Interstellar Boundary Explorer

Imaging the edge of out solar system and beyond — Discovering the global interaction between the solar wind and the interstellar medium

IBEX

First Results from the Interstellar Boundary Explorer

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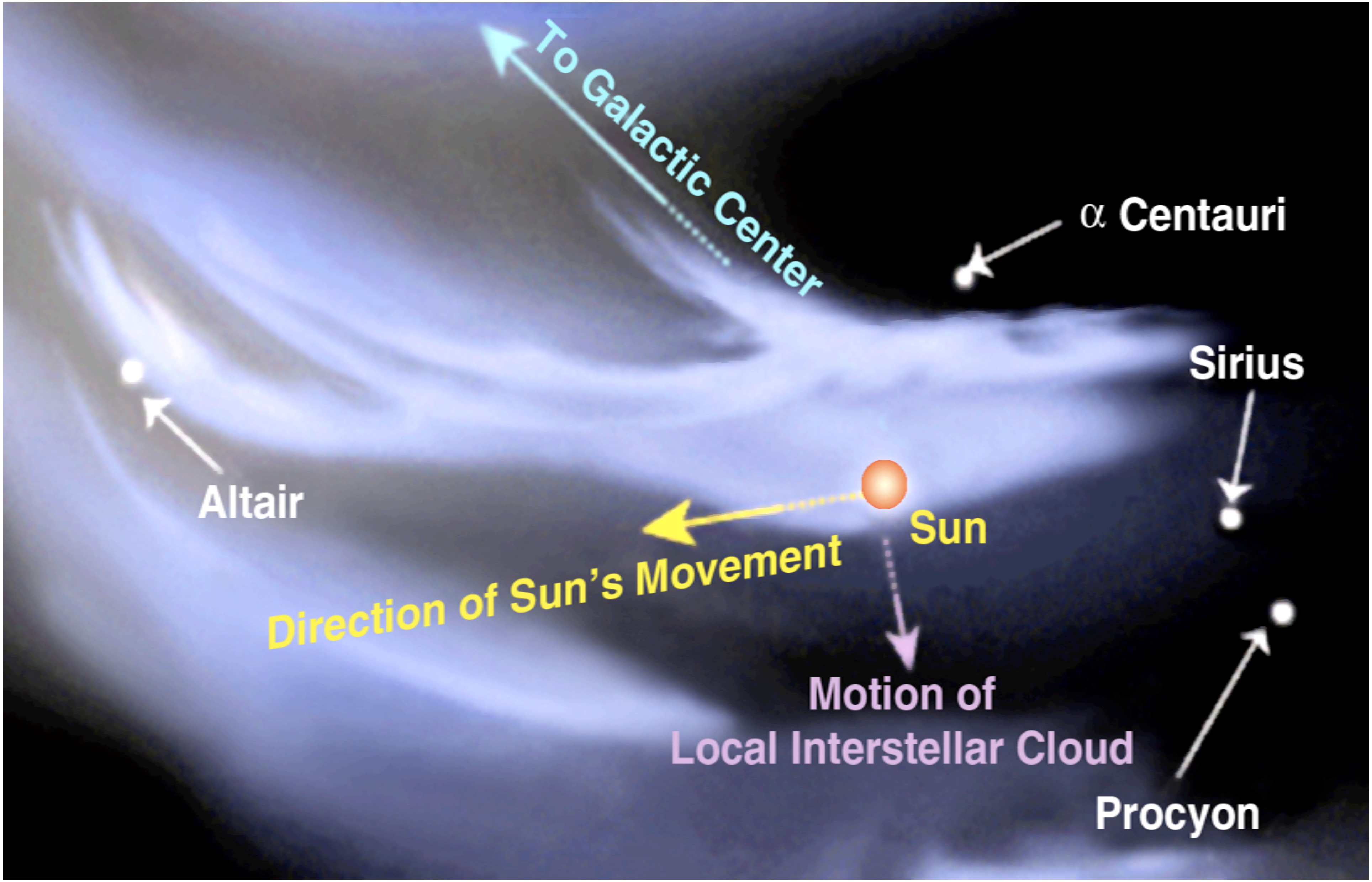
Seminar

Dec. 3, 2009

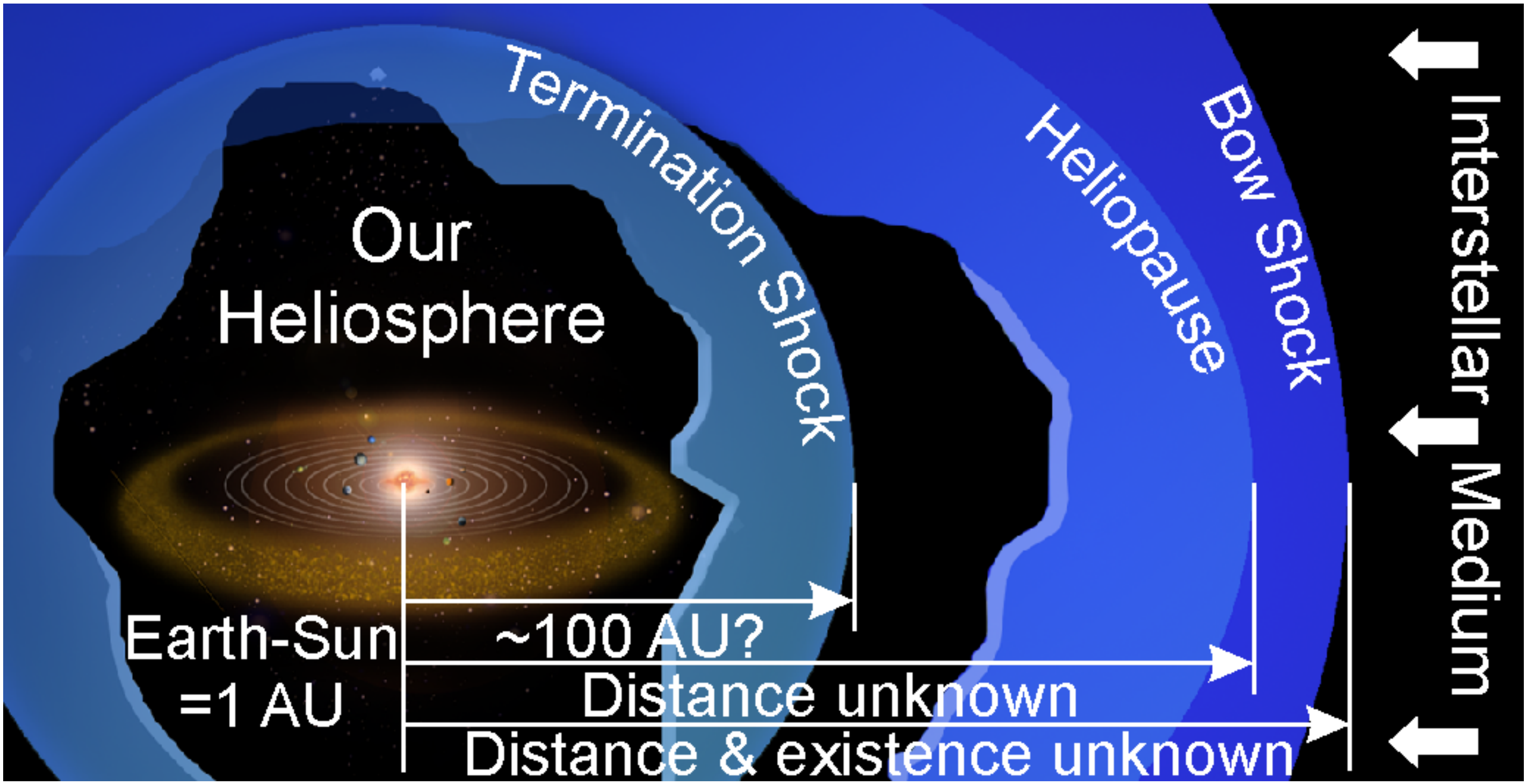
* On behalf of the entire IBEX Team


The Heliosphere
Our Home in the Galaxy
Interstellar Boundary Explorer
IBEX

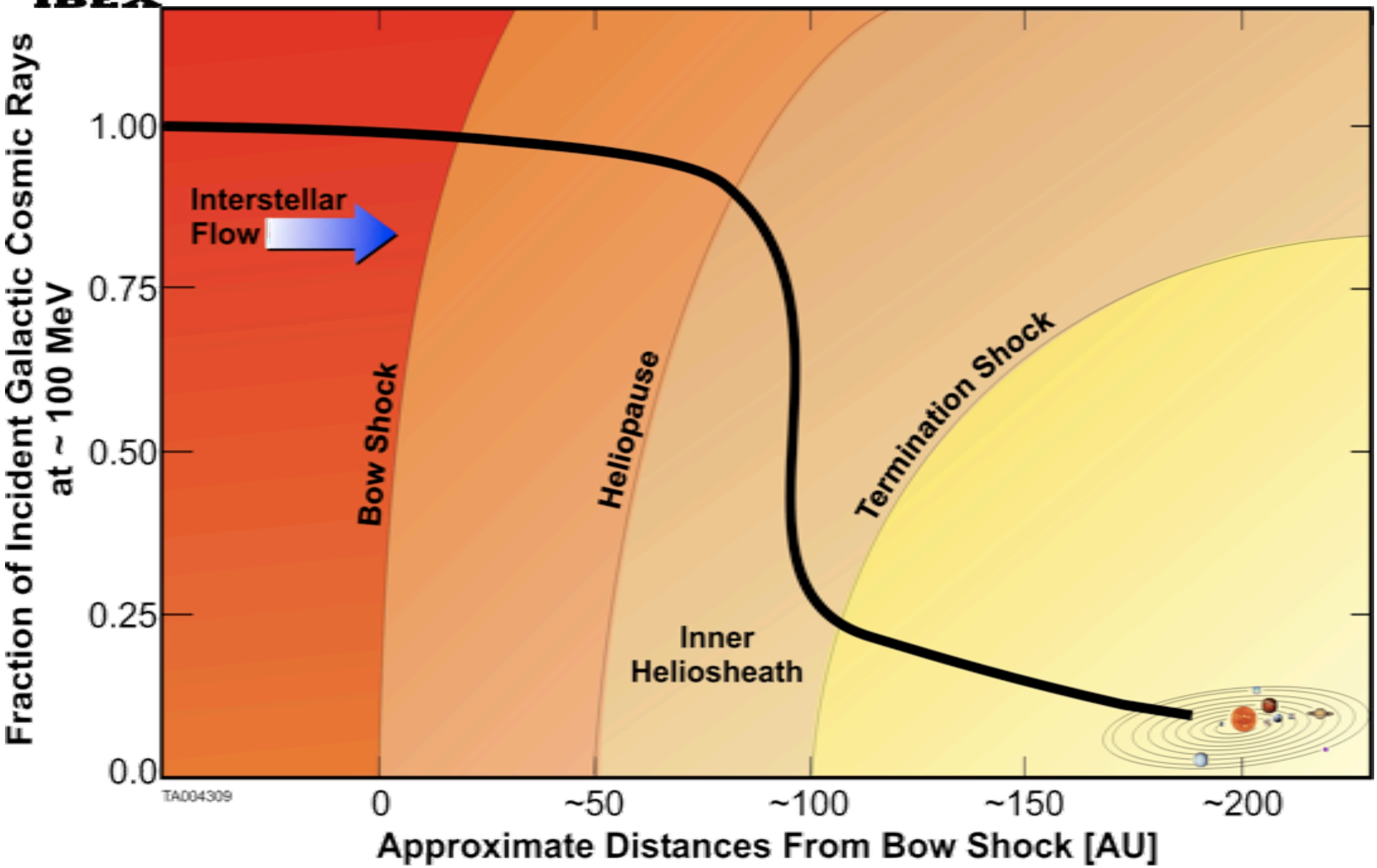
The Sun and Local Interstellar Medium (LISM)



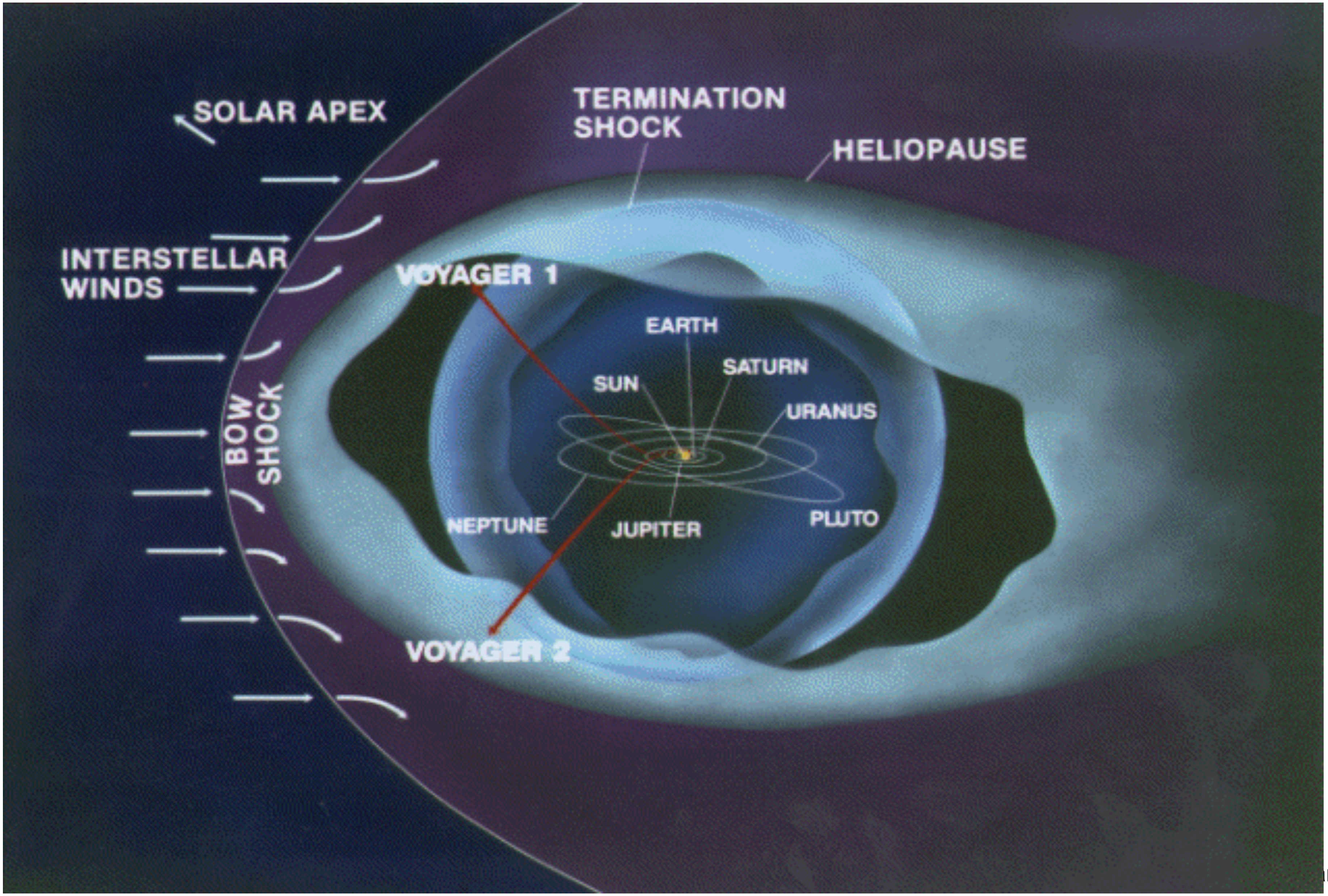
Our Heliosphere



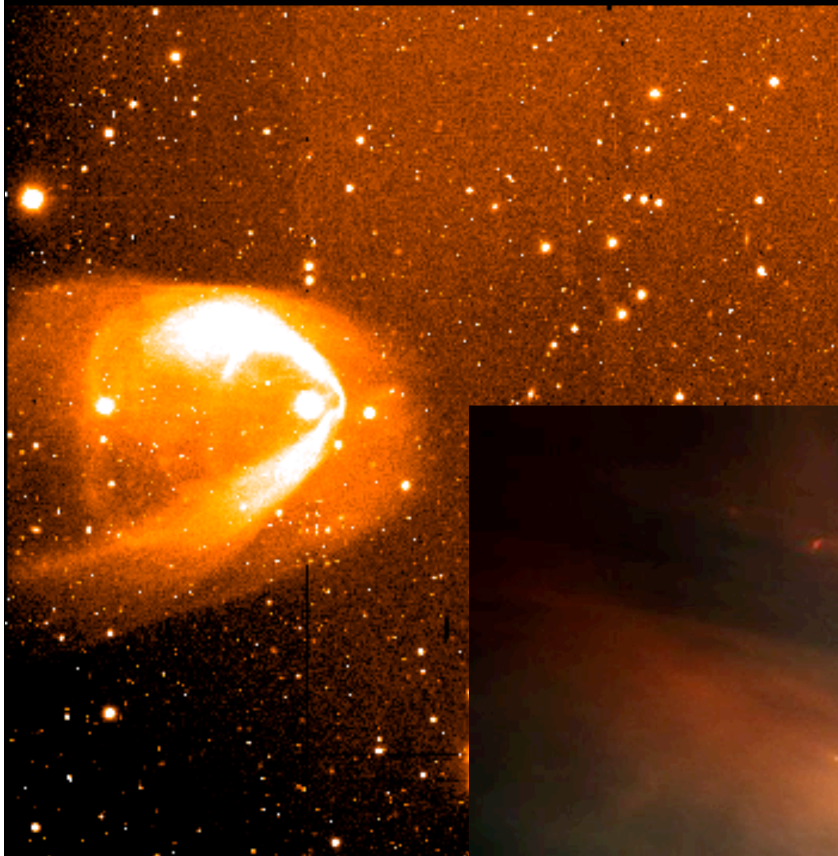
Relevant to Exploration: GCR Shielding

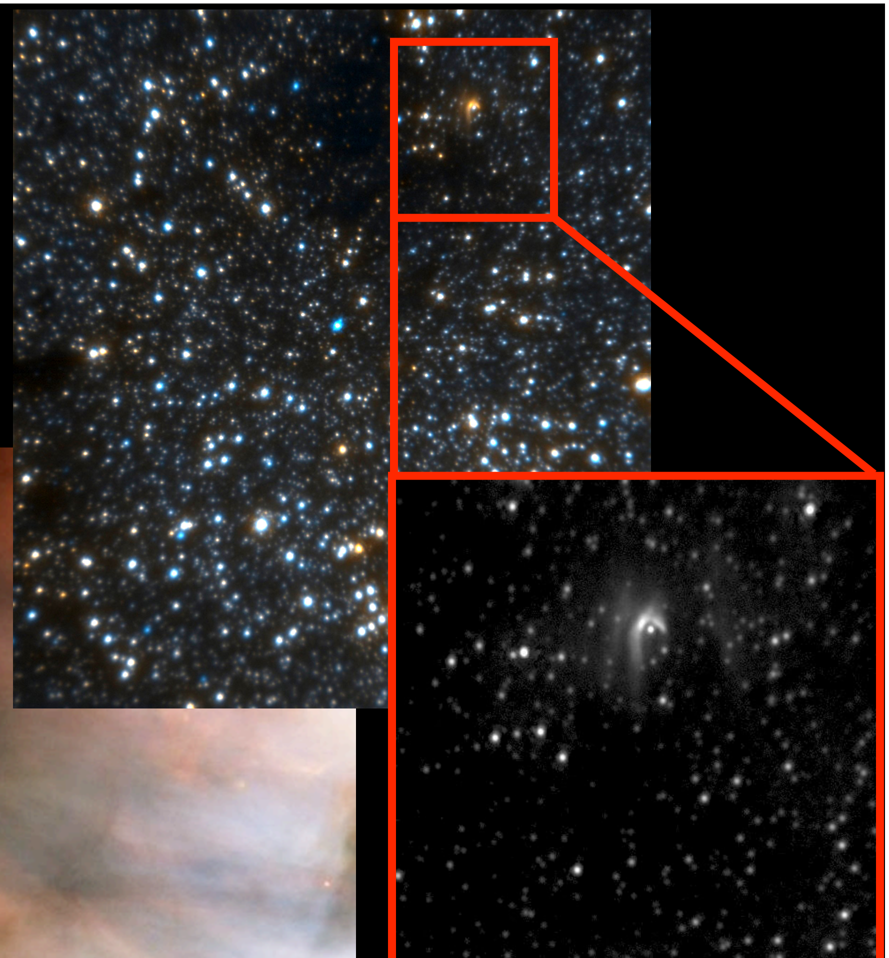


Voyager 1 & 2 in Heliosheath



Astrospheres





Closeup of IRS8, resolving the bow-shock of a fast-moving star

Left image courtesy of R. Casalegno, C. Conselice et al., WIYN, NOAO

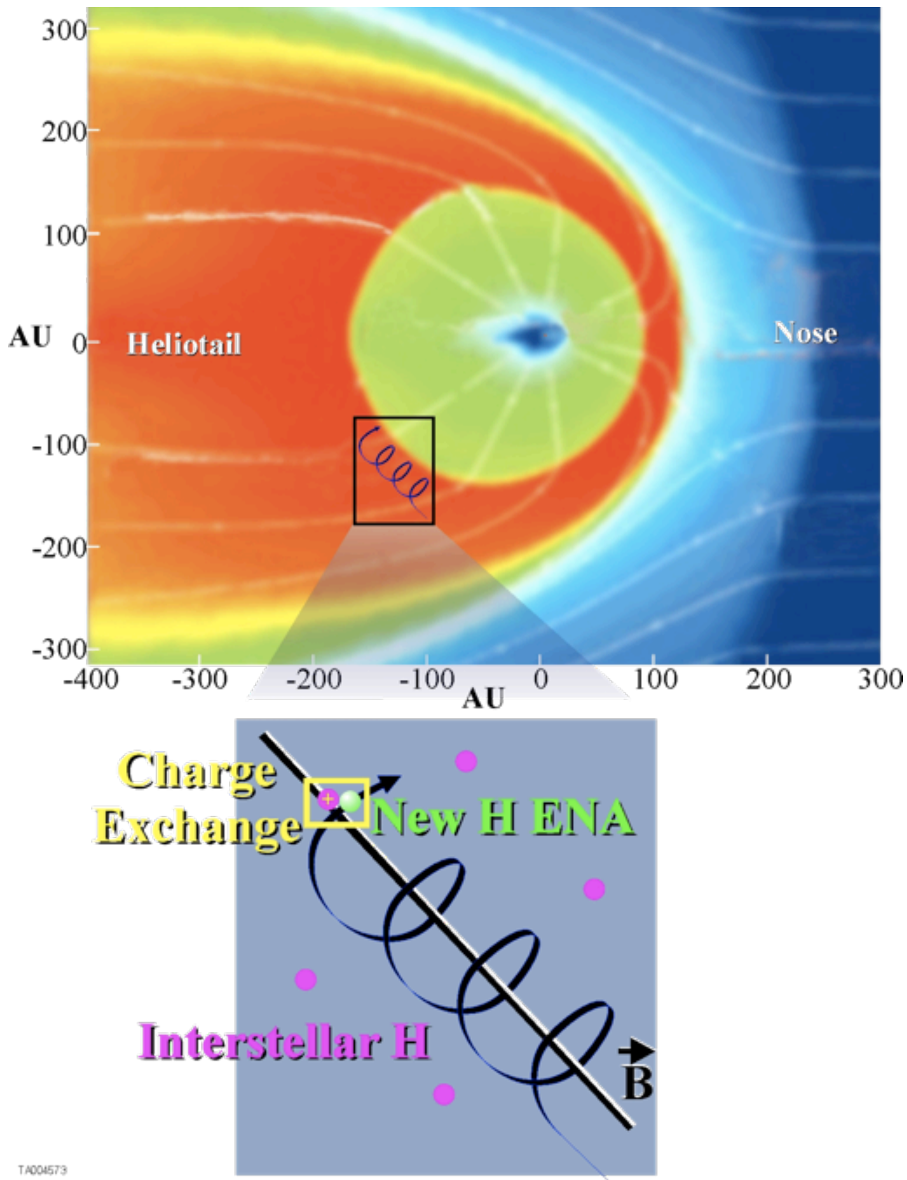
Other images from HubbleSite.org

Energetic Neutral Atoms [ENAs], ENA Imaging and IBEX Science

Interstellar Boundary Explorer

IBEX

ENAs Illuminate the Heliosheath



- Supersonic SW must slow down and heat before it reaches the interstellar medium
- Large numbers of interstellar neutrals drift into heliosphere
  - Ly-α backscatter
  - interstellar pickup ions
- Hot SW charge exchanges with interstellar neutrals to produce ENAs
- Substantial ENA signal from outside the TS guaranteed from first principles

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

IBEX Mission and Launch

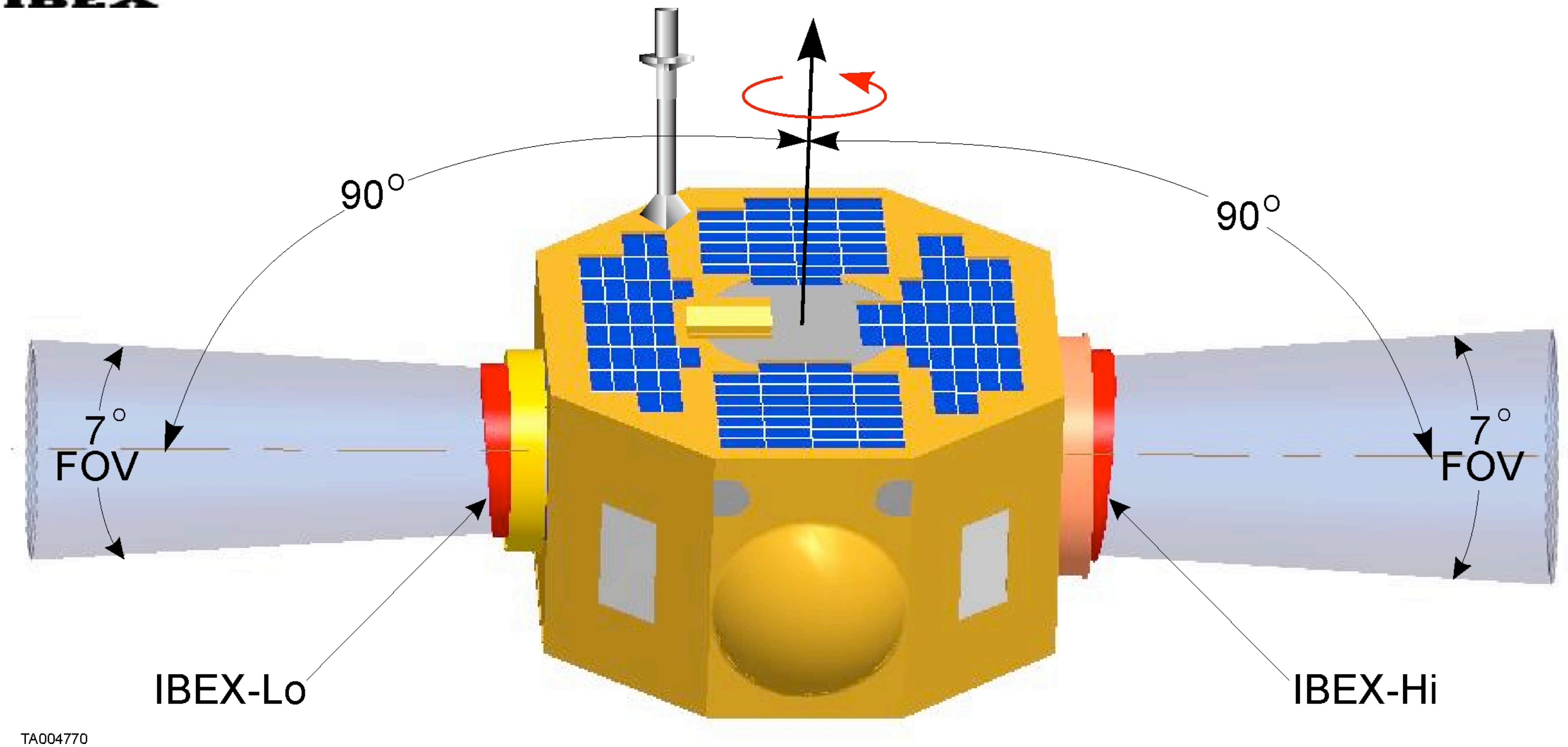
IBEX Mission

- Small Explorer
  - Smallest and cheapest type of full NASA mission
  - Foreign contributions: Swiss (hardware) and many country (science) contributions
- Fast Track Schedule
  - Selected: January 2005
  - Mission PDR: January 2006
  - Confirmation Rev: March 2006
  - Mission CDR: September 2006
  - Payload Delivery: September 2007
  - VAFB Delivery: July 2008
  - Launch: 19 October 2008

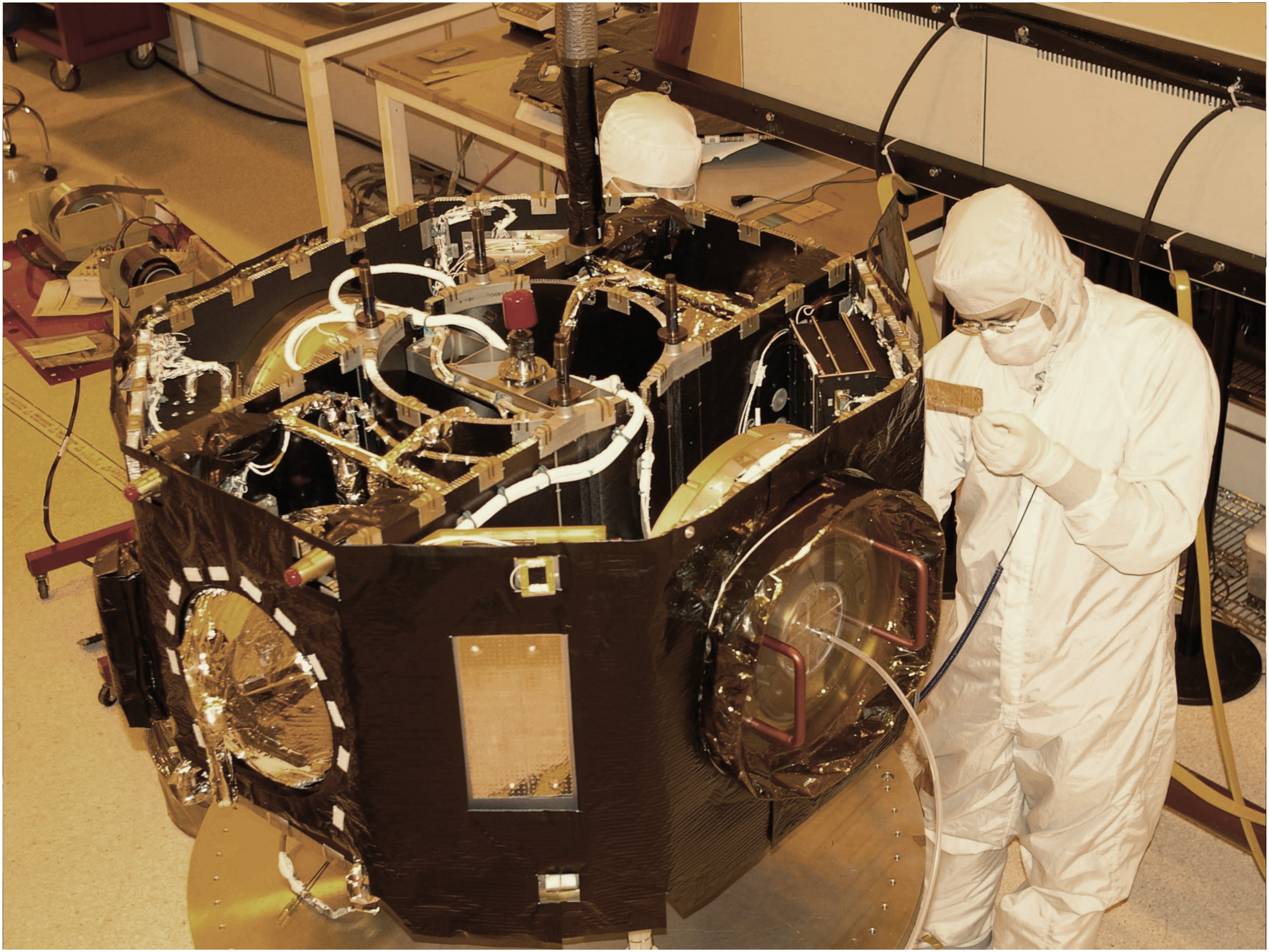
IBEX Formal Institutions

- PI Institution: Southwest Research Institute, San Antonio, TX USA
- Hardware-Producing Co-I Science Institutions
  - Applied Physics Laboratory, Johns Hopkins University, Laurel, MD USA
  - Lockheed Martin Advanced Technology Center, Palo Alto, CA USA
  - Los Alamos National Laboratory, Los Alamos, NM USA
  - NASA Goddard Space Flight Center, Greenbelt, MD USA
  - University of Bern, Switzerland
  - University of New Hampshire, Space Science Center, Durham, NH USA
- Other non-Hardware Co-I Science Institutions
  - Adler Planetarium, Chicago, IL USA
  - Boston University, Boston, MA USA
  - Massachusetts Institute of Technology, Cambridge, MA, USA
  - Moscow State University, Moscow, Russia
  - Space Research Centre of the Polish Academy of Sciences, Warsaw, Poland
  - Ruhr-Universitaet Bochum, Bochum, Germany
  - University of Alabama, Huntsville, Alabama USA
  - University of Bonn, Bonn, Germany
  - University of Chicago, Chicago, IL USA
  - University of Michigan, Ann Arbor, MI USA
  - University of Montana, Missoula, MT USA
  - University of Southern California, Los Angeles, CA USA

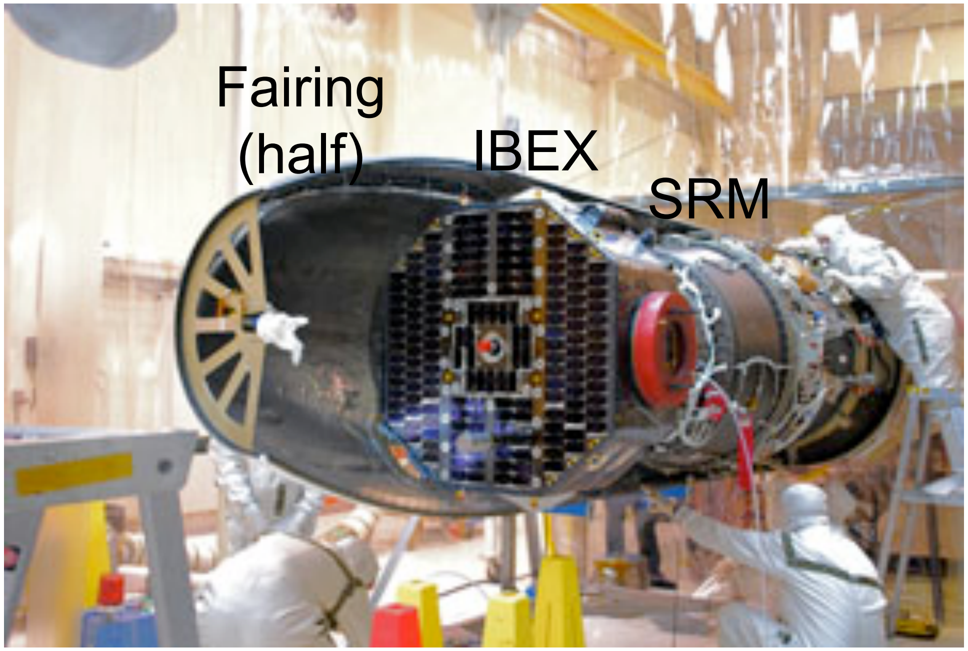
IBEX Spacecraft



- 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)



IBEX Orbit Raising Approach

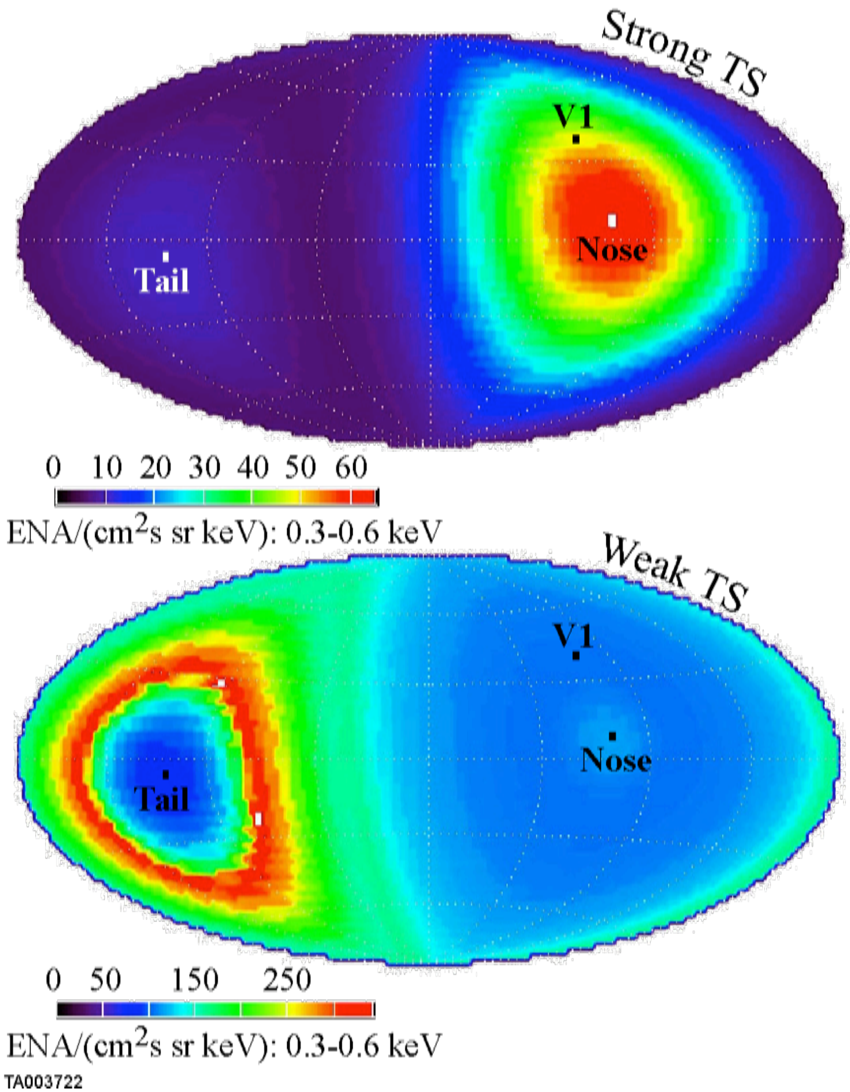


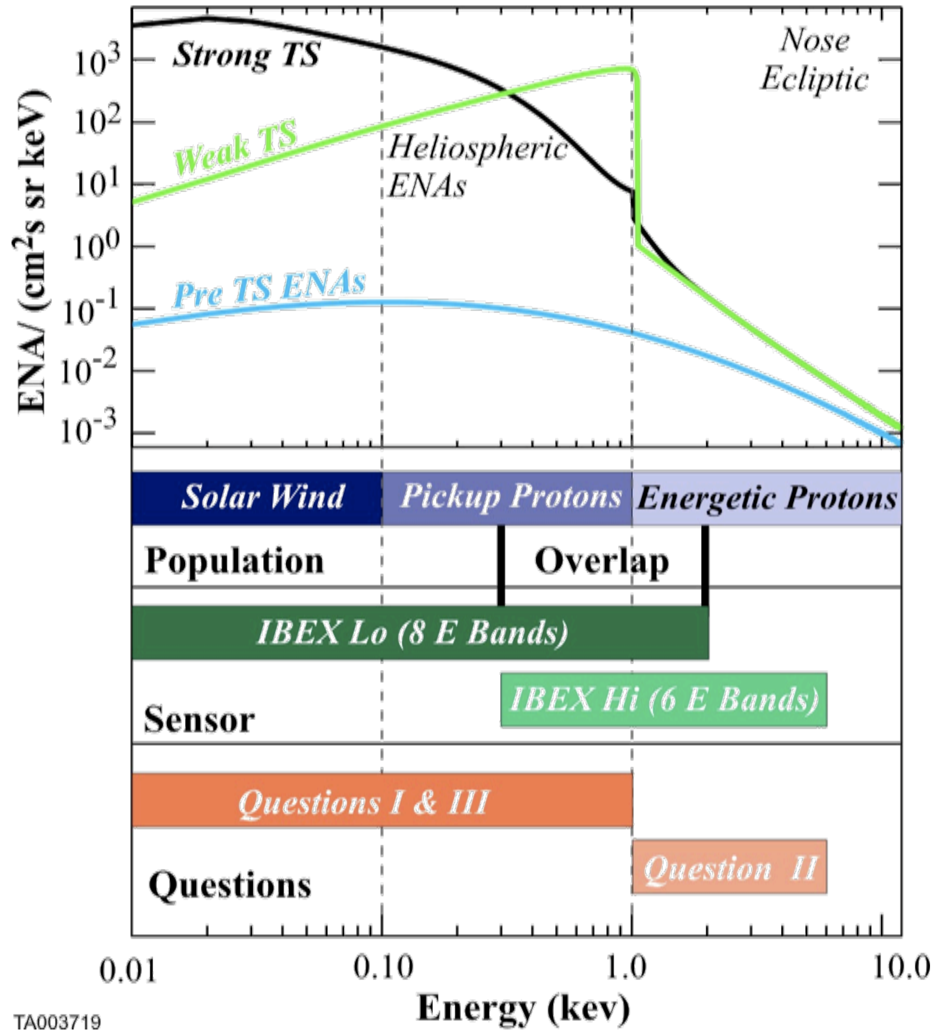
- No mission has ever used a Pegasus LV to achieve orbit higher than LEO (few hundred km)!
- IBEX apogee ~50 R_E
- New approach combines 3 orbit-raising methods
  - Pegasus launch vehicle
  - IBEX-supplied Solid Rocket Motor (SRM)
  - Hydrazine Propulsion System finishes orbit raising and trims out delta-V dispersions from solid rocket motors

"IBEX-like" Launches – New Capability

- Spacecraft maximum ~105 kg
- 50 Re nearly escape
  - Mass added to ensure no escape
  - Lunar assists possible
- Could send ~100kg virtually anywhere
  - Moon
  - L1 – ACE replacement
  - Other planets
- Cheapest dedicated small sat launch currently available for NASA and US missions

Global Images and Energy Spectra





Initial Heliospheric Observations

Five Papers in *Science* (online)

10/15/09

Interstellar Boundary Explorer

IBEX

IBEX Observations

- Energy-resolved maps of ENAs coming in from the outer heliosphere
  - Covers ~200 eV to ~6 keV
  - Built up over the first half of 2009
  - Generally reflect the solar minimum conditions that have persisted for past several years
- First *in situ* observation of interstellar H and O from the LISM (also measure He)

→ IBEX observations allow us to differentiate various particle populations providing information about nearer and more distant interactions of the heliosphere with the LISM and the interstellar environment itself

Science - IBEX Special Section

- McComas et al., First Global Observations of the Interstellar Interaction from the Interstellar Boundary Explorer
- Fuselier et al., Width and Variation of the ENA Flux Ribbon Observed by the Interstellar Boundary Explorer
- Funsten et al., Structures and Spectral Variations of the Outer Heliosphere in the IBEX Energetic Neutral Atom Sky Maps
- Schwadron et al., Comparison of Interstellar Boundary Explorer Observations with 3-D Global Heliospheric Models
- Möbius et al., Direct Observations of Interstellar H, He, and O by the Interstellar Boundary Explorer
- Krimigis et al., Imaging the Interaction of the Heliosphere with the Interstellar Medium from Saturn with Cassini

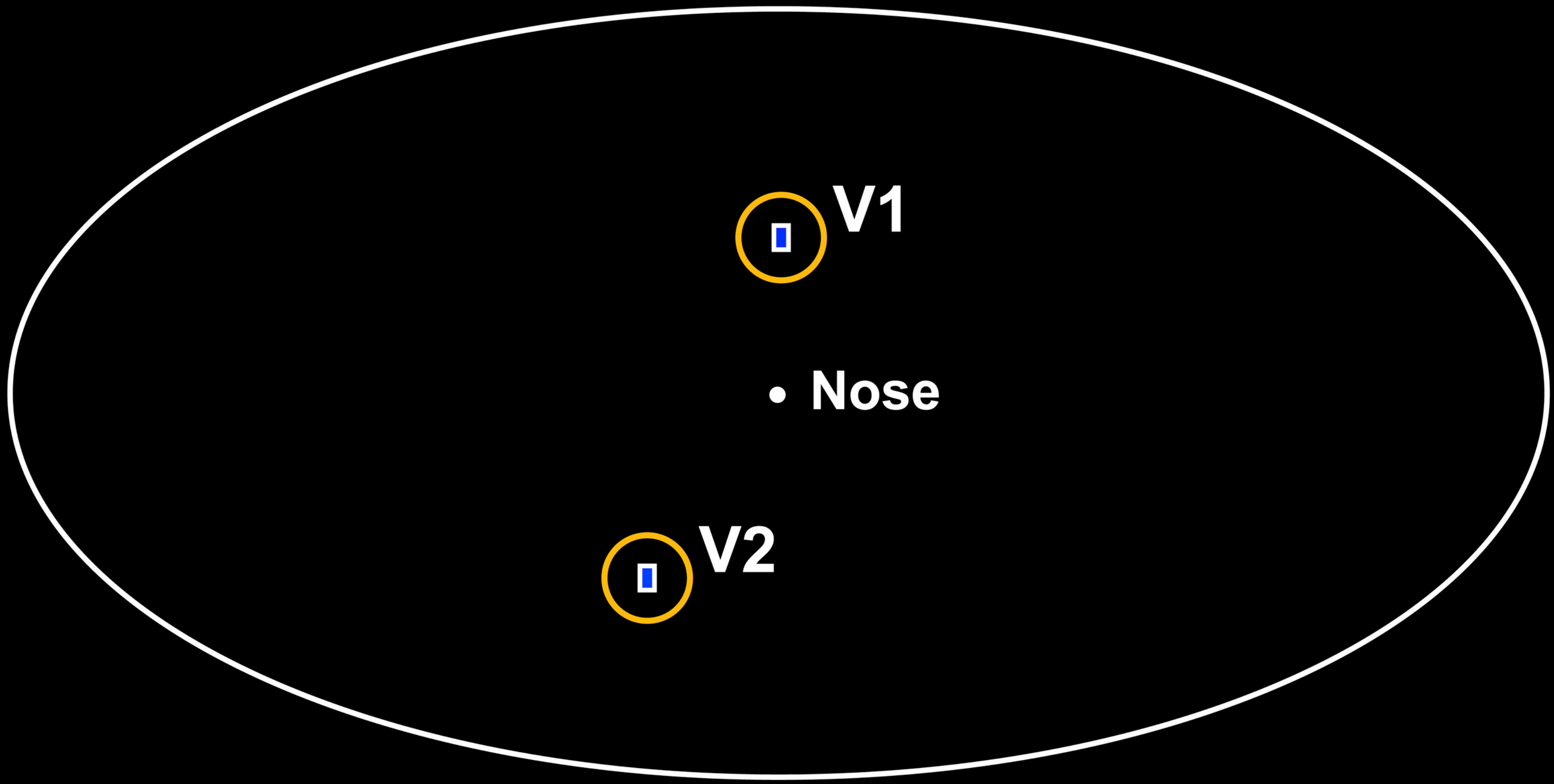
  (Complimentary observations at higher energies from Cassini)

Heliospheric ENAs

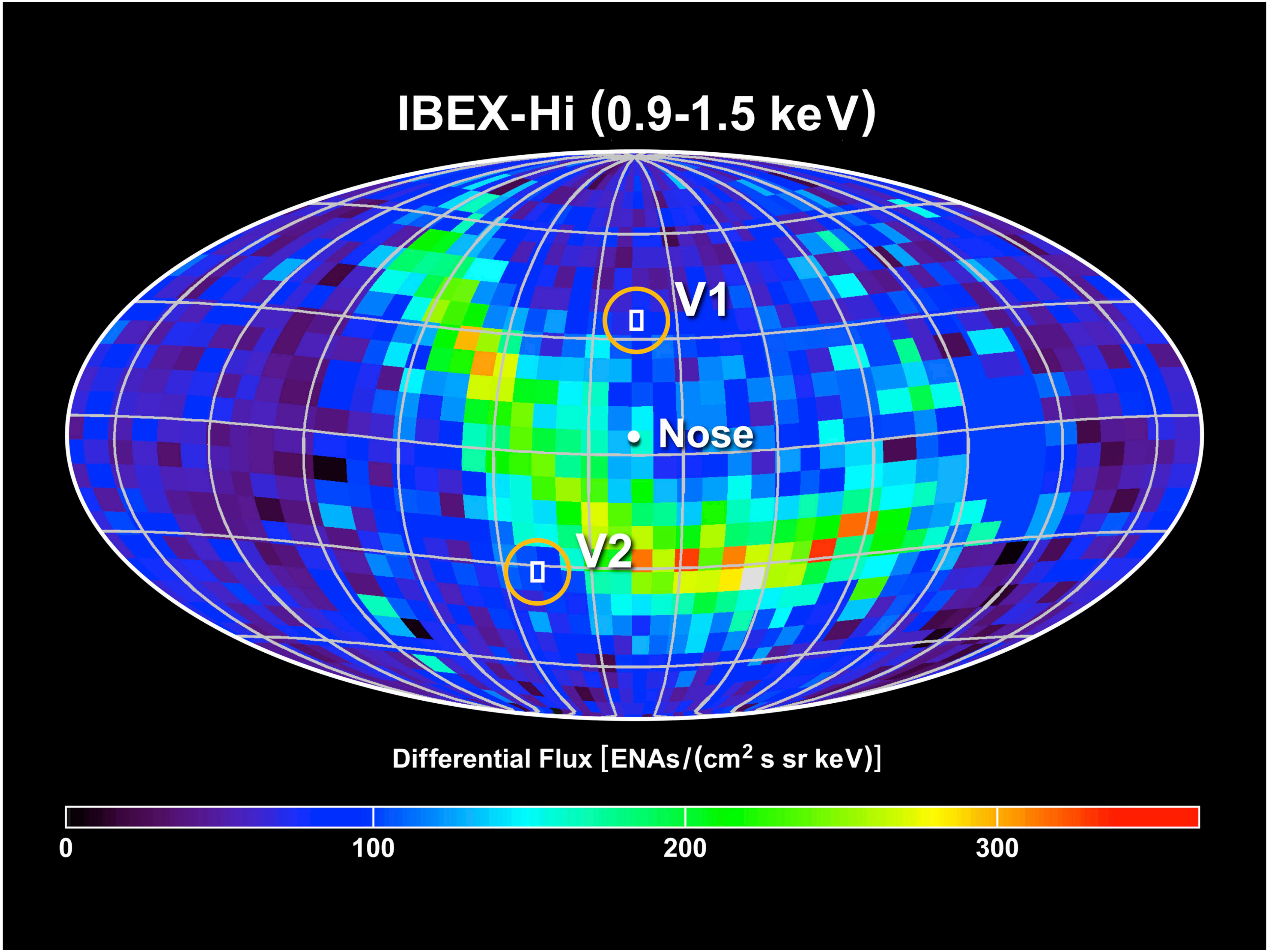
Interstellar Boundary Explorer

IBEX

IBEX-Hi (0.9-1.5 keV)



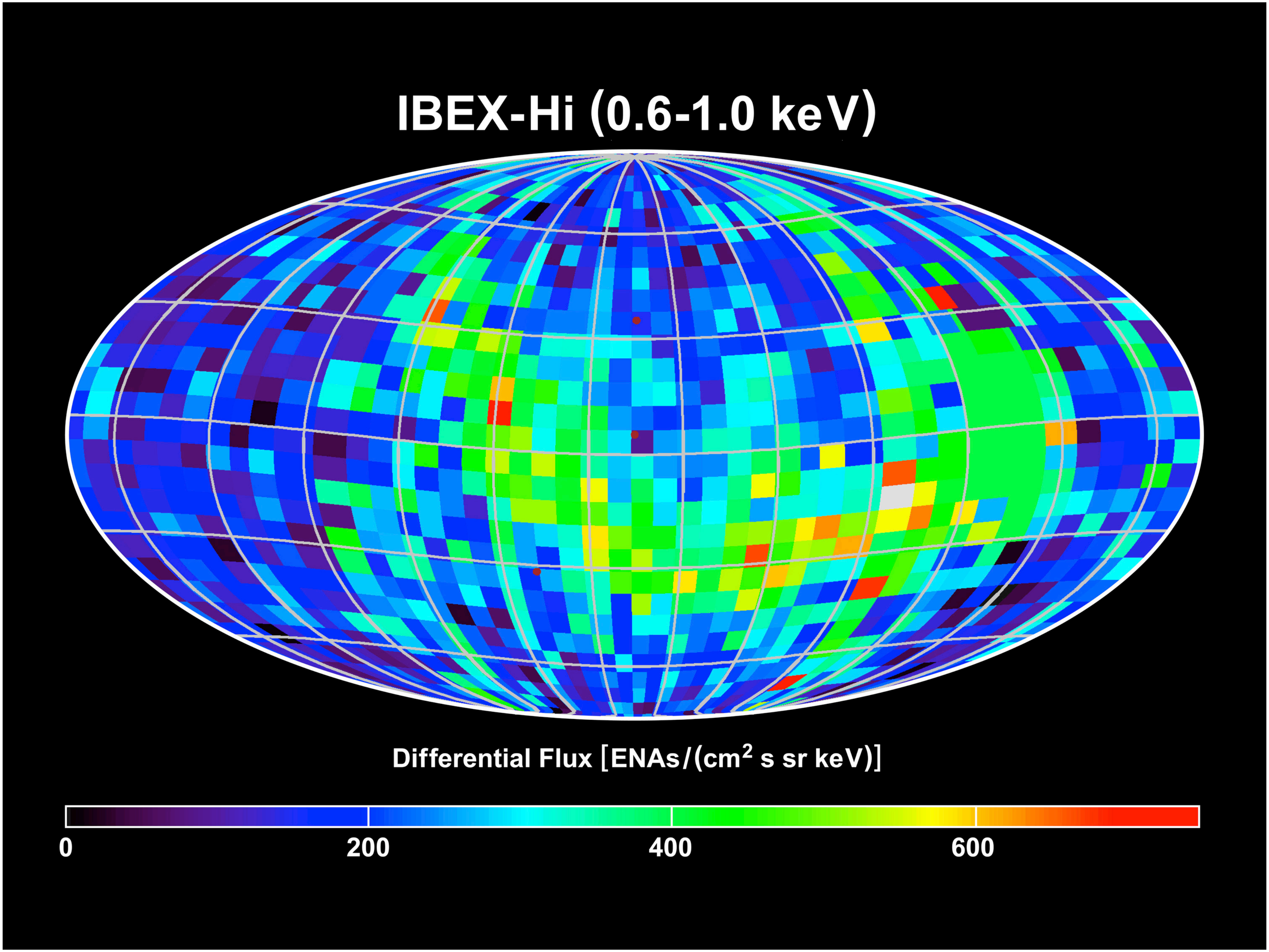
Mollweide all-sky projection showing locations of Voyagers
Voyagers provide detailed information in these two directions

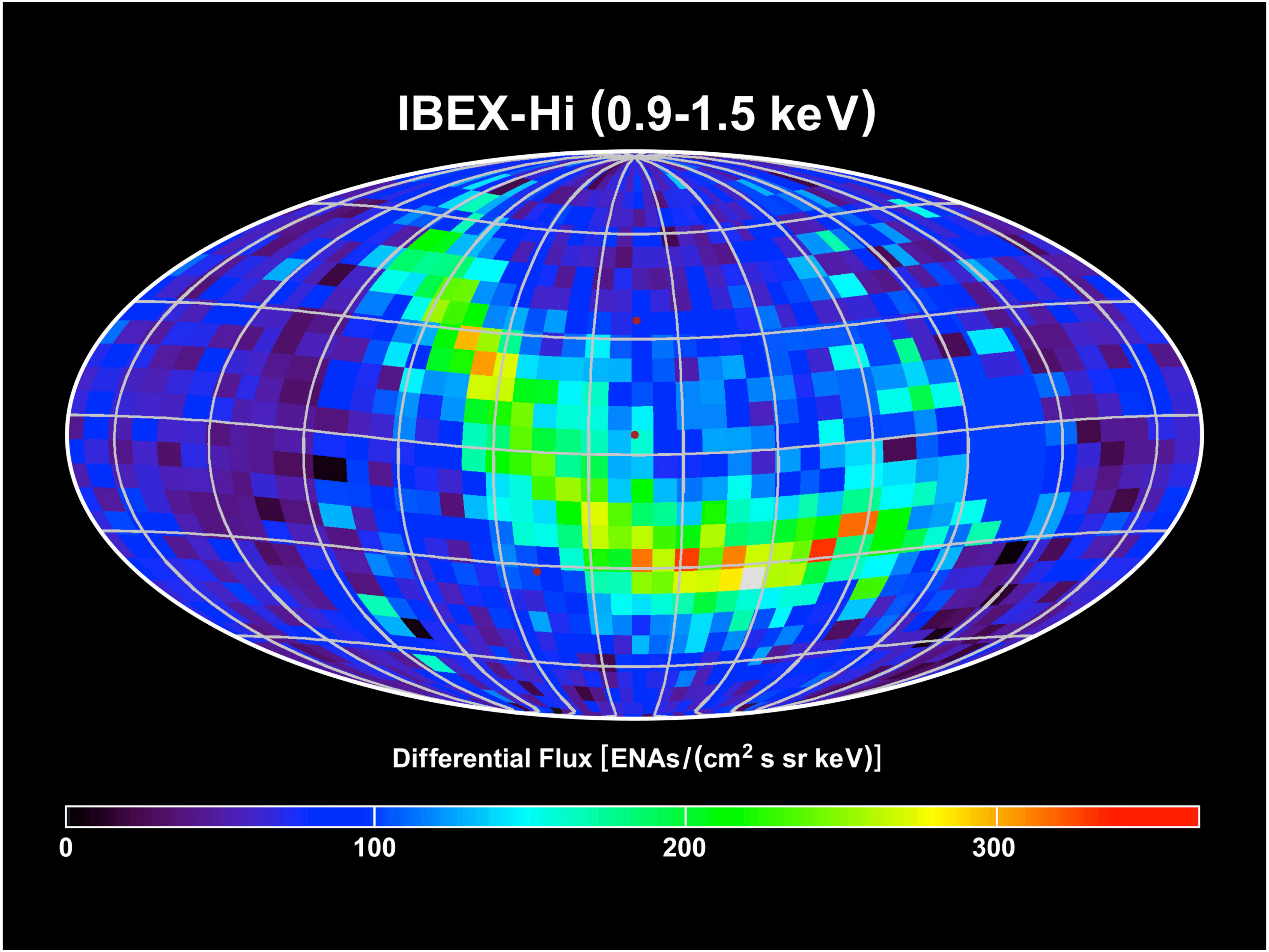

IBEX-Hi (0.9-1.5 keV)
V1
Nose
V2
Differential Flux [ENAs/(cm2 s sr keV)]
0
100
200
300

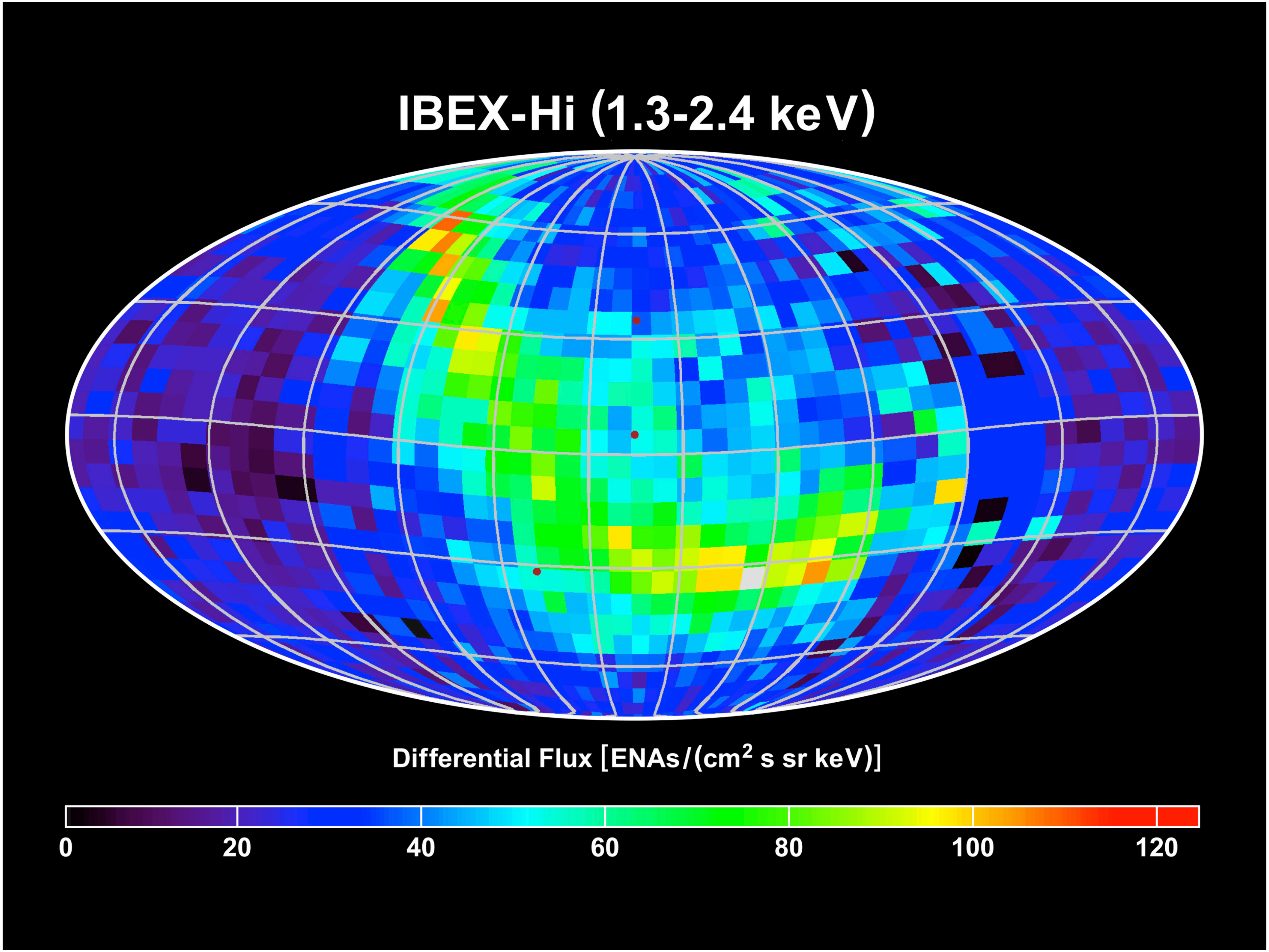
From Voyager to IBEX

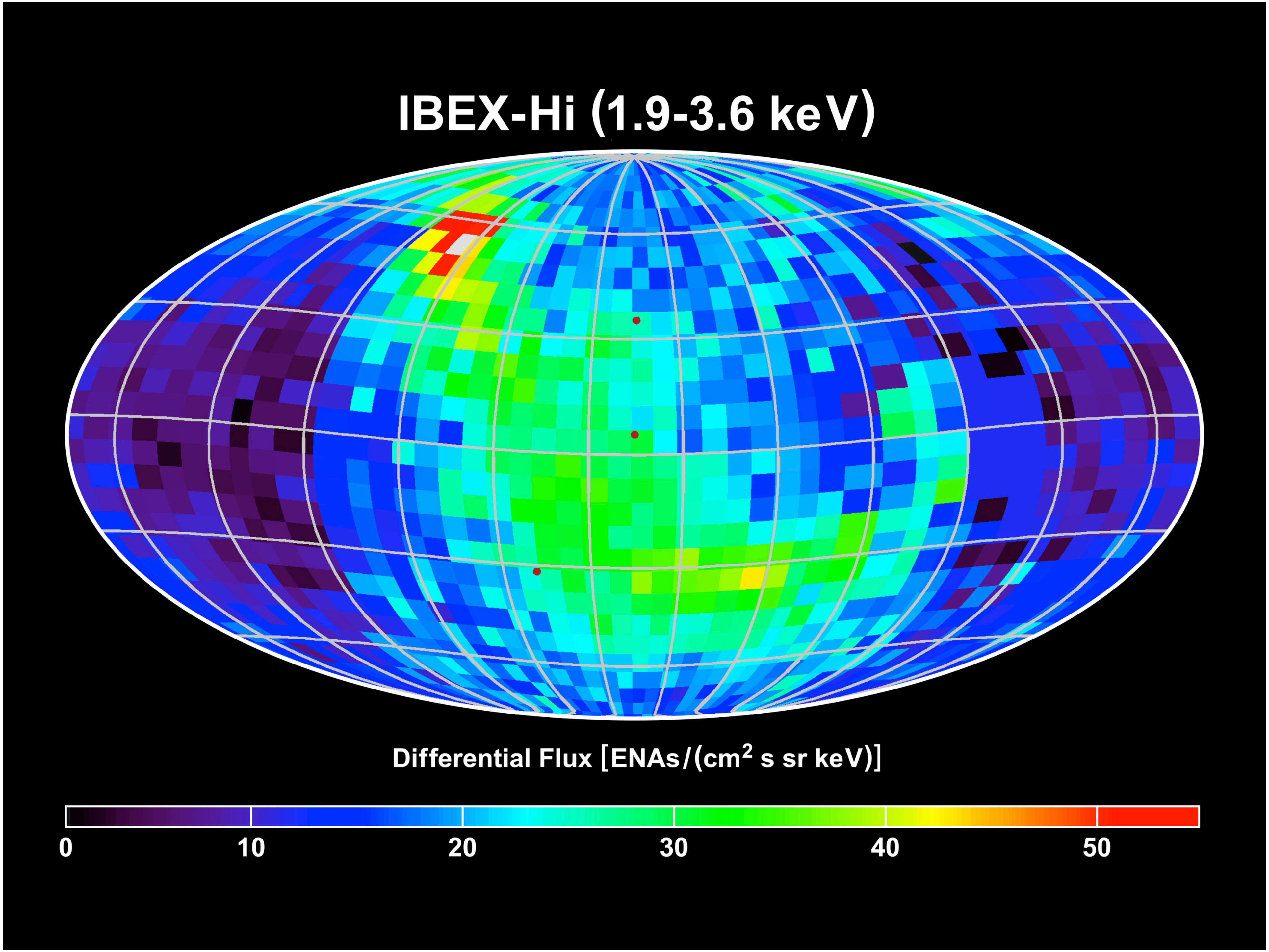
- Voyager 1 (V1) and later Voyager 2 (V2) provide excellent *in situ* measurements as they trace out two radial paths out through the inner heliosheath
- IBEX's energy–resolved, all-sky maps reveal the ***global*** interstellar interaction, elucidating the physical processes in all regions
- Most striking feature in the IBEX sky maps is an unexpected, bright, narrow "Ribbon" of ENA emissions snaking between the directions of the two Voyagers
- The ribbon is completely new and not predicted by any current model or theory

→ Understanding IBEX observations will require a revolutionary break from current thinking and the development of a new paradigm for understanding the heliospheric interaction

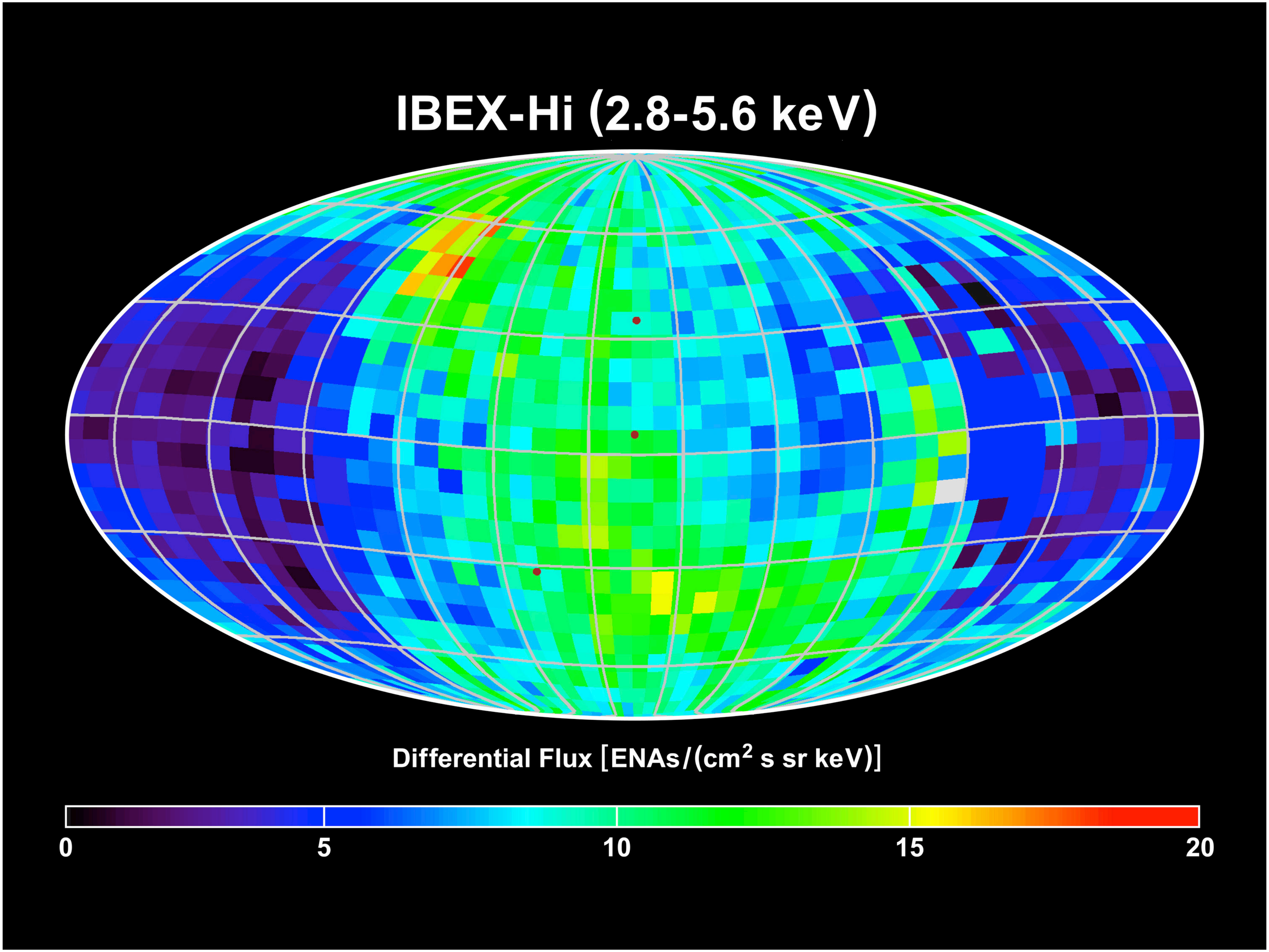

IBEX-Hi (0.6-1.0 keV)
Differential Flux [ENAs/(cm2 s sr keV)]
0
200
400
600


IBEX-Hi (0.9-1.5 keV)
Differential Flux [ENAs/(cm² s sr keV)]
0
100
200
300


IBEX-Hi (1.3-2.4 keV)
Differential Flux [ENAs/(cm2 s sr keV)]
0
20
40
60
80
100
120

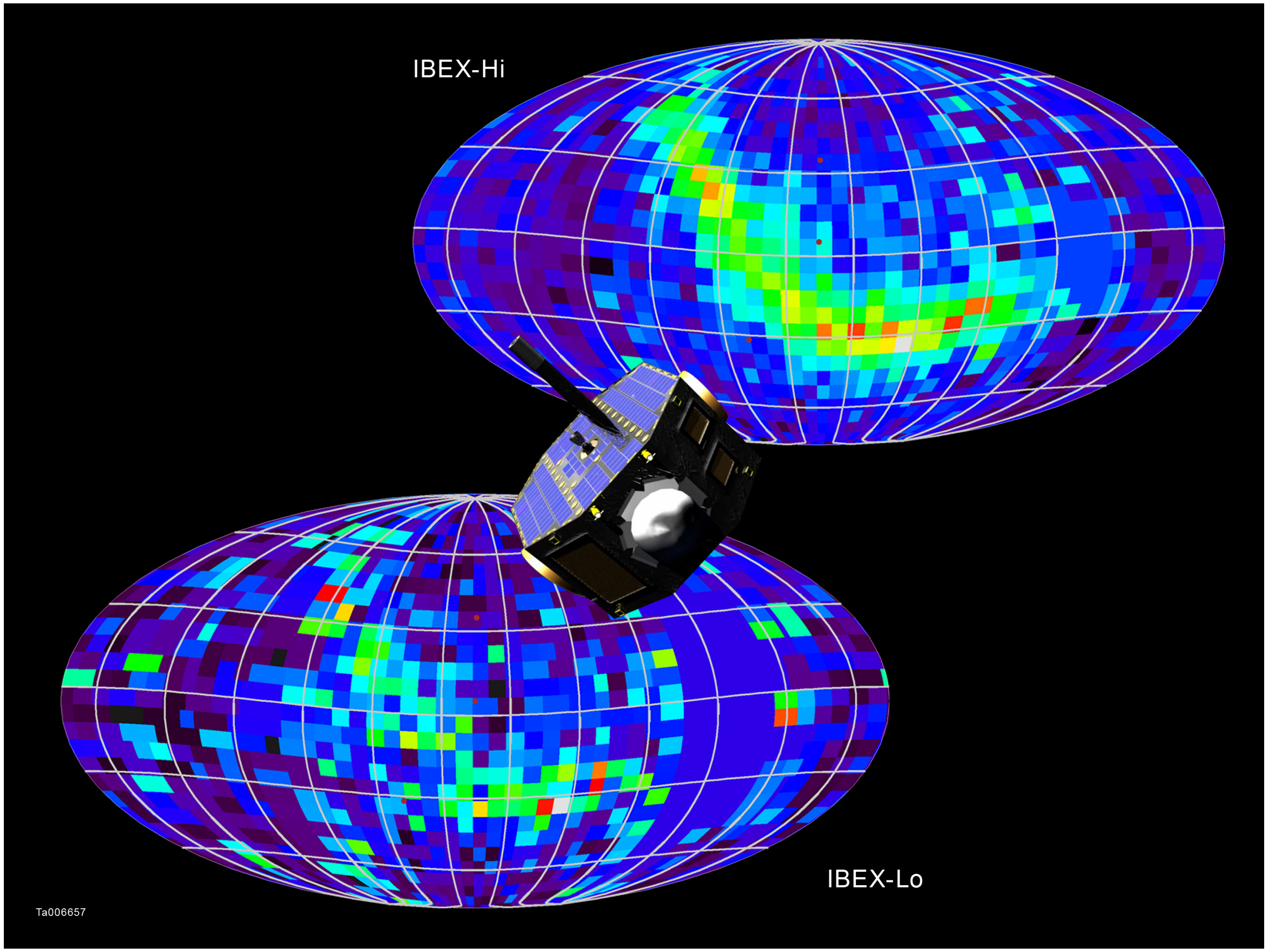


IBEX-Hi (1.9-3.6 keV)
Differential Flux [ENAs/(cm2 s sr keV)]
0
10
20
30
40
50



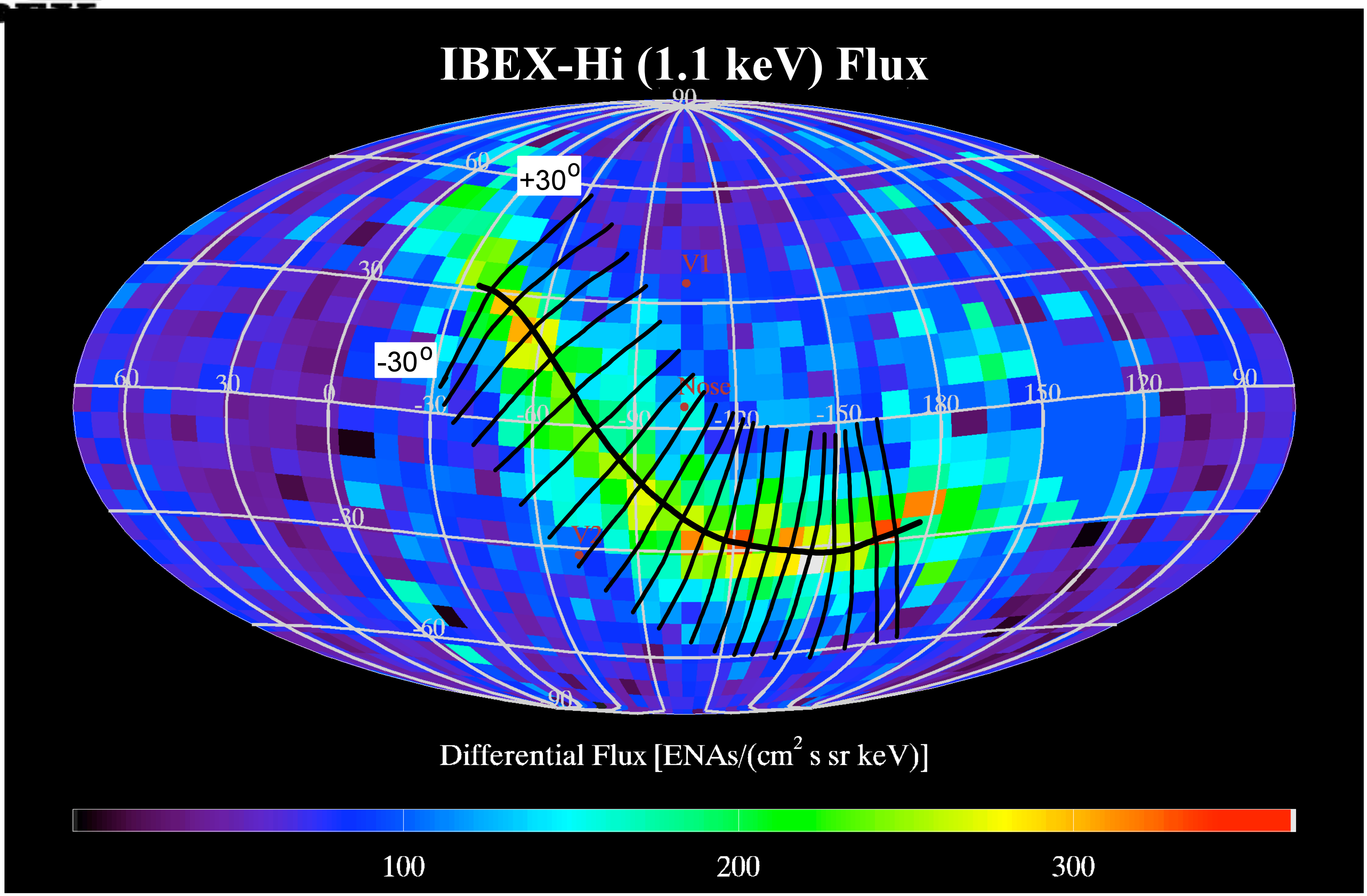
IBEX-Hi (2.8-5.6 keV)
Differential Flux [ENAs/(cm2 s sr keV)]
0
5
10
15
20

Independent Confirmation



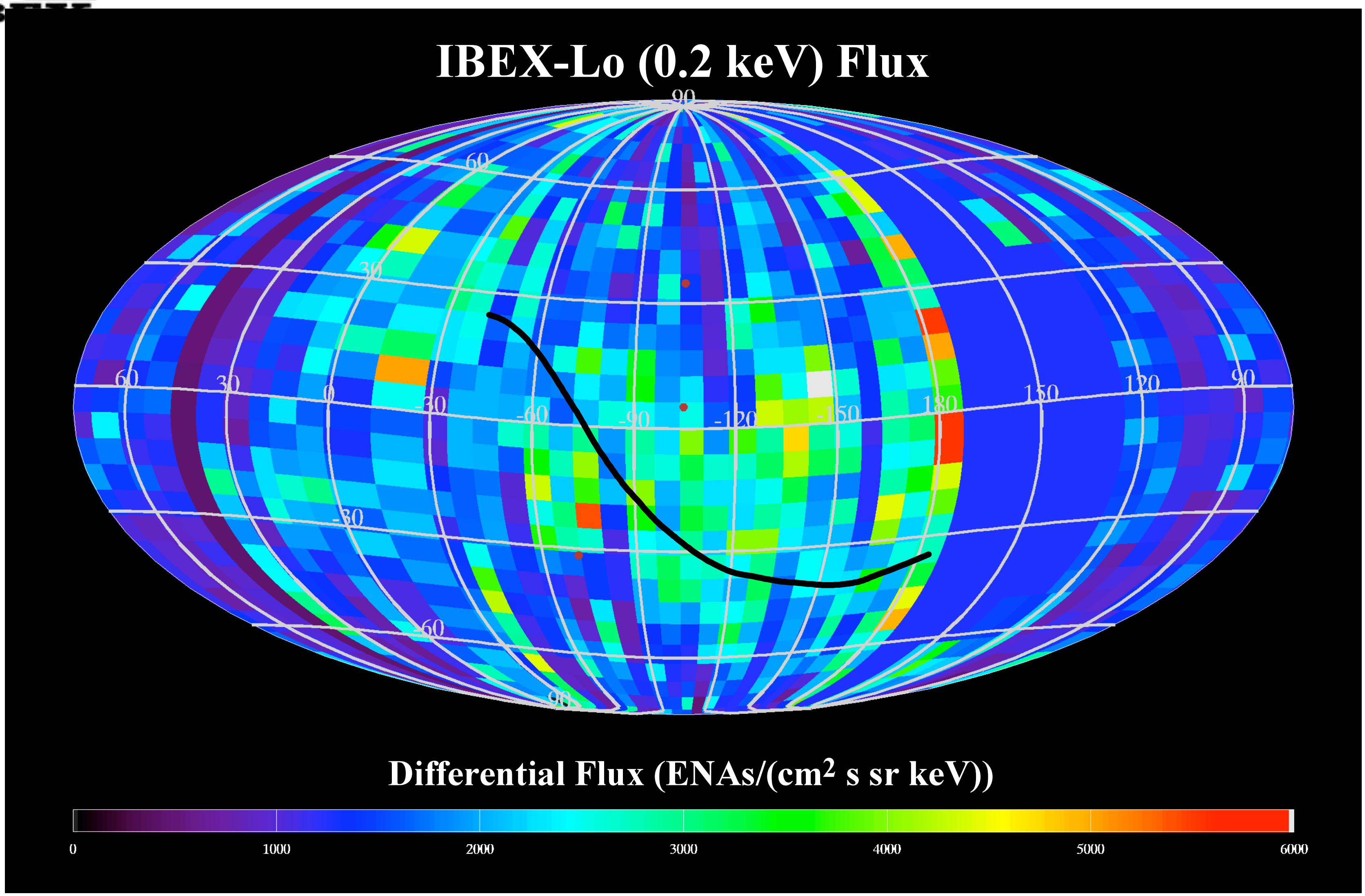
IBEX-Lo & Hi observations independently confirm ribbon (Hi at ~1.1 keV and Lo at ~0.9 keV shown)

Measuring the Ribbon Width



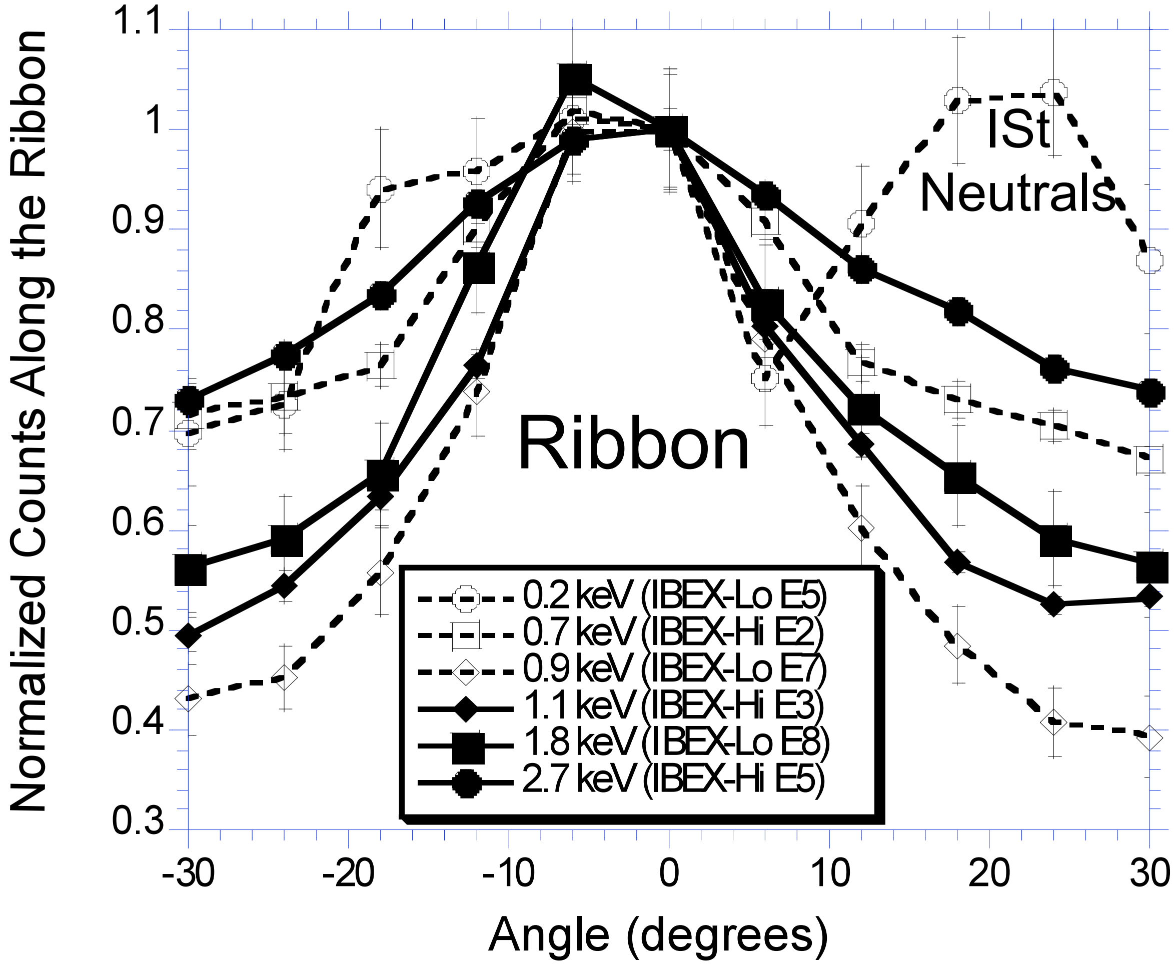
Average properties of the ribbon determined by averaging flux along the ribbon and ±30° from the center (use the 1.1 keV map as reference)

Ribbon Seen at 200 eV



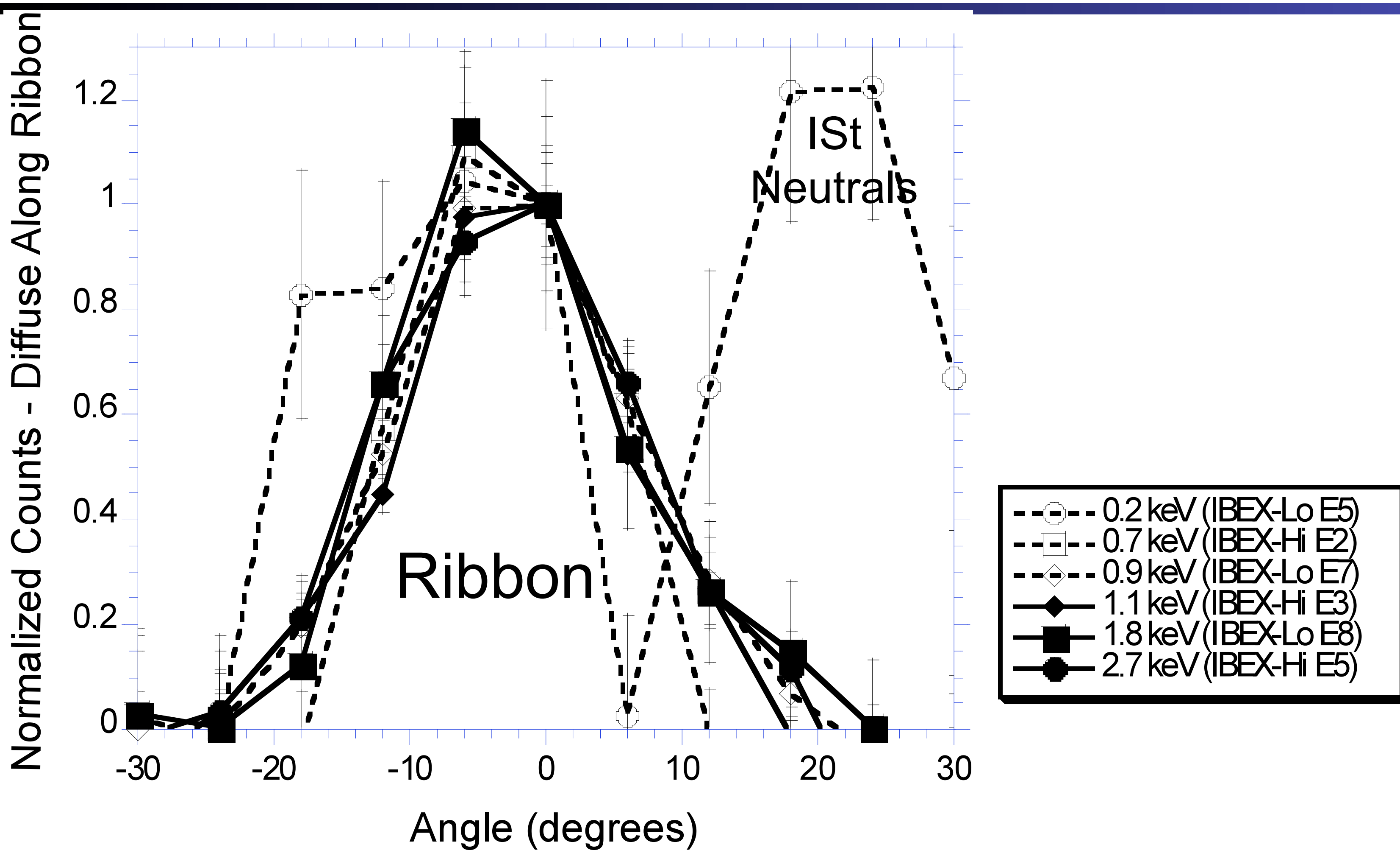
IBEX-Lo map shows evidence of the ribbon at least down to 0.2 keV
Black line shows the trace of the ribbon from the 1.1 keV map

Location and Apparent Width



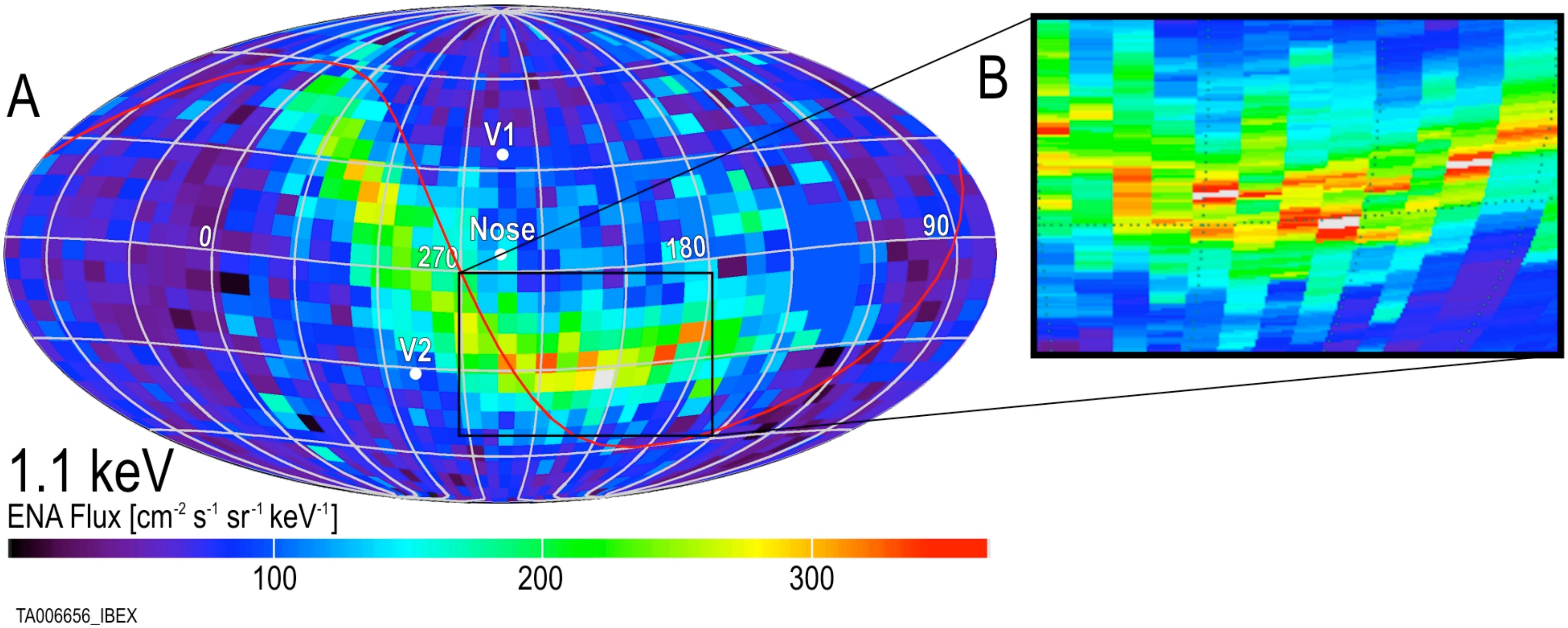
- Ribbon is asymmetric (results from features at higher angular res)
- Ribbon is located in the same place in the sky for all energies from 0.7 to 2.7 keV

Ribbon – Constant Ave Width



- Same as the previous figure, but removing the more globally distributed flux and renormalizing
- Width of the ribbon averages 20° for all energies except 0.2 keV

Ribbon Fine Structure

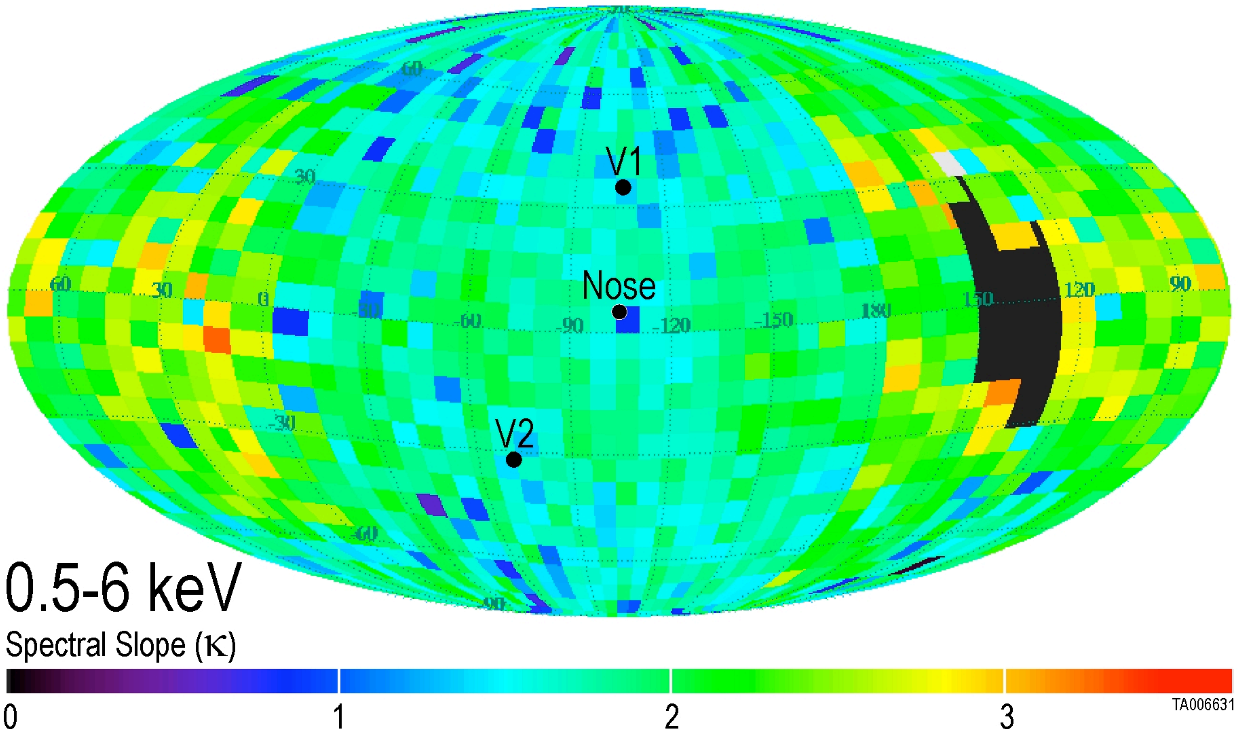


- Inset B shows 0.5 deg spin phase pixels summed to 100 ENAs (10% Poisson statistics)
- Ribbon comprised of numerous complex finer scale structures

Organization of ENA Flux

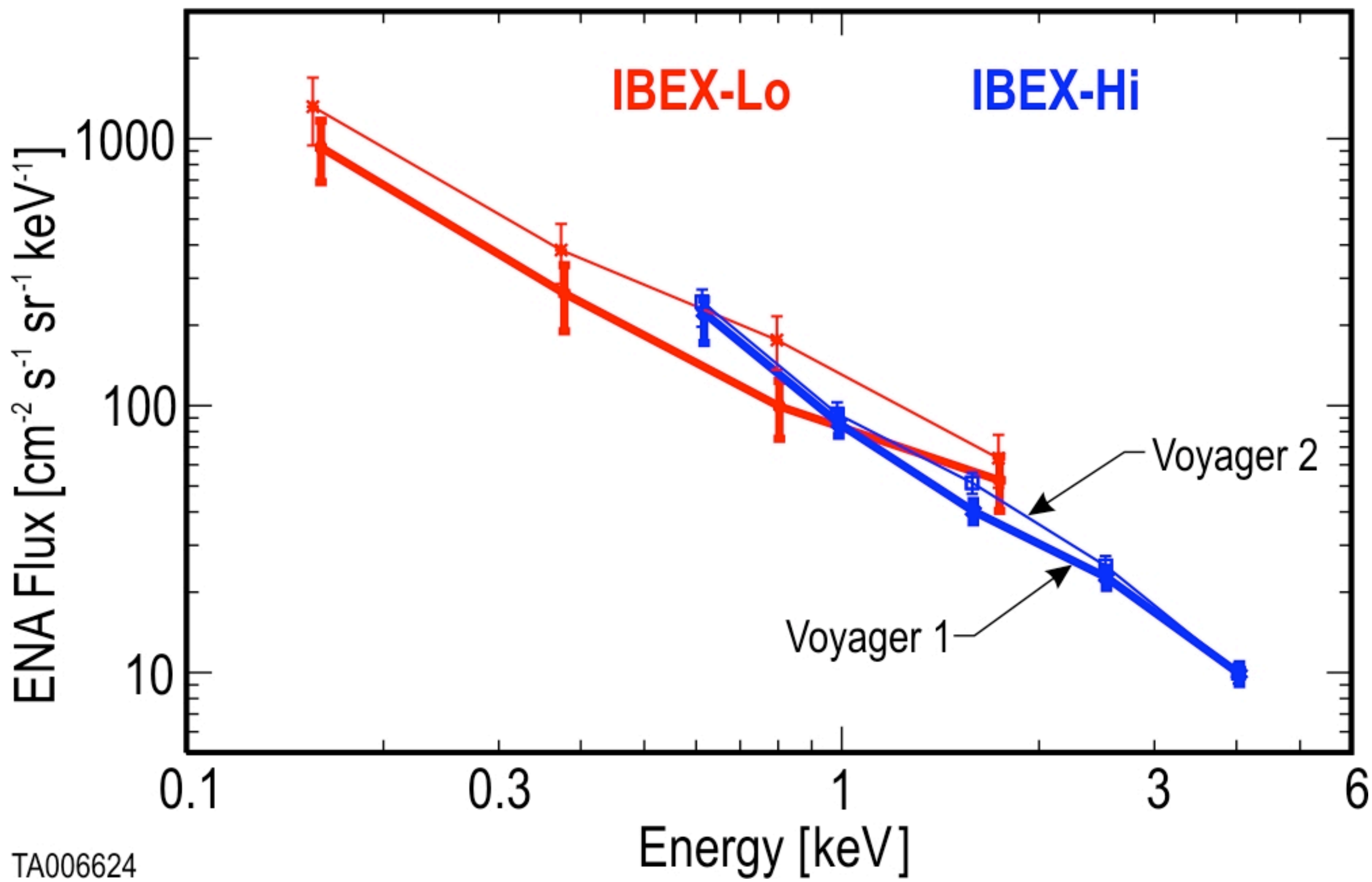
- “Ribbon” of bright ENA fluxes
  - Maxima reaching ~2-3 times brighter than the surrounding regions
  - Variable in width from <15º to >25º FWHM along length
  - Averages ~20º wide over 0.7-2.7 keV energy steps
  - Shows statistically significant fine structure
  - Ribbon passes ~25º away from the heliospheric nose
  - Brighter emissions from somewhat broader regions at higher latitudes in both hemispheres - around ~60º N and ~40º S
    - The northern bright region has a vastly different spectral shape than the rest of the Ribbon
  - Weakens, but also extends back behind the northern pole, nearly closing a loop on the sky
- Globally distributed ENA flux organized by ecliptic latitude and longitude (solar wind and ram direction) underlying bright Ribbon

Spectral Slopes of ENAs



- Power law spectral slopes of the ENA flux: log (flux) vs log E
- Variations ordered by ecliptic latitude and longitude (interstellar flow)
  - Generally consistent with ENAs from TS-heated, non-thermal plasma
- Flatter spectrum near poles than equator
  - Faster SW at higher lats → higher-energy PUIs than near the ecliptic
- Tail spectra significantly steeper than near the nose (k~1.5)
  - Possibly from longer line-of-sight (LOS) integrations at Low E toward tail
- Ribbon is barely visible in spectral slope map!

Spectra toward Voyager S/C



- Energy spectra for 20 pixels centered on Voyager S/C
- Nearly straight power laws with slopes of ~1.5 (V1) and ~1.6 (V2)

ENA Spectra in Different Regions

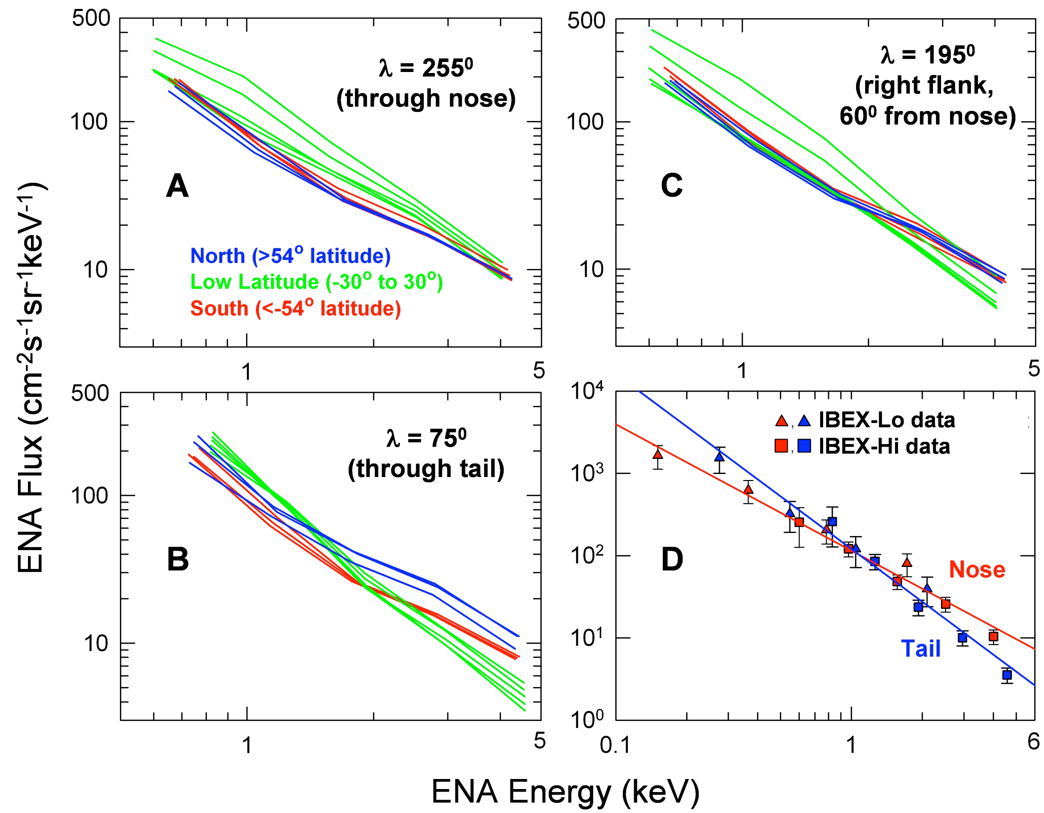
- Average fluxes from 24° longitude x 12° latitude pixels at different longitudes
- The highest flux spectra at low latitudes in (**A**) and (**C**) and northern latitudes in (**B**) contain the ribbon.

Figs. A-C: Fundamentally different spectral shapes between low and high latitudes

- **Low latitude spectra:**
  - Smooth, generally characterized with a single spectral index κ
- **Northern (β≥54°)** and **Southern (β≤-54°)** latitudes:
  - "bump" in spectrum above 2 keV
  - harder spectrum at highest energies compared to low latitudes
  - cannot be characterized with a single κ
  - Magnitude of the globally distributed flux at high latitudes is uniform: fluxes not in the ribbon lie within a 10% standard deviation around an average at each energy passband

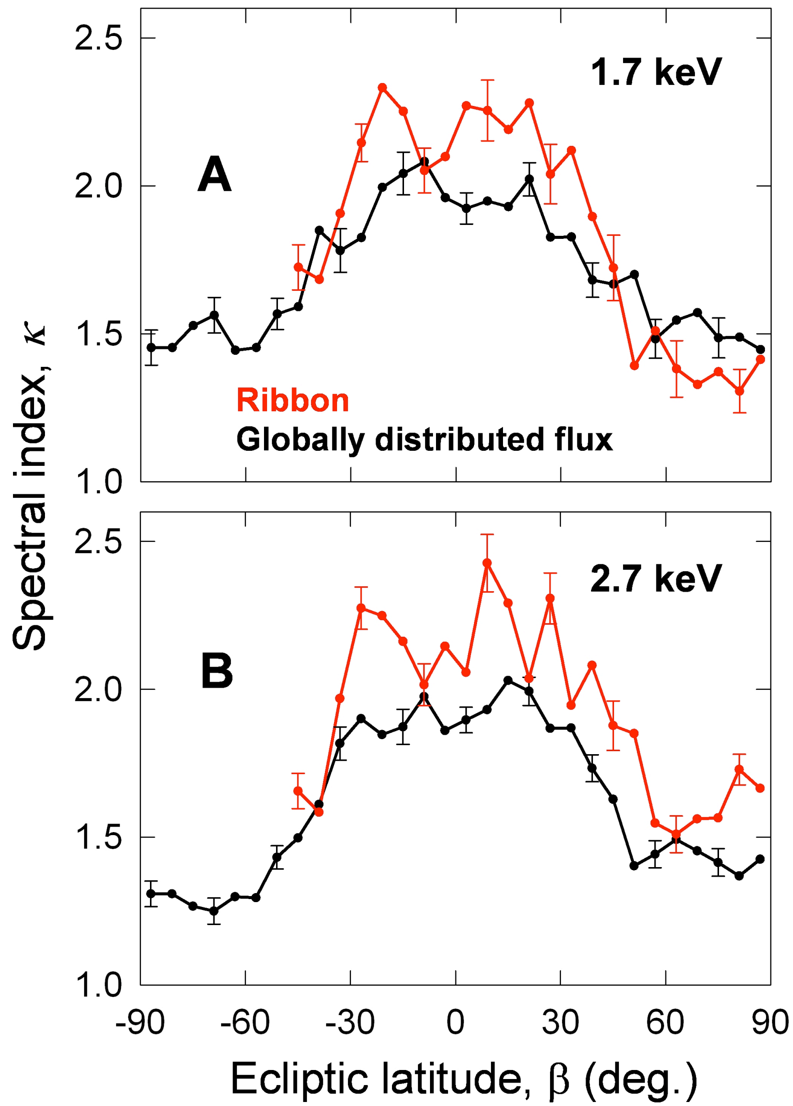
Fig. D: Nose and tail fluxes at low latitudes have different spectral slopes

- Spectra are from 20°x20° pixels centered on the nose (red) and tail (blue)
- fit over 9 energy passbands of IBEX.
- Error bars: counting statistics and systematic errors of +/-20% for IBEX-Hi and +/-30% for IBEX-Lo.



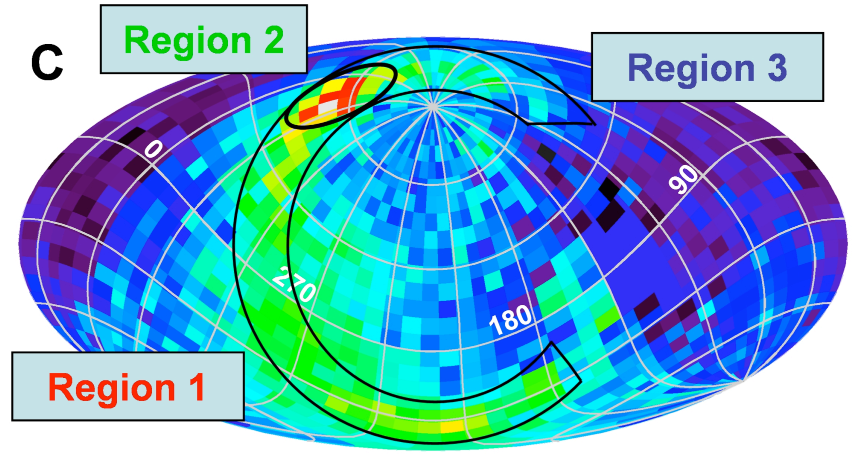
Spectral Index is Latitude Dependent

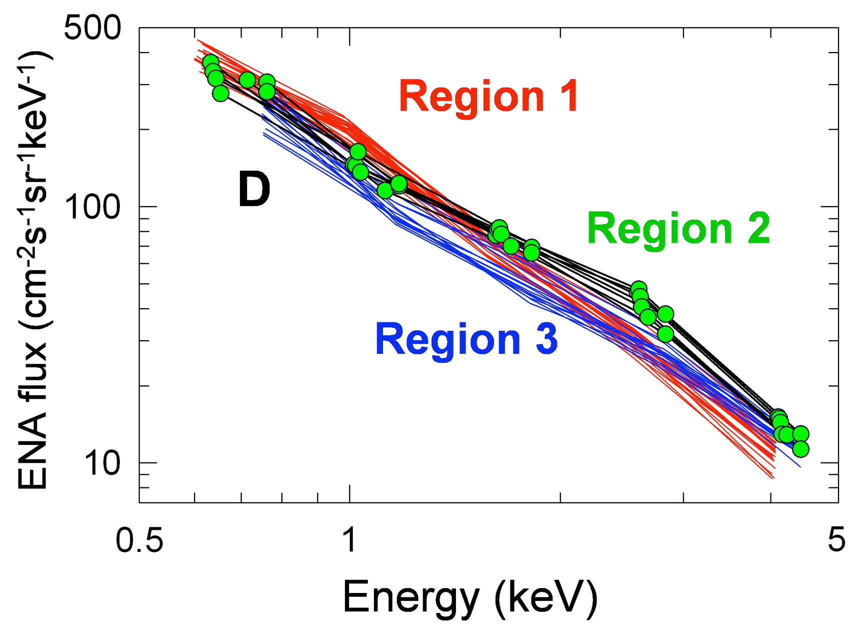
- Power law spectrum: Flux $\propto (E)^{-\kappa}$
- Average spectral index κ for the ribbon (red) and globally distributed flux outside the ribbon (black)
- Ribbon and globally distributed flux have similar κ:
  - **same type of plasma, with no additional dynamic processes associated with the ribbon**
- κ varies systematically with ecliptic (and therefore heliographic) latitude:
  - **plasma ordered by heliographic latitude**
  - **harder spectrum (lower κ) at high latitudes associated fast solar wind**
  - **softer spectrum (higher κ) at low latitudes associated slow solar wind**



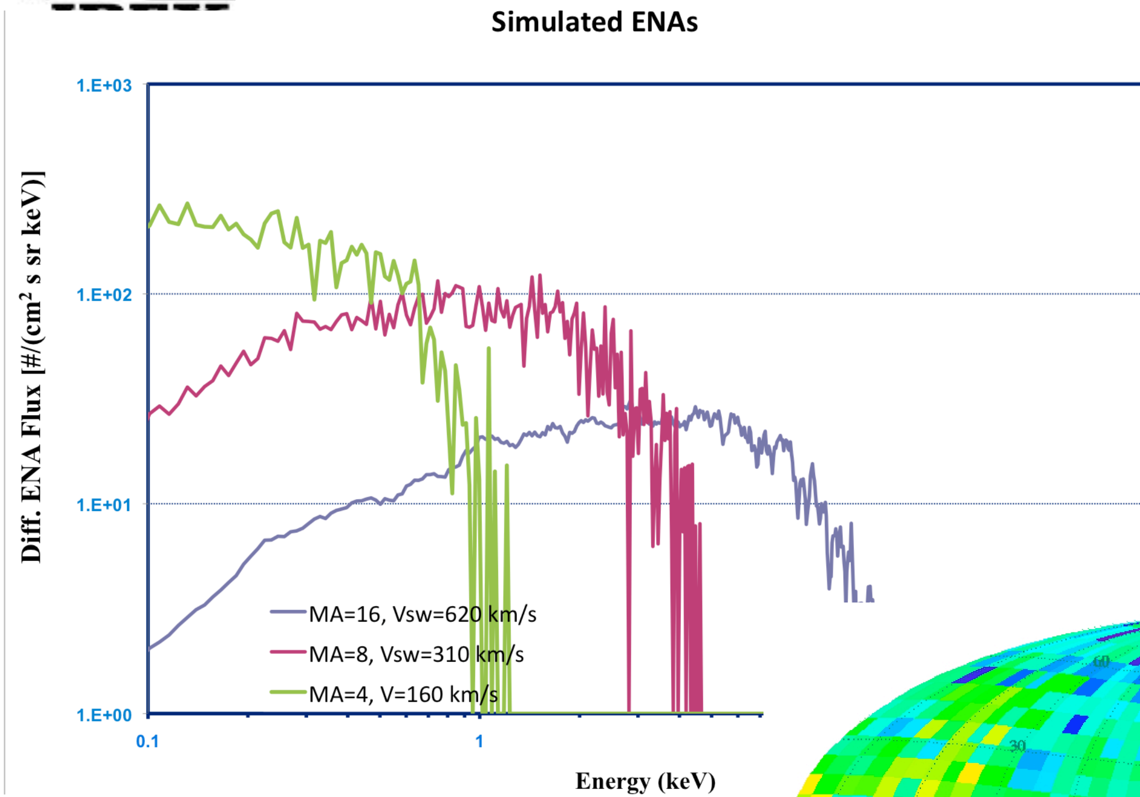
Interesting "knot" of emission in the ribbon

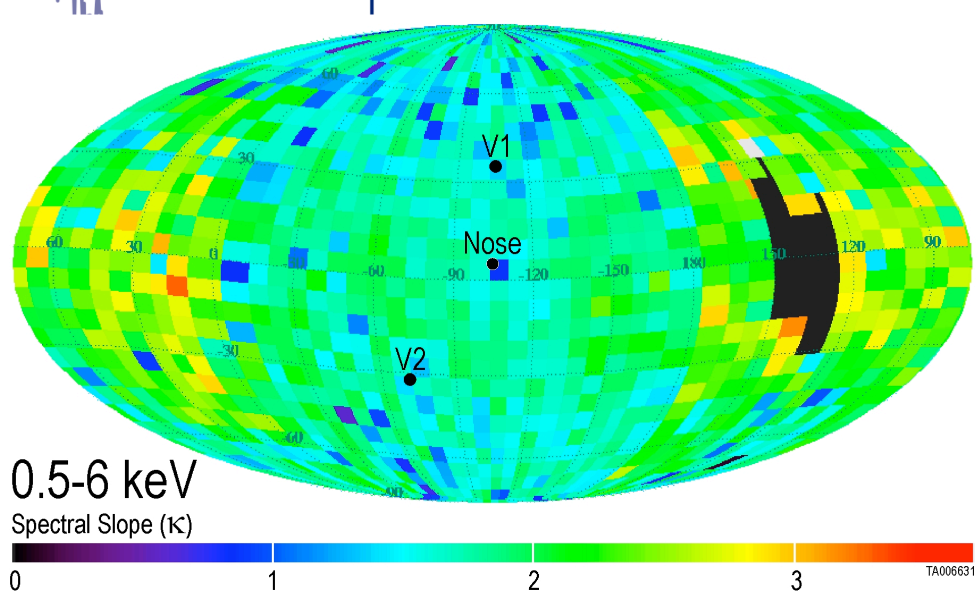
- 2.7 keV flux map, centered on ecliptic (λ, β)=(221°, 39°)
- Looks like the arc forms a circle; more on this later
- Ribbon has three distinct regions based on spectral shape:
  - Region 1: characteristic of low latitude spectra (smooth, generally characterized with a single κ)
  - Region 2:
    - highly variable flux over small spatial scales
    - spectral shape similar to high latitudes, but slope at highest energies is more characteristic of low latitudes.
  - Region 3: characteristic of high latitude spectra ("bump" above 2 keV, cannot be characterized with a single κ)





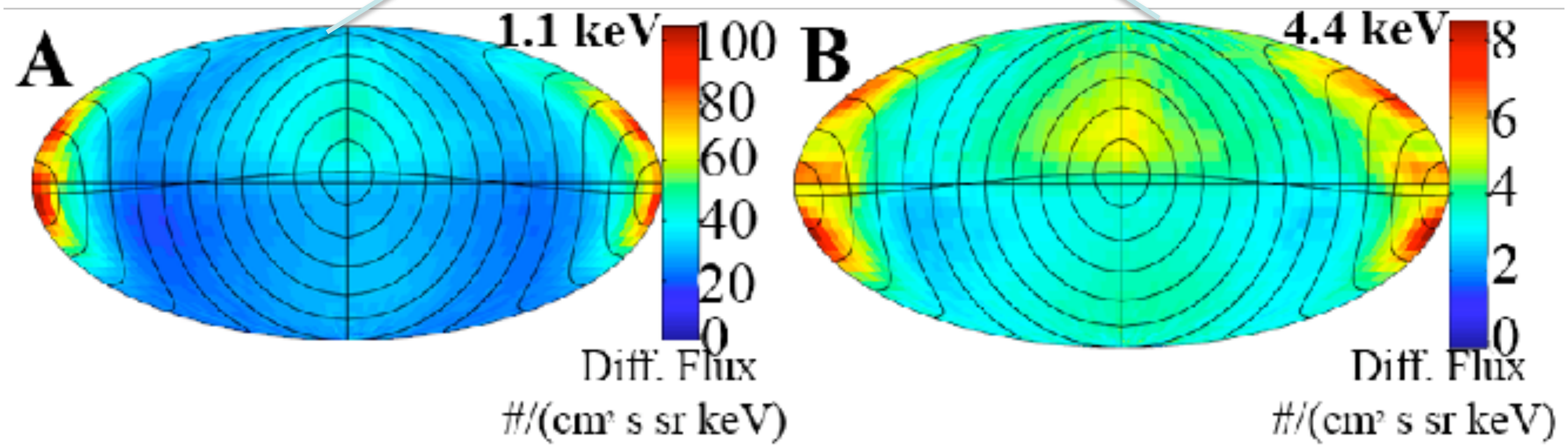
Spectral Slopes of ENAs





Model Predictions of ENA Maps

Pogorelov et al., *Astrophys. J. Lett.*, 2009:
MHD-neutral simulation with self-consistent kappa distribution



κ =1.6,
B_{LISM}=3 μG

Model-IBEX Comparison

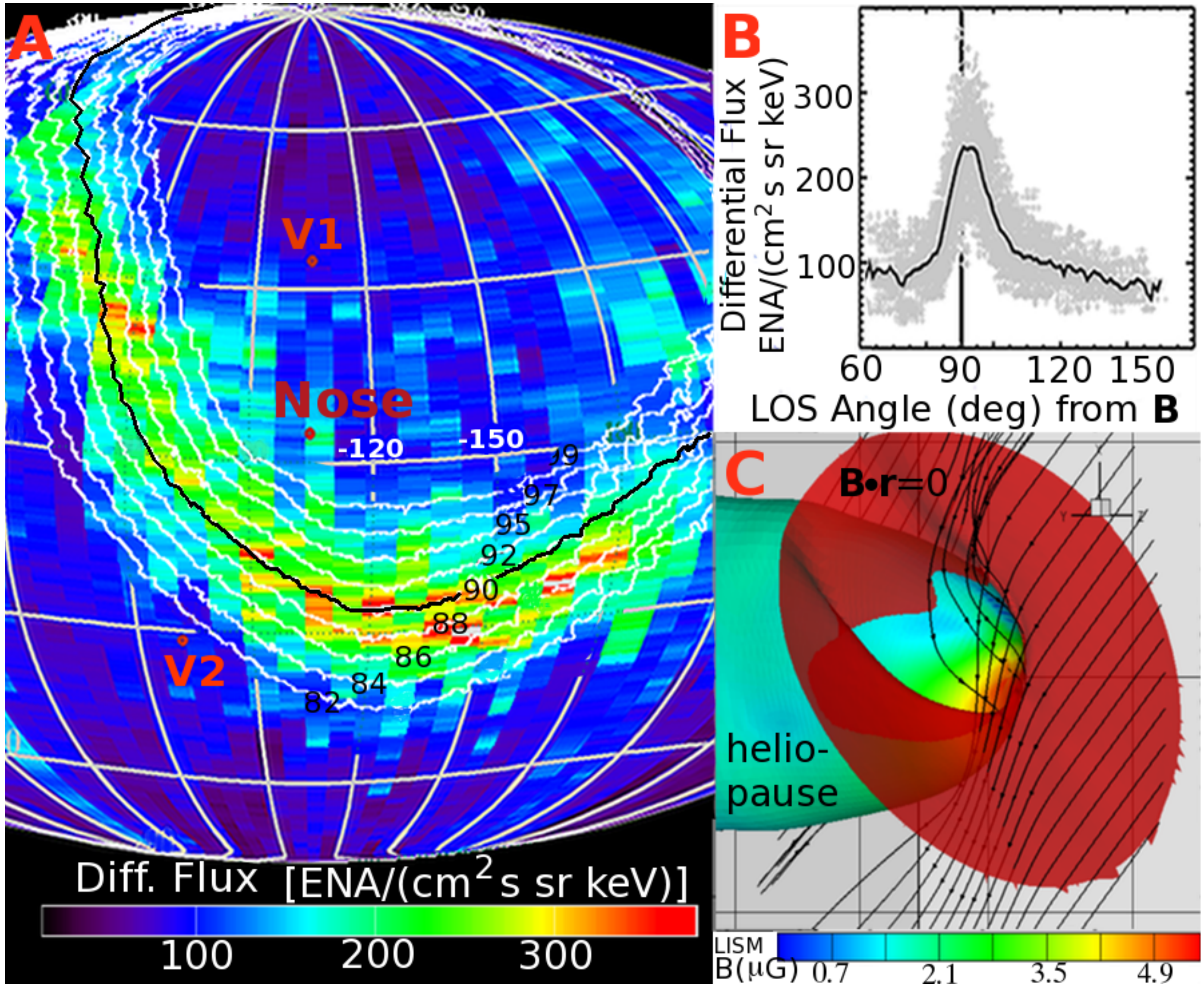
- Model 1:
  - Prested et al., *JGR.* **113**, 6102 (2008)
  - MHD Model (BATS-R-US)
  - Imposed Kappa Dist.
  - B_{LISM} =1.8 μG
  - κ =1.6
- Model 2:
  - Pogorelov et al., *ApJL.* **695**, 31 (2009).
  - MHD-Neutral Model
  - Self-consistent Kappa Dist.
  - B_{LISM} =3 μG
  - κ =1.6

Observed and simulated ENA Fluxes at 0.44, 1 and 4 keV, respectively.

Source	IBEX	Model 1 (3)	Model 2 (12)
	ENAs/(cm^2 s sr keV)	**ENAs/(cm^2 s sr keV)** *(% rel. to IBEX obs.)*	
Nose	**470** **96** **9**	230 *(49%)* 60 *(63%)* 6 *(67%)*	150 *(31%)* 43 *(45%)* 5.6 *(62%)*
Tail	**530** **120** **4**	30 *(6%)* 17 *(14%)* 4 *(100%)*	360 *(68%)* 100 *(83%)* 8 *(200%)*
North Pole	**410** **76** **9**	150 *(37%)* 45 *(59%)* 5 *(56%)*	110 *(28%)* 34 *(45%)* 4 *(48%)*
South Pole	**360** **70** **9**	130 *(36%)* 40 *(57%)* 5 *(56%)*	89 *(25%)* 30 *(43%)* 4 *(44%)*
Rt. Flank (Long. = -165°)	**230** **70** **6**	190 *(83%)* 50 *(71%)* 5 *(83%)*	110 *(48%)* 35 *(50%)* 4.3 *(72%)*
Lt. Flank (Long.= -45°)	**380** **86** **7**	170 *(45%)* 46 *(53%)* 5 *(71%)*	110 *(30%)* 33 *(38%)* 4.3 *(61%)*

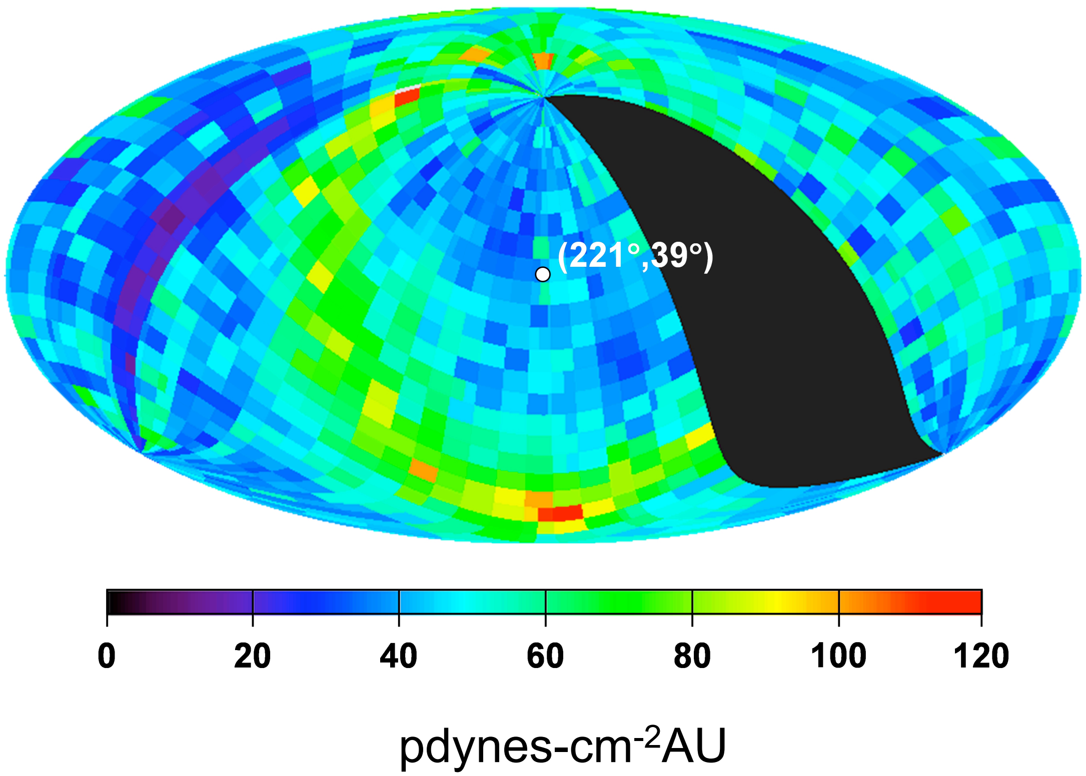
Ribbon Correlates with **B•r**=0

- A: 1.1 keV Map with contours **B•r** angle from Model 2 and the LOS over 10 AU outside heliopause
- B: Flux as function of LOS angle from **B**
- C: Global structure of heliopause and **B•r**=0 surface



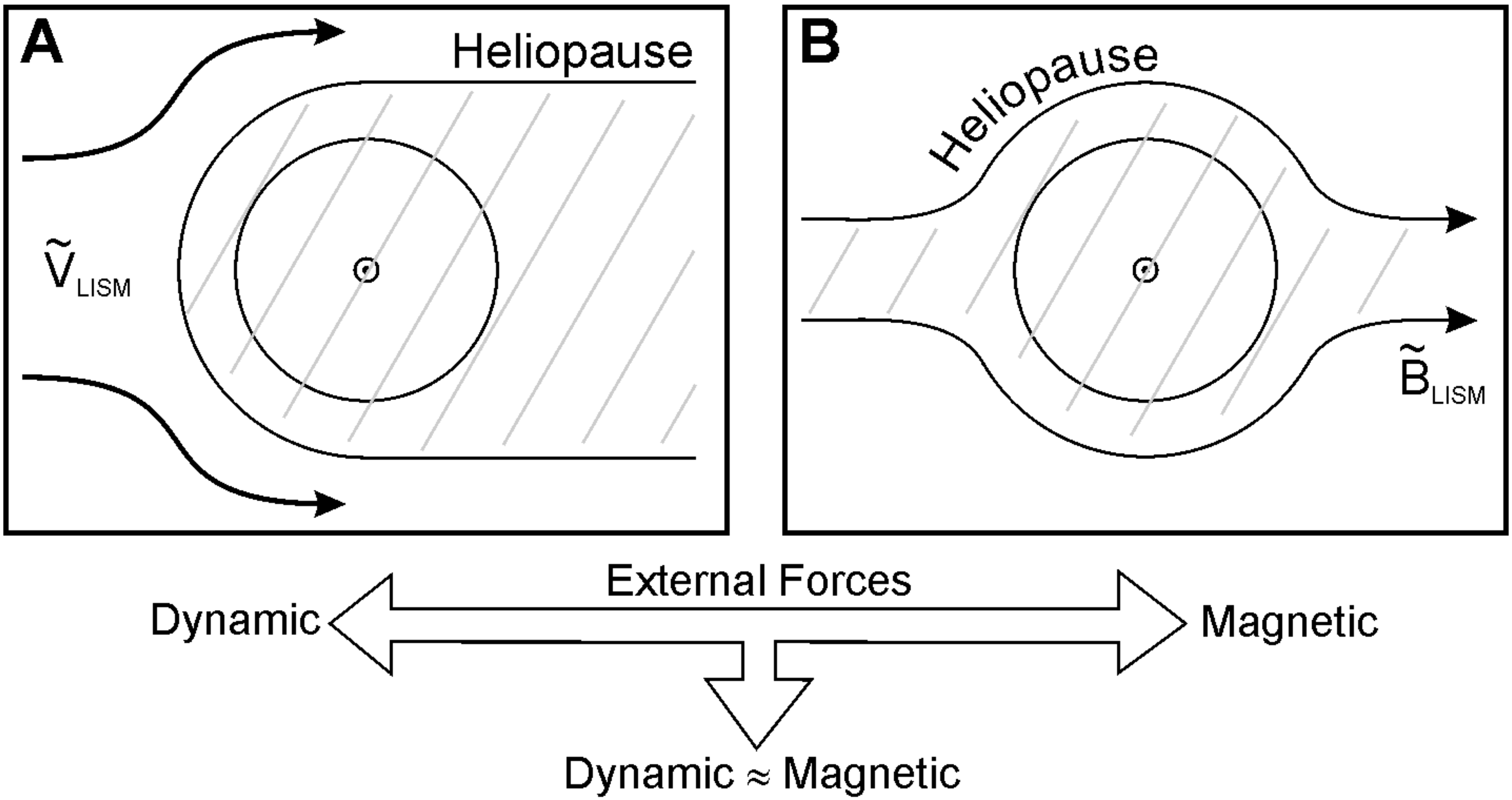
Ribbon: Arc of Higher Pressure?

- Map: *P*L*
  - *P* = ion pressure over 0.2-6 keV
  - *L* = thickness of emission region
- Ribbon pressure (~100 pdynes-cm^{-2}AU) is about 2x that of the globally distributed flux
- Forms a nearly perfect circle in the sky!
  - Centered at ecliptic (221^{o}, 39^{o})
  - High *P*L* arc lies ~72^{0} from center
  - Center is offset ~46^{0} from nose



LISM magnetic field likely aligned with direction of arc center at ecliptic (221^{o},39^{o})!

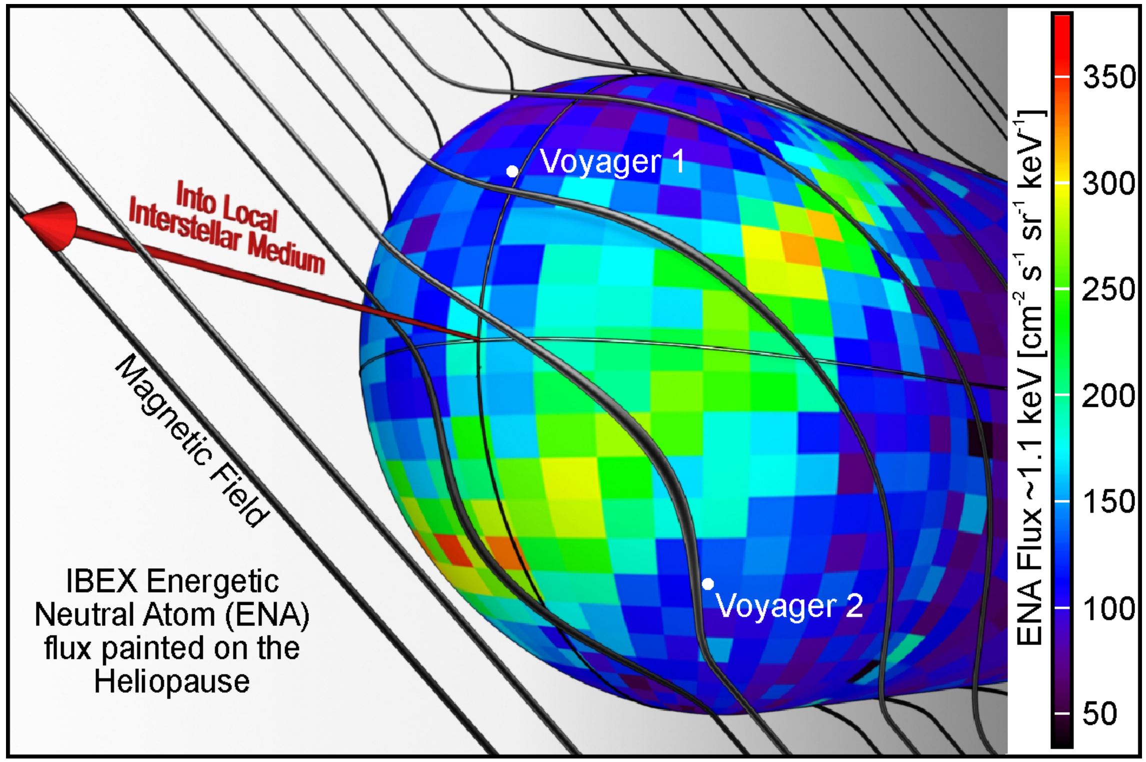
Parker [1961] Interactions



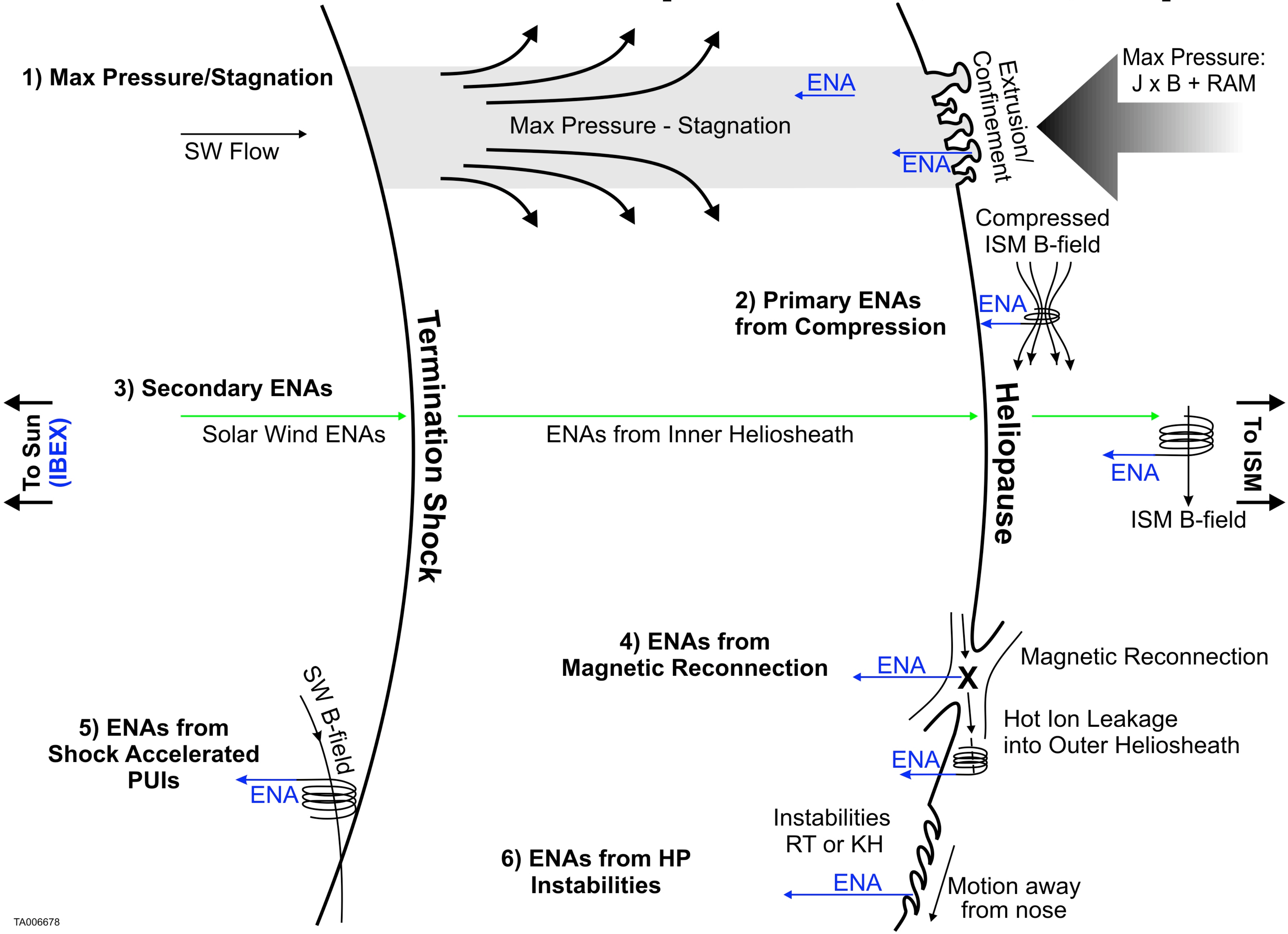
IBEX results indicate both external forces are important!

A New Paradigm

- Discovery of the ribbon
  - Not ordered by ecliptic coordinates
  - Not ordered by interstellar flow
- Requires reconsideration of our fundamental concepts of interaction
- Possible explanation could be based on LISM B-field playing central role
- External field wraps around and compresses the heliopause
- Ribbon closely matches locations where a model external field just outside the heliopause, the field is transverse to IBEX's radial-viewing LOSs

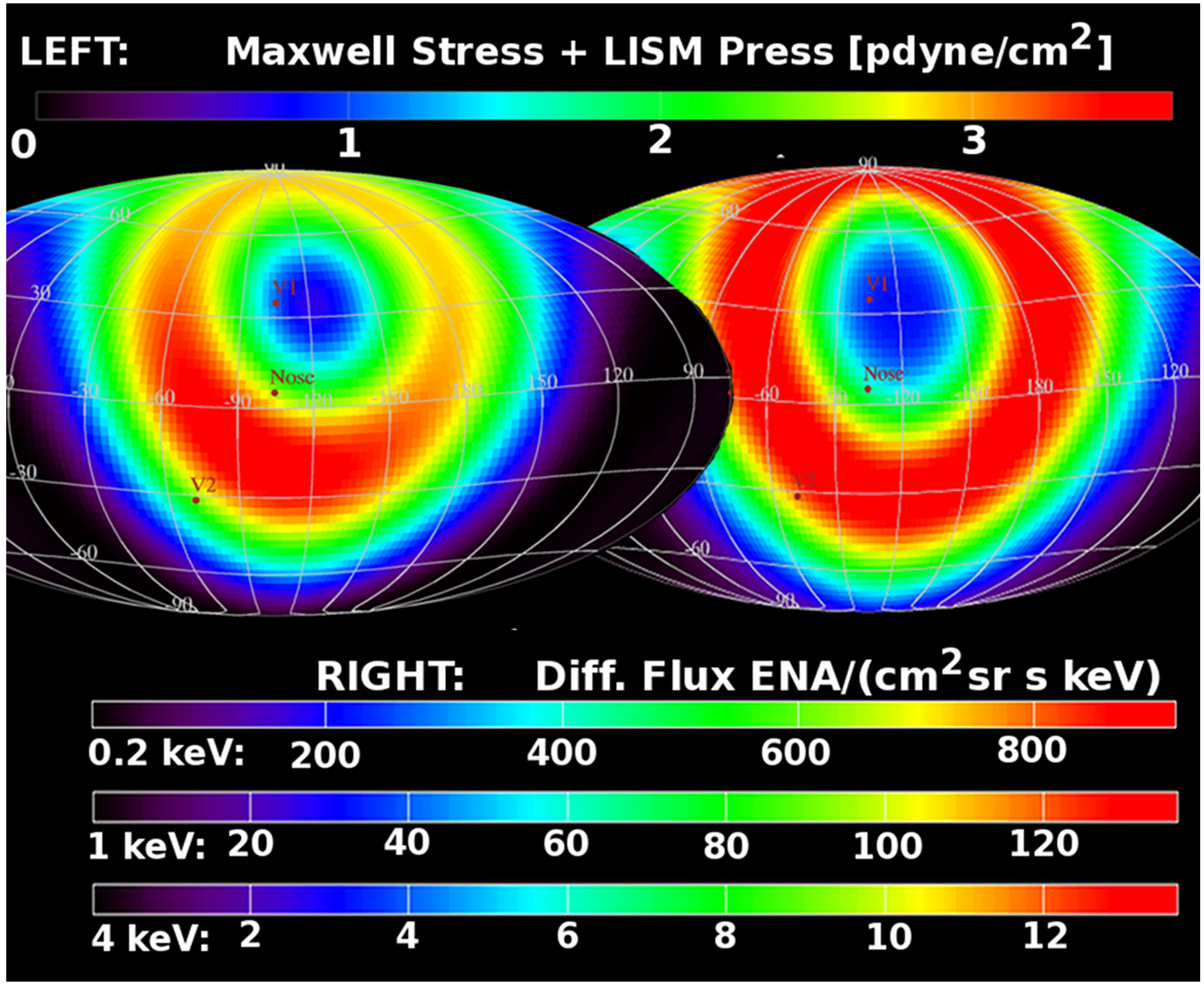


Possible Sources of IBEX Ribbon [McComas et al., *Science*, 2009]



What could cause the Ribbon?!

- **Left:** Force-per-unit Area from **JxB** and LISM ram pressure (B_{LISM}=2.5 μG)
- **Right:** Field draping around heliosheath compresses plasma and leads to enhanced ENA emission
  - Need an enhanced suprathermal population in outer heliosheath
  - Possible source from neutrals created in the supersonic solar wind



Ideas about Source of Ribbon 1/3

- External plasma dynamic and magnetic (**J**x**B**) forces → a localized band of maximum total pressure around HP
- Enhanced pressure at HP propagates throughout the inner heliosheath, adjusting the plasma properties and bulk flow
- Ribbon might indicate the true region of highest pressure in the inner heliosheath. → stagnation flow region
  - Ribbon would divide flows, analogous to a continental divide
  - Potentially explains why flows at the Voyager locations appear to be more directed away from the ribbon than from the nose.
  - Radial outflow → zero and plasma density maximizes, producing copious ENAs that naturally map the region of maximum pressure
  - Additional pressure might also extrude region of HP forming limited outward bulges with high density and little bulk flow
  - Consistent with fact that Ribbon has a similar spectral slope as the surrounding regions, suggesting that this feature is not dominated by dynamical effects (e.g., different energization processes at the TS or elsewhere) but simply reflects the accumulation of particles

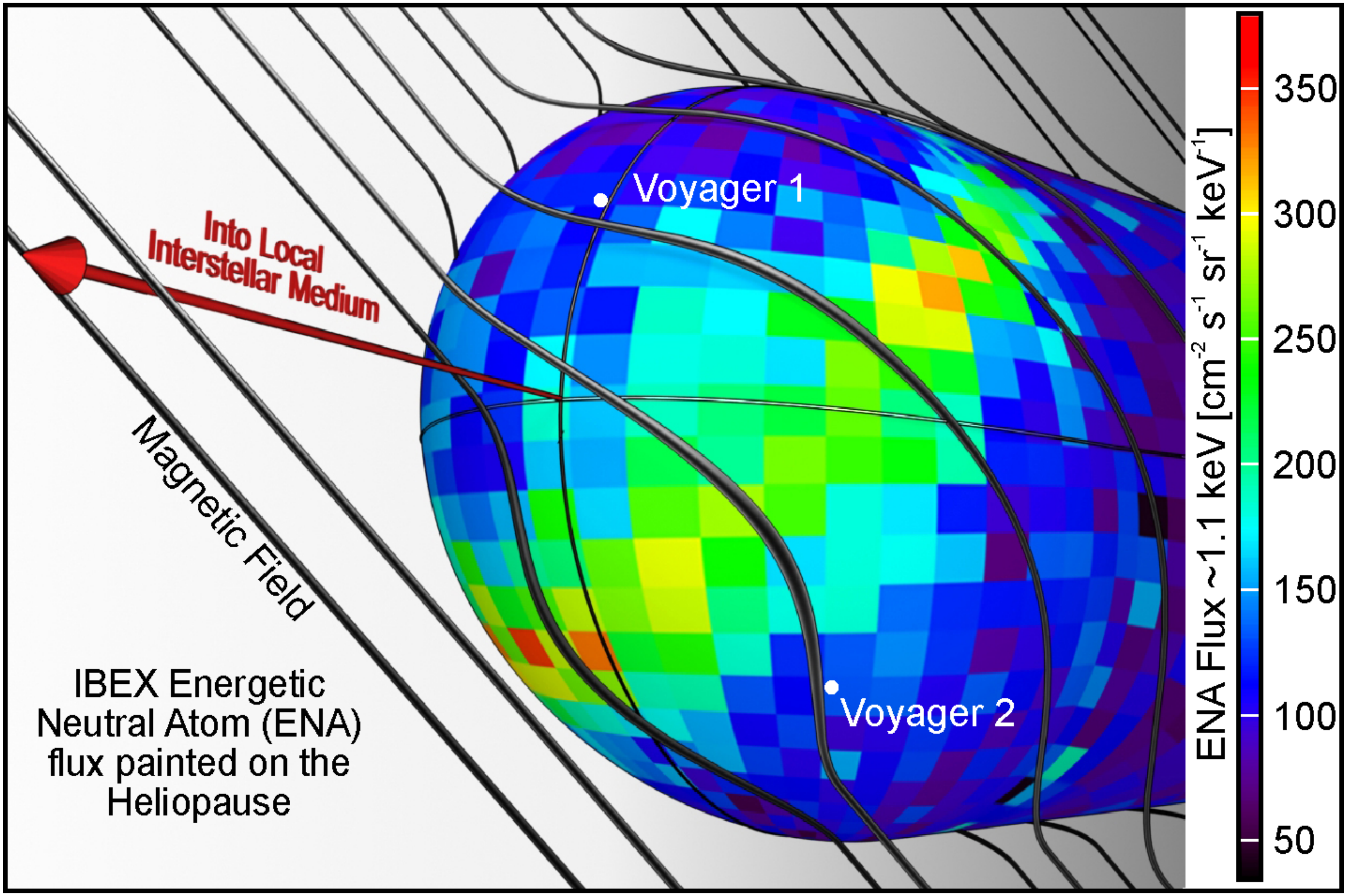
Ideas about Source of Ribbon 2/3

- Large-scale, Rayleigh-Taylor-like instabilities might trap hot, inner-heliosheath plasma in narrow structures
  - Can be driven by neutrals destabilizing the HP
  - Some models show large, semi-coherent structures with higher ion densities and sizes >10s of AU, moving tailward
- Magnetic reconnection across the HP would also allow suprathermal heliosheath ions out into the cooler, denser outer heliosheath, potentially confined in narrow structures
- ENAs might come from outside HP
  - Compression of the external field would enhance densities and provide perpendicular heating → ENAs where BdotR=0
  - ENAs from inner heliosheath/SW reionize in outer heliosheath
  - Producing a strong, narrow feature requires ions reneutralize before significant scattering occurs
- ENAs might somehow be coming from inside the TS
  - Perhaps from shock-accelerated PUIs propagating inward through the region where the solar wind decelerates just inside TS

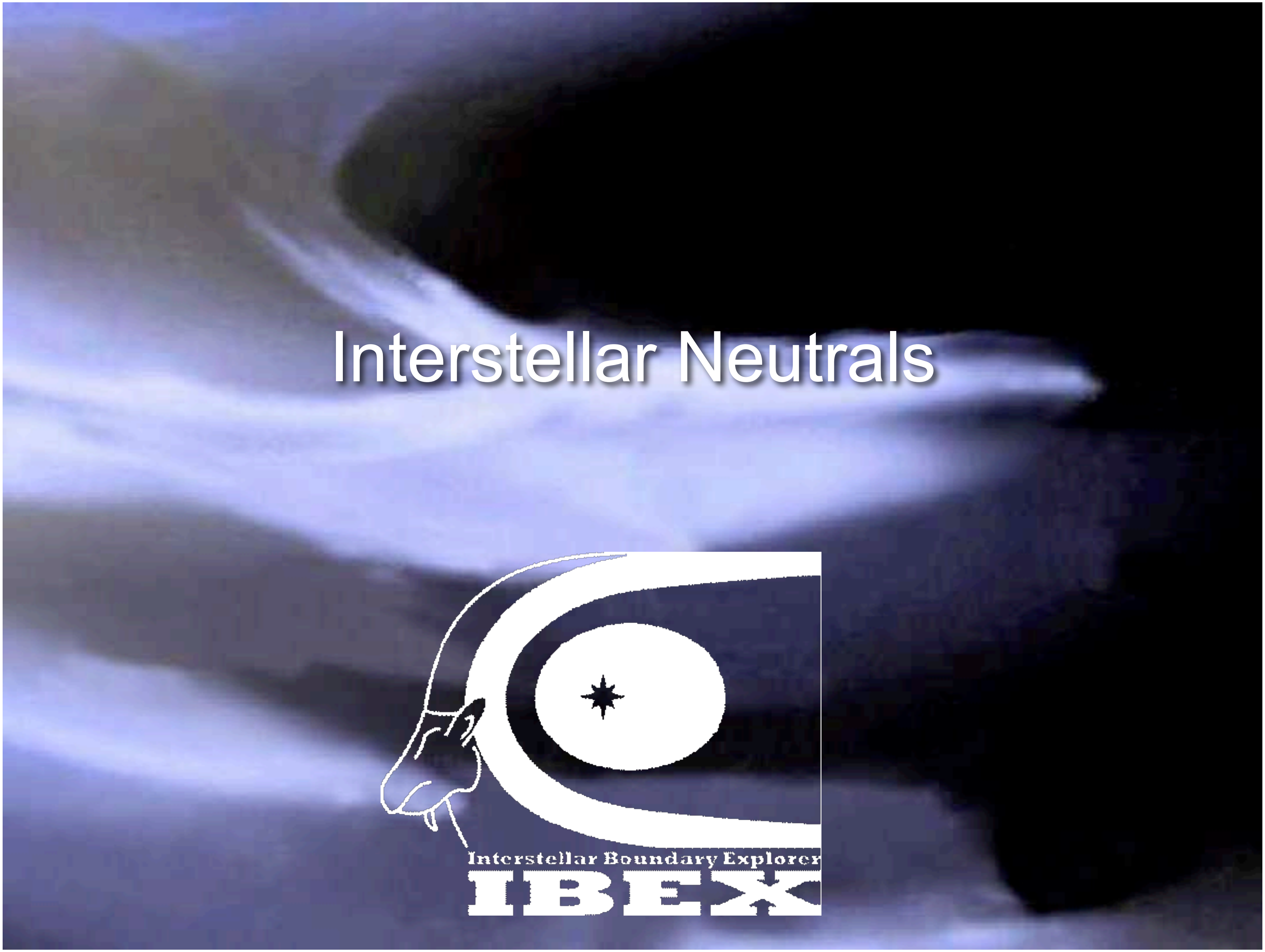
Ideas about Source of Ribbon 3/3

- Brightest regions of ribbon at mid/high latitudes
  – Slow and fast solar winds interact in CIRs
  – Ribbon missions at least partially related to the solar wind properties as well as to the external environment
- Ribbon appears continuous but could be string of localized, overlapping “knots” of emission
- Other ideas need to be developed/examined
- While IBEX data support some earlier ideas, in other areas a completely new paradigm is needed for understanding the interaction between our heliosphere and the galactic environment.

The View with IBEX - 2009



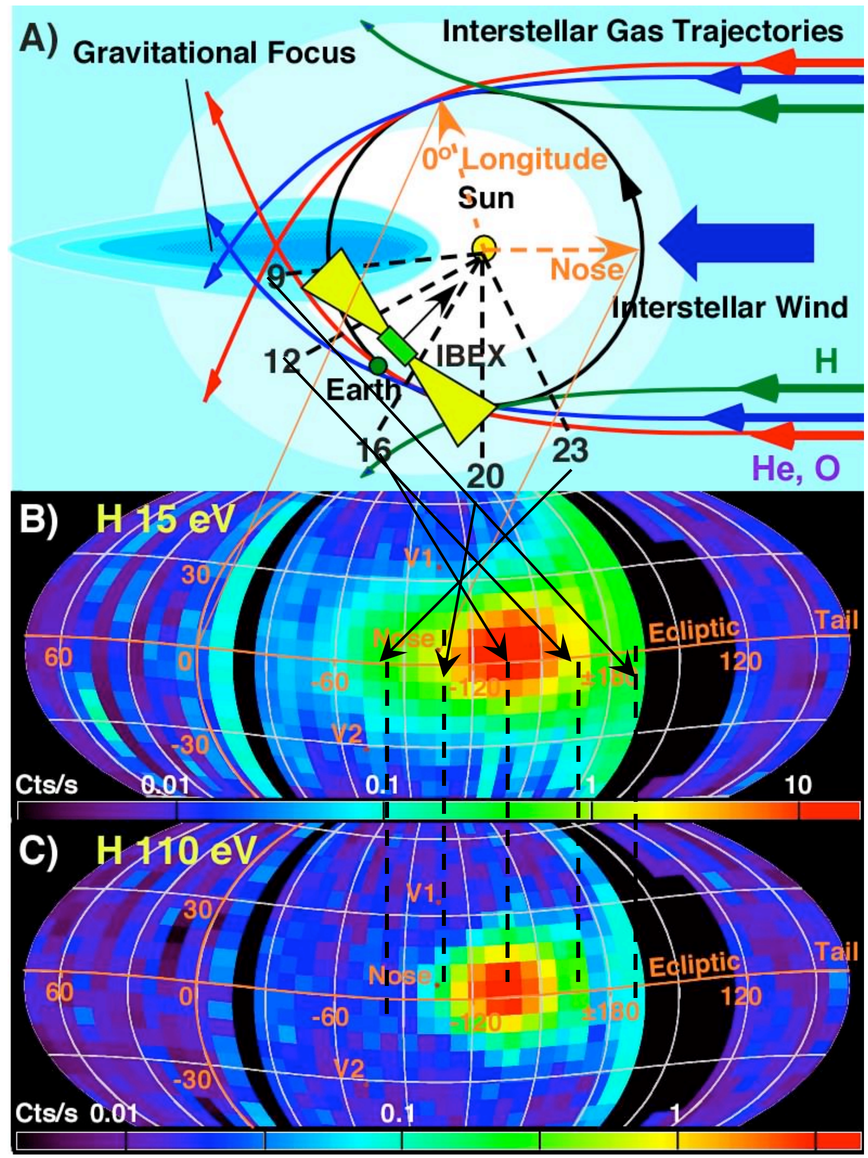
Interstellar Neutrals



Interstellar Boundary Explorer
IBEX

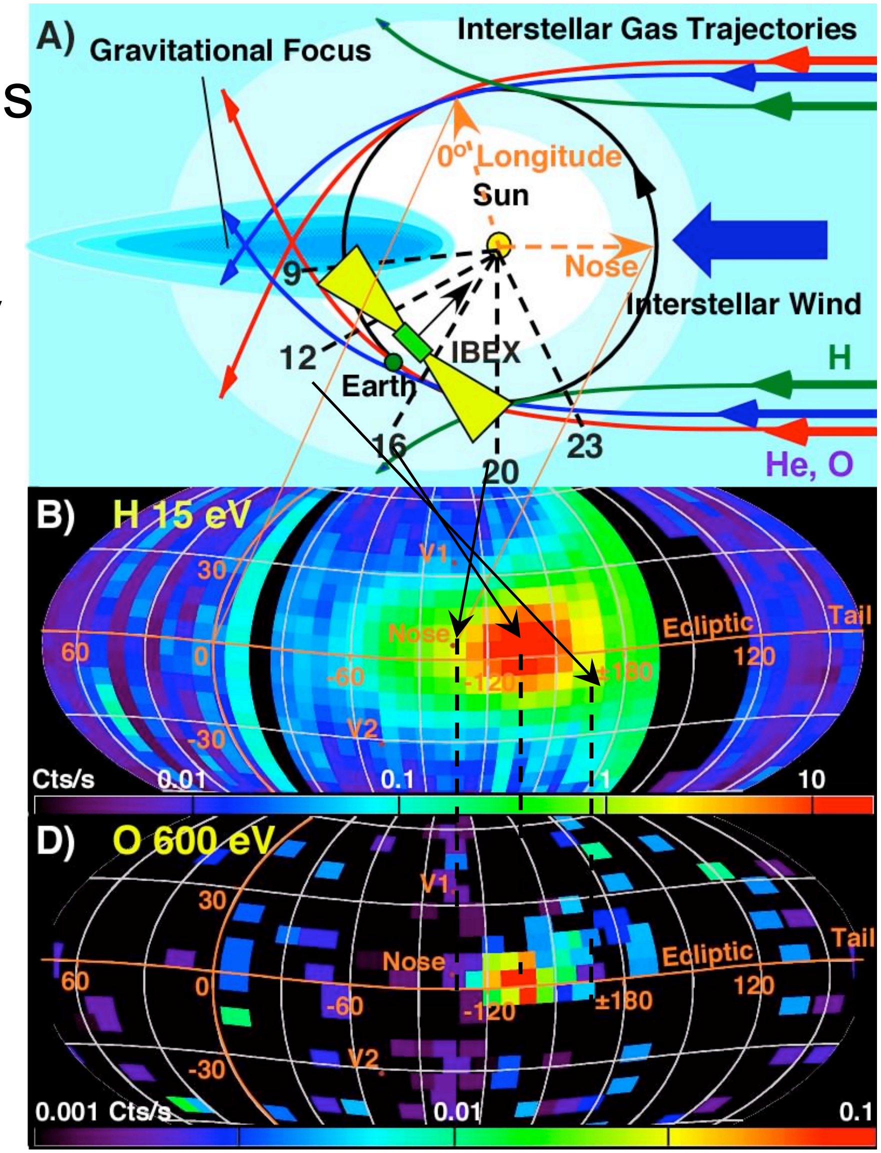
LISM Gas Flow in IBEX-Lo Maps

- Interstellar Gas flow clearly visible in IBEX-Lo Maps
  Orbit 9 – 28 at 15 eV
  Orbit 9 – 21 up to 110 eV
- Flow peak seen in Orbit 16 from positive latitude
- - Flow at 15 eV up to Orbit 28
  consistent with LISM H
  - Up to 110 eV in Orbit 9-21
  consistent with LISM He



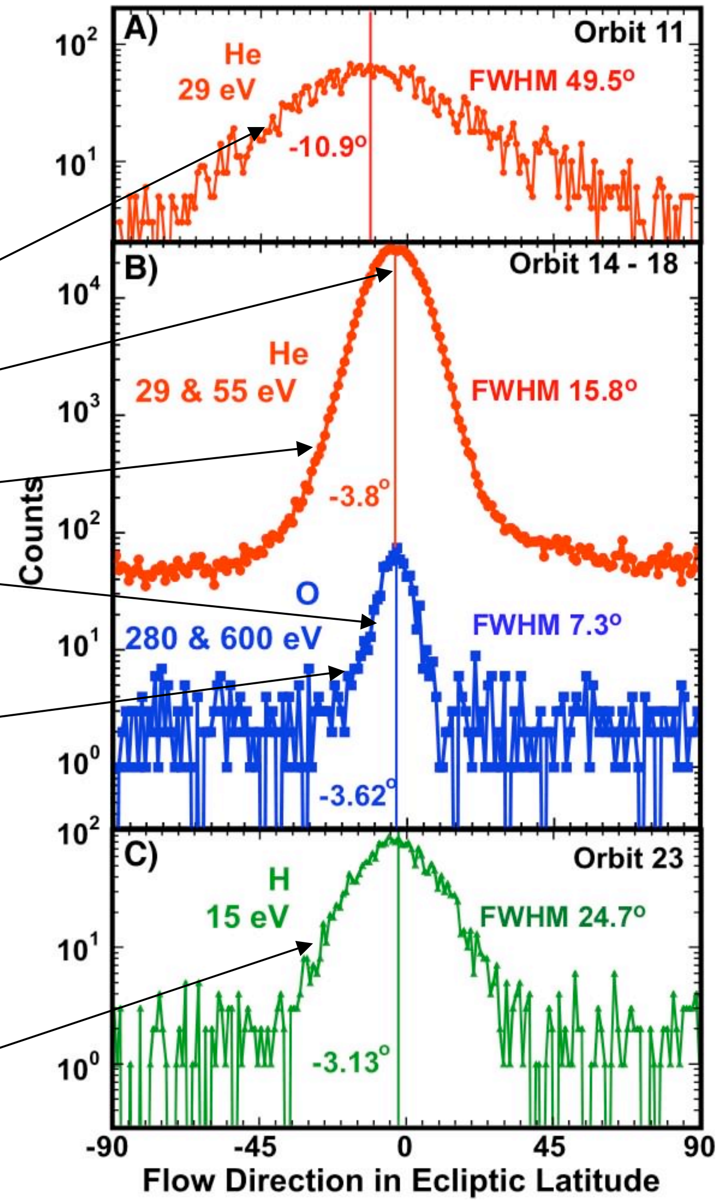
LISM Gas Flow in IBEX-Lo Maps

- Interstellar Gas flow
  clearly visible in IBEX-Lo Maps
  Orbit 9 – 28 at 15 eV
  Orbit 9 – 21 up to 110 eV
  Orbit 14 – 18 at 280 & 600 eV
- Flow peak seen in Orbit 16 from positive latitude
- - Flow at 15 eV up to Orbit 28 consistent with LISM H
  - Up to 110 eV in Orbit 9-21 consistent with LISM He
  - At 280 & 600 eV in Orbit 14-18 consistent with LISM O extension to higher latitude and smaller longitude



LISM Flow Latitude Distributions

- IBEX spin produces latitudinal angular distributions
- Very wide angular distribution in Orbits 9-11 in Focusing Cone
- LISM Flow points into negative latitude as observed previously
- Width of He ≈ 2x that of O Flow consistent with same Temperature
- O distribution asymmetric towards negative latitude
  Substantial excess in Counts!
  Consistent with Lyα Asymmetry!
- H distribution wider, but strongly affected by radiation pressure



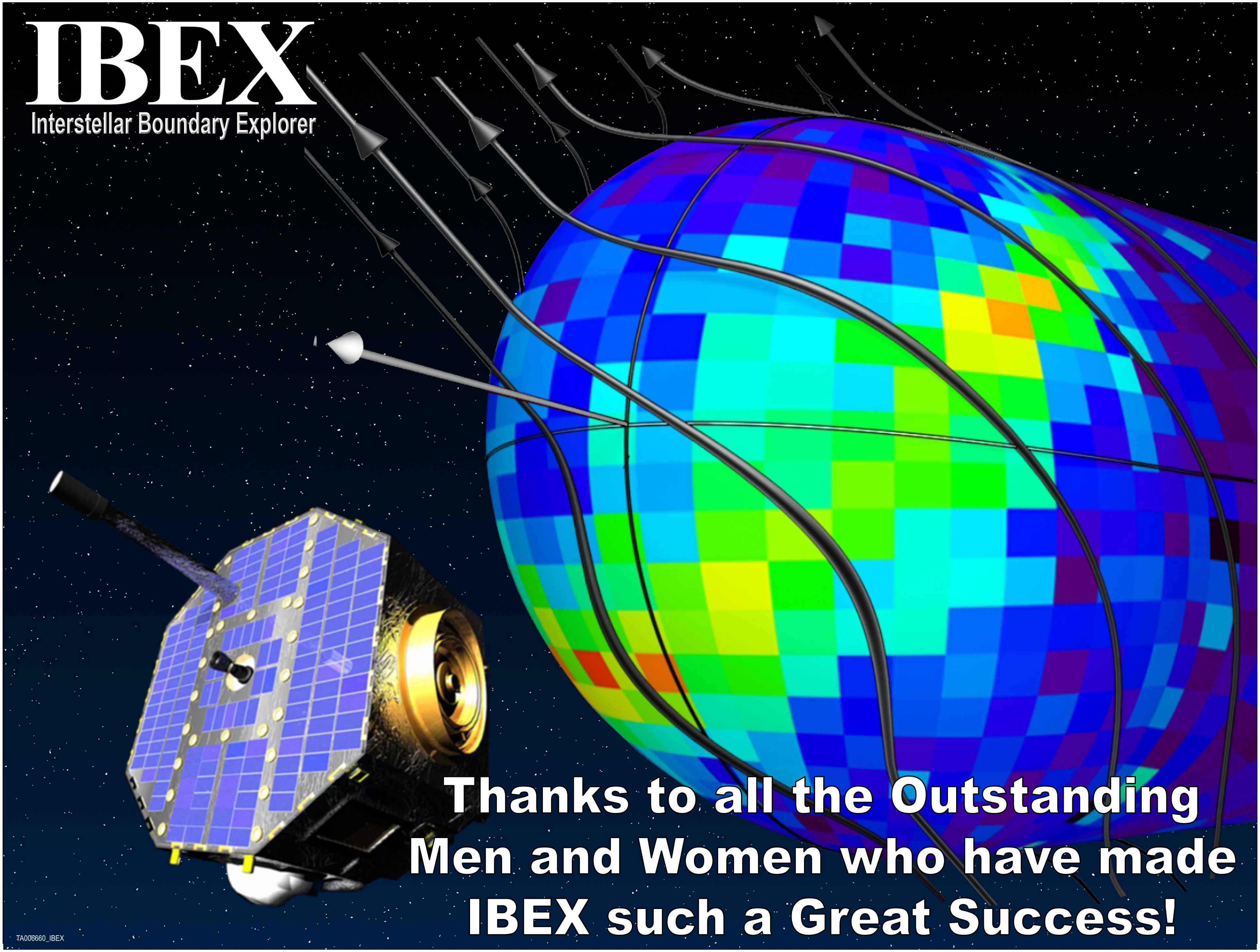
Concluding Remarks

Interstellar Boundary Explorer

IBEX

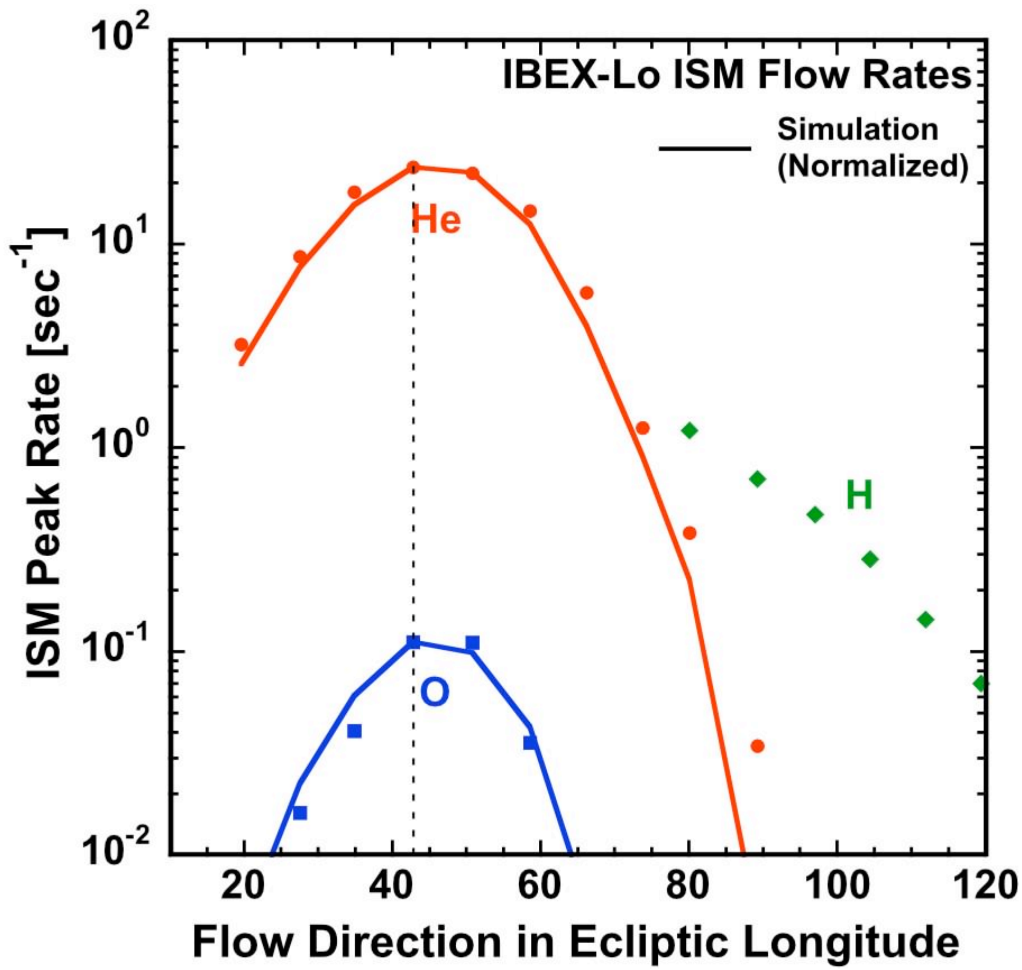
IBEX

- IBEX is a remarkable mission of Discovery and Exploration
- IBEX has provided the first ever sky maps of ENAs from ~200eV - ~6keV
- Discovery of Ribbon of ENA emission snaking between directions of Voyagers and apparently ordered by external magnetic field in LISM
- First direct measurements of Interstellar H, O
- IBEX observations leading development of new paradigm for heliosphere/interstellar interaction
- Second set of sky maps currently underway – so much more discovery science to come!!!


IBEX
Interstellar Boundary Explorer
Thanks to all the Outstanding Men and Women who have made IBEX such a Great Success!
TA006660_IBEX

Ecliptic Longitude Distribution

- He and O peak flow rates in ecliptic longitude compared with simulated rates (Bzowski et al. 2009) for
  V_{He} = 26.3 km/s
  T_{He} = 6300 K (Witte 2004)
  (normalized to peak)
- He and O consistent with the same LISM parameters
- H at greater longitude
  ⟹ Points to strong radiation pressure effects



- Ionization & Radiation Pressure Solar Cycle Dependent

Interstellar Neutrals - Summary

- IBEX observed Neutral H, He, and O at 1 AU
  Neutral H and O being observed for the first time
- Flow direction in latitude is consistent with earlier observations
- Width of the angular flow distributions of He and O
  is consistent with the same temperature in the LISM
- H distribution points to strong radiation pressure effects
- The O flow distribution in latitude shows an asymmetry towards negative latitude and a visible foot in the map view
- Simultaneous observations of H, He, and O allow determination of LISM filtering and deflection in the outer heliosphere.
- Detailed LISM flow study planned in spring 2010
  using high angular resolution and full duty cycle of IBEX-Lo

LISM Flow Species Determination

- Each Neutral Atom species
  produces characteristic C+O/H ratios
  on the IBEX-Lo Neutral-to-Ion Conversion Surface
  as established in sensor calibrations
- Observation at 15-110 eV up to Orbit 19 agrees with He
- Observation at 600 eV in Orbits 16-18 agrees with O
- Observations at 15 eV starting Orbit 23 agrees with H

Table 1: Observed Species Branching Ratios

	E(eV)	%C+O	E(eV)	%C+O	E(eV)	%C+O	E(eV)	%C+O
Orbit 10-11	15	7	29	6	55	8	110	14
Orbit 13-19	15	14	29	18	55	16	110	11
110-135 eV He	*15*	*11-14*	*29*	*13-20*	*55*	*11-19*	*110*	*8-13*
Orbit 23	15	1			Orbit 16-18		600	100
15-29 eV H	*15*	*0-1*			*600 eV O*		*600*	*99*