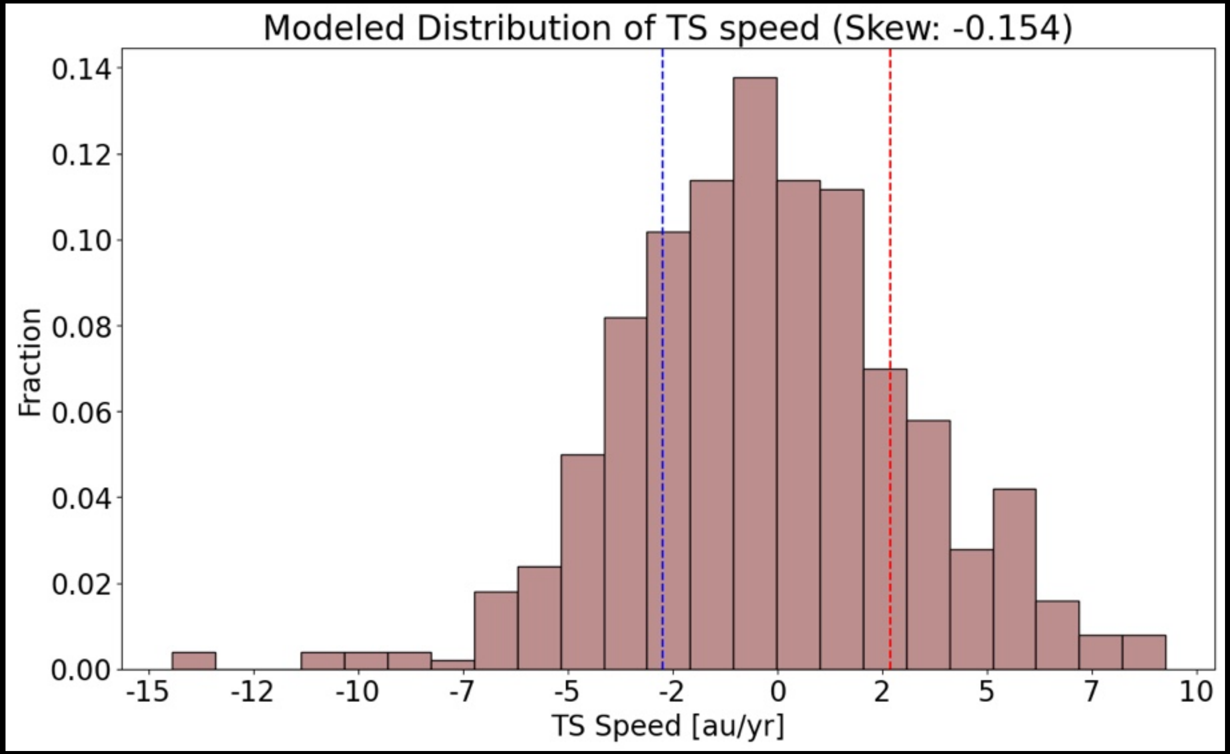
What could cause this?

Burlaga et al. (2008)



Multiple Crossings of the Termination Shock Observed by Voyager 2

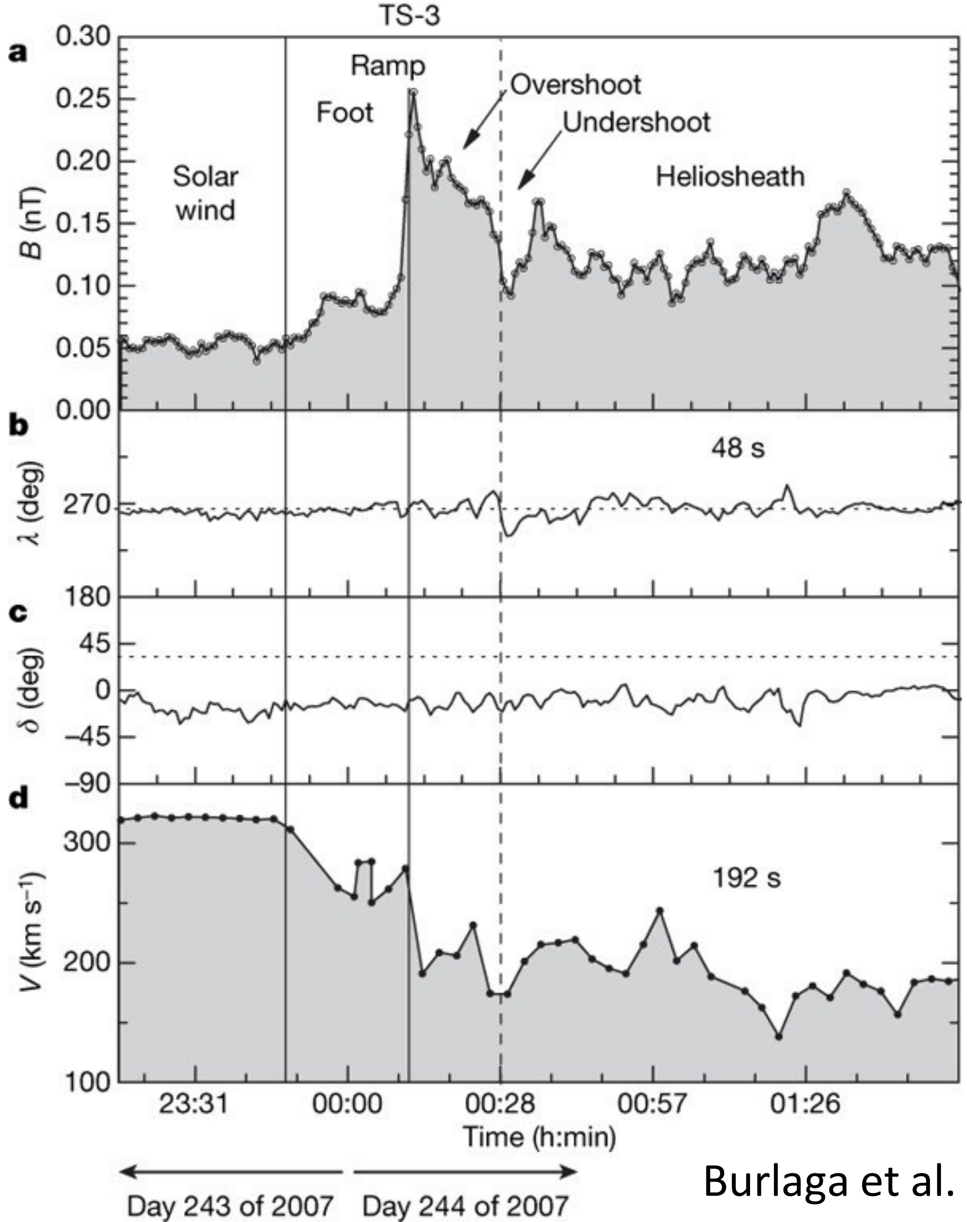
One explanation that could partly explain this is solar-cycle variations.



Variations Across the Termination Shock

See distinct shock structure of the termination shock through Voyager observations

The termination shock has a width, which can act as a source of ion acceleration for particles with insufficient energy to overcome the cross-shock potential

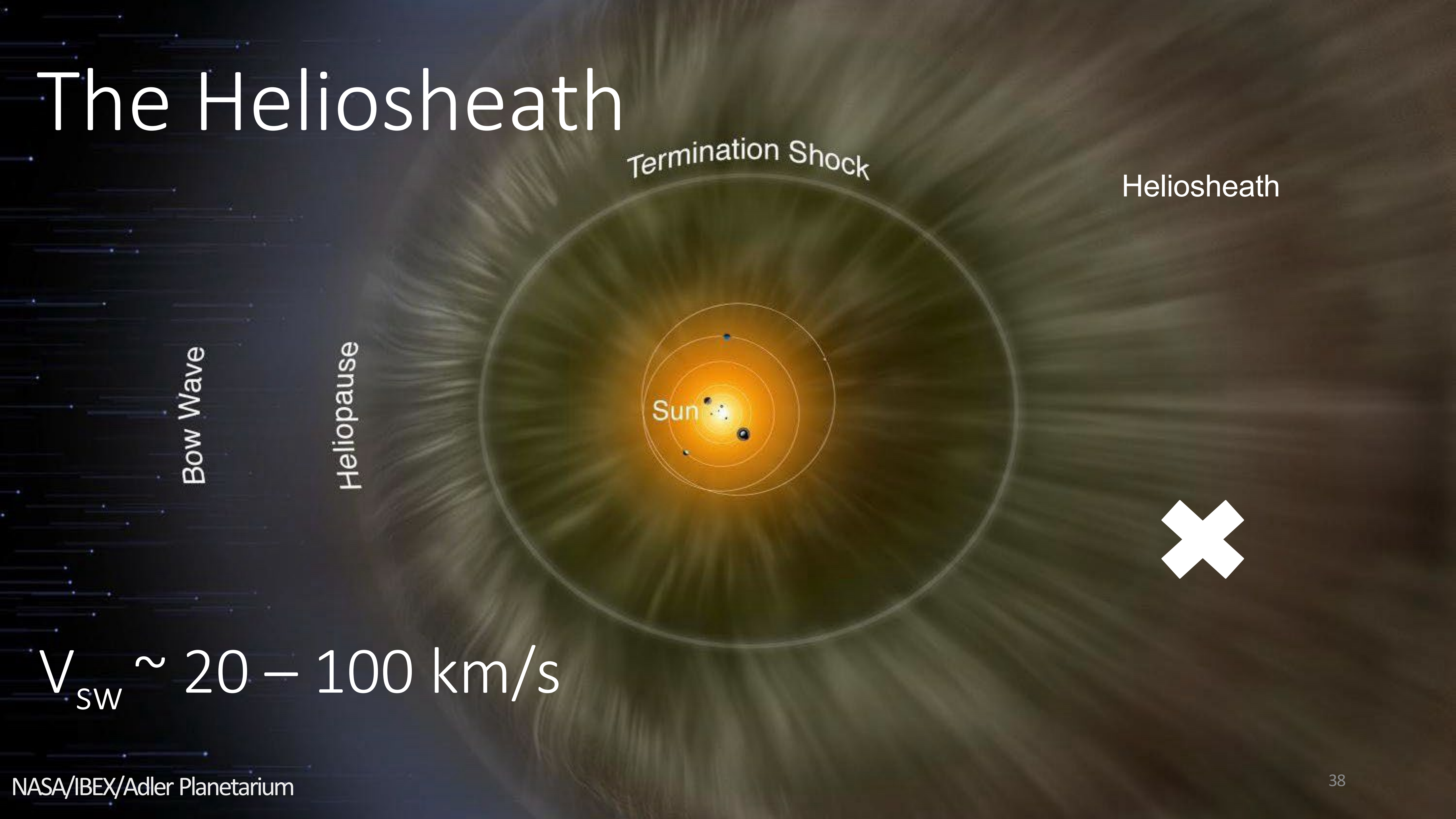


Burlaga et al. (2008)

The Heliosheath

More questions than answers

The Heliosheath



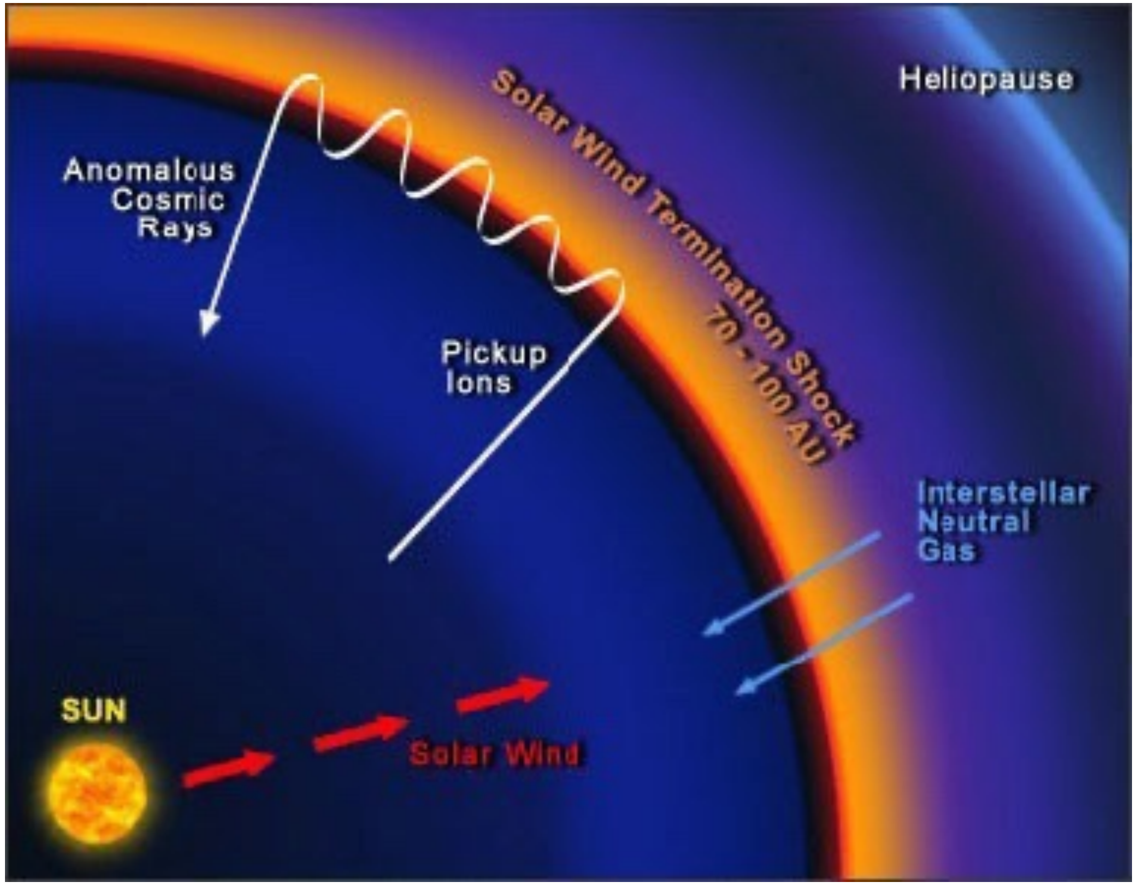
$V_{sw} \sim 20 - 100$ km/s

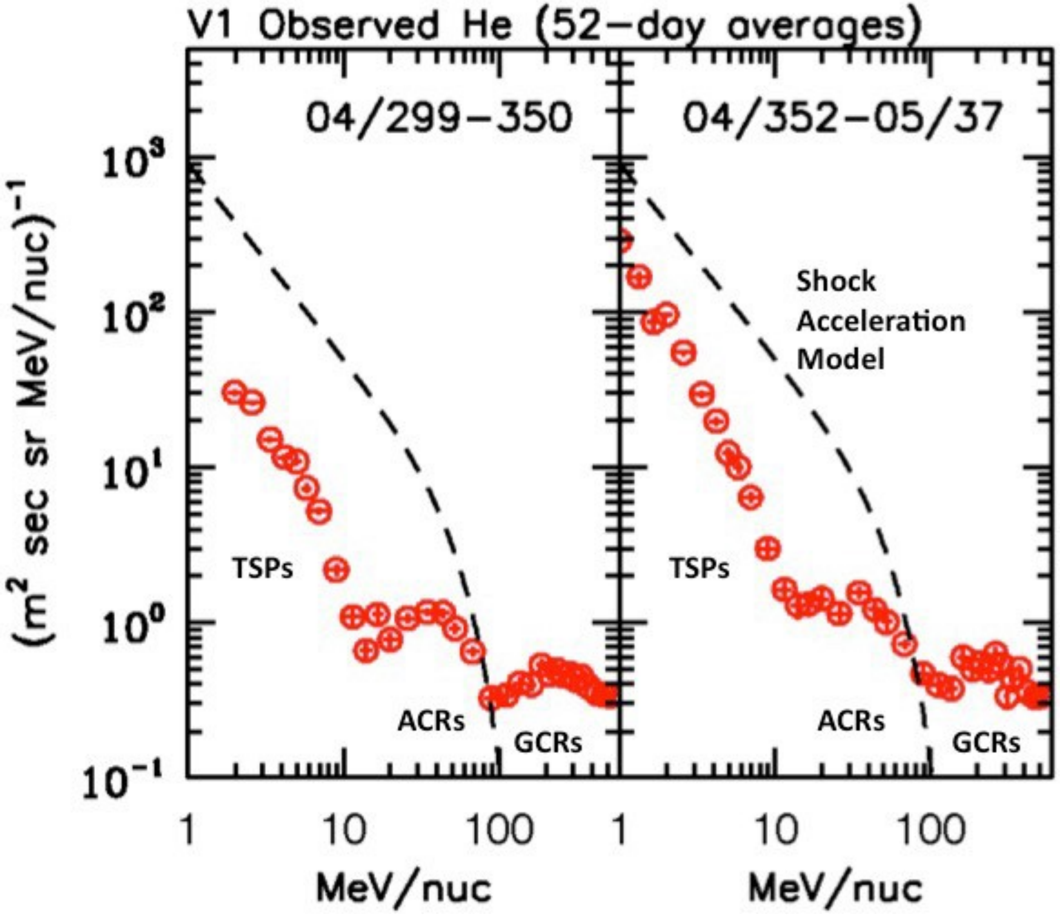
NASA/IBEX/Adler Planetarium

Quick Overview of the Heliosheath

- High beta plasma (thermal pressure dominates)
- Flow speeds around 100 km/s
- PUI temperature around 1e7 K
- Thermal solar wind ion temperature around 1e5 K
- Plasma density on order of 1e-3 cm^{-3}

Anomalous Cosmic Rays are Supposedly Accelerated at the Termination Shock – Are They?



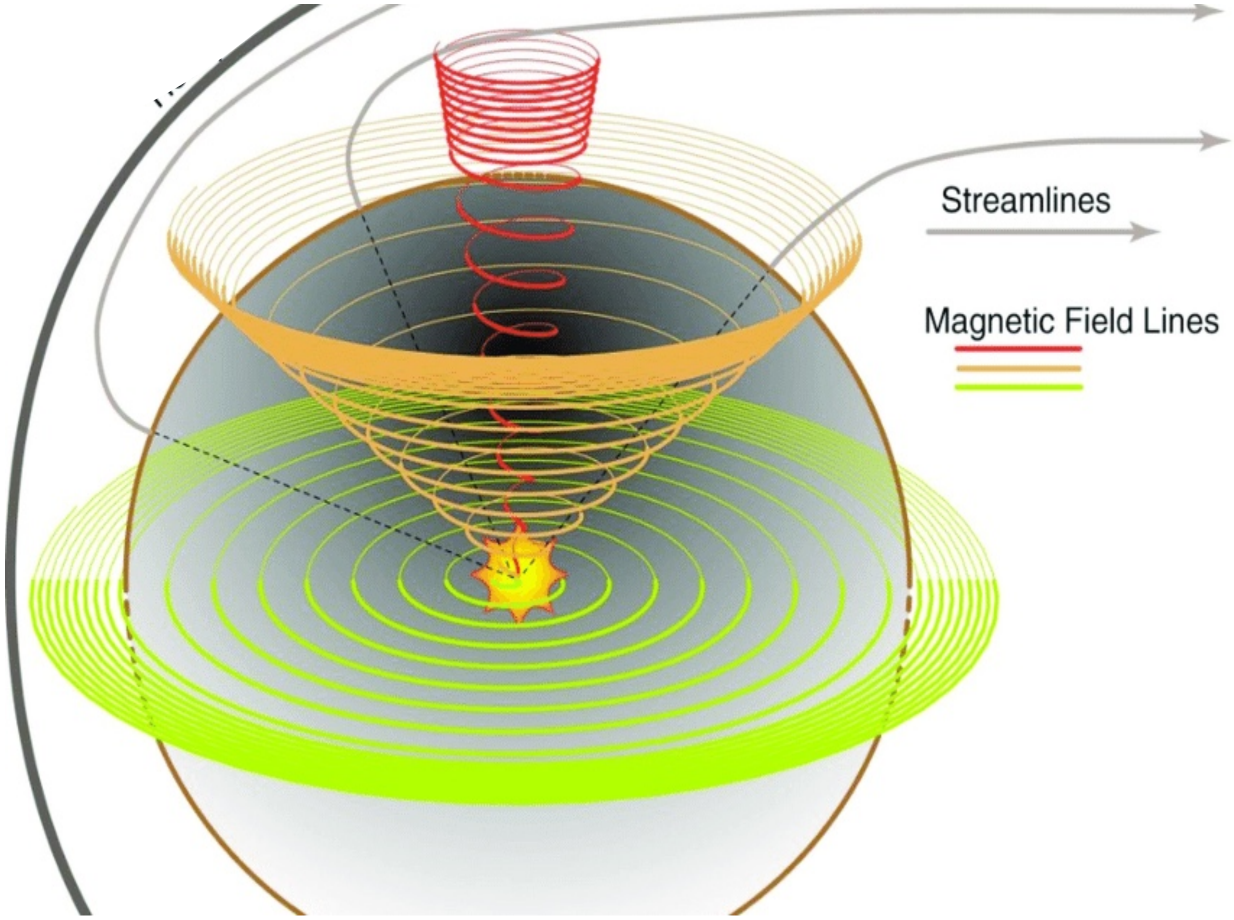


Role of the Solar Magnetic Field in the Heliosheath

- In the heliosheath, the solar magnetic field becomes tightly compressed in line with the solar wind (frozen-in property).

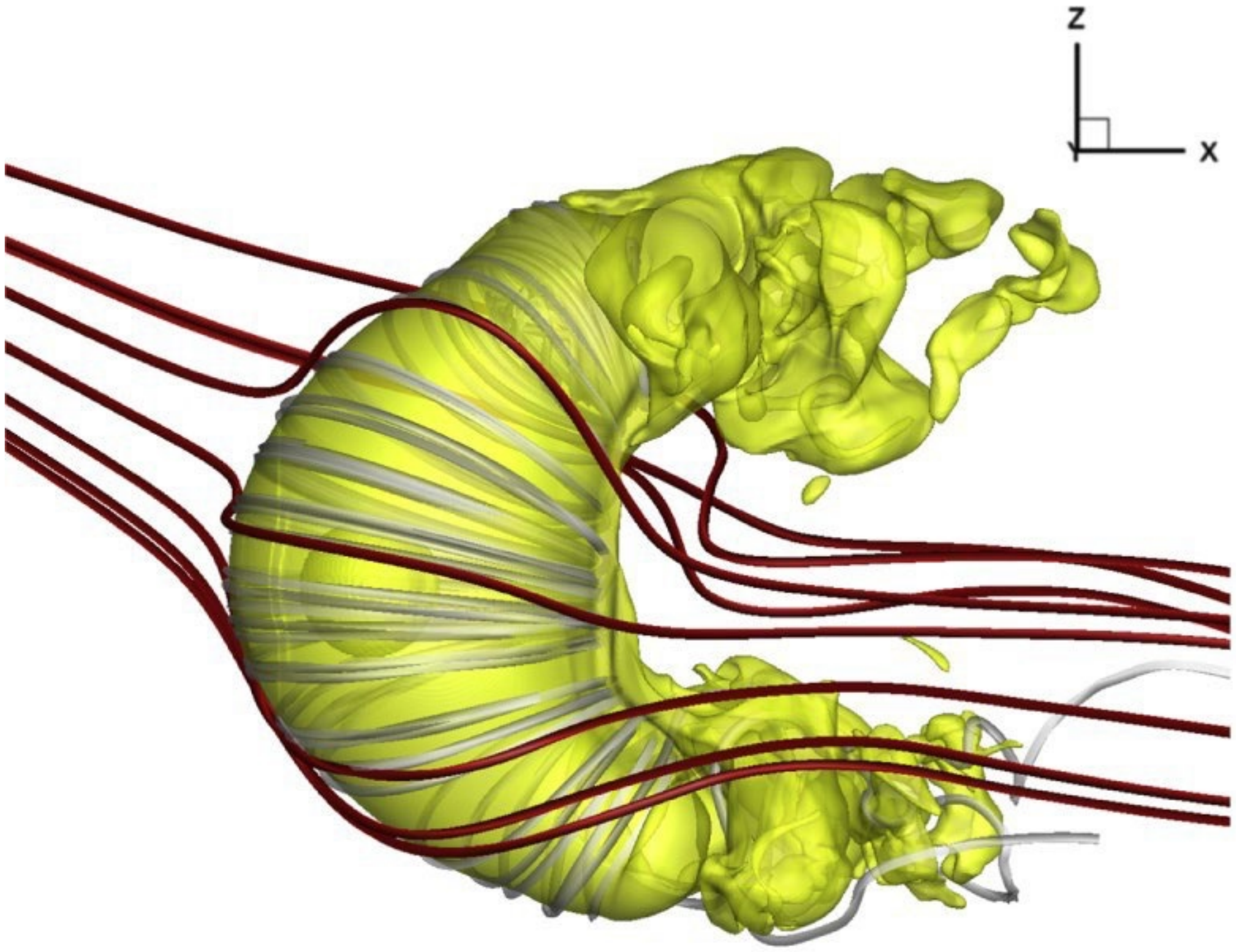
- Magnetic flux increases, and overall magnetic field strength is higher.

- The magnetic field has a higher tension, or resistance to stetching!



Role of the Solar Magnetic Field in the Heliosheath

- Magnetic field in the heliosheath is dominant enough to collimate the plasma into lobes.
- “Croissant” heliosphere structure in the heliotail!

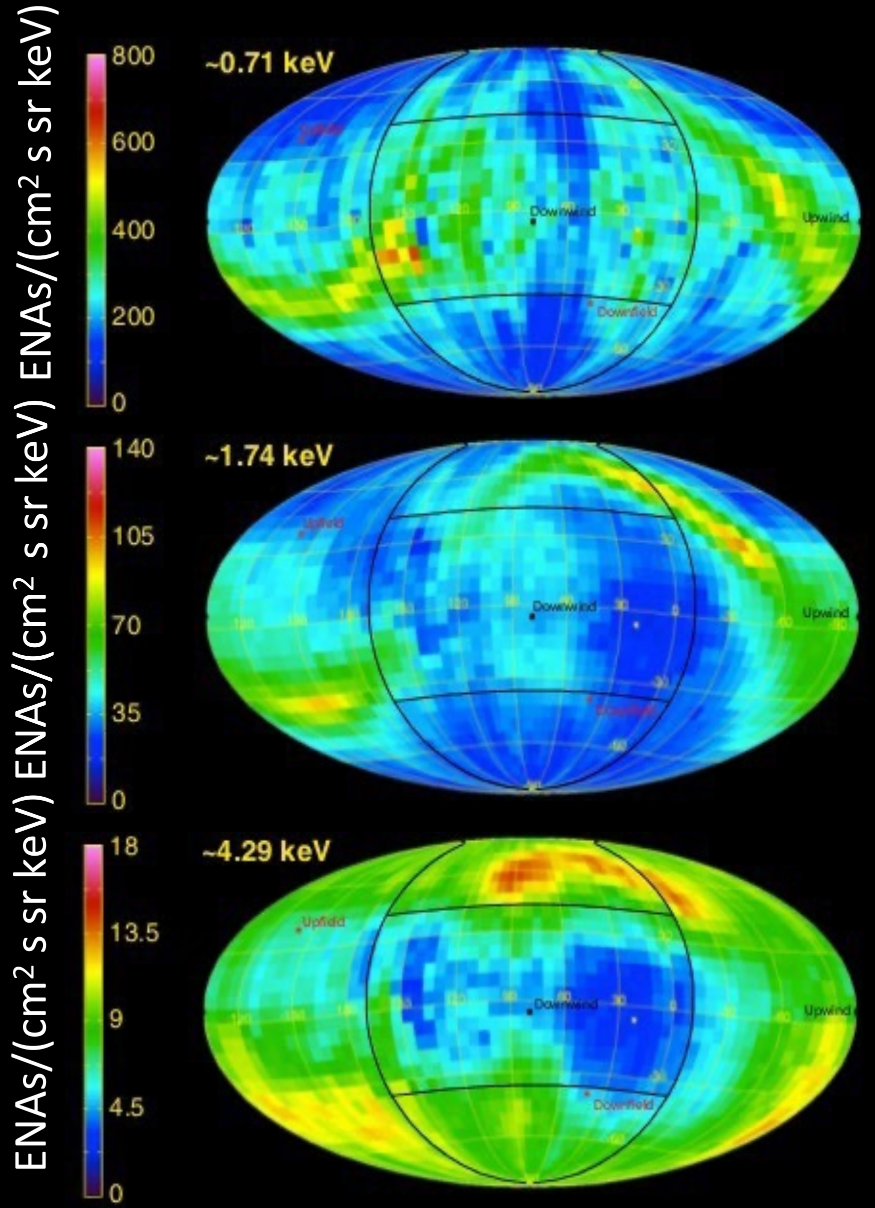


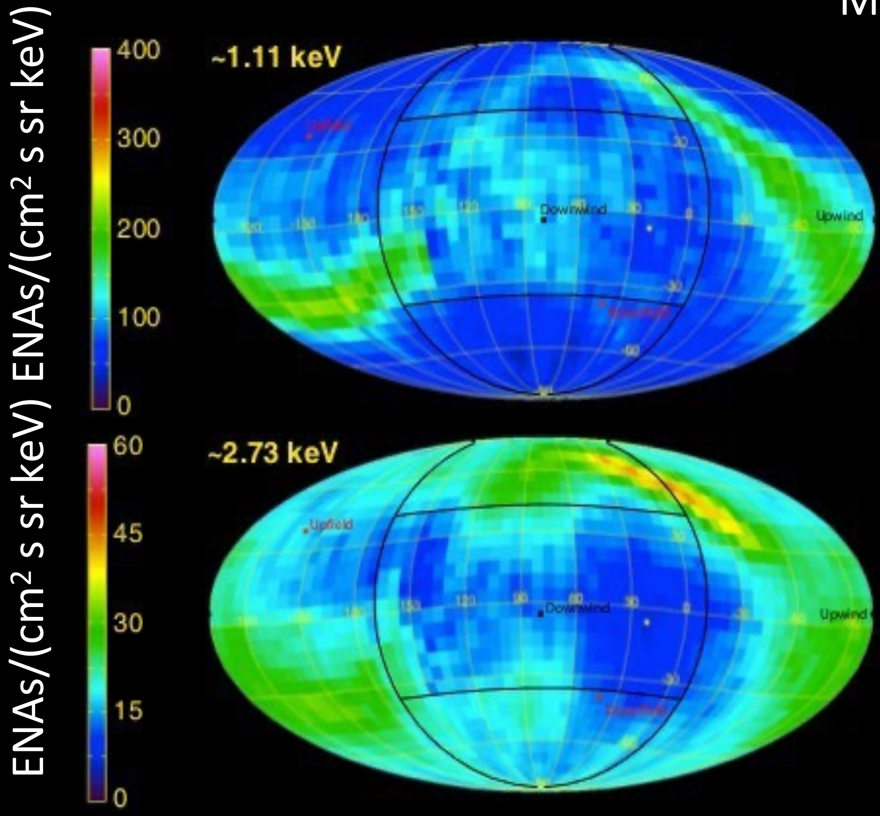
(a)

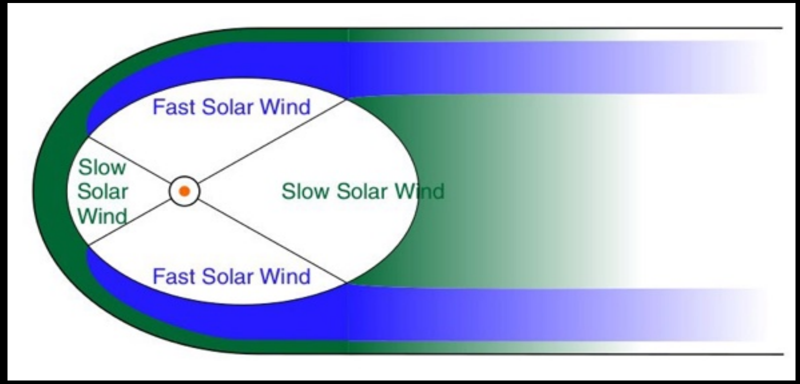
Opher et al. (2015)

Also in the Heliotail, IBEX Observations

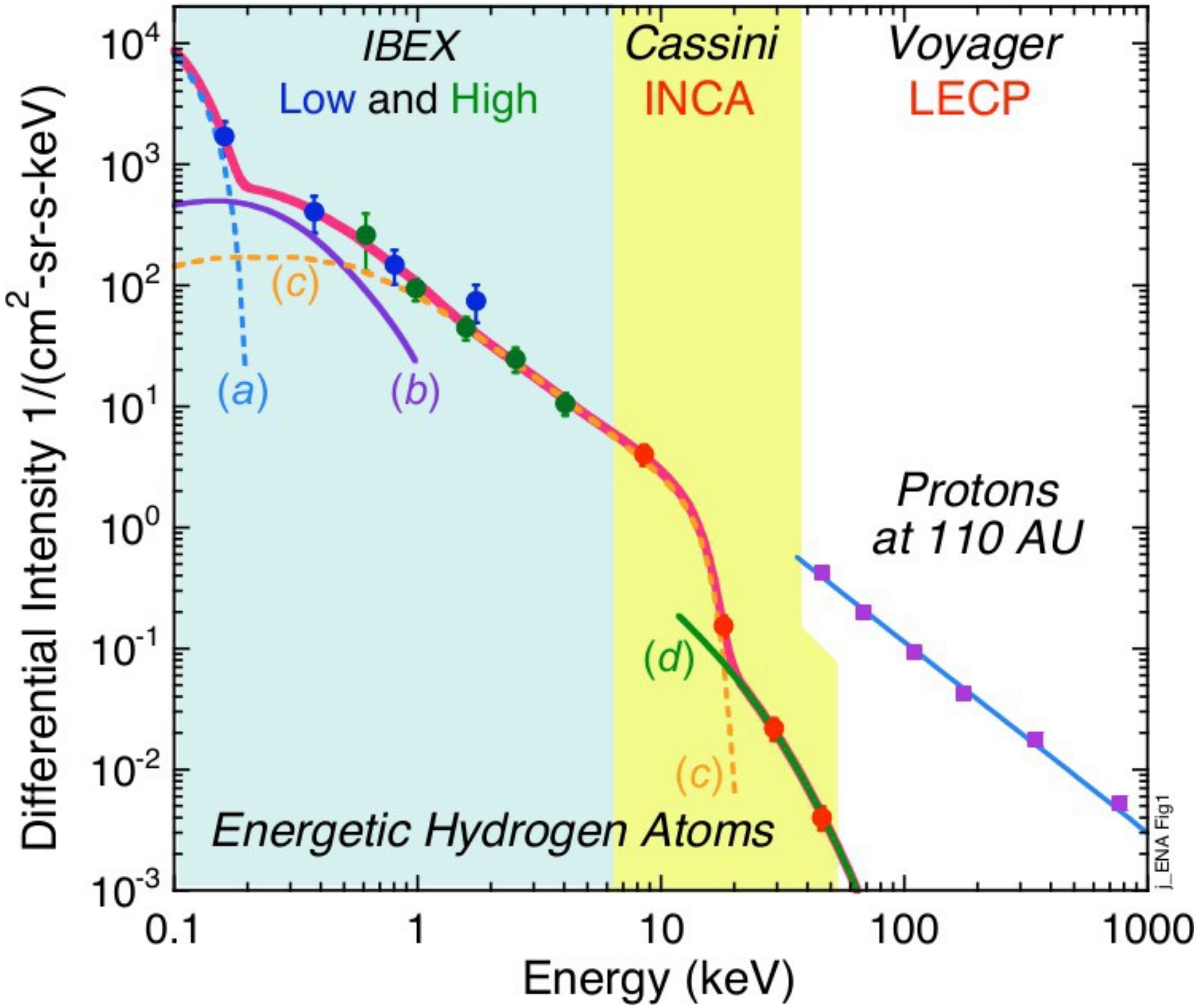
McComas et al. (2013)







Ions in the Heliosheath



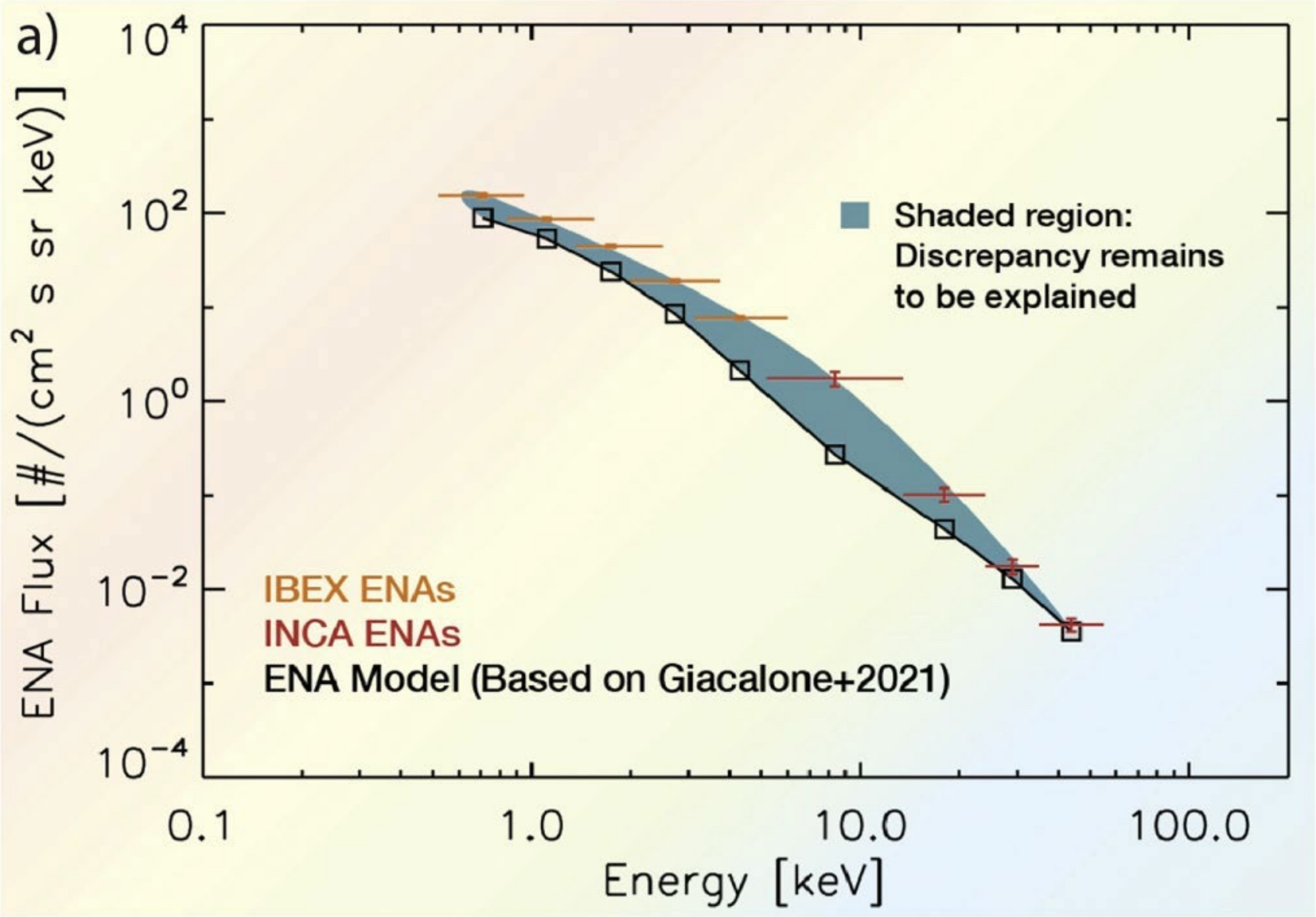
Gloeckler & Fisk (2010)

- Different ion populations contribute to different ENA energies
- PUIs accelerated at the termination shock are an important source of ENAs in the heliosheath

Acceleration in the HS

Comparing ENA models that only utilize PUI acceleration at the termination shock to ENA observations show a distinct, energy-dependent gap

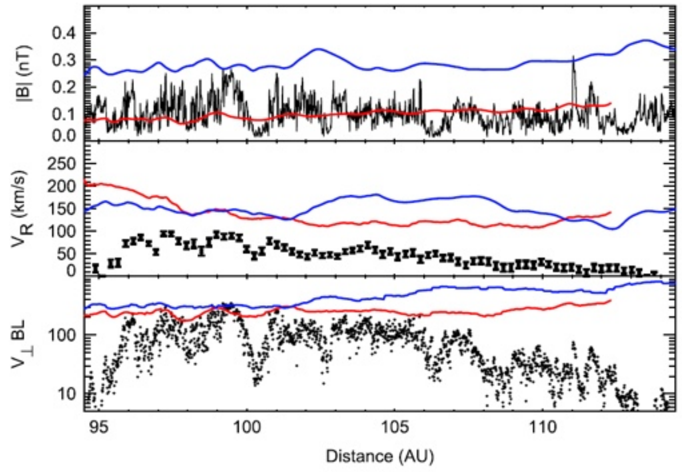
Lack of quantitative agreement between models and observations indicate PUI acceleration is occurring in the heliosheath! (Turbulence, reconnection, it is still an open question)



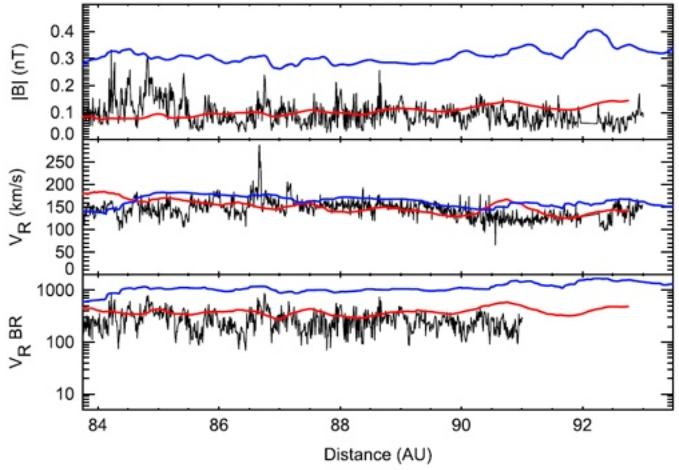
Gkioulidou et al. (2022)

Non-Conservation of Magnetic Flux

- The magnetic flux was observed to be non-conserved in the heliosheath.
- Non-ideal magnetohydrodynamic (MHD) effects? (Dissipation, reconnection, solar-cycle variations).
- Challenge for models to reproduce the decrease in the magnetic field in the far heliosheath.



V1

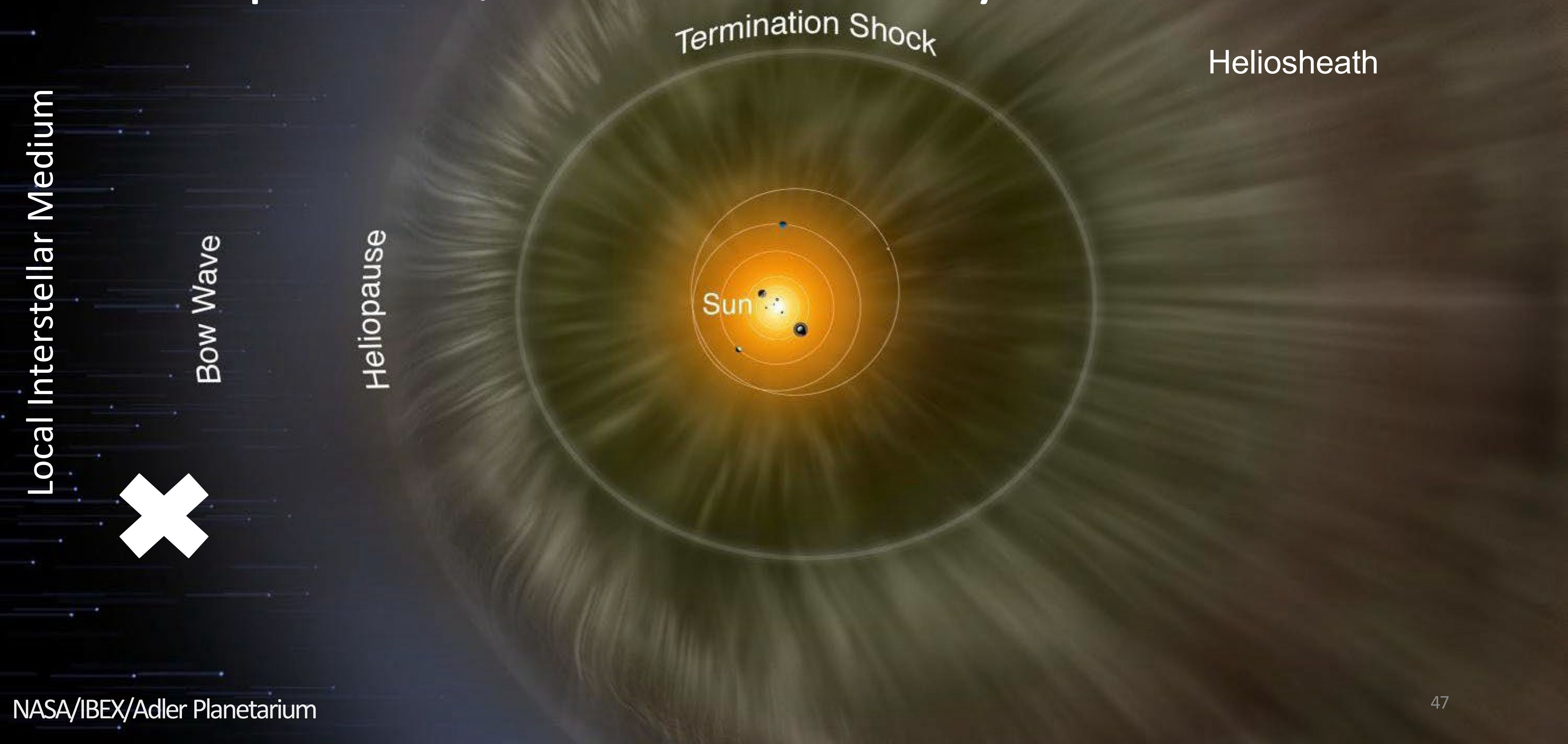


V2

Another mystery!

Michael et al. 2015

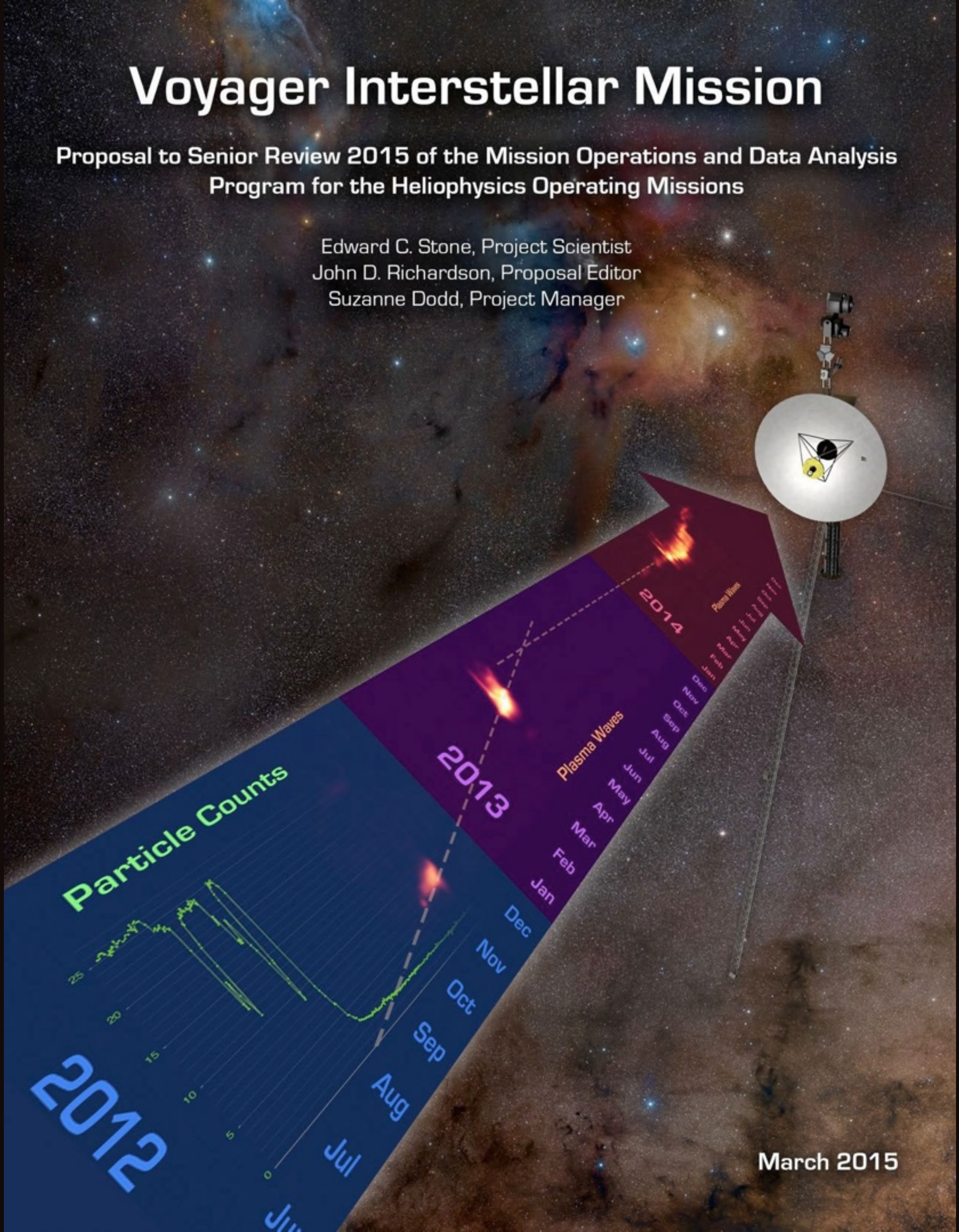
Heliopause, ISM and Beyond!



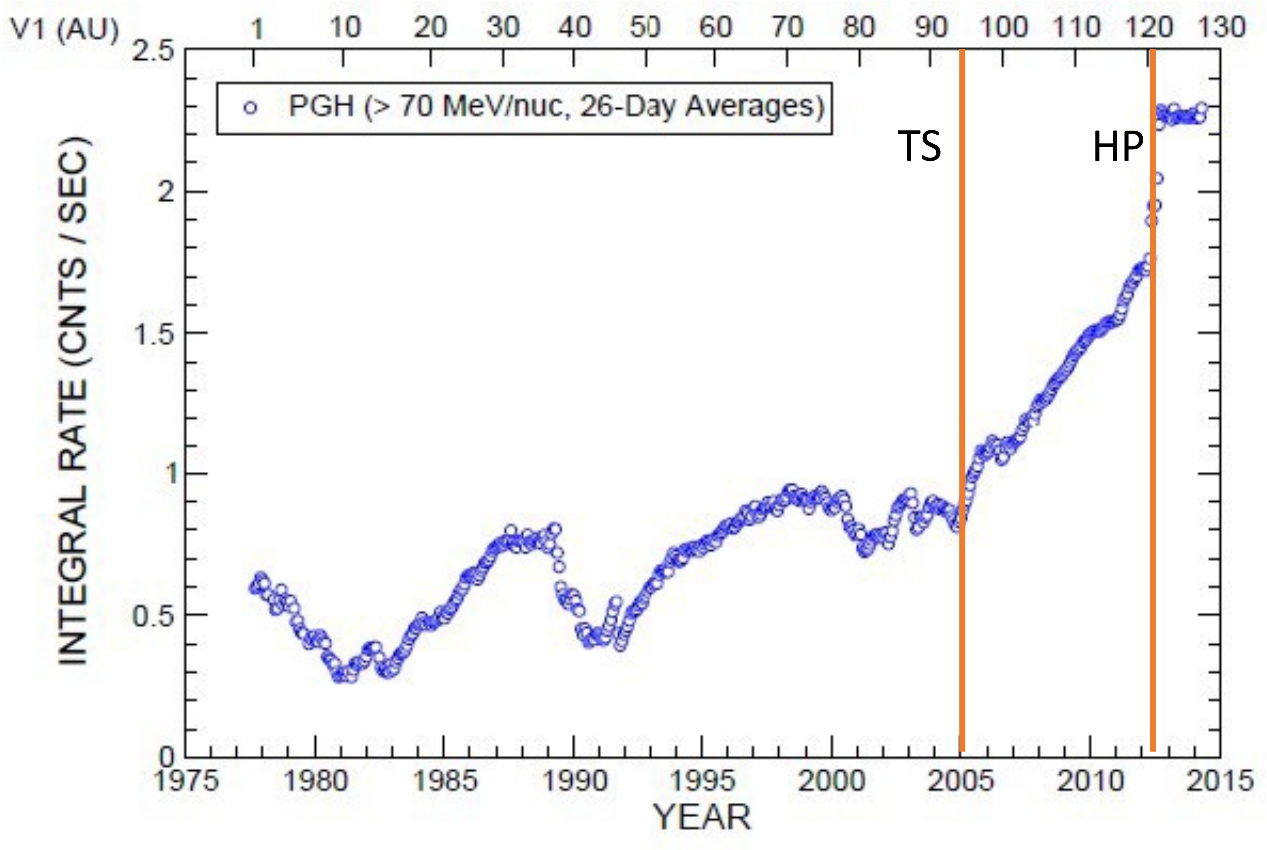
NASA/IBEX/Adler Planetarium

Quick Overview of the Interstellar Medium

- Much cooler than heliospheric plasma (pristine temperature about 6530 K)
- Much denser than heliospheric plasma (pristine ISM density about 0.06 cm^{-3})
- Much slower than heliospheric plasma (pristine ISM speed about 26.3 km/s)


Voyager Interstellar Mission
Proposal to Senior Review 2015 of the Mission Operations and Data Analysis
Program for the Heliophysics Operating Missions
Edward C. Stone, Project Scientist
John D. Richardson, Proposal Editor
Suzanne Dodd, Project Manager
Particle Counts
2012
Jul
Aug
Sep
Oct
Nov
Dec
2013
Plasma Waves
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
2014
March 2015

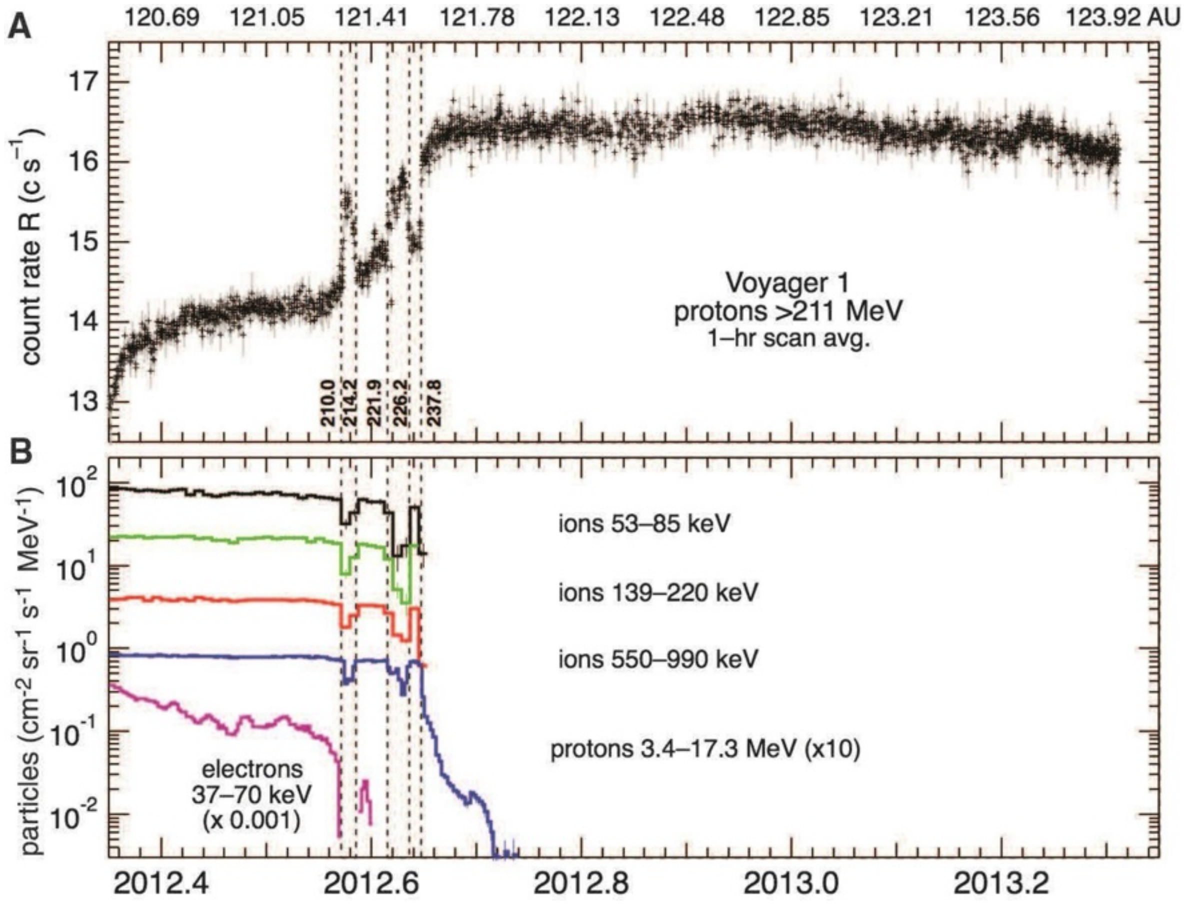
Most of the Galactic Cosmic Rays(about 75%) are Filtered in the Heliosheath



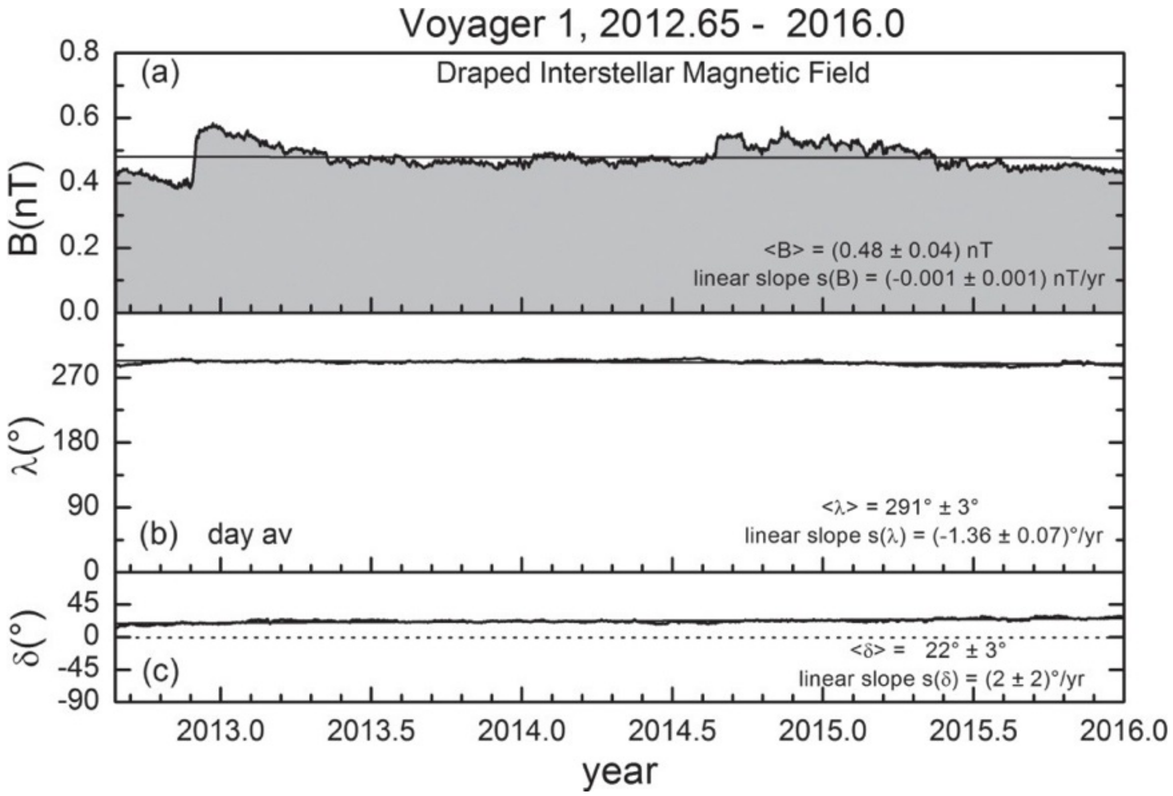
Courtesy of Ed Stone

- The heliopause (at least in the upwind direction) is a tangential discontinuity that delineates the solar wind from the interstellar medium

Confusion When Voyager 1 Crossed the Heliopause – what happened to the magnetic field measurements?

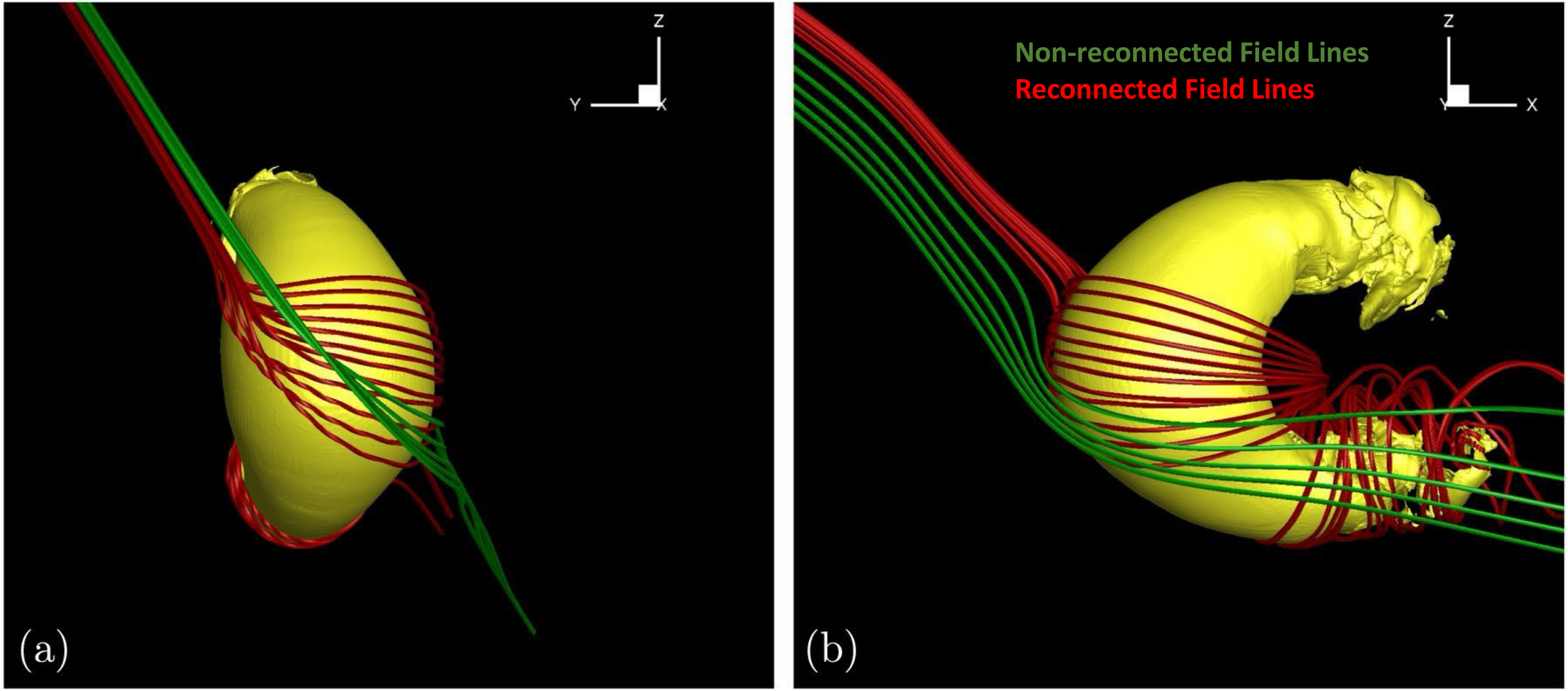


The magnetic field did not rotate!!!



Interstellar Magnetic Field Lines Reconnect with Solar Field Lines at the Heliopause

Opher et al. (2017)



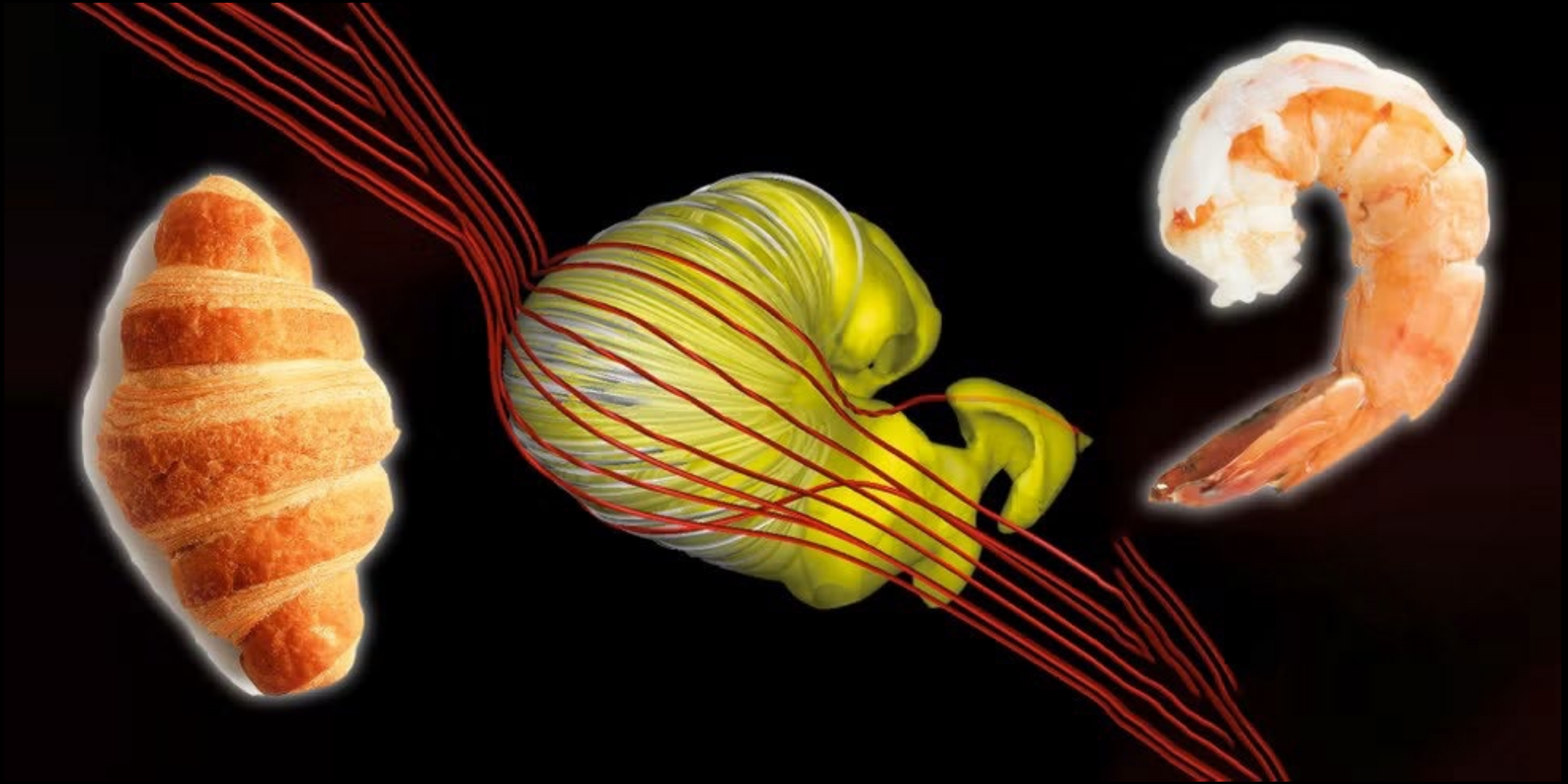
Solar Magnetic Field Persist into the ISM?

- Some ideas proposed that reconnection at the flanks of the heliosphere, along with solar cycle variation, will encourage solar magnetic field to continue propagating past the heliopause.

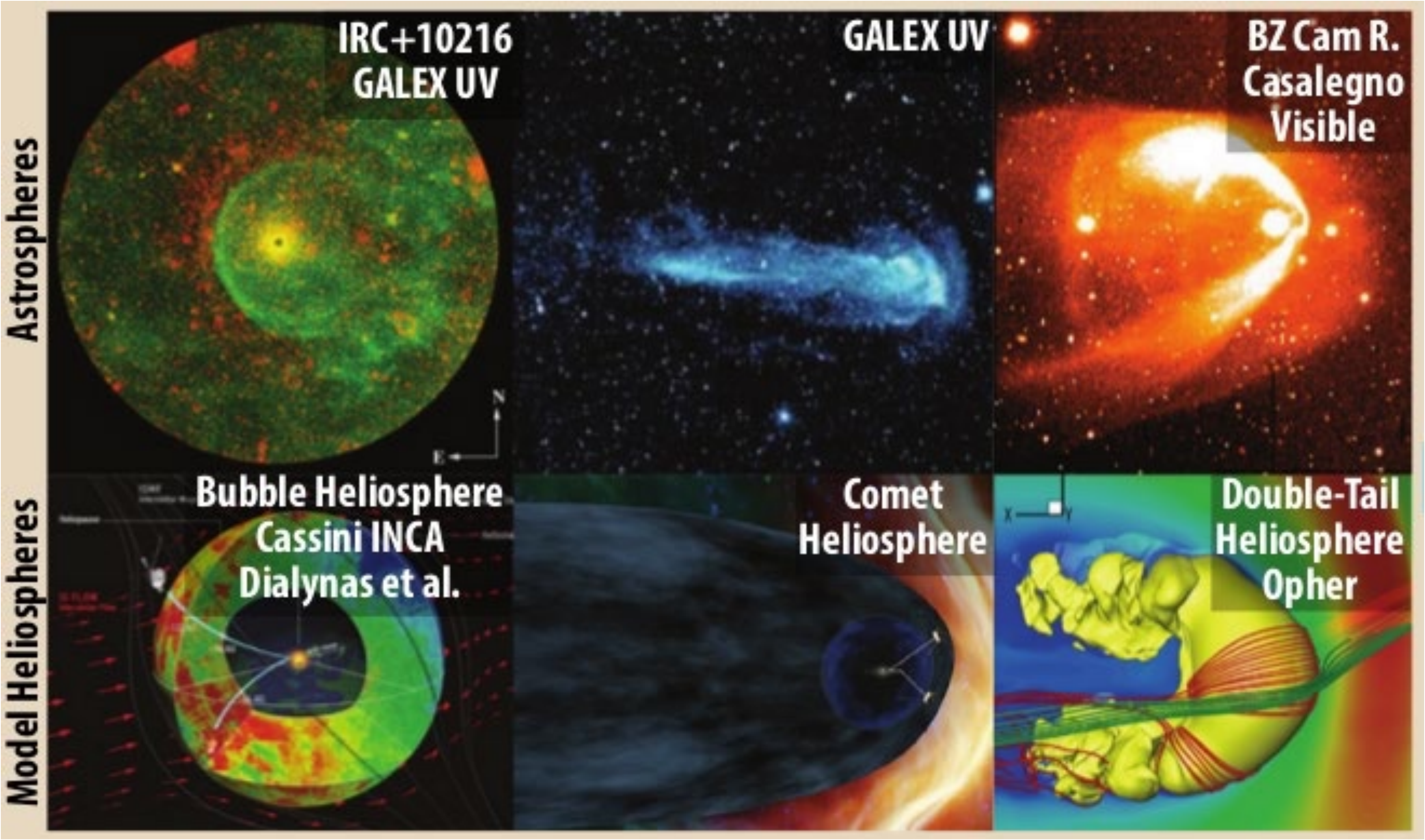
Open questions of the (outer) heliosphere

Only a select few of many!

What is the shape of the heliosphere?



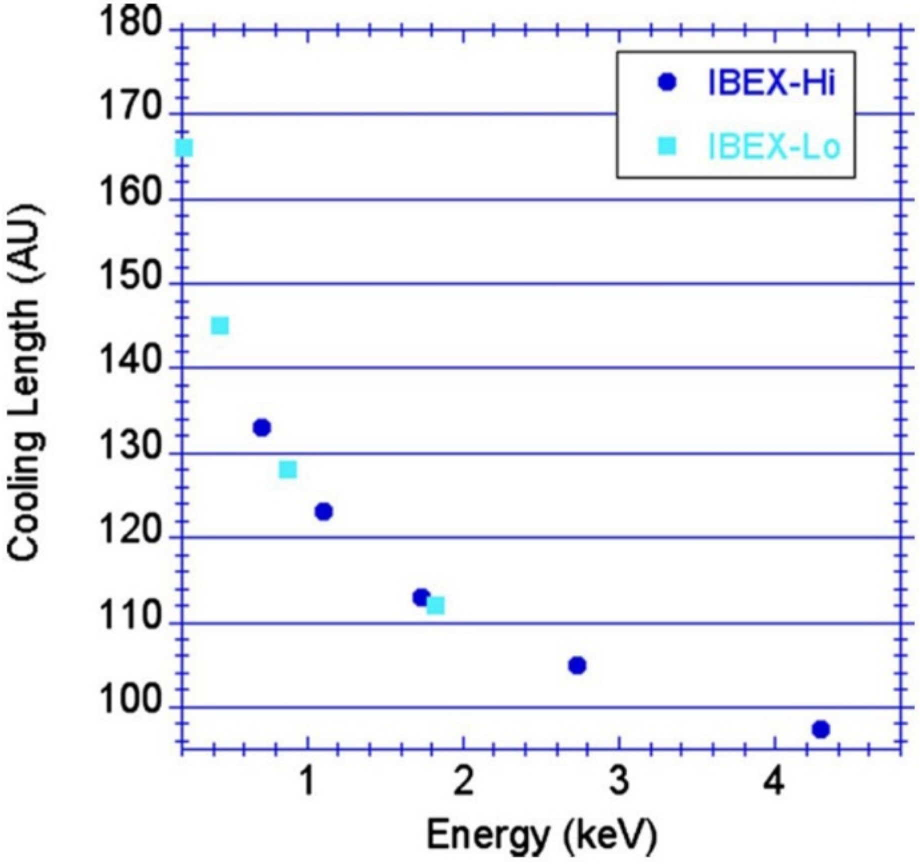
Different Views of the Heliosphere



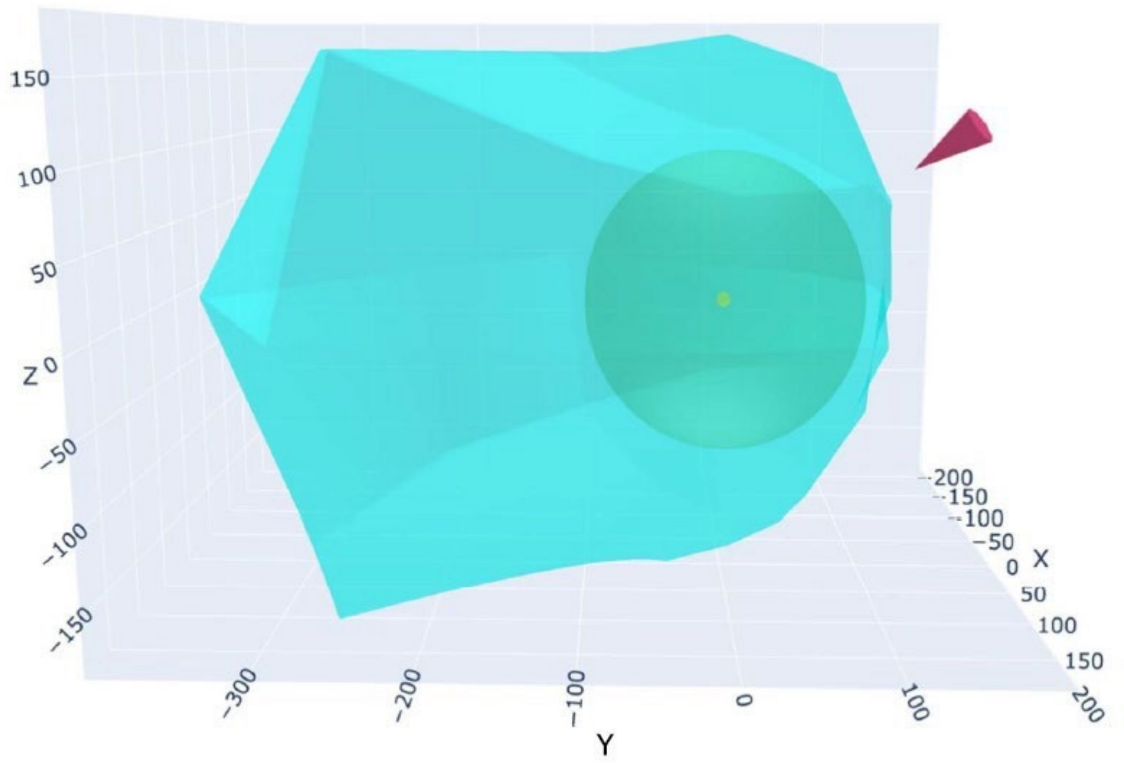
SHIELD

IBEX-Hi Observational Limitations

Previous studies have shown that extinction of PUIs in the heliosphere limits how far the heliotail can be probed to approximately 300 AU, yet ***this is the first work to definitively compare a short-tail and long-tail heliosphere at IBEX-Hi energies*** *to determine if the heliopause distance or effects from changes in the heliosheath flow are distinguishable via ENAs*

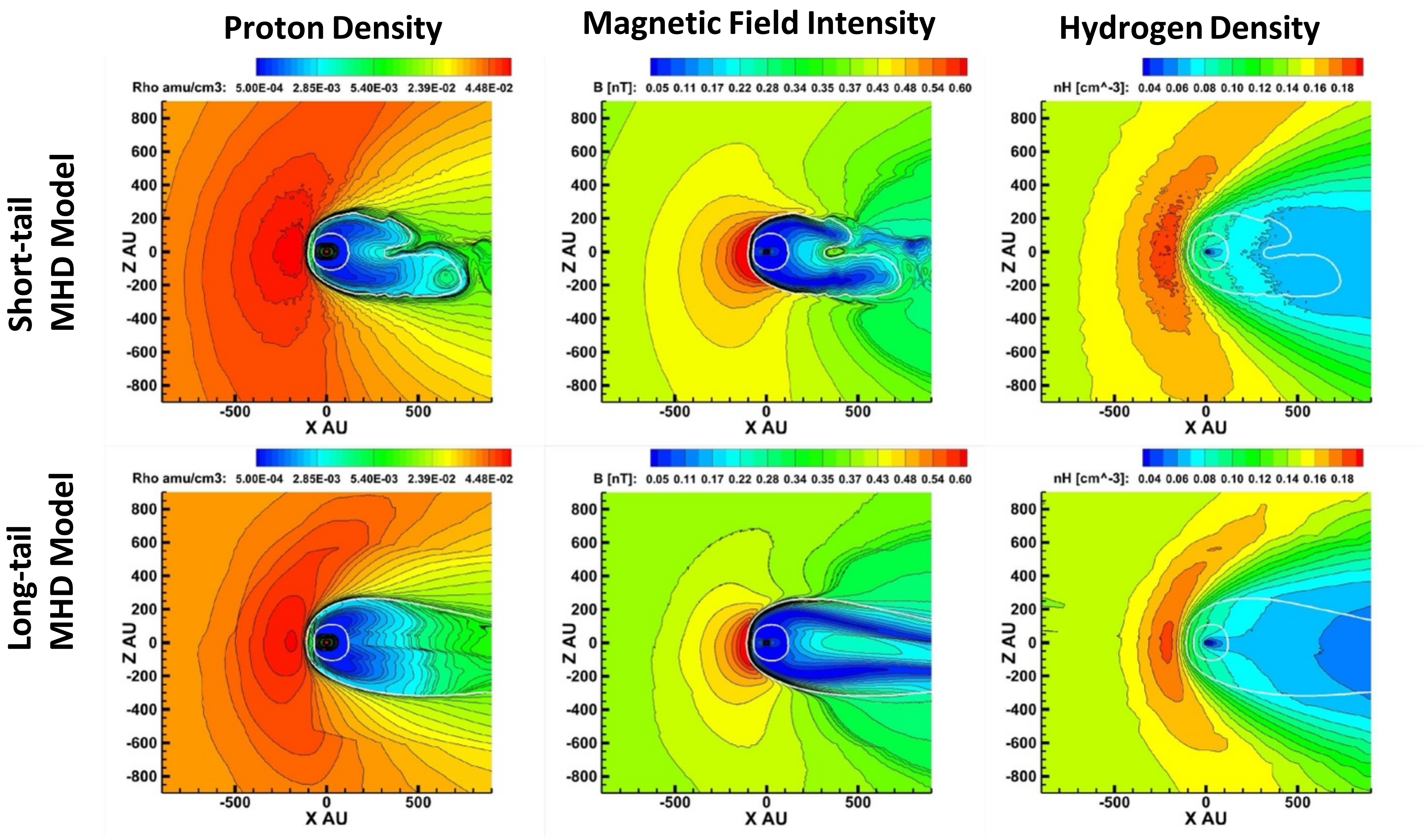


Schwadron et al. (2014)



Reisenfeld et al. (2021)

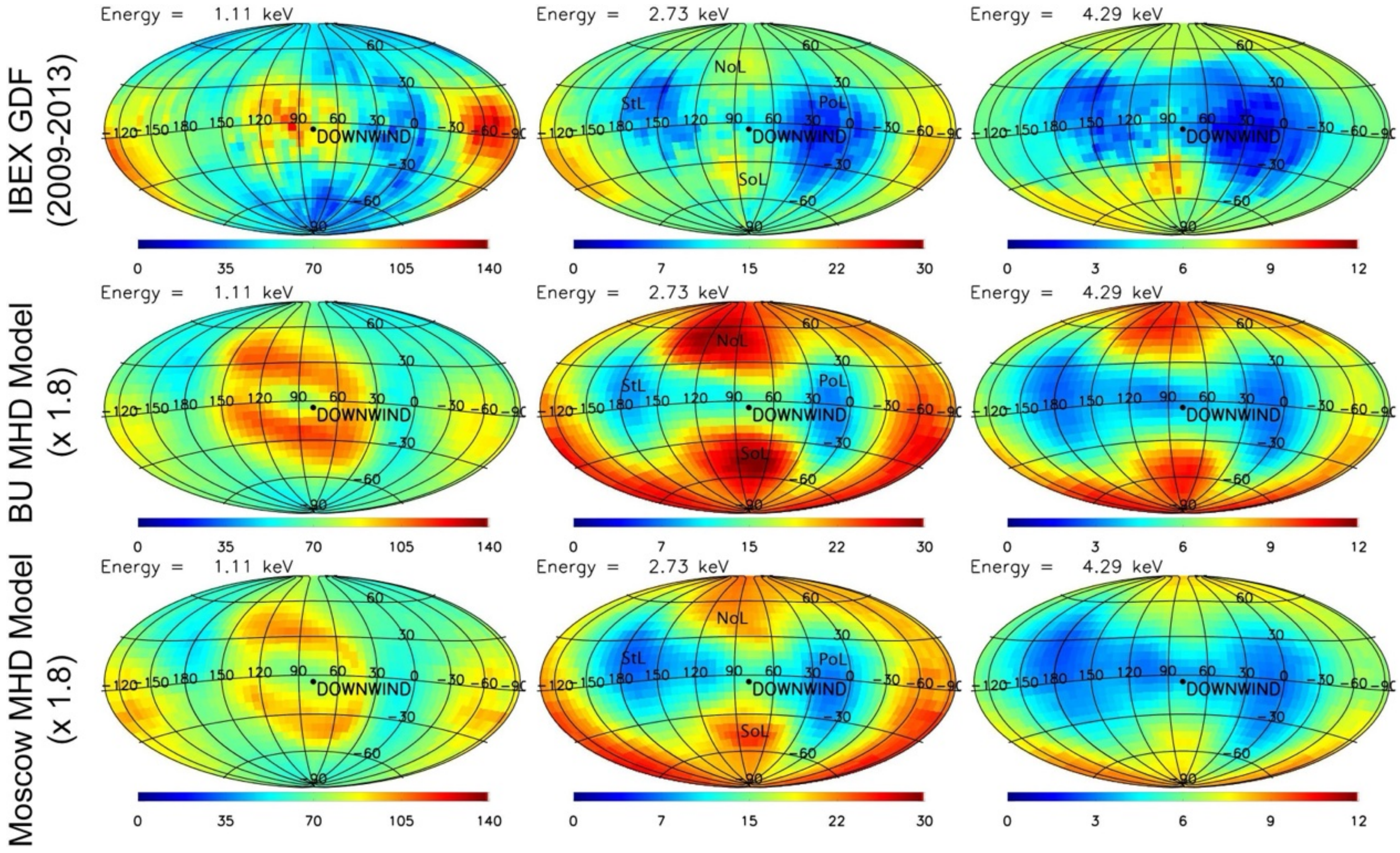
Different Heliotail Shapes Show Similar Profiles Out to 300-400 au



Kornbleuth et al. (2021a)

Different Modeled Heliotails Produce Similar ENA Maps

Using the same ENA model, the short (BU) and long (Moscow) tail heliospheres produce quantitatively similar ENA profiles



Kornbleuth et al. (2021b)

What is the direction and intensity of the interstellar magnetic field?

The Interstellar Magnetic Field Direction is Constrained by the Deflection of Neutral H

-Due to the lower frequency of charge exchange, neutral He is largely unaffected by the presence of the heliosphere

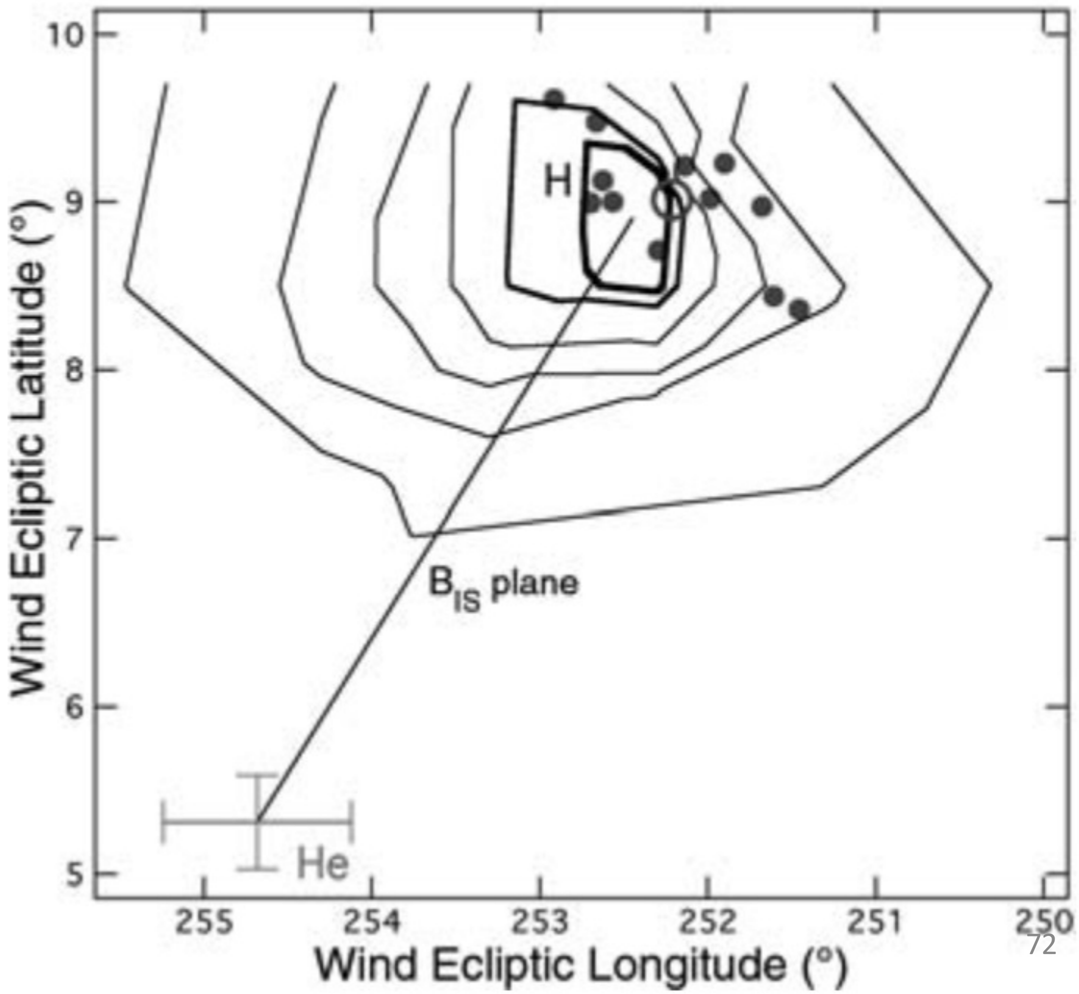
- Can observe the neutral He flow to deduce interstellar flow direction

-Neutral H is more susceptible to charge exchange, and is affected by slowed down interstellar plasma in front of the heliosphere

-The newly created neutral H has a slight deflection relative to the neutral He flow

-The interstellar magnetic field strongly correlates with this deflection – only gives the plane!

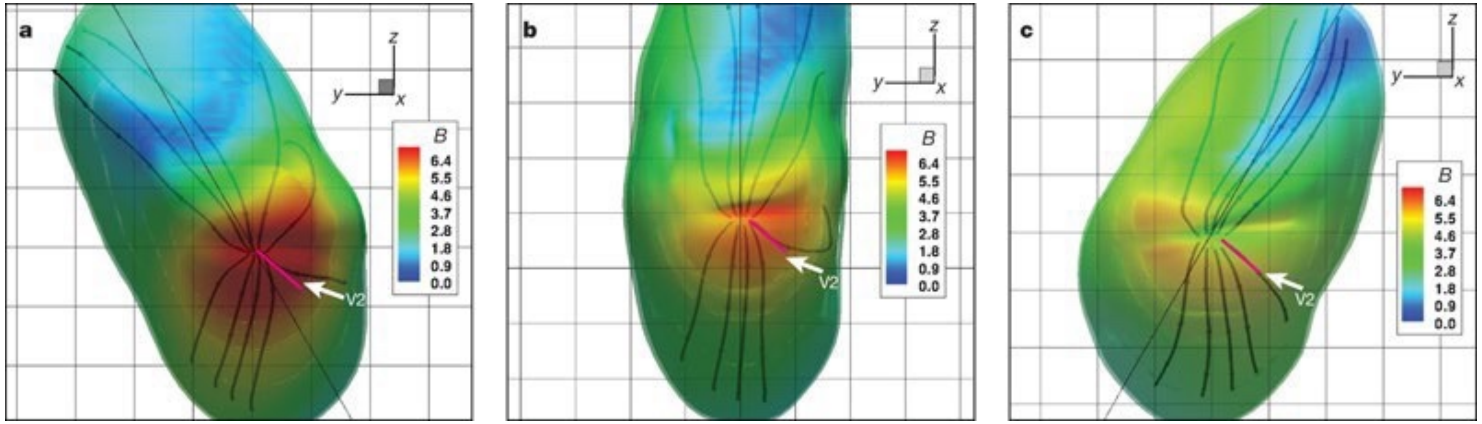
Lallement et al. (2005)



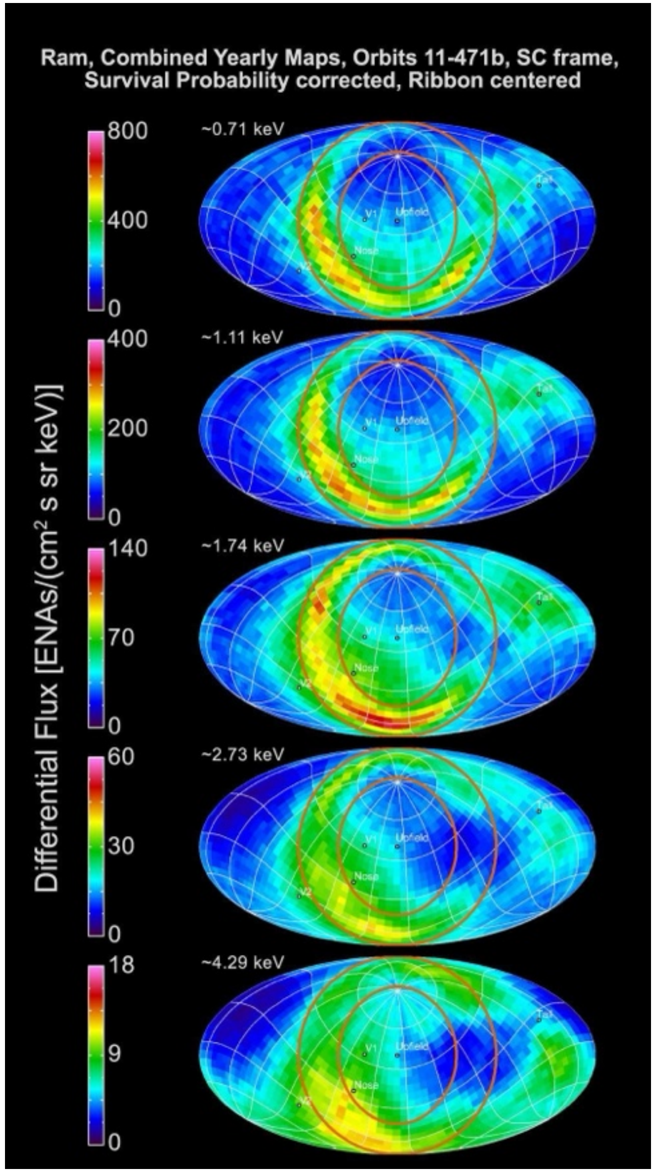
Attempts to Further Constrain the Interstellar Magnetic Field

The flows in the heliosphere are affected by the interstellar magnetic field

Could the IBEX Ribbon seen in ENA observations directly relate to the direction of the interstellar magnetic field?

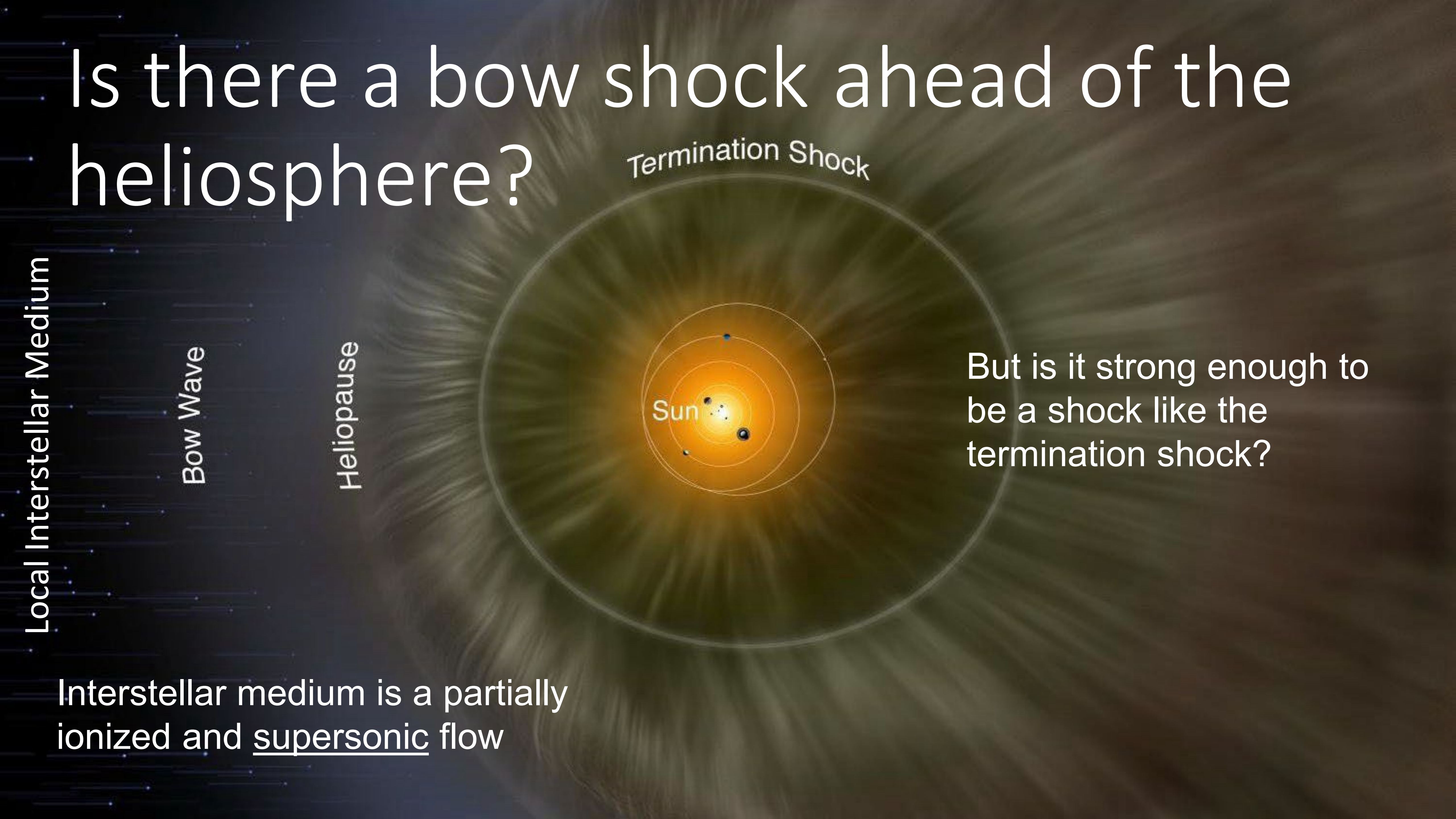


Opher et al. (2007)



McComas et al. (2020)

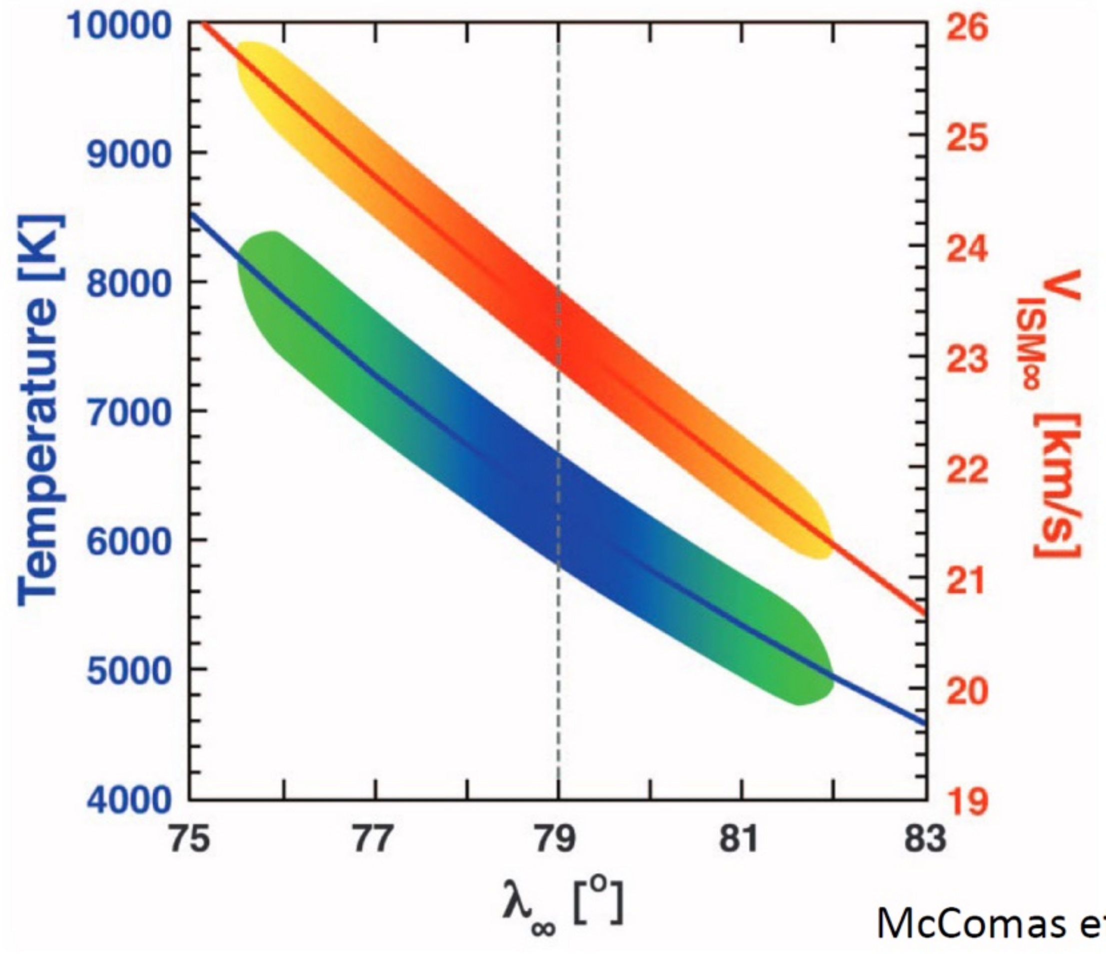
Is there a bow shock ahead of the heliosphere?

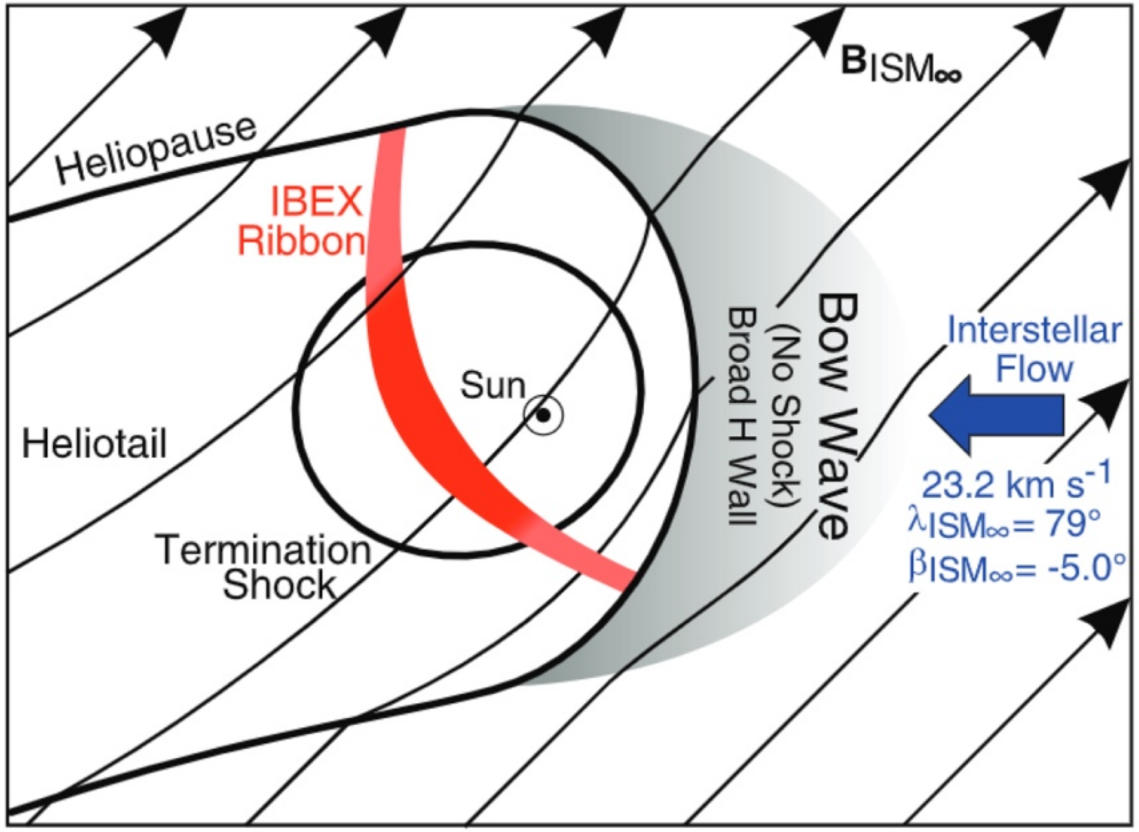


But is it strong enough to be a shock like the termination shock?

Interstellar medium is a partially ionized and <u>supersonic</u> flow

IBEX Observations Constrained the Pristine Interstellar Flow Speed and Temperature – Results Suggested there was no bow shock ahead of the heliosphere





McComas et al. (2012)

Local Neighborhood of the Sun

The Sun moves 18pc/Myr