Observations of the Very Local Interstellar Medium with the IBEX and Voyager Spacecraft

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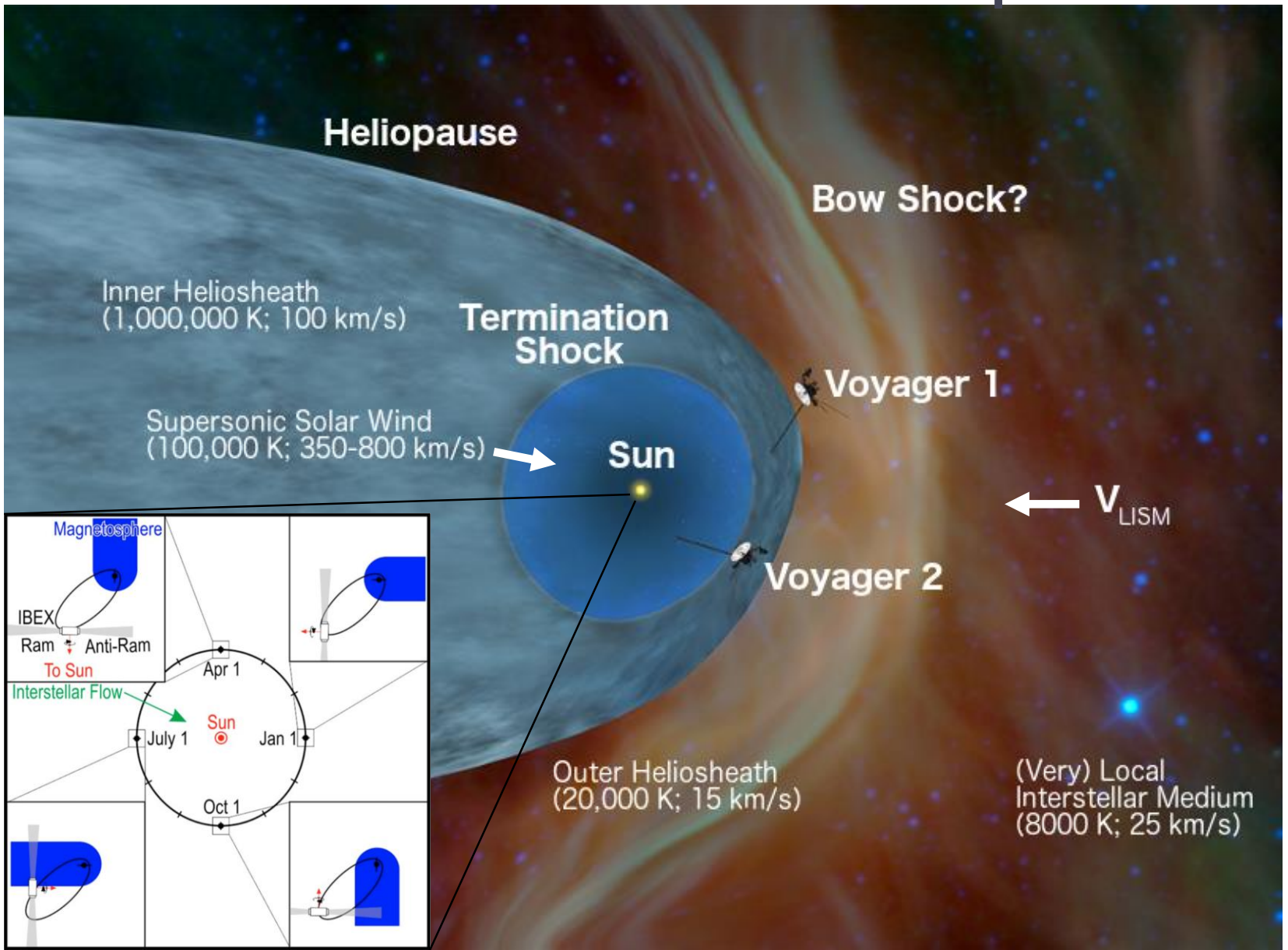
TeVPA 2017
Columbus, Ohio

Outline

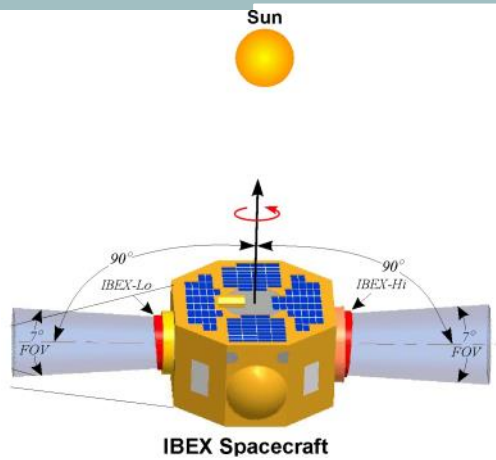
- The Heliospheric Boundaries
- Observing Energetic Neutral Atoms (ENAs) with the Interstellar Boundary Explorer (IBEX)
  - The IBEX Ribbon and the Very Local Interstellar Magnetic Field
- Voyager 1 in situ Observations of the Very Local Interstellar Medium (VLISM)
  - Magnetic Field Draped Around the Heliosphere, Turbulence Spectrum

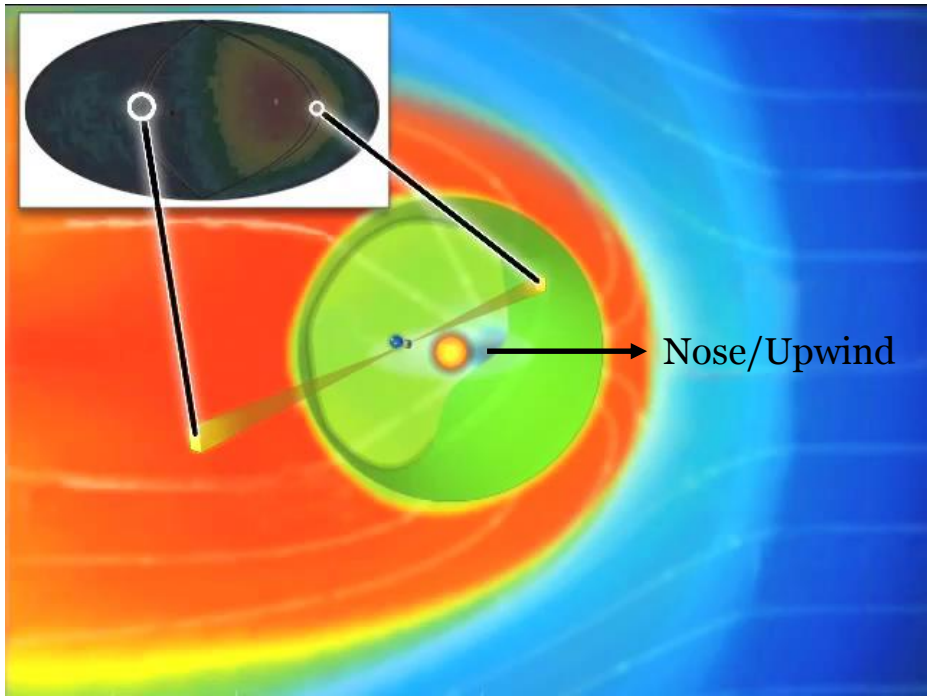
Boundaries of the Heliosphere

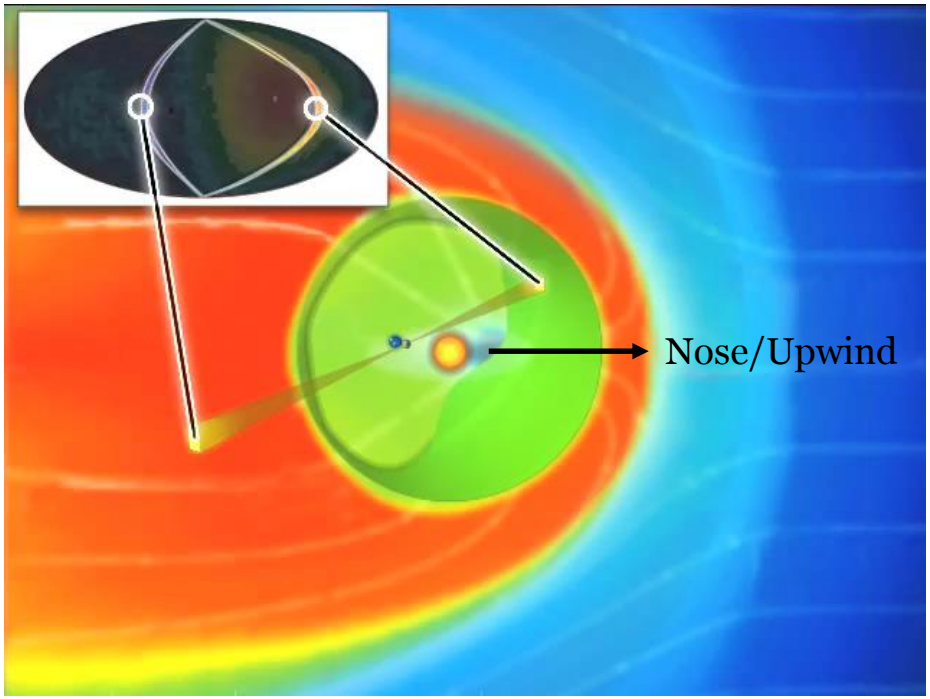


Observing Energetic Neutral Atoms (ENAs) with IBEX

Observing ENAs: Creating All-sky Maps in 6 Months

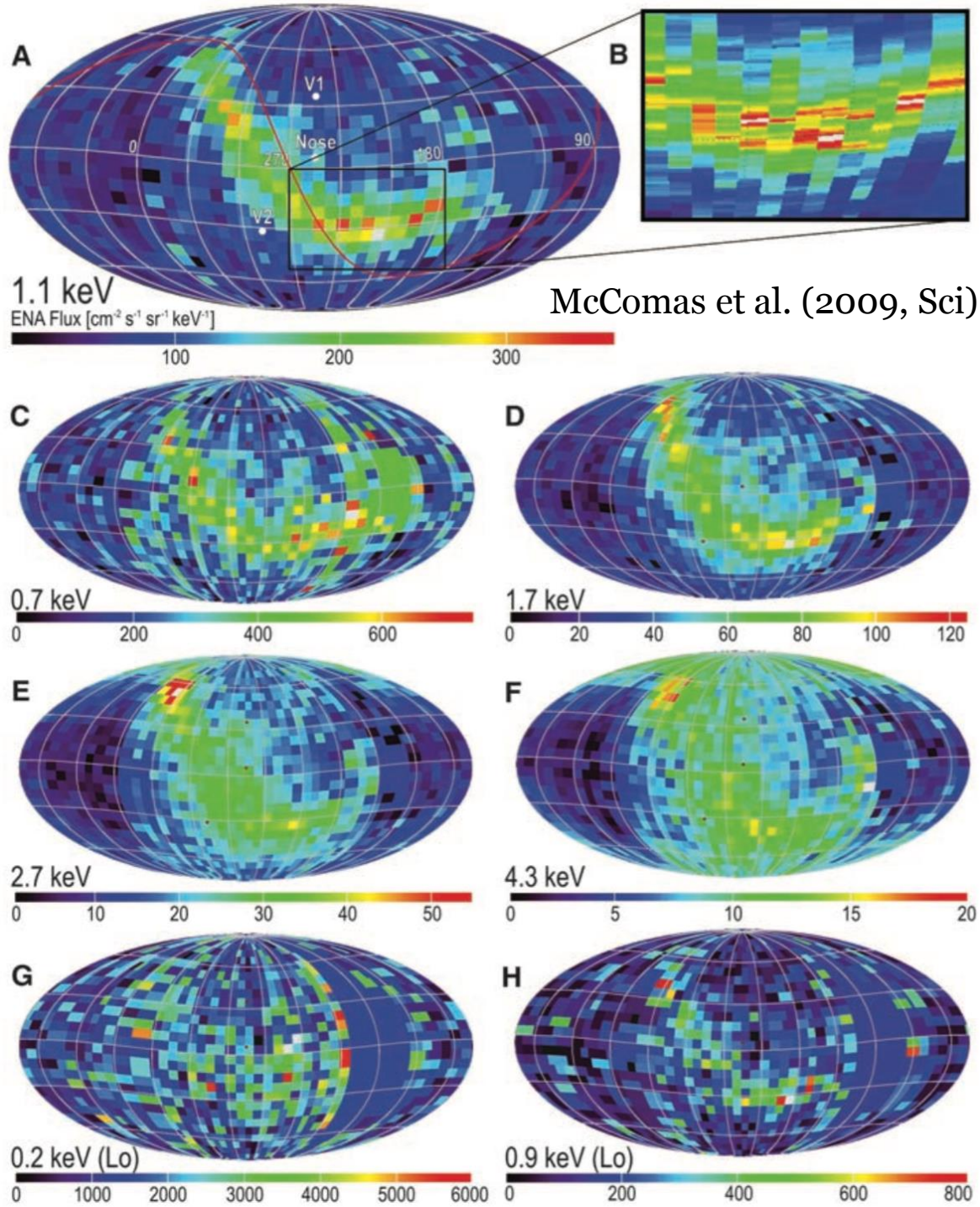






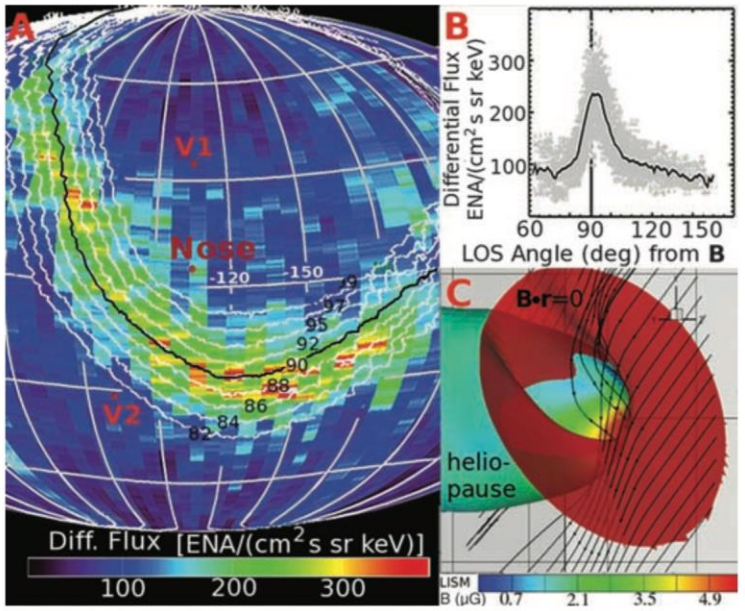
Credit: IBEX Team/SwRI

First IBEX Observations

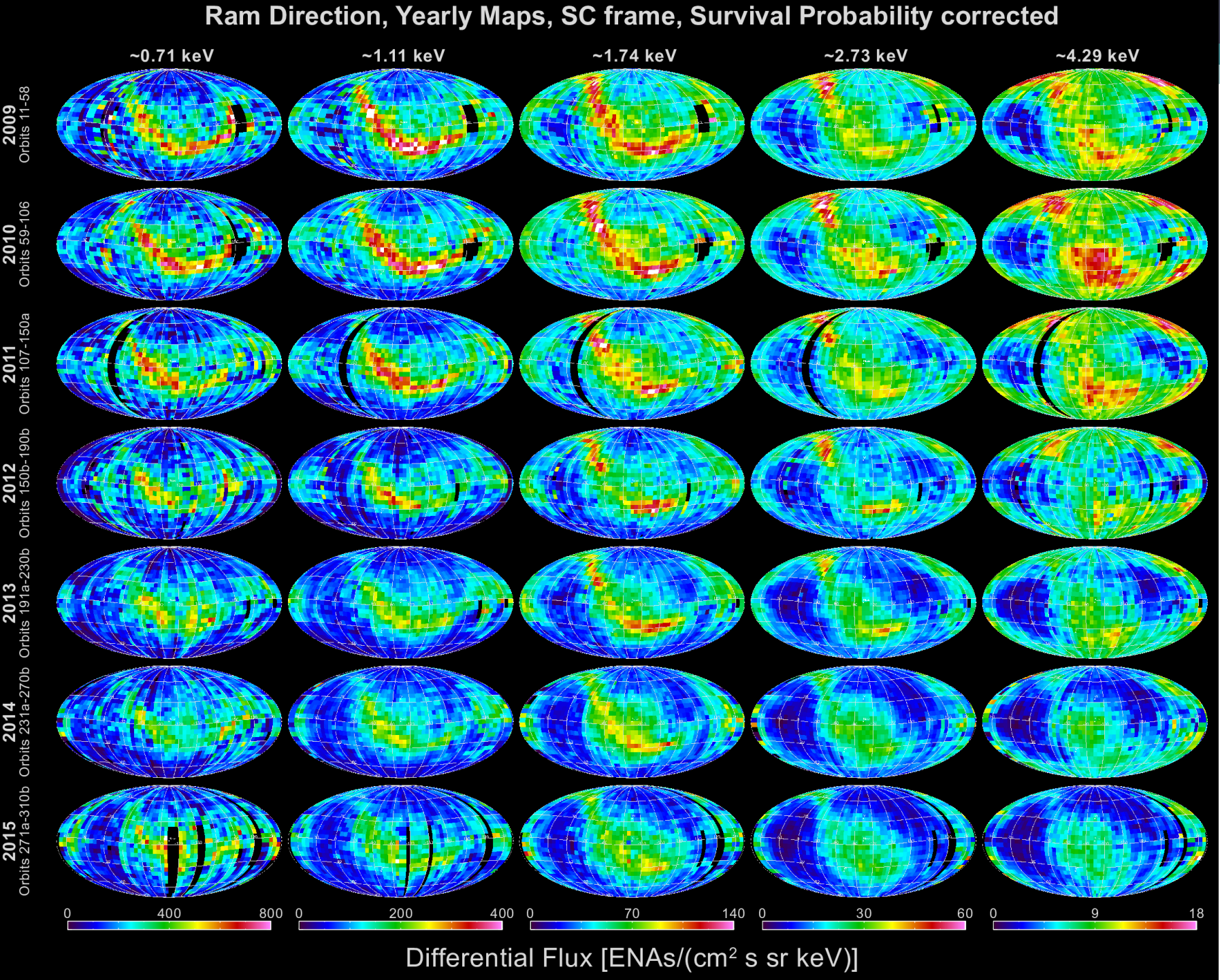


McComas et al. (2009, Sci)

- First all-sky maps produced/published in 2009
- "Ribbon" completely unexpected, but realized to be connected to the local ISMF:



Schwadron et al. (2009, Sci)


Ram Direction, Yearly Maps, SC frame, Survival Probability corrected
~0.71 keV
~1.11 keV
~1.74 keV
~2.73 keV
~4.29 keV
2009 Orbits 11-58
2010 Orbits 59-106
2011 Orbits 107-150a
2012 Orbits 150b-190b
2013 Orbits 191a-230b
2014 Orbits 231a-270b
2015 Orbits 271a-310b
0 400 800
0 200 400
0 70 140
0 30 60
0 9 18
Differential Flux [ENAs/(cm² s sr keV)]

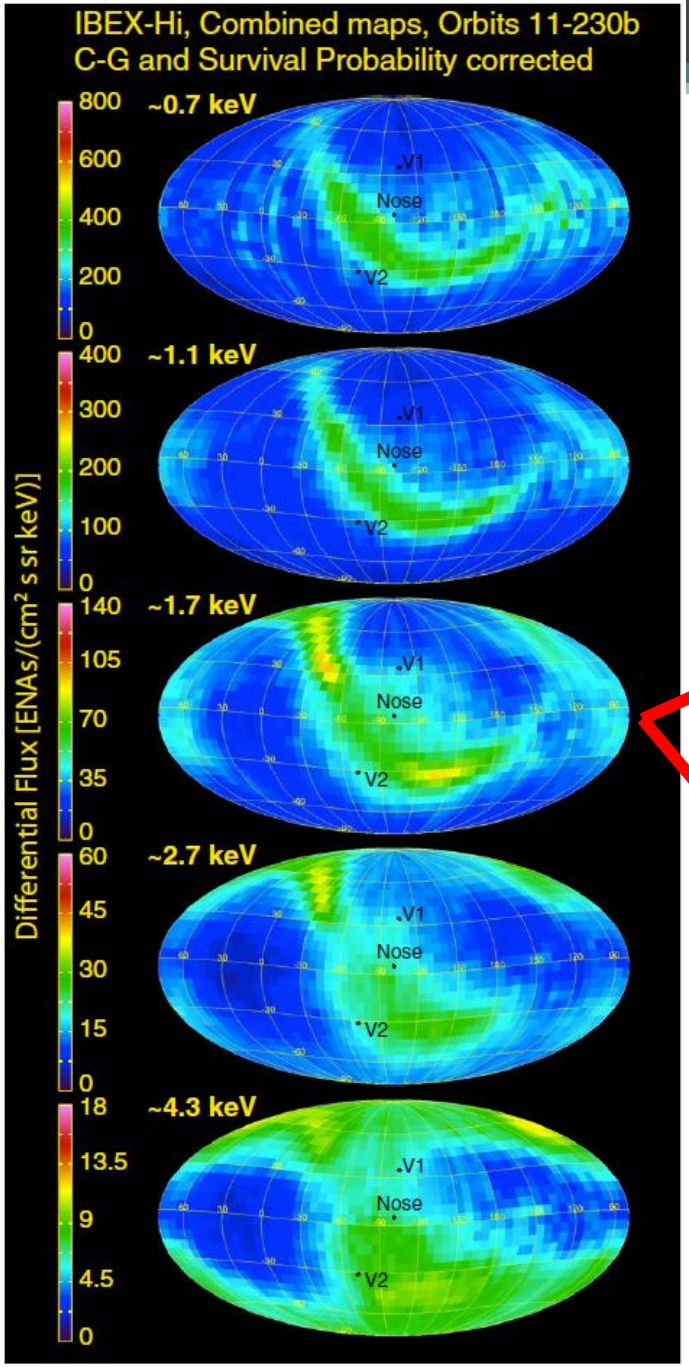
Some IBEX Discoveries of the VLISM

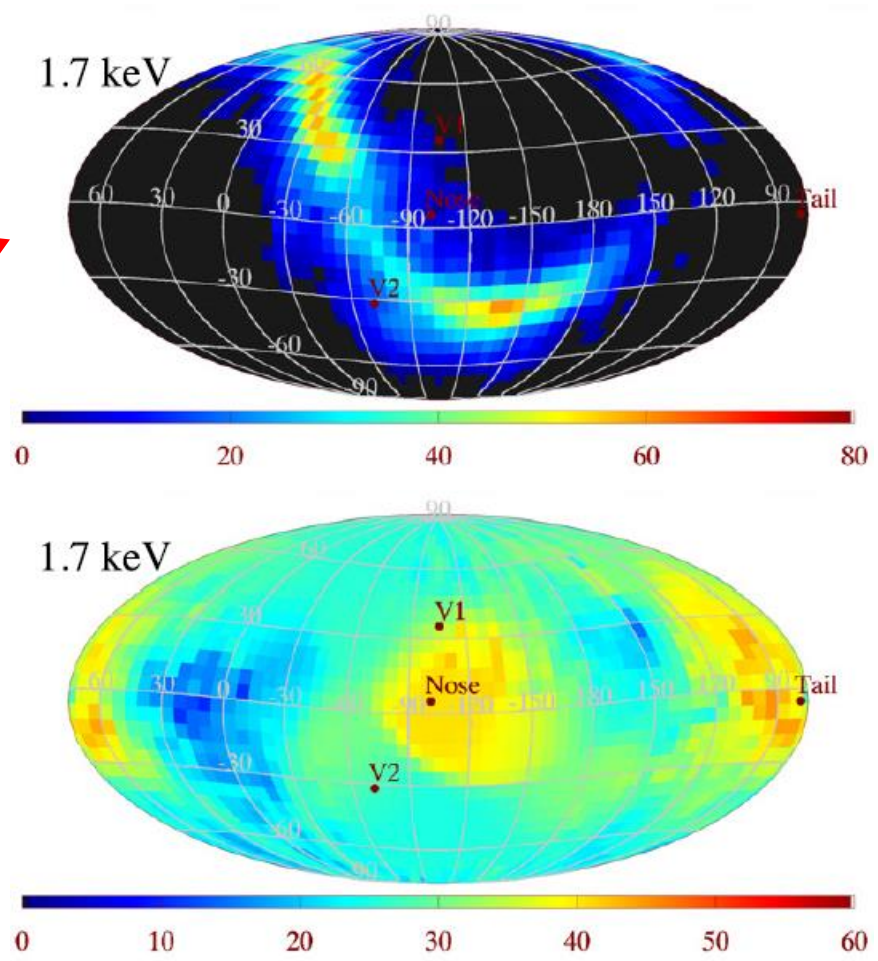
McComas et al. (2017, ApJS)

Interstellar Medium	
First direct observations of interstellar hydrogen, deuterium, oxygen, and neon	Möbius et al. (2009) Bochsler et al. (2012) Rodríguez Moreno et al. (2013)
Discovery of secondary population of He (the "warm breeze")	Kubiak et al. (2014)
First connection of LISM environment from *IBEX* to TeV cosmic rays	Schwadron et al. (2014a)
Discovery that the heliosphere might have a bow wave ahead of it instead of a bow shock	McComas et al. (2012a) Zank et al. (2013)
First precise estimate of interstellar field strength as well as direction	Zirnstein et al. (2016b)
Refined ISN He flow direction, temperature, and speed	McComas et al. (2015b) Schwadron et al. (2015a) Bzowski et al. (2015)
VLISM is warmer than previously expected	McComas et al. (2015a) Möbius et al. (2015b)
Co-planarity of ISN He, H, He Warm Breeze, the *IBEX* Ribbon center, and the interstellar magnetic field deduced from the Ribbon	ApJ Supp. Series (2015) Kubiak et al. (2016) Zirnstein et al. (2016b)
Determination of the local gas Ne/O ratio from neutral flow observations	Bochsler et al. (2012) Park et al. (2014)
Confirmation of He and O secondary component possibly from the VLISM	Park et al. (2016)
First quantitative derivation of ISN O properties; evidence for significant processing in the VLISM	Schwadron et al. (2016a)
First direct sampling of ISN H and its evolution during the solar cycle	Saul et al. (2012, 2013)
Independent derivation of solar radiation pressure from ISN H observations revealed to be greater than that inferred from solar Lyα flux data	Katushkina et al. (2015)
Possible IS dust filament in the VLISM and correlation with LISM inflow direction	Frisch et al. (2015)
First derivation of IS flow longitude from symmetry of IS PUI cutoff at 1 au and connection to *IBEX* measurements	Möbius et al. (2015c)

The IBEX Ribbon and the Interstellar Magnetic Field

The IBEX Ribbon

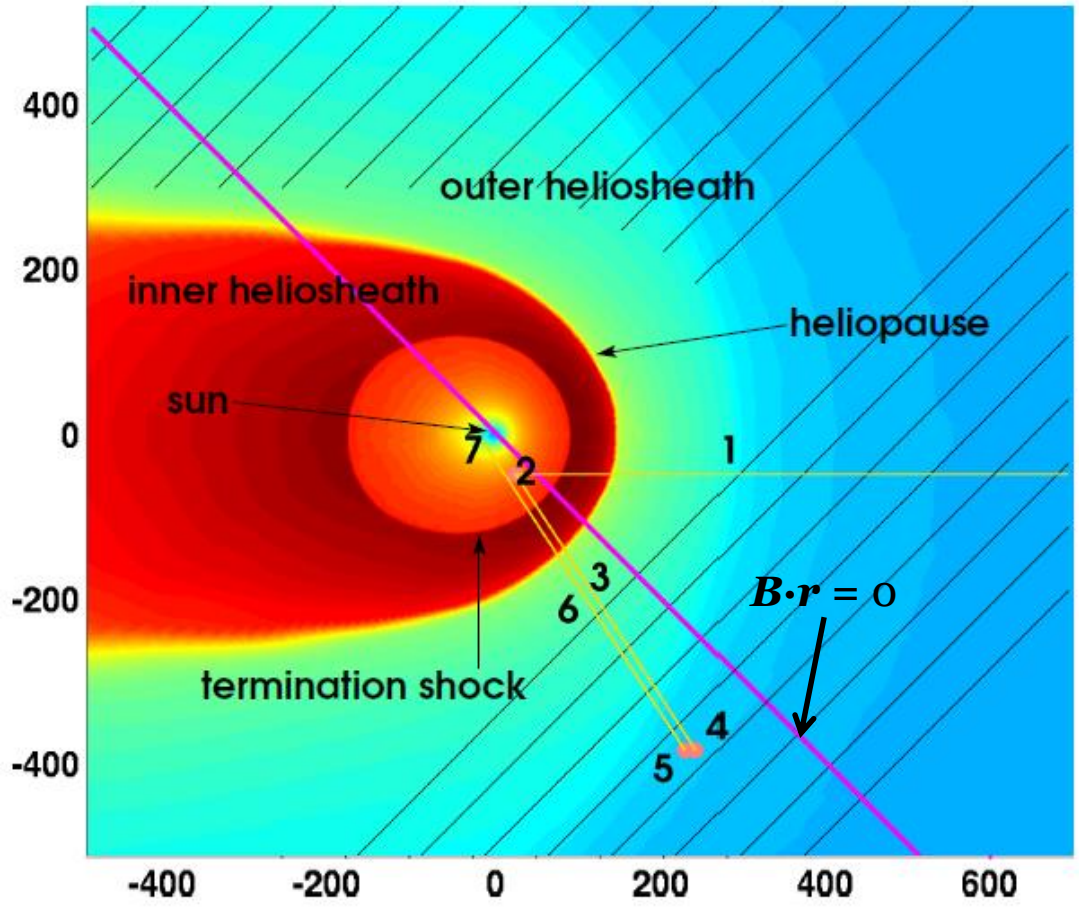




McComas et al. (2014, ApJS)

Schwadron et al. (2014, ApJS)

How is the Ribbon created? Likely via the "Secondary ENA" Process

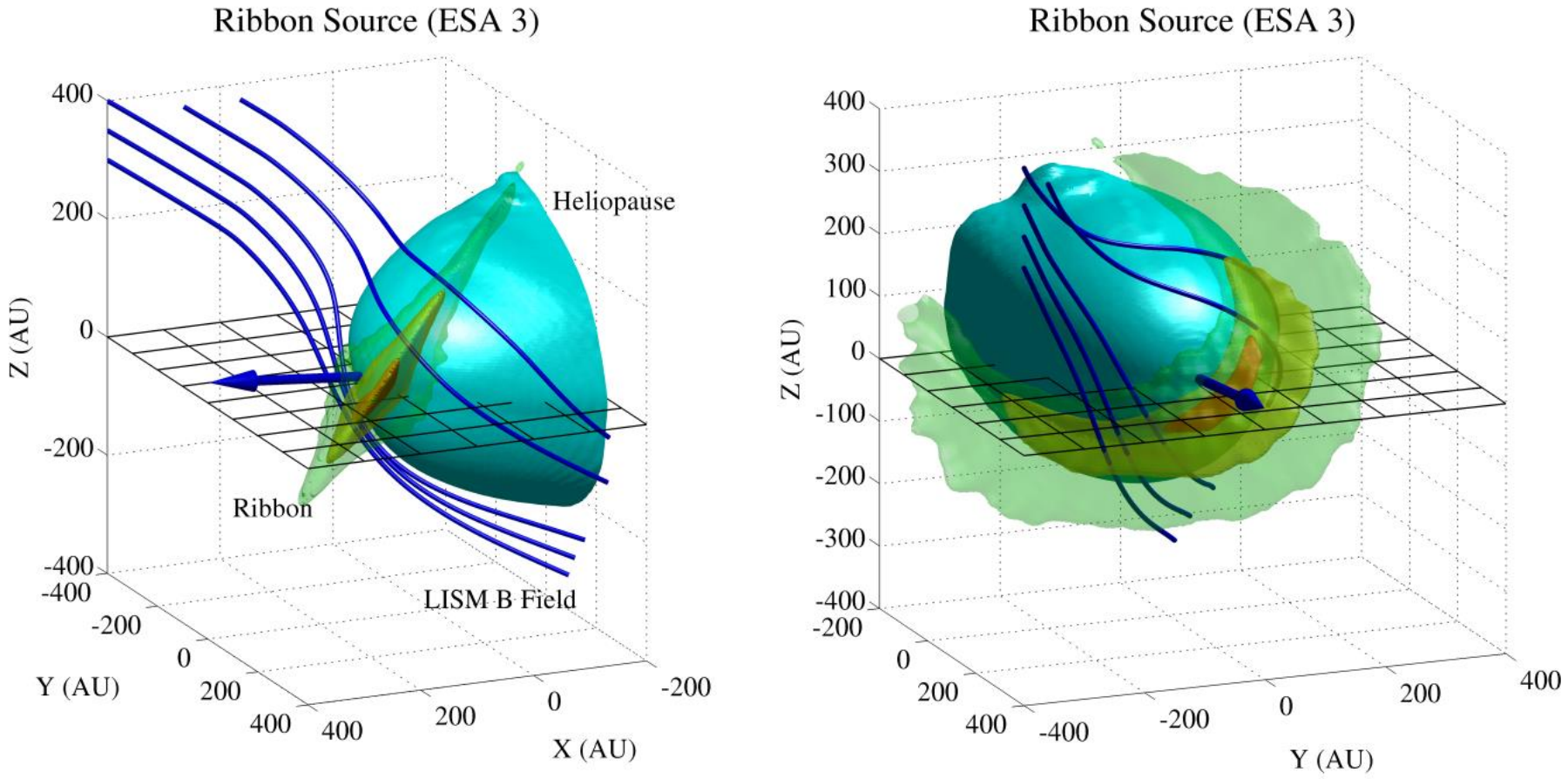


1. Interstellar neutral atoms travel inside heliosphere
2. Neutral atom charge-exchanges with solar wind ion
3. New "primary" ENA travels outside heliosphere
4. Primary ENA charge-exchanges with interstellar ion, creating pickup ion
5. Pickup ion charge-exchanges with interstellar neutral atom, creating "secondary" ENA
6. Secondary ENA travels back inside heliosphere
7. Secondary ENA may be detected by IBEX

Ribbon Production Rate (E = 1.11 keV)

$(cm^3\ s\ sr\ keV)^{-1}$

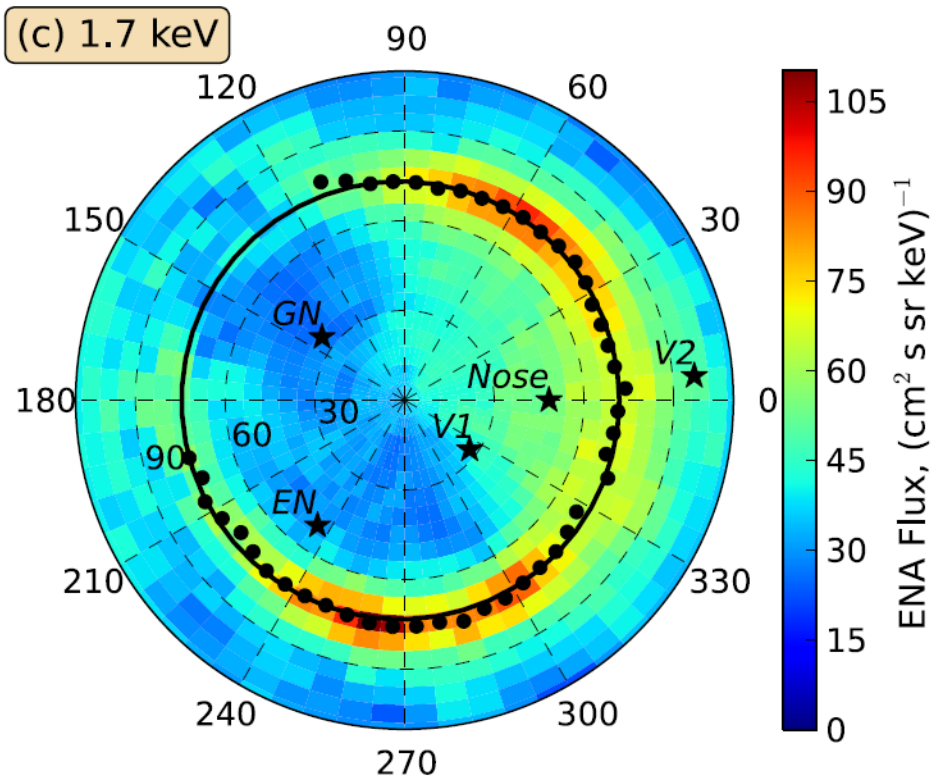
Isocontour levels: 70% (orange), 25% (yellow), 10% (green)



Zirnstein et al. (2015, ApJL)

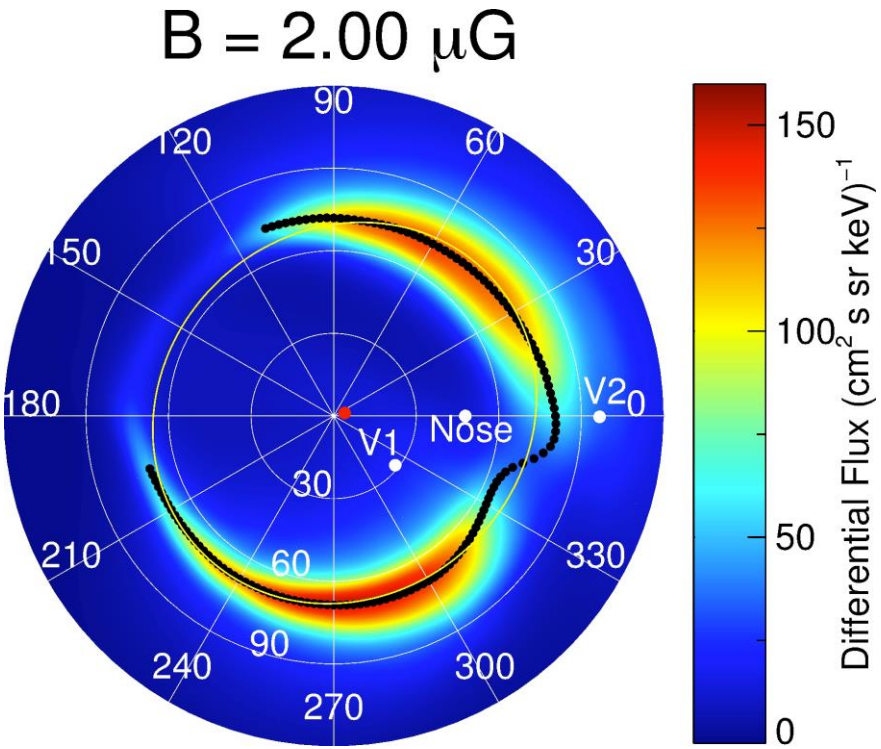
Simulate Ribbon in Different Configurations of B_{LISM}

IBEX Data



Funsten et al. (2013, ApJ)

Simulation

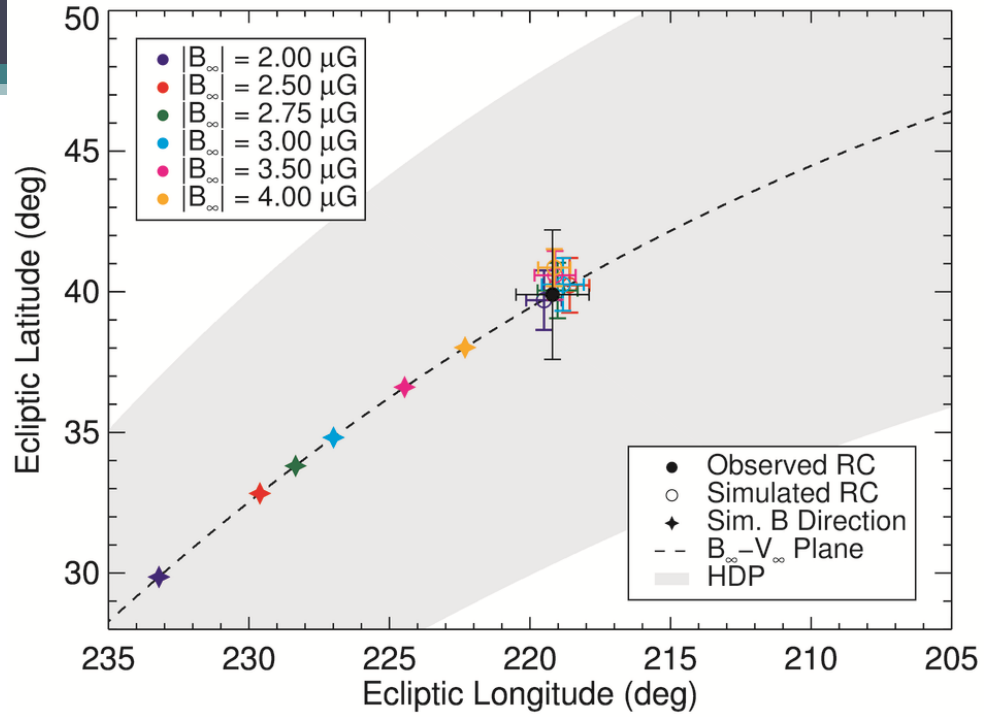


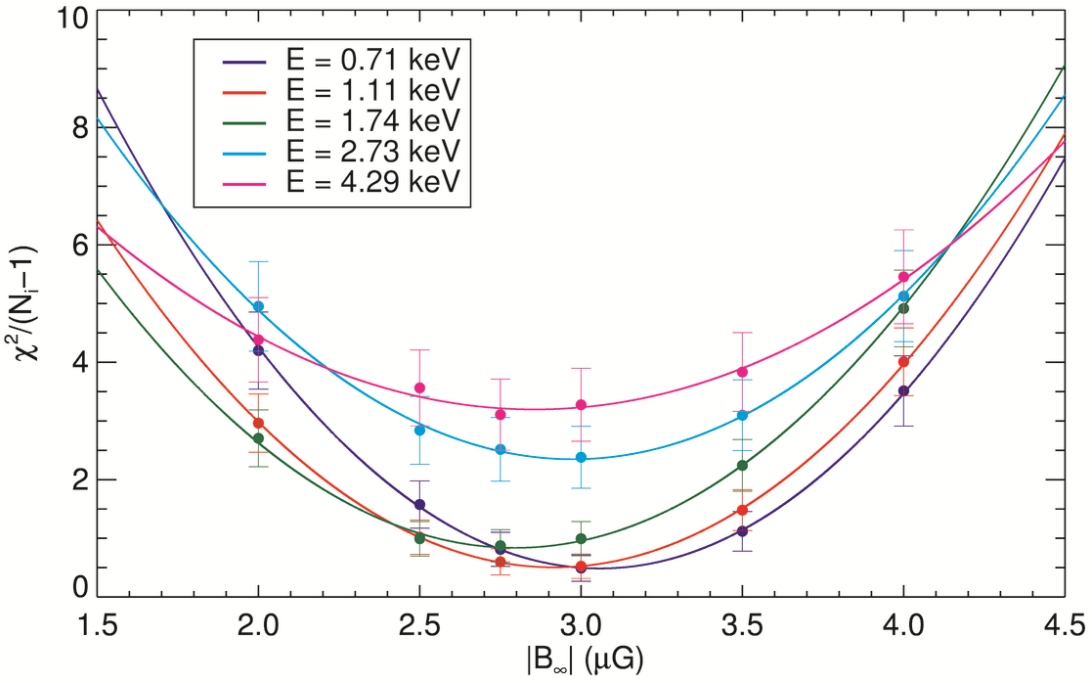
Zirnstein et al. (2016, ApJL)

Derive B_{LISM} Based on Model-Data Ribbon Comparison

ENA Energy (keV)	Magnitude (μG)
0.71	3.06 ± 0.12
1.11	2.92 ± 0.11
1.74	2.79 ± 0.13
2.73	2.98 ± 0.21
4.29	2.86 ± 0.31
Combined	**2.93 ± 0.08**

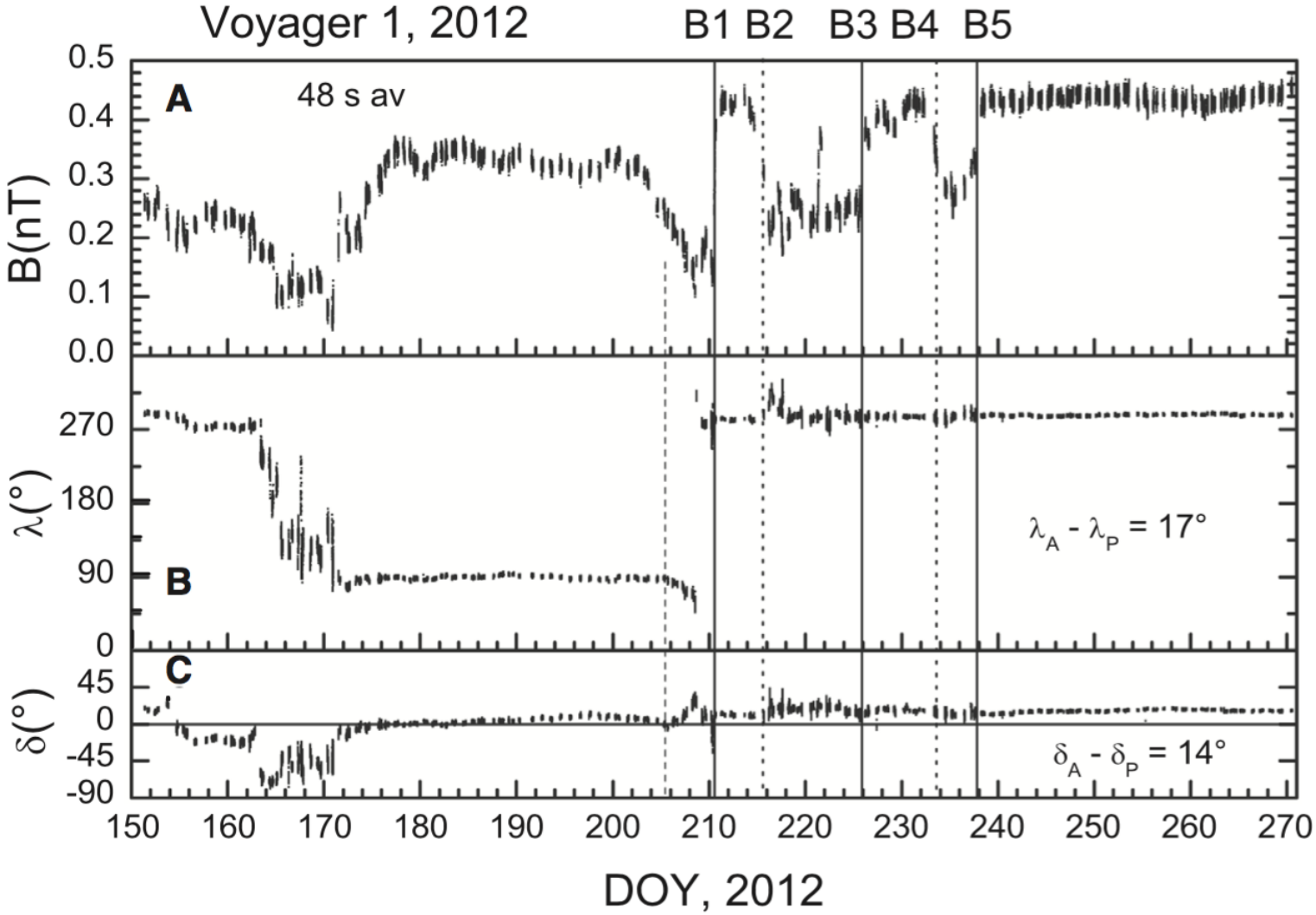
B_{LISM} Direction:
Ecliptic Coord. - (227.3°, 34.6°)
Galactic Coord. – (26.0°, 50.1°)





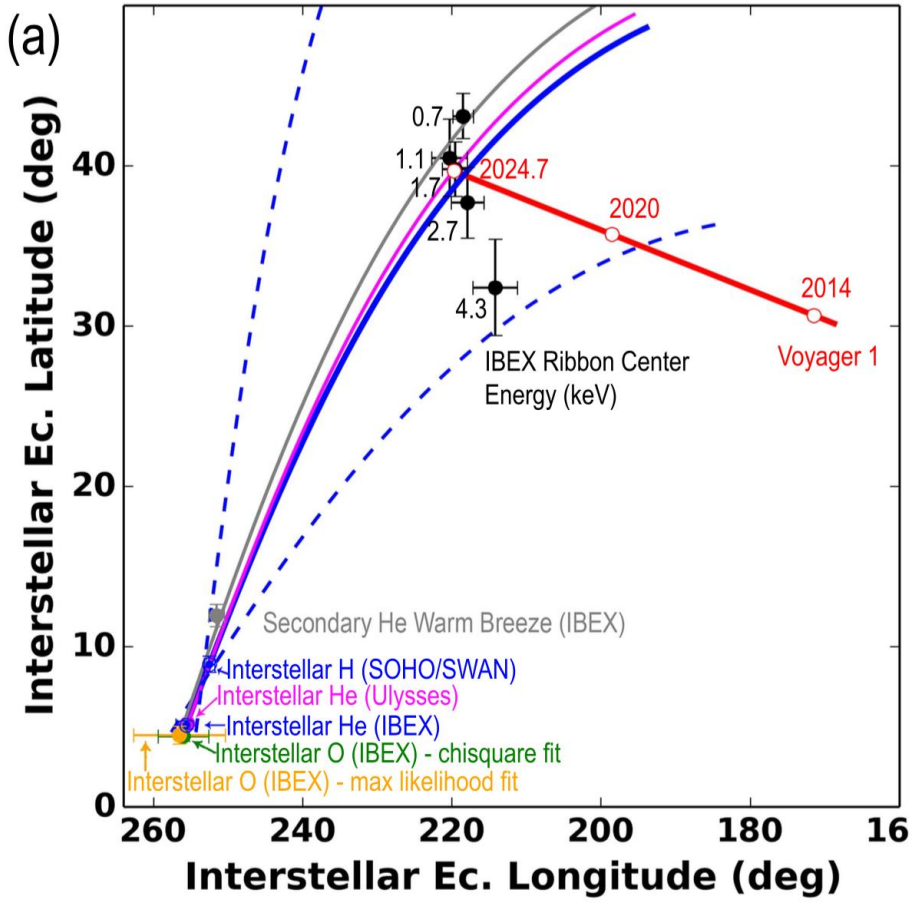
Voyager 1 In Situ Observations of the VLISM

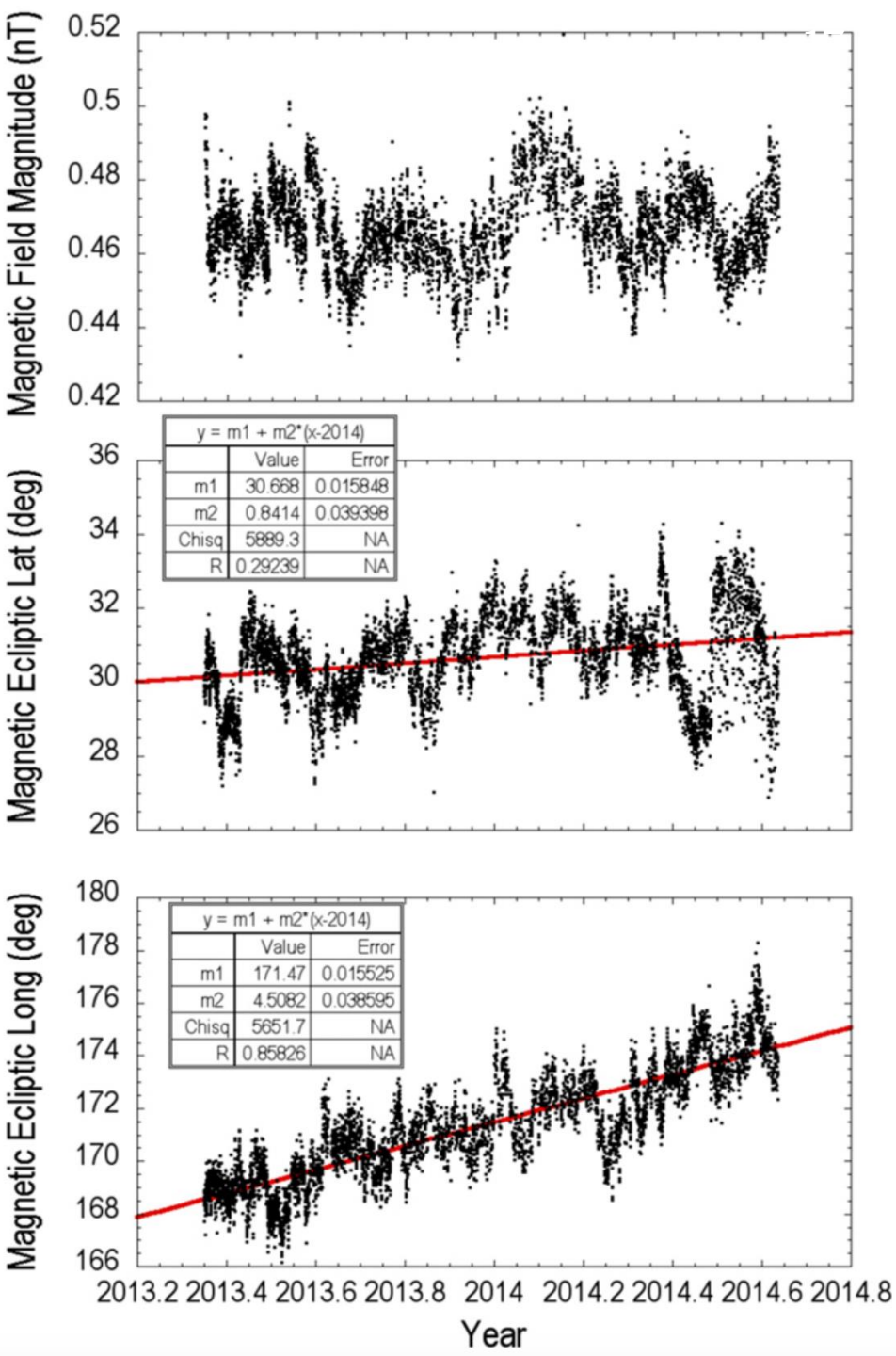
Voyager 1 Observations of the VLISM Magnetic Field (*Burlaga et al. 2013, Sci*)



Connecting V1 ISMF Observations to IBEX Neutral Observations

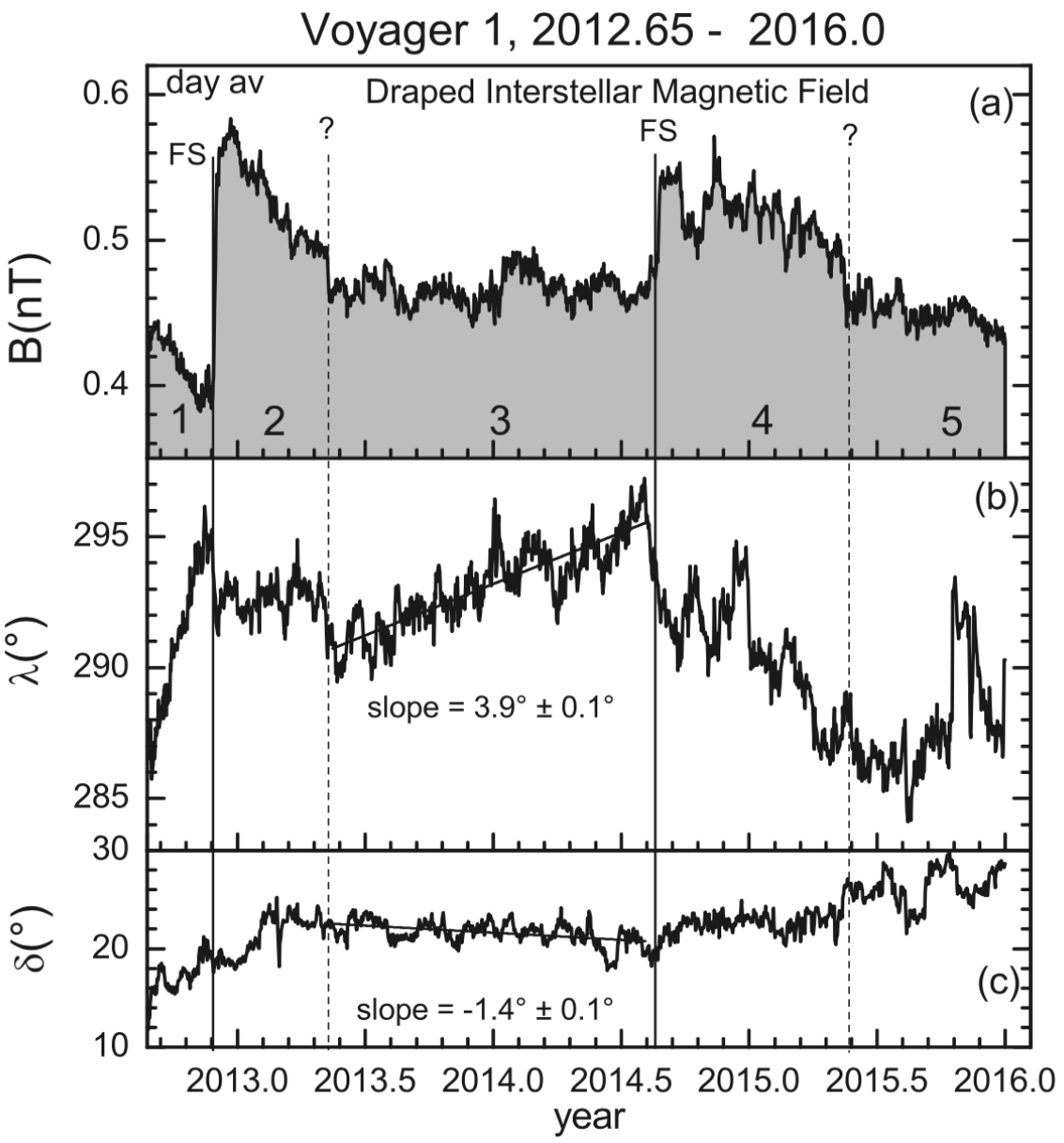
Schwadron et al. (2015, 2016)



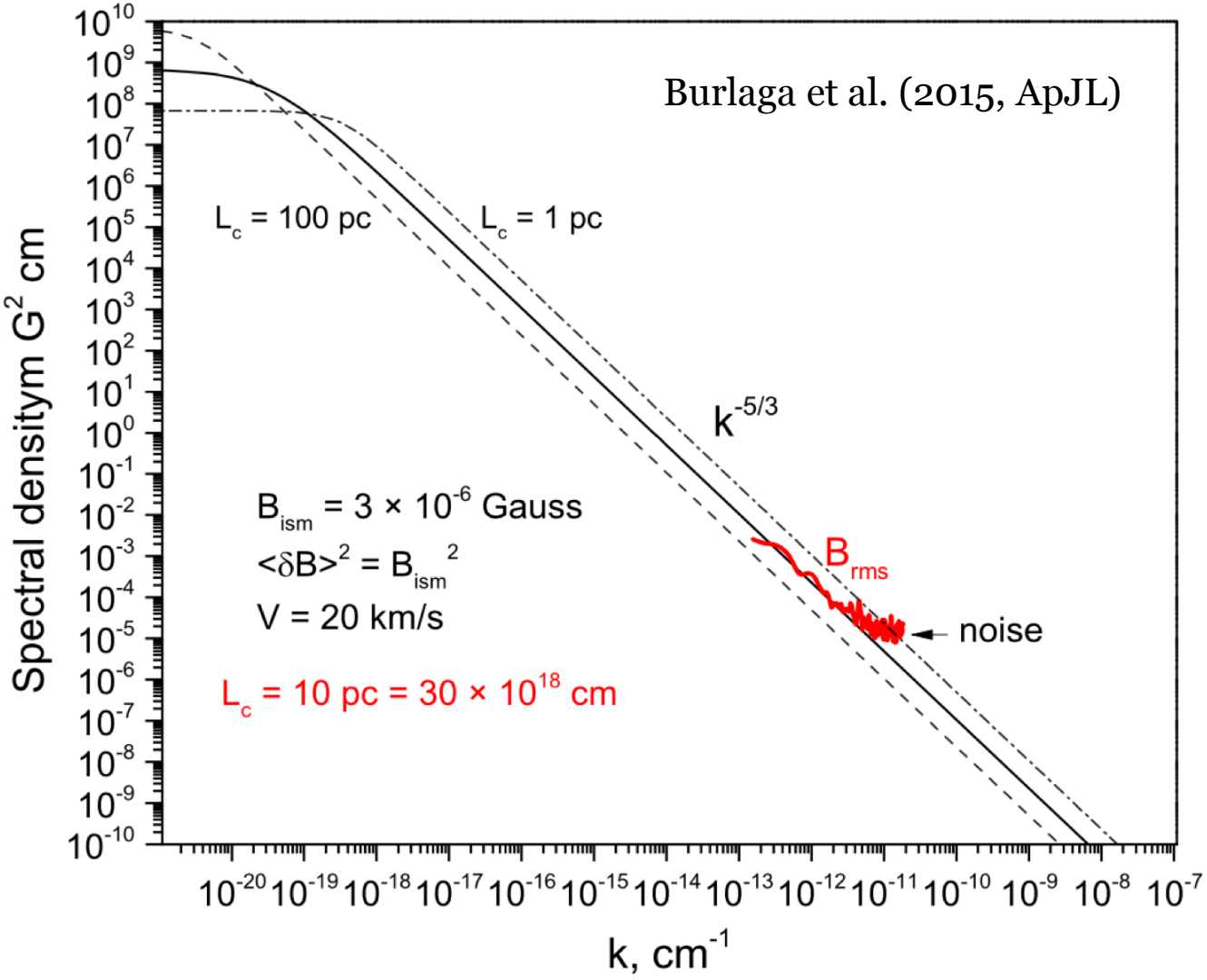


Voyager 1 Observations of the VLISM Magnetic Field (*Burlaga et al. 2016, ApJ*)

- The "unfolding" of the VLISM magnetic field is much more complicated
- Voyager observes evidence of heliospheric shocks propagating through the VLISM



The VLISM Turbulence Spectrum

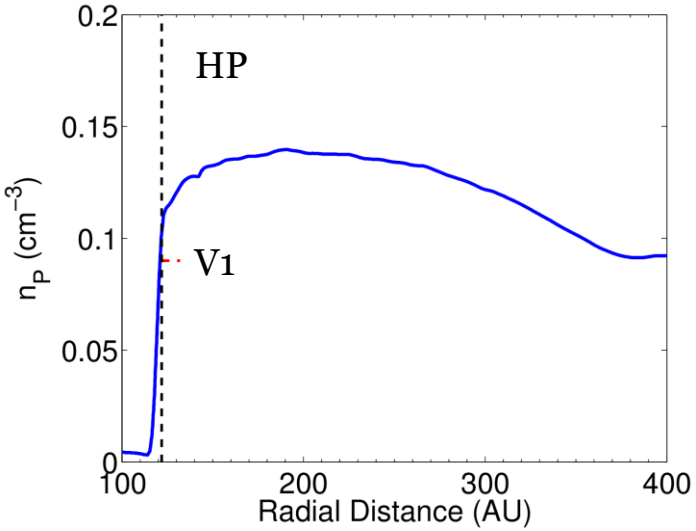


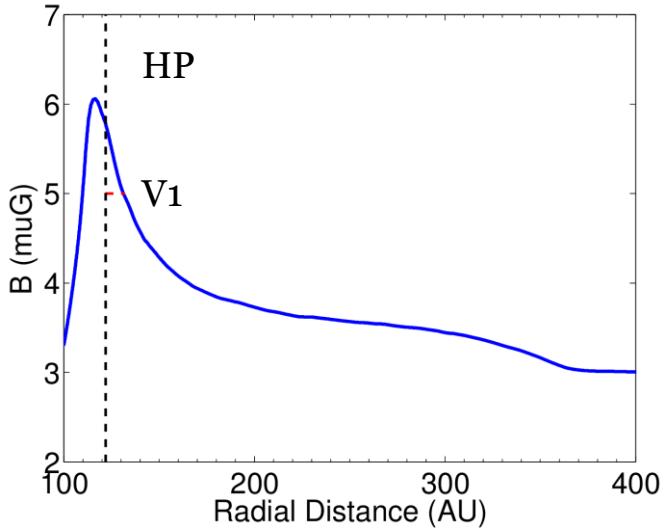
- Voyager 1 observations of the interstellar spectral density (red), and Kolmogorov power law spectra for different outer scale lengths.
- **NOTE:** The model and data were plotted incorrectly in the published figure. The observed spectral density is actually **~100 times higher** than the predicted Kolmogorov spectrum for L_c = 10 pc.

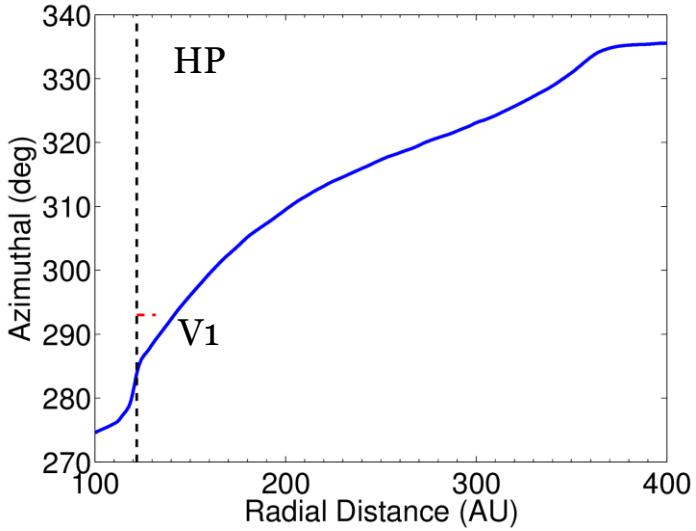
Conclusions

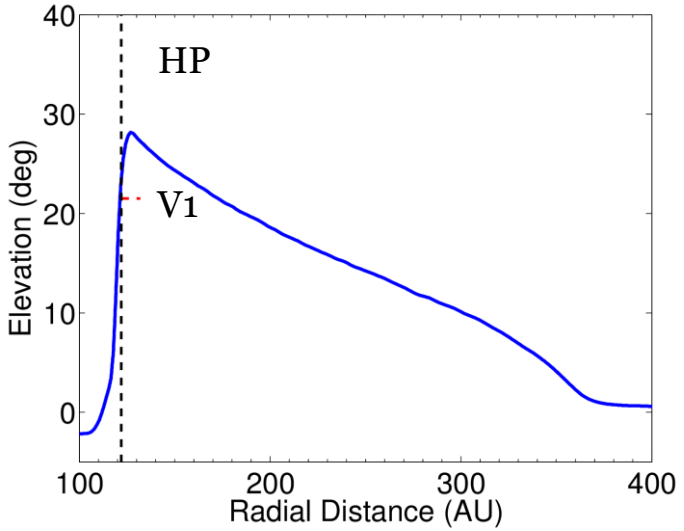
- IBEX observes interstellar matter (H, He, Ne, O) and energetic neutral atoms produced in the solar wind – VLISM interaction
- IBEX observations of the Ribbon at ~keV energies reveal the VLISM magnetic field draped around the heliosphere
  - Derive magnitude (2.9 μG) and direction (227°, 35°) of local magnetic field (undisturbed by the heliosphere)
- Voyager 1 has been observing the VLISM since August 2012, including the interstellar magnetic field, (indirectly) interstellar plasma density, and galactic cosmic ray spectrum
- Voyager 2 is still in the inner heliosheath, models predict it could cross the heliopause within the next few years
  - Voyager 2 has a working plasma instrument!
  - Some models predict Voyager 2 will cross the heliopause at a distance similar to Voyager 1 (~120 AU), which is in early 2019

Simulation Comparison to Voyager 1 Measurements outside the HP

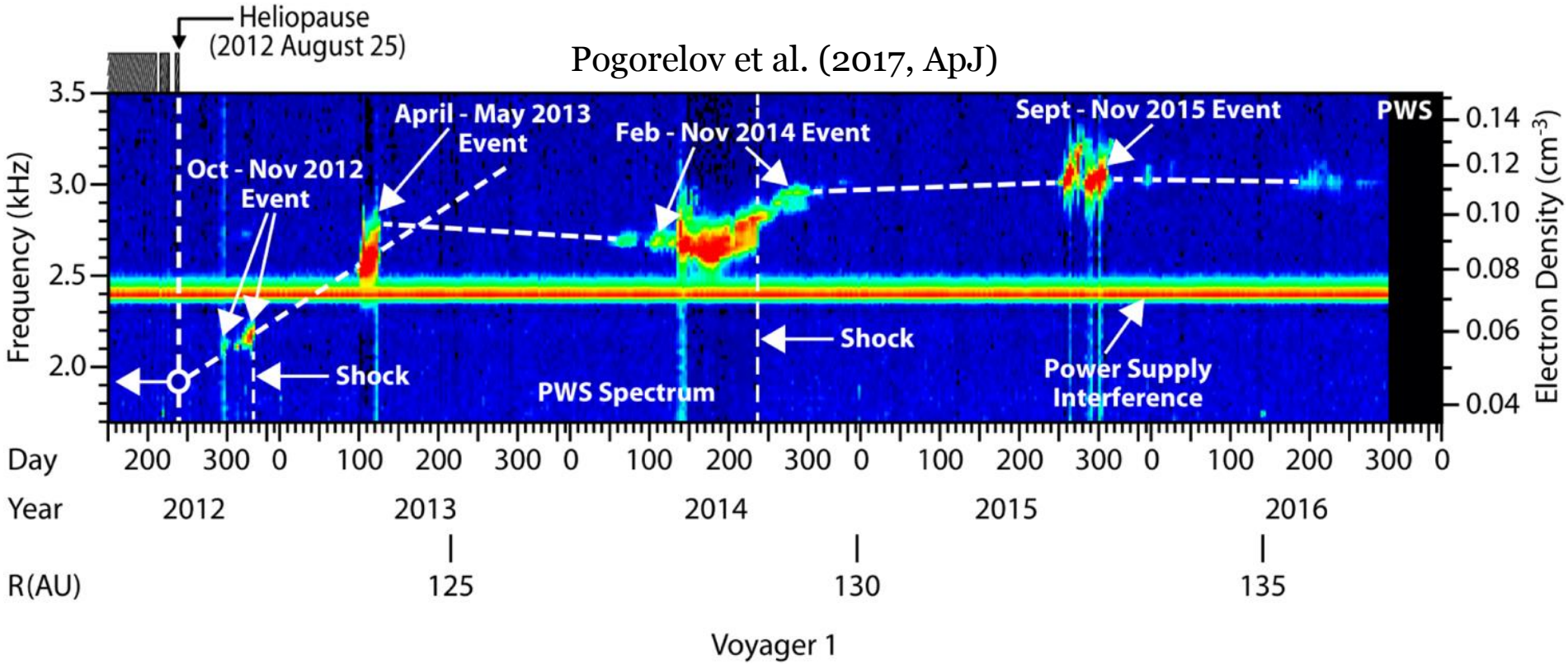








(Indirect) Observation of the Compressed Interstellar Plasma Density



- Voyager 1 does not have a working plasma particle detector (stopped working in 1981), but has used the Plasma Wave Instrument (PWS; Gurnett et al. 2015) to determine the plasma density via the detection of electron plasma oscillation events associated with heliospheric shocks