Centrum Badań Kosmicznych PAN
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Interstellar Neutrals and Pickup Ions from IBEX and New Horizons

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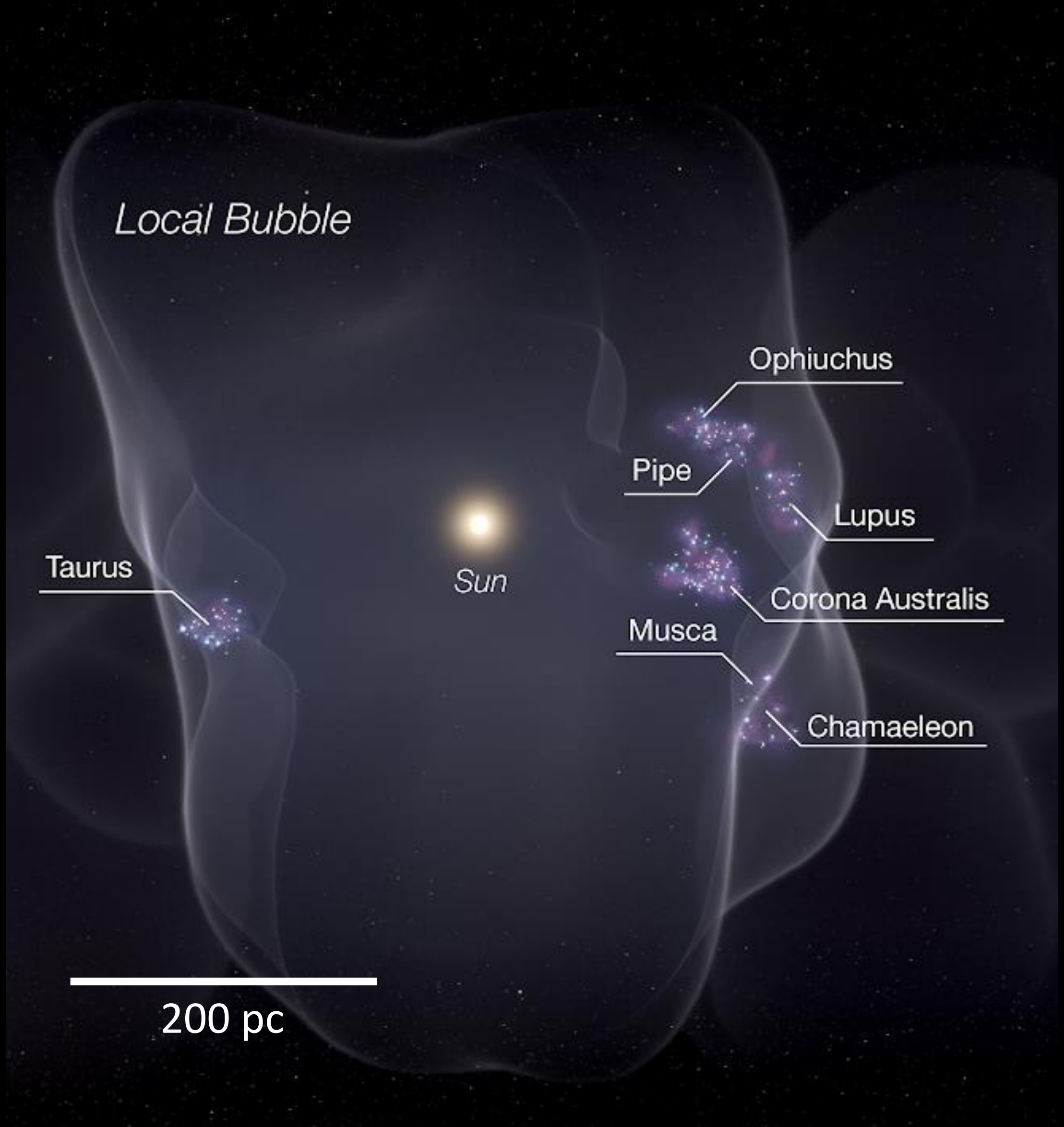
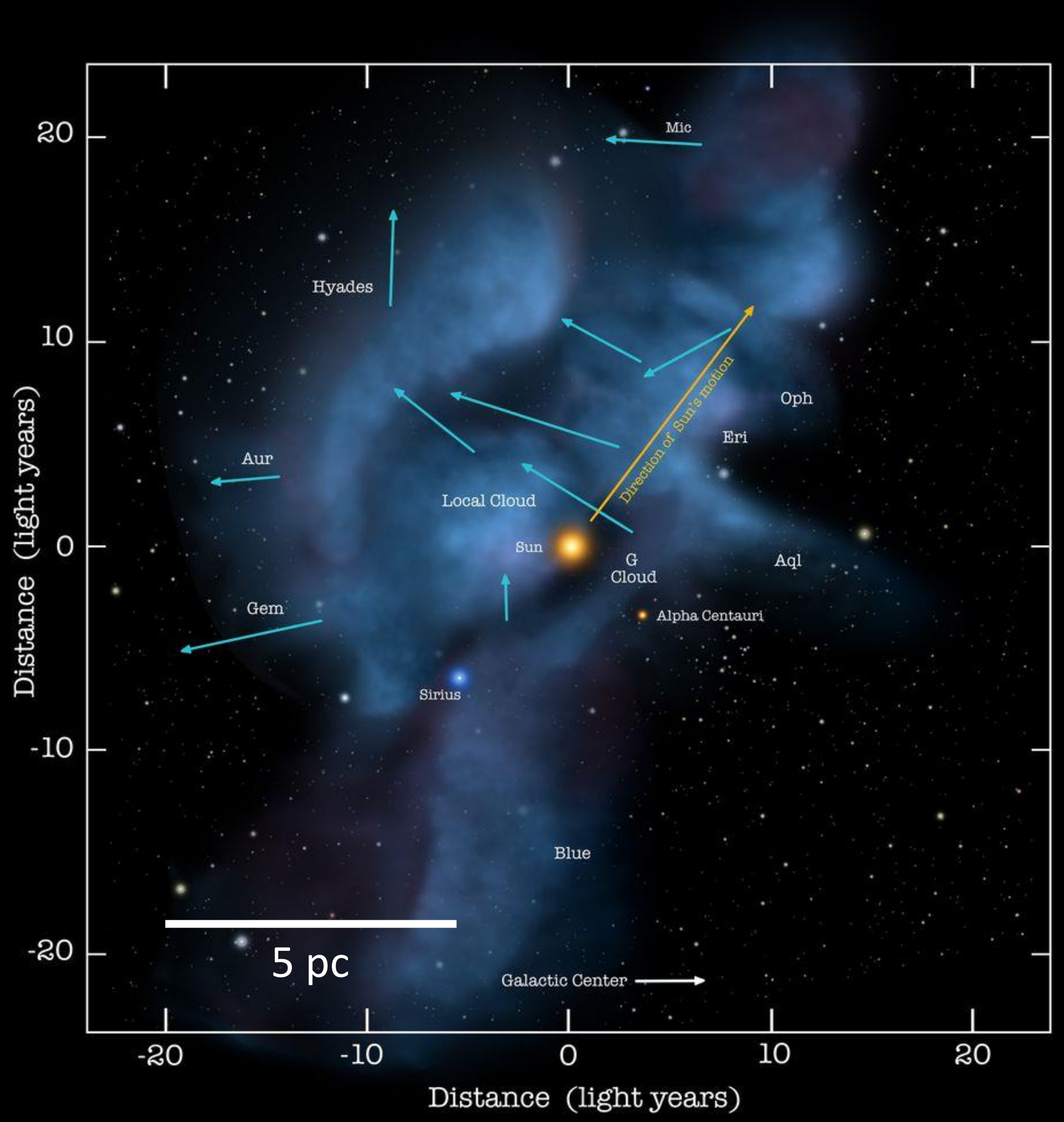
Our interstellar neighborhood



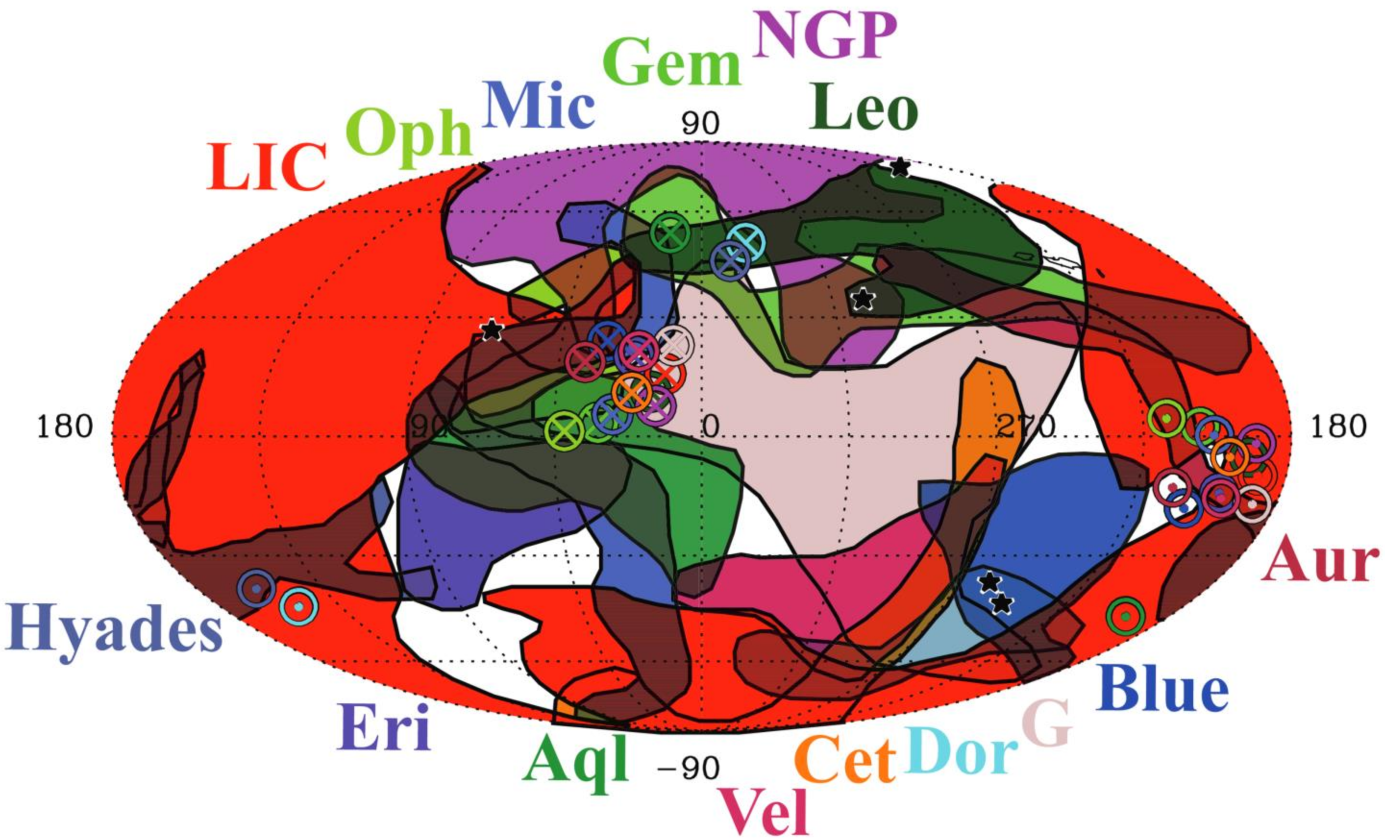
STScI, CfA, Harvard

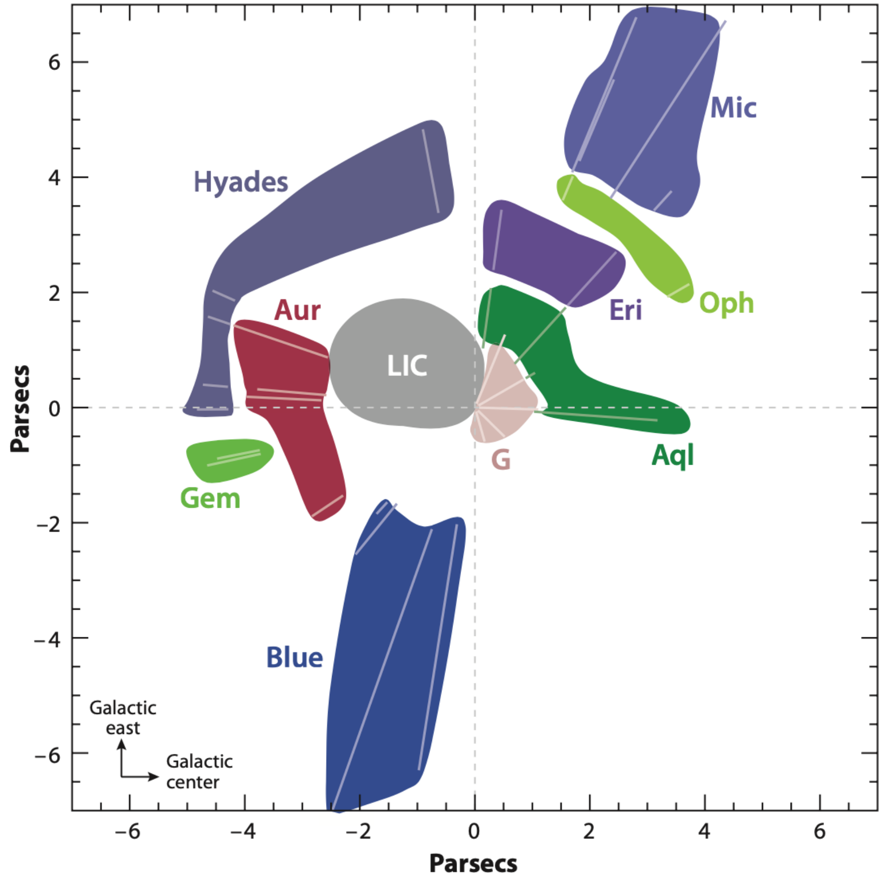


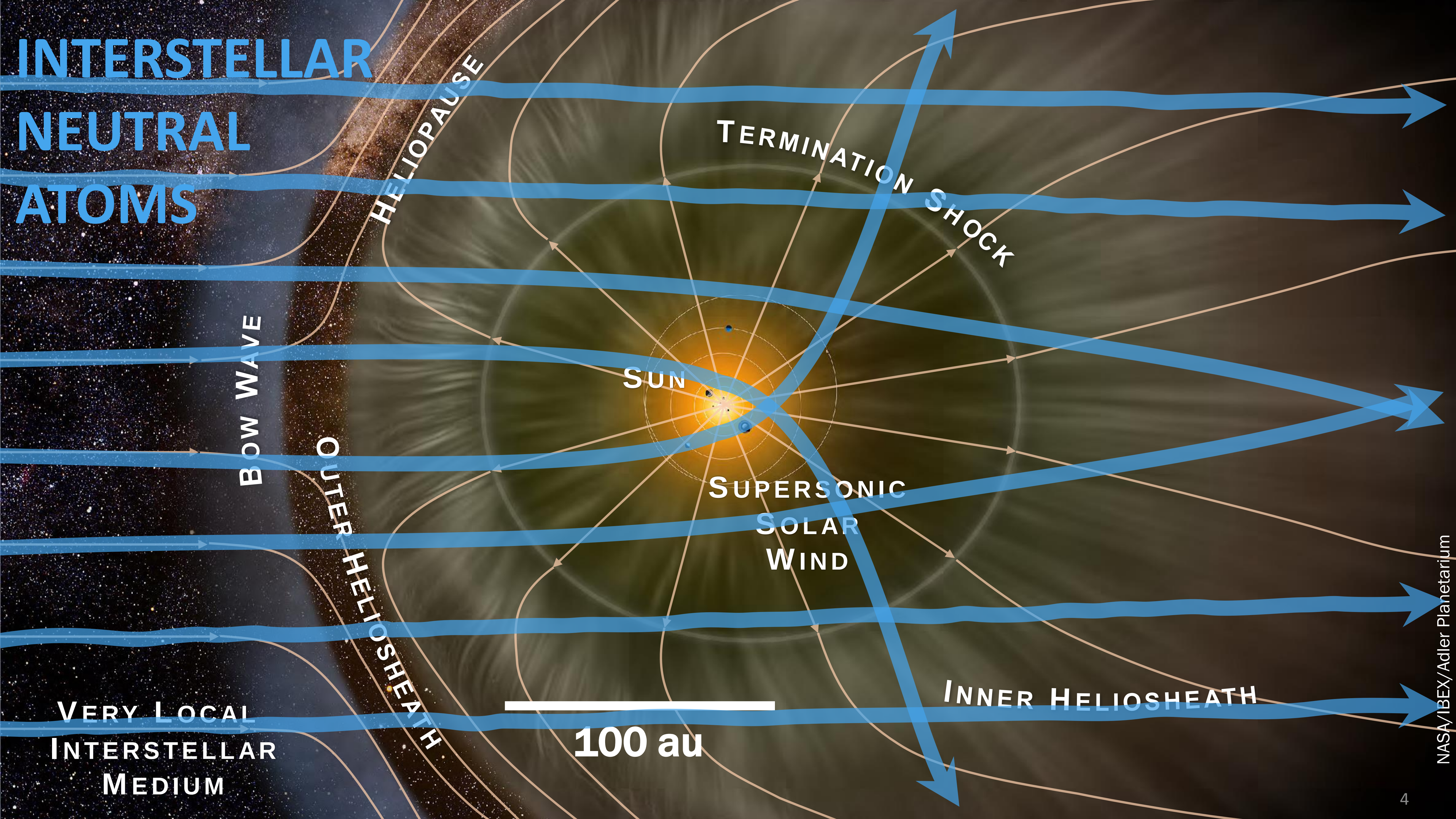
NASA/Goddard/Adler/U. Chicago/Wesleyan

Complex of Local Interstellar Clouds (CLIC)

Redfield & Linsky (2008, ApJ 673:283)

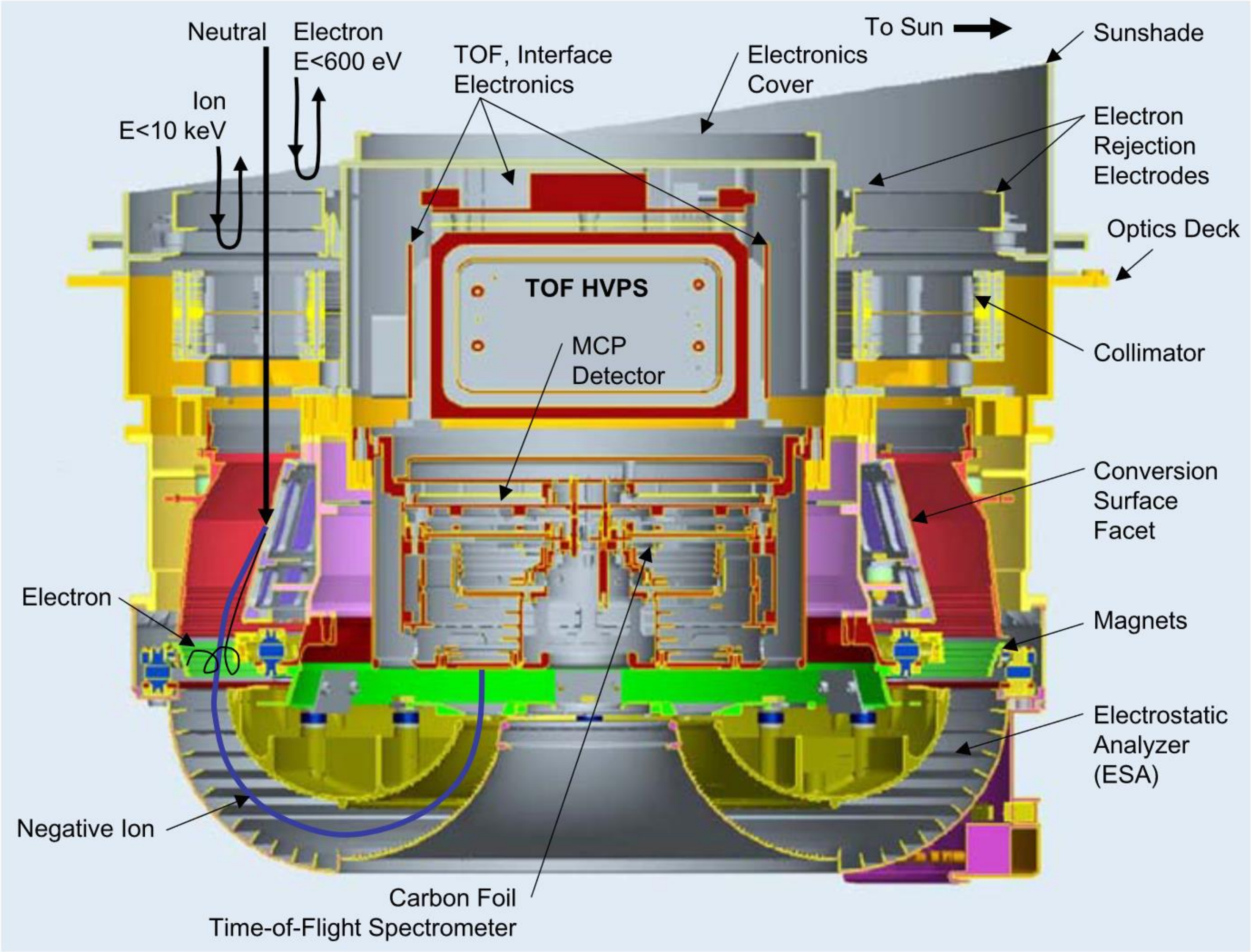


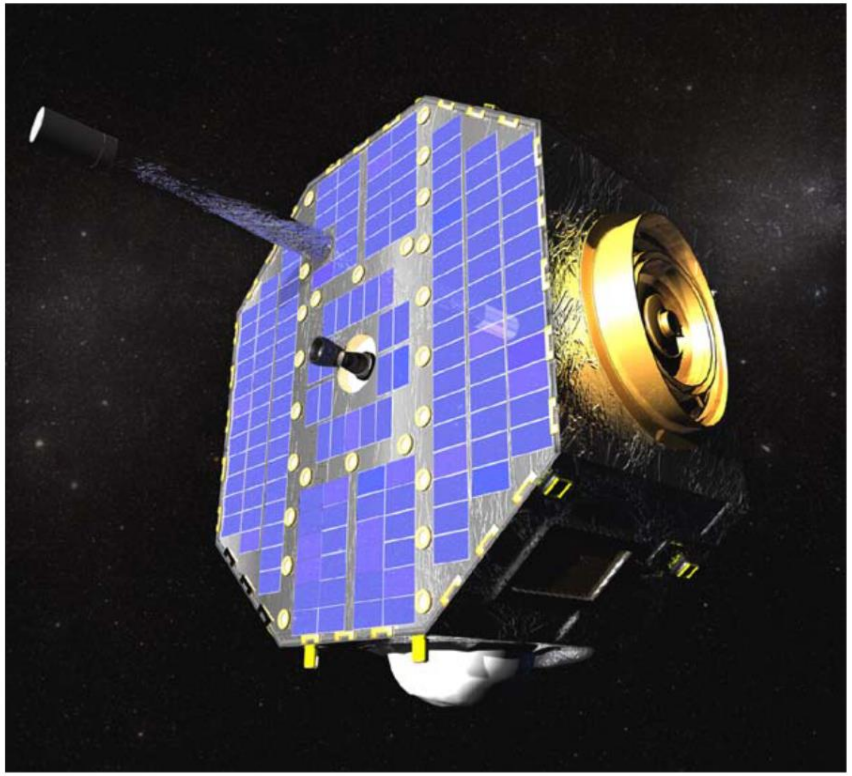



INTERSTELLAR
NEUTRAL
ATOMS
HELIOPAUSE
TERMINATION SHOCK
BOW WAVE
SUN
OUTER HELIOSHEATH
SUPERSONIC
SOLAR
WIND
INNER HELIOSHEATH
VERY LOCAL
INTERSTELLAR
MEDIUM
100 au
NASA/IBEX/Adler Planetarium

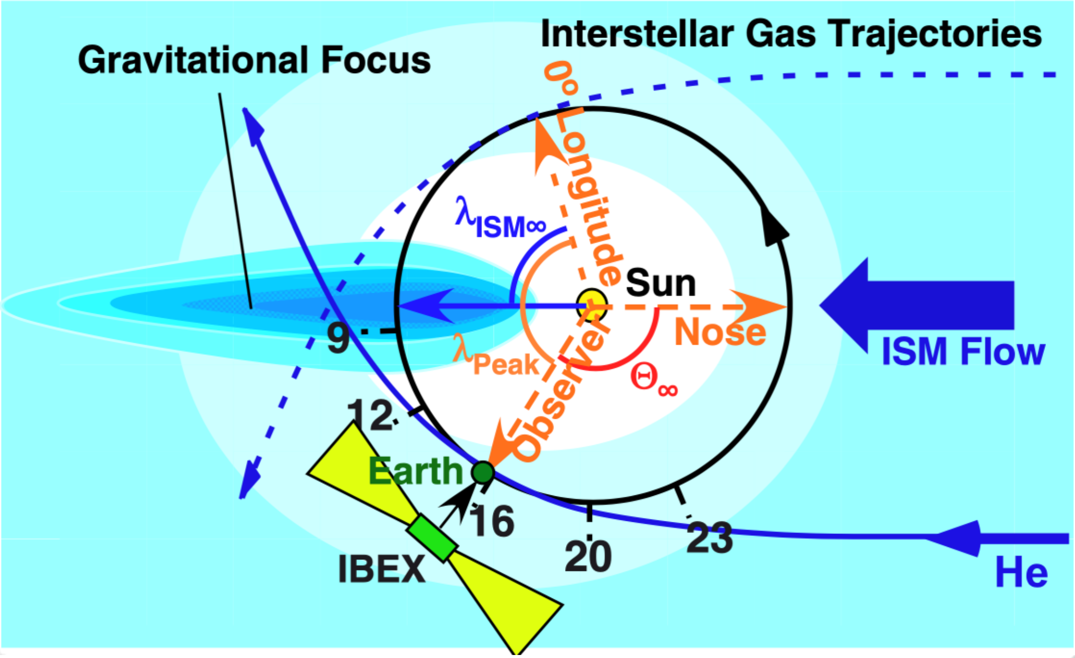
Detection of ISN atoms on IBEX

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

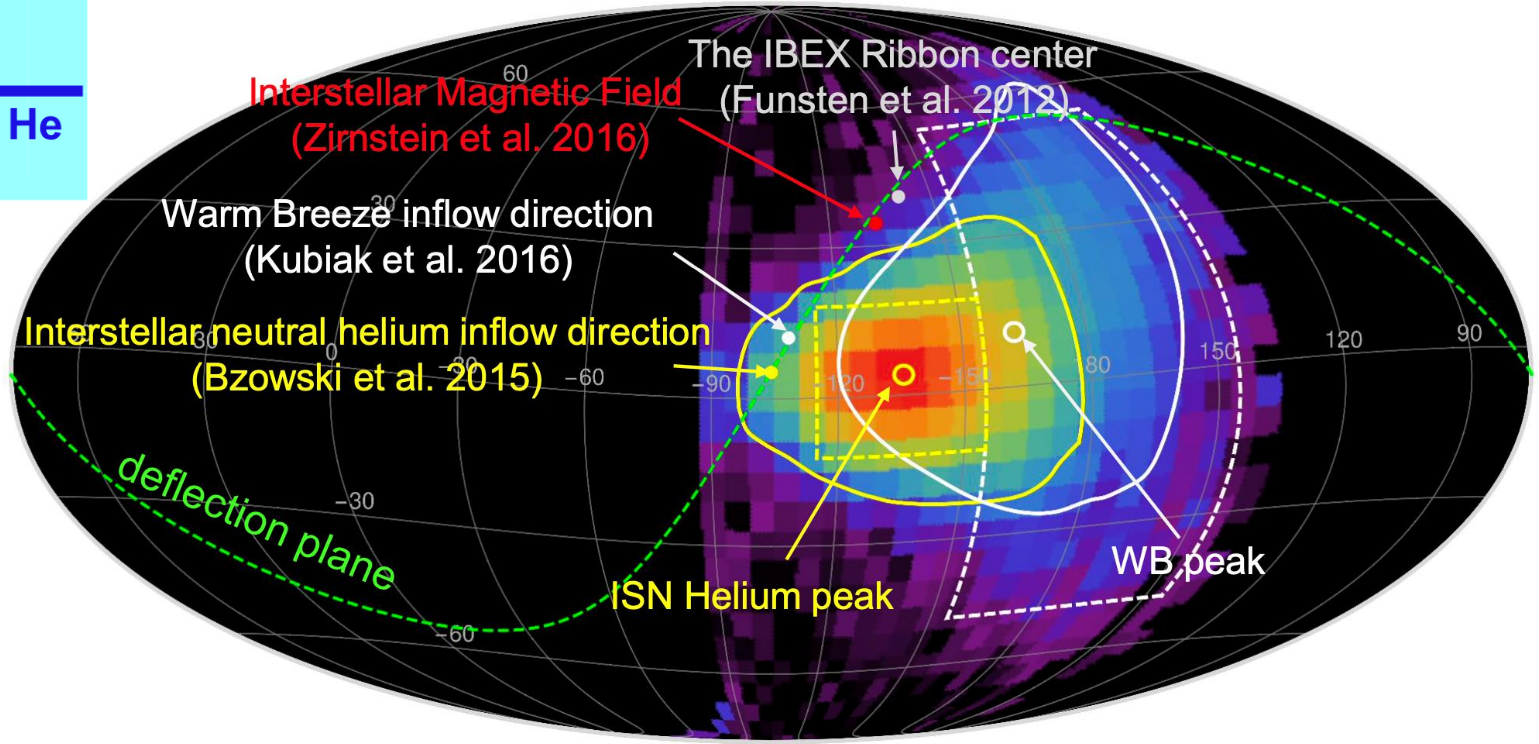




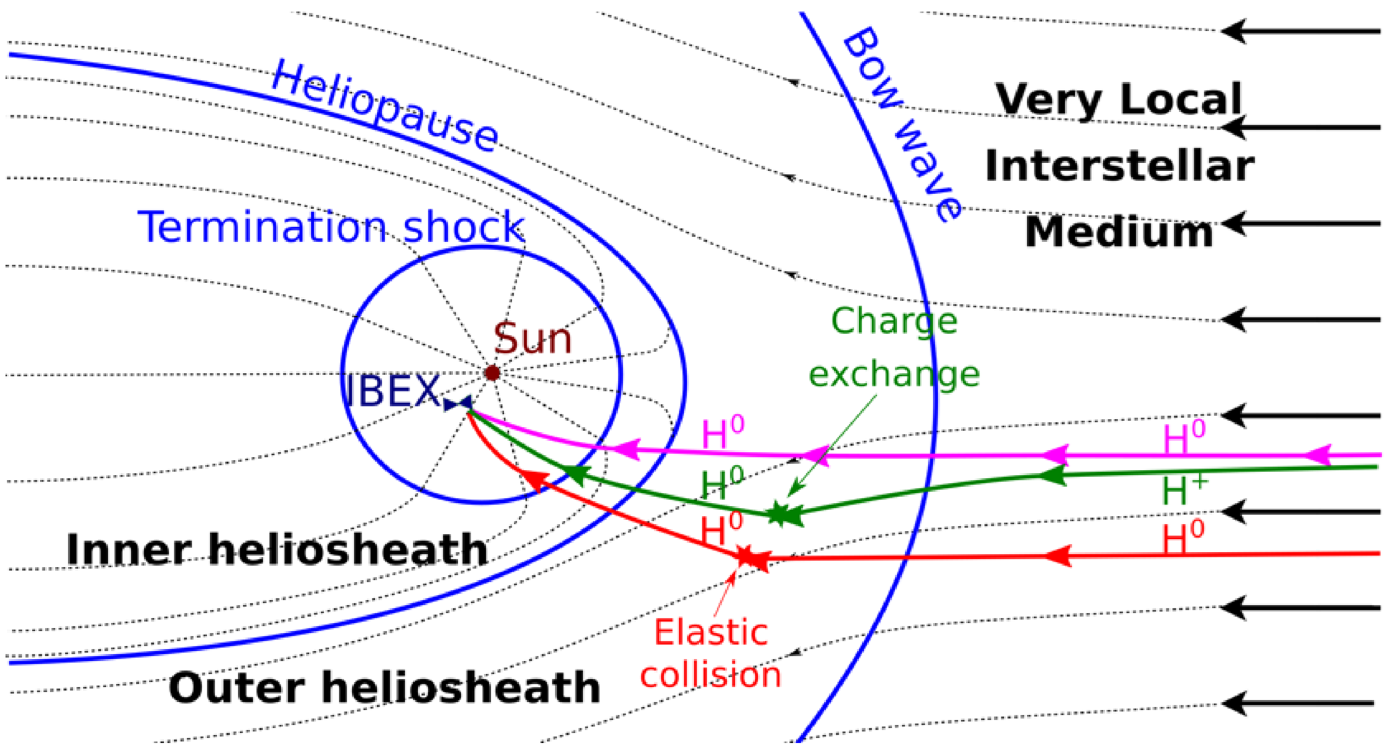
Observations of ISN wind by IBEX



Möbius et al. (2012, ApJS 198:11)



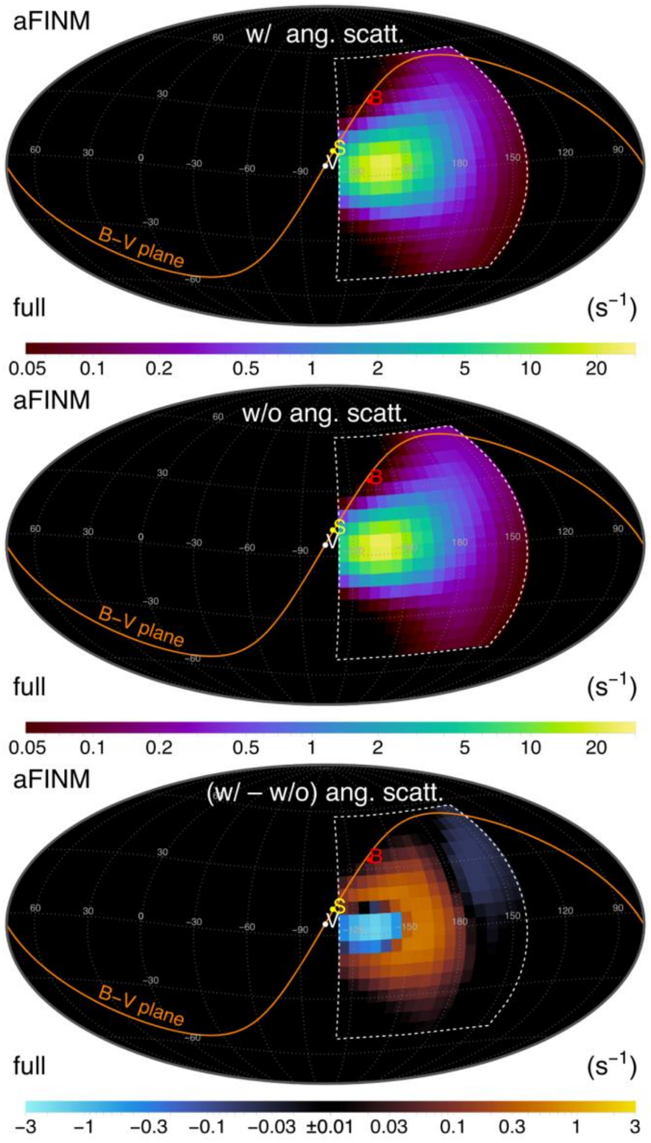
ISN population in the heliosphere **is not** pristine

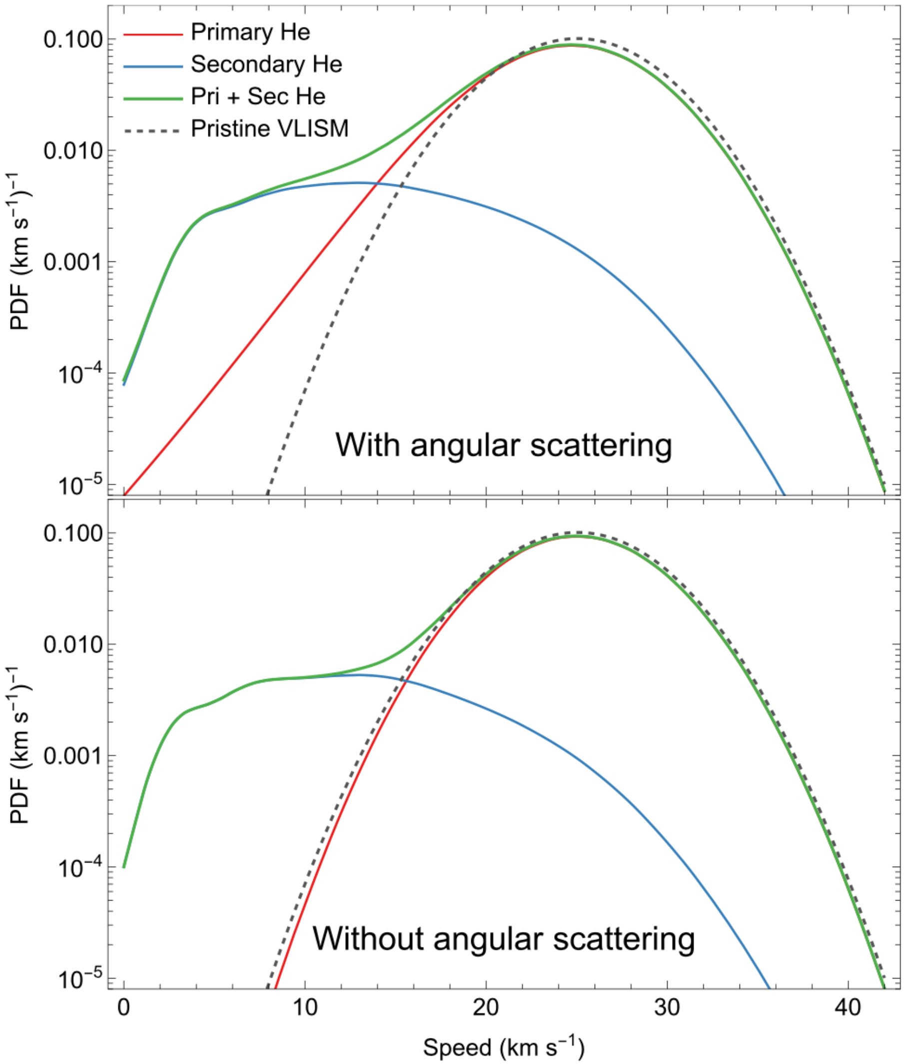


- **Charge exchange collisions:**
  - Losses to primary population
  - Production of secondary population
  - ~5% of He atoms, ~50% of H atoms
  - Mostly resonant collisions
- **Elastic collisions:**
  - Slowdown and heating
  - Angular scattering of colliding particles
  - Most atoms undergo multiple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

Filtration with angular scattering

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





Initial parameters for global fitting

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

Table 1. Initial Pristine VLISM Conditions for Modeling

Parameter	Symbol p	Baseline value p^0	Variation Δp	Modified value p^1
Speed	v (km s^{-1})	25.4	+0.4	25.8
Inflow ecliptic longitude	λ (°)	255.7	–0.5	255.2
Inflow ecliptic latitude	β (°)	5.1	–0.1	5.0
Temperature	T (K)	7500	+260	7760
ISN hydrogen density	n_{H^0} (cm^{-3})	0.11	+0.044	0.154
Plasma density	n_{pl} (cm^{-3})	0.0856	–0.0106	0.075
Magnetic field strength	B (μG)	2.93	+0.24	3.17
B-V angle	α (°)	39.5	–1.8	37.7
B-V plane inclination	γ (°)	52.2	+3.6	55.8
He$^+$ density	n_{He^+} (cm^{-3})	0.00898	+0.00036	0.00934

Parameters were selected in early 2020

McComas et al. (2015, ApJS 220:22)

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

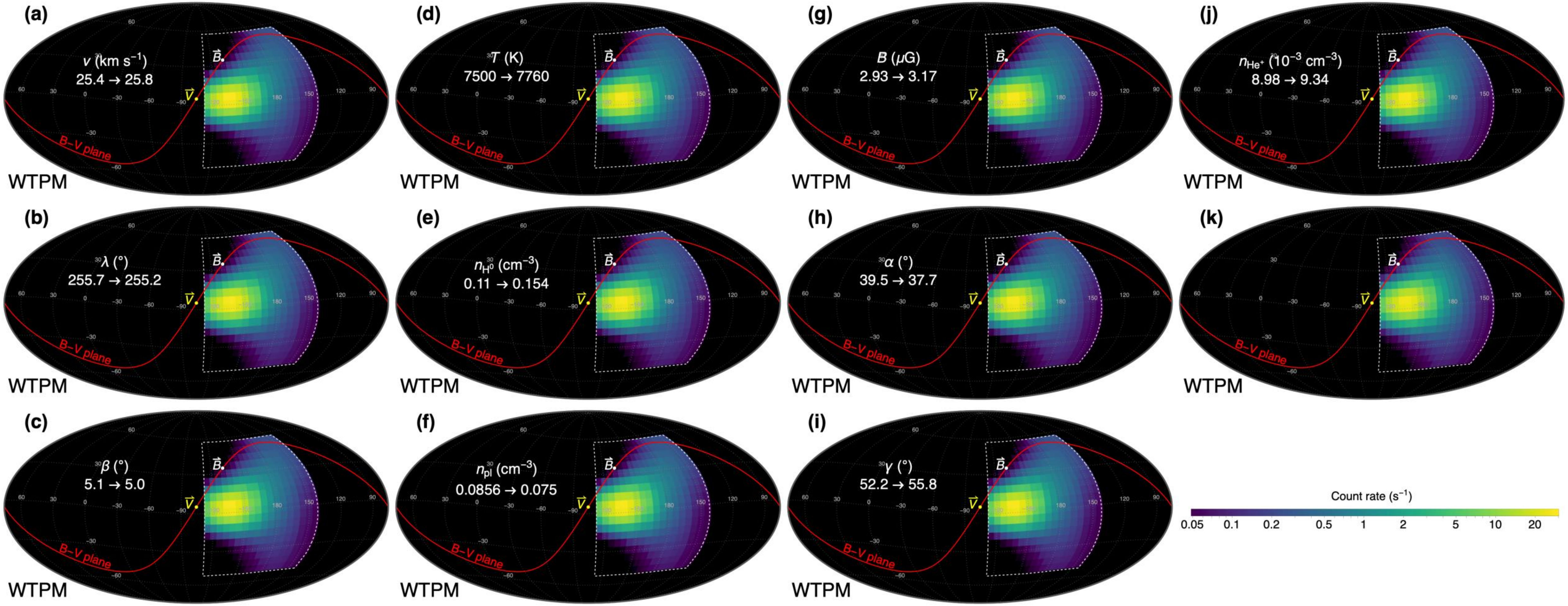
Filtration factor reduced
Bzowski & Heerikhuisen (2020, ApJ 888:24)
Based on TS density of 0.09 cm^{-3}

From the analysis of the IBEX ribbon position
Zirnstein et al. (2016, ApJL 818:L18)

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

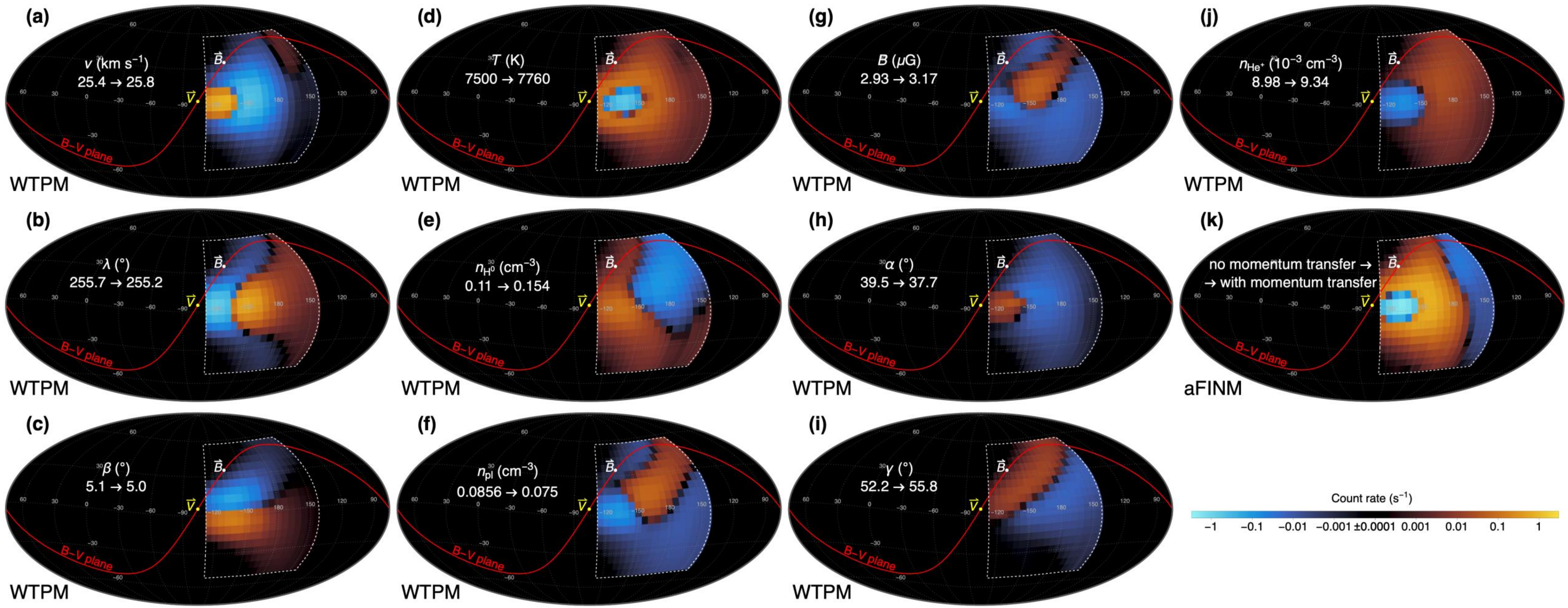
Maps with modified parameter values

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



Difference maps

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



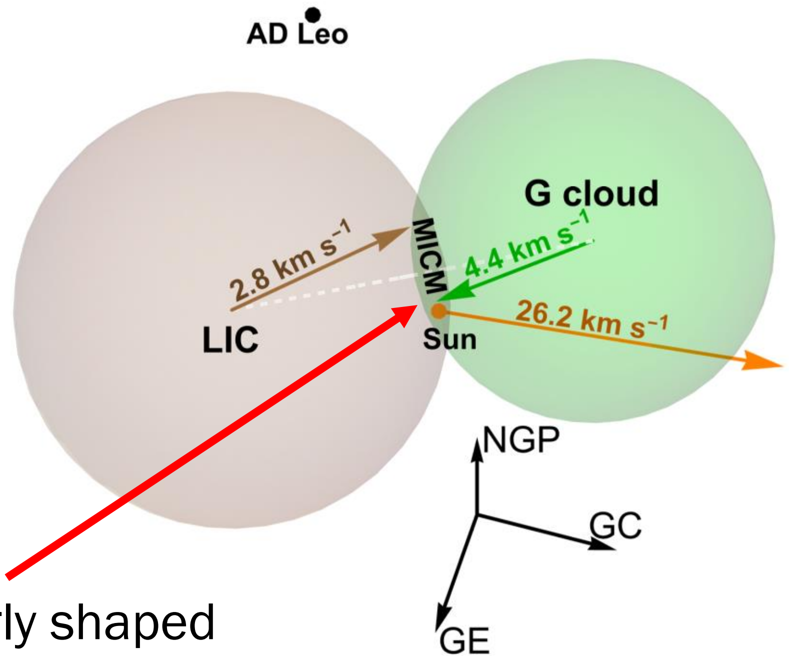
Best-fit parameters with and without angular scattering effects

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

	Without		With
Speed:	26.20±0.17 km s^{-1}	**+0.43 km s^{-1}** →	26.63±0.17 km s^{-1}
Inflow longitude:	255.58°±0.19°		255.73°±0.19°
Inflow latitude:	5.10°±0.15°		5.04°±0.15°
Temperature:	8010±110 K	**-660 K** →	7350±110 K
B-V inclination:	54.5°±0.6°		53.7°±0.6°
He^+ density:	(9.9±0.7)×10^{-3} cm^{-3}		(9.7±1.2)×10^{-3} cm^{-3}

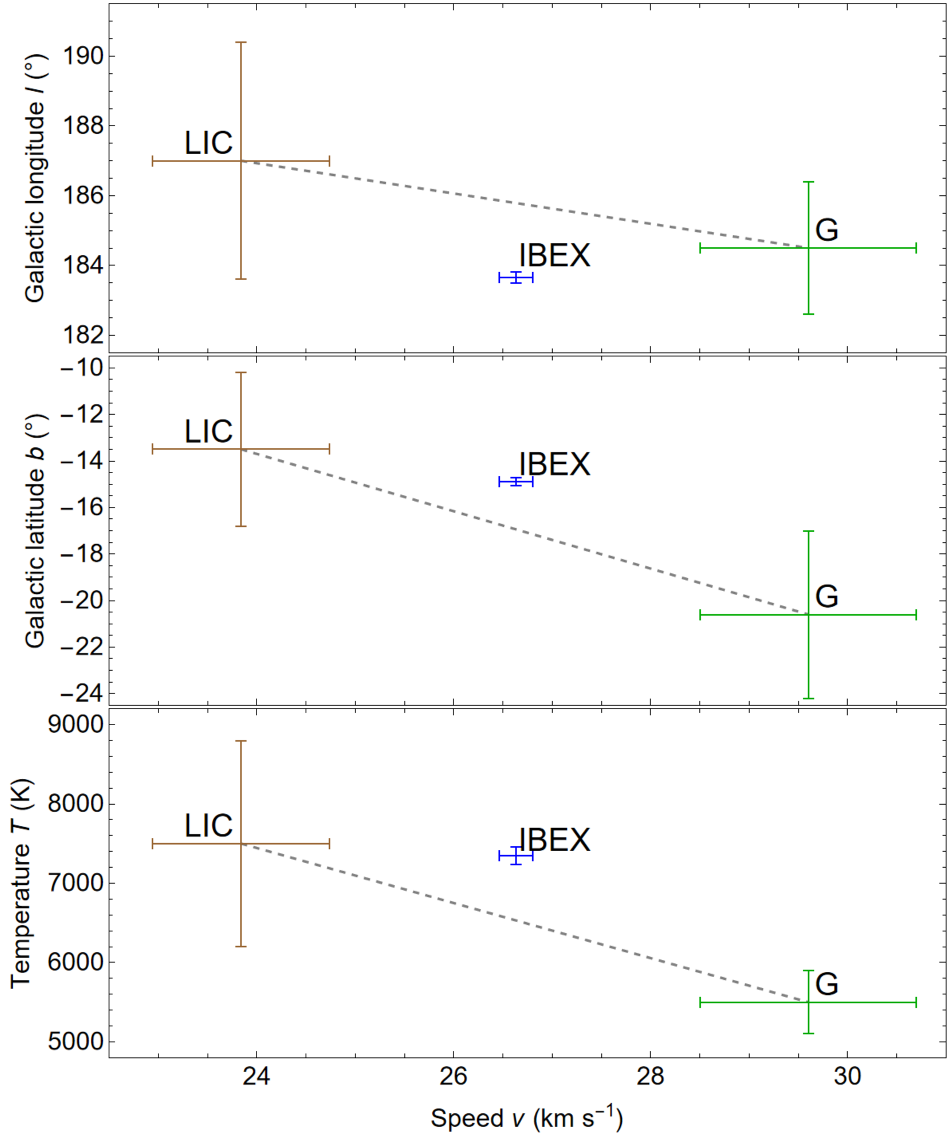
Interstellar clouds vs ISN He flow in the heliosphere

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



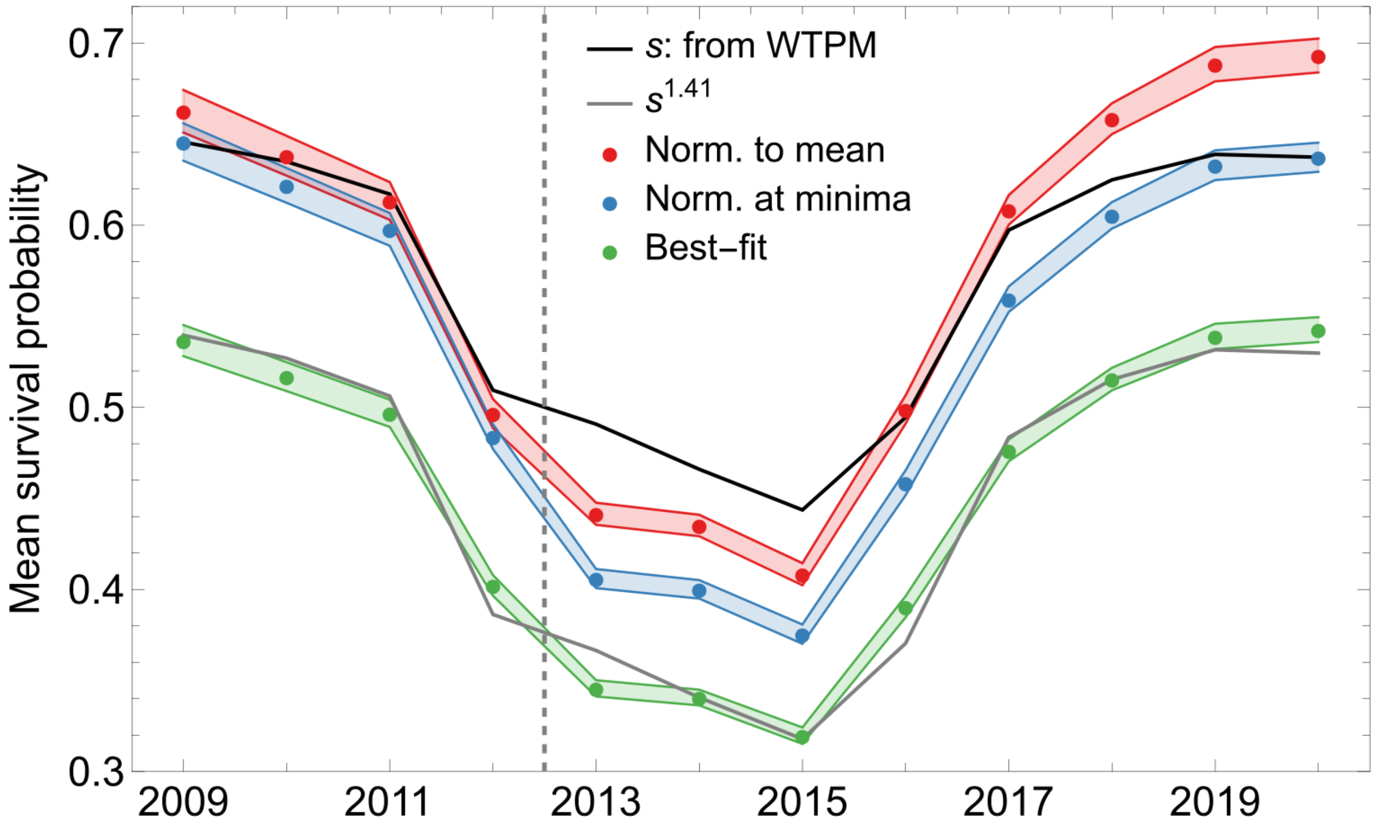
Lenticularly shaped mixing region

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



Time-evolution of ISN helium flux magnitude

Swaczyna et al. (2022, ApJS 259:42)

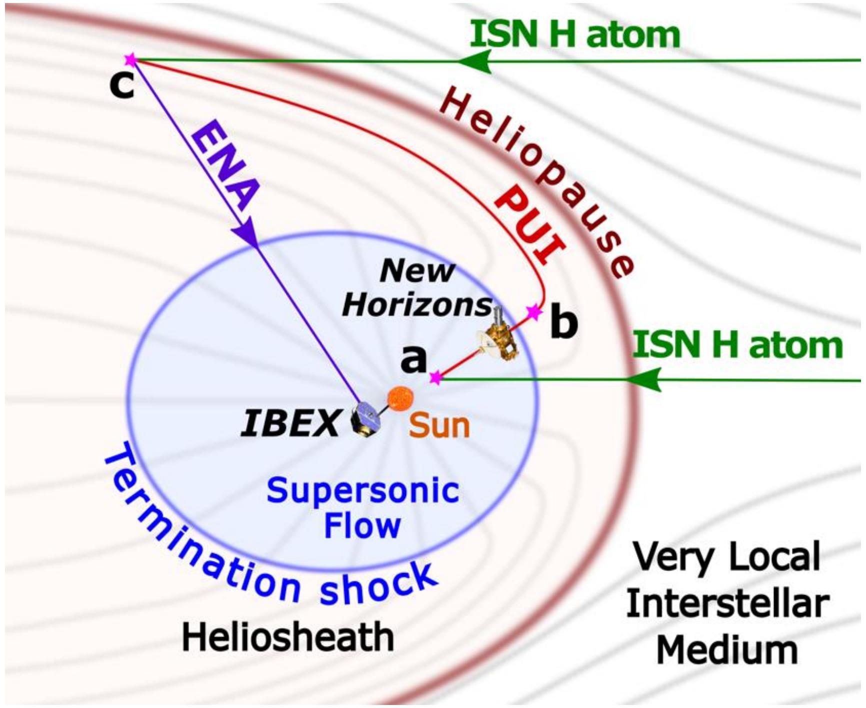


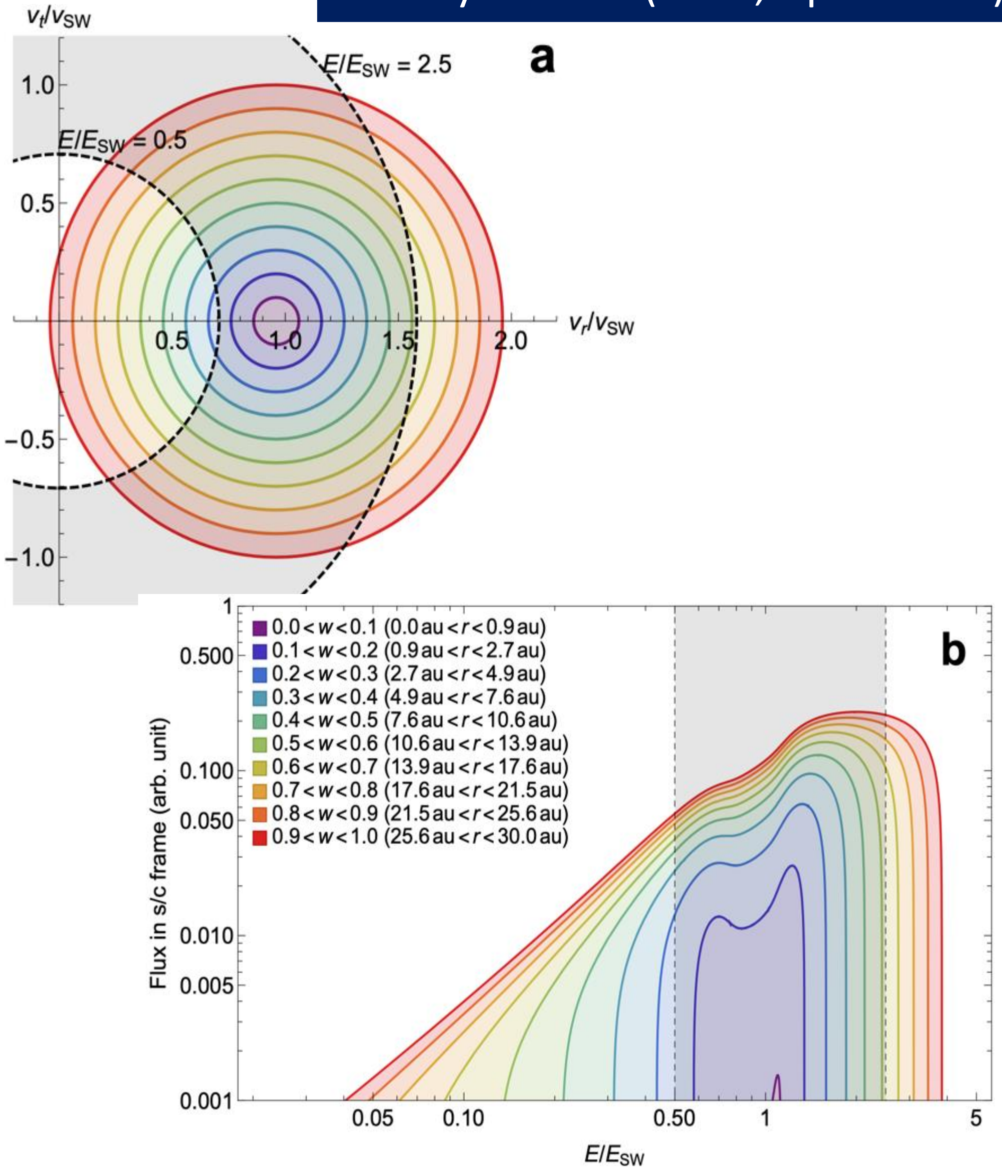
- ISN helium atoms are ionized in the heliosphere mostly by photoionization.
- Photoionization models predict lower amplitude (black line) of the fluxes than observed (color bands)
- Consistency for either:
  - Higher ionization in the solar maximum by 20% and unchanged in the minimum
  - Higher ionization by 40% over the entire solar cycle (gray line)

Pickup ions and abundance of ISN hydrogen

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

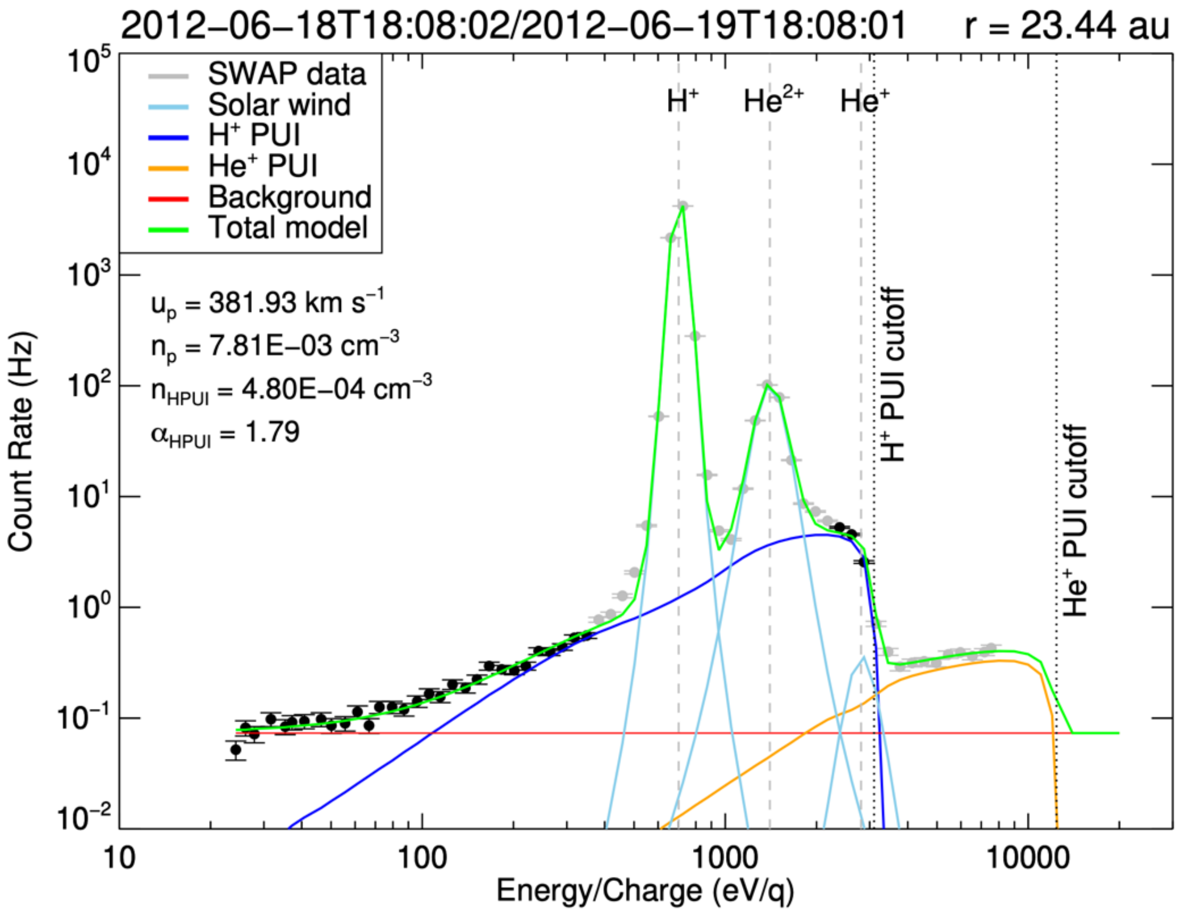
- Interstellar neutral → Ionization → Pickup ions
- Pickup ions accumulate in the solar wind
- Characteristic filled shell distribution
- Measured by Solar Wind Around Pluto (SWAP) on New Horizons





SWAP observations of the solar wind

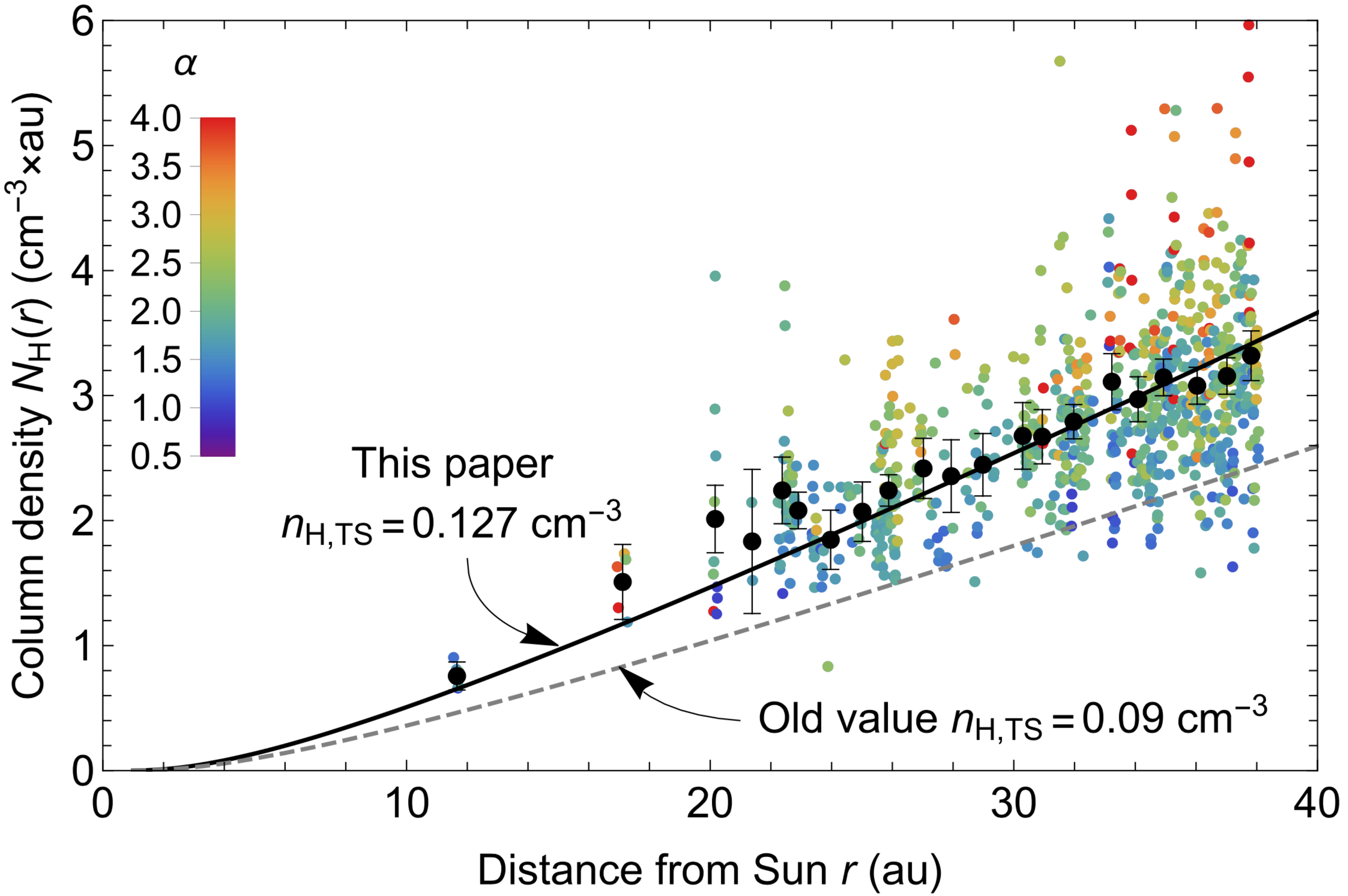
- Energy per charge: 0.023 – 7.87 keV/*q*
- 64 logarithmically spaced energy bins: $\Delta E/E$ = 8.5% FWHM
- Data accumulated over 1-day periods
- Identified components:
  - Solar Wind (SW) protons
  - SW alpha particles
  - SW He^+ ions
  - Hydrogen PUIs
  - Helium PUIs
  - Background: penetrating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



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

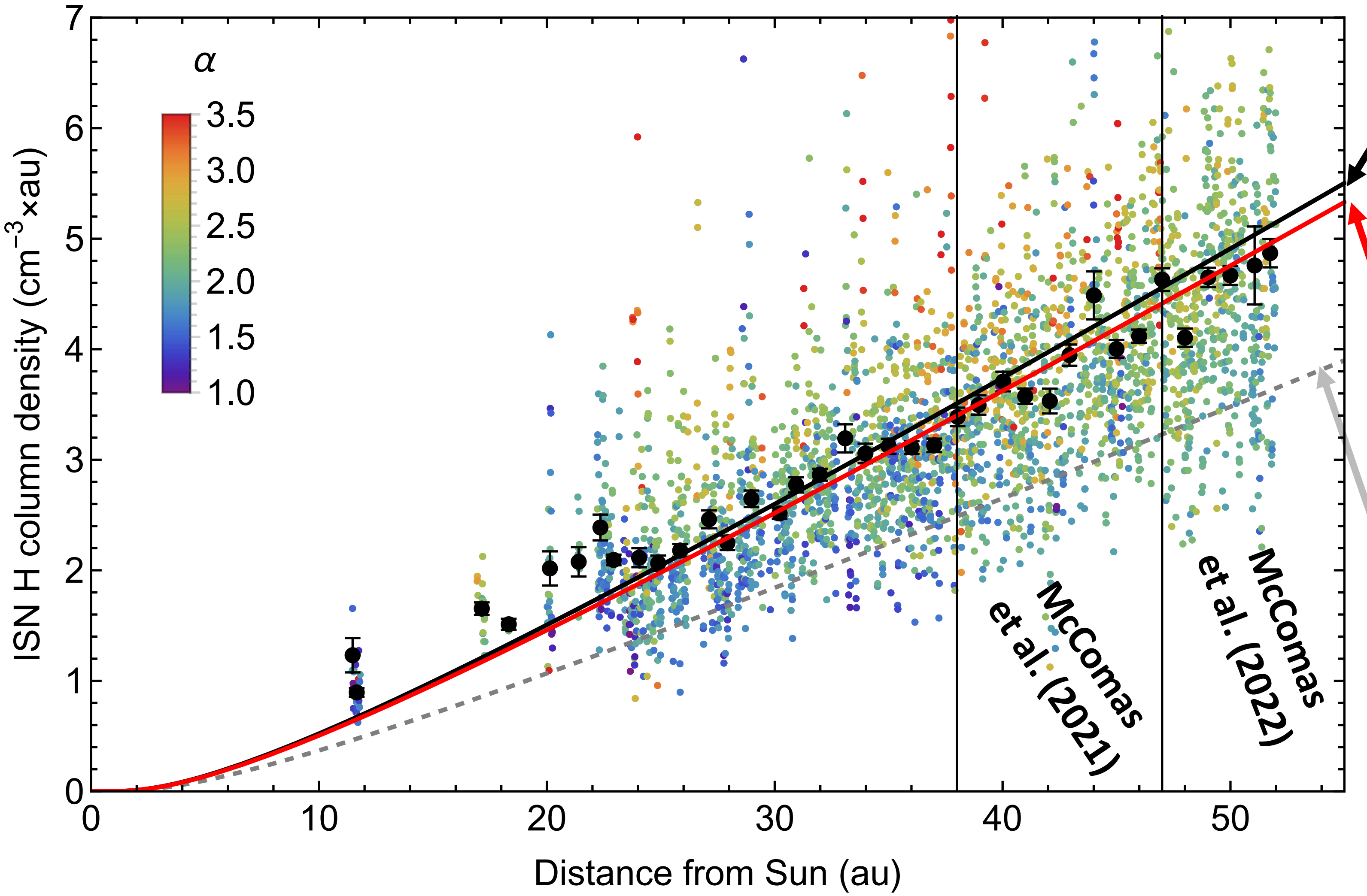
Column density of ISN hydrogen

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



New observations up to 52 au

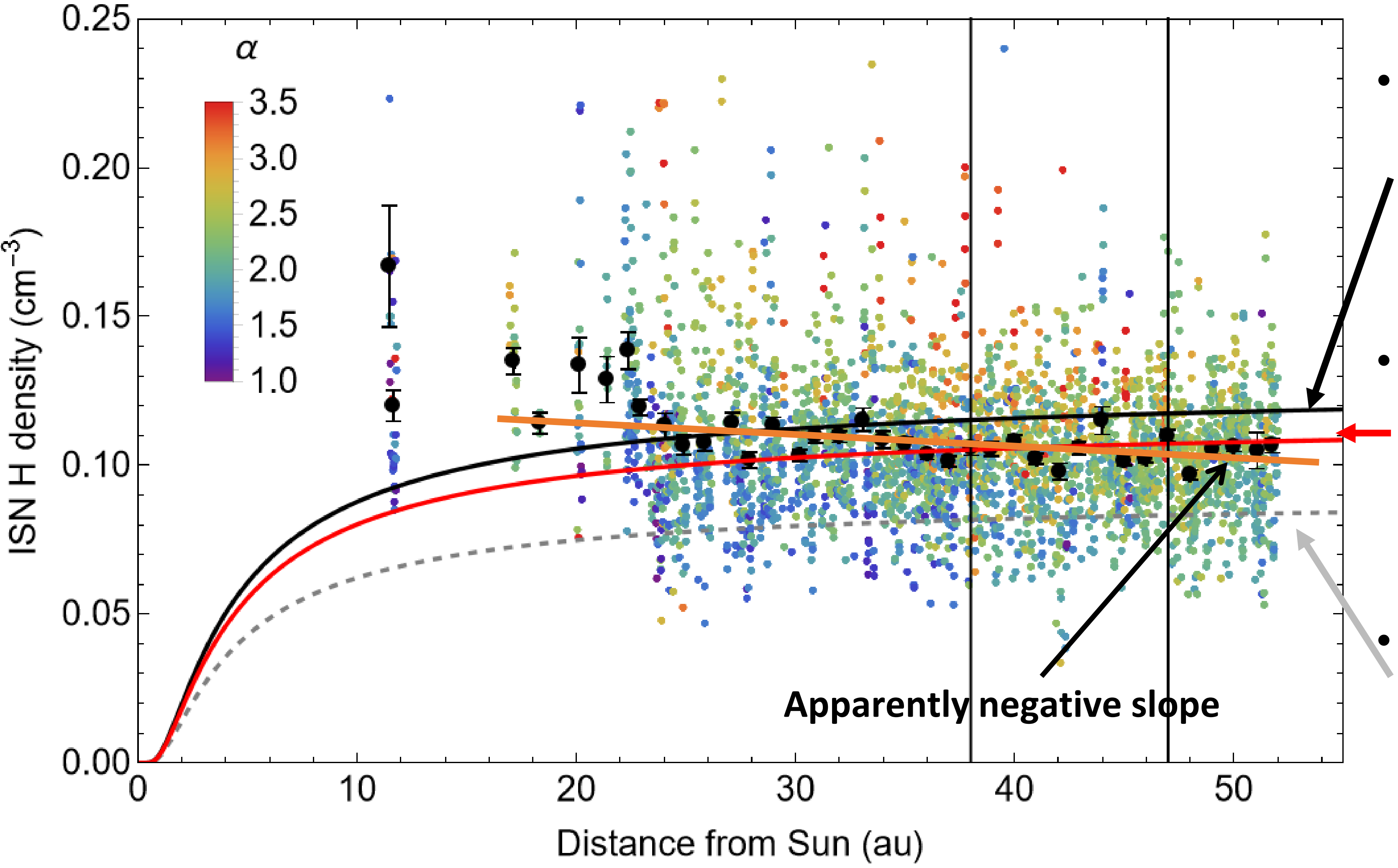
PRELIMINARY RESULTS



- Previous fit (Swaczyna et al. 2020) data up to ~38 au $n_{H,\infty}$ = 0.127 cm^{-3}
- New fit data from 22 au to ~52 au: $n_{H,\infty}$ = 0.123 cm^{-3}
- Old consensus (Bzowski et al. 2008) $n_{H,\infty}$ = 0.09 cm^{-3}

New observations up to 52 au

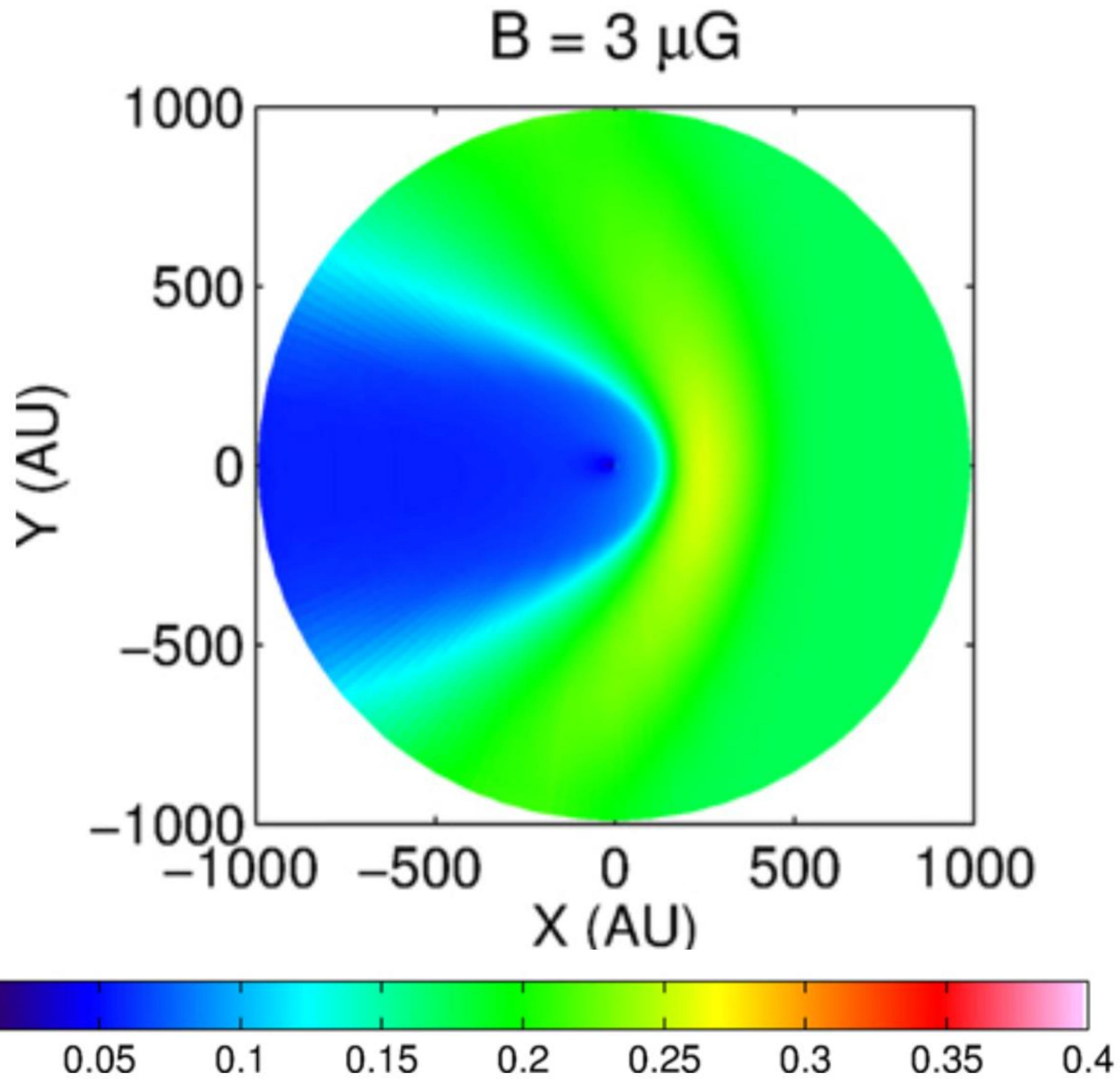
PRELIMINARY RESULTS



- Previous fit (Swaczyna et al. 2020) data up to ~38 au $n_{H,\infty} = 0.127\ cm^{-3}$
- New fit data from 22 au to ~52 au: $n_{H,\infty} = 0.116\ cm^{-3}$
- Old consensus (Bzowski et al. 2008) $n_{H,\infty} = 0.09\ cm^{-3}$

Modulation of interstellar neutral hydrogen density

Heerikhuisen et al. (2014, ApJ 784, 73)



- Density in the pristine VLISM is not the same as the termination shock density!
- Swaczyna et al. (2020) used Mueller et al. (2008) „filtration factor":

  n_{TS} = 0.127 cm^{-3} -> n_{pVLISM} = 0.195 cm^{-3}

- PRELIMINARY RESULT based on three global heliosphere models:

  $n_{30\ au}$ = 0.108 cm^{-3} -> n_{pVLISM} = 0.177 cm^{-3}

Summary

- The interstellar neutrals, as a seed population for the pickup ions and later also for the energetic neutral atoms, play a very important role in the physics of the heliosphere.
- Direct sampling observations with IBEX (and soon also with IMAP) are critical to study the distribution function, which informs on the physical conditions in the interstellar medium.
- Pickup ion observations provide insight into the interstellar neutral atom density and its modulation.
- The observed modulations from direct sampling and PUI observations do not agree with the models. Possible solution:
  - Large-scale waves of ISN densities in the LISM (works for both)
  - Solar-cycle effects on the outer boundary modulation (more likely for hydrogen)
  - Stronger ionization in the solar wind (more likely for helium)