CENTRUM BADAŃ KOSMICZNYCH PAN
SPACE RESEARCH CENTRE PAS

Interstellar Medium Surrounding the Heliosphere

Paweł Swaczyna

Space Research Centre of the Polish Academy of Sciences (CBK PAN)

pswaczyna@cbk.waw.pl

Previously at: **Department of Astrophysical Sciences, Princeton University**

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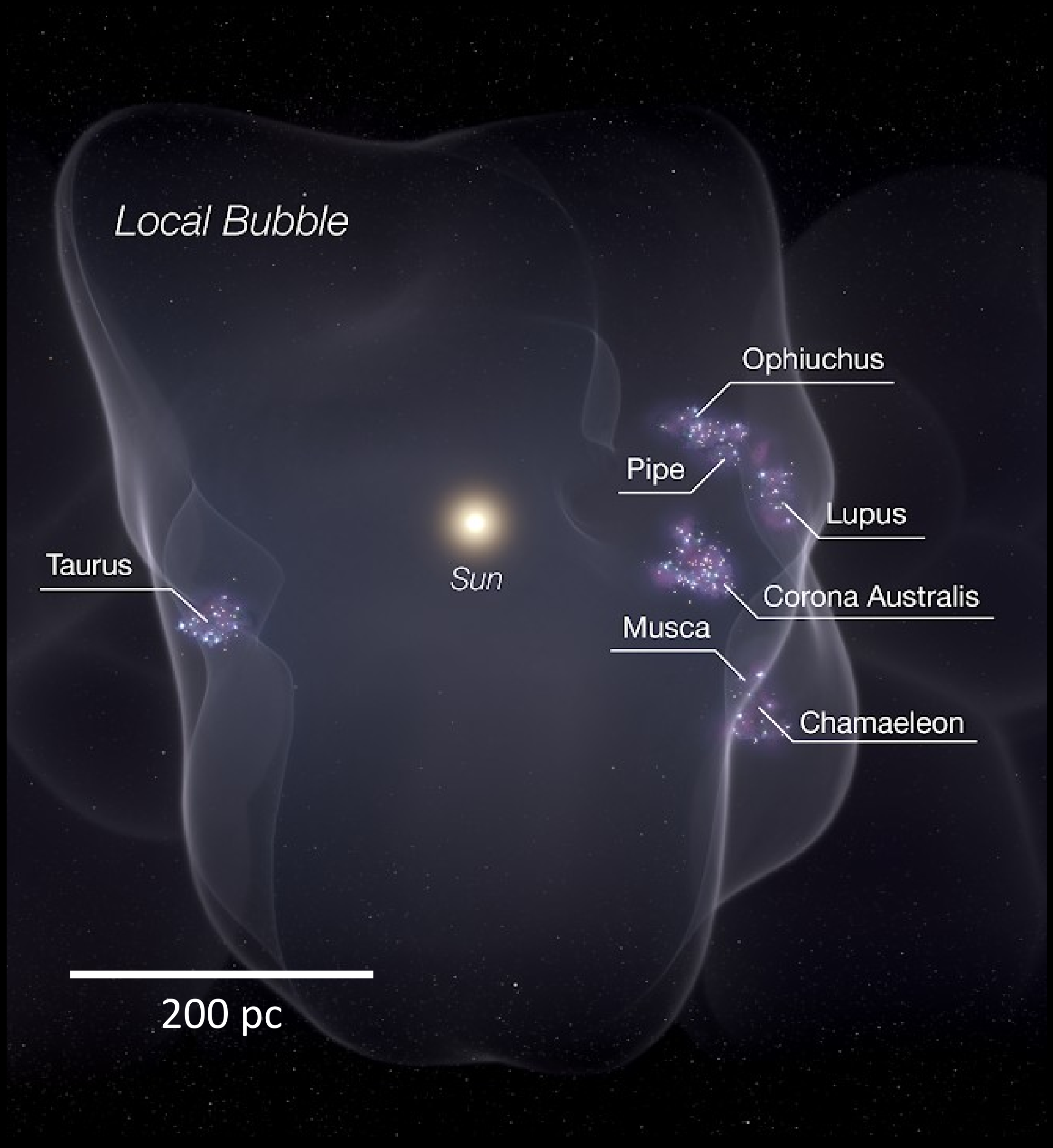
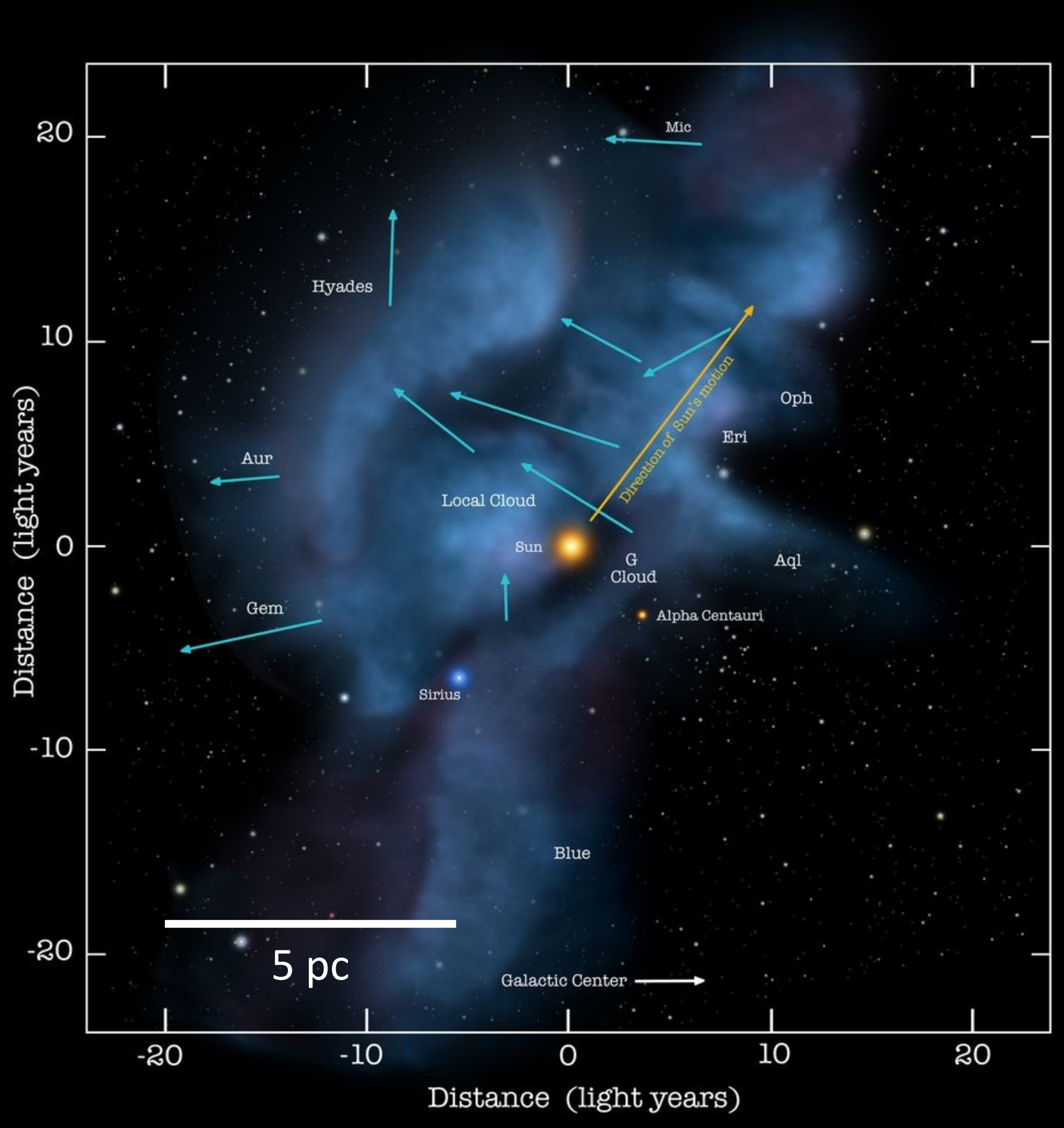
Our interstellar neighborhood

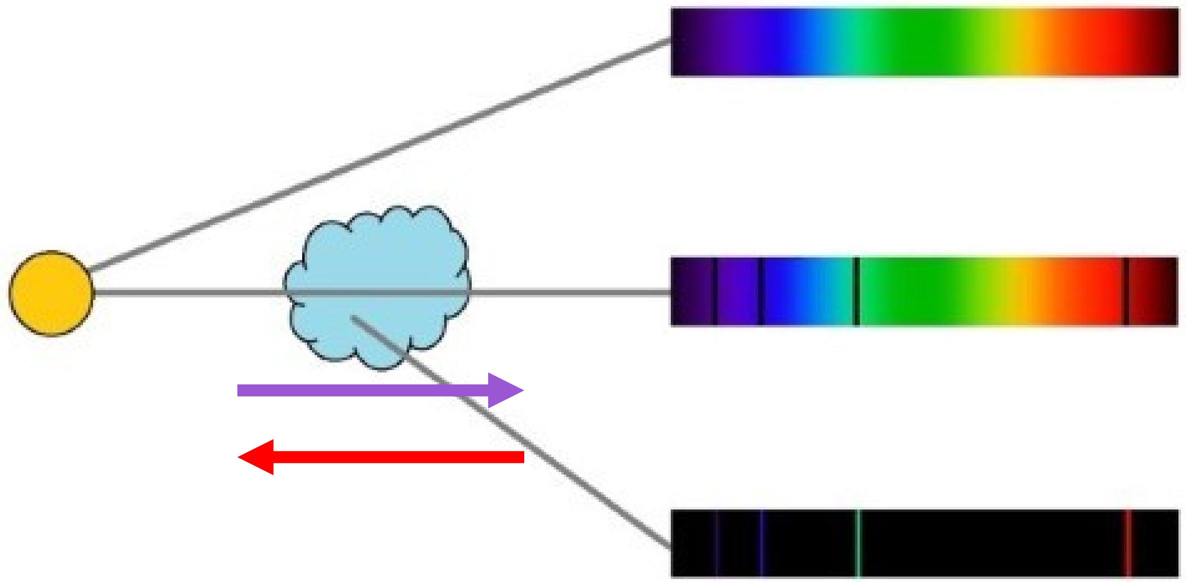
STScI, CfA, Harvard

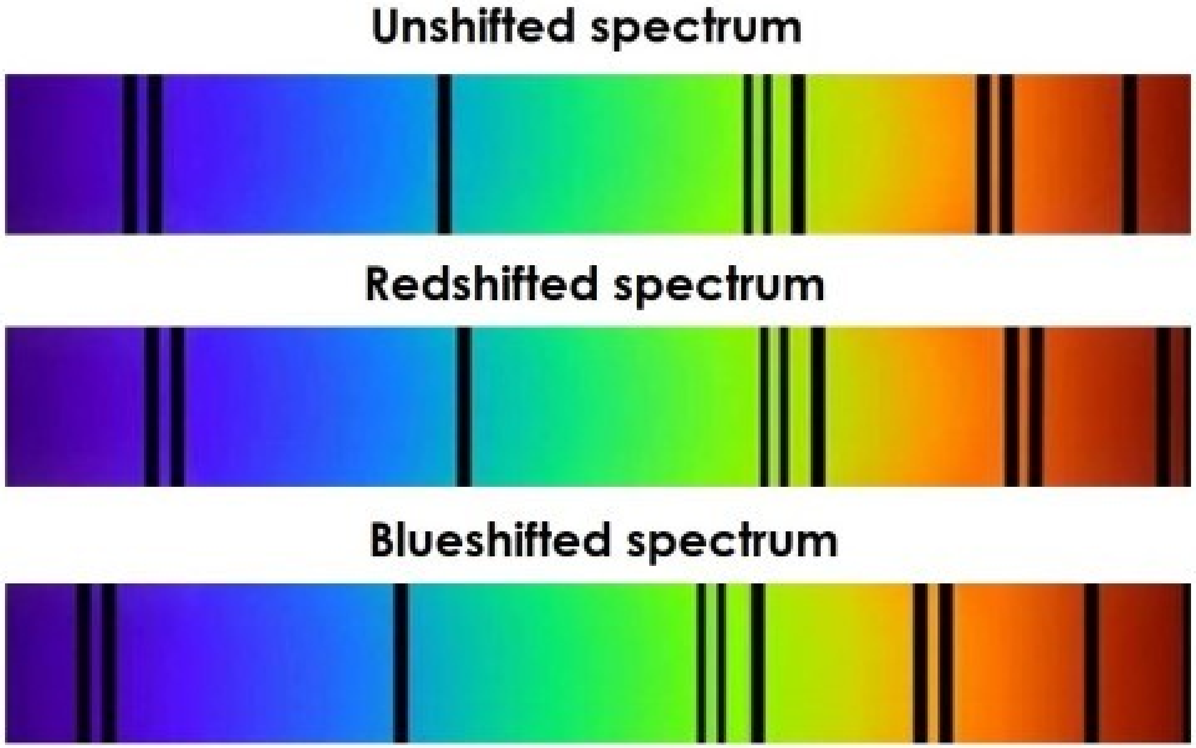




NASA/Goddard/Adler/U. Chicago/Wesleyan

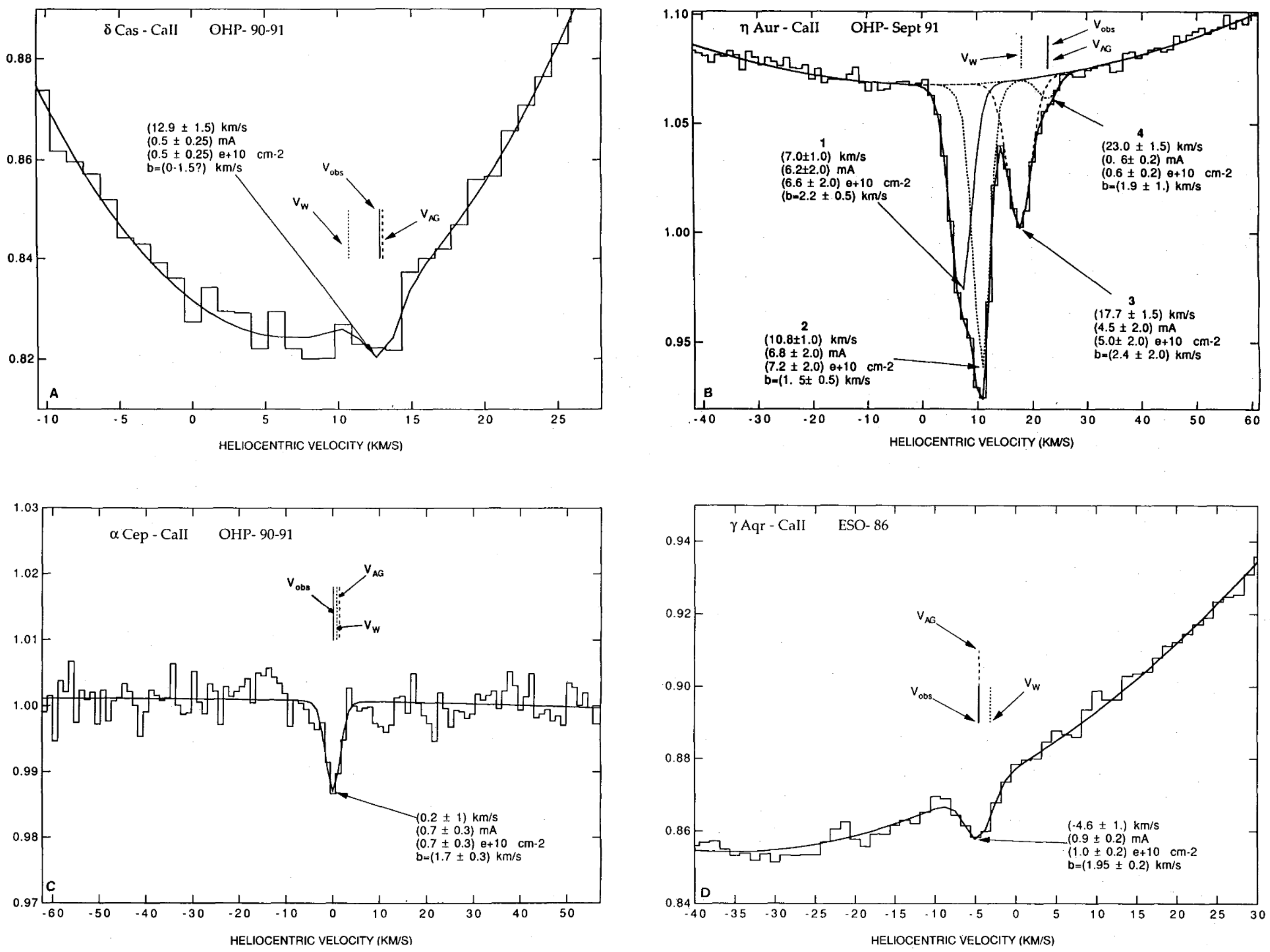
Absorption by interstellar clouds

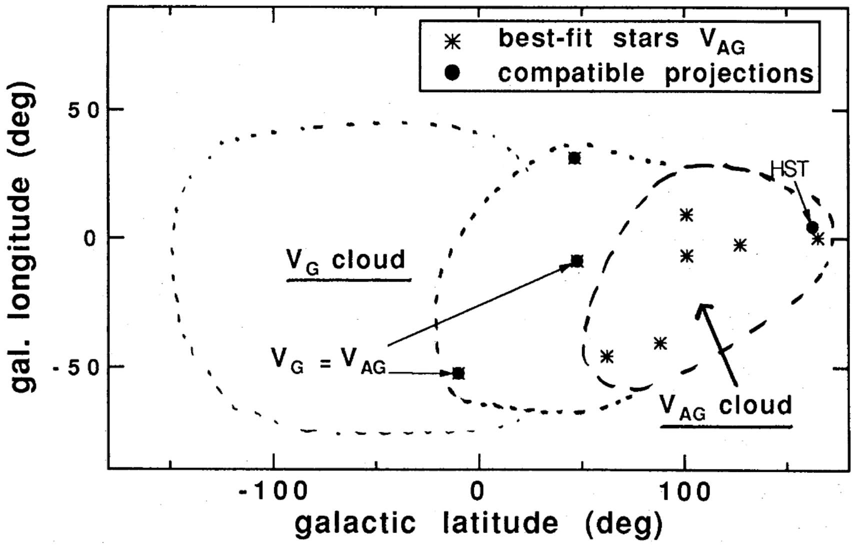




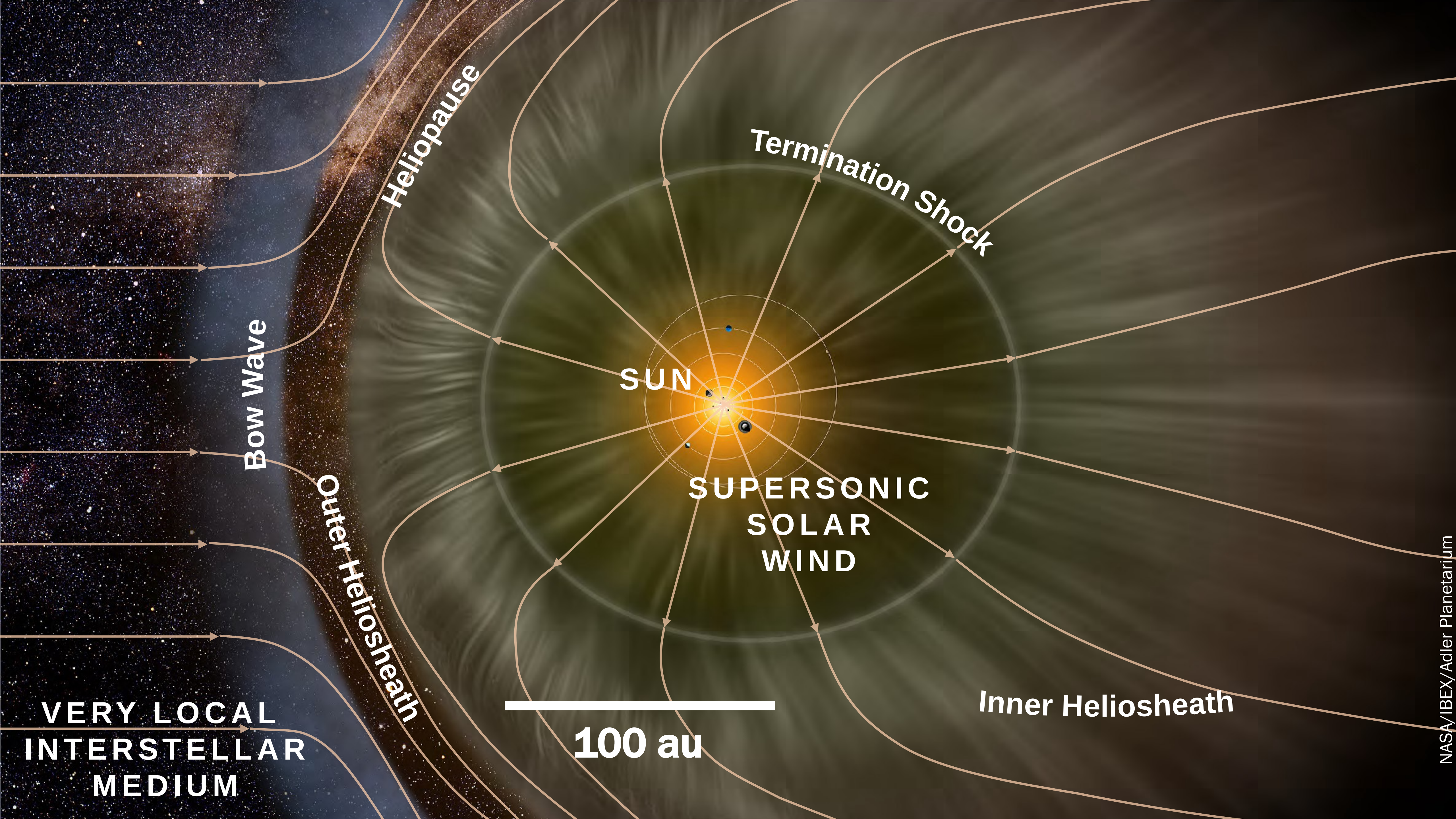
Galactic (G) and anti-galactic (AG) clouds

Lallement & Bertin (1992)



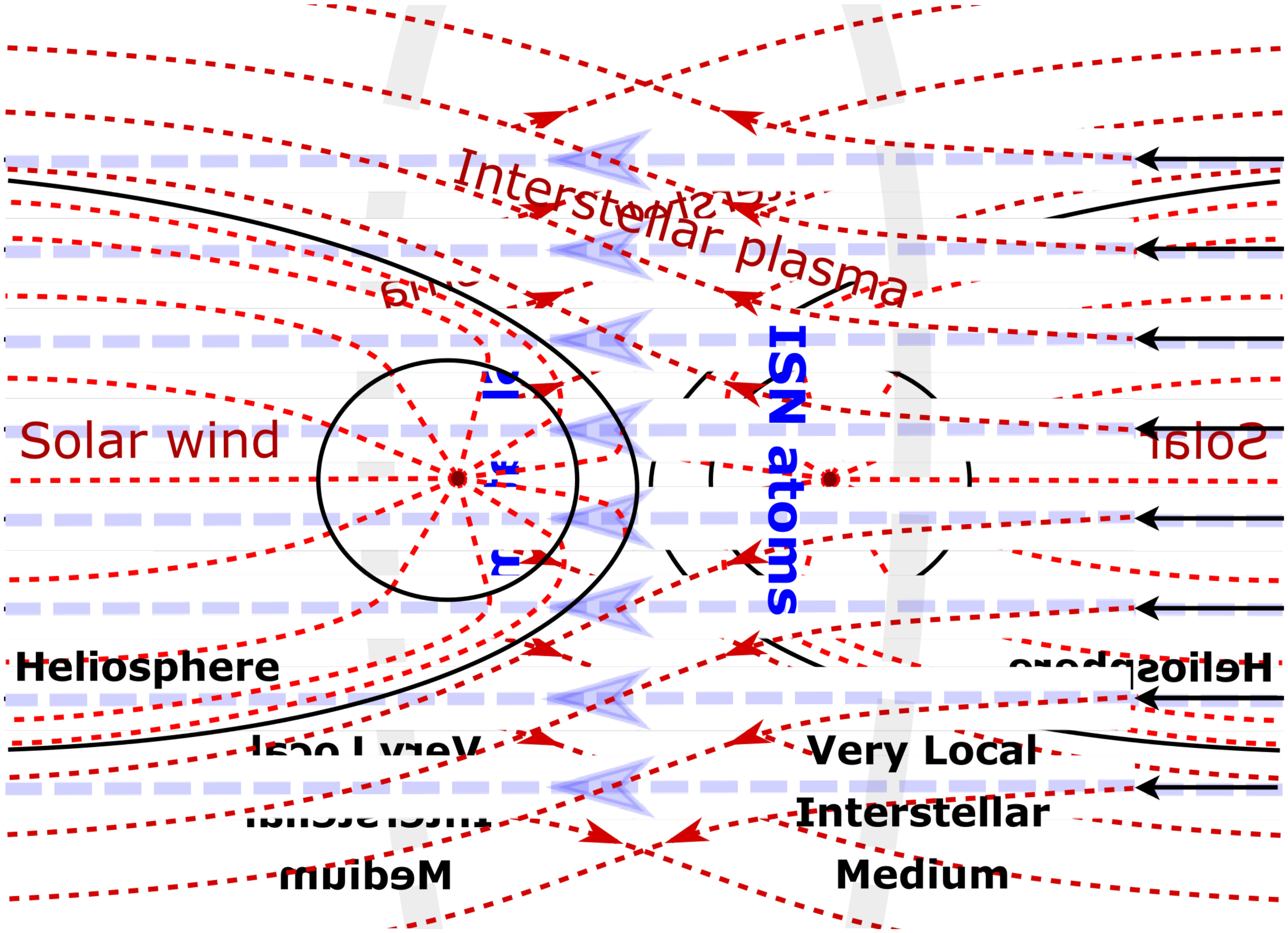


> *The Sun is in a very small patch of gas, undetected by visible and UV measurements, just between the two G (29.4 km s^{-1}) and AG (25.7 km s^{-1}) clouds.*

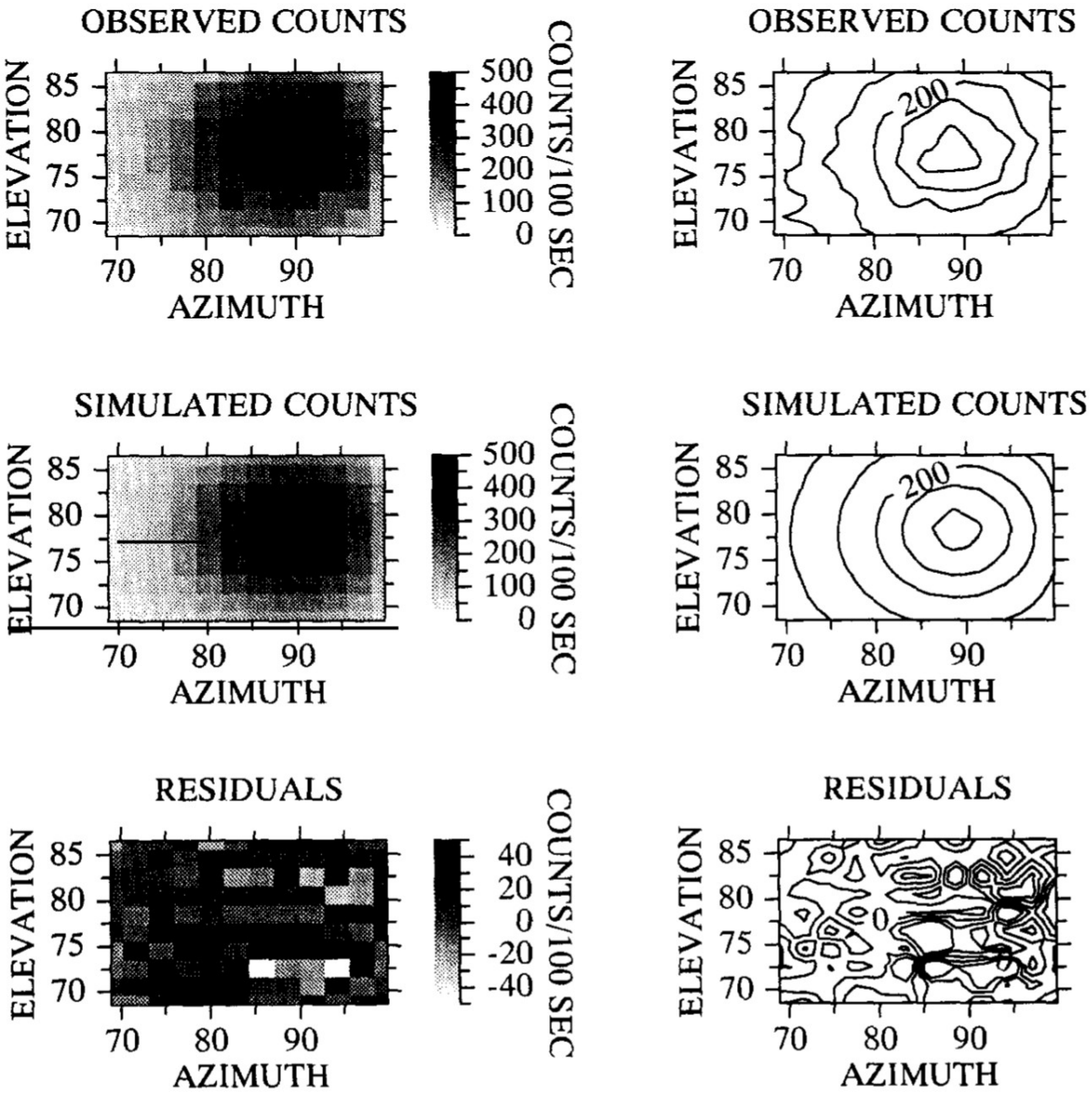


Heliopause
Termination Shock
Bow Wave
SUN
SUPERSONIC
SOLAR
WIND
Outer Heliosheath
Inner Heliosheath
100 au
VERY LOCAL
INTERSTELLAR
MEDIUM
NASA/IBEX/Adler Planetarium

Interstellar neutral atoms in the heliosphere



Ulysses observations



Witte et al. (1993, AdSpR 13, 121)

– Velocity $\mathbf{v}_\infty$: 26.0 ± 1.0 km/s
ecliptic longitude λ_∞ : $72.0° \pm 2.4°$
ecliptic latitude β_∞ : $-2.5° \pm 2.7°$
– Temperature T_∞ : 6700 ± 1500 K

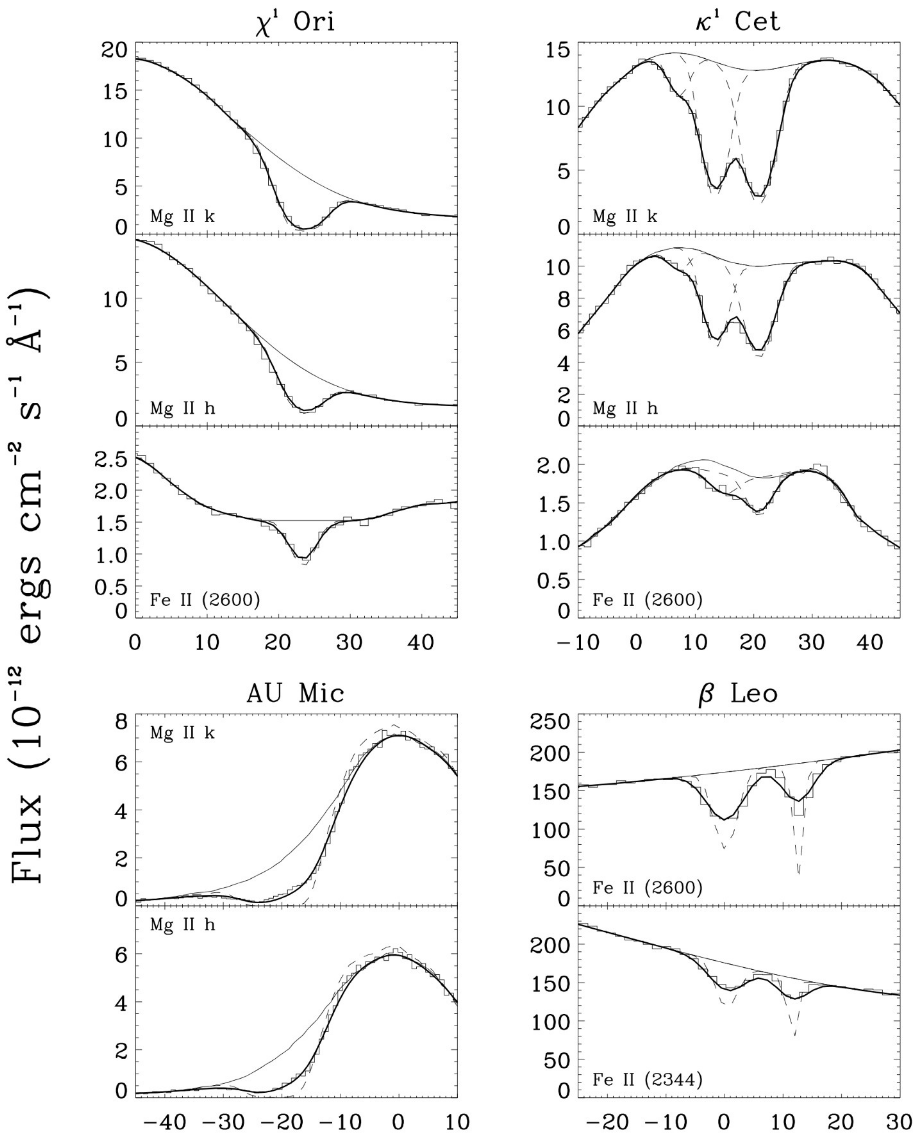
Lallement & Bertin (1992)

“*The Sun is in a very small patch of gas, undetected by visible and UV measurements, just between the two G (29.4 km s^{-1}) and AG (25.7 km s^{-1}) clouds.*”

Bertin et al. (1993, JGR 98, 15193)

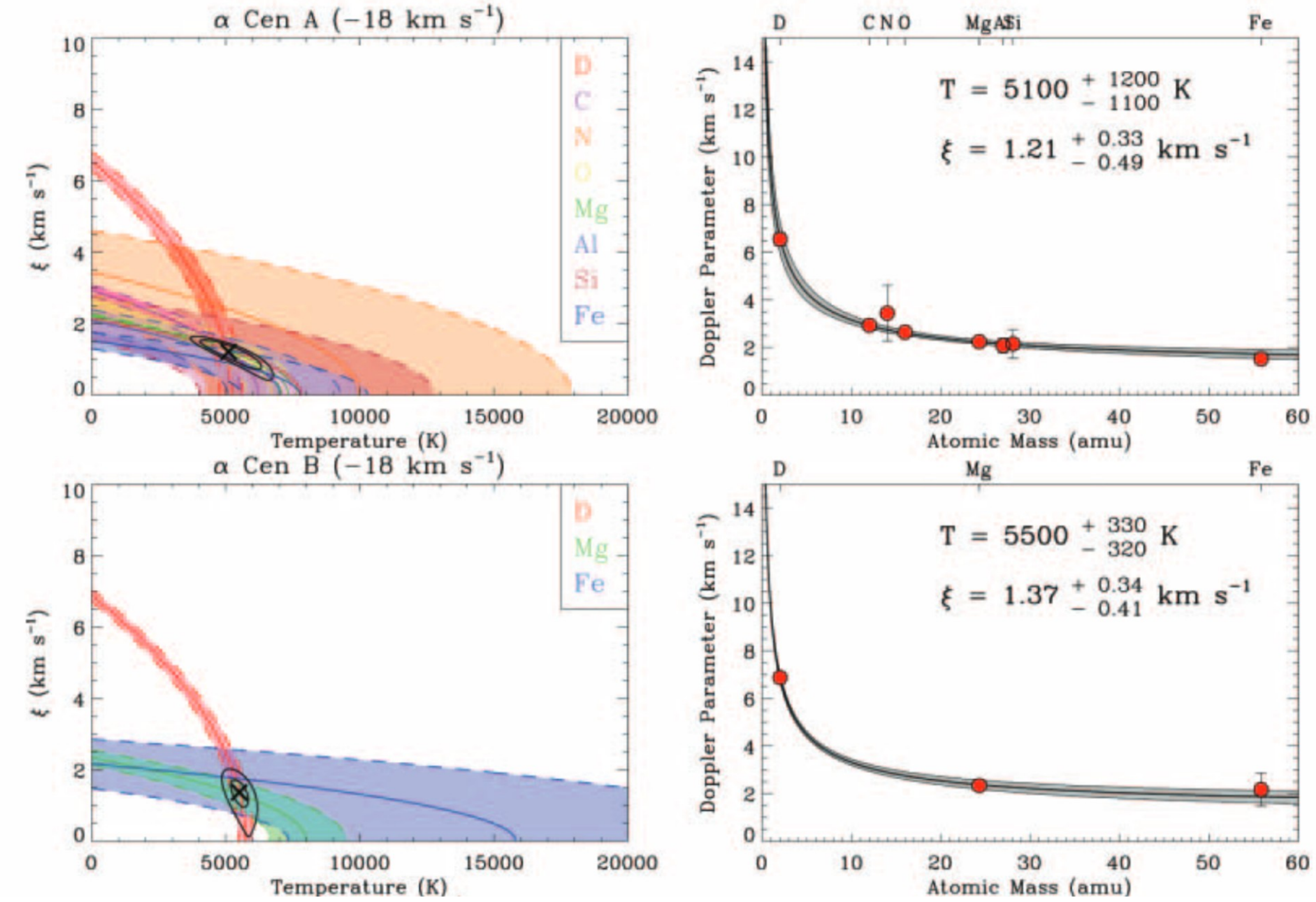
“*It (the velocity of the interstellar neutral helium atoms) is found to be in perfect agreement with the LIC (AG cloud) properties.*”

Redfield & Linsky model of the LISM



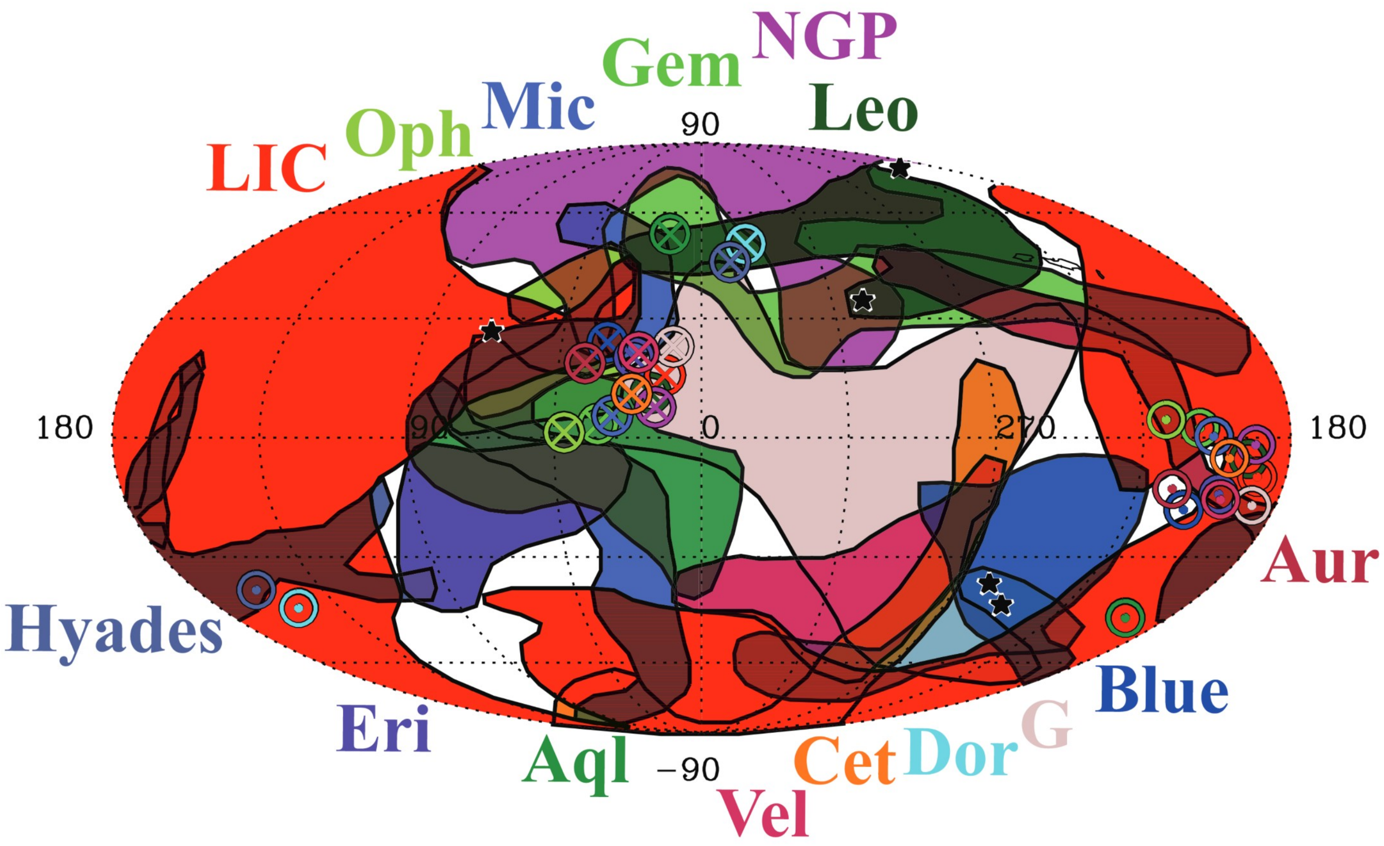
← Redfield & Linsky (2002)

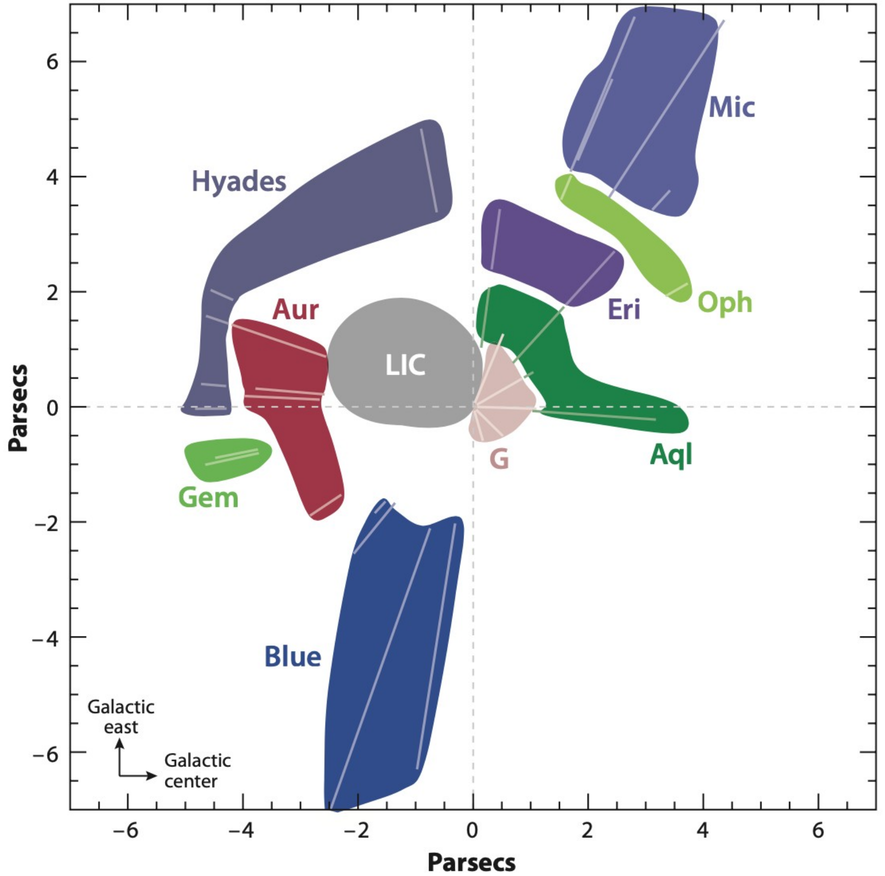
Redfield & Linsky (2004) ↓



Complex of Local Interstellar Clouds (CLIC)

Redfield & Linsky (2008, ApJ 673:283)



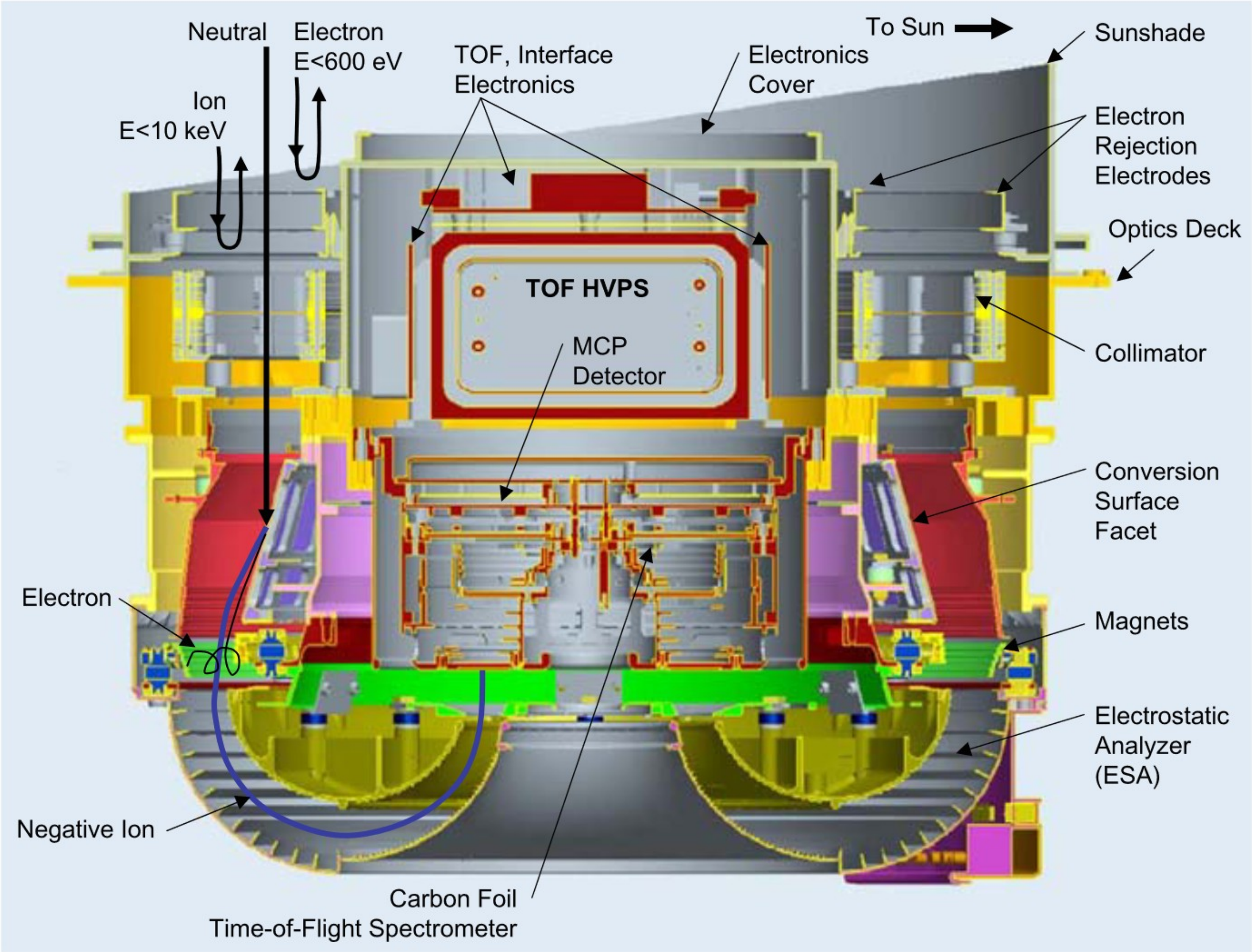


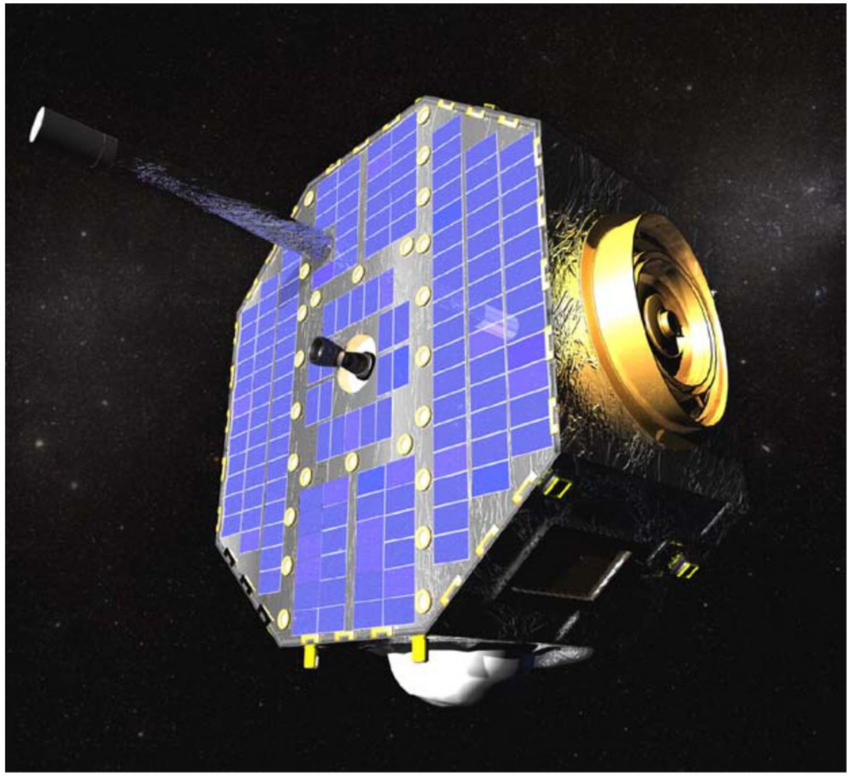
Cloud Name	Number of Sight Lines	V_0 (km s^{-1})	l_0 (deg)	b_0 (deg)	χ^2_ν
LIC	79	23.84 ± 0.90	187.0 ± 3.4	−13.5 ± 3.3	2.2
G...	21	29.6 ± 1.1	184.5 ± 1.9	−20.6 ± 3.6	1.3

The revised LIC and GC flows are inconsistent with the local flow seen in the heliosphere

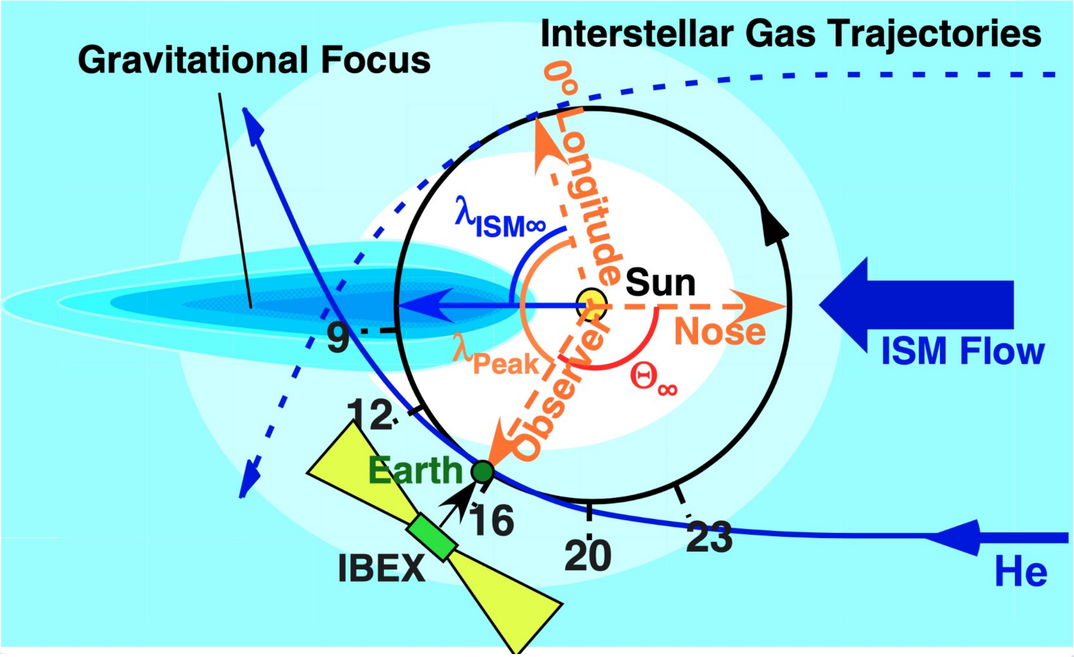
Detection of ISN atoms on IBEX

Fuselier et al. (2009, SSRv 146:117)

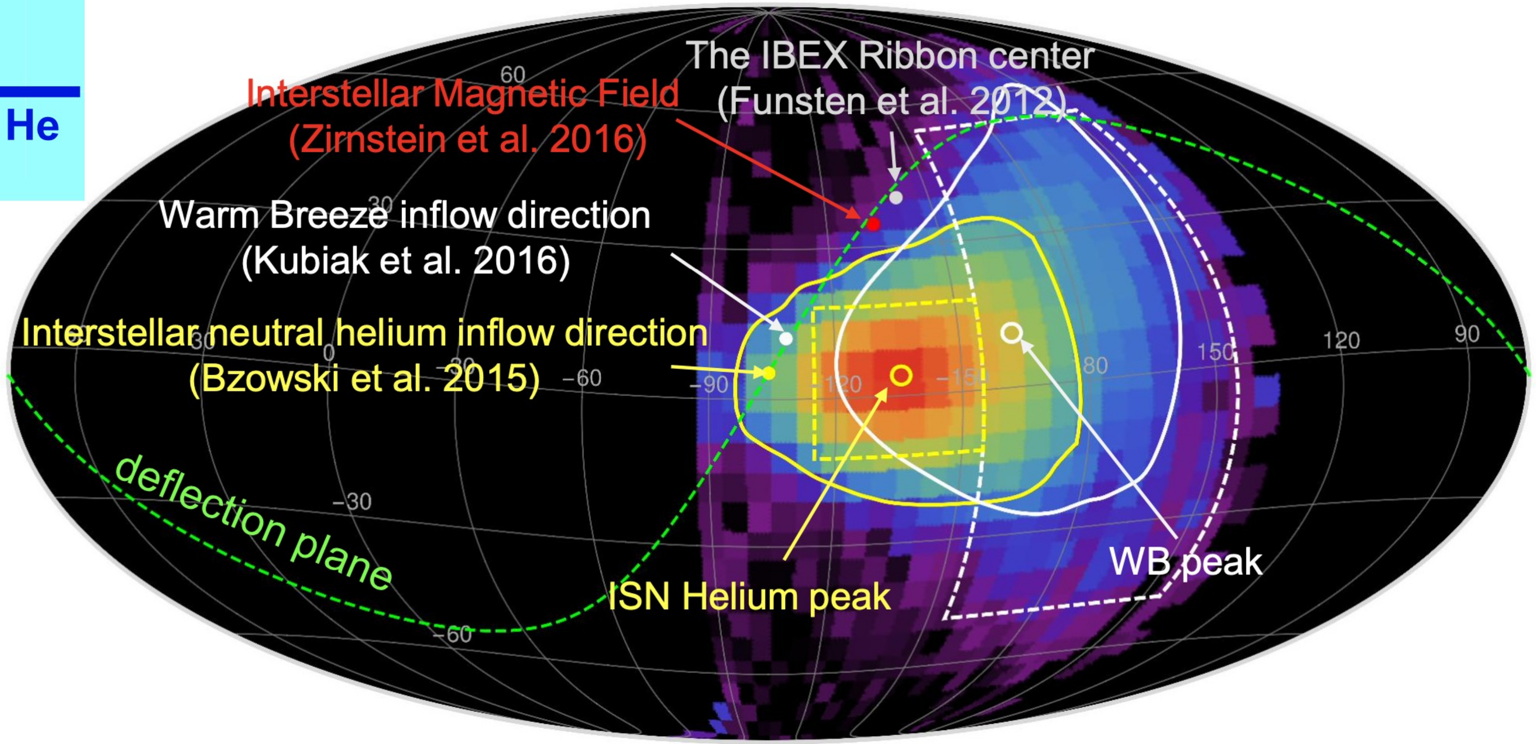




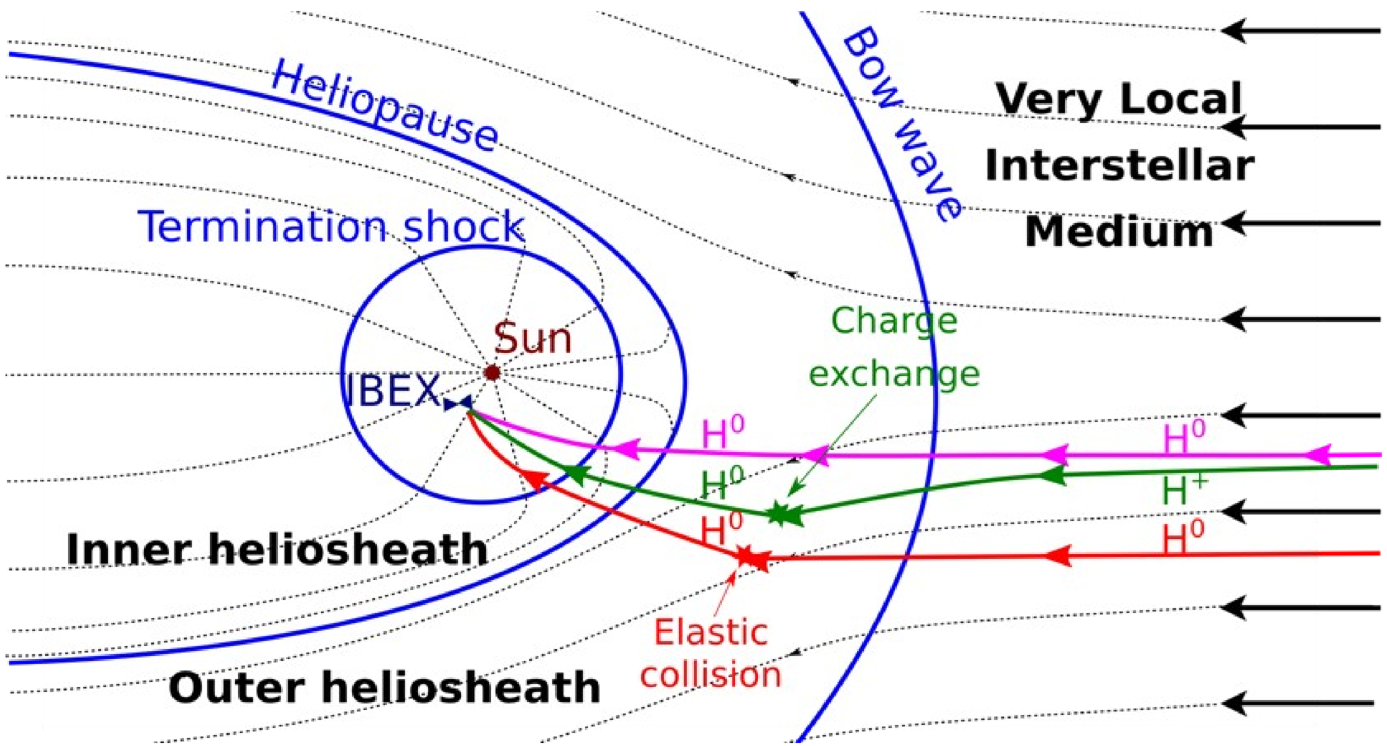
Observations of ISN wind by IBEX



Möbius et al. (2012, ApJS 198:11)



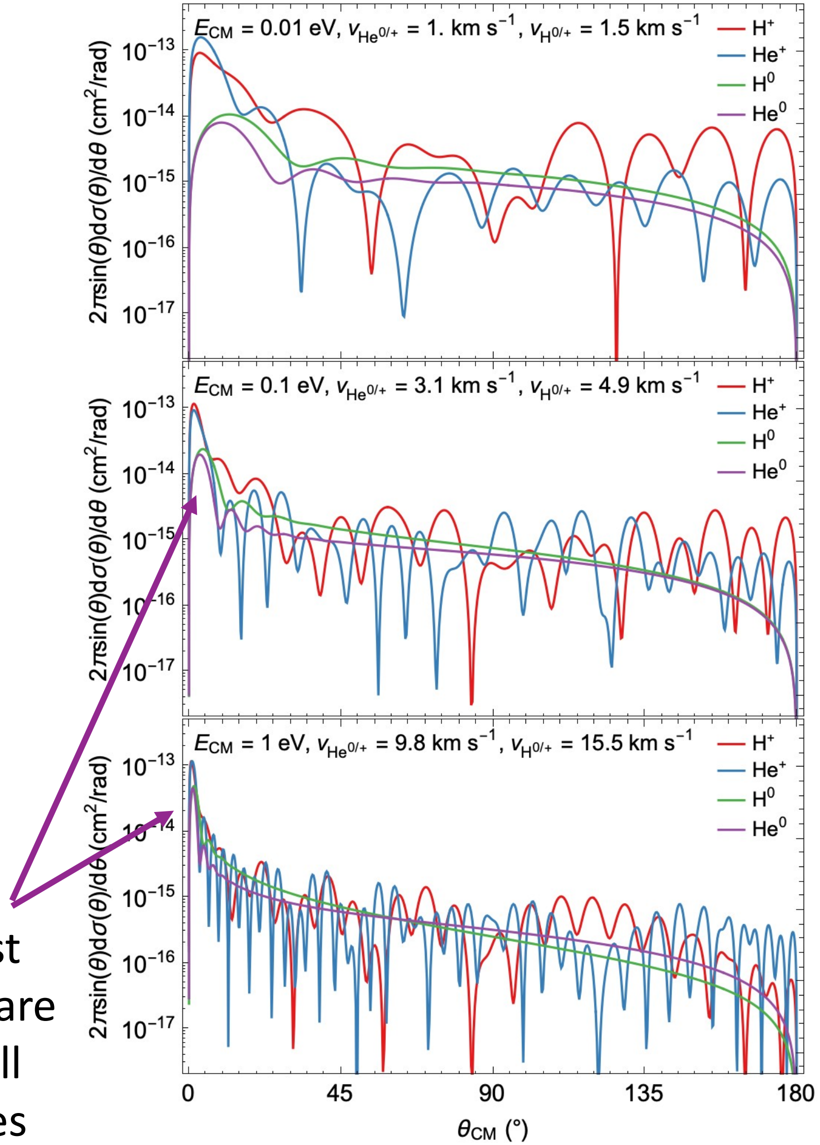
ISN atom collisions in the outer heliosheath



- **Charge exchange collisions:**
  - Losses to primary population
  - Production of 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

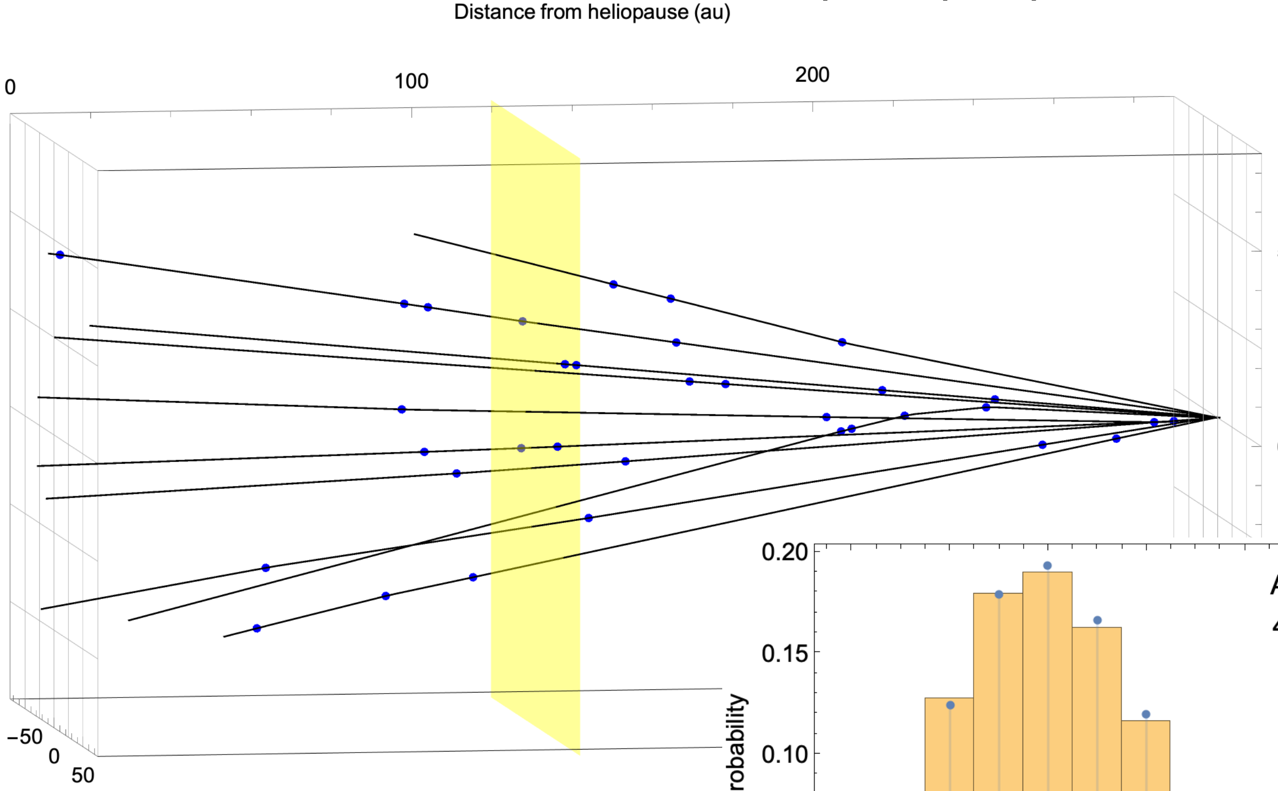
Elastic collision differential cross sections

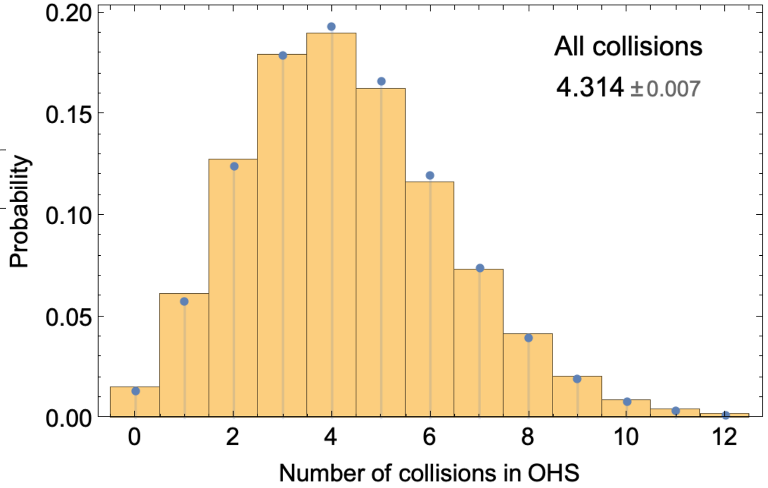
Swaczyna et al. (2021, ApJL 911:L36)



Most likely are small angles

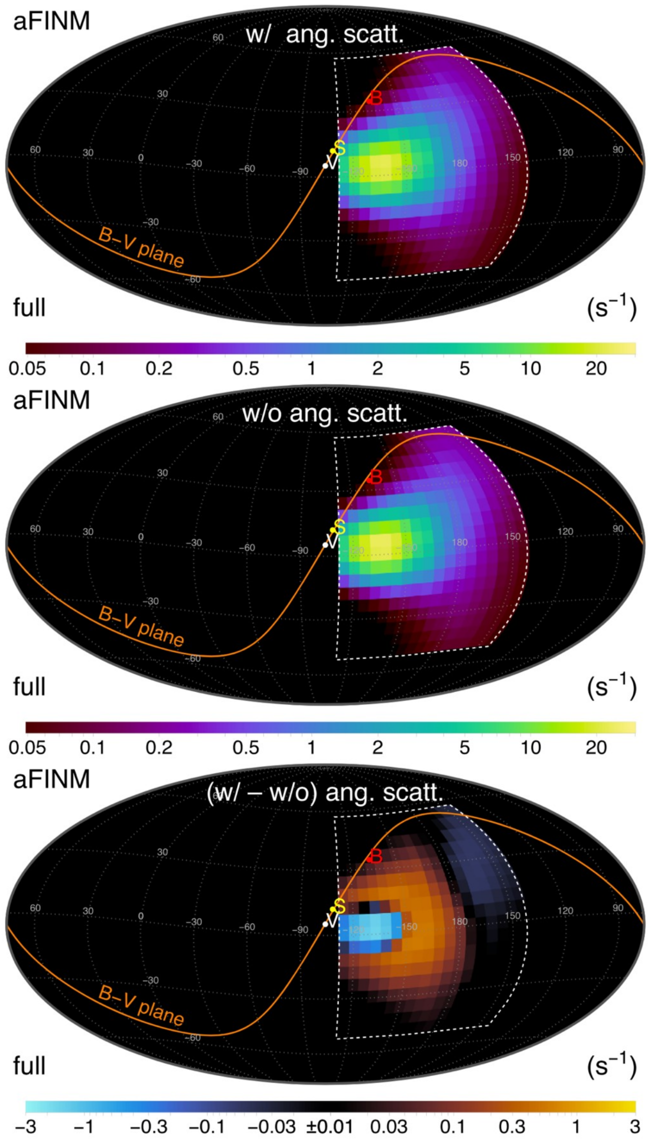
← Collisions of He atoms with H^+, He^+, H^0, and He^0

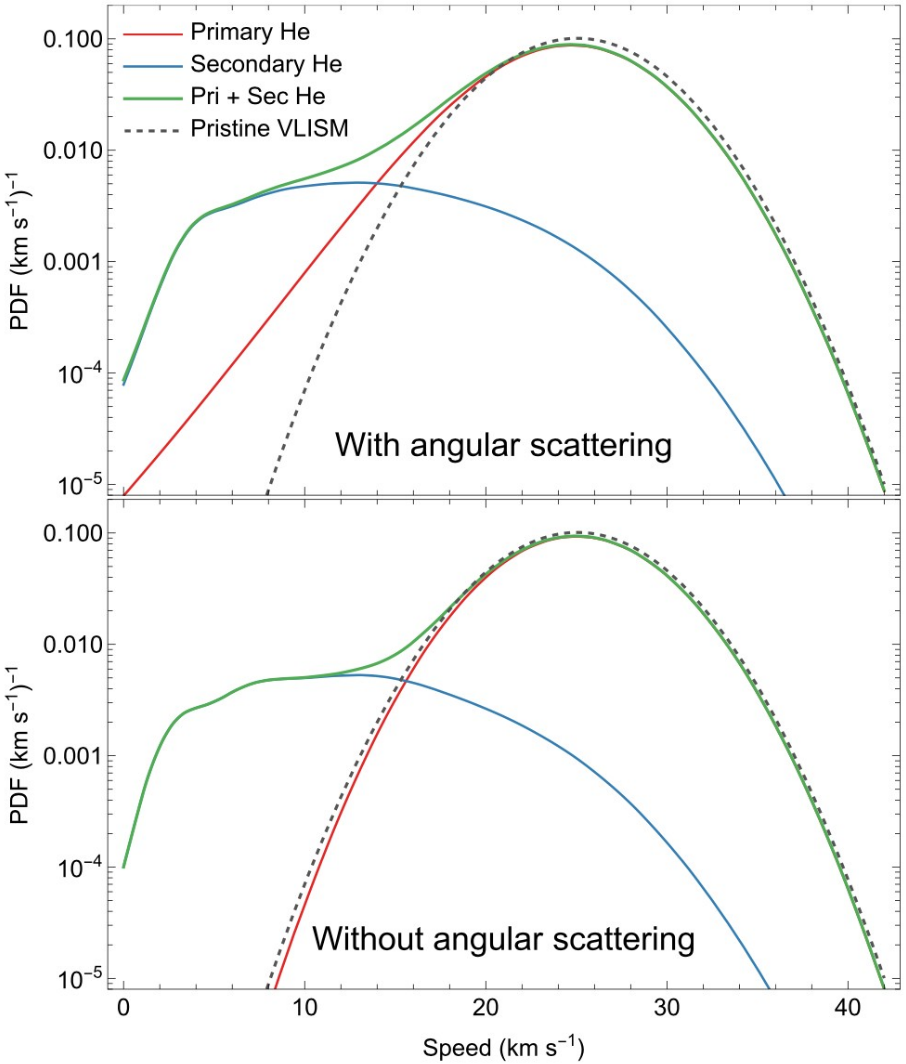




Filtration with momentum transfer

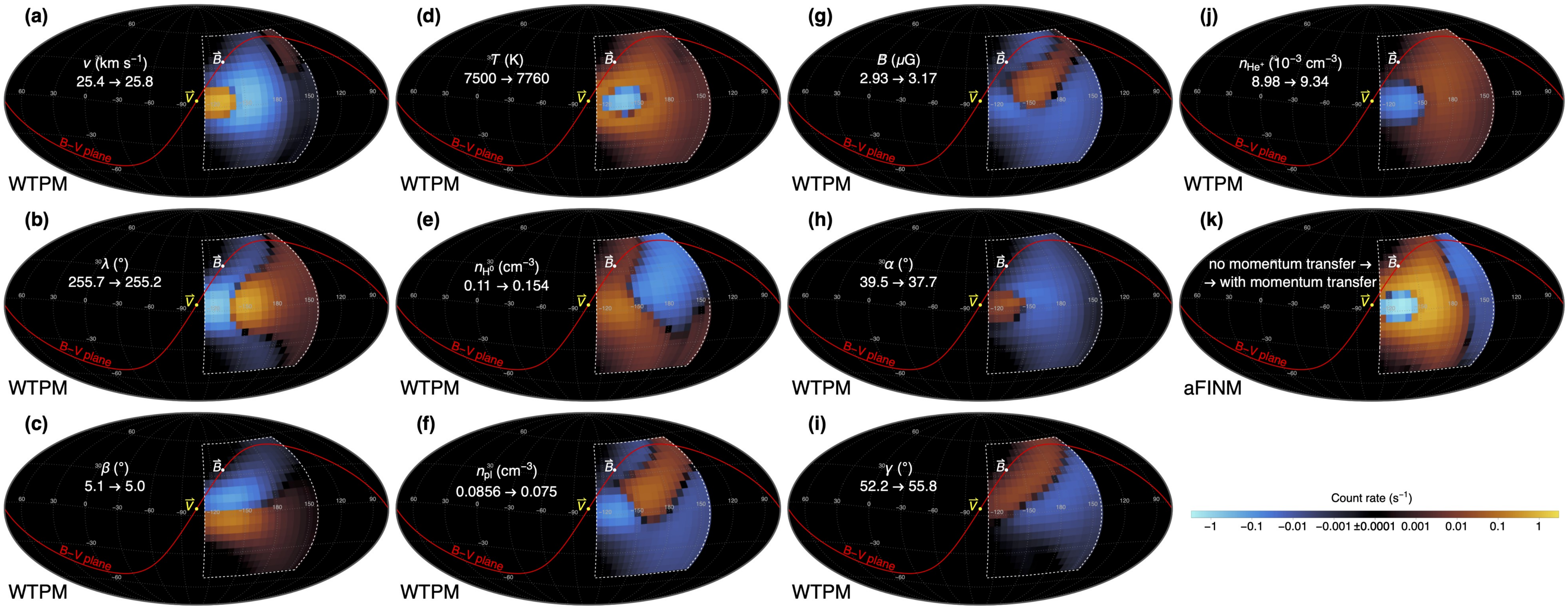
Swaczyna et al. (2023, ApJ 943:74)





Influence of interstellar conditions

Swaczyna et al. (2023, ApJ 953:107)



Derivation of interstellar conditions

Swaczyna et al. (2023, ApJ 953:107)

Linear interpolation of modeled flux:

p – parameters describing interstellar conditions

Fitting with χ^2 minimization:

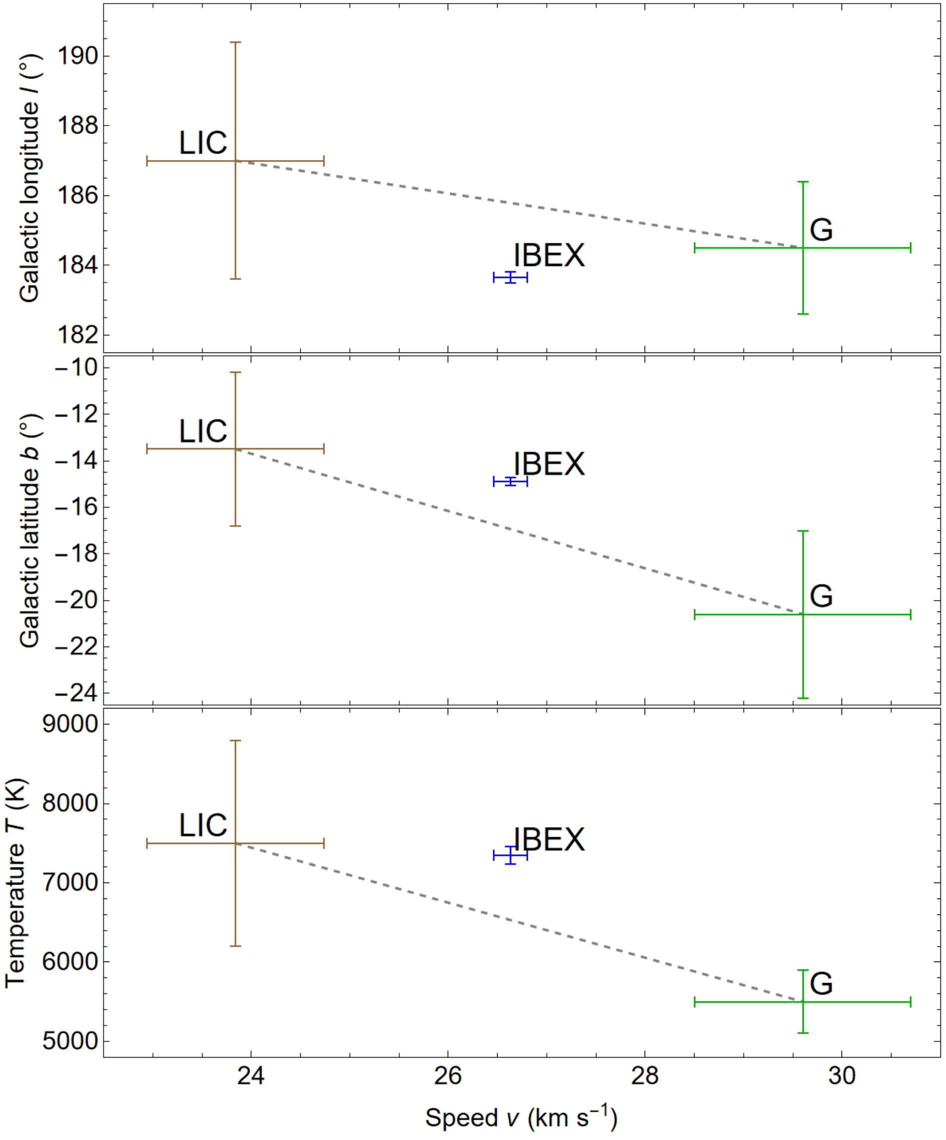
Best fit parameters

- without angular scattering effects
  - speed: 26.20 ± 0.17 km s^{-1}
  - inflow direction: (255.58°±0.19°, 5.10°±0.15°)
  - temperature: 8010±110 K
  - He^+ density: $(9.9\pm0.7)\times10^{-3}$ cm^{-3}
- with angular scattering effects
  - speed: 26.63 ± 0.17 km s^{-1}
  - inflow direction: (255.73°±0.19°, 5.04°±0.15°)
  - temperature: 7350±110 K
  - He^+ density: $(9.7\pm1.2)\times10^{-3}$ cm^{-3}

Interstellar clouds vs ISN He flow in the heliosphere

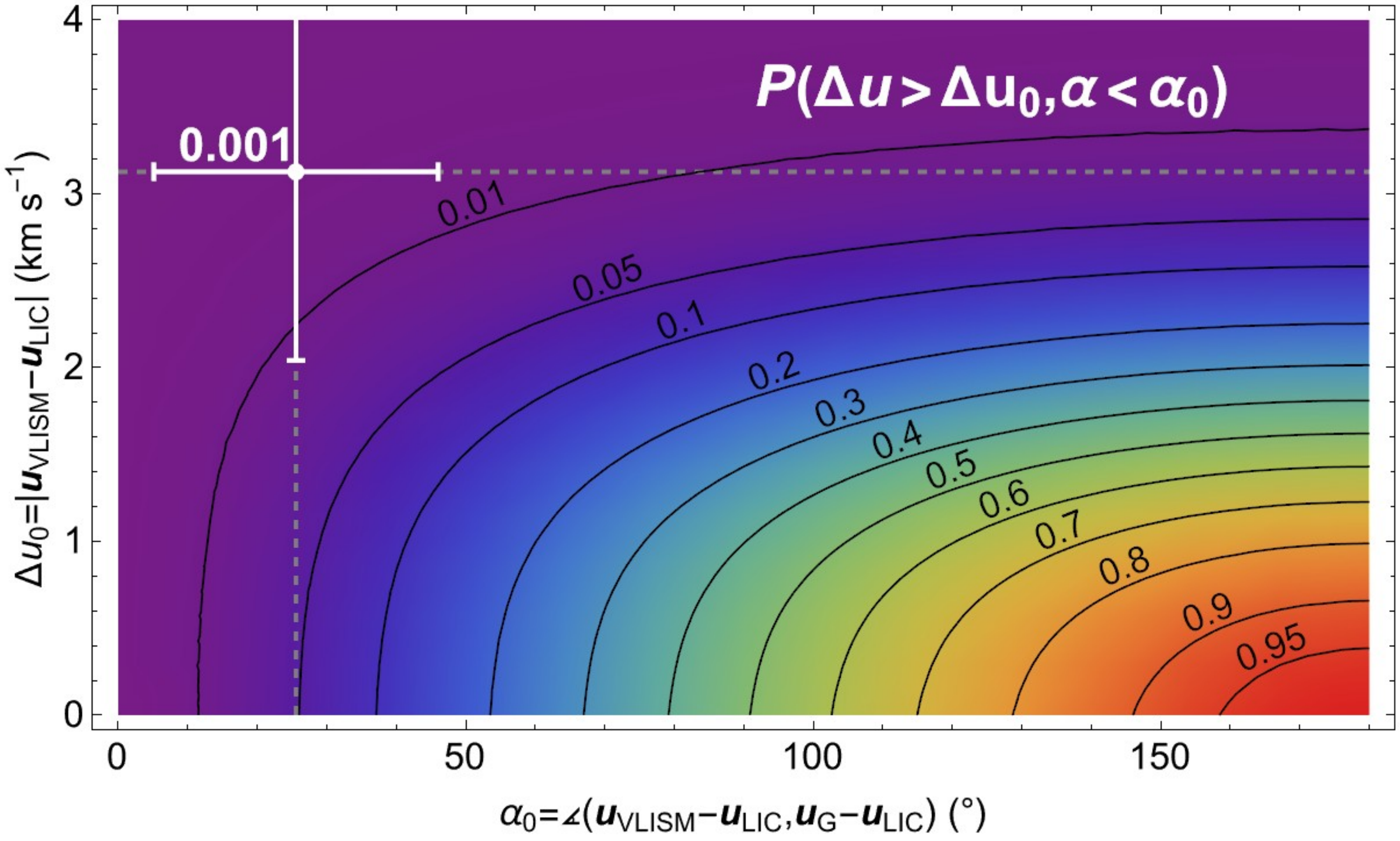
Cloud	Speed (km s⁻¹)	Galactic long. (°)	Galactic lat. (°)	Temperature (K)
LIC	23.84±0.90	187.0±3.4	−13.5±3.3	7500±1300
G Cloud	29.6±1.1	184.5±1.9	−20.6±3.6	5500±400
IBEX	26.63±0.17	183.6±0.2	−14.9±0.2	7350±110

updated from Swaczyna et al. (2022, ApJL 937:L32)



A turbulence in the LIC? – Very unlikely

updated from Swaczyna et al. (2022, ApJL 937:L32)



Mixed Interstellar Cloud Medium (MICM)

updated from Swaczyna et al. (2022, ApJL 937:L32)

Conservation laws for mixed medium:

$$M_{\mathrm{MICM}} = M_{\mathrm{LIC}} + M_{\mathrm{G}}$$

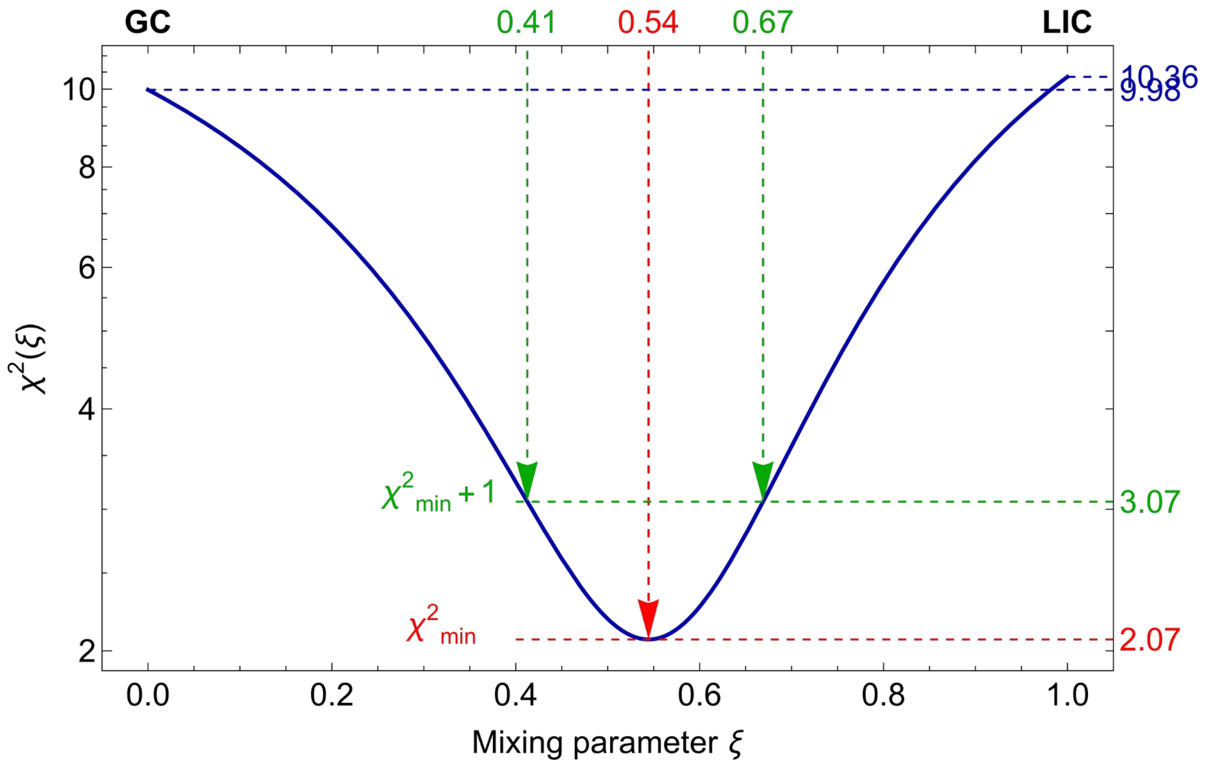
$$M_{\mathrm{MICM}}\boldsymbol{u}_{\mathrm{MICM}} = M_{\mathrm{LIC}}\boldsymbol{u}_{\mathrm{LIC}} + M_{\mathrm{G}}\boldsymbol{u}_{\mathrm{G}}$$

$$\boldsymbol{u}_{\mathrm{MICM}} = \xi\boldsymbol{u}_{\mathrm{LIC}} + (1-\xi)\boldsymbol{u}_{\mathrm{G}}$$

$$\xi = M_{\mathrm{LIC}}/M_{\mathrm{MICM}},\ 1-\xi = M_{\mathrm{G}}/M_{\mathrm{MICM}}$$

ξ - mixing parameter

Hypothesis	ξ	k	χ^2	AIC
LIC	1	0	10.36	10.36
G Cloud	0	0	9.98	9.98
MICM	0.54±0.13	1	2.07	3.60

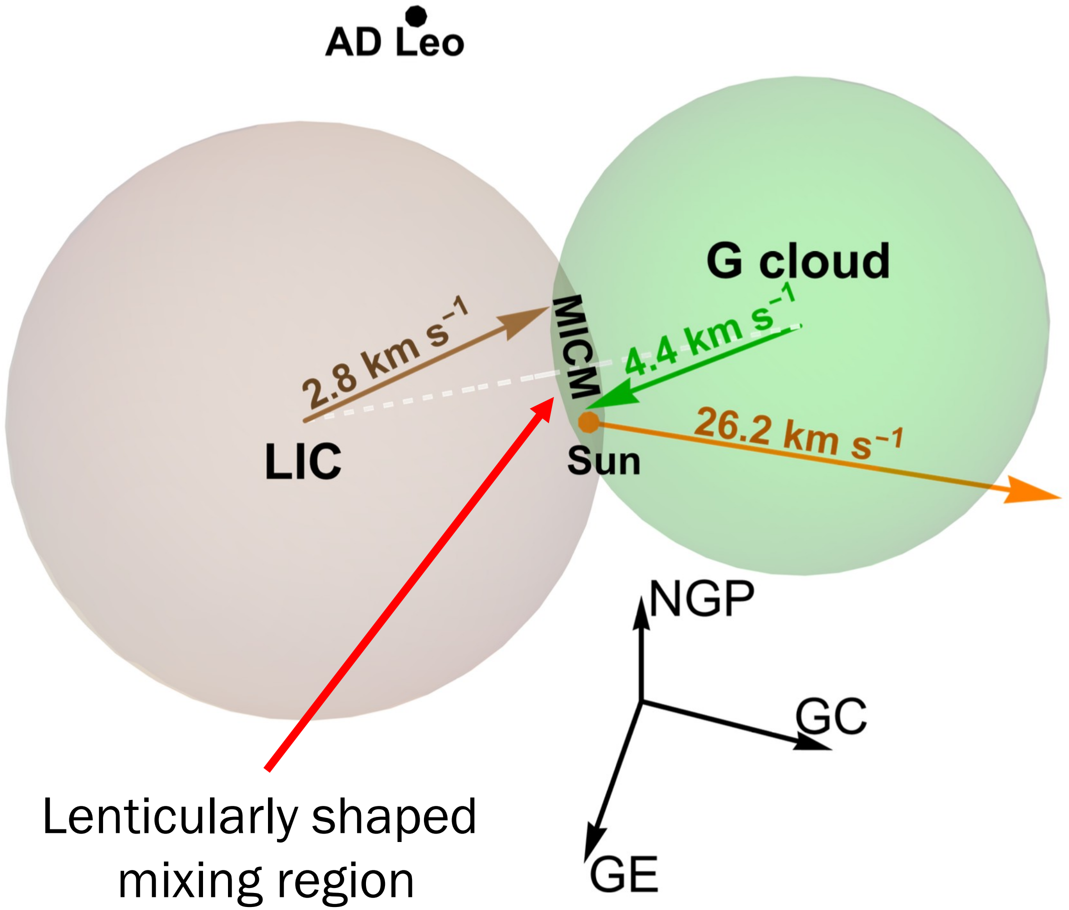


AIC strongly prefers the MICM model

Model of mixing clouds

Swaczyna et al. (2022, ApJL 937:L32)

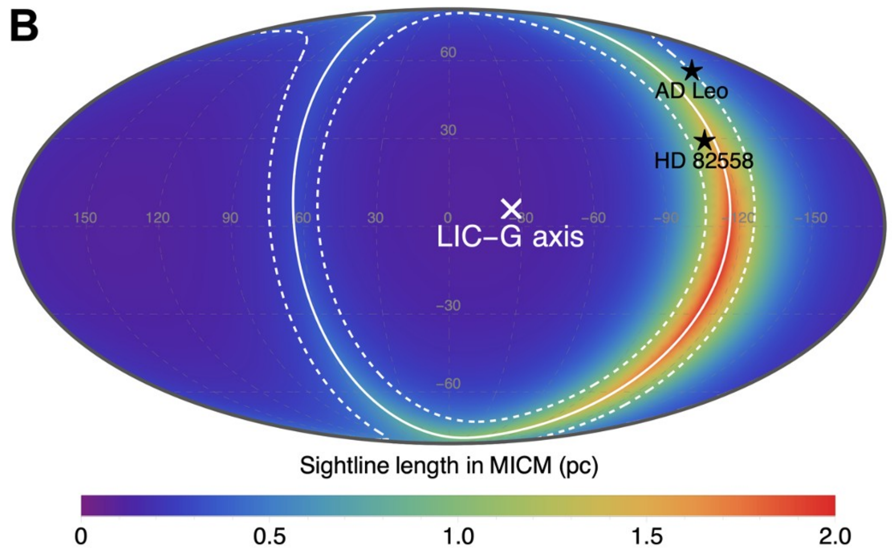
Illustrative model: LIC and G cloud modeled as spherical bodies.



Lenticularly shaped mixing region

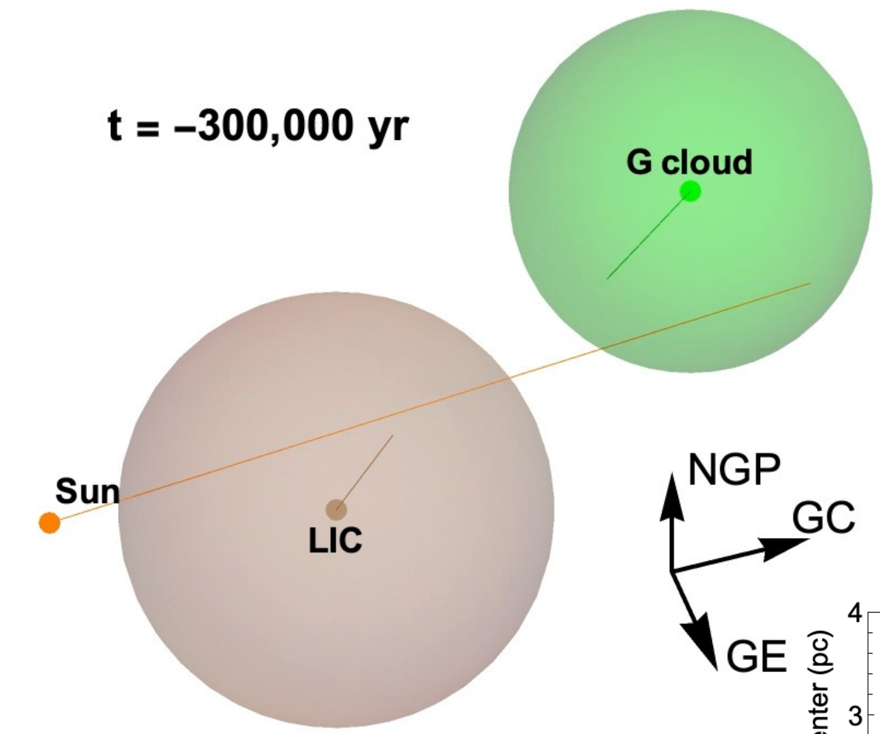
- Two know lines of sight w/ average ISN H density >0.13 cm^{-3}:

  AD Leo: 0.19 cm^{-3} and HD 82558: 0.20 cm^{-3}



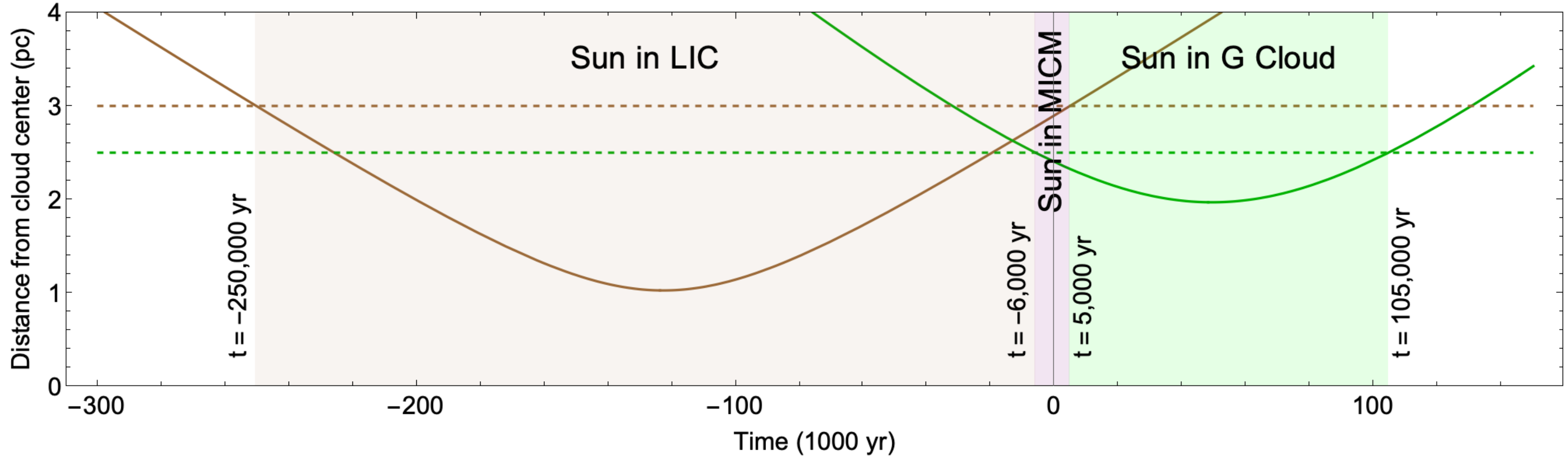
- Lenticular shape of MICM → increased density along the great circle about the axis between LIC and G cloud centers

Time evolution of MICM



Sun history in the LIC/G/MICM

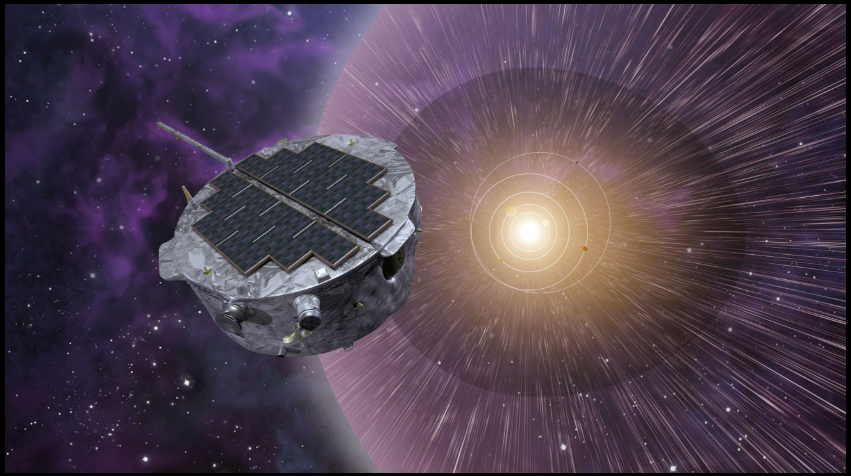
- 250k yr ago Sun enters the LIC
- 100k yr ago LIC and G collides – MICM created
- 6k yr ago Sun exits LIC enters MICM
- In 5k yr Sun exits MICM enters G
- In 105k yr Sun exits G



Future

Interstellar Mapping and Acceleration Probe

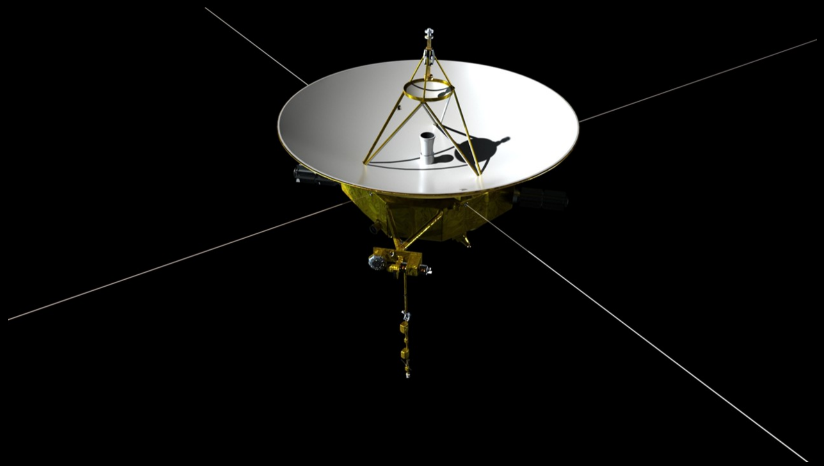
Launch scheduled in 2025



- Next generation ISN atom detector placed on a pivot platform
- Greater flexibility in imaging the ISN population distribution functions

Interstellar Probe

Concept (possible launch in 2030s)



- First dedicated mission for interstellar medium study: >350 au in 50 years
- In situ and remote observations
- Multigenerational effort

Summary

Takeaway message:

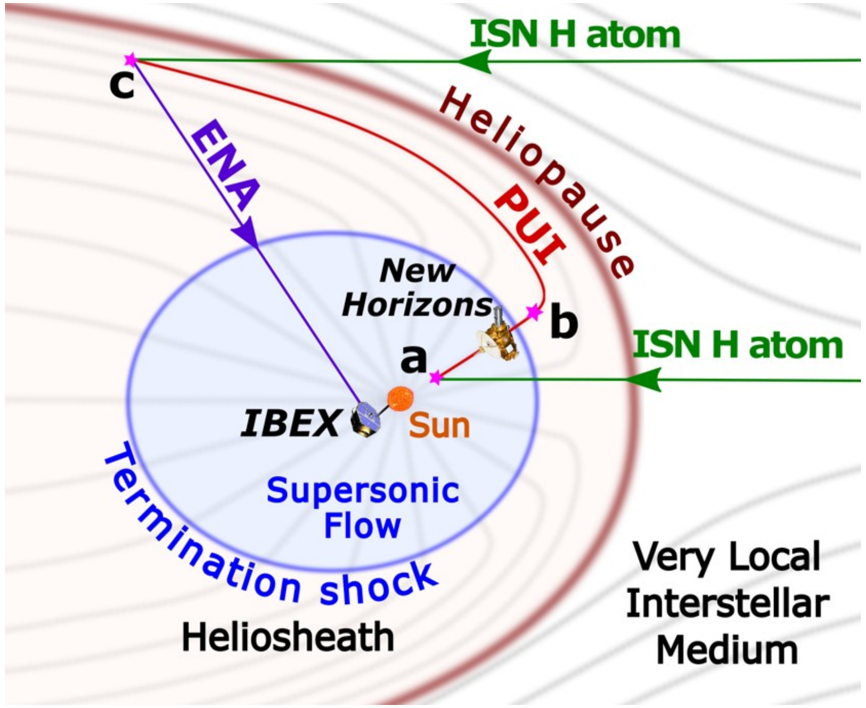
- Synergy between direct observations of interstellar atoms and observations of absorption lines from interstellar material near the Sun enables detailed study of the nearest ISM.
- Interstellar flow derived near the Sun is consistent with an almost 50/50 mixture of the two nearest interstellar clouds → **the Sun is inside a mixing region**.

Outlook:

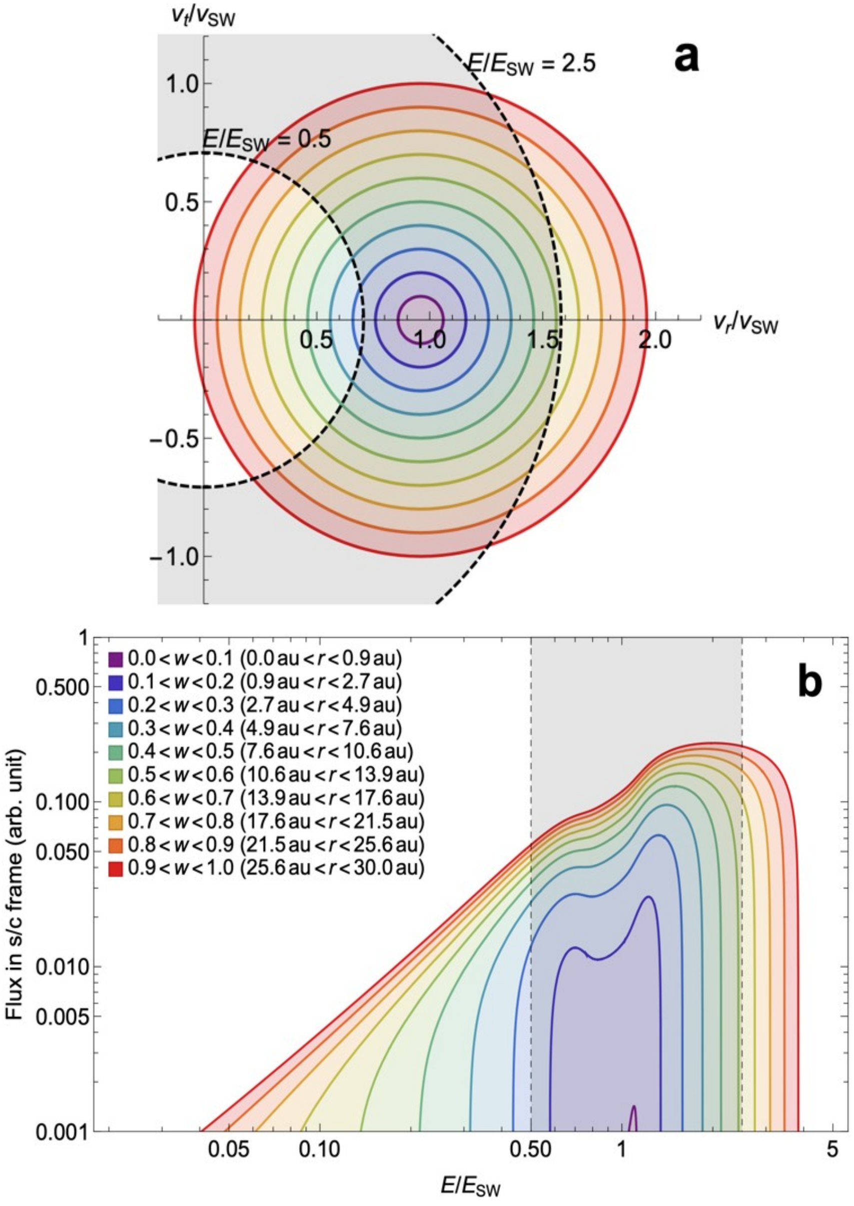
- Further observations of absorption lines with the Hubble Space Telescope should allow for better constrain of the mixing region (additional observation time granted in HST Cycle 31).
- The next generation ISN detector (IMAP-Lo) should give better insight into non-equilibrium distribution in the nearby interstellar medium.
- These observations may pave the path for the Interstellar Probe mission, which would be the first humankind mission dedicated to in situ observation of interstellar medium.

Backup slides

Pickup ions and abundance of ISN hydrogen

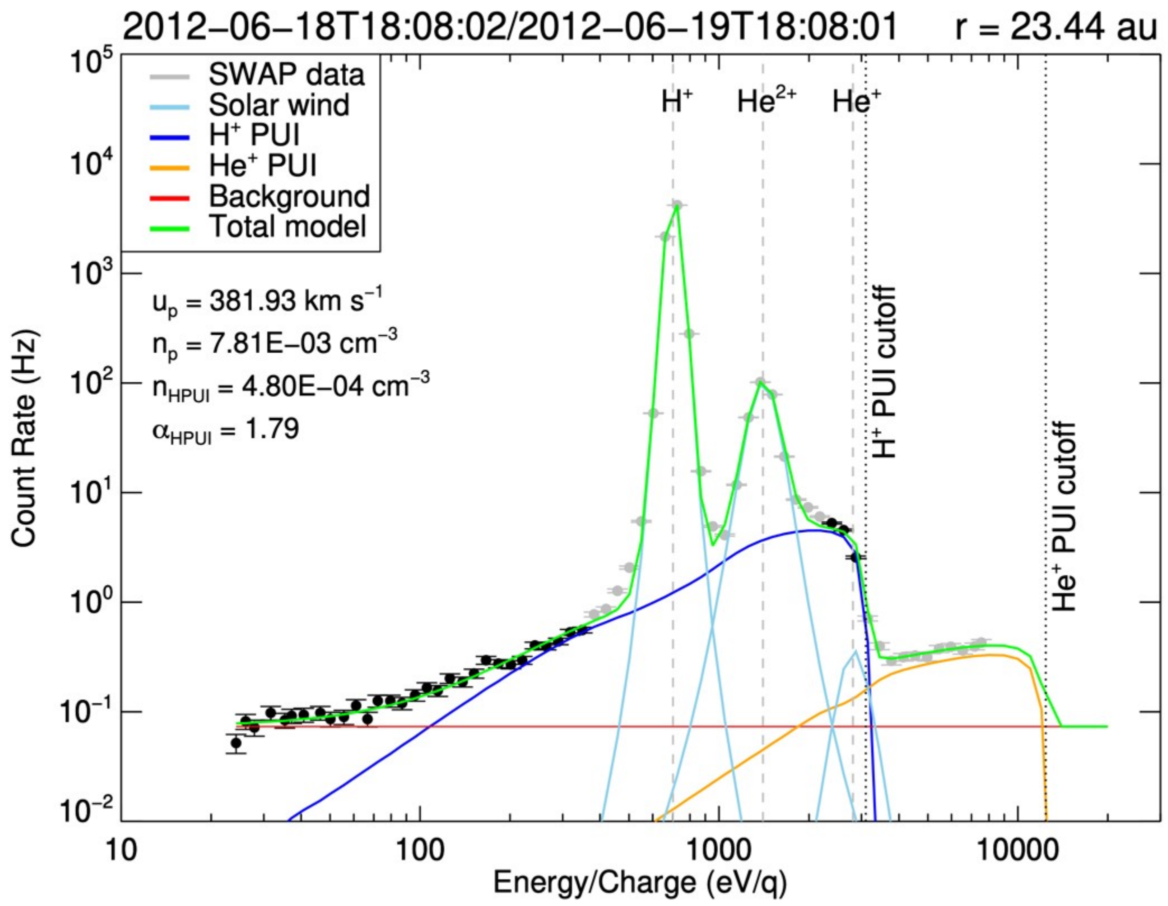


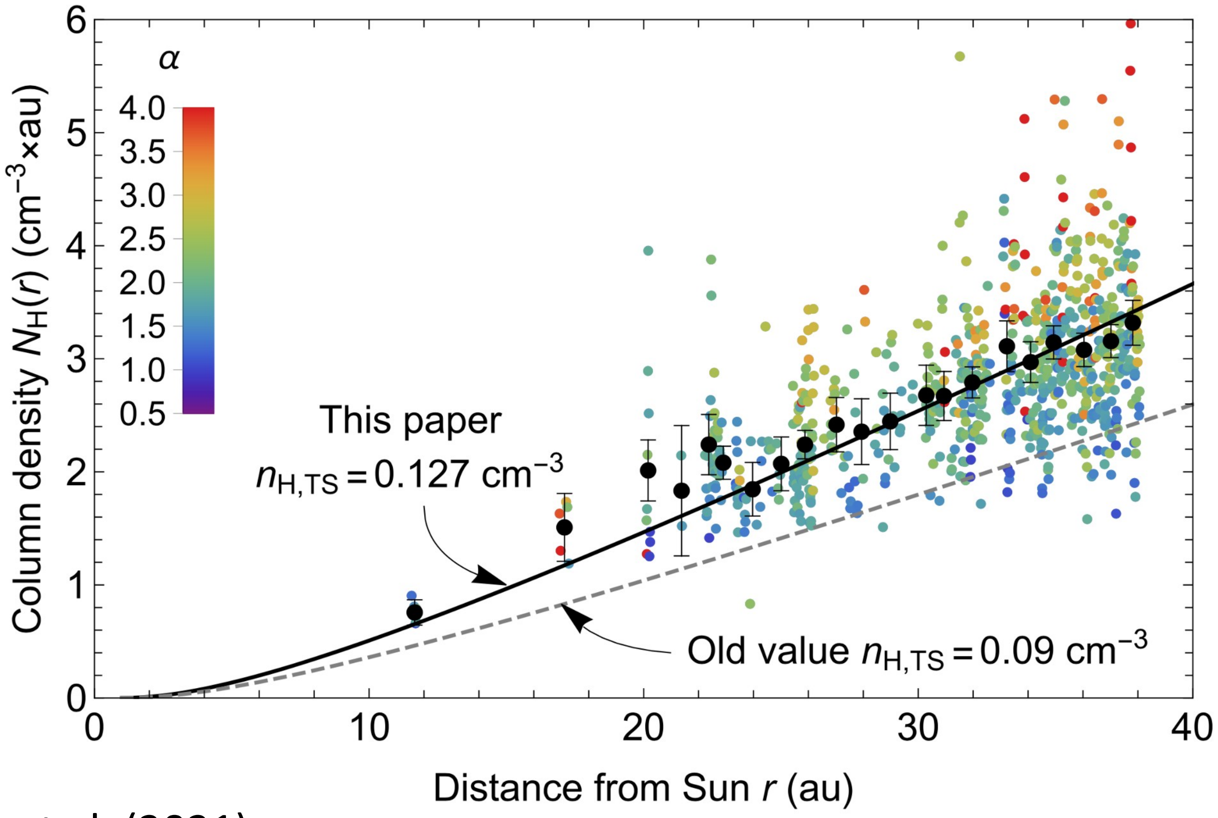
- Interstellar neutral → Ionization → Pickup ions
- Pickup ions accumulate in the solar wind
- Characteristic filled shell distribution
- Measured by Solar Wind Around Pluto (SWAP) on New Horizons



Swaczyna et al. (2020)

Interstellar hydrogen density from New Horizons





Swaczyna et al. (2021)