Charge-Exchange Between Monte-Carlo Neutrals and MHD Plasma Applied to the Heliosphere

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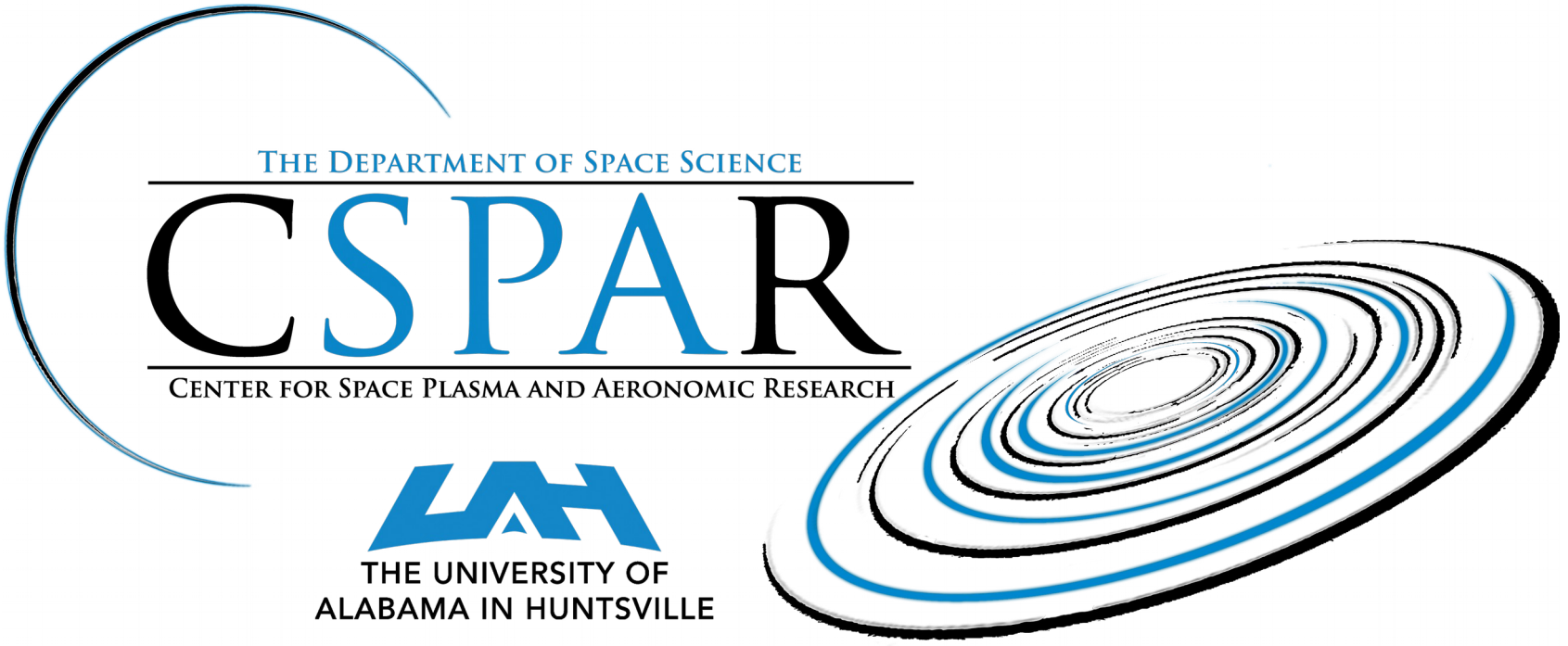

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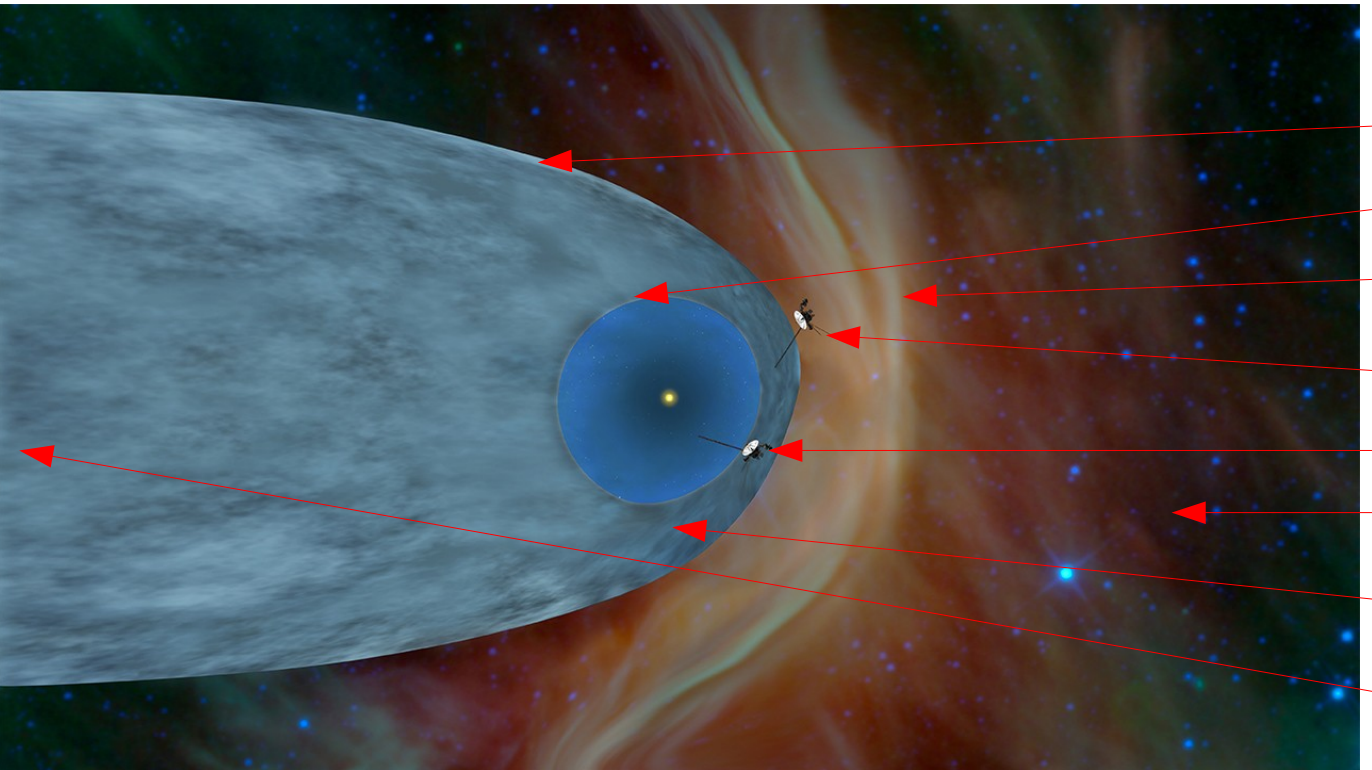
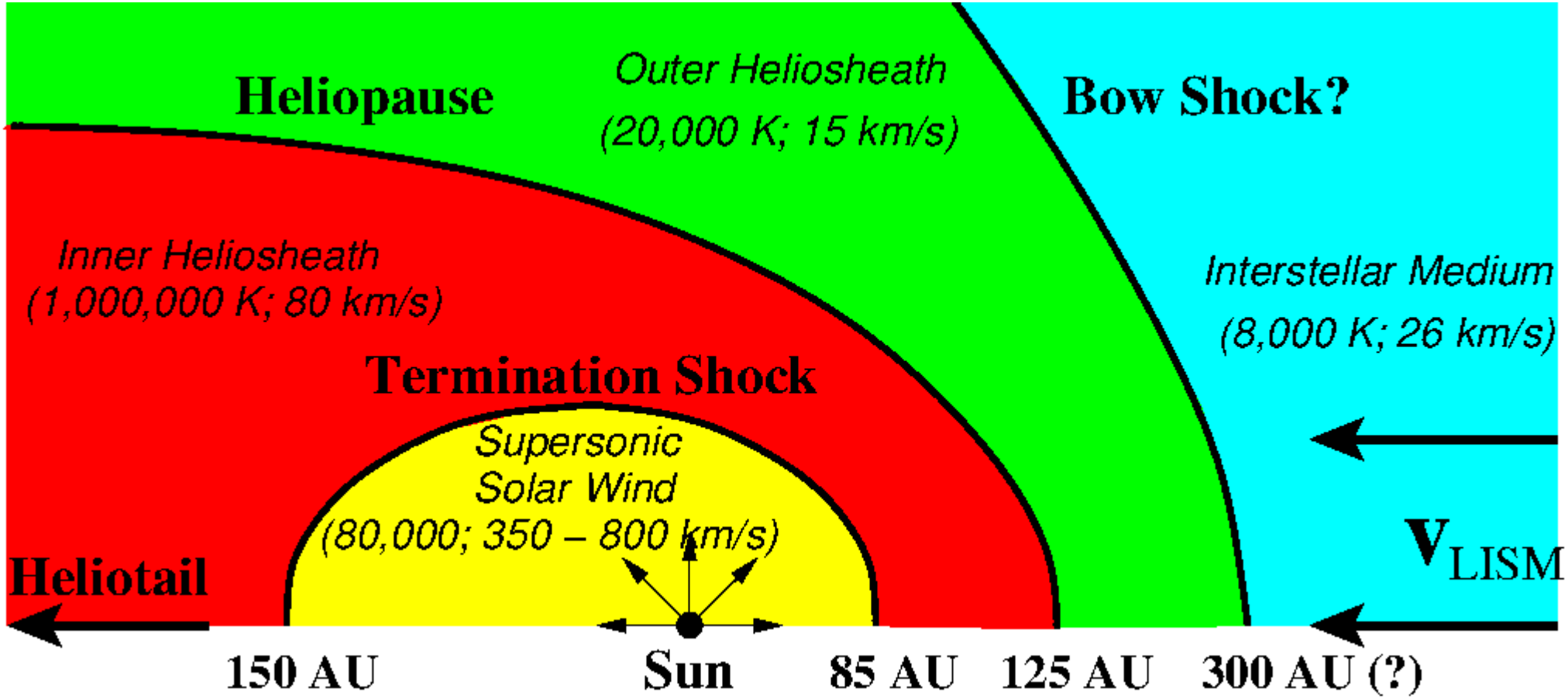
The Heliosphere

- The heliosphere forms out of the collision between two plasma flows – the solar wind (SW) and the nearby plasma of the galaxy known as the local interstellar medium (LISM).
- The two plasma flows don't mix, but are instead separated by a tangential discontinuity known as the heliopause.
- The motion of the Sun through the LISM creates a tail of SW plasma that can stretch thousands of astronomical units (AU).

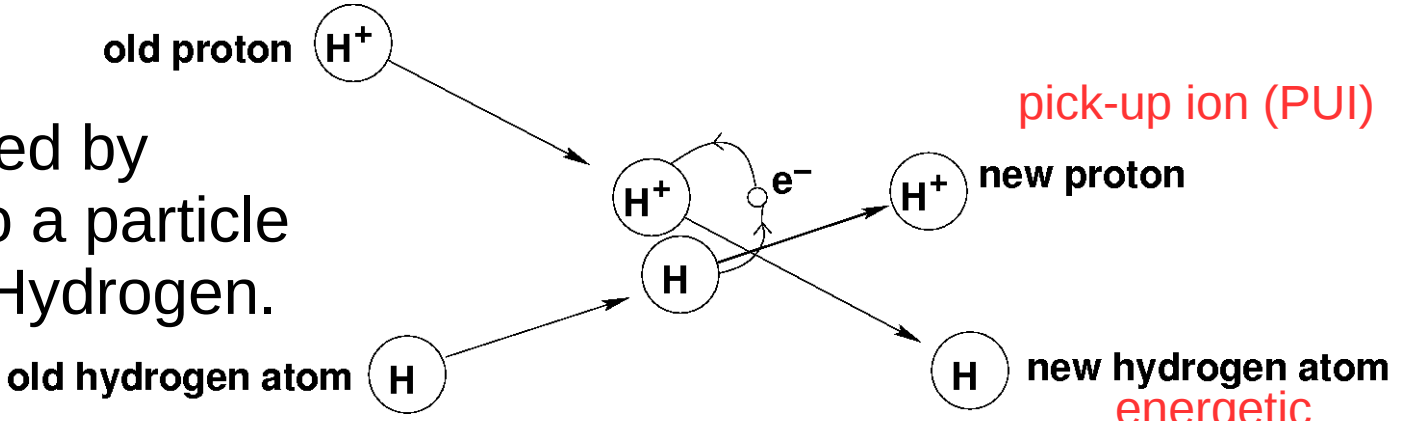


Properties of the SW-LISM Interaction

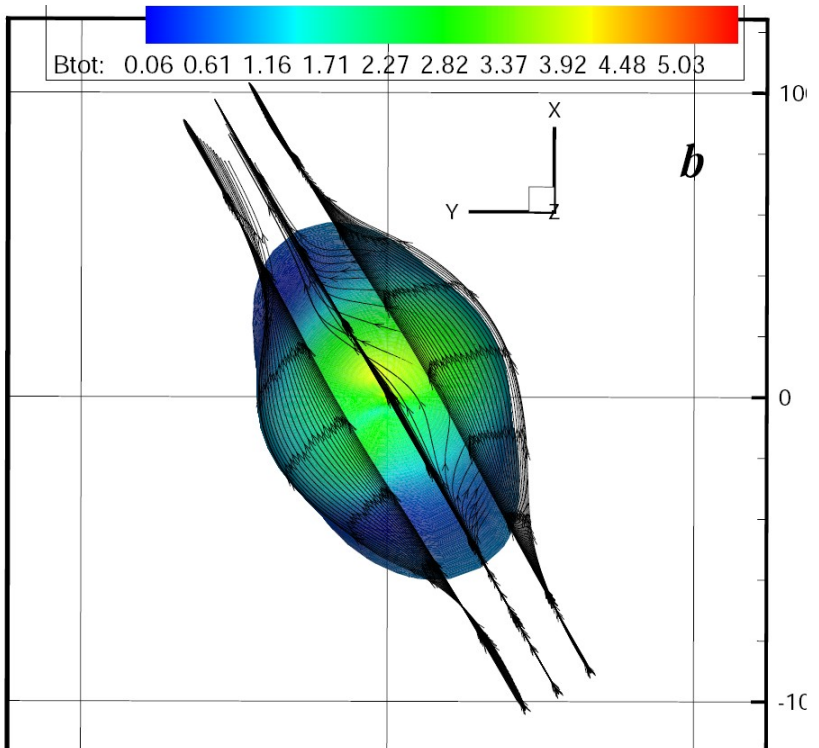
- Local Interstellar Medium: partially ionized – $n_p \sim 0.07$, $n_H \sim 0.2$ cm^{-3}
- Neutrals move on ballistic trajectories – can cross heliopause
- Charge-exchange couples ions & neutrals, all other collisions are ignored.
- Neutrals have large mean-free-paths (~100 AU) → non-symmetric distribution functions – energetic neutral atoms (ENAs)



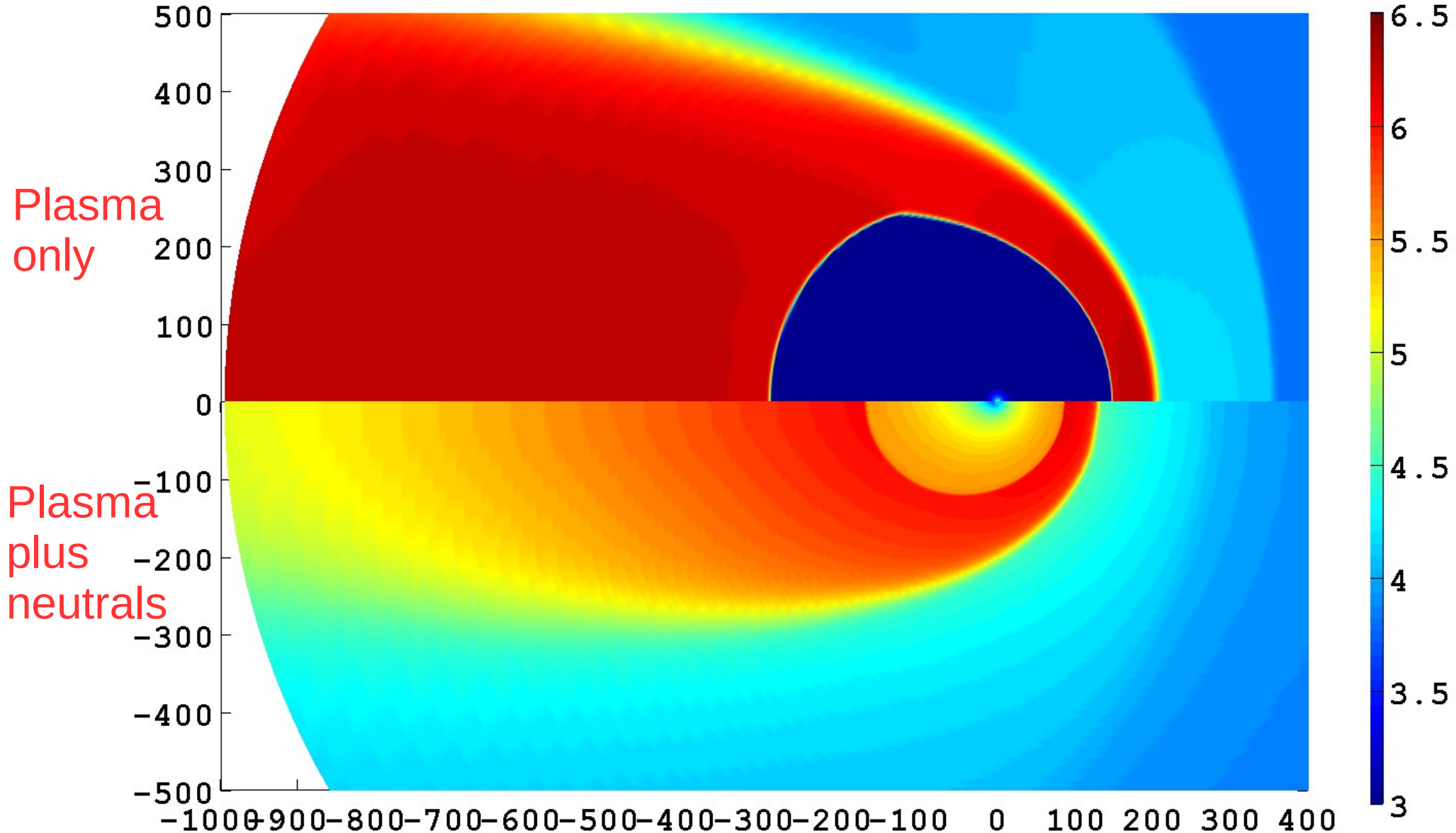
Modeling the SW-LISM Interaction



- MHD for ions coupled by charge-exchange to a particle module for neutral Hydrogen.
- Every time a ch-ex occurs in the particle code, changes in energy & momentum are added to a grid of source terms to be passed to the MHD module. Ions & neutrals are iterated (often to a steady-state).
- Non-thermal ions – i.e. pick-up ions (PUIs) – are approximated by using a "kappa" distribution for all supersonic & subsonic SW plasma.
- Presence of LISM magnetic field warps the heliopause and introduces a full 3D structure.

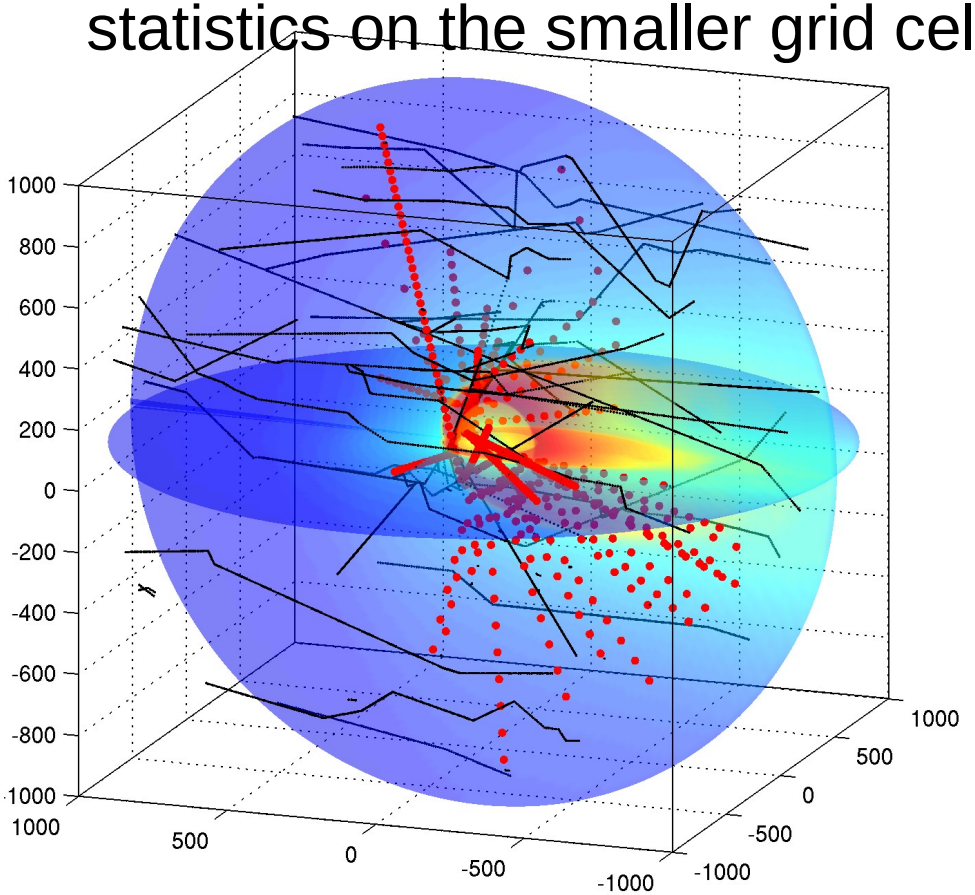


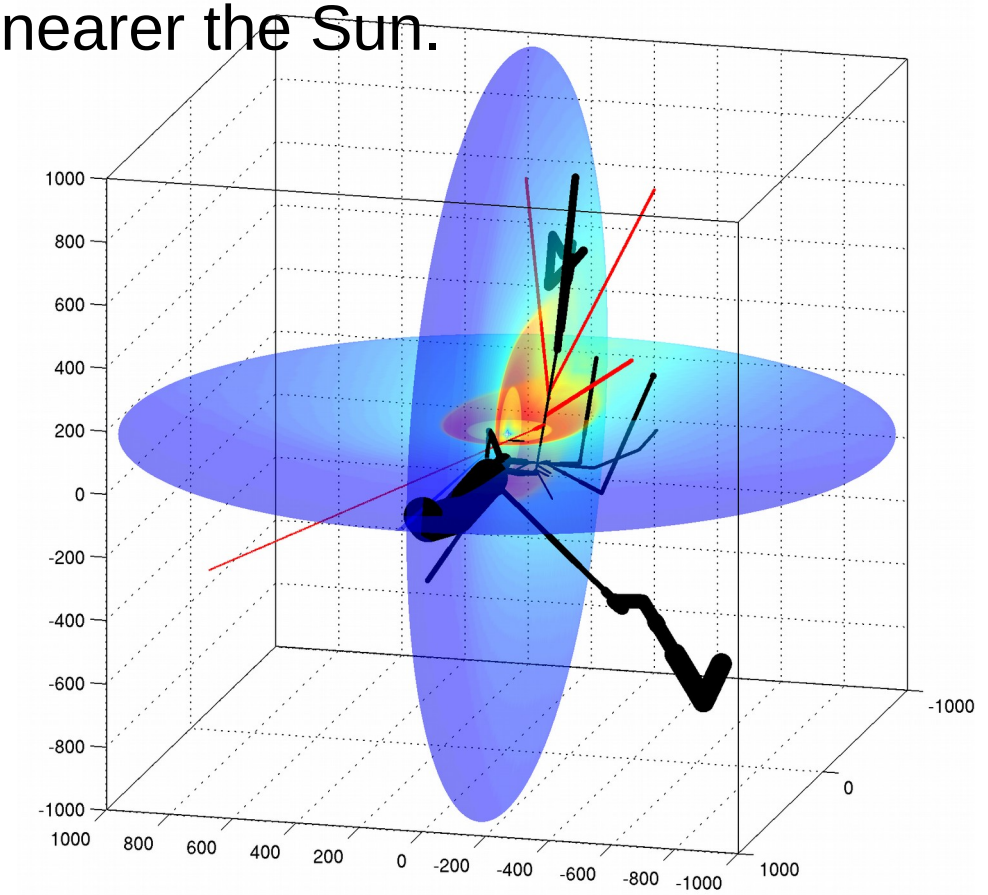
Axially-symmetric solution without neutrals (top) and the same solution with neutrals (bottom). Colors represent plasma temperature on a $\log_{10}$ scale.



Kinetic Simulation of Neutral Hydrogen

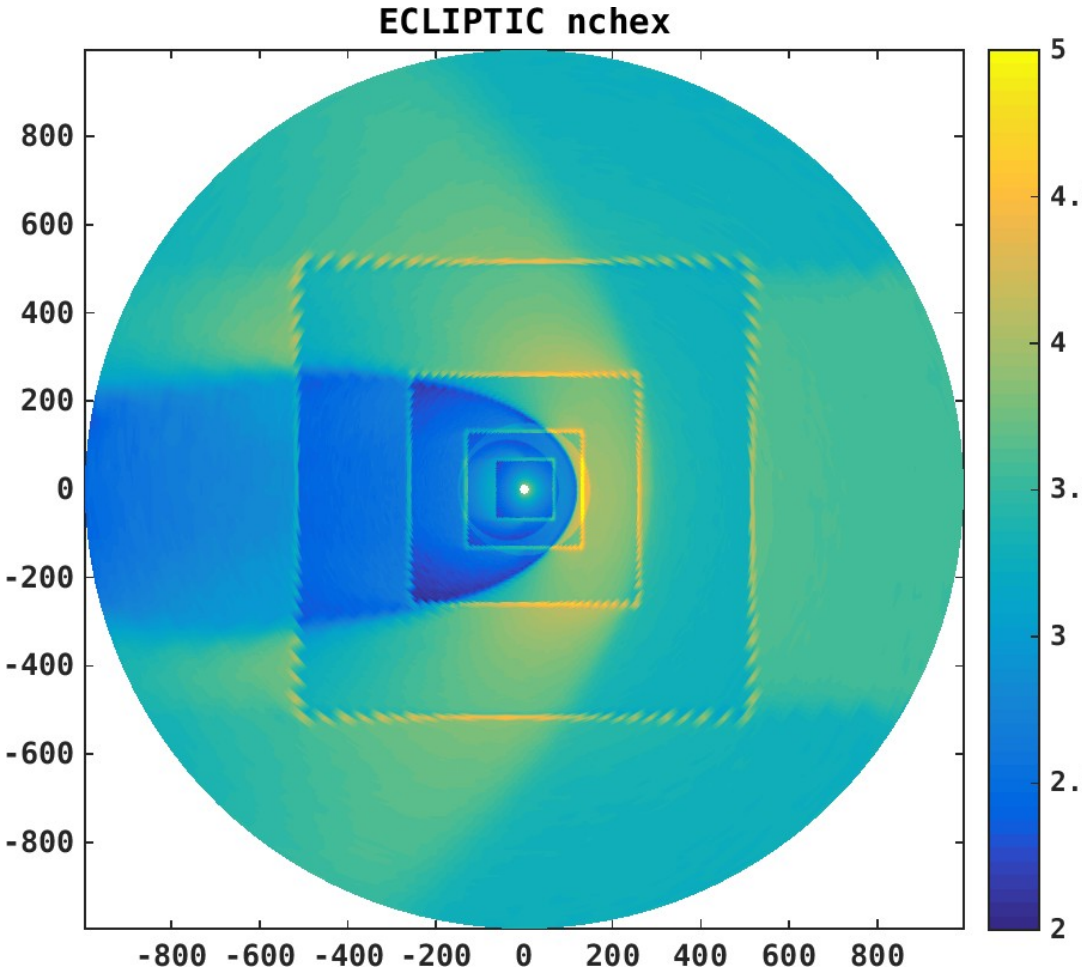
- Monte-Carlo algorithm that treats H-atoms as particles.
- Charge-exchange collisions occur based on local plasma conditions and alters particle velocities.
- Energy & Momentum changes of charge-exchange events are recorded on a grid and passed to the MHD code as source terms.
- MHD & neutrals codes iterate.
- Include splitting of trajectories to improve charge-exchange statistics on the smaller grid cell nearer the Sun.





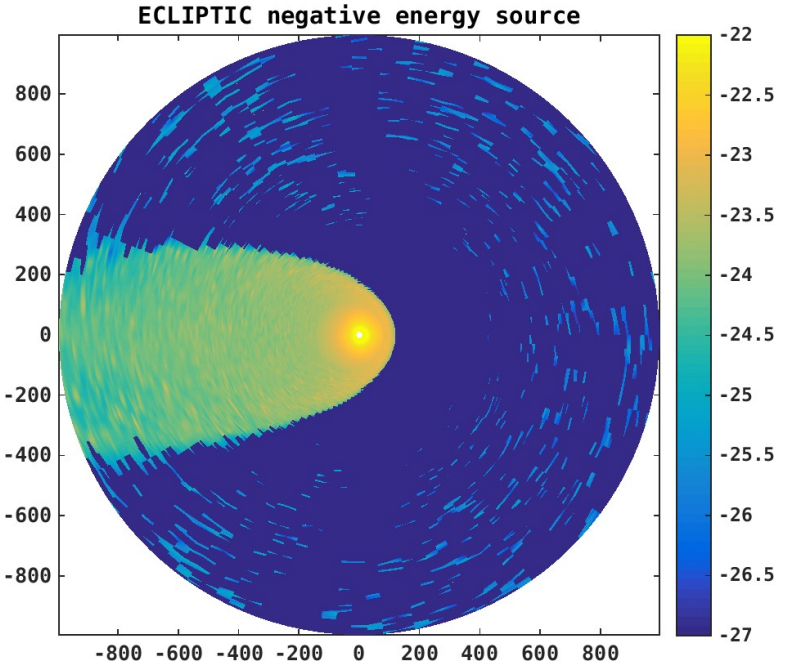
Feed-back of charge-exchange onto plasma through MHD source terms

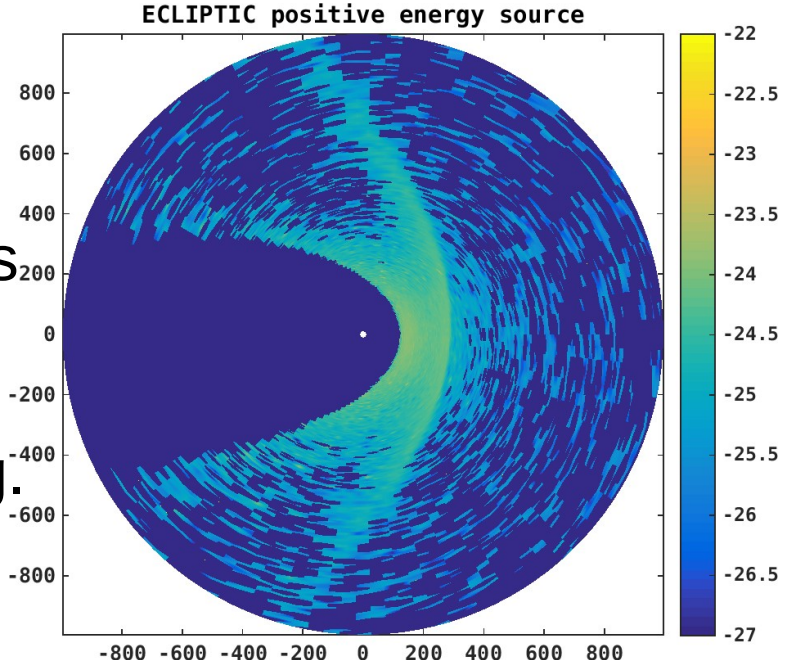
The change in energy and momentum of the H-atom during each charge-exchange event is added to a source term grid that is applied to the MHD code at the next iteration.

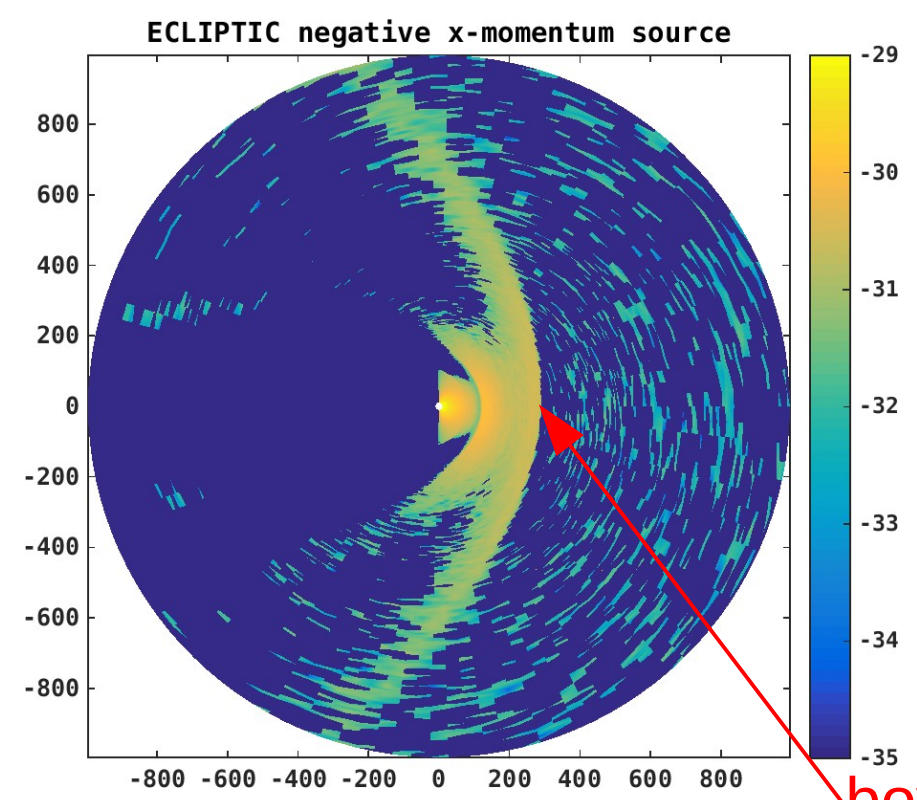


($\log_{10}$ color scales)

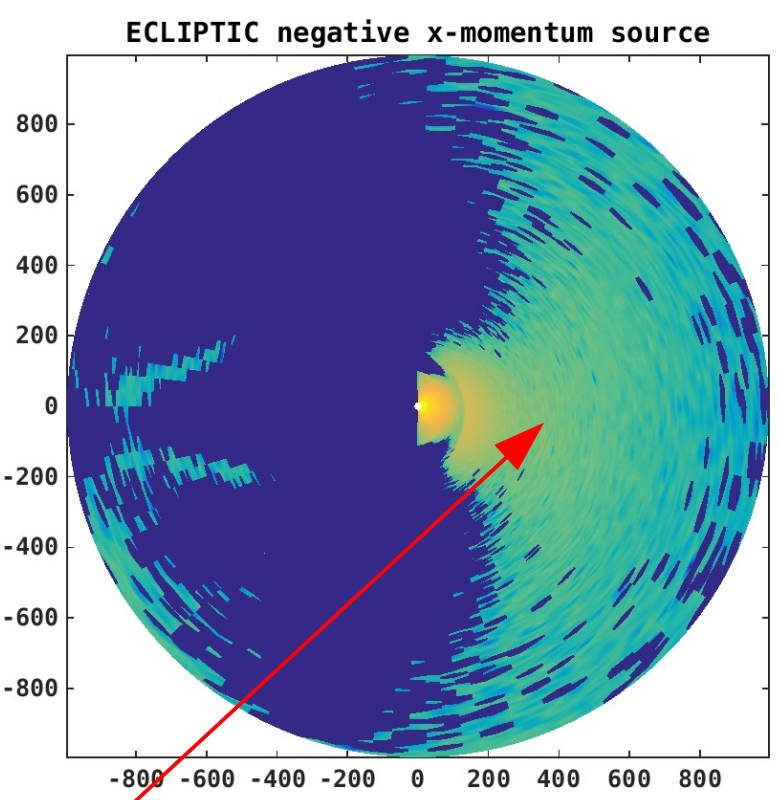
Nested squares due to particle splitting.





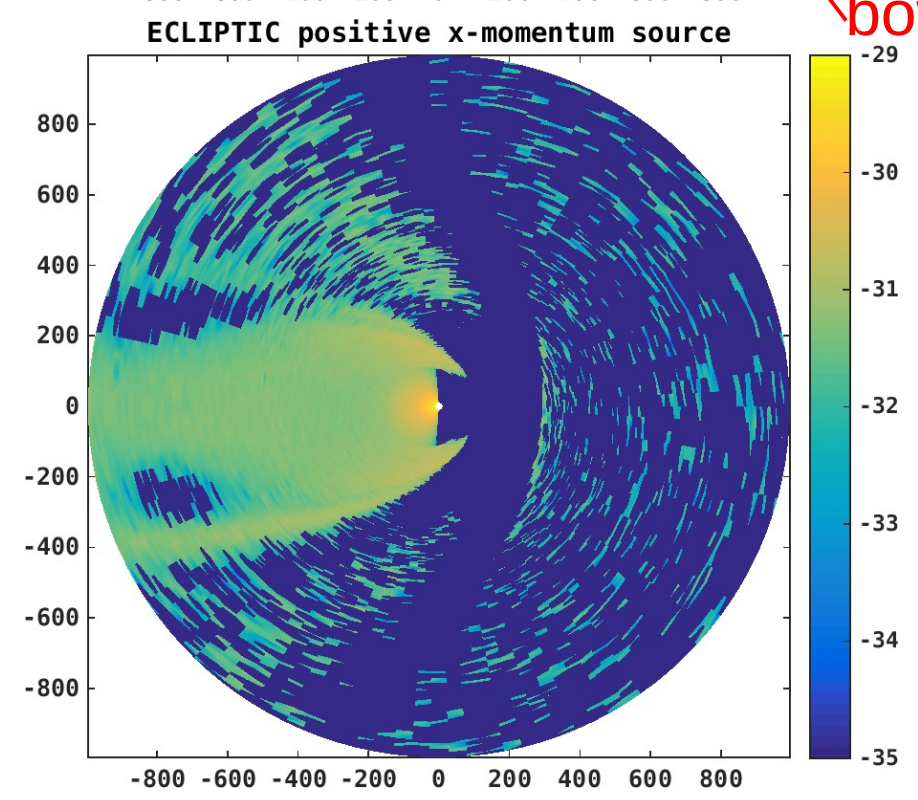


Momentum source in horizontal direction on a log scale.



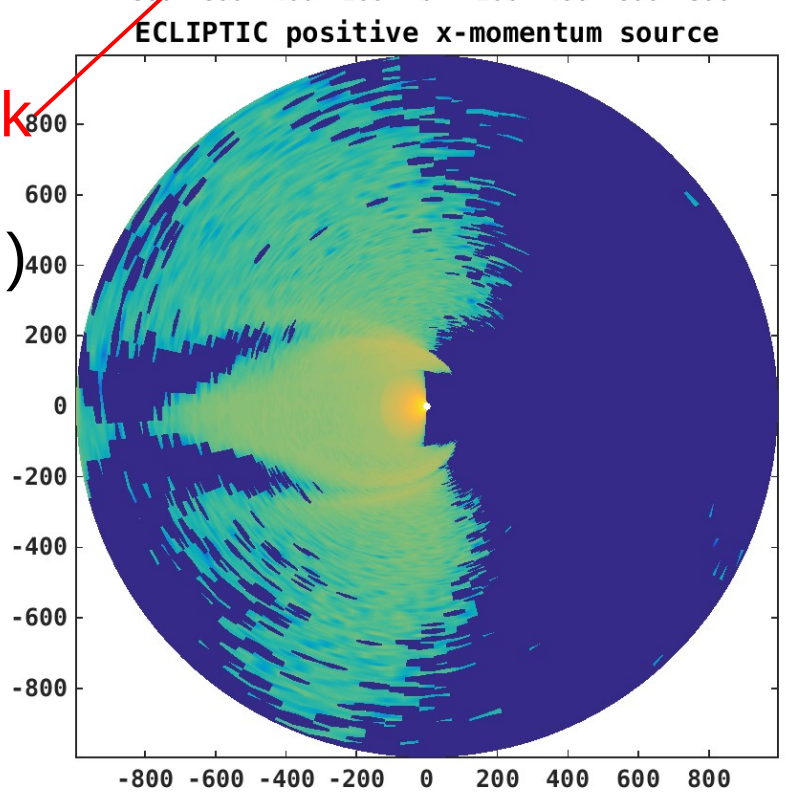
2 μG (left)

bow shock



no bow shock

4 μG (right)



Voyager & IBEX Missions

- V1 & V2 crossed the TS at 94 (2004) & 84 AU (2007) – asymmetry likely due to time-dependence and distortion of the heliosphere by the LISM magnetic field.
- It is believed that V1 crossed the heliopause in August of 2012 at 121 AU.
  A narrower than expected heliosheath?

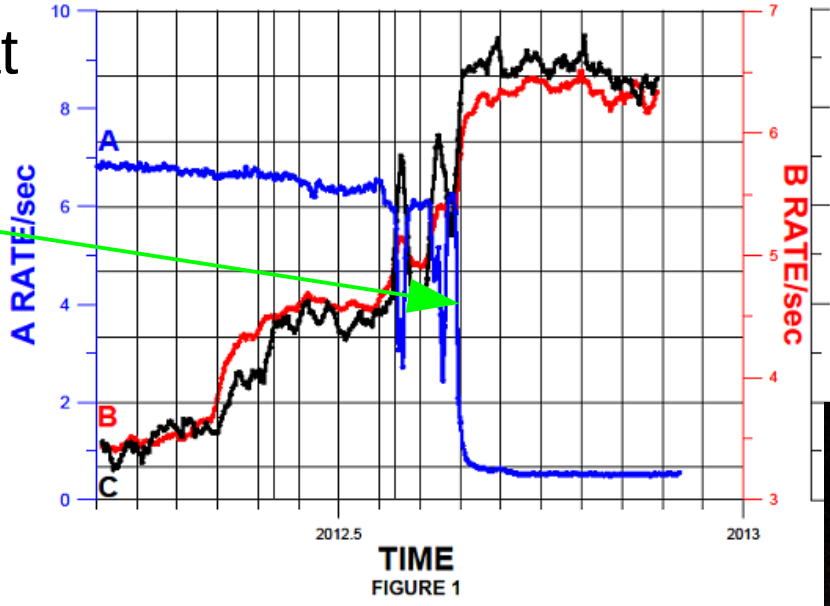
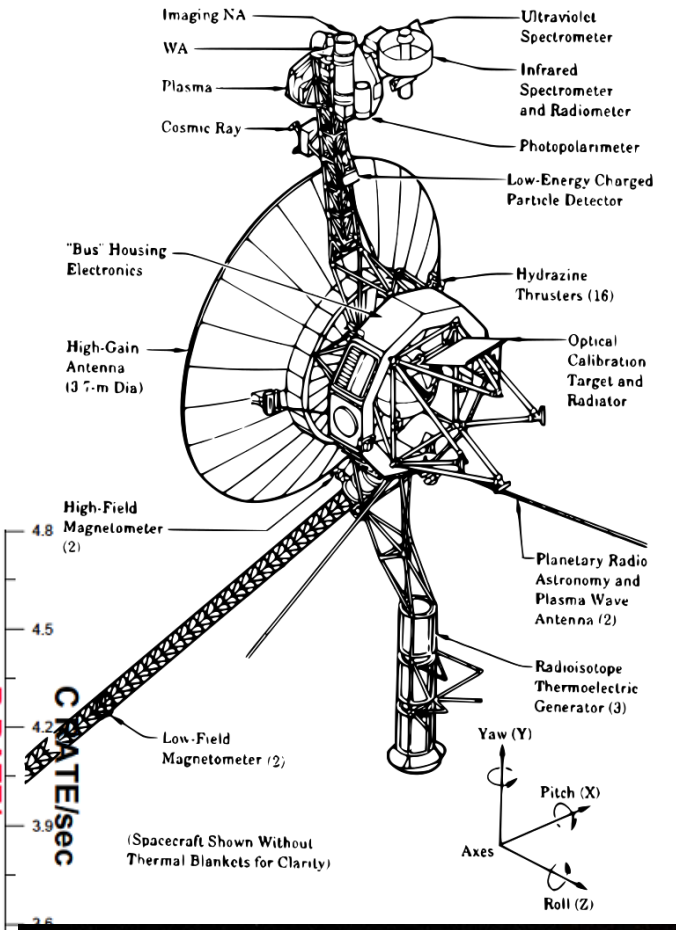
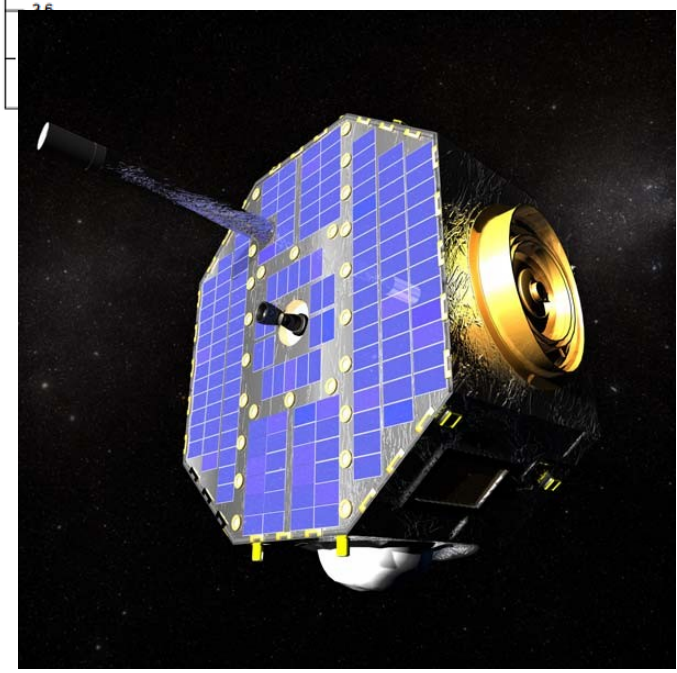


FIGURE 1

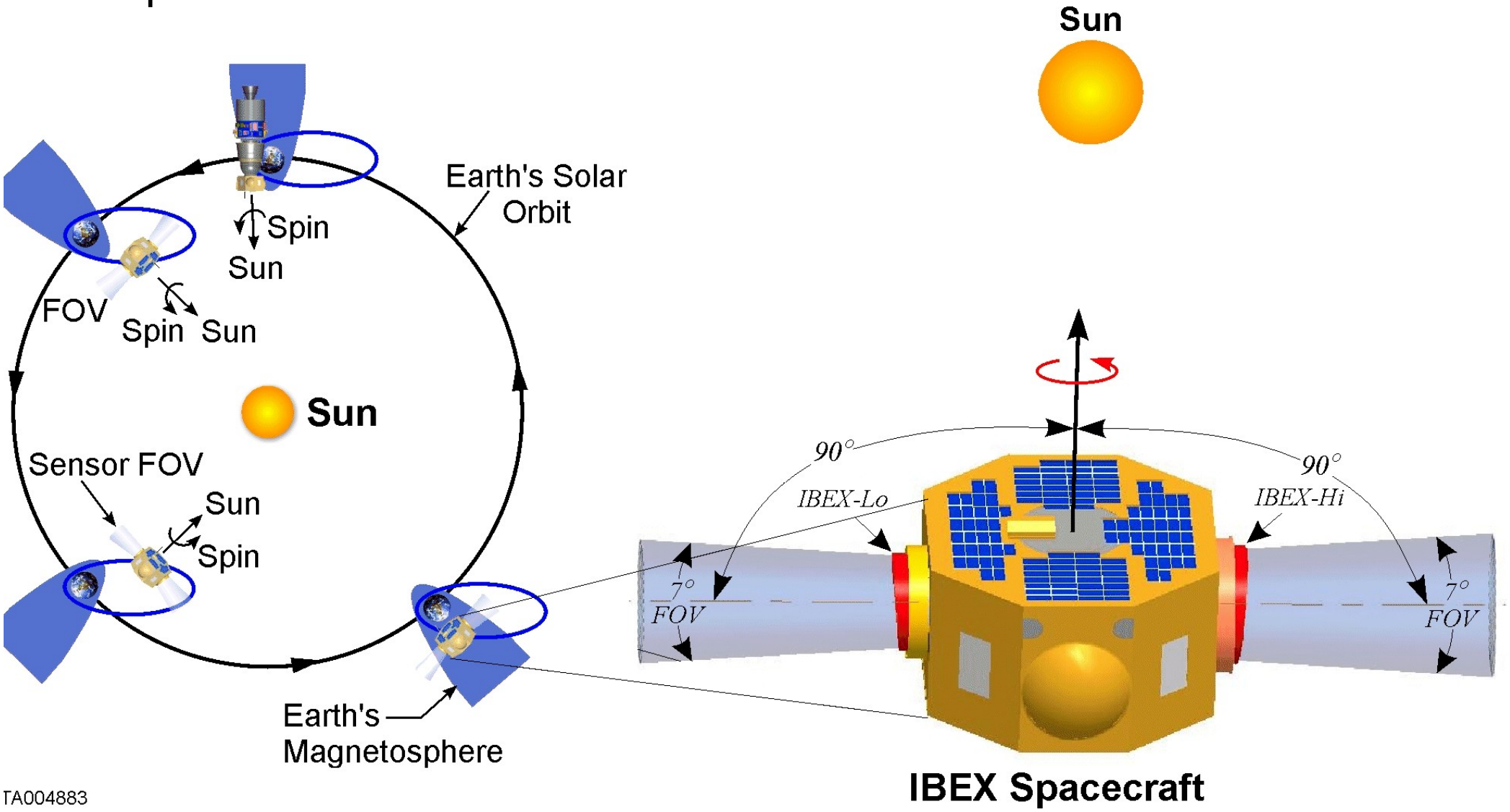




- The Interstellar Boundary Explorer (IBEX) provides all-sky maps of ENA (energetic neutral atom) flux, from earth-orbit.
- IBEX's global line-of-sight data nicely complements Voyagers' point data.

IBEX All-sky Maps

- By spinning and orbiting the sun, IBEX looks at every point in the sky at least once every six months, thereby generating an all-sky map of ENA flux.



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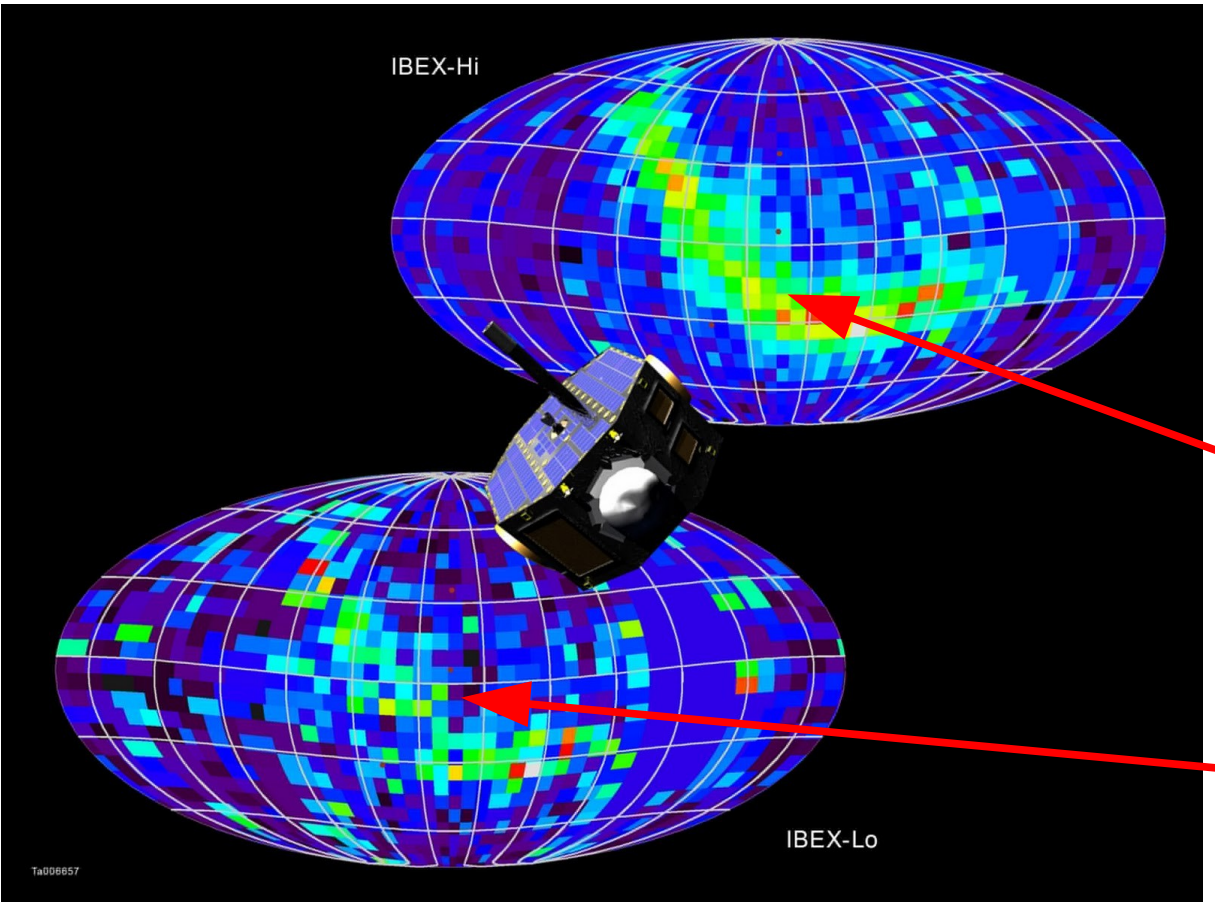
The IBEX Ribbon

- An unexpected feature in the IBEX maps was a “ribbon” of enhanced flux that threads across most of the sky at energies of a few hundred eV and higher.
- Ribbon shape and properties fairly steady over timescale of years.
- A number of mechanism have been put forward, but all have at least some draw-backs.

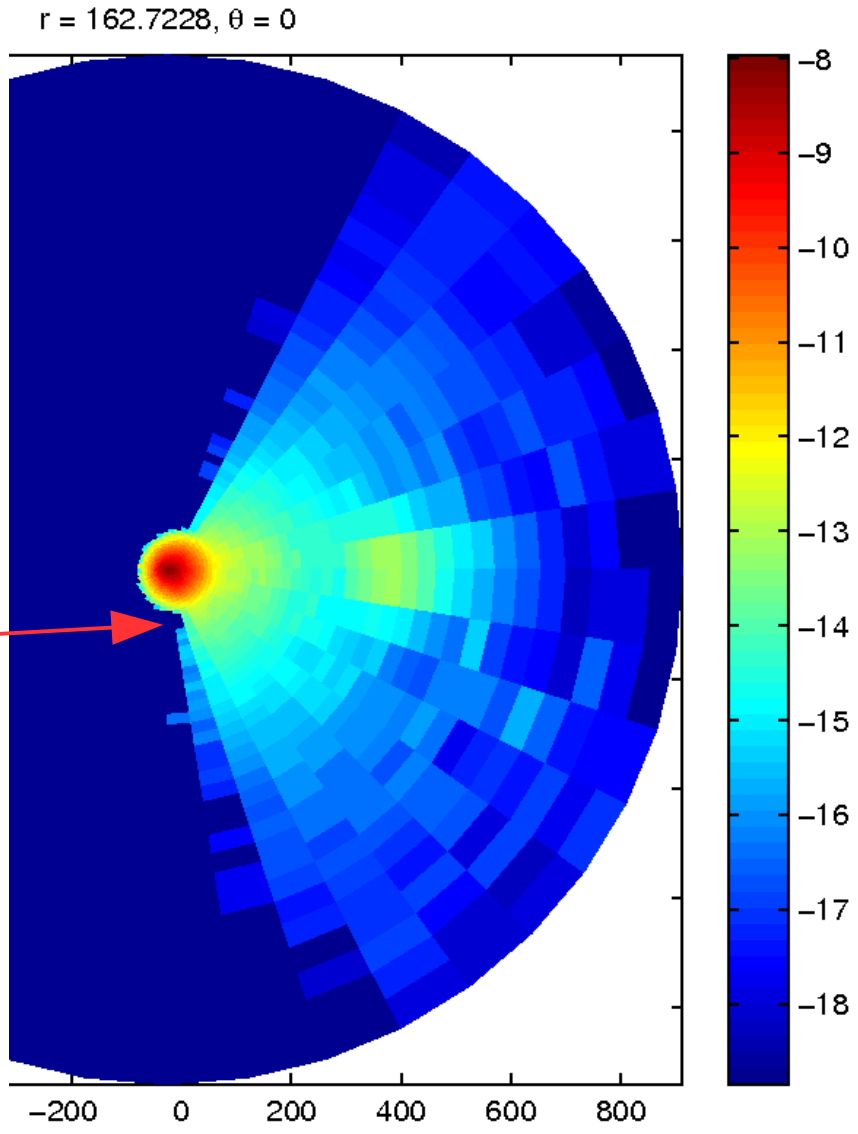


- We incorporated a mechanism based on “secondary ENAs” into our codes and showed that the ribbon obtained in the simulations has similar features to the ribbon in the data.

Ribbon seen by IBEX-Hi & IBEX-Lo independently.

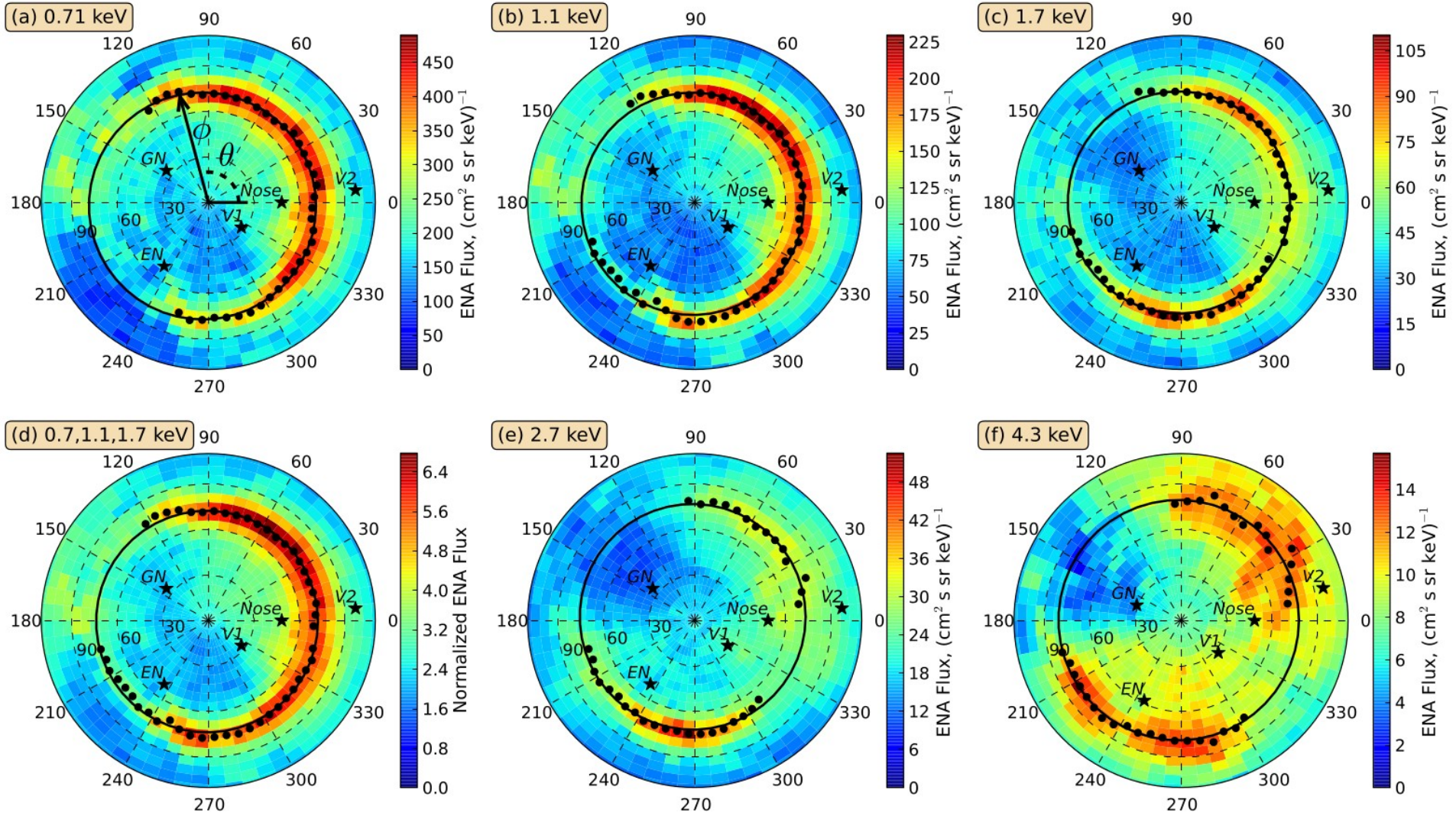
Simulating ENA Flux

- We (Zirnstein) developed a code that integrates ENA trajectories backward from 1 AU, accumulating gains and losses along the way.
- This approach allows for various physical processes to be included: different plasma distribution (PUIs), different ionization & radiation pressure models, spacecraft response function etc.
- We can introduce the ribbon into the formulation, provided we have the Hydrogen velocity distribution function at each point outside the heliopause.
- We compute contributions to the ribbon by taking the charge-exchange rate of primary ENAs and assuming that the resulting PUIs become secondary ENAs with partial shells that depends on their pitch-angle.



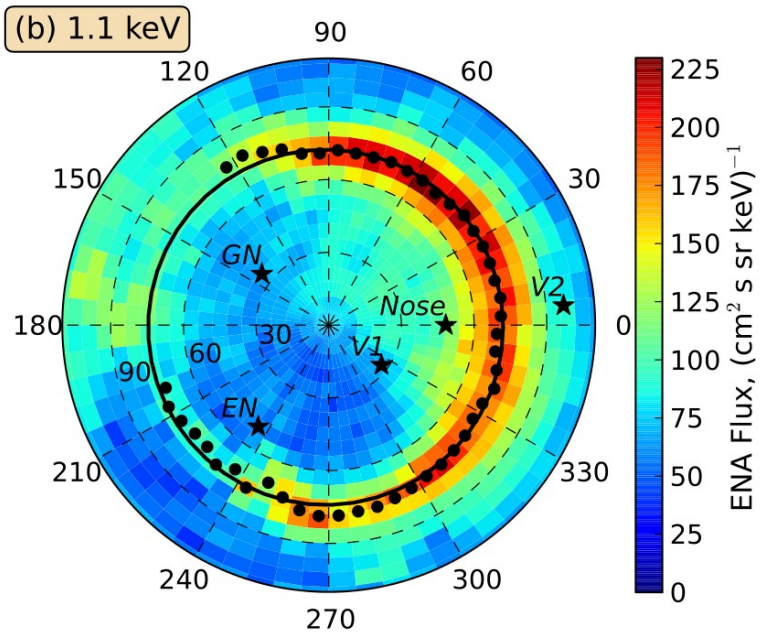
Circularity of the IBEX Ribbon

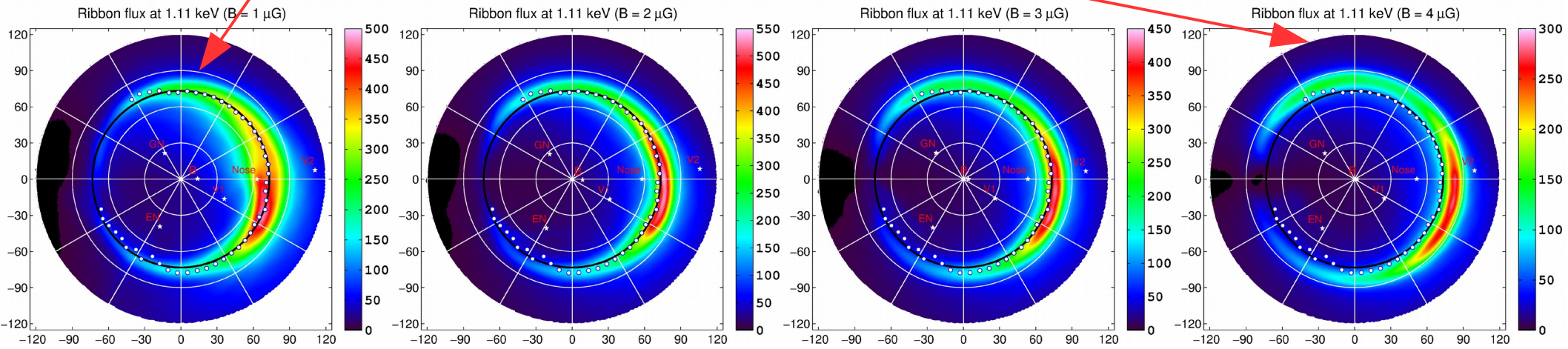
- Funsten et al (2013, 2015) analyzed the ribbon in the IBEX data, and found it to closely approximate a circle.
- The centers align well at all energies, except 4.3 keV (the highest).



Circularity of the Simulated Ribbon and implications for $|B_{LISM}|$

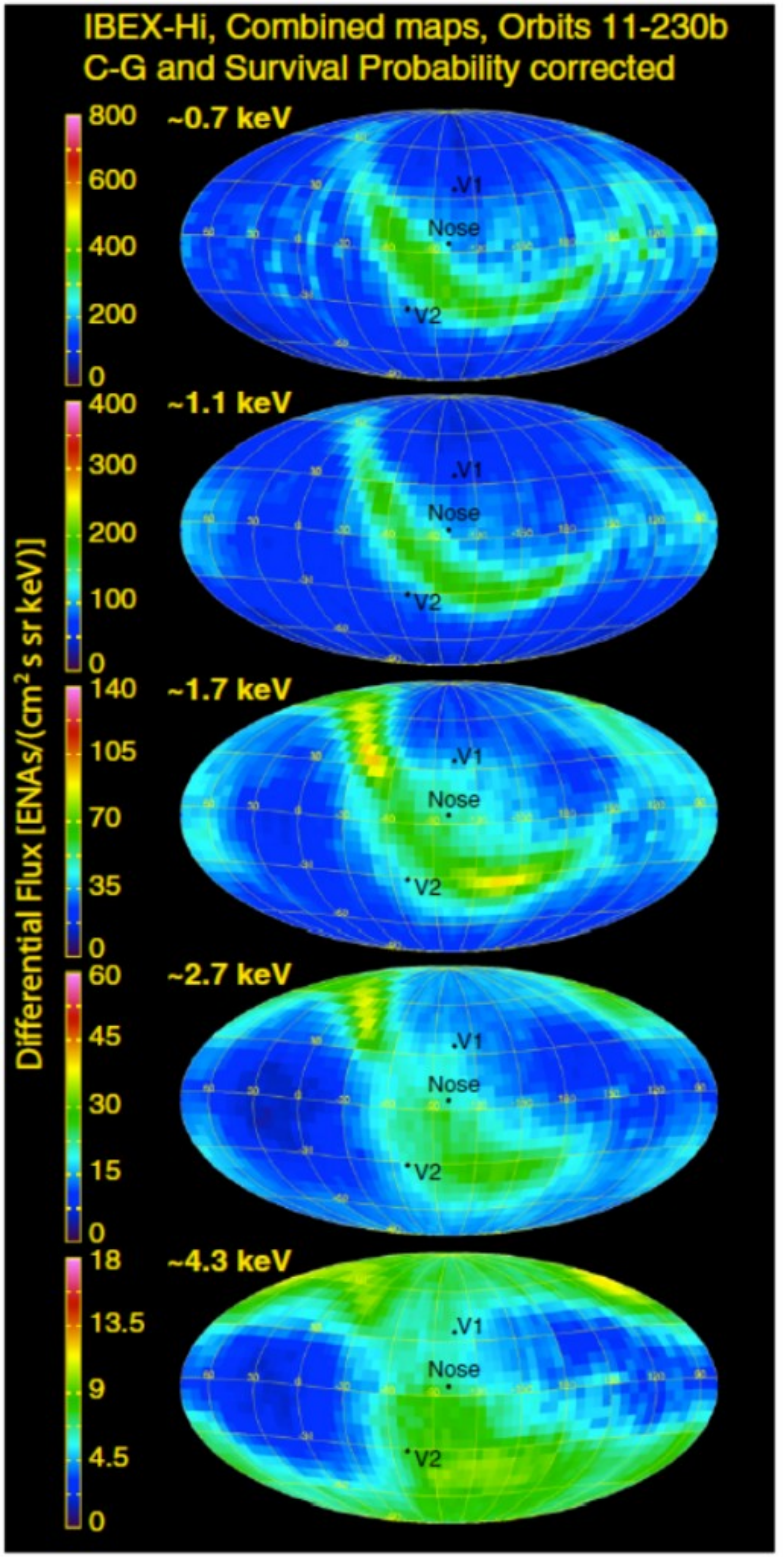
- The remarkable match between the circularity of the ribbon in the data and the simulated ribbon can be used to determine which interstellar field strength is more likely (Heerikhuisen et al, 2014).
- The ribbon at 1 μG (left) is too wide, while at 4 μG (right) the radius is too big. Hence $|B_{LISM}|$ is likely 2 to 3 μG.

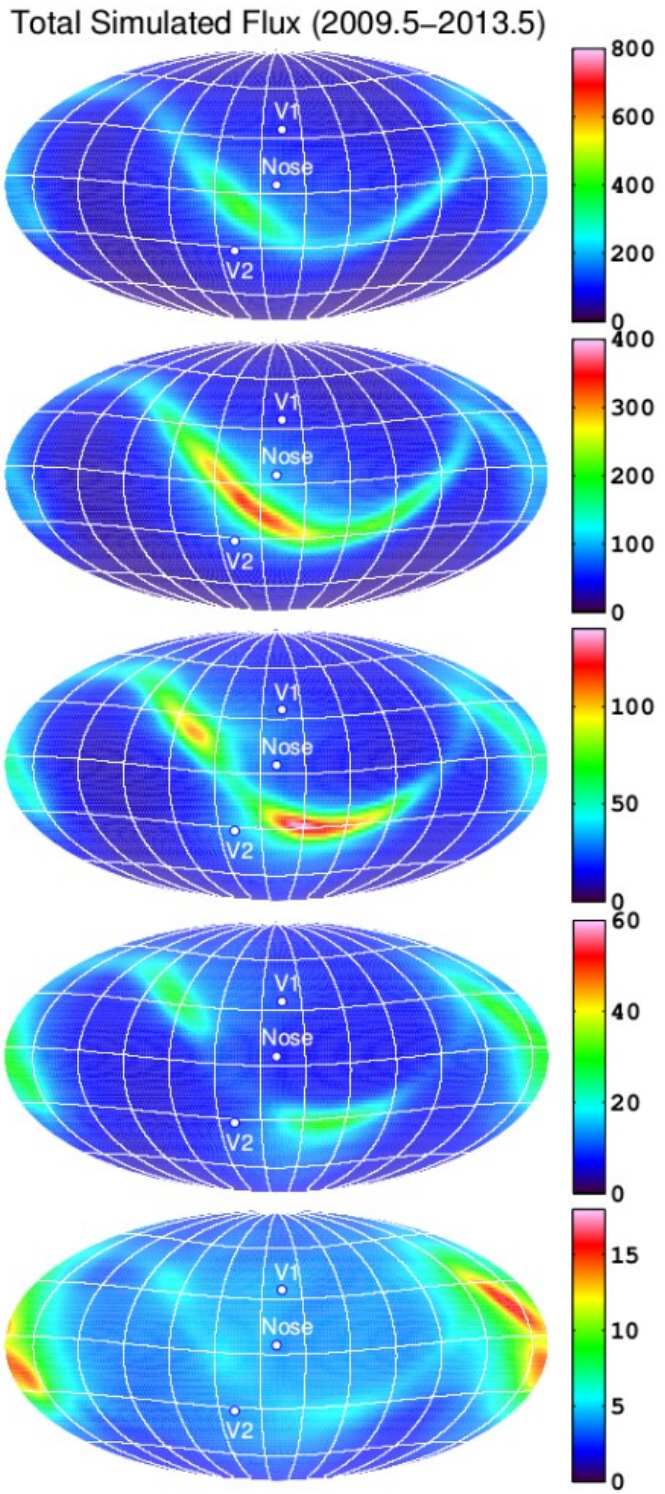




Comparison of flux integrated over the IBEX energy bins above ~500 eV, for the average flux between 2009.5 and 2013.5

Note that the direction of the interstellar magnetic field has not been fully optimized to match the ribbon location in the simulation.

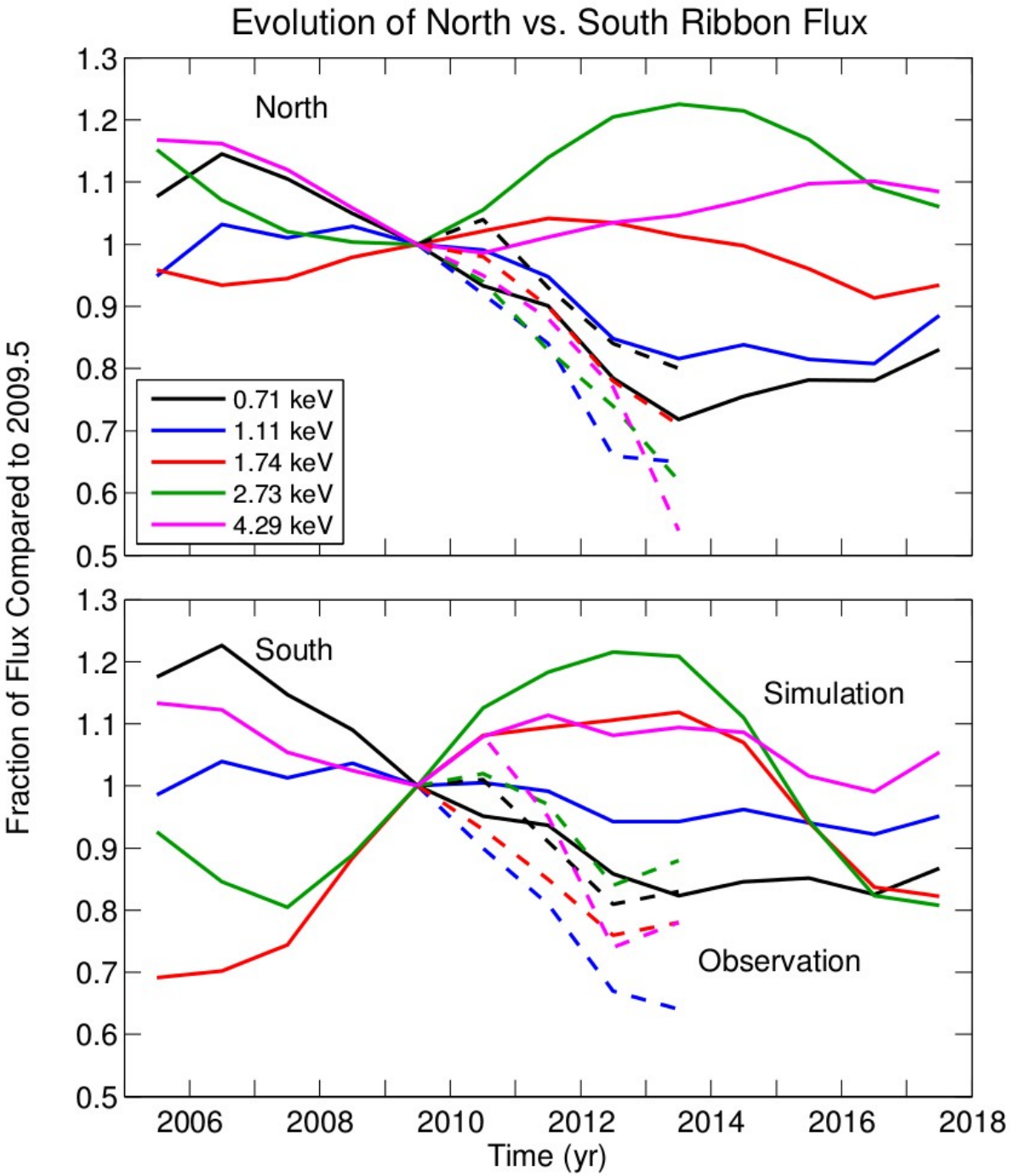




Better time-dependent modeling still needed

Despite using observations of the solar wind for the final 20 years of the run, our simulations do not predict the large decrease in non-ribbon flux observed over the last 5 years.

Solid lines are from the simulation, dashed lines are data from IBEX.



Summary

- SW-LISM interaction strongly moderated by neutral hydrogen.
- We model the SW-LISM interaction using an MHD approach for ions, coupled to a kinetic approach for neutral Hydrogen.
- We can model the IBEX ribbon based on secondary ENAs – various scenarios possible.
- The circularity of the simulated and observed ribbons is remarkably similar. Can be used to diagnose LISM conditions (e.g. magnetic field) based on how will the resulting simulation matches the IBEX data.
- We can simulate a simplified solar cycle. Can be used to understand time-dependence of outer boundaries, and ENA flux from the IBEX ribbon – appears more SW fidelity is needed to match non-ribbon trends.