# Gdzie kończy się Układ Słoneczny i co jest dalej?

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# Where is the boundary of the Solar System?

- The answer is a matter of taste
- Some people say „at the Kuiper Belt”
- Some people say „at the Oort Cloud”
- Some people say „the Oort Cloud does not exist”
- Whichever notion we take, the question is: so where is this boundary, actually?
- What we more or less know is the distance where Sun’s gravity dominates that of the Galactic disk (it’s about $10^4$ AU). Is this the boundary of the Solar System?
- I say: there is a natural, well defined boundary – the heliopause!
- But where is it in space? Stand by…

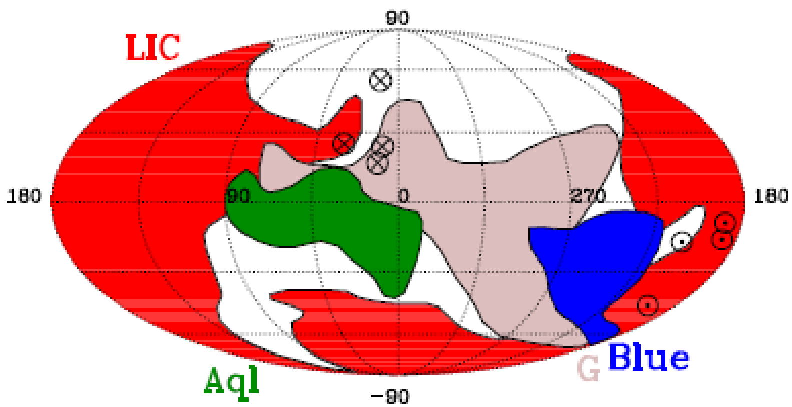
# What is beyond this boundary?

- Most people agree: a warm, partially ionized, magnetized matter processed by a series of Supernova explosions a couple of millions years ago
- How does it look like? Two competing views here:

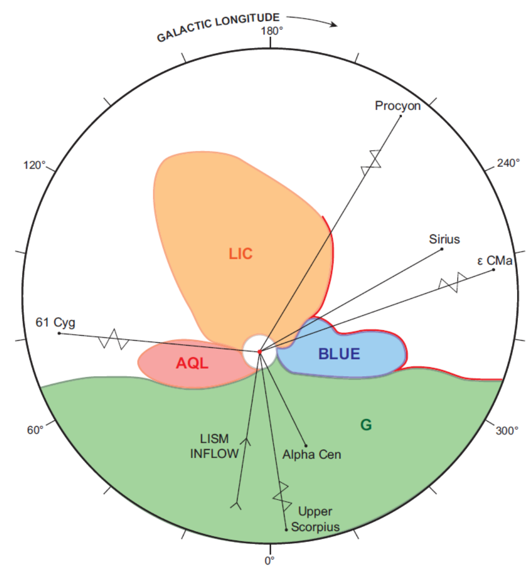
- A complex of relatively small, „stiff" but turbulent, cirrus-like clouds (a few pc across, 7000 K, 0.2 $cm^{-3}$)
- A hot, ionized, rarefied ($10^{-3}$ $cm^{-3}$, 1 MK) in between

- A large turbulent „cumulus" cloud (a few hundred pc across, 7000 K, 0.2 $cm^{-3}$)
- No hot, ionized, rarefied ($10^{-3}$ $cm^{-3}$, 1 MK)
- A large-scale velocity gradient within the cloud

Gry & Jenkins, A&A 567, A58, 2014



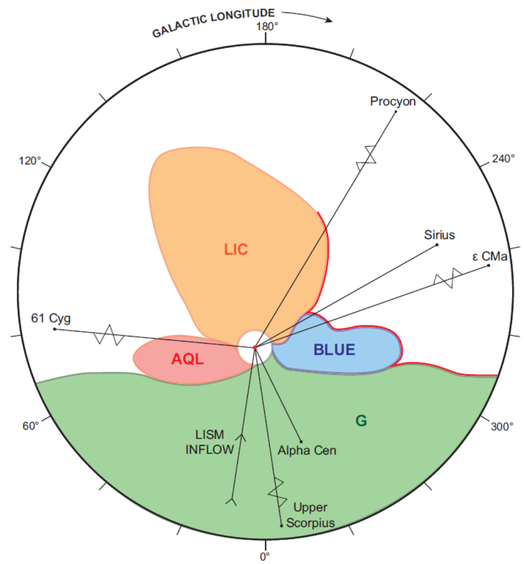

Linsky et al., ApJ 886:41, 2019




Drawing courtesy J. Linsky

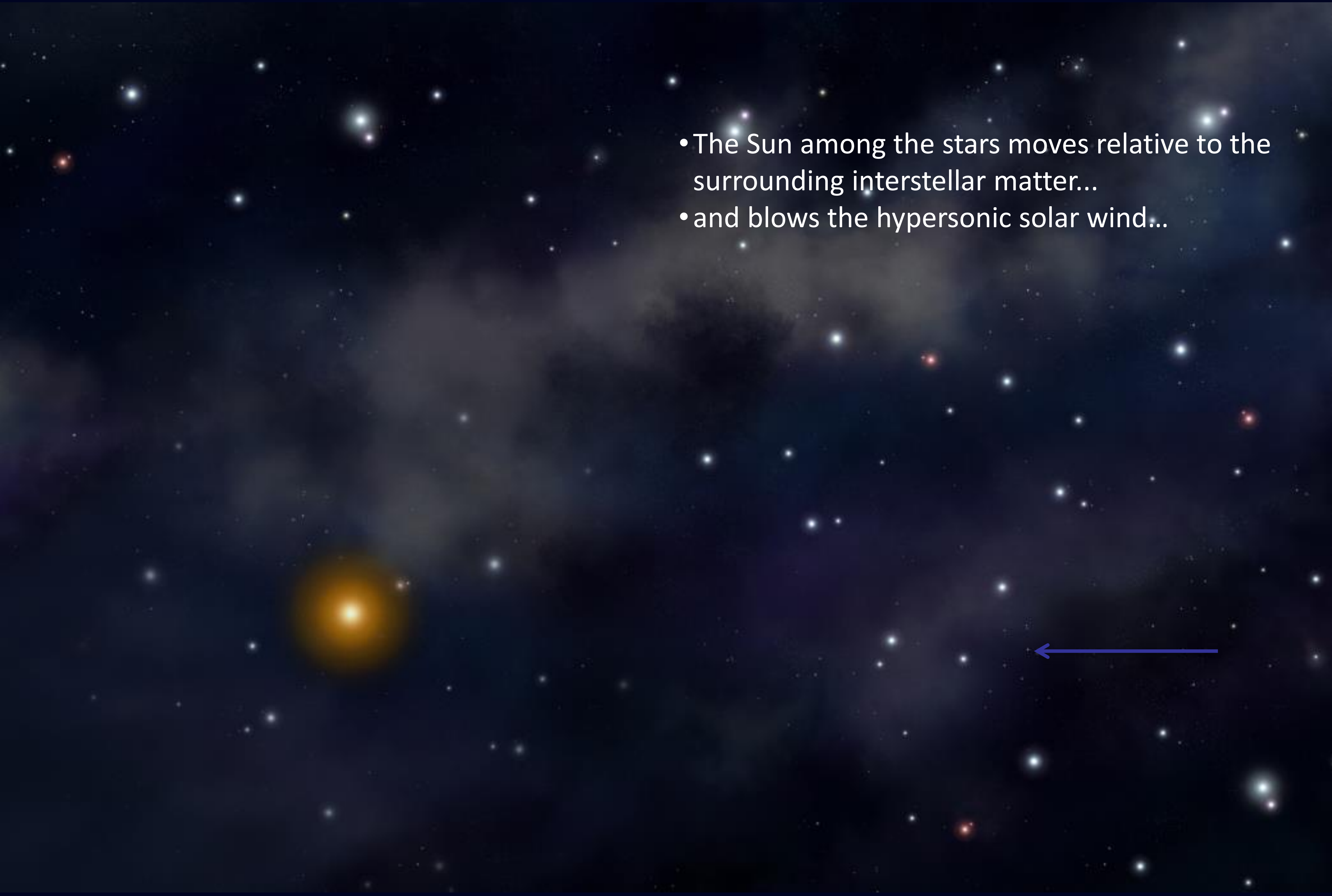
# What is beyond this boundary?

- Both these competing views are based on the same set of observations!
- These are observations of interstellar absorption in the spectra of nearby stars
- Personally I prefer the „Cumulus View”
- If not „Cumulus”, then why is the Sun exactly at the boundary between as many as four nearby clouds??? Aren’t they just one inhomogeneous cloud?
- Four small clouds nearby at the Sun’s location are unlikely but not impossible
- So the simple answer to the title question: I don’t know!!!
- We don’t exactly know what is at a few or a few dozen pc away
- Bu we know what is within ~1000 AU
- How? From observations of the heliosphere using neutral atoms sampled at 1 AU
- Let us start from the origins of the heliosphere




Courtesy: J. Linsky

- The Sun among the stars moves relative to the surrounding interstellar matter...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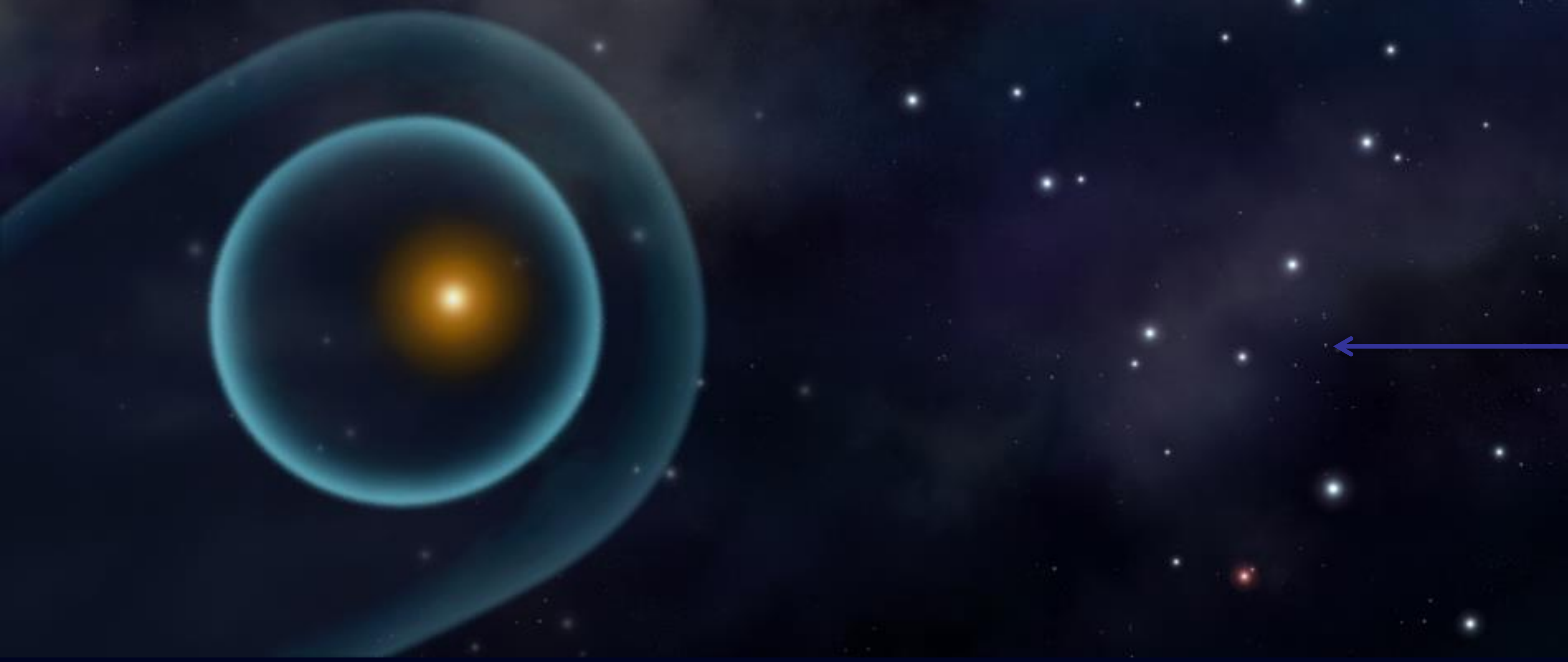

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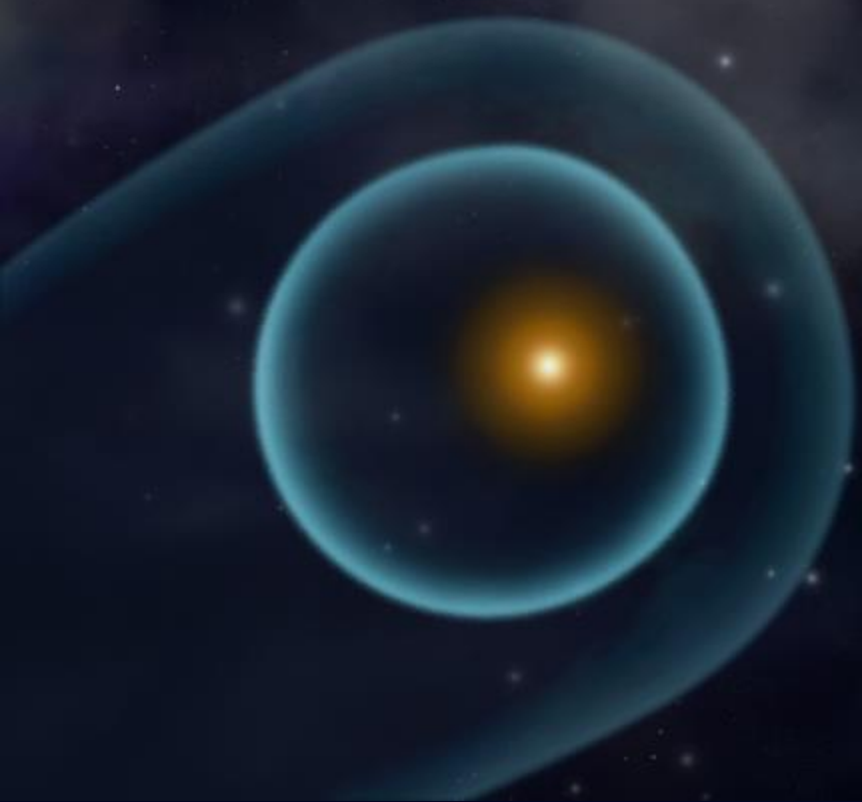
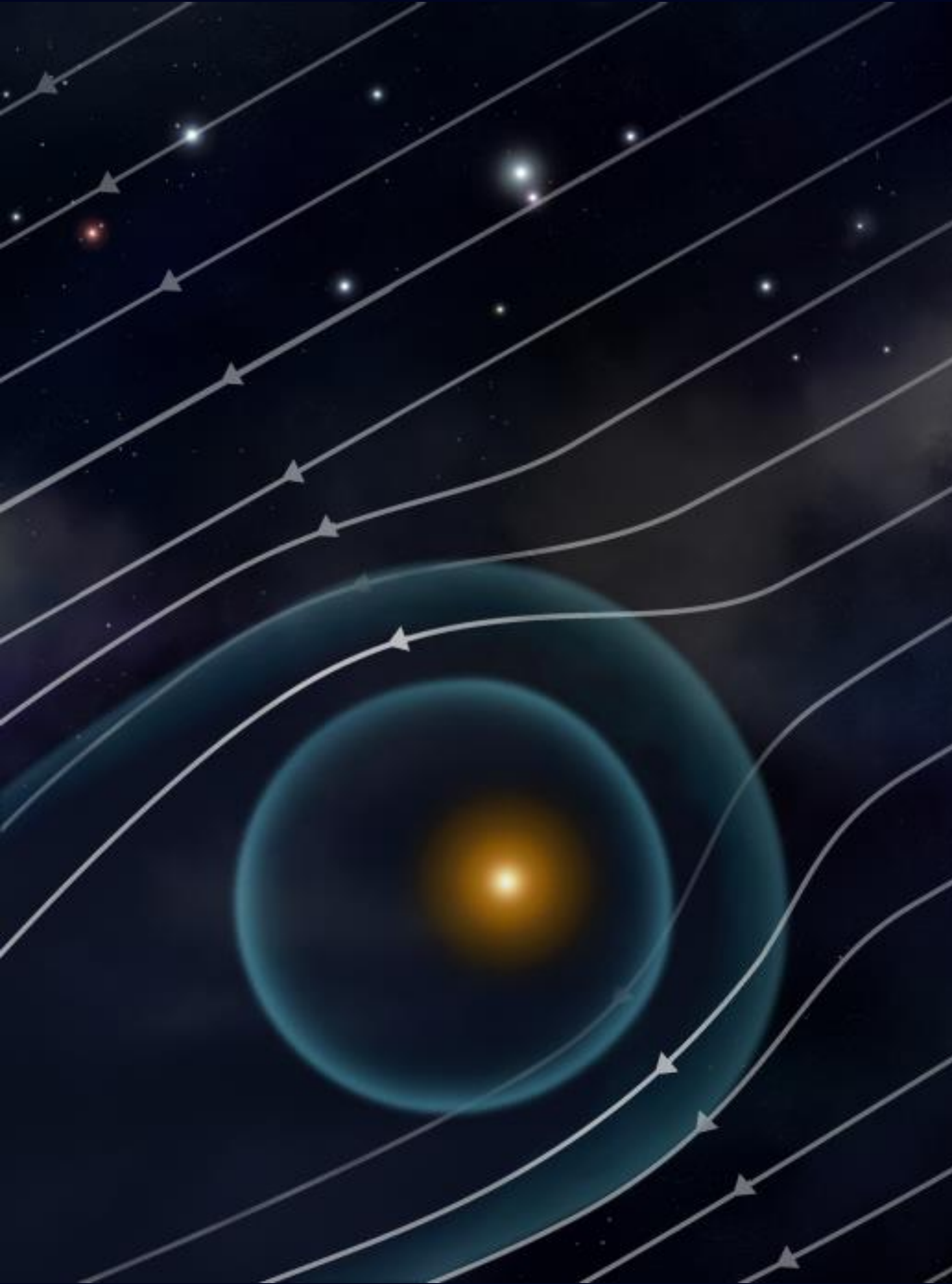
- The region between the termination shock and the heliopause is called the inner heliosheath





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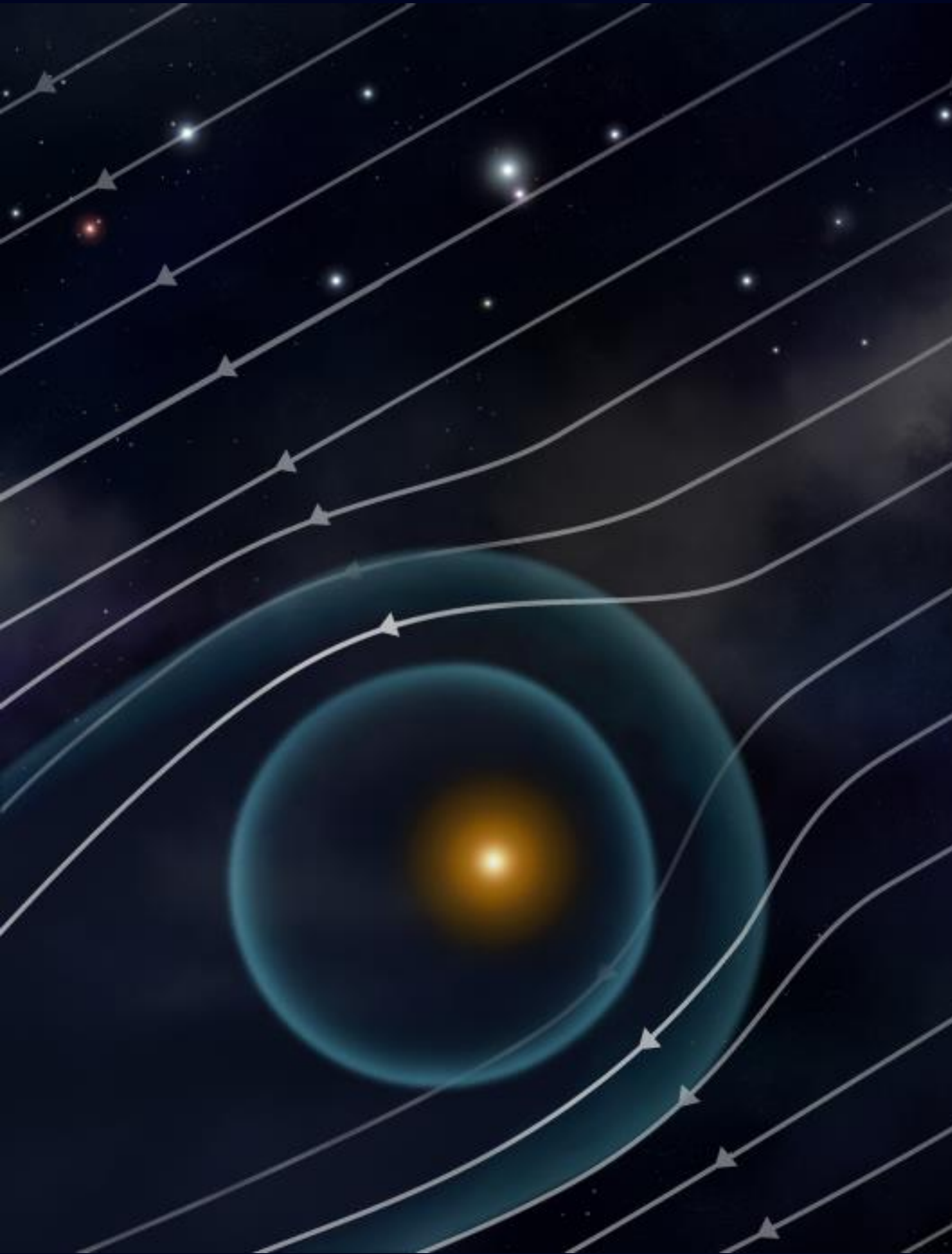

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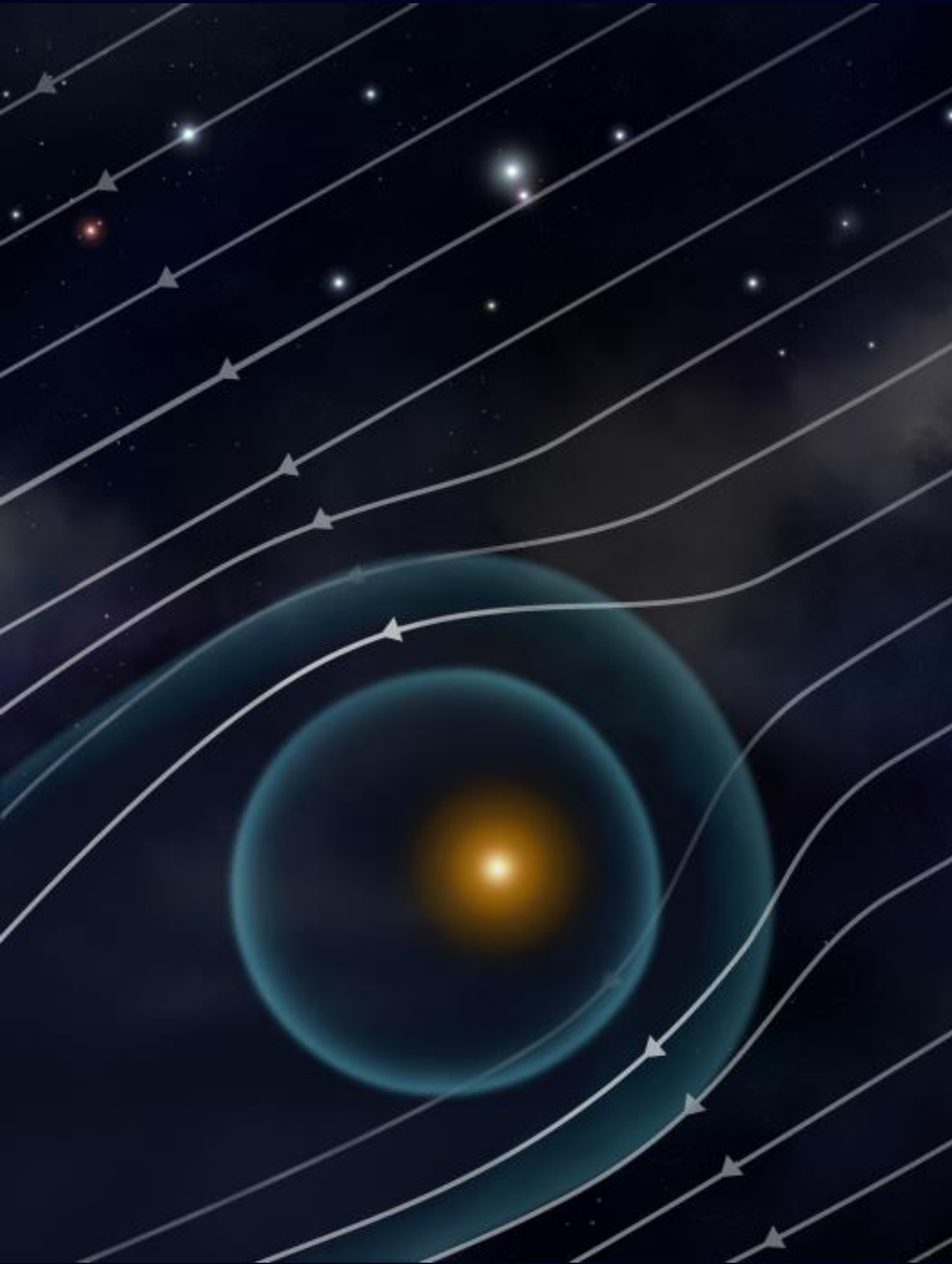

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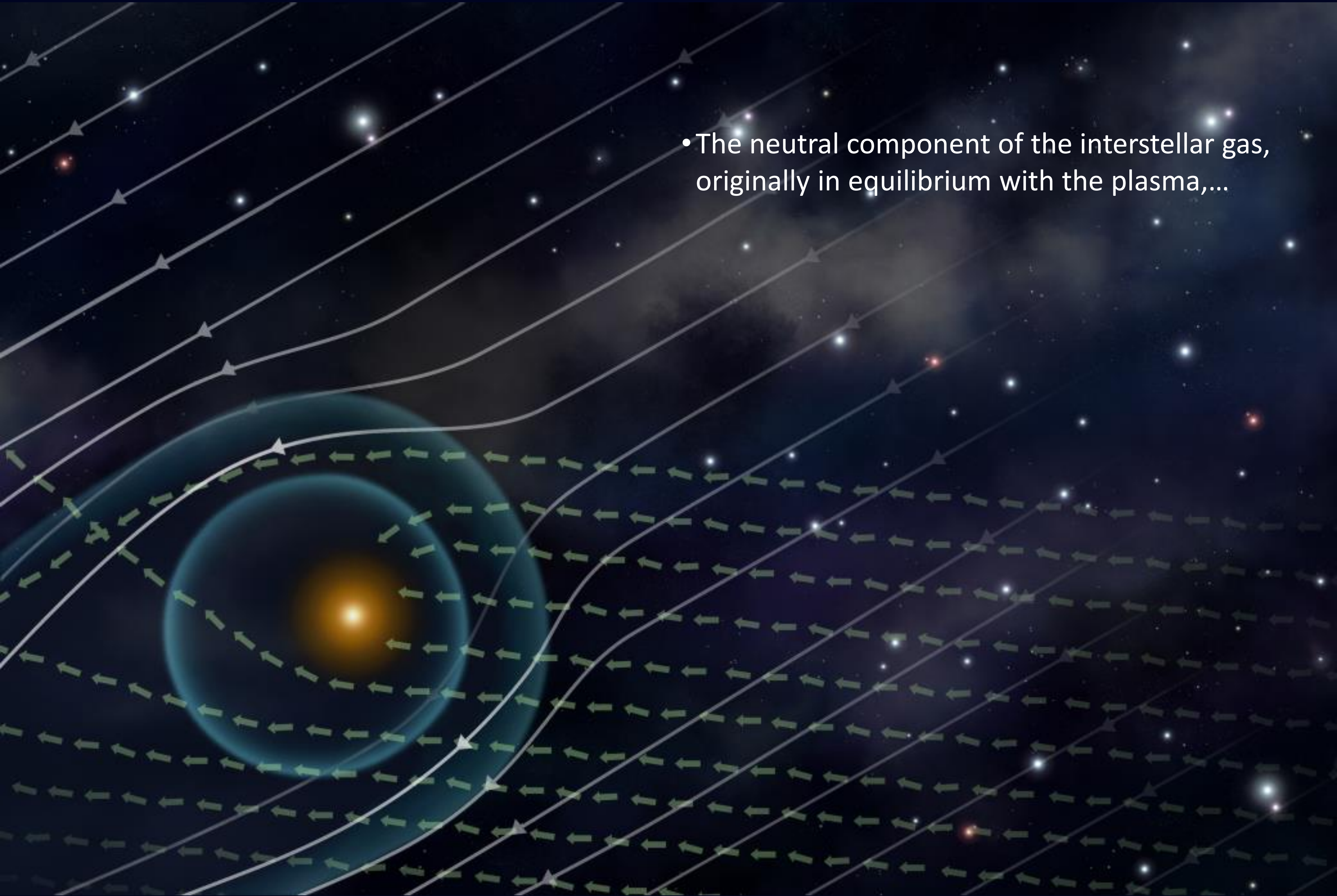
- which pushes the heliotail somewhat to the side.



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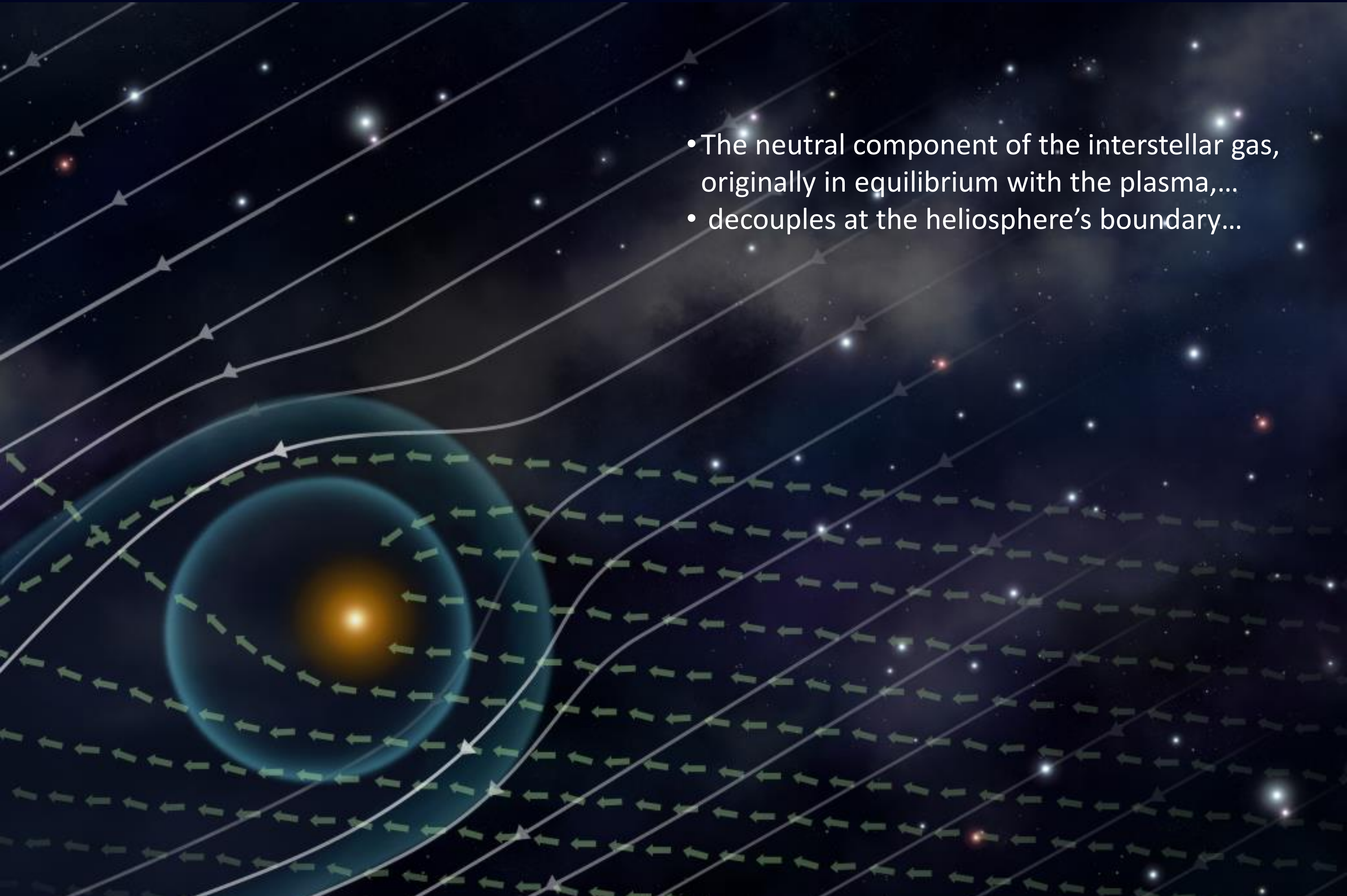

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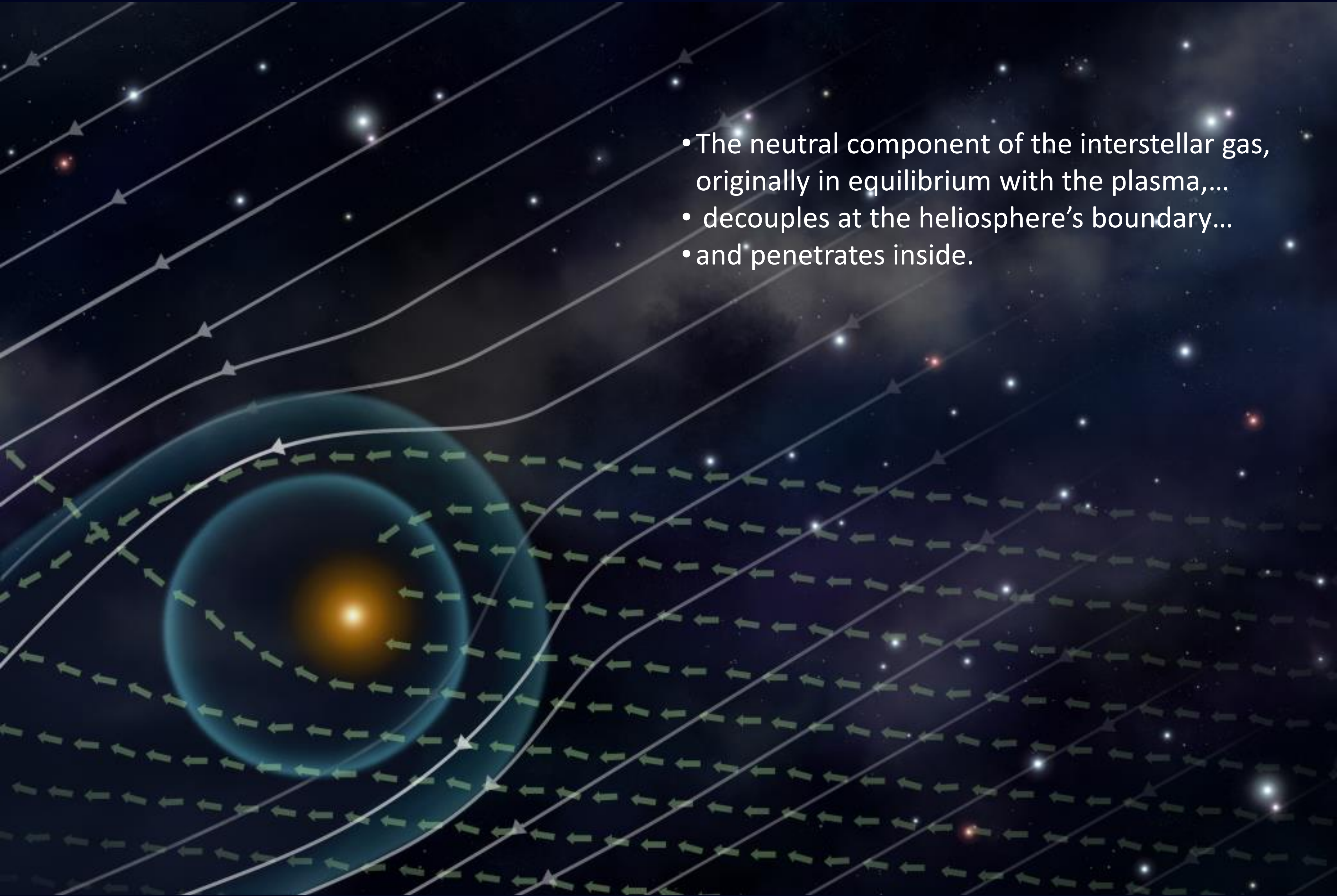

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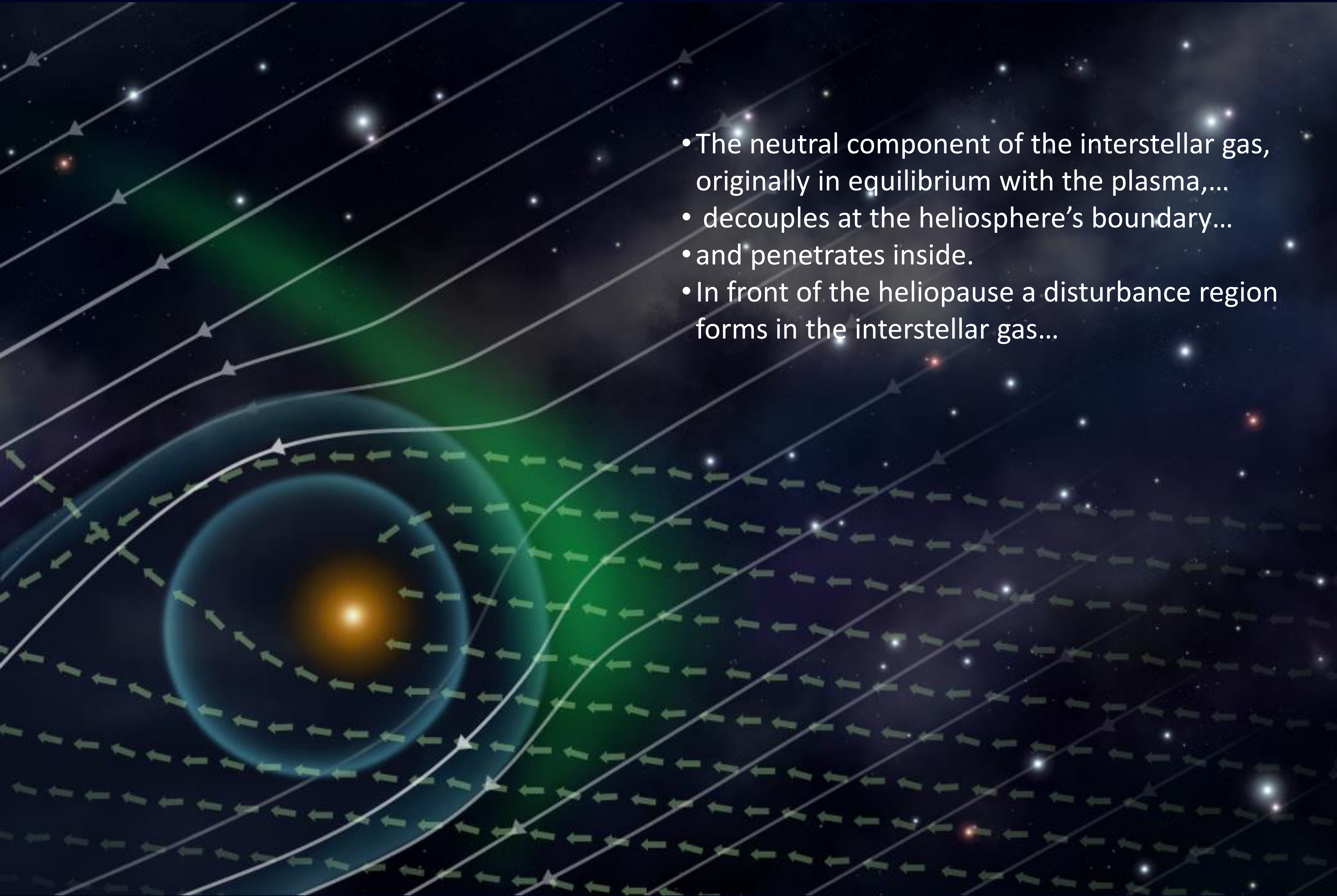

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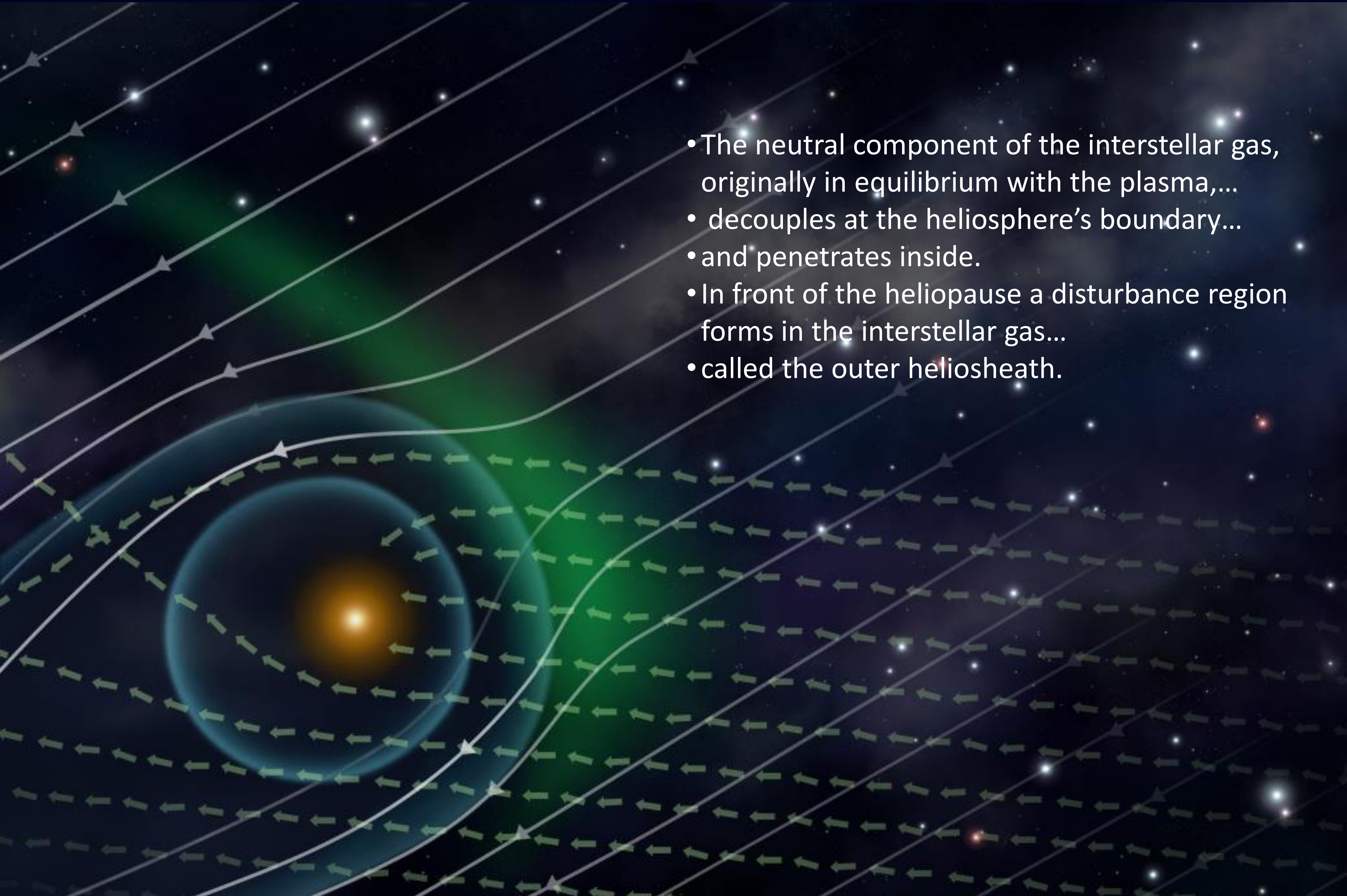

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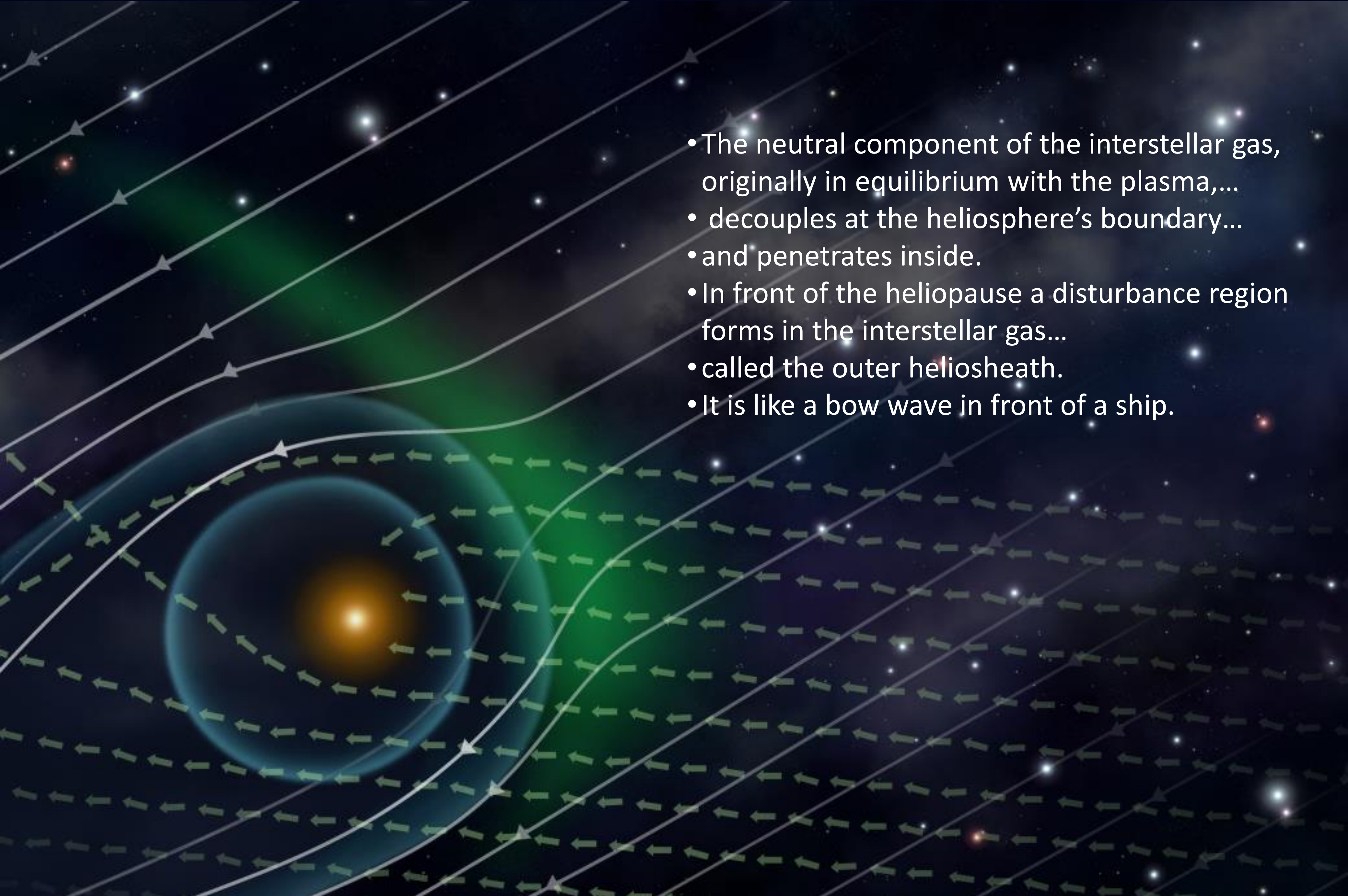

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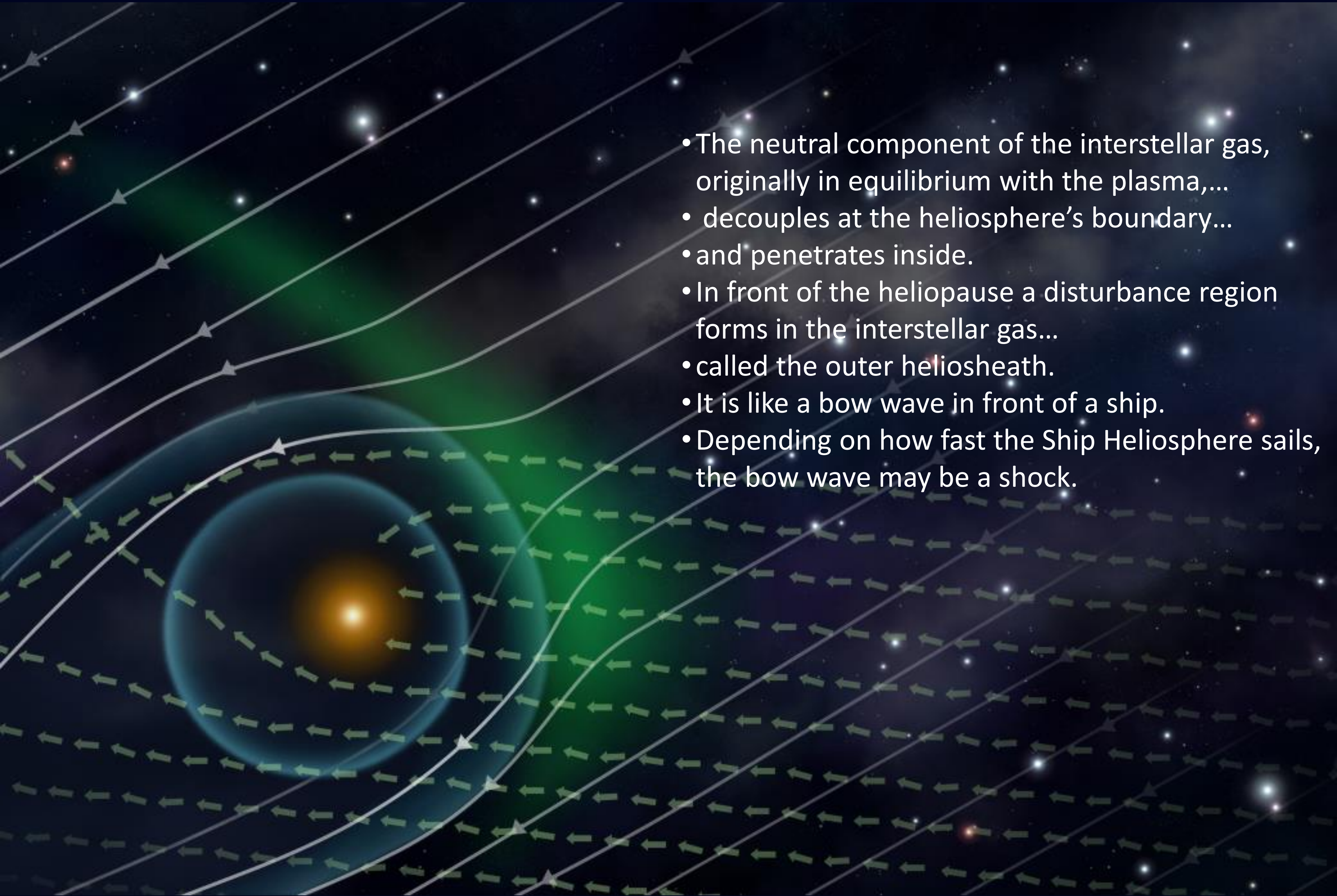

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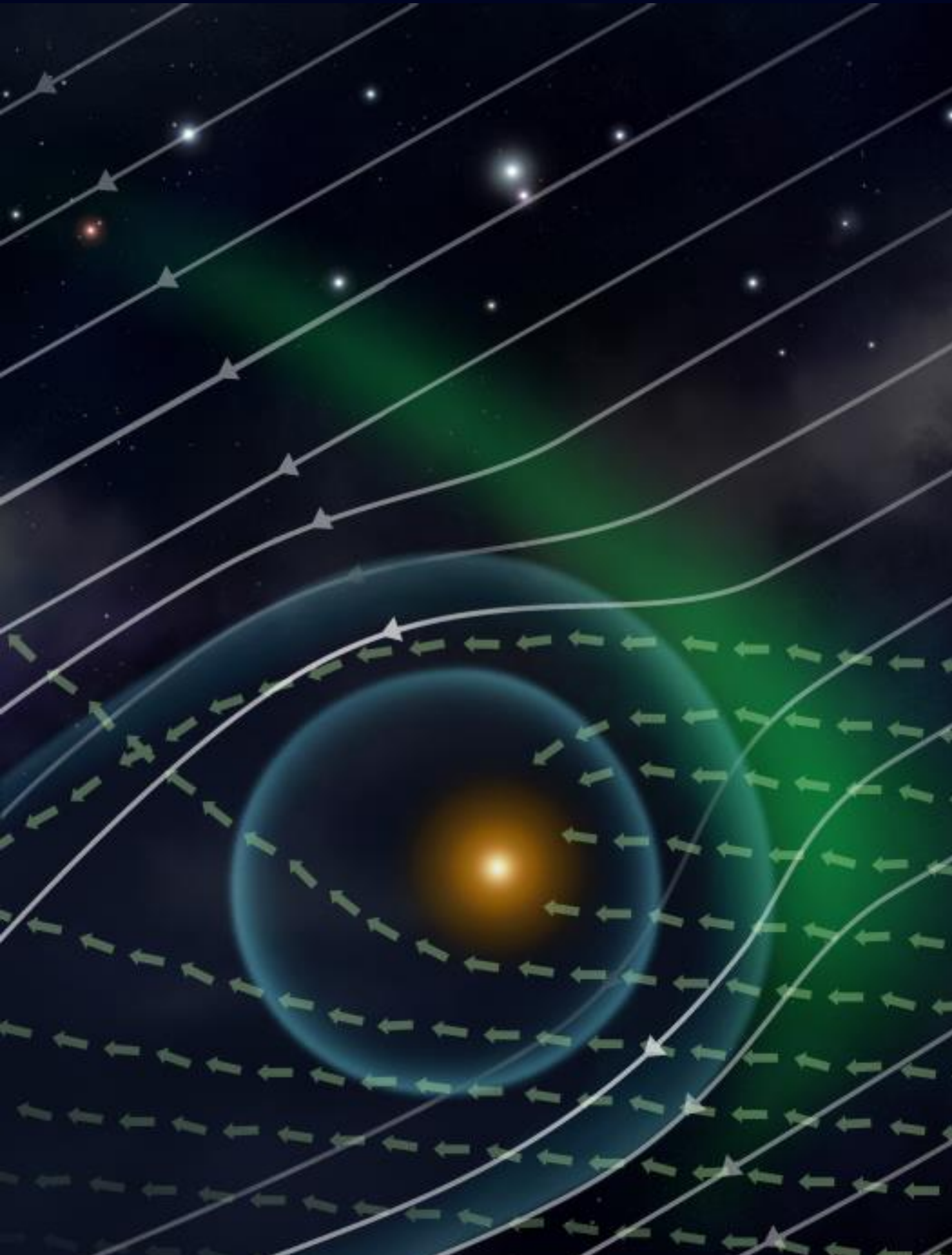

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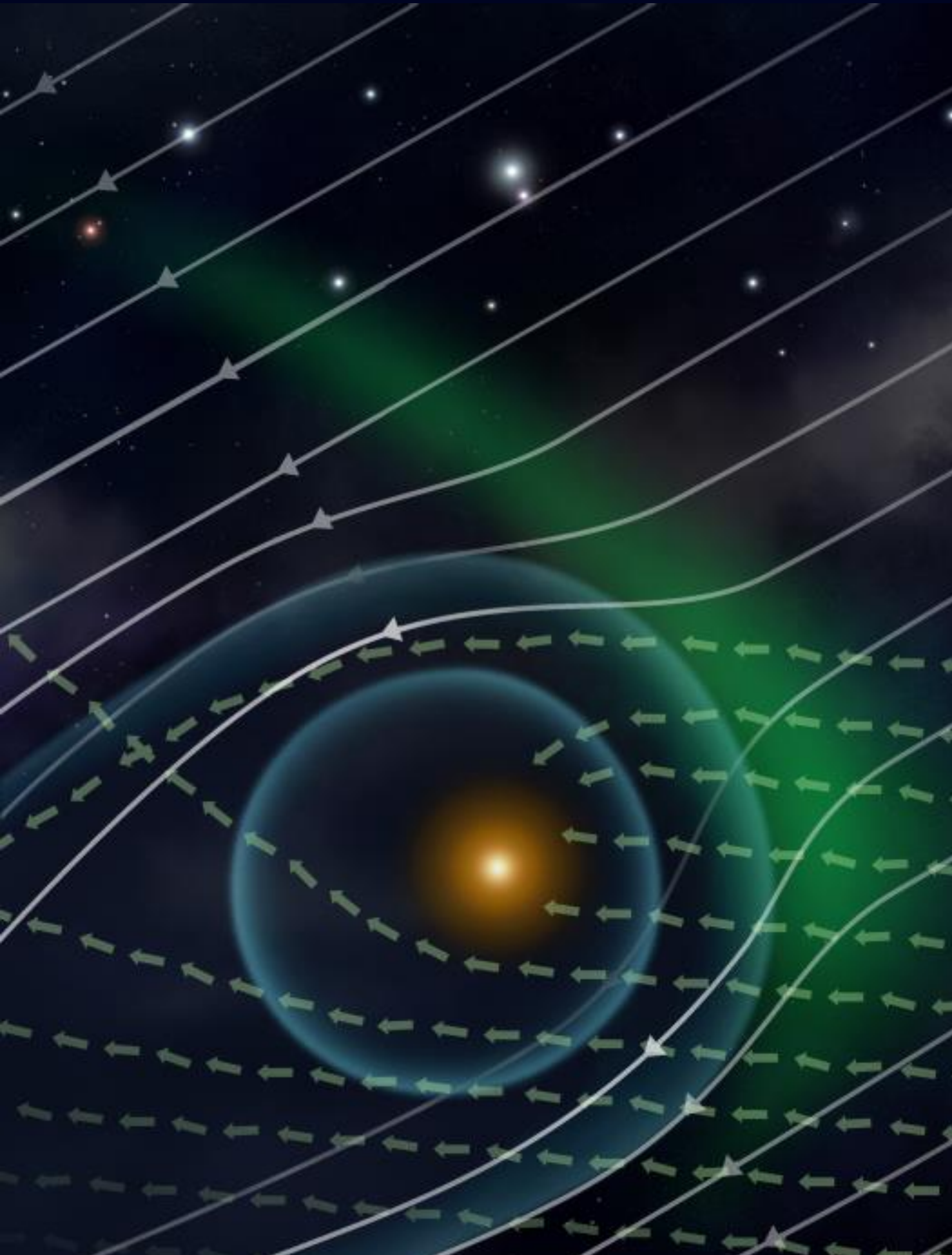

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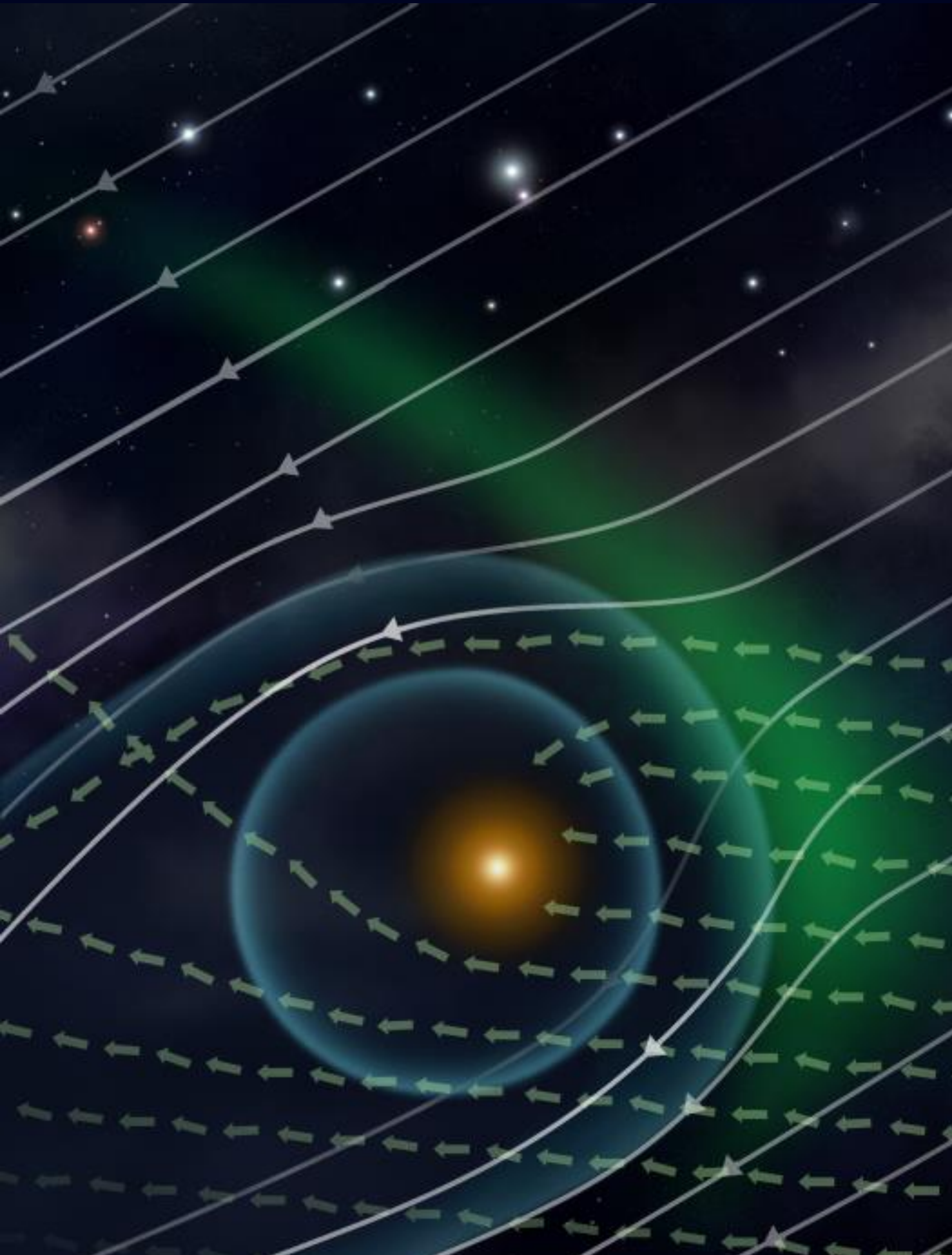

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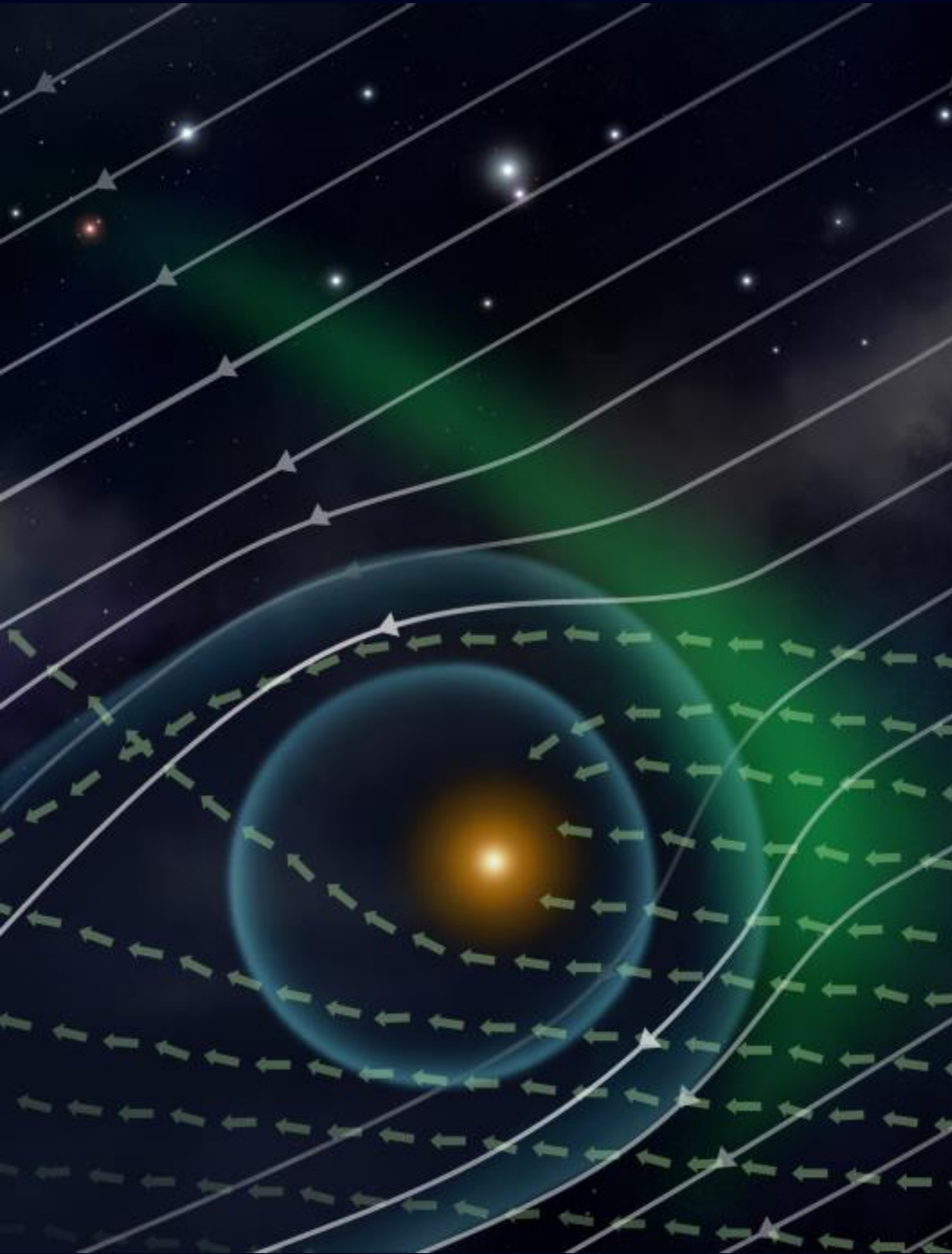

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- … and thus interact, forming new distinct populations of plasma and neutral particles
- Some of these neutral particles also enter the heliosphere.

# Modulation of interstellar gas inside the heliosphere

Neutral interstellar atoms inside the heliosphere are subject to loss processes. These are:

- Charge exchange with solar wind ions: $H + p \rightarrow H_{ENA} + H^{+}_{PUI}$

Reaction rates are:

- proportional to SW flux and $1/r^2$, strong function of heliolatitude, time-dependent

PUI = pickup ion; i.e. ion picked up by the magnetic field frozen in the solar wind

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- Impact of solar wind electrons: $H + e \rightarrow H^+_{PUI} + 2\,e$

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- proportional to solar EUV flux $1/r^2$, modulated in solar cycle
- strong function of electron temperature, falls off faster than $1/r^2$ and thus important only within a few AU from the Sun

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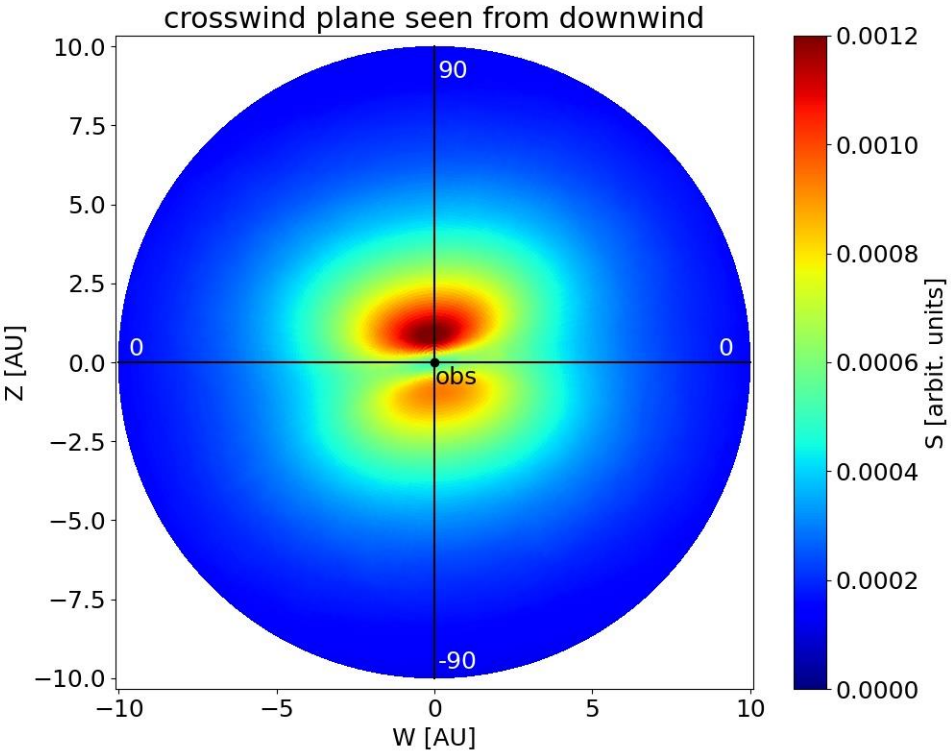
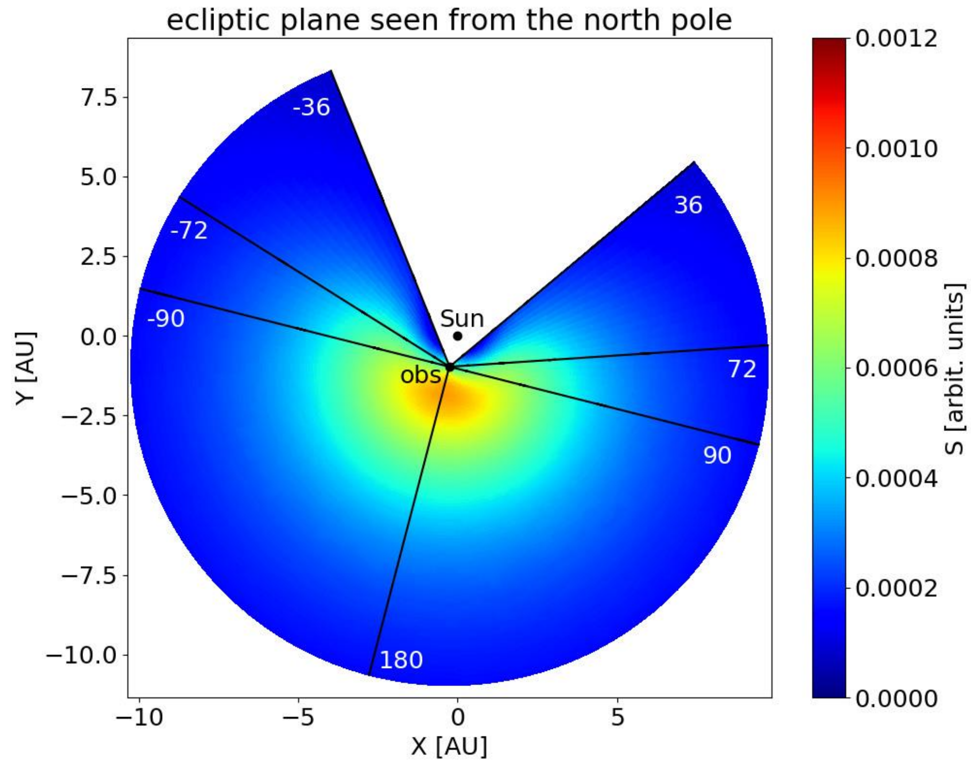
# Density of neutral H in the Solar System

- Due to interaction with the solar environment, a characteristic ISN H density pattern appears, evolving during the solar activity cycle
- The Solar EUV and the 3D structure of solar wind are strongly modulated during the 11 year cycle of solar activity
- Thus, the density distribution of ISN H is mostly determined by the solar activity



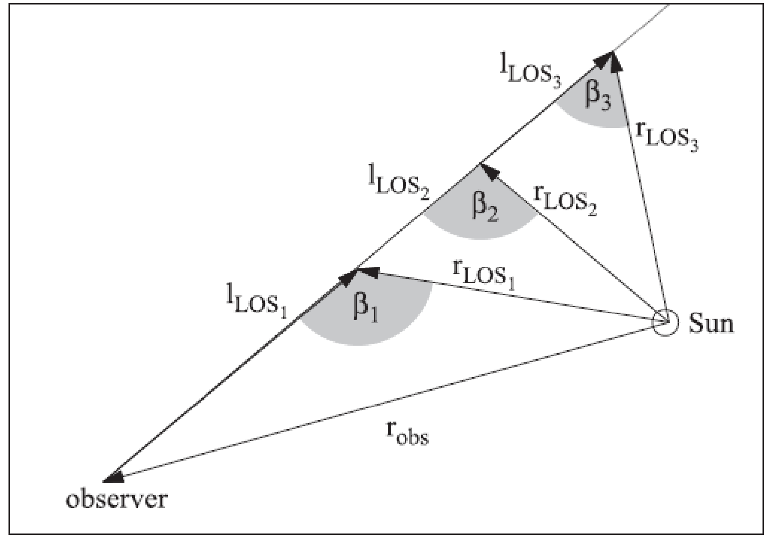



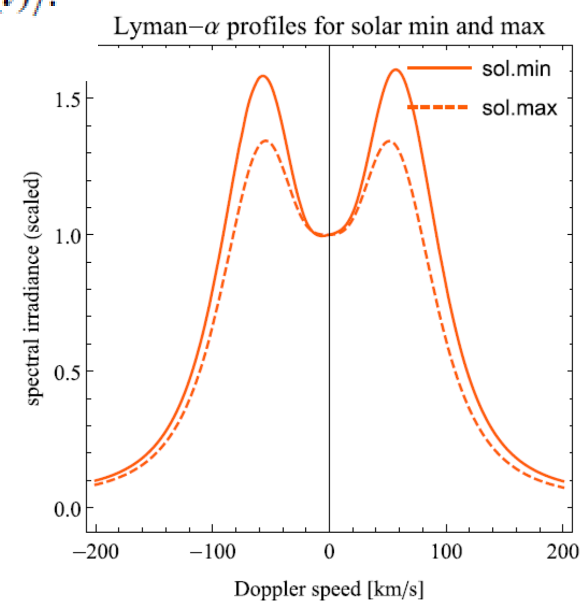
# Helioglow: what is it?

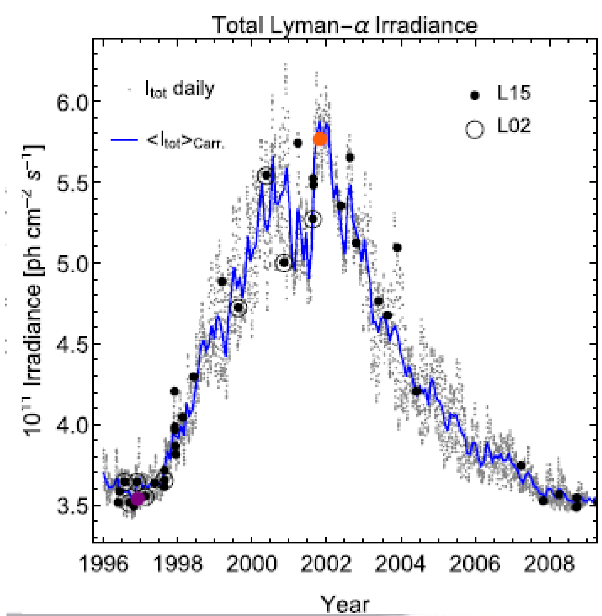
- Helioglow is fluorescence of neutral H and He atoms excited by the strong solar Lyman-alpha and He 58.4 nm emission lines

$$I_{\rm glow}(r_{\rm obs}, \hat{l}) = \frac{\pi\, e^2}{m_e\, c} f_{\rm osc,H}\, p_{\rm H} \times \int_0^\infty dl\, \psi(\beta) \left( \frac{r_{\rm E}}{r_{\rm LOS}} \right)^2 n(l)\, \langle \mu(l) \rangle.$$

- Solar Lyman-alpha gas a dual role: (i) shapes the hydrogen gas distribution by radiation pressure (ii) illuminates this gas



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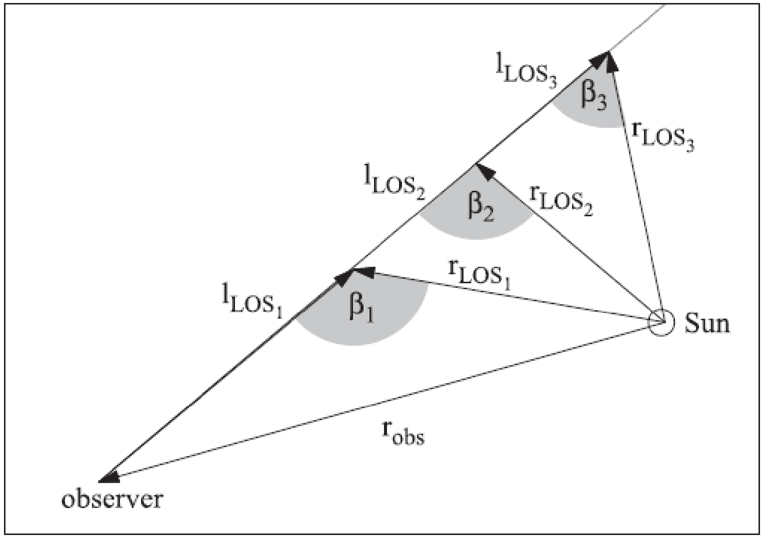
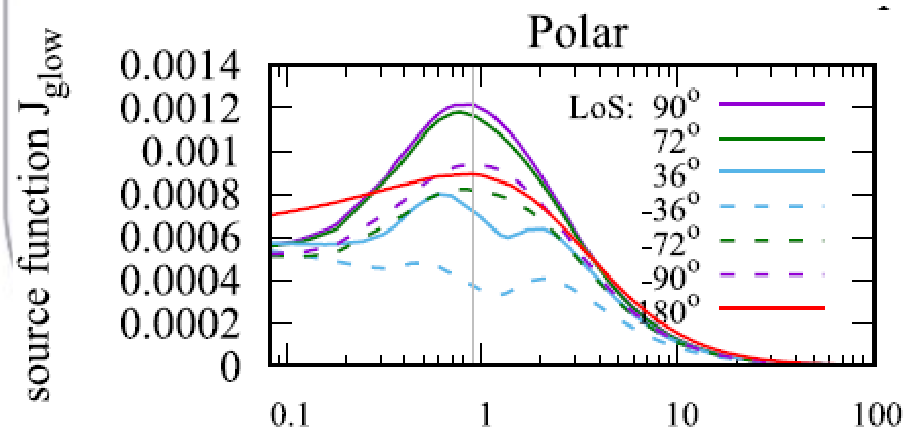
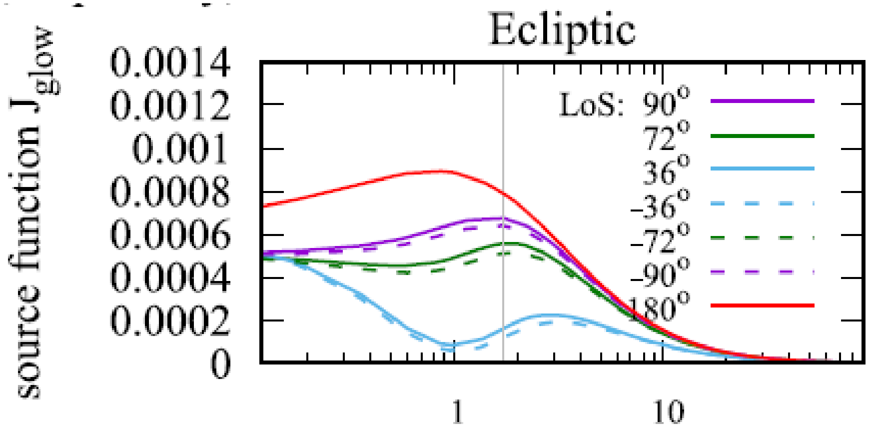



- Source function traces the density distributionalong the line of sight



# How to study the heliosphere?

- The most obvious choice (for astronomer): study the helioglow and use heliospheric models
- Spectral observations of iso-speed contours due to the Doppler effect provide insight on the velocity
- Idea simple, results model-free…
- but only within ~10 AU from the Sun
- Inferring velocity beyond the heliospheric boundary requires complex modeling.

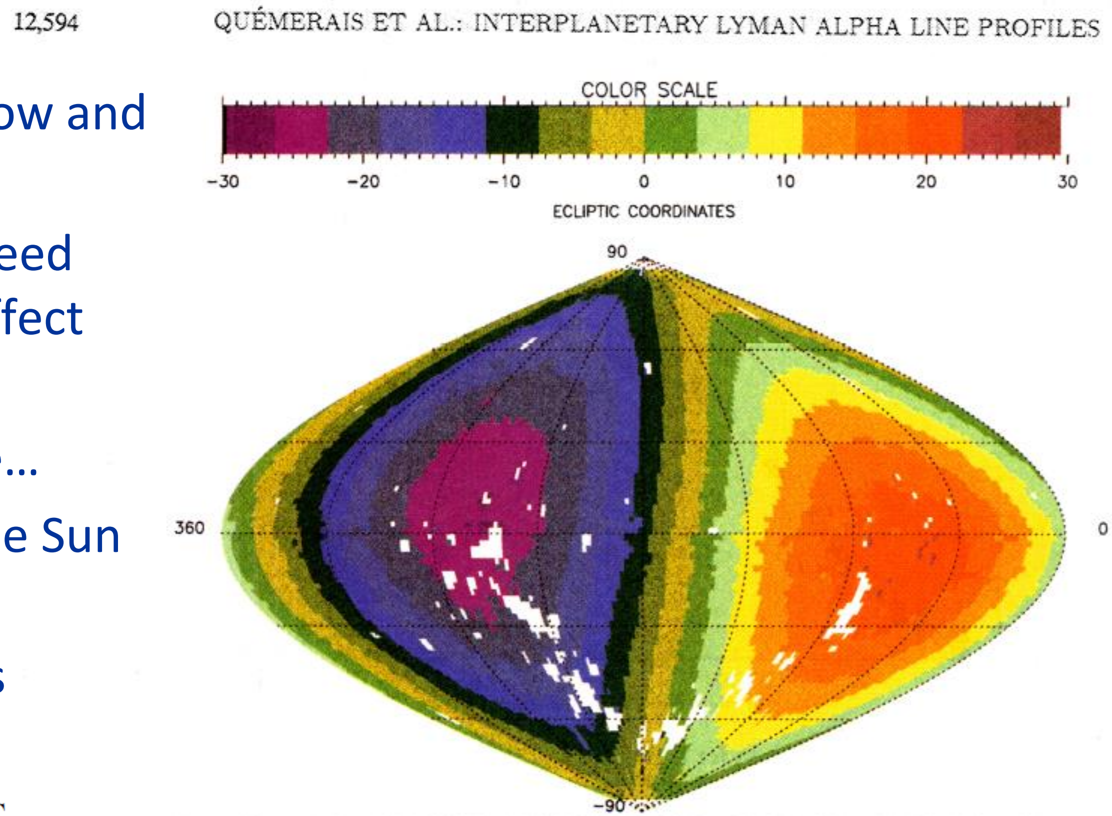
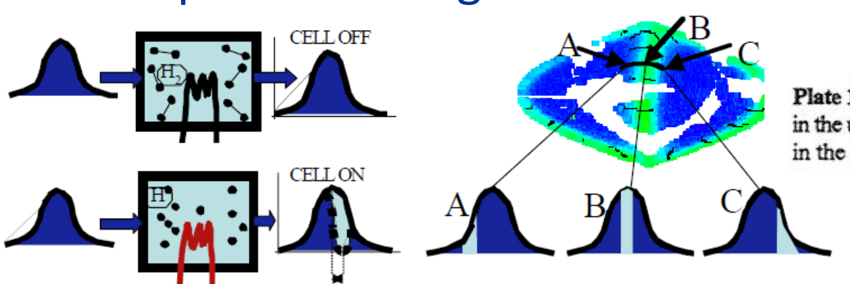



**Plate 1.** Full-sky velocity distribution relative to the Sun. The color code is in km s$^{-1}$ relative to the solar rest frame. The apparent velocity in the upwind direction is −25.4 km s$^{-1}$. In the downwind direction, it is close to 21.6 km s$^{-1}$. Data gaps are due to the presence of hot stars in the line of sight or, at the poles, for lack of sufficient Doppler shift scan between the cell and the Sun.




Lallement et al. 2005

# How to study the heliosphere?

- Photometric full-sky maps of the helioglow are potentially an alternative
- The distribution of the helioglow intensity in sky is a function of the flow parameters far from the Sun
- But interpretation challenging:



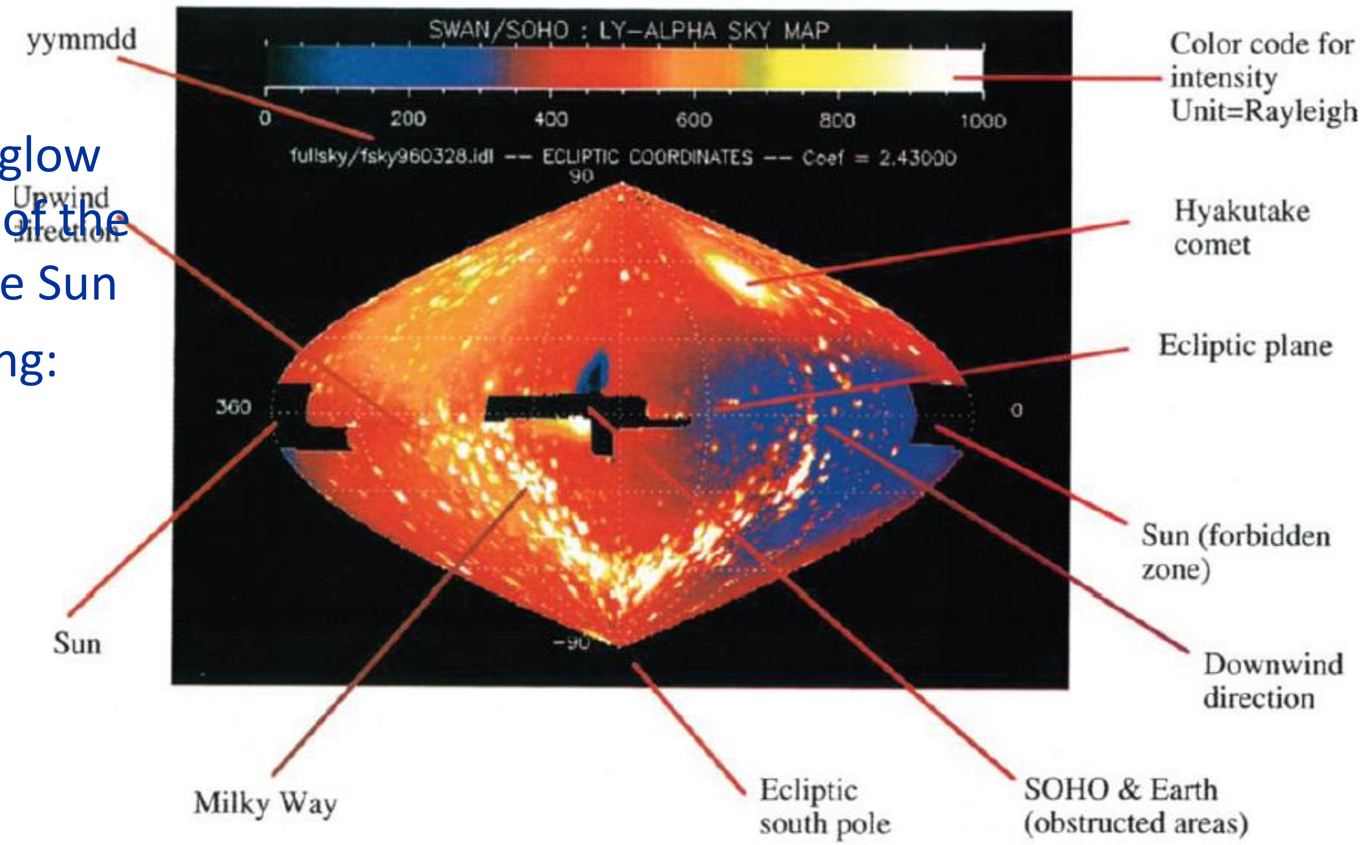
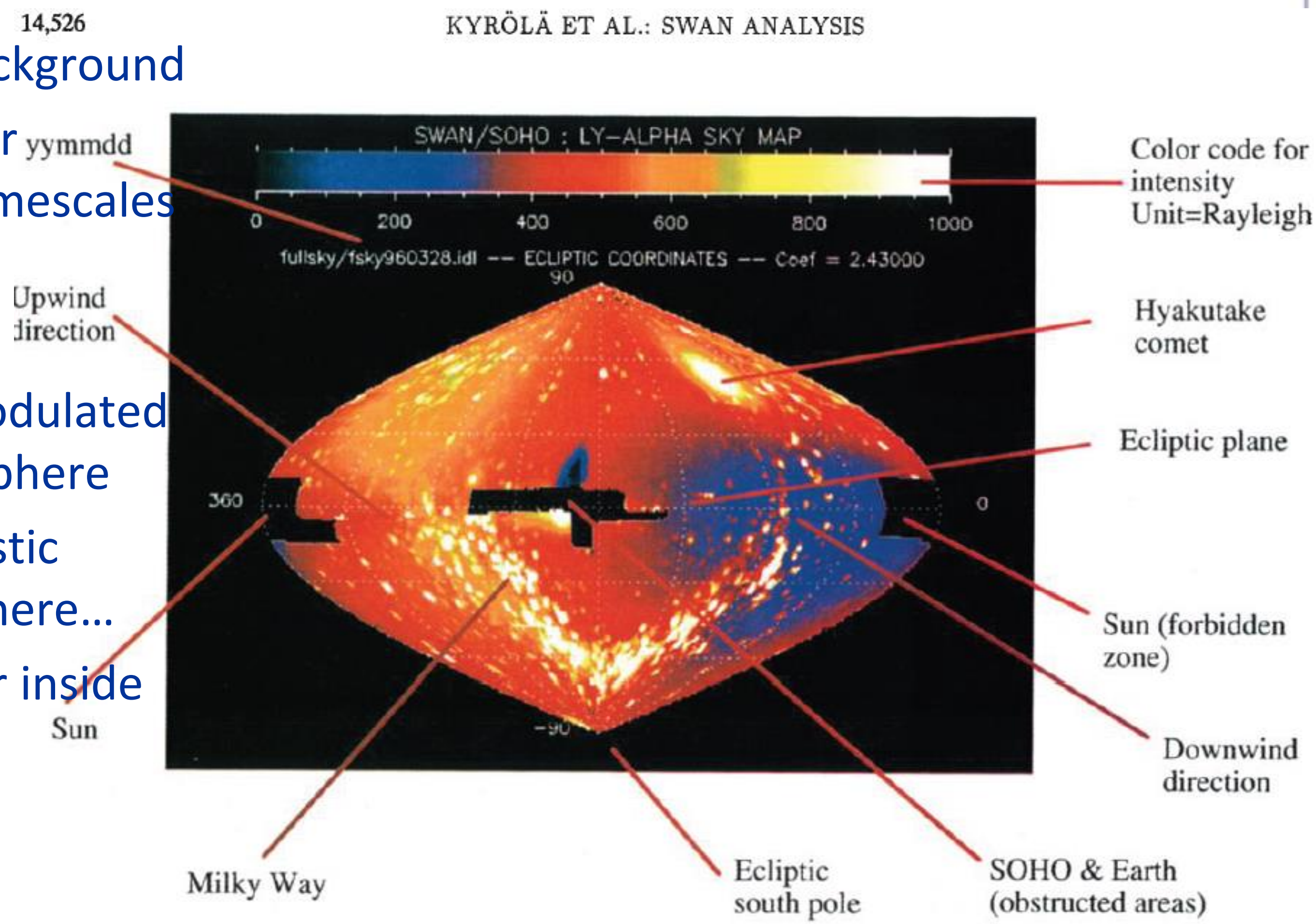



**Plate 1.** SWAN all sky map March 28, 1996.

# How to study the heliosphere?

- Strong extraheliospheric background
- Strong variations of the solar illuminating radiation (on timescales from days to solar cycle)
- Range limited to < 10 AU
- Interstellar gas is heavily modulated by the Sun inside the heliosphere
- Interpretation needs a realistic global model of the heliosphere…
- and of the radiation transfer inside the heliosphere.

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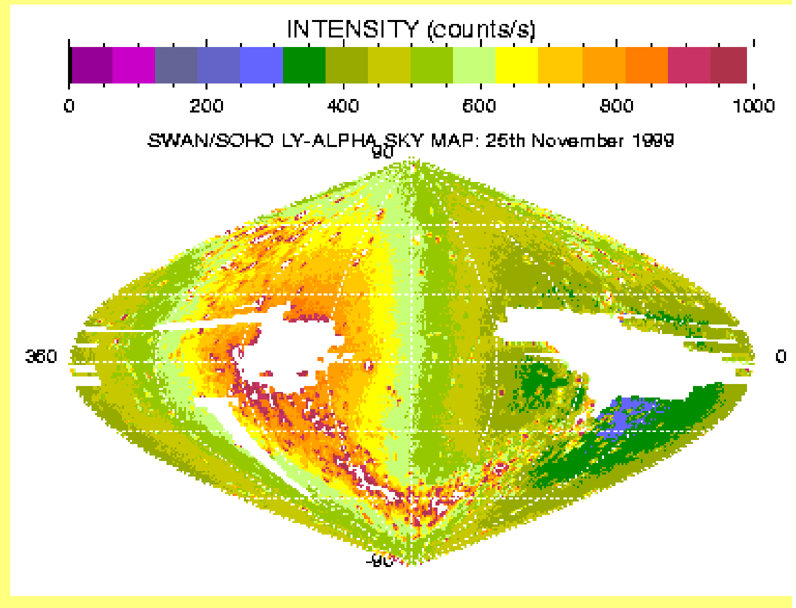
# Modulation of the helioglow

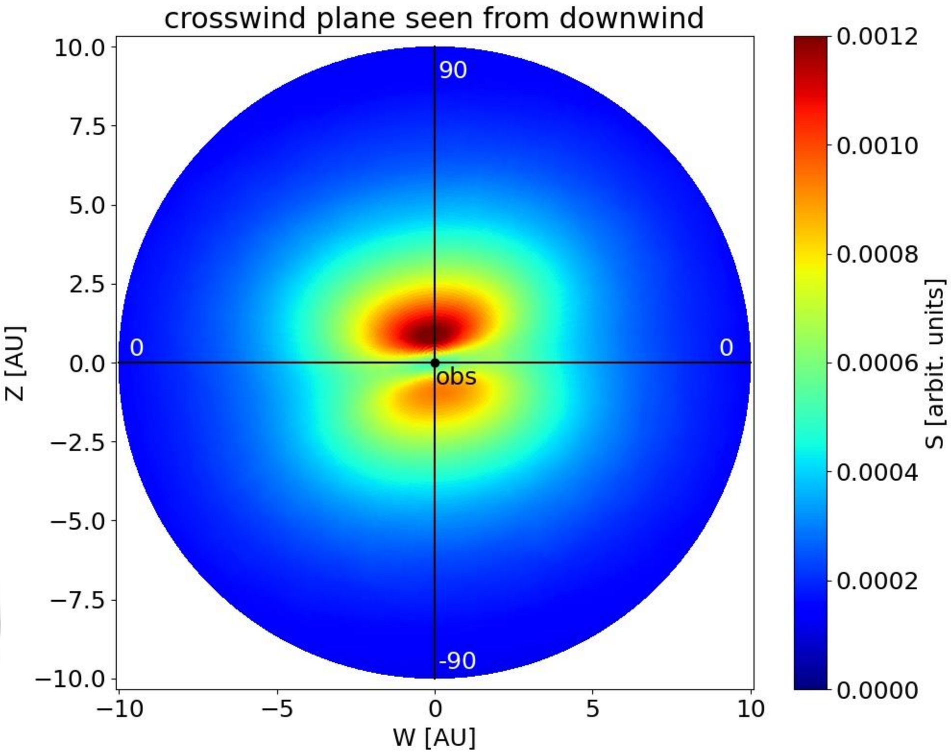


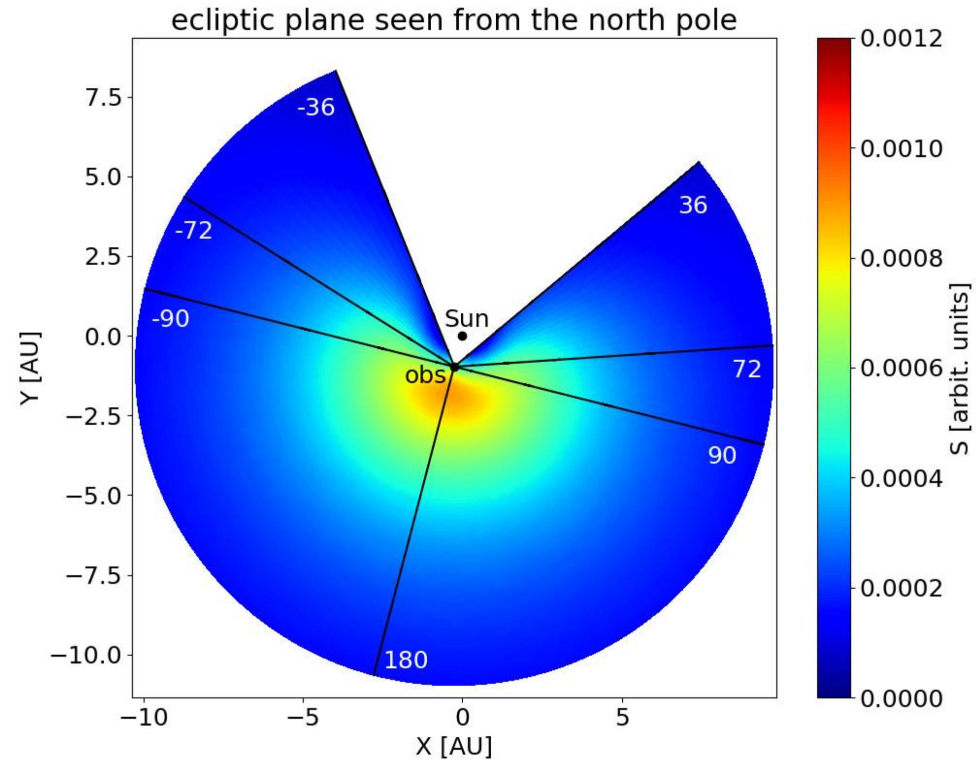

- The result is a complex structure of the helioglow…
- … and its variations with solar activity
- Optical imaging of neutral interstellar gas from 1 AU gives view of a material already heavily processed in the heliosphere
- Gas seen from 1 AU located within ~10 AU from the Sun
- It obscures the view of unperturbed medium
- No direct access to the processes at the boundary, which shape the heliosphere

- **Hence, the heliosphere based on optical imaging heavily relies on modeling**
- **No direct ways to support or reject models**

# Helioglow better suited for 3D solar wind

- Due to interaction with the solar environment, a characteristic ISN H density pattern appears, evolving during the solar activity cycle
- The density distribution of ISN H is mostly determined by the solar activity
- Thus, the helioglow is better suited to study the global solar wind than the interstellar matter



# Alternative ways of studying heliosphere

- In situ sampling: good but very costly, only 2 spacecraft available (Voyagers)
- Good carriers of information on long distances in the heliosphere are **neutral atoms**
- Different energies correspond to different regions in the outer heliosphere and beyond
- Different species bring information on different processes & locations

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- **Pros**:
  - observations can be carried out remotely (1 AU)
  - good for both local interstellar gas and heliospheric physics
- **Challenges**:
  - detection technology
  - transport effects must be recognized

Provided the only two hard measurements of the distance to the heliopause

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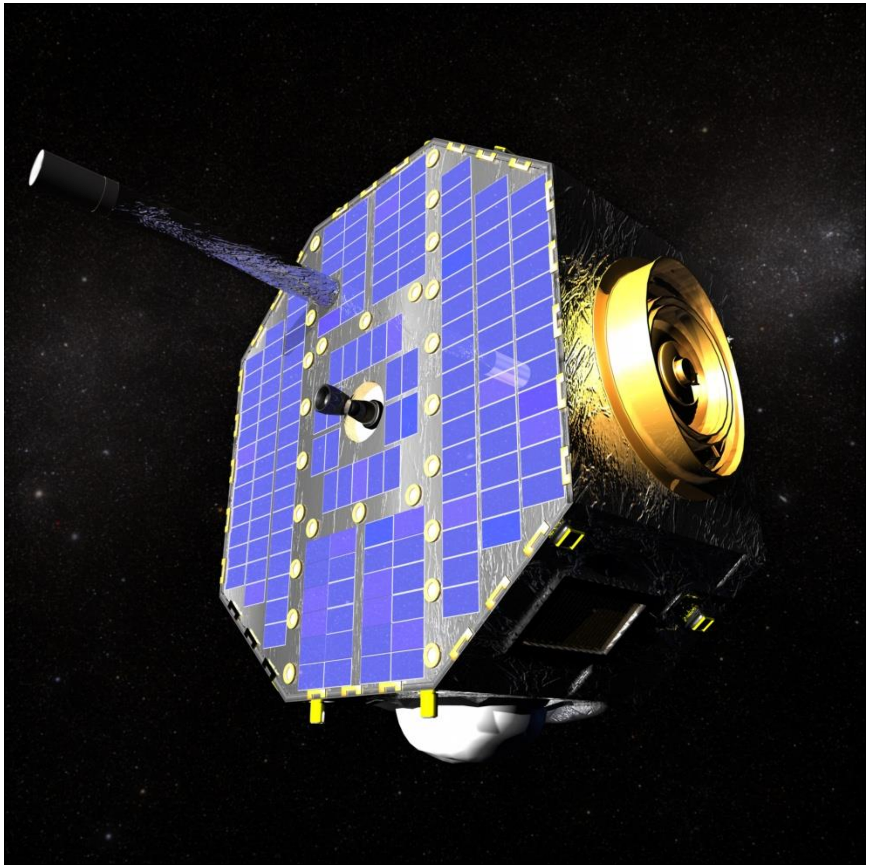
- Physics behind: the reaction of resonant charge exchange
- Ubiquitous in all regions of the heliosphere
- Colliding partners do not change momentum, but exchange charge
- Thus a former ion becomes a neutral atom and runs away from the reaction site unimpeded
- It carries information on the physical state of the parent plasma at long distances…
- … just as good old photons in astronomy

# Interstellar Boundary Explorer

- Dedicated spacecraft, First Neutral Atom Astronomy space mission:
- Interstellar Boundary Explorer (IBEX)
- Study and understand the interaction of the heliosphere with its interstellar neighborhood…
- …by direct sampling of interstellar atoms and heliospheric ENAs.

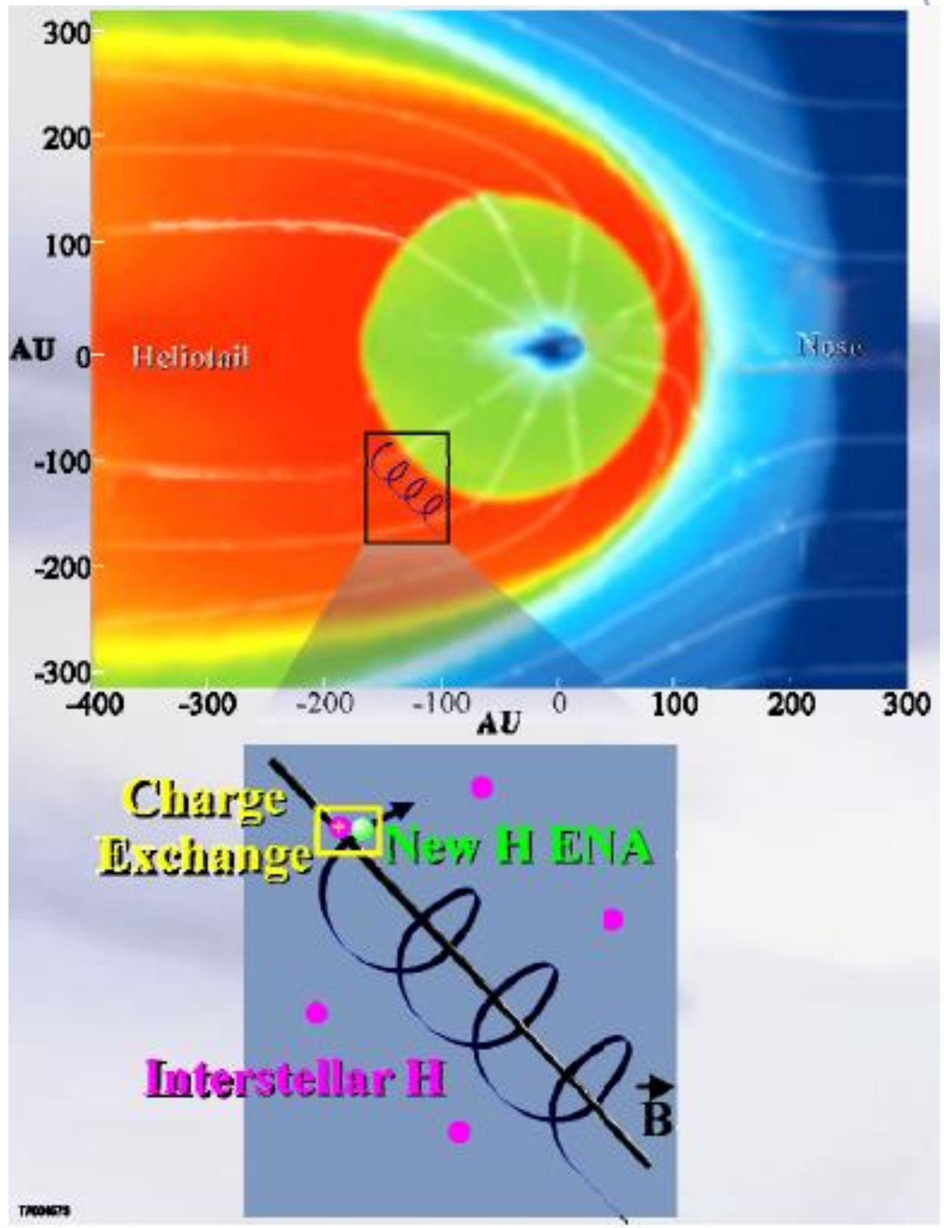


# Interstellar Boundary Explorer

- IBEX measures heliospheric ENAs that are protons which have exchanged charge with the ambient neutral hydrogen inside the heliosphere
- Line-of-sight measurements:

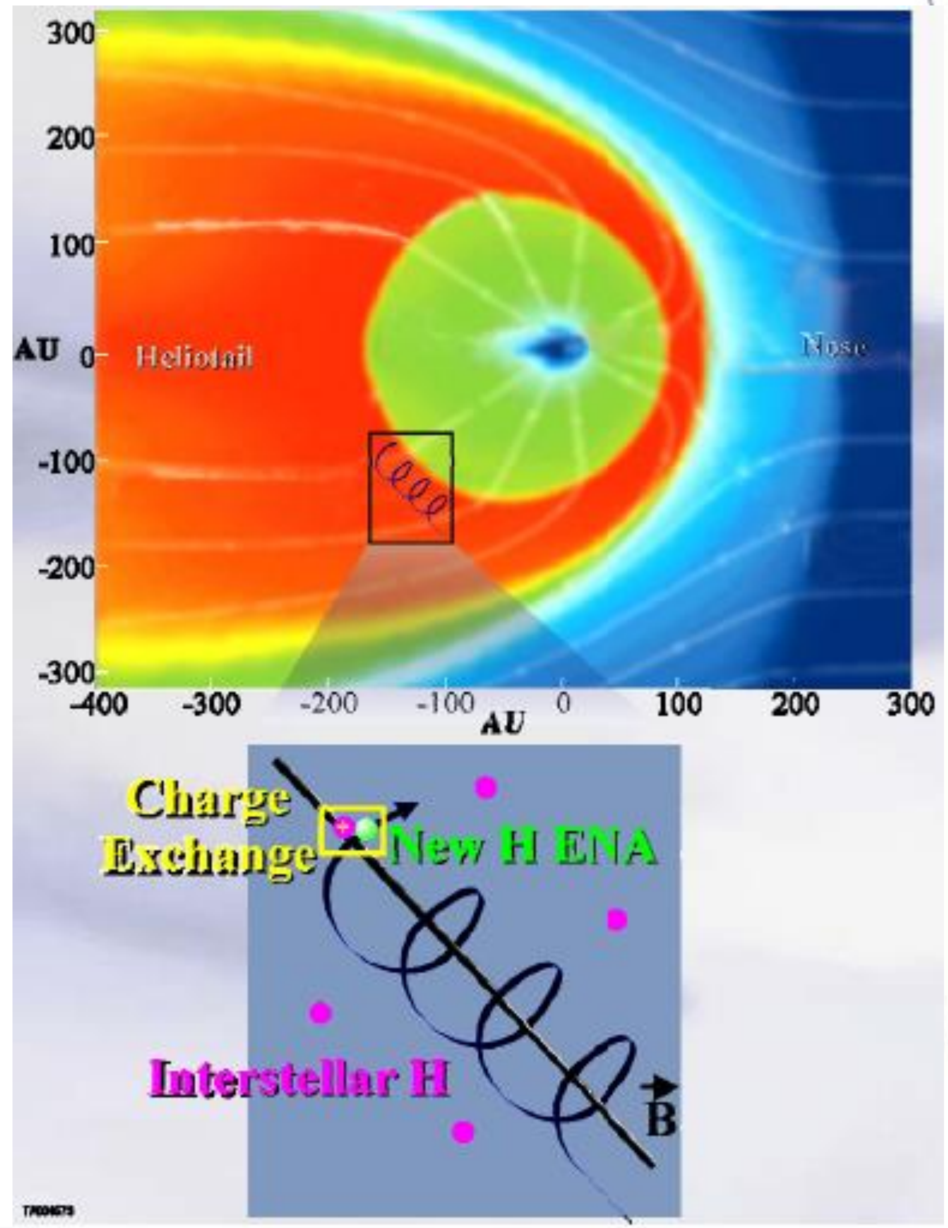
$$J_{ENA} = \int dx\, n_H\, J_{ION}\, \sigma$$

- Reaction in the plasma reference system, i.e. moving
- Thus ENAs must be corrected for the Compton - Getting effect (equivalent to photon redshift)

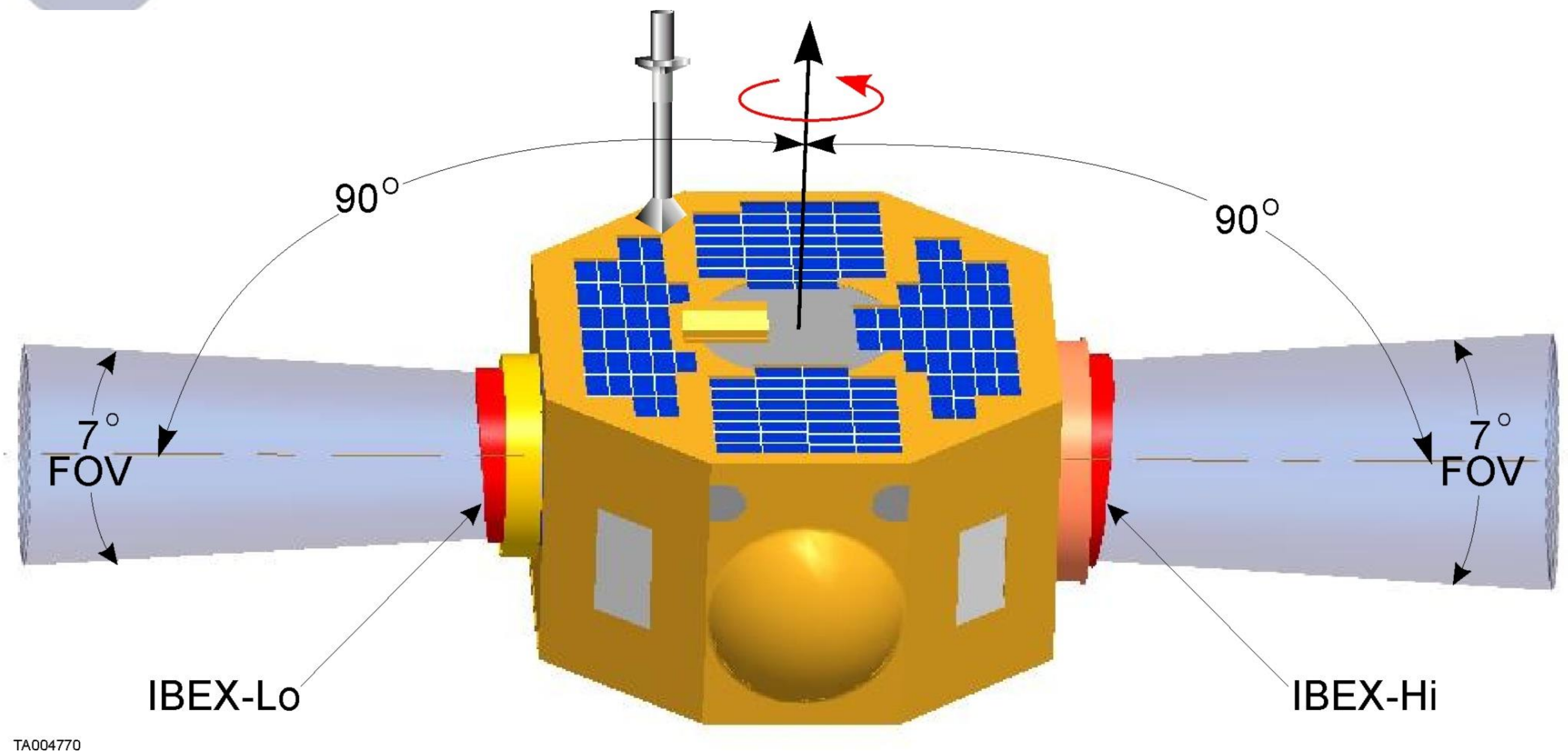


# Interstellar Boundary Explorer

- Unlike photons, propagation speed is a function of energy, thus atoms detected simultaneously were not created simultaneously
- ENA propagate almost straight lines, but not the slowest ones
- Additional correction needed for the motion of the detector
- Several species accessible:
- In addition to heliospheric H ENAs, IBEX also measures interstellar He, O, Ne, H.
- It has even successfully detected interstellar D! (M.A. Kubiak et al. & Rodriguez et al., 2013)



# IBEX S/C: Simple Sun-Pointed Spinner

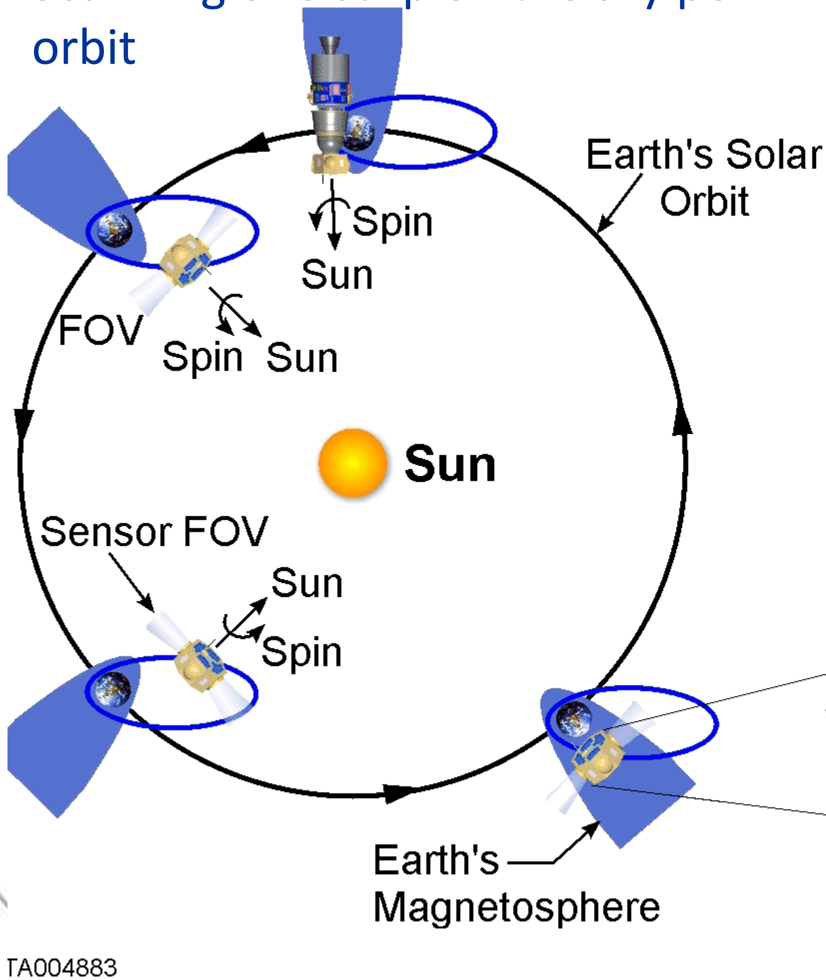


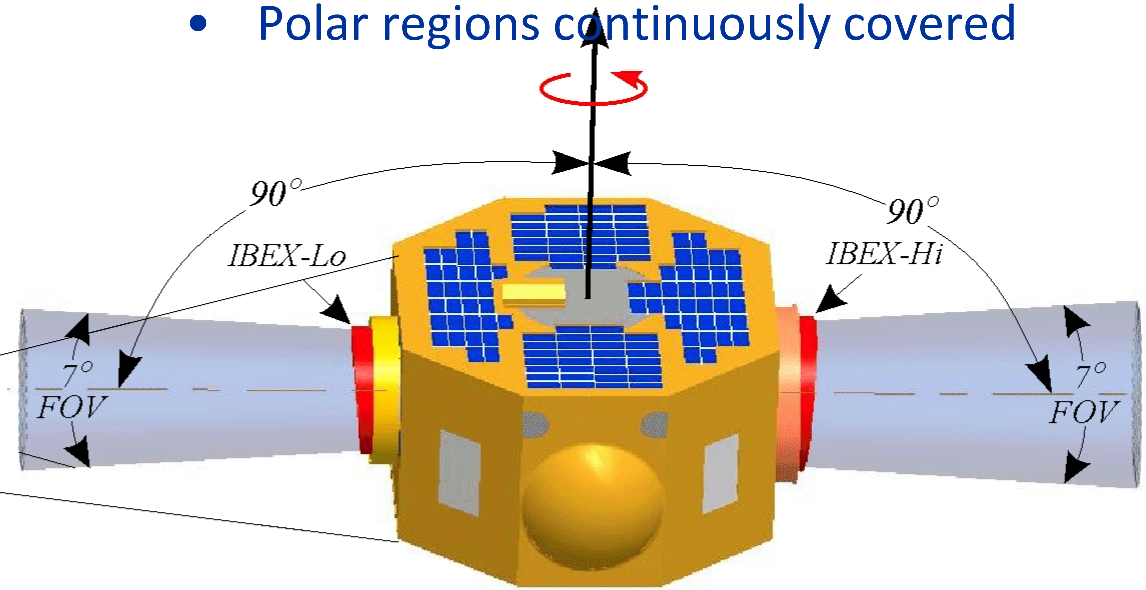

- Two huge aperture single pixel ENA cameras:
  - IBEX-Lo (~10 eV to 2 keV)
  - IBEX-Hi (~300 eV to 6 keV)
- Simple sun-pointed spinner (4 rpm)

# Interstellar Boundary Explorer

- Elongated, 50 $R_E$ orbit
- Spin axis fixed during an orbit
- Scanning one strip on the sky per orbit

- Two single-pixel mass spectrometers
- Continuous switching energy channels
- Energy range from 0.01 to 6 keV
- Set of full-sky maps: ½ year
- Better: wait 1 year, homogeneous energy full sky
- Polar regions continuously covered




IBEX Spacecraft

# IBEX largest surprise

- Before launch, the signal from the inner heliosheath was expected to be organized along the interstellar gas upwind – downwind axis
- Depending on the character of the interaction, the maximum signal was expected either from upwind or from downwind
- IBEX looked and discovered this:

# IBEX largest surprise

- The Ribbon!!!
- Arc-like structure, offset from upwind direction, ~170° in diameter
- Spectrally different from the ambient flux, slightly changing with time.
- Not predicted by any models!
- ~10 explanations proposed by now…

The Astrophysical Journal Supplement Series, 203:1 (36pp), 2012 November

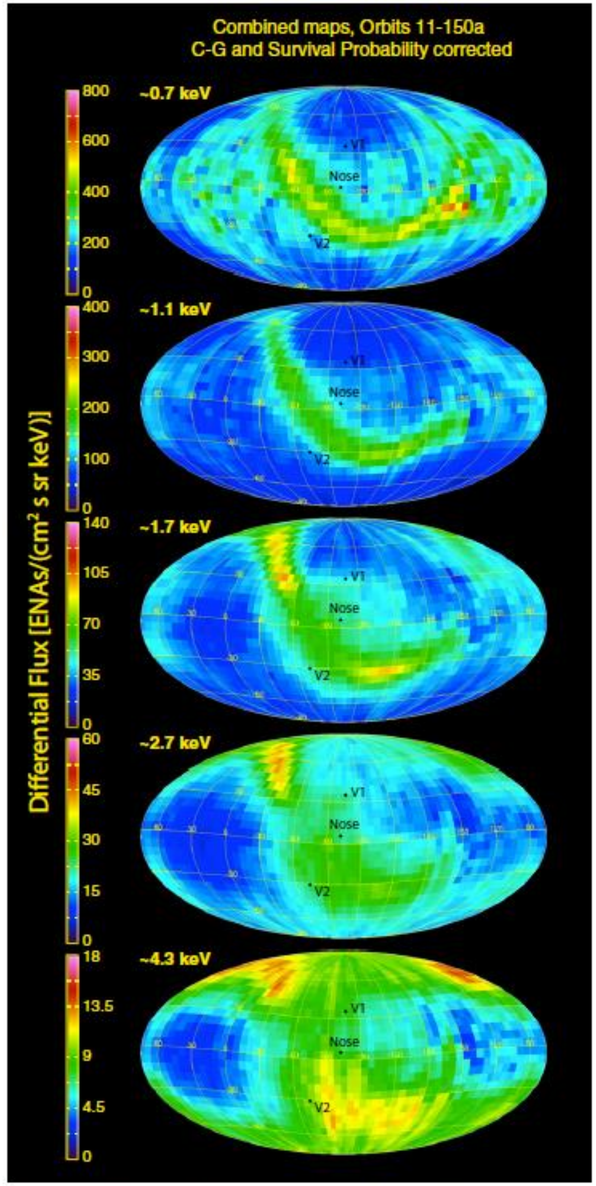



Figure 14. "Best" statically combined survival probability corrected maps, representative of inward-directed ENA fluxes in the outer heliosphere, before any losses. Data are C-G corrected and in a format similar to Figure 7. Again, C-G correction of statistically noisy data around the "hole" on the right side

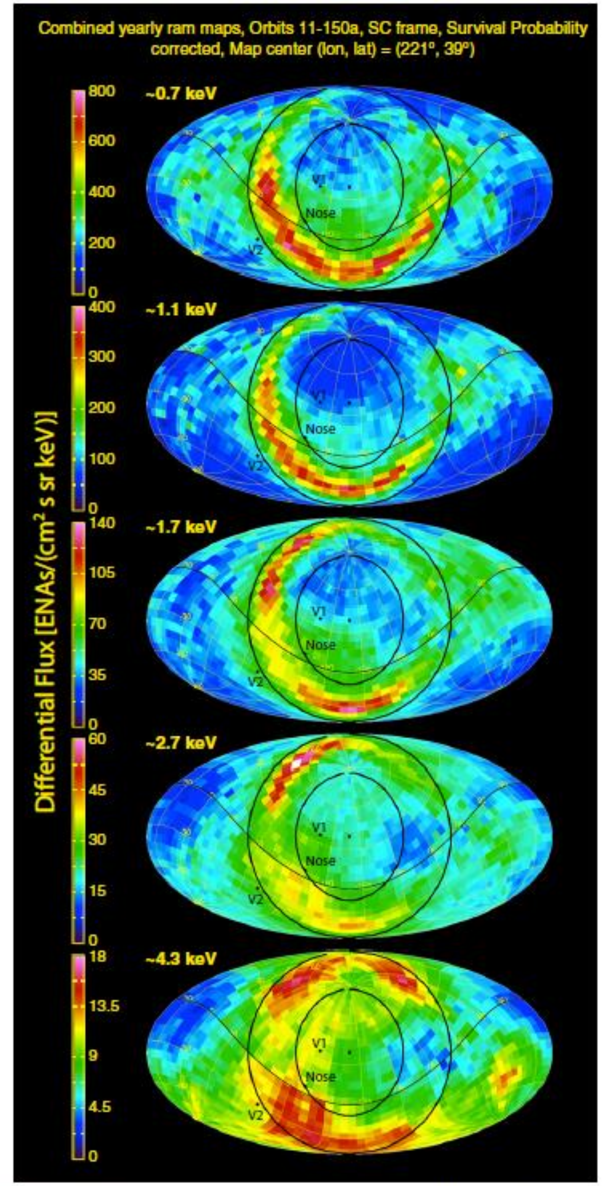
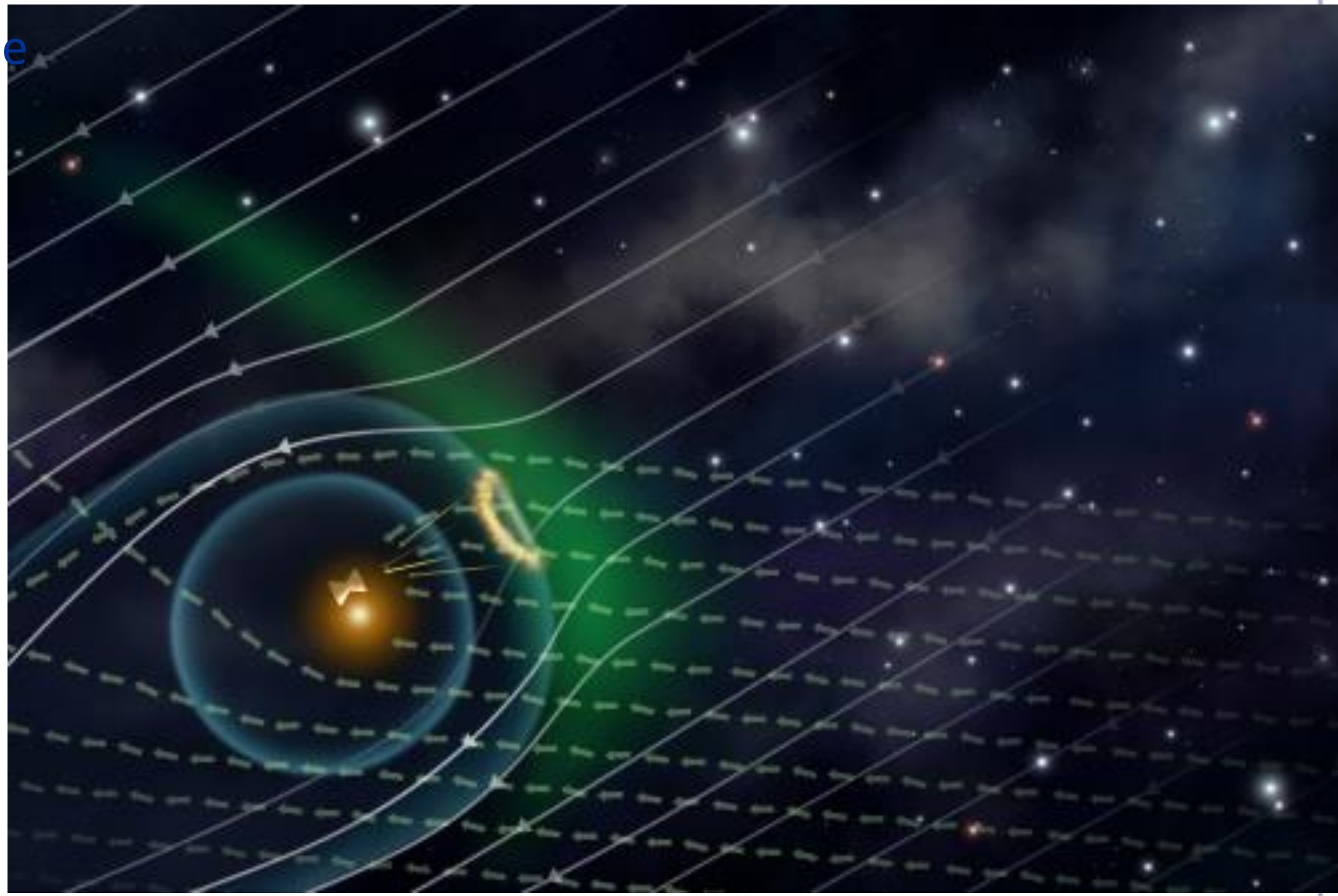



Figure 29. Survival probability corrected ram maps in a Mollweide projection centered on the symmetry direction. The ecliptic is identified by the black line, while circles bracket the Ribbon to help guide the eye.

# IBEX largest surprise

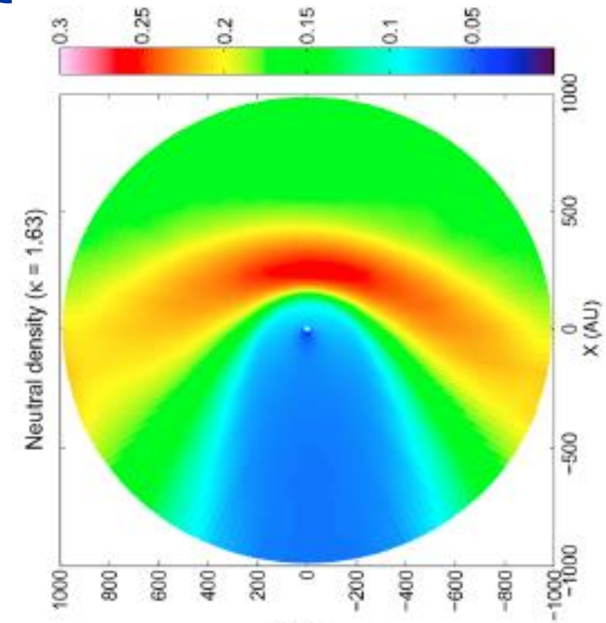


- Most likely is this: Ribbon is the location where ENAs running away from the heliosphere:
  - get ionized
  - are picked up by the interstellar magnetic field draped at the heliopause
  - gyrate perpendicular to the field lines
  - eventually are neutralized again and come back to the heliosphere (the Heerikhuisen mechanism)
- Thus the center of the Ribbon points to the direction of the magnetic field (after field wrapping is taken into account)

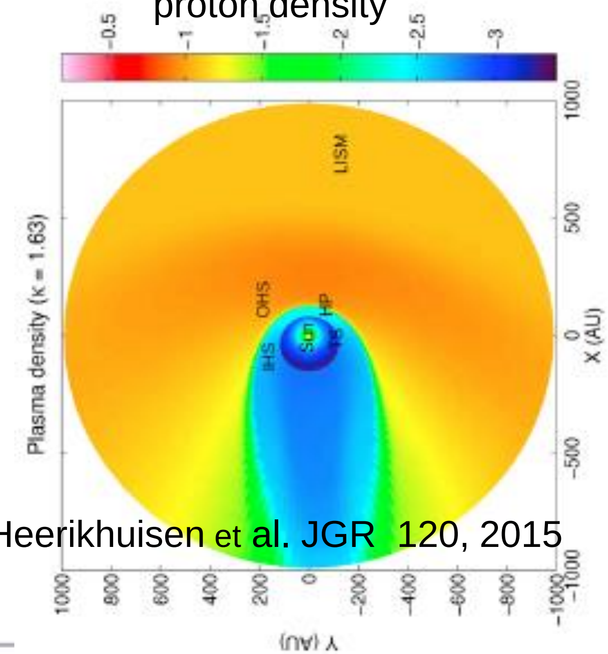
# ENAs in the heliosphere

- Heliospheric ENAs are former solar wind ions that have exchanged charge with interstellar H atoms in the inner heliosheath
- We see mostly ENAs from the inner heliosheath
- This region holds several co-existing ion populations
- ENAs inherit the energy from the parent ions, 0.7 – 100 keV
- For ENAs to be observable at 1 au, their parent ions must have had velocity directed at the Sun
- For some ion populations, that's not so easy and we don't see them
- Charge exchange intensity drops with the energy because the cross section drops with the energy

neutral H density



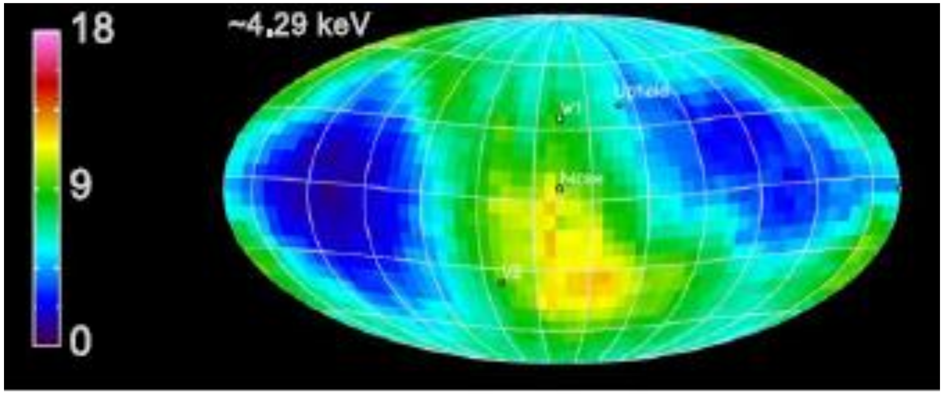

proton density




Heerikhuisen et al. JGR 120, 2015

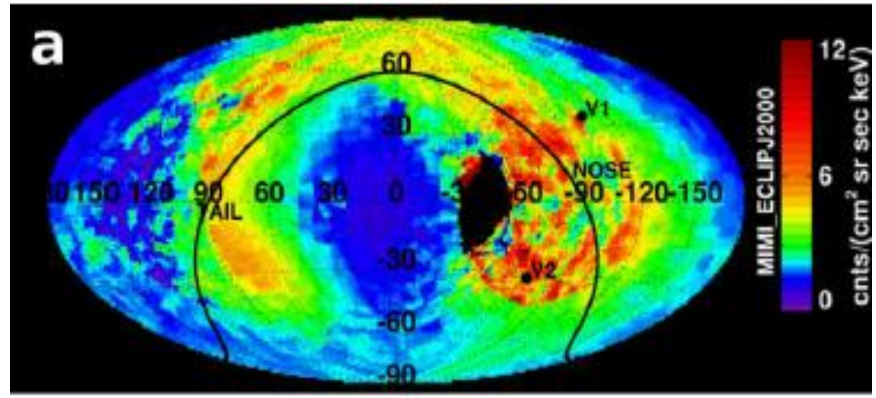
# Observations of ENAs at different energies

**IBEX-Hi, ~4 keV**



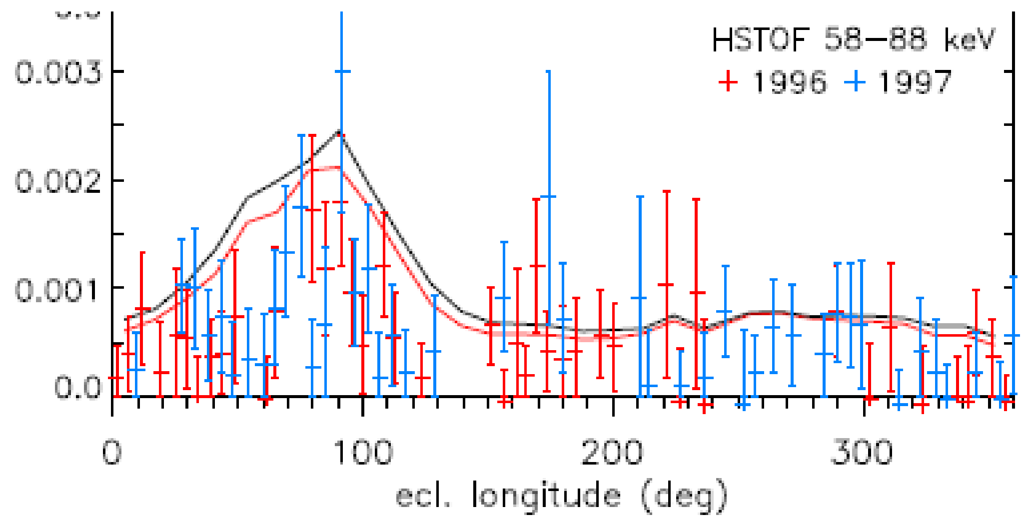

McComas et al., ApJS 248:26, 2020

**Cassini INCA, ~5-13 keV**



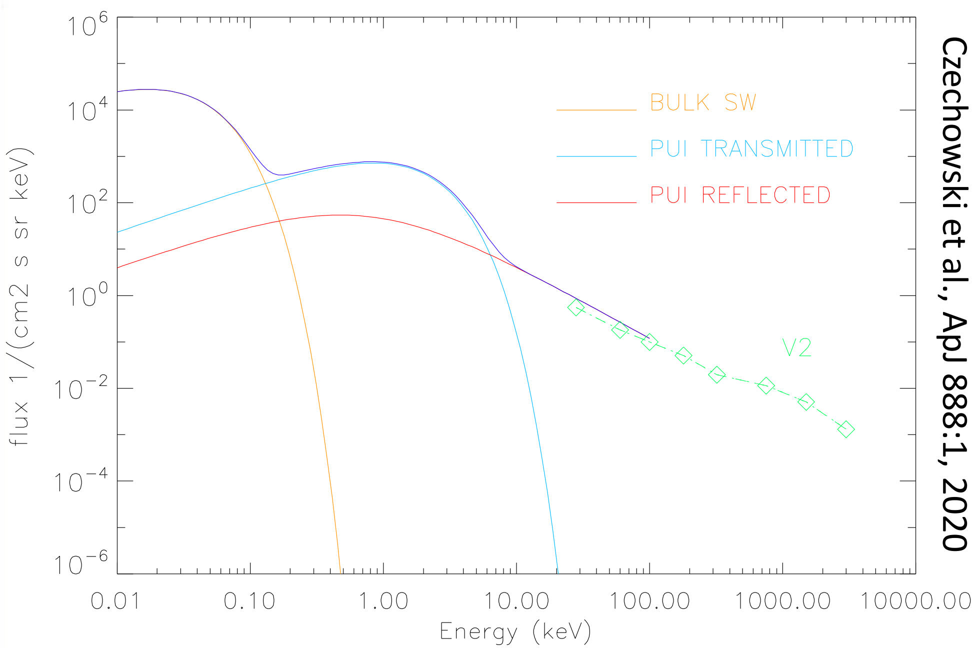

Dialynas et al.,J.Phys.C 900, 012005, 2017.

- Provide a global view of the heliosheath
- Different sky distributions at differ energies
- Different ENA energies represent different ion populations
- What are the parent ion populatio




Czechowski et al., ApJ 888:1, 2020

# Ion populations in the heliosheath




Czechowski et al., ApJ 888:1, 2020

Zank theory!
Zank et al.,
– JGR 101, 457, 1996
– ApJL 708, 1092, 2010

- Core ions make the bulk plasma flow
- Pickup ions provide pressure (hot!)
- Suprathermal ions flow with the plasma and are source of highest-energy ENAs

- Core solar wind
- Pickup ions (transmitted)
- Pickup ions (reflected, accelerated and only then transmitted)
- These are parent populations for the ENAs

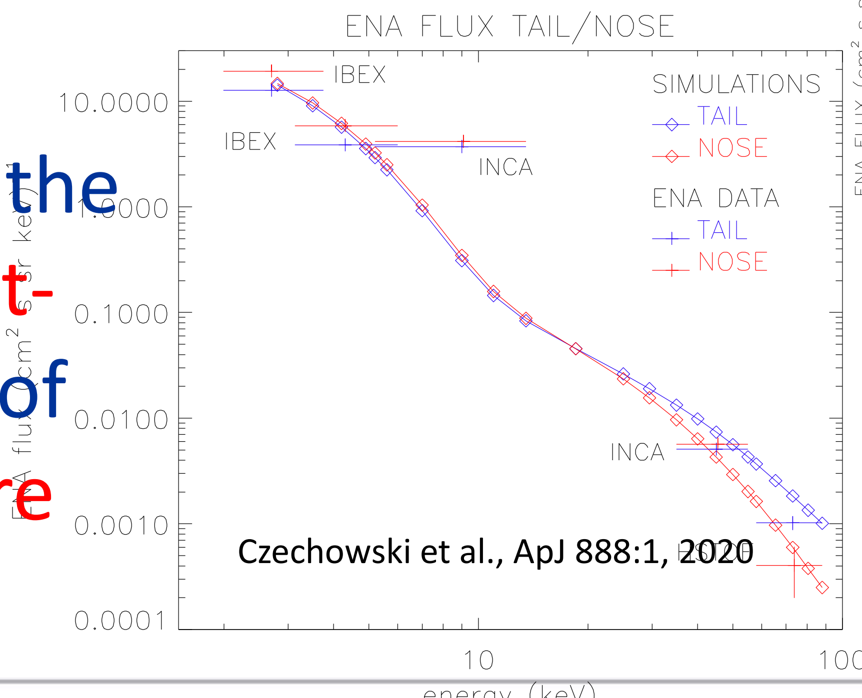
# ENAs in the heliosphere simulated

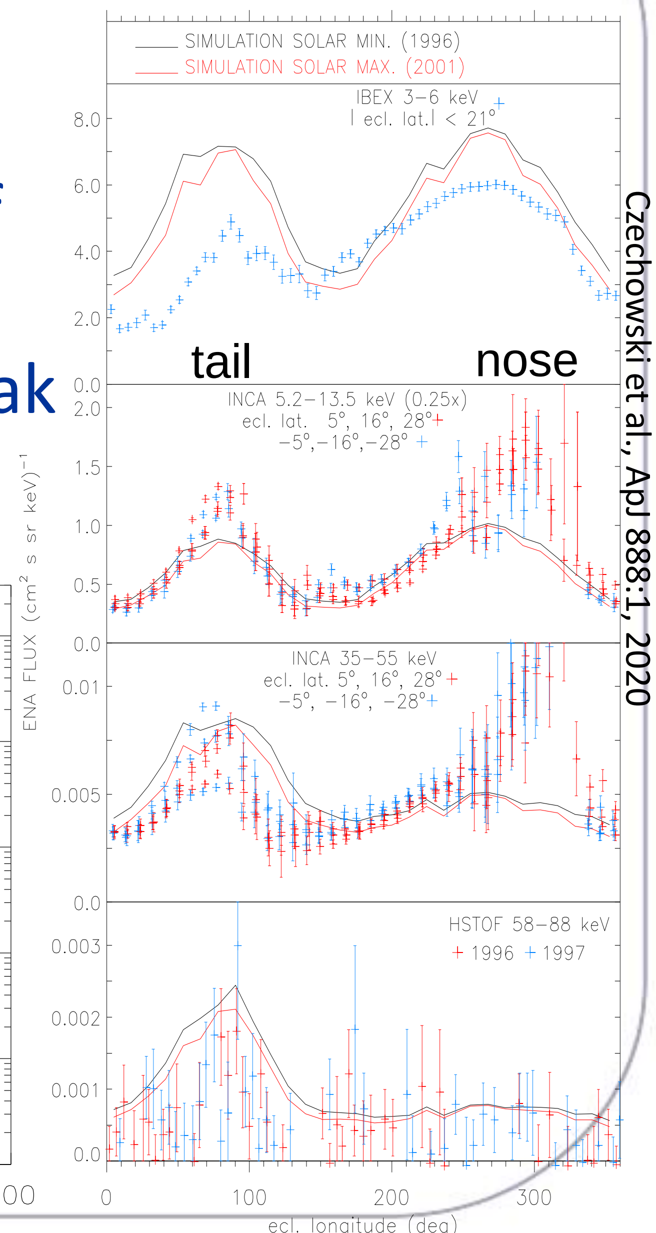
- This scenario tested in simulations
  - Realistic PUI distribution at the termination shock from WTPM & SHOIR
  - Global heliosphere simulations performed for observation-based LISM & SW conditions using the Huntsville model
  - TS shock strength from in situ Voyager observations
  - Energy-dependent c-x cross section
  - Gradual attenuation of parent ions due to c-x losses accounted for
  - Re-ionization of ENAs for large paths in the tail region taken into account

# ENAs understood

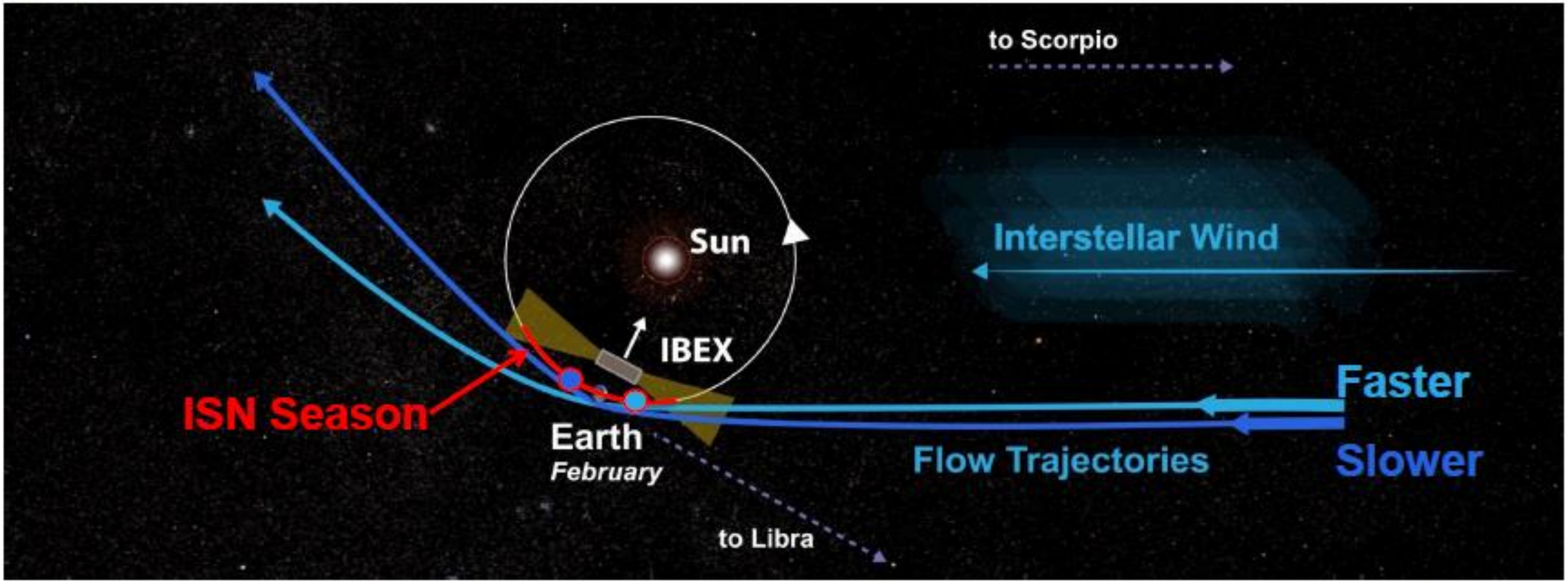
- Obtained:
  - Reproduction of the spatial structure of ENAs
  - Note the transition from 2-peak to1-peak
  - Reproduction of ENA spectrum

All this within the classical comet-like paradigm of the heliosphere



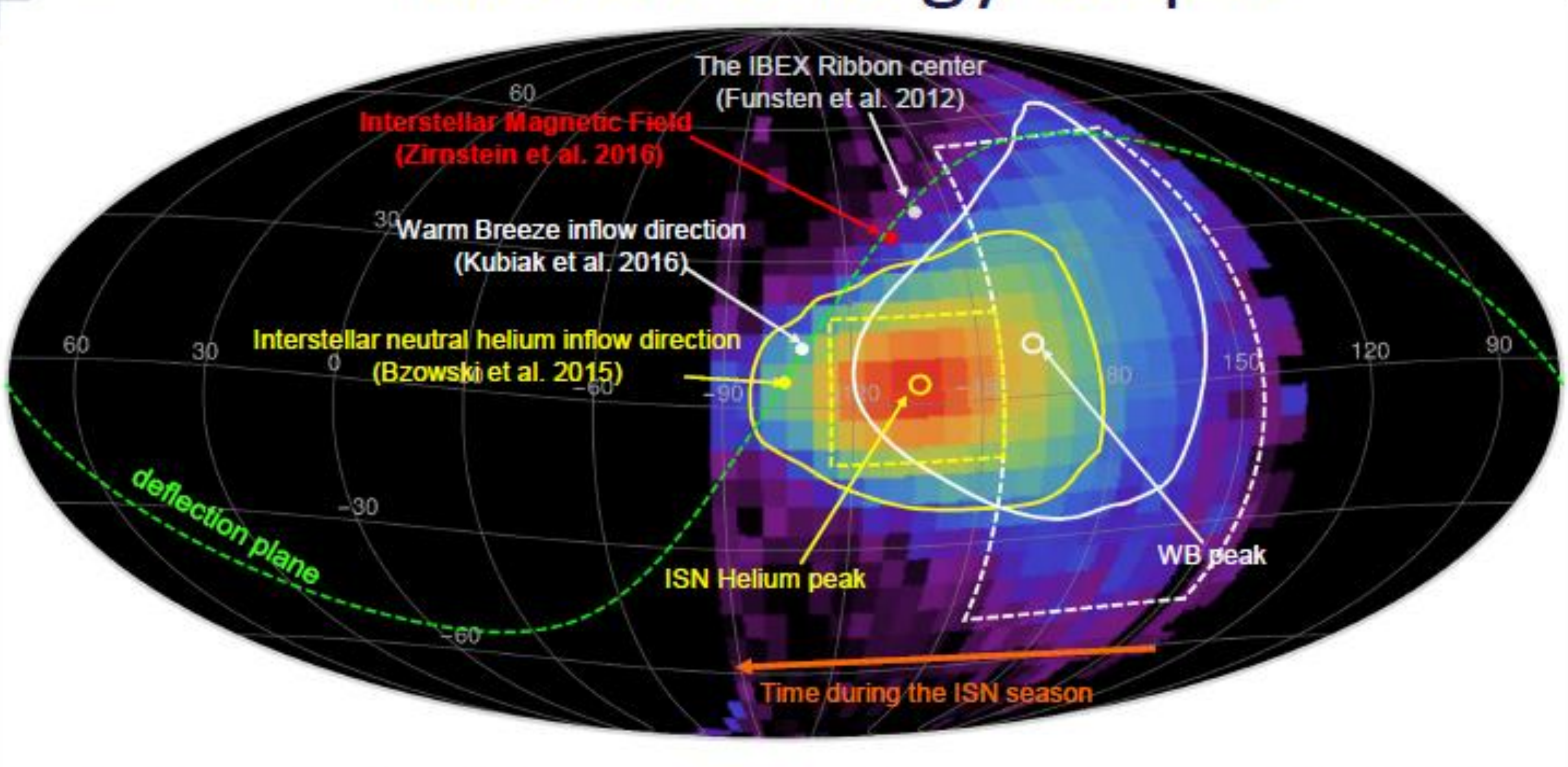



# IBEX-Lo observations of ISN atoms




- The **gravitational bending** of the atom trajectories (velocity-dependent) is "lensing" the ISN He flux distribution observed by *IBEX* at 1 au
- **Slower ISN He atoms are observed earlier during the ISN season**
- The gravity is compensated for **ISN H atoms** by the radiation pressure (→ **observed late during the ISN season**)
- Wide energy channels of *IBEX*-Lo → information about atom velocity is lost
- This analysis: ***IBEX*-Lo energy step 2 observations** – almost entirely **ISN He atoms**

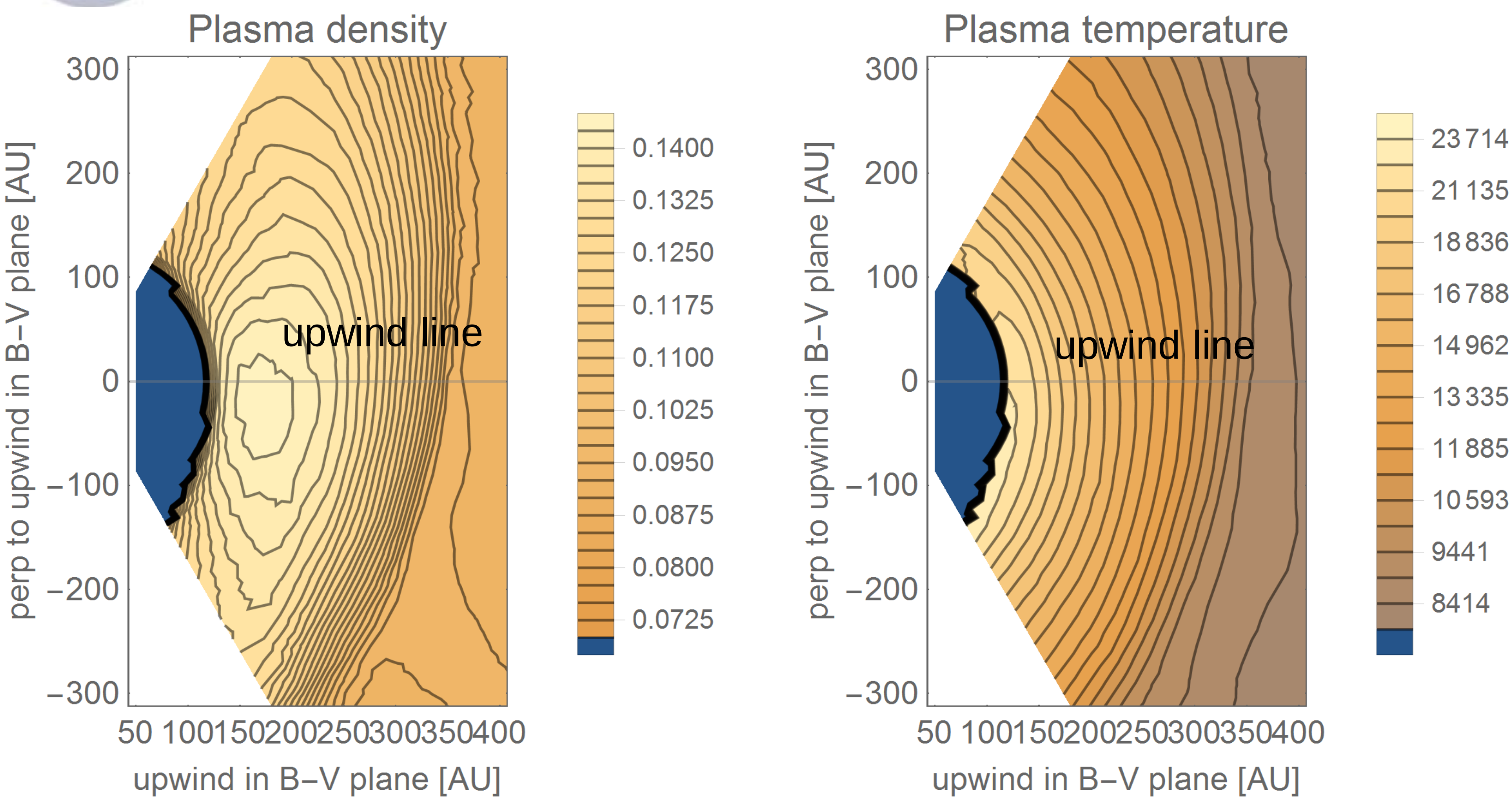
# *IBEX*-Lo energy step 2




- The interstellar neutral He (ISN He) signal observed by *IBEX* is a superposition of **the primary ISN He** directly from the Local Interstellar Medium (LISM) and of **the secondary population**, created in the outer heliosheath due to charge exchange between $He^+$ and He
- **The simulated signal is sensitive to**
  - the direction and speed of Sun's motion in the LISM
  - direction and strength of unperturbed $B_{IMF}$ field
  - temperature and density of $He^+$ in OHS

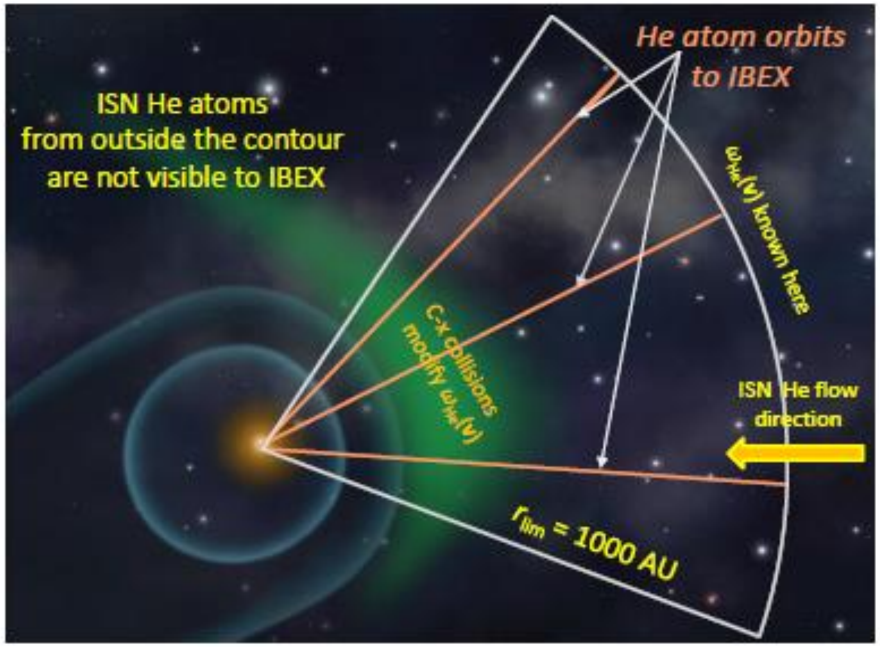
**_IBEX_ ISN He data suitable to study the LISM conditions!**

# Plasma within OHS: B-V plane



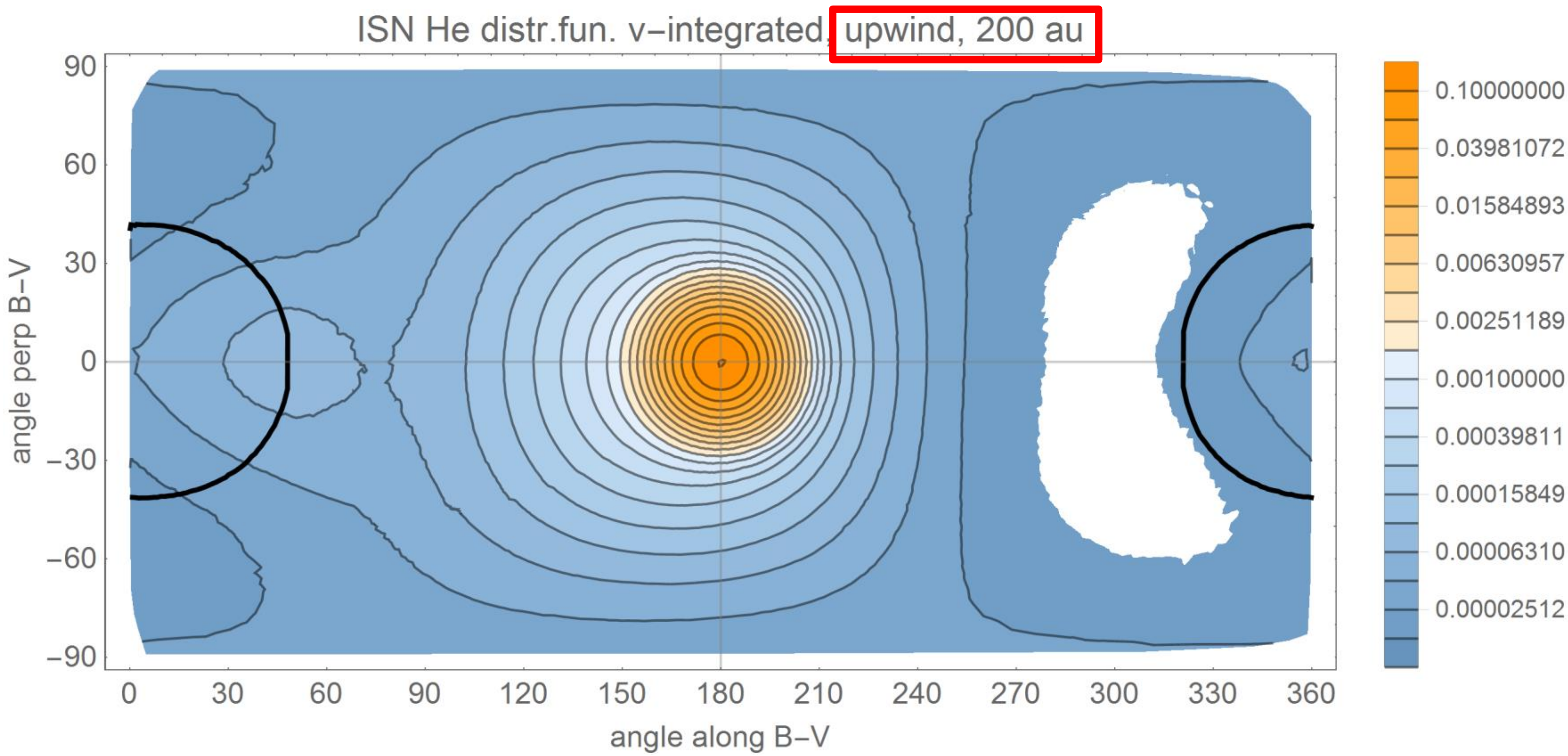

- Plasma within B-V plane
- Note the asymmetry relative to upwind direction due to I/S B field.
- Note the temperatures are much higher than those obtained from WB fitting

# Synthesizing the *IBEX* ISN He signal



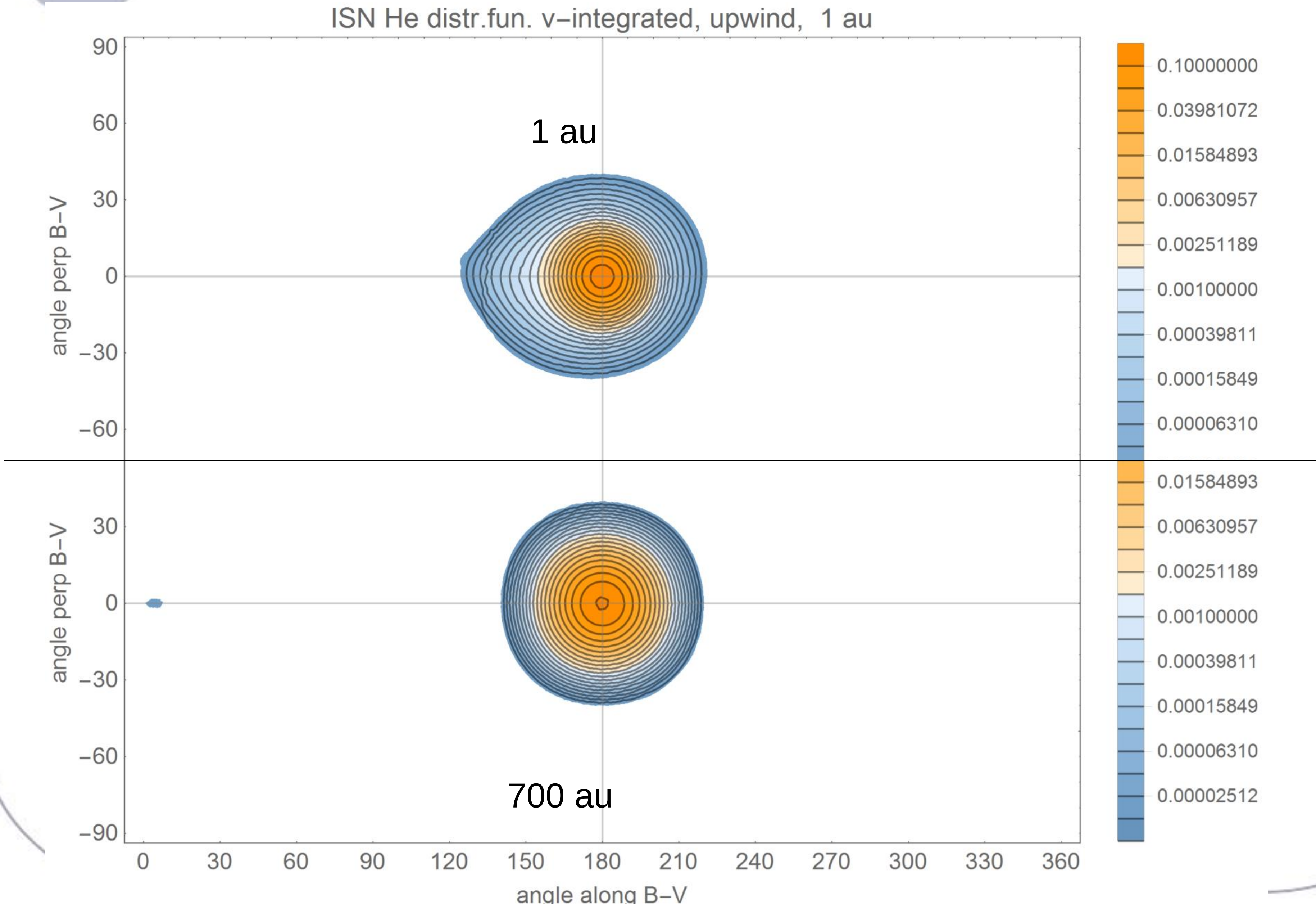

- Allow for **charge exchange collisions** in front of HP (outer heliosheath) $He + He^+ \leftrightarrow He^+ + He$
- Charge exchange with the more abundant H, $H^+$ much less important because the cross section ~250 times lower
- Collisions will **populate and de-populate hyperbolic atom trajectories** known to hit IBEX-Lo
- Only the observable trajectories are considered. All other trajectories are ignored
- **The starting values** for populating the orbits are adopted based on the adopted distribution function for the **unperturbed LISM**
- Synthesize the signal observed by IBEX-Lo by **solving the production and loss balance equation for all trajectories hitting *IBEX***

# Distribution function of ISN He in OHS



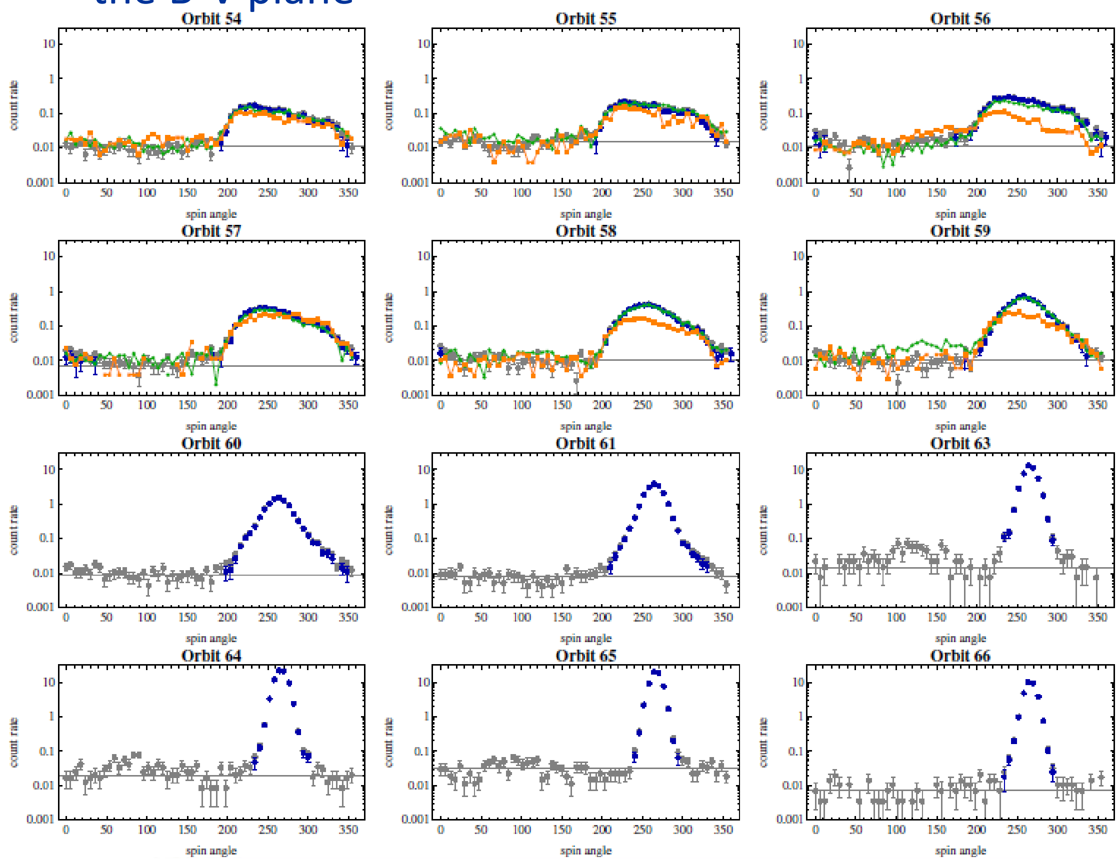

Simulated distribution function of ISN He in the outer heliosheath. The symmetry axis seems to the the plane defined by the Sun’s velocity vector and the B field vector

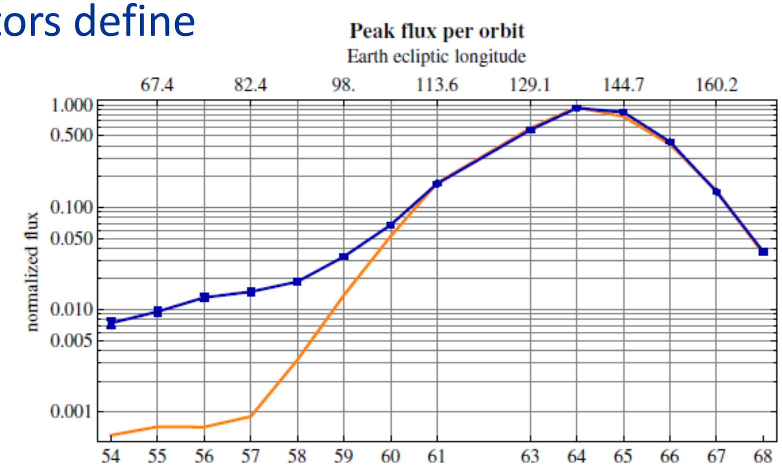
# Distribution function of ISN He

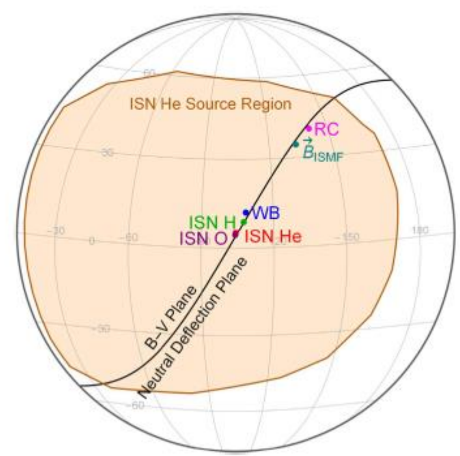


# IBEX-Lo observations of ISN atoms

- In addition to the expected flow of ISN He atoms IBEX discovered an additional signal
- It was dubbed the Warm Breeze
- It is the secondary population, coming from chargé exchange between ISN gas and plasma in the outer heliosheath
- Direction and speed of the Warm Breeze determined
- Found deflection from the ISN direction. The two vectors define the B-V plane



# LISM conditions: what we know, and how?

- **ISN H density**: $n_{H,TS}$=0.09±0.02cm$^{-3}$ (at the termination shock; from SW slowdown & PUIs at *Ulysses*; Richardson et al. 2008, Bzowski et al. 2008)

  → hence in the LISM: **$n_{H,LISM}$ = 0.016±0.04 cm$^{-3}$** (Bzowski et al. 2009)
- **ISN He density**: **$n_{He,LISM}$=0.0150±0.015 cm$^{-3}$** (from *Ulysses* $He^{++}$ & $He^{+}$ PUI and ISN He direct sampling, Gloeckler et al. & Witte 2004)
- **Temperature**: **$T_{LISM}$ = 7500 K**
- **Sun's velocity**: **$v_{LISM}$ = 25.4 km/s**

  **($\lambda_{LISM}$, $\beta_{LISM}$) = (255.7°, 5.1°)**

  (from ISN He direct sampling @ *Ulysses* & *IBEX*, Witte 2004 & McComas et al. 2015)
- **Magnetic field: $B_{IMF}$ = 2.93±0.08 μG**

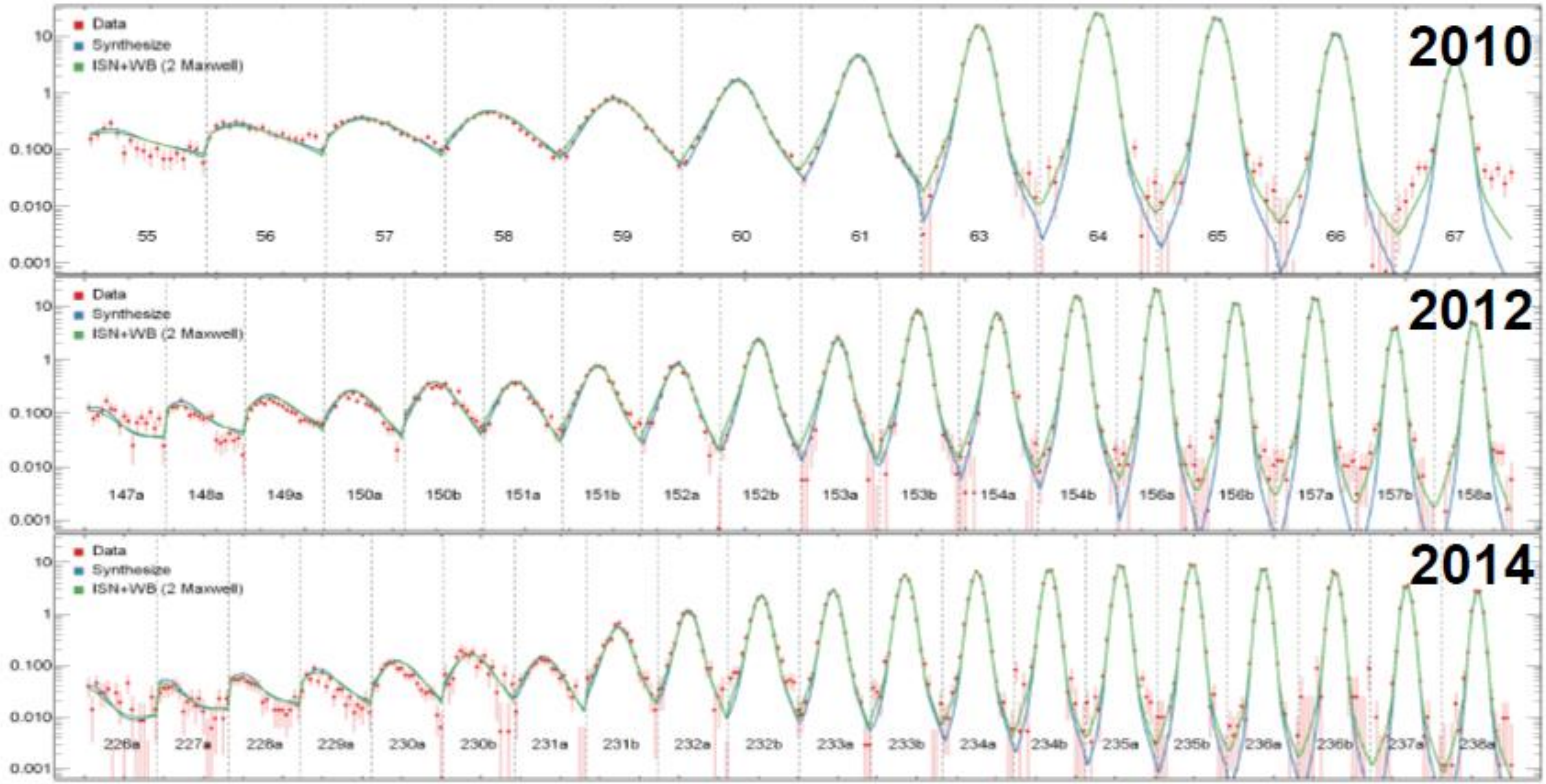
  **($\lambda_{IMF}$, $\beta_{IMF}$) = (227.28°±0.69°, 34.62°±0.45°)**

  (from fitting heliosphere model to HP distance and *IBEX* Ribbon center & diameter; agreement btwn Zirnstein et al. 2016, Grygorczuk et al. 2011, Heerikhuisen et al. 2011, also Frisch et al. 2015 from starlight polarization on IS dust grains)
- $B_{IMF}$ direction additionally supported by being co-planar with the neutral deflection plane; secondary ISN He from IBEX direct-sampling of ISN He, **($\lambda_{sec}$, $\beta_{sec}$) = (251.6°±1.4°, 12.0°±0.9°)** (Kubiak et al. 2016)
- **Solar wind ram pressure** at all heliolatitudes: in-ecliptic (*OMNI*, since 1960-ties) & out-of-ecliptic (IPL scintillation, since ~1985, Tokumaru et al. 2015, Sokół et al. 2013, 2015)

# LISM plasma

- **Heliosphere** is created due to **pressure balance at the heliopause.** Pressure terms:
  - plasma ram pressure $p = \rho v^2$; $\rho$: mass density
  - magnetic pressure $B^2/8\pi$ (B: $\mu$G)
  - thermal pressure
  - ACR & CR pressure
- Ram pressure dominates both at the LISM and SW sides
- Magnetic pressure of second importance
- Thermal and ACR/CR pressures negligible
- Plasmas composed mostly of $H^+$ & $He^{++}$ (SW) and $H^+$ & $He^+$ (LISM); **$He^+$ contribution not negligible!**
- LISM conditions determined mostly by ionizing radiation from
  - nearby stars
  - hot plasma from the Local Bubble (LB)
  - hypothetical conductive interface between LIC and LB
- Ionization state of LISM at the Sun: balance between photoionization and radiation absorption
- Absorption very wavelength-selective
- $He^+/He$ & $H^+/H$ poorly known but needed in LISM studies!

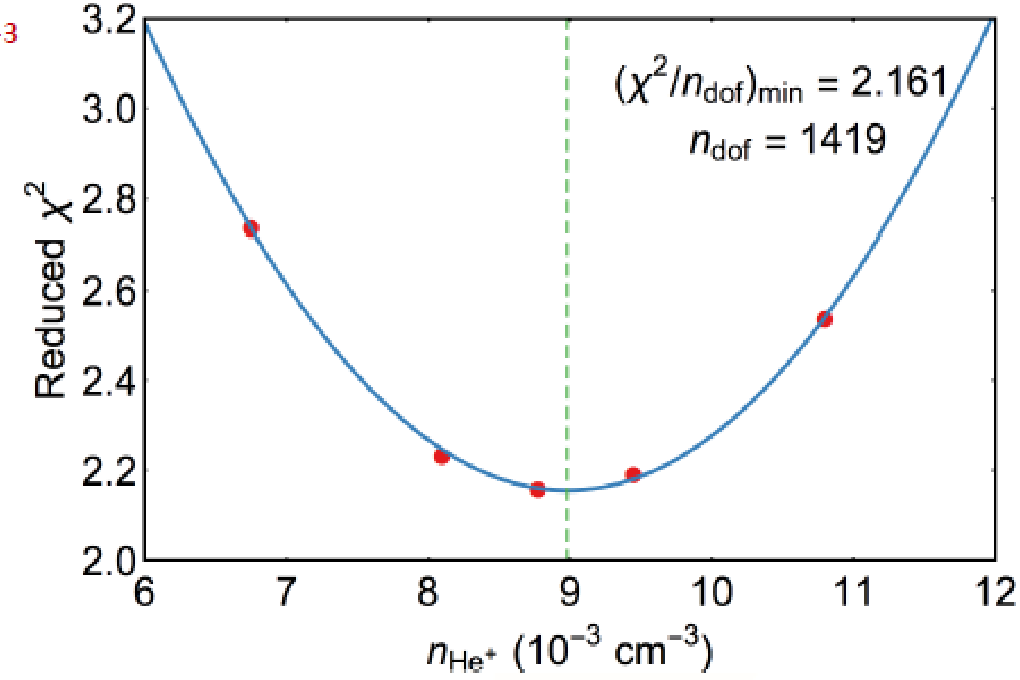
# Data and modeled signal




- Both the two-population model and the current model give very similar signals
- Small differences mostly at the wings for some orbits

# Results

- **Best $\chi^2$ for $n_{He^+} = (8.98 \pm 0.12) \times 10^{-3}$ cm$^{-3}$**
- $\chi^2_{min}/n_{dof} = 2.161$ with $n_{dof} = 1419$
- **Three parameters fitted**:
  - $n_{He^+}$
  - IBEX He response (sensitivity)
  - sensitivity reduction after PAC voltage reduction in 2012
- For good fit expected $\chi^2_{min}/n_{dof} \approx 1$ room for improvement...




- For the same data range and **2 Maxwell-Boltzmann populations**: primary (Bzowski et al. 2015) and Warm Breeze (Kubiak et al. 2016): $\chi^2_{min}/n_{dof} = 2.204$
- The inflow direction, speed, and temperature of the LISM is not fitted in this study!
- The estimated **uncertainty results from fitting solely**, likely there are larger systematic uncertainties

# Table of LISM properties

- The following table summarizes the LISM properties known from the previous studies and this analysis

| quantity | value | reference |
|---|---|---|
| Plasma mass density[1] | $\rho_p = 0.09\ m_p\ cm^{-3}$ | Zirnstein et al. 2016 |
| LISM temperature | $T_{LISM} = 7500 \pm 300$ K | McComas et al. 2015, Bzowski et al. 2014, Woods et al. 2015 |
| H number density | $n_H = 0.16 \pm 0.04\ cm^{-3}$ | Bzowski et al. 2009 |
| He number density | $n_{He} = (15.0 \pm 1.5) \cdot 10^{-3}\ cm^{-3}$ | Gloeckler et al. 2004, Witte 2004 |
| **$H^+$ number density** | **$n_{H+} = (5.41 \pm 0.36) \cdot 10^{-2}\ cm^{-3}$** | **This work** |
| **$He^+$ number density** | **$n_{He+} = (8.98 \pm 0.91) \cdot 10^{-3}\ cm^{-3}$** | **This work** |
| **H ionization degree** | **$X_H = 0.26 \pm 0.05$** | **This work** |
| **He ionization degree** | **$X_{He} = 0.37 \pm 0.05$** | **This work** |
| **Electron density** | **$n_e = (0.063 \pm 0.003)\ cm^{-3}$** | **This work** |
| Magnetic field strength | $B_{IMF} = 2.93 \pm 0.08\ \mu G$ | Zirnstein et al. 2016 |
| Magnetic field direction[2] | $(\lambda_{IMF}, \beta_{IMF}) = (227.28° \pm 0.69°, 34.62° \pm 0.45°)$ | Zirnstein et al. 2016 |
| Sun's speed in LISM | $v_{Sun} = 25.4 \pm 0.4$ km $s^{-1}$ | McComas et al. 2015 |
| Sun's direction in LISM[2] | $(\lambda_{Sun}, \beta_{Sun}) = (257.7° \pm 1.4, 5.1° \pm 0.2)$ | McComas et al. 2015 |
| B-V plane normal[2,3] | $(\lambda_{BV}, \beta_{BV}) = (349.7°, 37.8°)$ | McComas et al. 2015 & Zirnstein et al. 2016 |

[1]$m_p$ = proton mass; [2]J2000 ecliptic coordinates; [3]obtained as the direction of the $\boldsymbol{v}_{Sun} \times \boldsymbol{B}_{IMF}$ vector

# Summary

- **Fluxes of interstellar neutral He atoms observed by IBEX are sensitive to details of the physical state of the plasma in the outer heliosheath**
- Detailed analysis of the ISN He signal allows for determination of the $He^+$ density in the LISM
- The **$He^+$ density in the LISM** obtained in this study is **$8.98 \times 10^{-3}$ cm$^{-3}$**
- Results of various heliospheric studies seem to show **a consistent picture of the heliosphere:**
  - the IBEX ribbon signal likely formed in the secondary ENA mechanism, and thus connected with the magnetic field outside the heliosphere
  - the Voyager in situ obs are consistent with the LISM paramtrs determined independently
  - the ISN He signal is composed of the primary and secondary components
  - the ionization state of the LISM **at the heliosphere** results from the interstellar radiation field, partly aborbed inside the LISM; here **we determined ionization degree of H and He**

# Concluding remarks

- Heliosphere is our astrophysics laboratory, where we can study the interaction between the stars and surrounding interstellar medium with unprecedented level of detail
- Neutral atoms in the heliosphere are fascinating:
- They transport Energy and momentum across plasma with little interaction
- They are able to cross borders unpenetrable for charged particles
- They bring information on the stare of plasma t their birth sites
- They enable studying the interstellar matter without leaving the solar system
- They are able to constrain heliospheric models and the boundaries of the Solar System
- The heliospheric physics has never been as fascinating as now!