# Interstellar Neutral Atoms from the Very Local Interstellar Medium to 1 au

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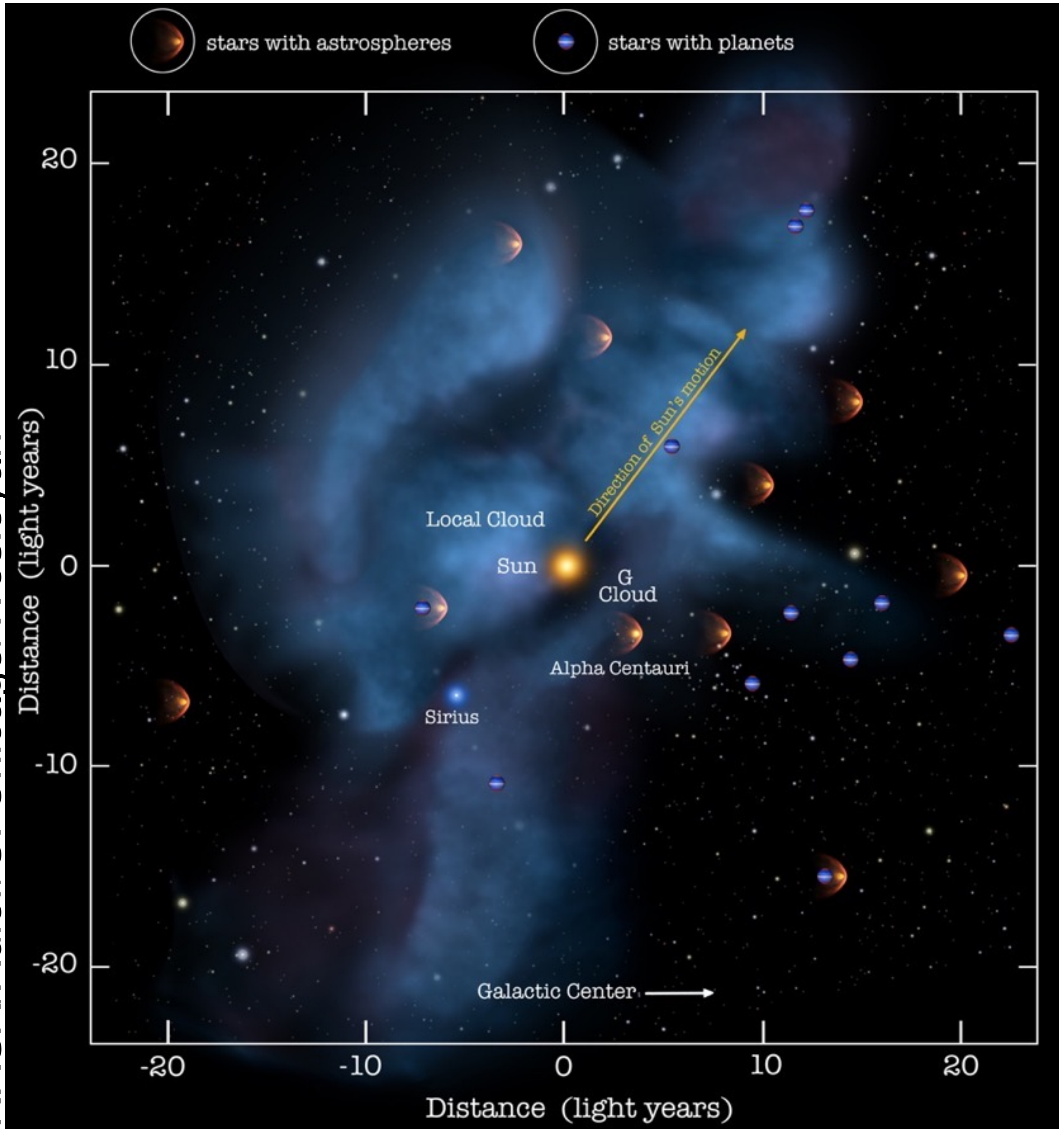
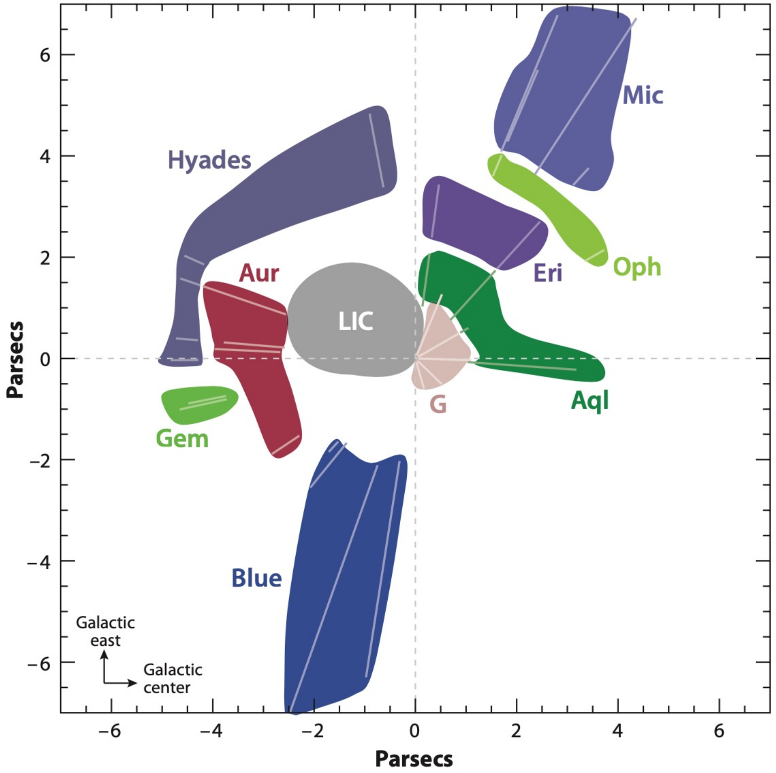
# Our interstellar neighborhood




NASA/Adler/U. Chicago/Wesleyan

Local Interstellar Medium:

- 15 warm, partially ionized clouds AND
- fully ionized hot plasma around them

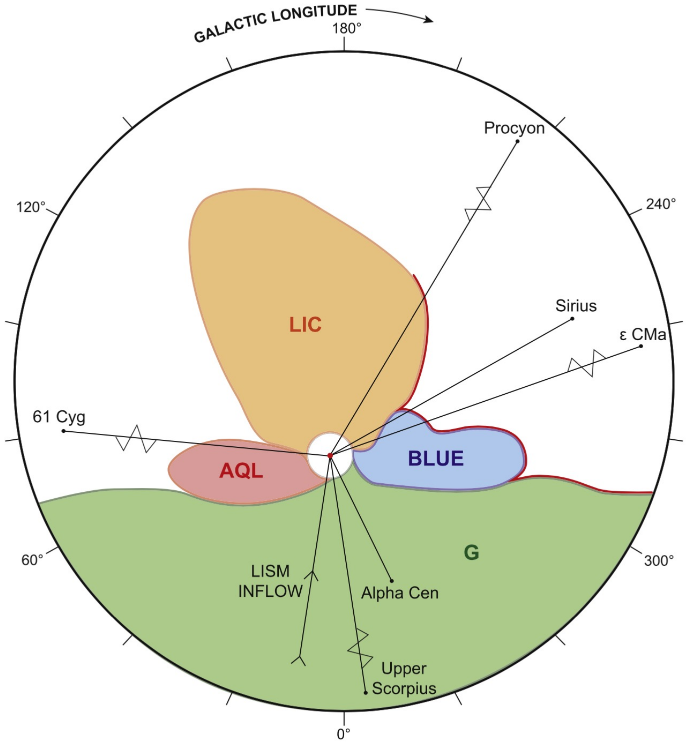



Frisch et al. 2911, ARA&A 49:237

# Pristine Very Local Interstellar Medium

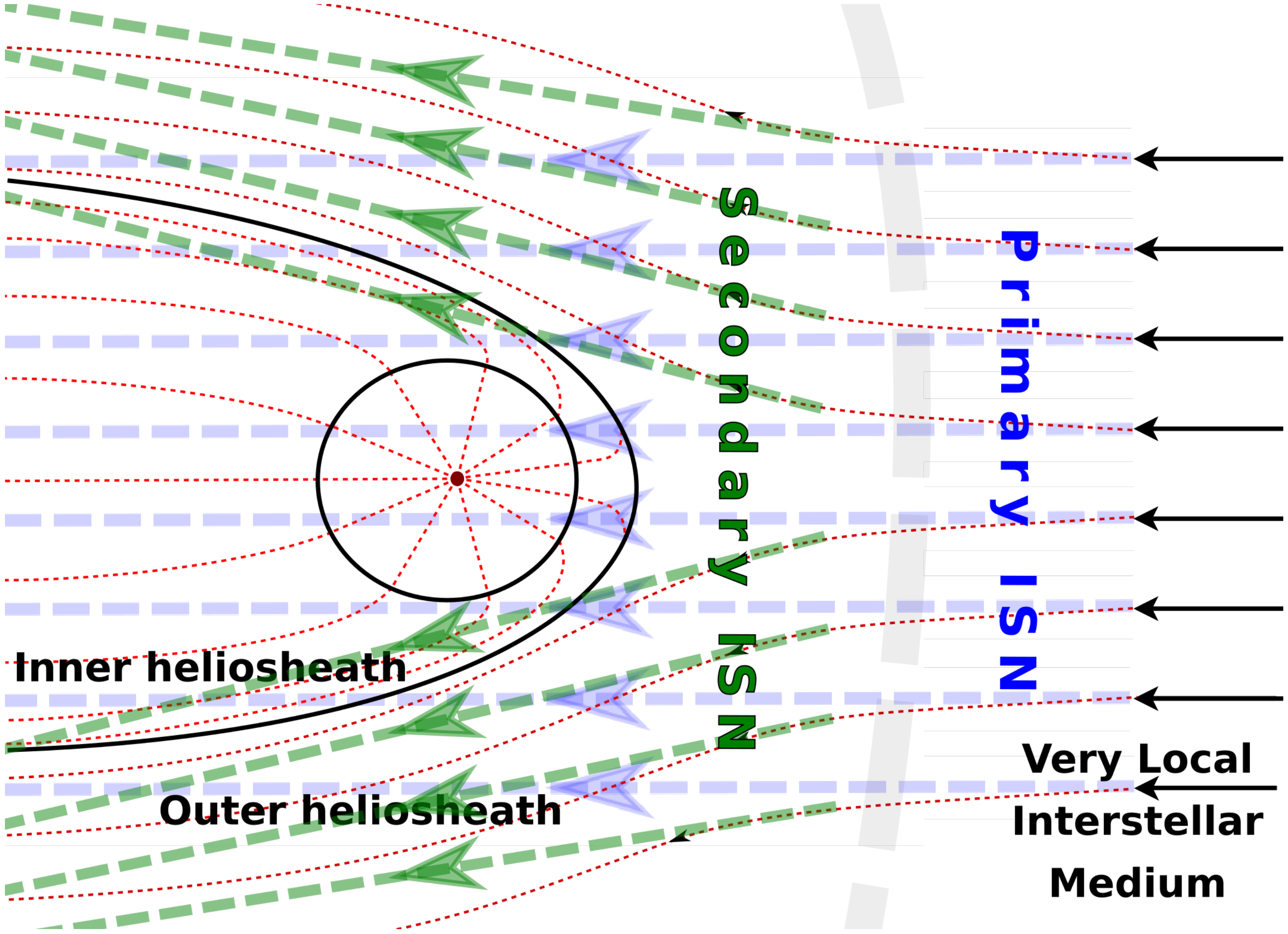
- **Local Interstellar Cloud (LIC)** is defined as:
  1) warm cloud inside which Sun (and heliosphere) is located
  2) specific cloud identified by Redfield and Linsky (2008)
- **Are these two definitions compatible?**
- Verification: observations of interstellar neutrals inside the heliosphere (e.g., IBEX).
- Here: **Pristine Very Local Interstellar Medium (VLISM)** denotes the interstellar medium through which the Sun moves, before it is modified by the heliosphere.
- Plasma – neutral atoms equilibrium in the pristine VLISM (?)

- Linsky et al. (2019): LIC ≠ pristine VLISM:
  *„The LIC cloud provides the closest match to the inflow parameters provided by IBEX, Ulysses, and STEREO, but the match is not perfect"*




Linsky et al. 2019, ApJ 886:41

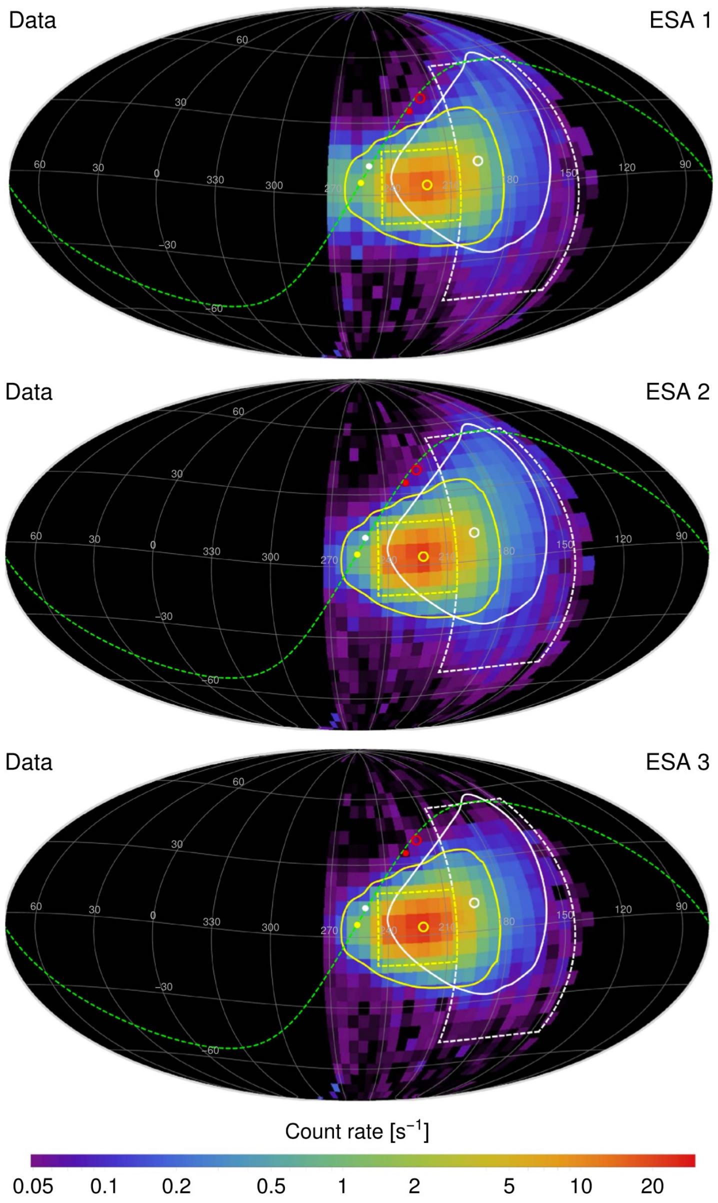
# Two populations of ISN atoms




Plasma flow is diverted around the heliopause, but ISN atoms can freely penetrate the heliosphere.

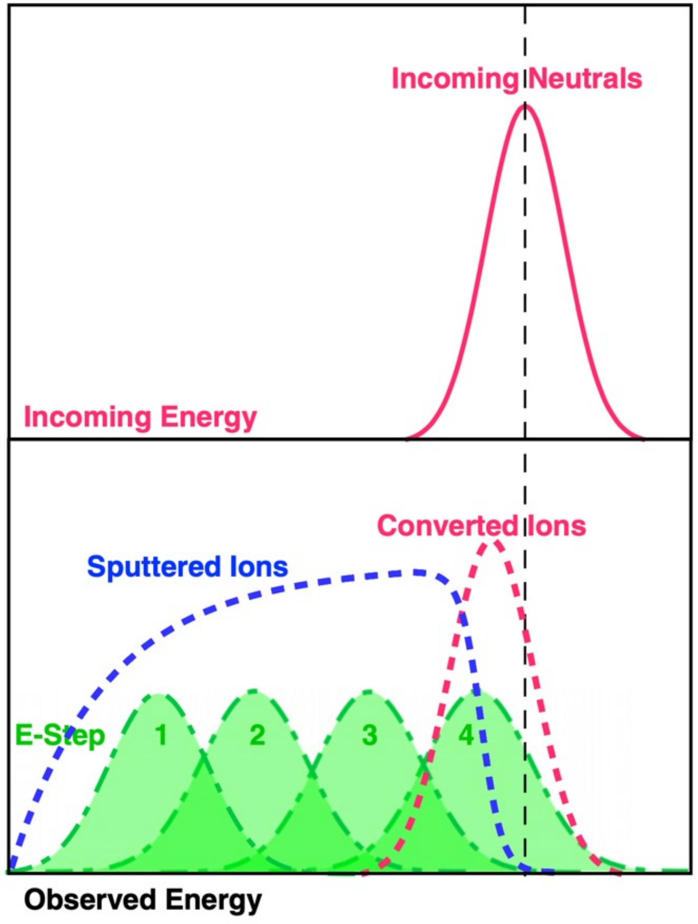
- **Primary ISN atoms:**
  - From pristine Very Local Interstellar Medium (VLISM)
- **Secondary ISN atoms:**
  - Created in the outer heliosheath from perturbed plasma by charge exchange process

# IBEX-Lo observations of Interstellar neutral helium



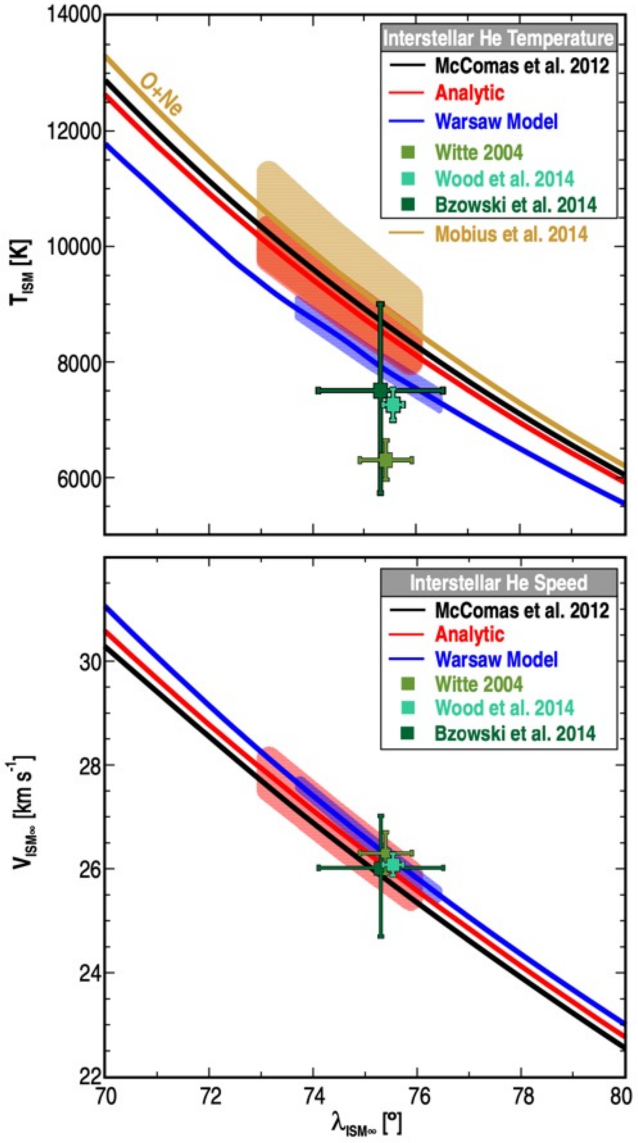

Swaczyna et al. (2018, ApJ 854, 119)

- Helium atoms do not produce negative ions on the conversion surface…
- … but can sputter negative ions from the conversion surface.
- Energy spectrum of sputtered ions is wide and thus ISN He atoms are observed in all four lowest IBEX-Lo energy steps.




Möbius et al. (2012, ApJS 198, 11)

# Primary ISN: Ulysses – IBEX enigma




McComas et al. (2015, ApJ 801, 28)

- First round of quantitative analysis from IBEX-Lo using two first years of observations:

  Bzowski et al. (2012, ApJS 198, 12)

  Möbius et al. (2012, ApJS 198, 11)

  $\lambda_{\rm ISN}$ ~79°, $v_{\rm ISN}$ ~23 km s$^{-1}$, $T_{\rm ISN}$ ~ 6200 K

- Inconsistent with Ulysses values:

  Witte et al. (2004, AdSpR 34, 61)

  $\lambda_{\rm ISN}$ ~75°, $v_{\rm ISN}$ ~26 km s$^{-1}$, $T_{\rm ISN}$ ~ 6300 K

- Reanalyzes of Ulysses observations:

  Bzowski et al. (2014, A&A 569, A8)

  Wood et al. (2014, ApJ 801, 62)

  $\lambda_{\rm ISN}$ ~75.5°, $v_{\rm ISN}$ ~26 km s$^{-1}$, **$T_{\rm ISN}$ ~ 7400 K**

- With four more years of IBEX-Lo data:

  McComas et al. (2015, ApJ 801, 28)

  Bzowski et al. (2015, ApJS 220, 28)

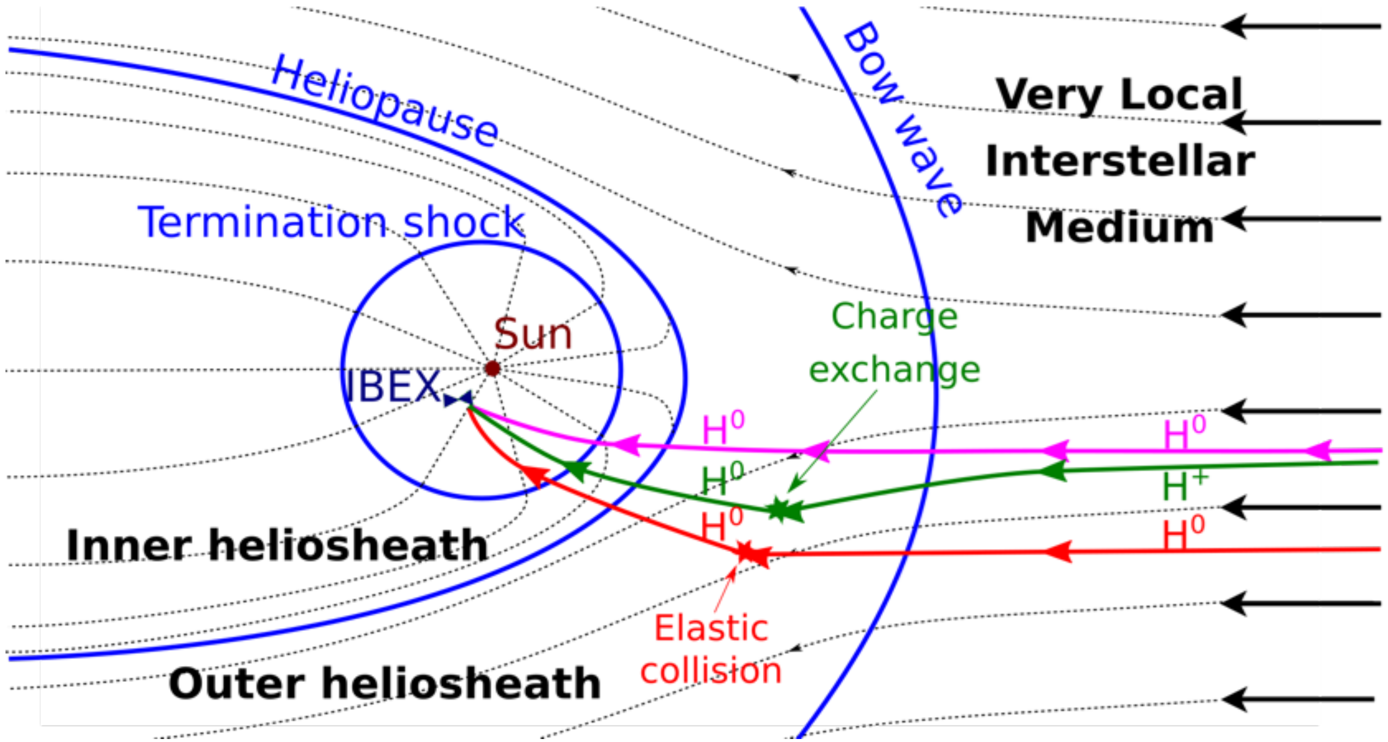
  Schwadron et al. (2015, ApJS 220, 25)

  Möbius et al. (2015, ApJS 220, 24)

  **$\lambda_{\rm ISN}$ ~75.5°, $v_{\rm ISN}$ ~26 km s$^{-1}$, $T_{\rm ISN}$ ~ 7500 K**

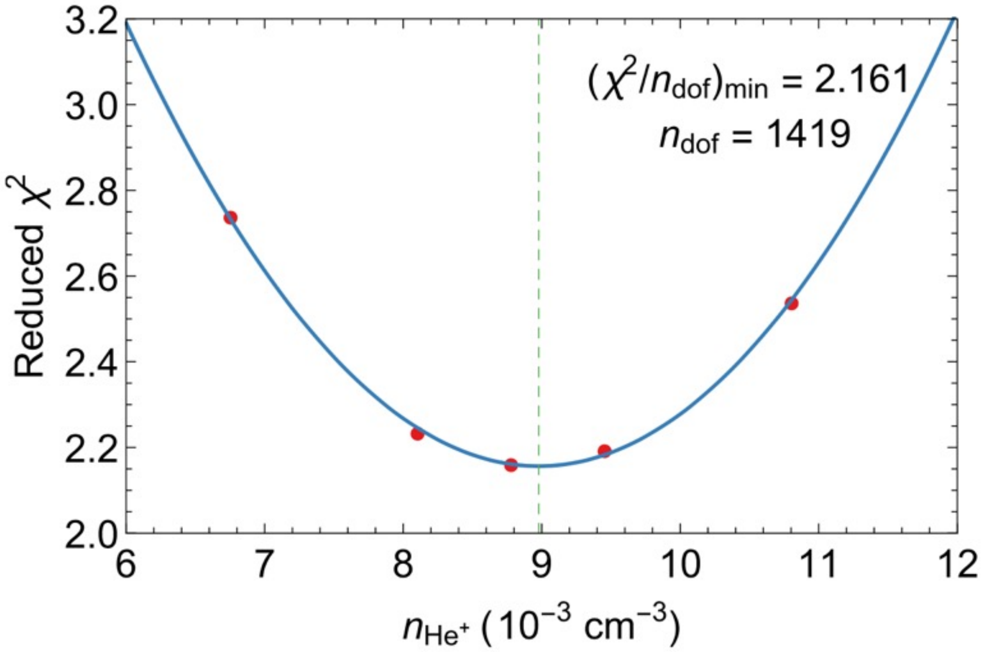
**Consistency restored**

# Collisions in the outer heliosheath




- Charge exchange collisions:
  - Losses to the primary population
  - Production of the secondary population
  - ~5% of He atoms, ~50% of H atoms
  - Mostly resonant collisions
- Elastic collisions:
  - Slowdown and heating
  - Angular scattering of colliding particles
  - Most atoms undergo multiple collisions
  - Collisions with multiple species

# Secondary population – density of $He^+$




**Bzowski et al. (2019, ApJ 882, 60):**

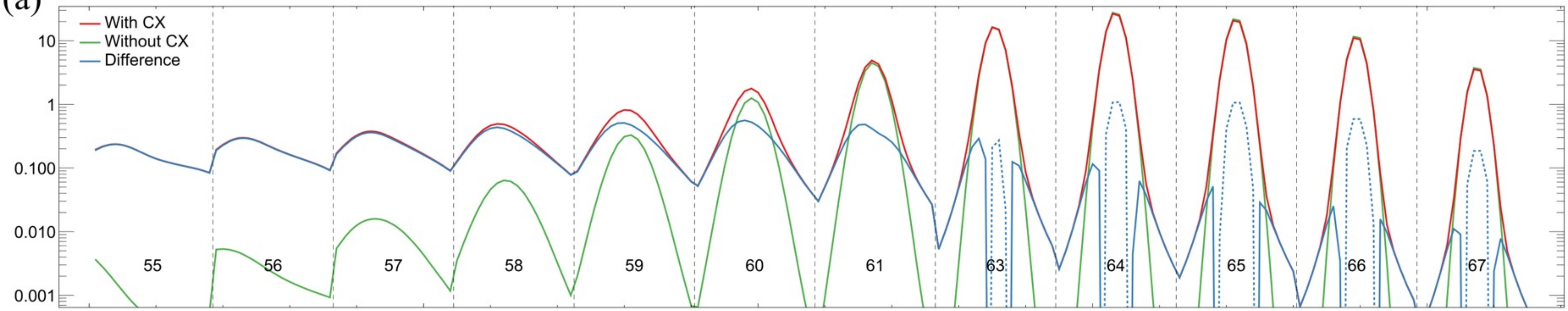
- Losses and production of He atoms in the outer heliosheath in result of charge exchange collisions:

$$He^+ + He^0 \rightarrow He^0 + He^+$$

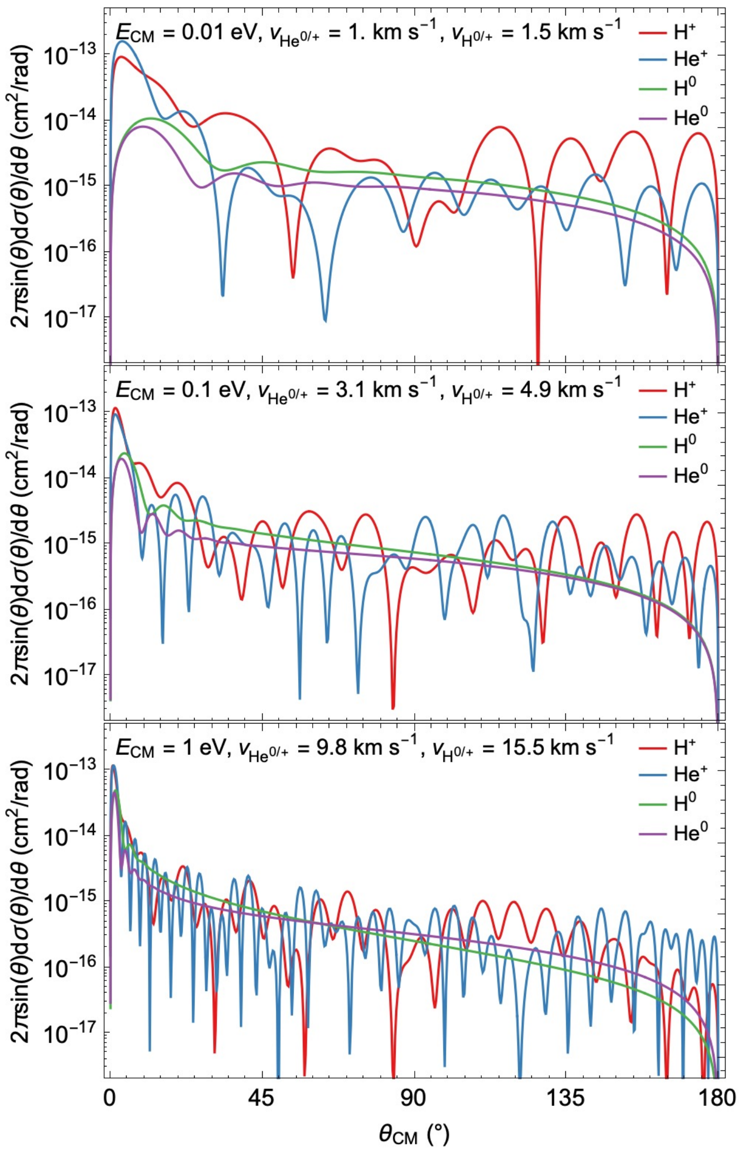
- Source of Warm Breeze
- We can find VLISM density of $He^+$

**0.089(12) cm$^{-3}$**

(a)

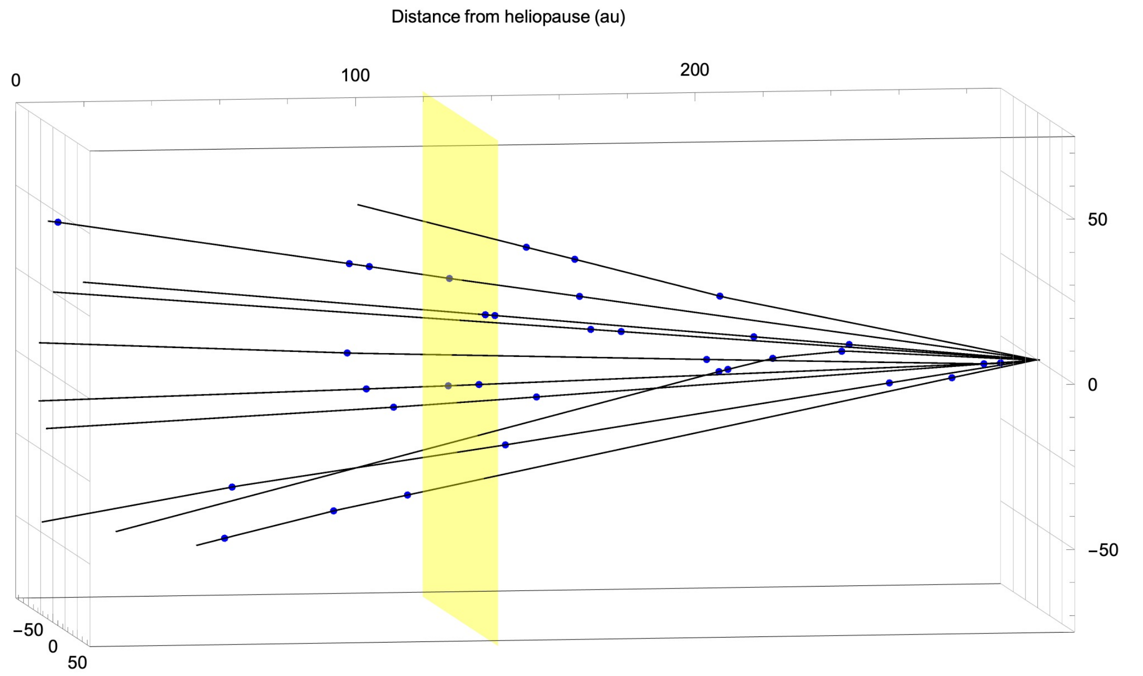


# Elastic collisions of ISN He atoms

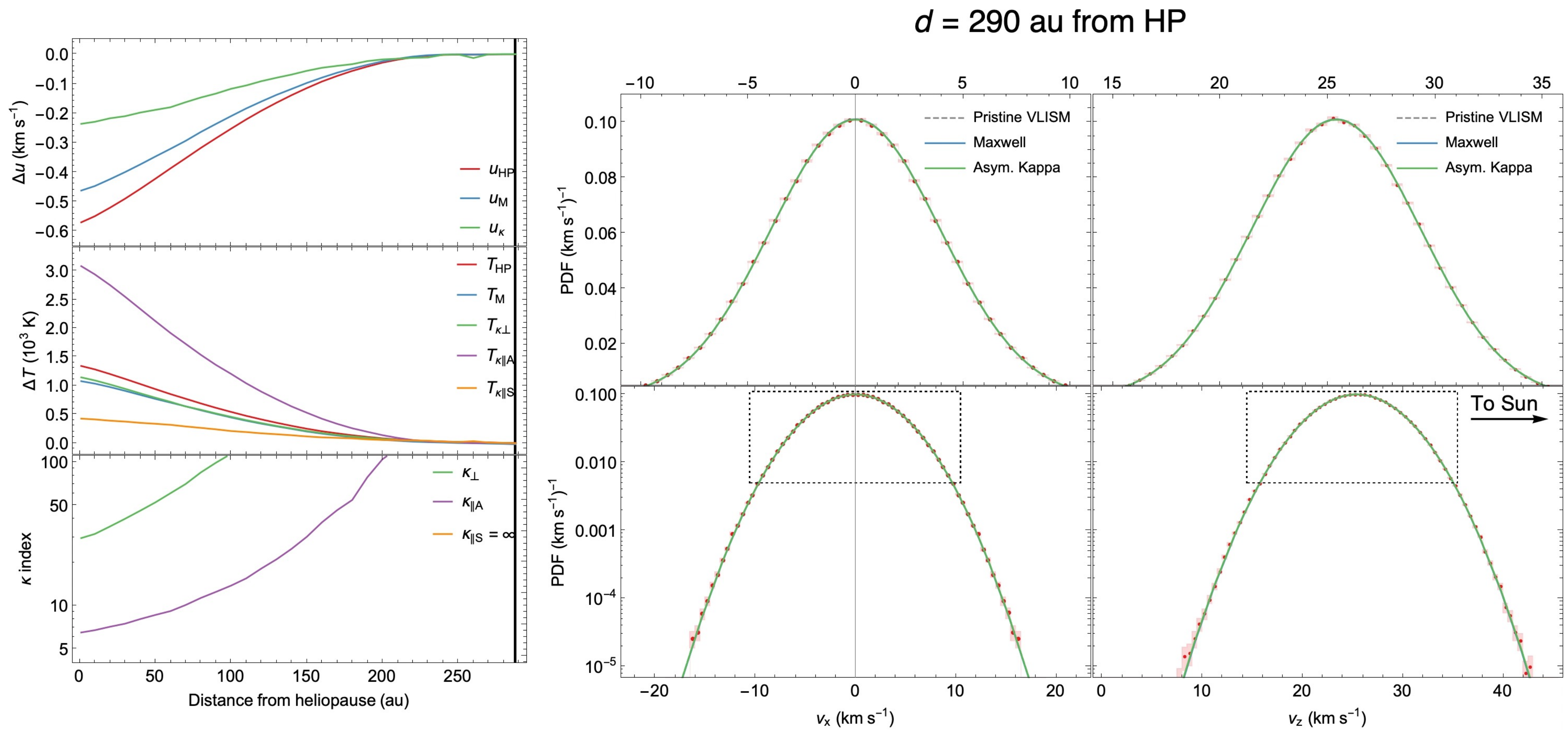



**Swaczyna et al. 2021, ApJL 911:L36**

- Elastic collision → partial momentum exchange
- Most scattering angles are very small
- Average number of collisions in the outer heliosheath: 4.3 with protons: 1.6, with neutral H: 2.6, with $He^+$: 0.16

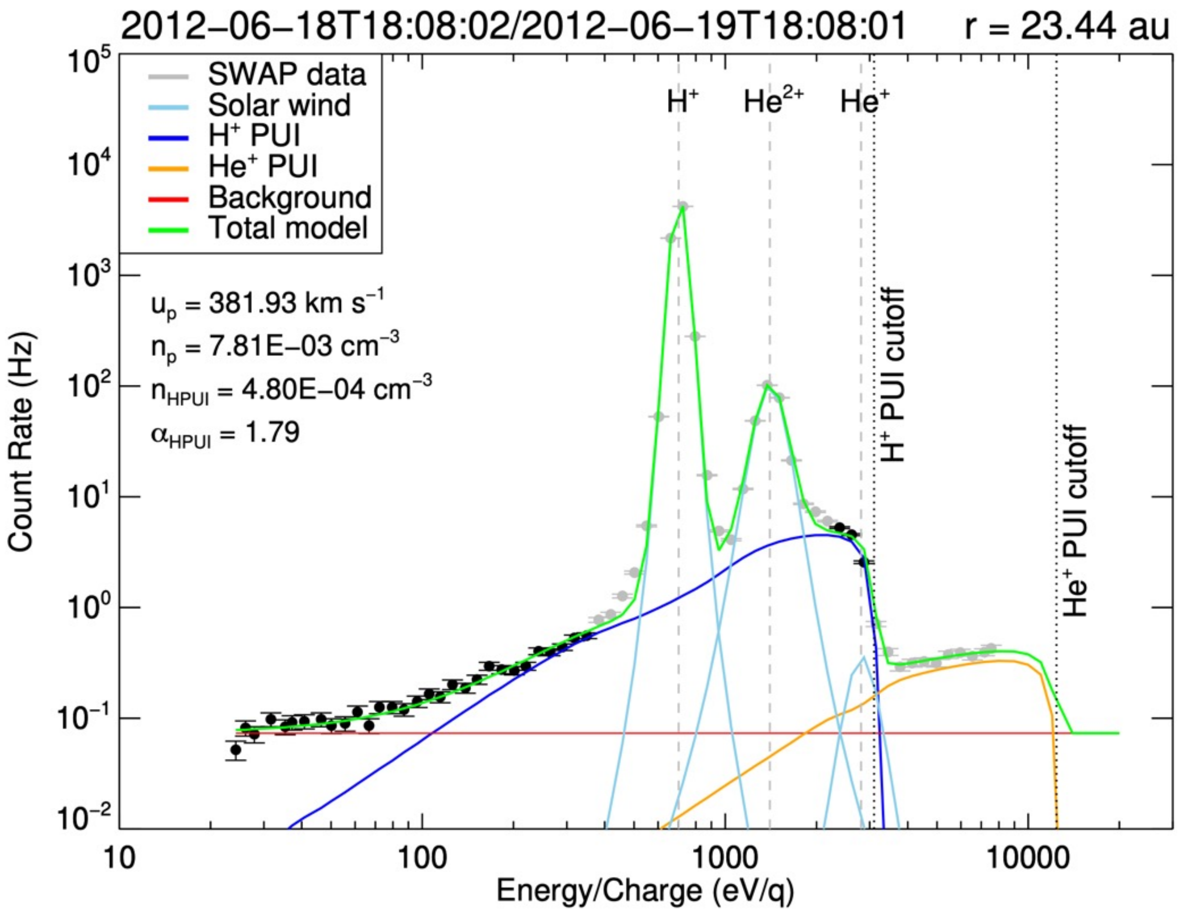


# Slowdown and heating of ISN He



# SWAP observations of the solar wind

- Energy per charge: 0.023 – 7.87 keV/$q$
- 64 logarithmically spaced energy bins: $\Delta E/E$ = 8.5% FWHM
- Data accumulated over 1-day periods
- Identified components:
  - Solar Wind (SW) protons
  - SW alpha particles
  - SW $He^{+}$ ions
  - Hydrogen PUIs
  - Helium PUIs
  - Background: penetrating particles

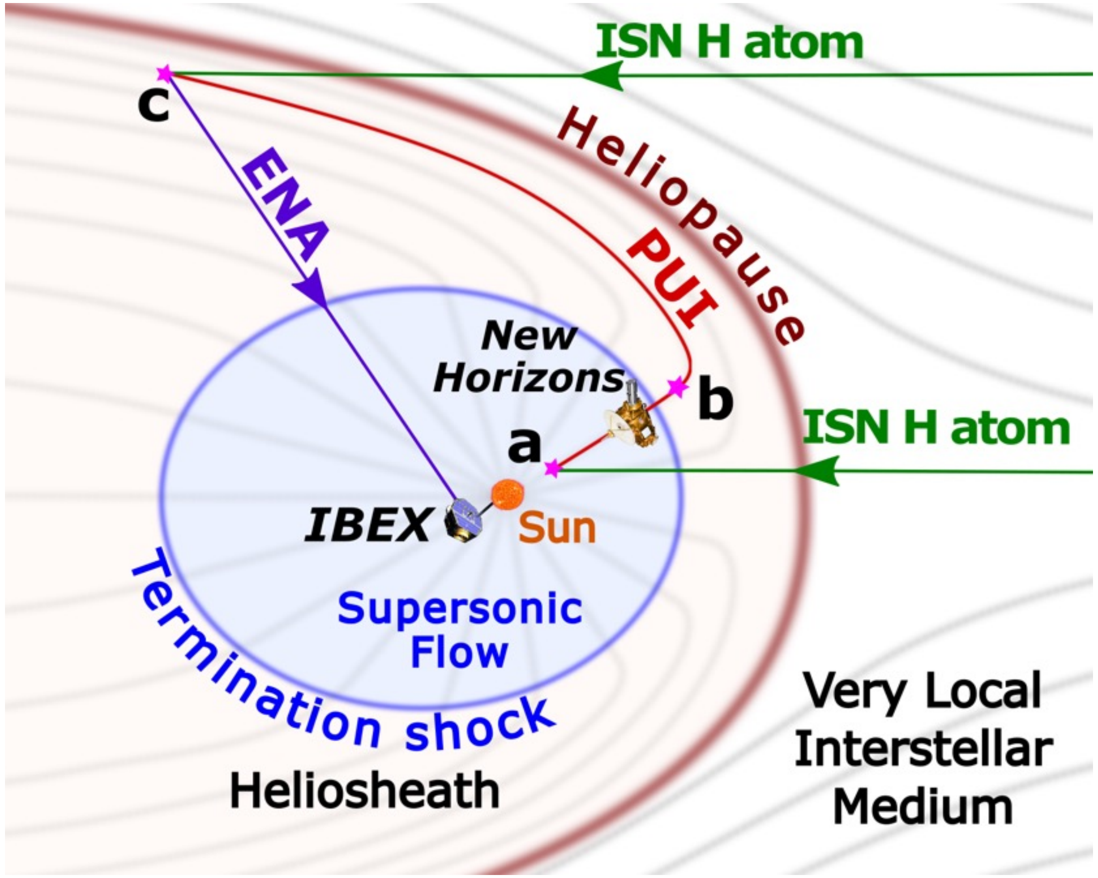



Swaczyna et al. (2020, ApJ 903, 48)

# Pickup ions from ISN atoms

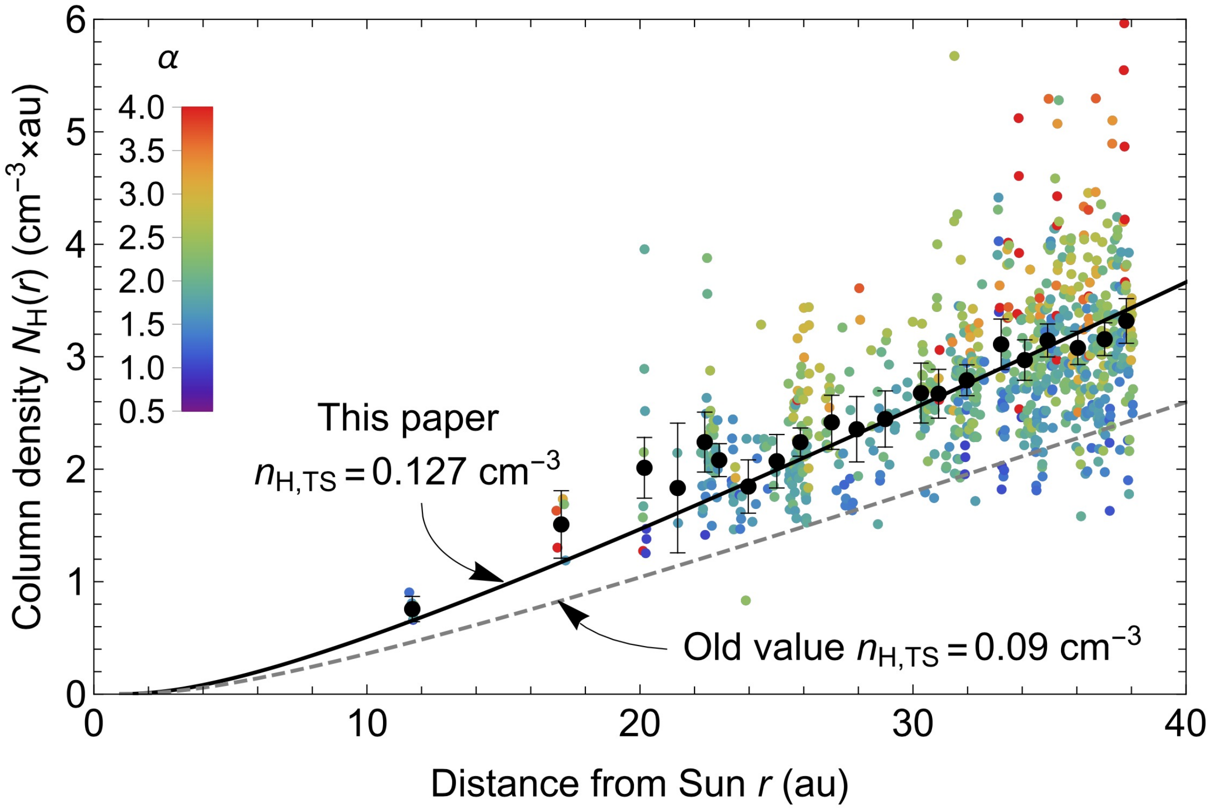
- New Horizons does not observe ISN hydrogen atoms directly.
- Ionization of ISN H atoms ⟶ pickup ions (PUIs)
- SWAP observations: fraction of PUIs in SW flux is proportional to the column density of ISN H:

$$n_{\mathrm{PUI}}(r) = \frac{r_0^2}{r^2}\frac{\beta_0}{u_{\mathrm{sw}}}\int_0^r n_{\mathrm{H}}(r')dr' \equiv \frac{r_0^2}{r^2}\frac{\beta_0}{u_{\mathrm{sw}}} N_{\mathrm{H}}(r)$$



# Column density of ISN hydrogen

- The column density of ISN hydrogen increases as New Horizons moves away from the Sun (color dots; averages over 1-au bins in black).
- Ionization rates using proton density measured by SWAP
- Density of ISN He inside the heliosphere, but far from the Sun
  - $n_{H,TS}$ $= 0.1268$
    $\pm 0.013_{(\sigma)}$
    $\pm 0.005_{(instr)}$
    $\pm 0.004_{(\lambda)}$
    $\pm 0.003_{(method)}$
    $\pm 0.0015_{(He+)}$
    $\pm 0.0011_{(stat.)}$ $cm^{-3}$
- Combined uncertainty: $\pm$ 0.015 $cm^{-3}$




Swaczyna et al. (2020, ApJ 903, 48)

# Summary

## What can we learn?

- Direct observations of primary ISN He atoms → flow and temperature of the pristine VLISM
- Secondary ISN He → plasma flow in the outer heliosheath
- Continuous observations over solar cycle → evolution of ionization processes inside the heliosphere
- Pickup ions → high precision density of interstellar neutrals in the heliosphere

Processes modifying the ISN populations needs to be well known to find an accurate picture.

## Connections

- **IBEX-Lo - Voyagers**: in situ observations of outer heliosheath. Are they consistent with the picture given by the secondary ISN He?
- **SWAP - IBEX-Hi/INCA**: ISN H density is a key parameter for ENA studies.
- Lyman α observations → weighted integrated density of ISN H.
- Ionization data sources → Is the observed modulation of ISN He consistent with the ionization models?
- *Models, models, models…*