The IBEX Ribbon and its Relation to the Solar-Interstellar Interaction

Eric J. Zirnstein

Space Physics Group
Department of Astrophysical Sciences, Princeton University
Princeton, NJ 08540, USA

CRA 2023 Workshop, May 18, 2023

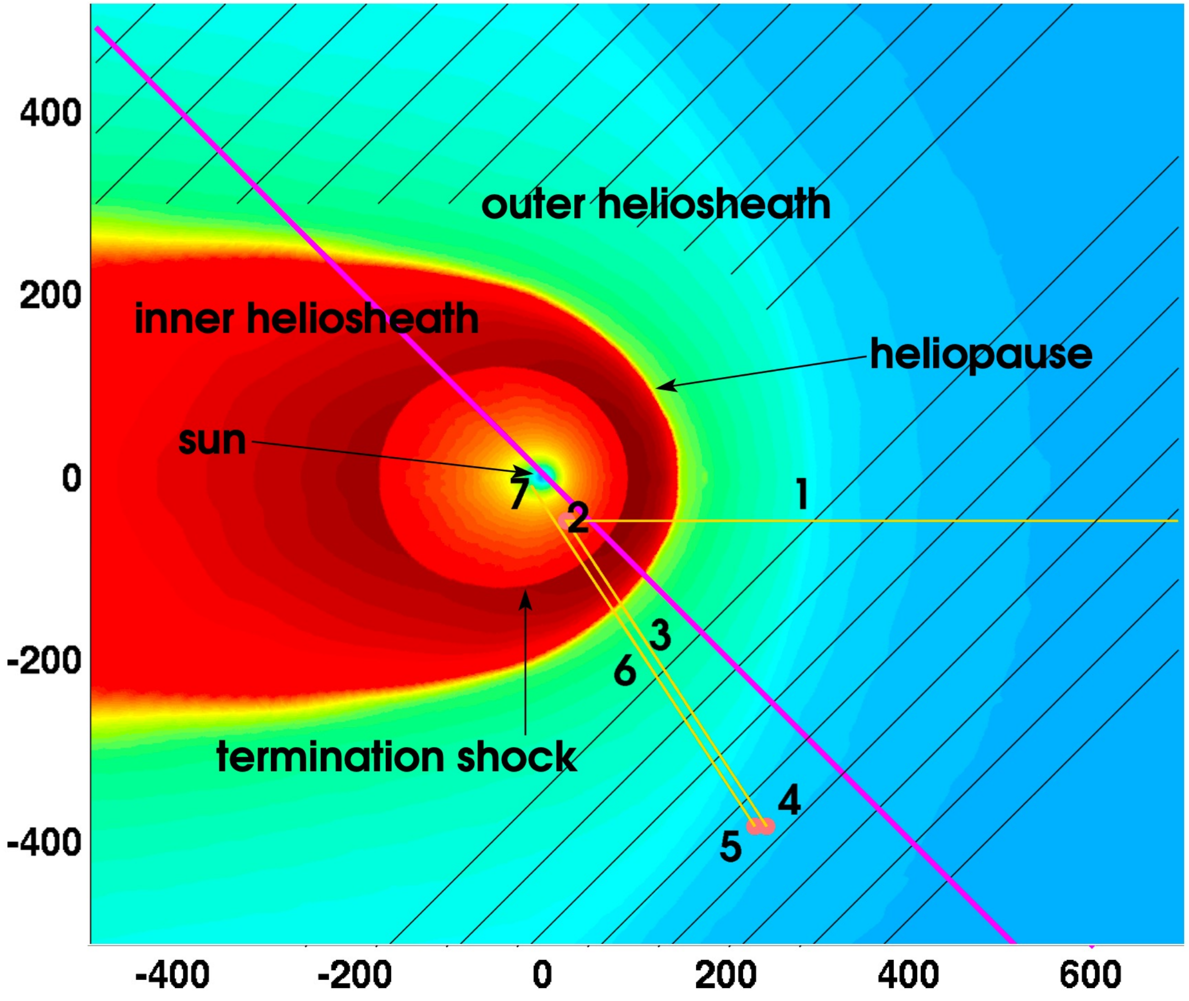
Outline

Topical questions:

- What is the IBEX Ribbon and how is it formed?
- How is the Ribbon related to the Interstellar Medium?
- What are the macro and micro-physical processes governing the Ribbon's properties?
- What is the latest information we have about the local interstellar magnetic field (ISMF)?

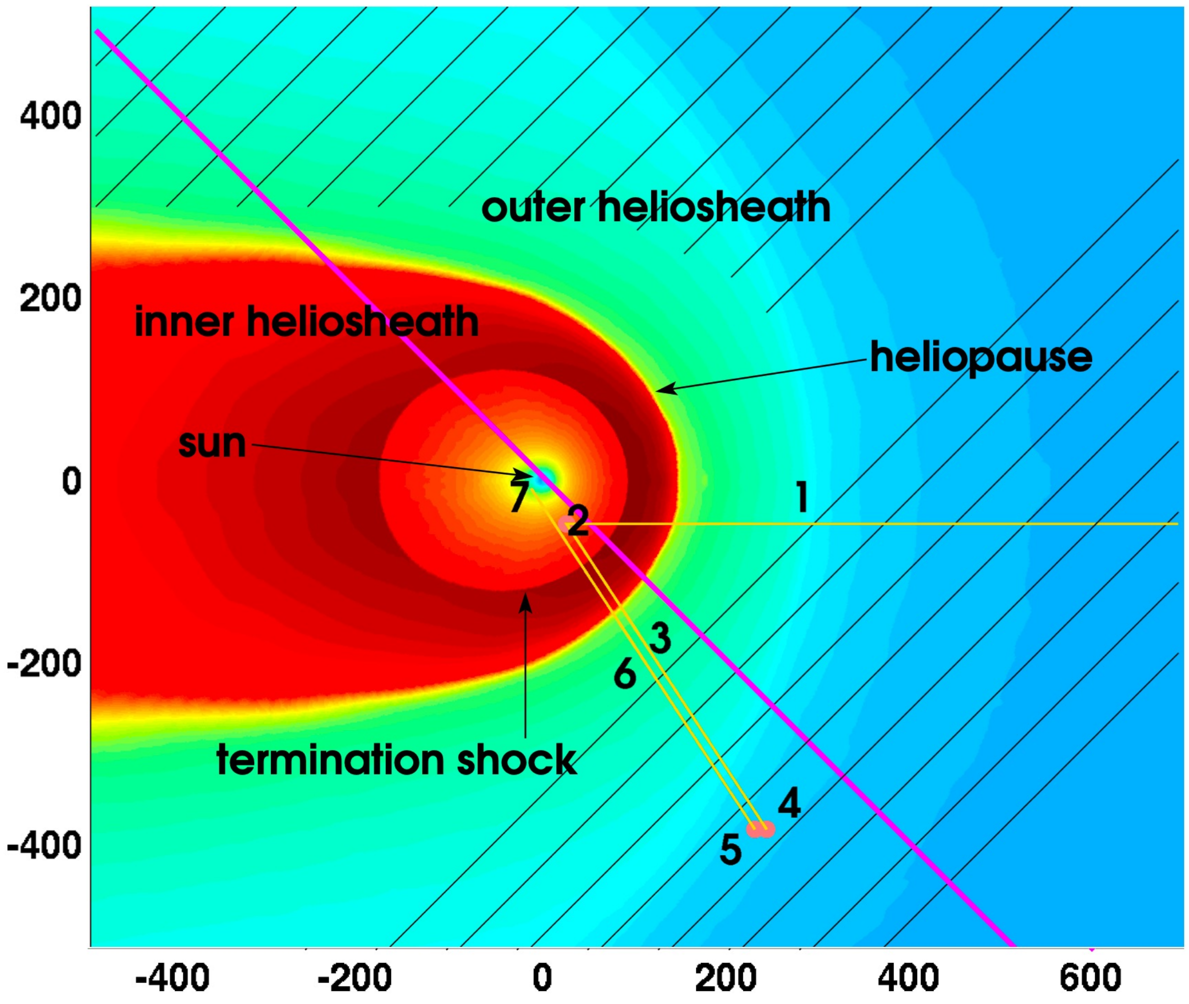
- ***Part 1: Ribbon intensity***
  - *Small scales from PUI transport*
  - *Large scales from ISMF draping*
  - *All scales from neutral SW/PUI source*
- ***Part 2: Ribbon structure***
  - *Both PUI dynamics and ISMF draping, turbulence*
- ***Part 3: Ribbon position and circularity***
  - **Mostly* due to ISMF draping*
- ***Part 4: Comparison with Voyager data***
  - *Simulated ISMF independently derived from IBEX data compared to Voyager in situ field measurements*
- ***Part 5: Ribbon evolution***
  - *Governed by solar cycle*
- ***Conclusions***

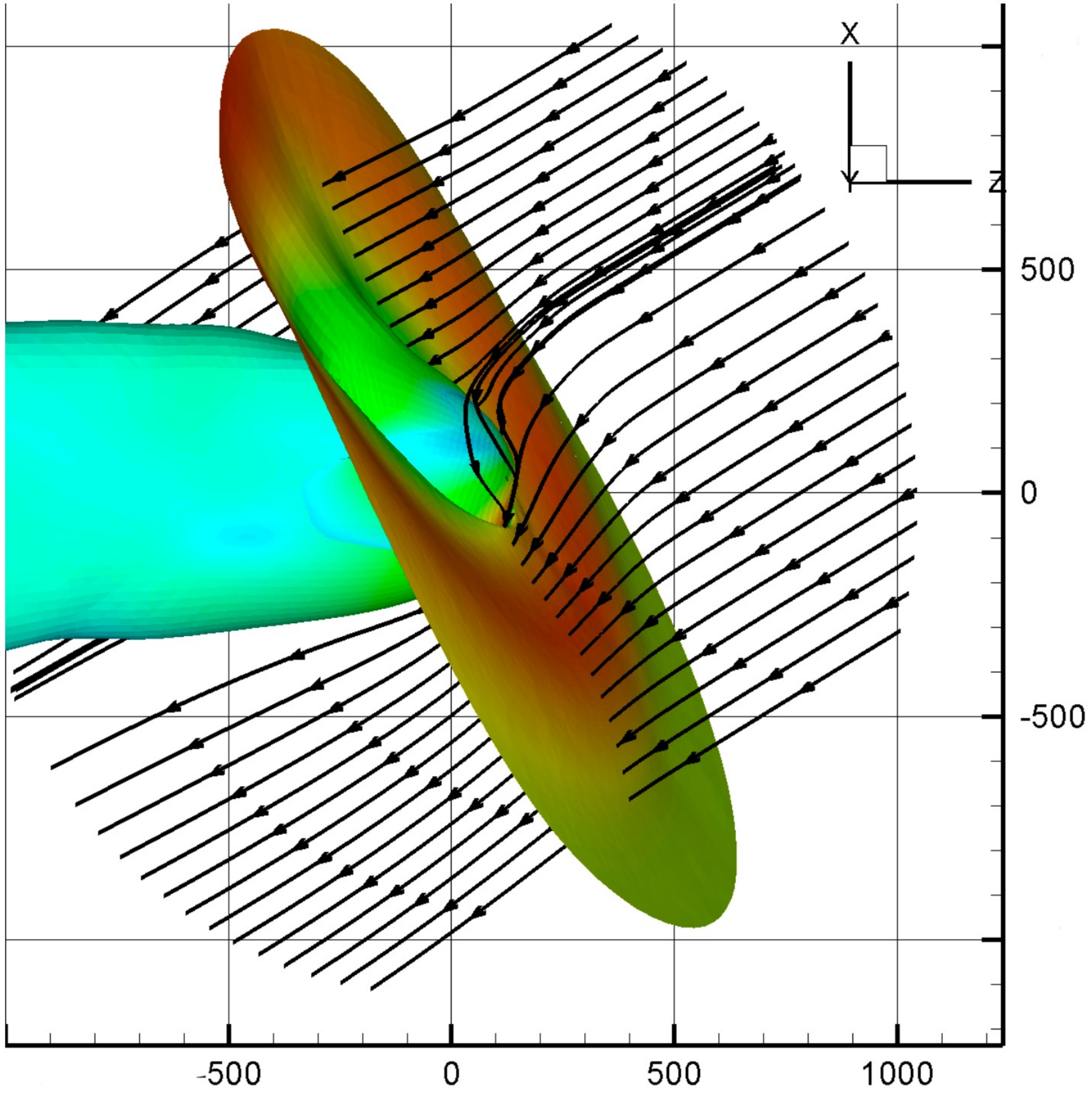
How is the Ribbon Formed?



- 1) Interstellar neutrals propagate into the heliosphere
- 2) Neutral charge exchanges with solar wind ion
- 3) Solar wind ion is neutralized ("primary ENA"), continues its original trajectory radially outwards and likely escapes the heliosphere
- 4) Neutral solar wind particle ionizes in interstellar medium, "PUI" gyrating in local field
- 5) PUI charge exchanges with another interstellar neutral, becoming neutralized ("secondary ENA")
- 6) Some secondary ENAs propagate back inside the heliosphere
- 7) Some secondary ENAs are observed by IBEX

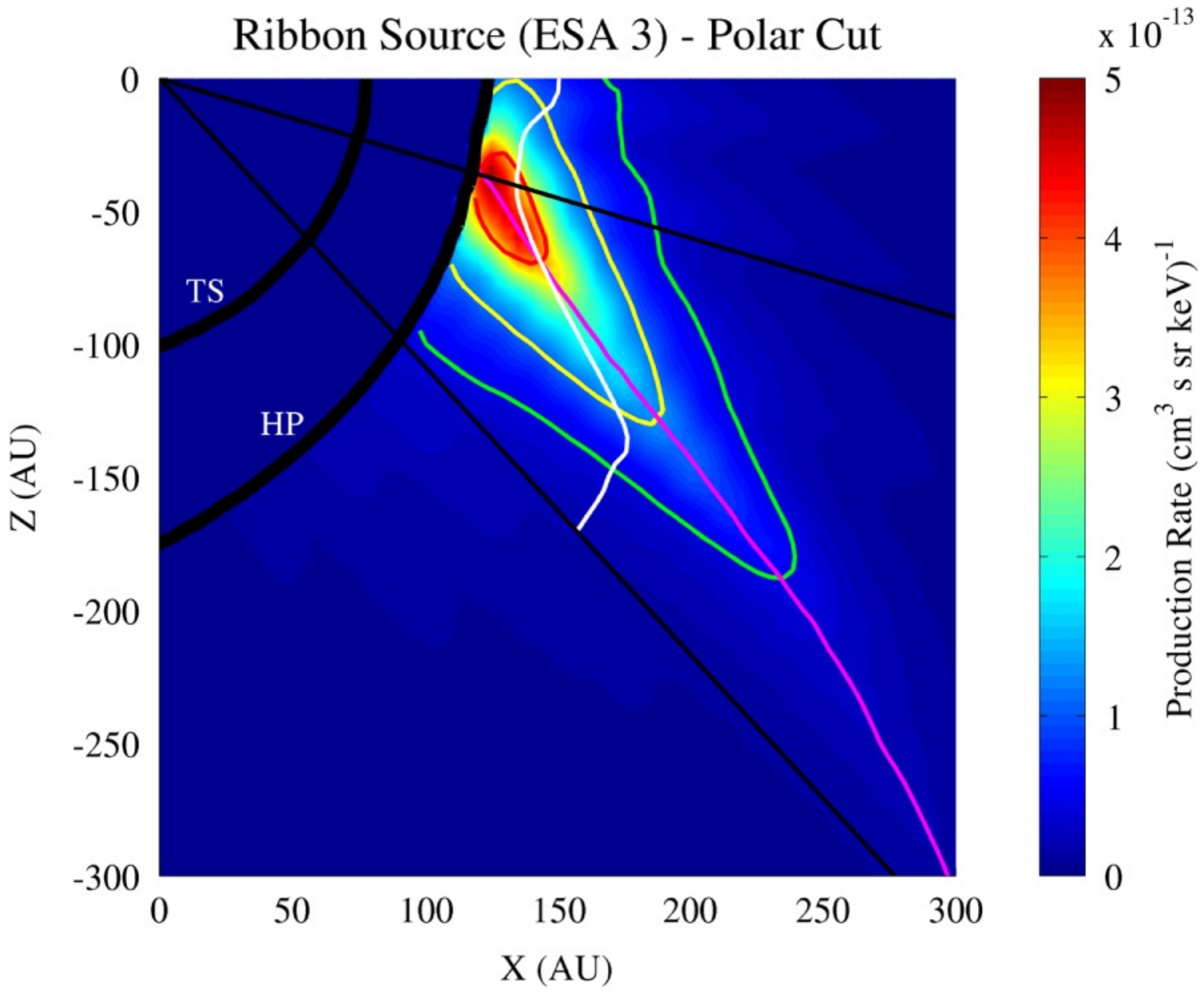
How is the Ribbon Formed?





Draping of the ISMF and its Effects on the Ribbon

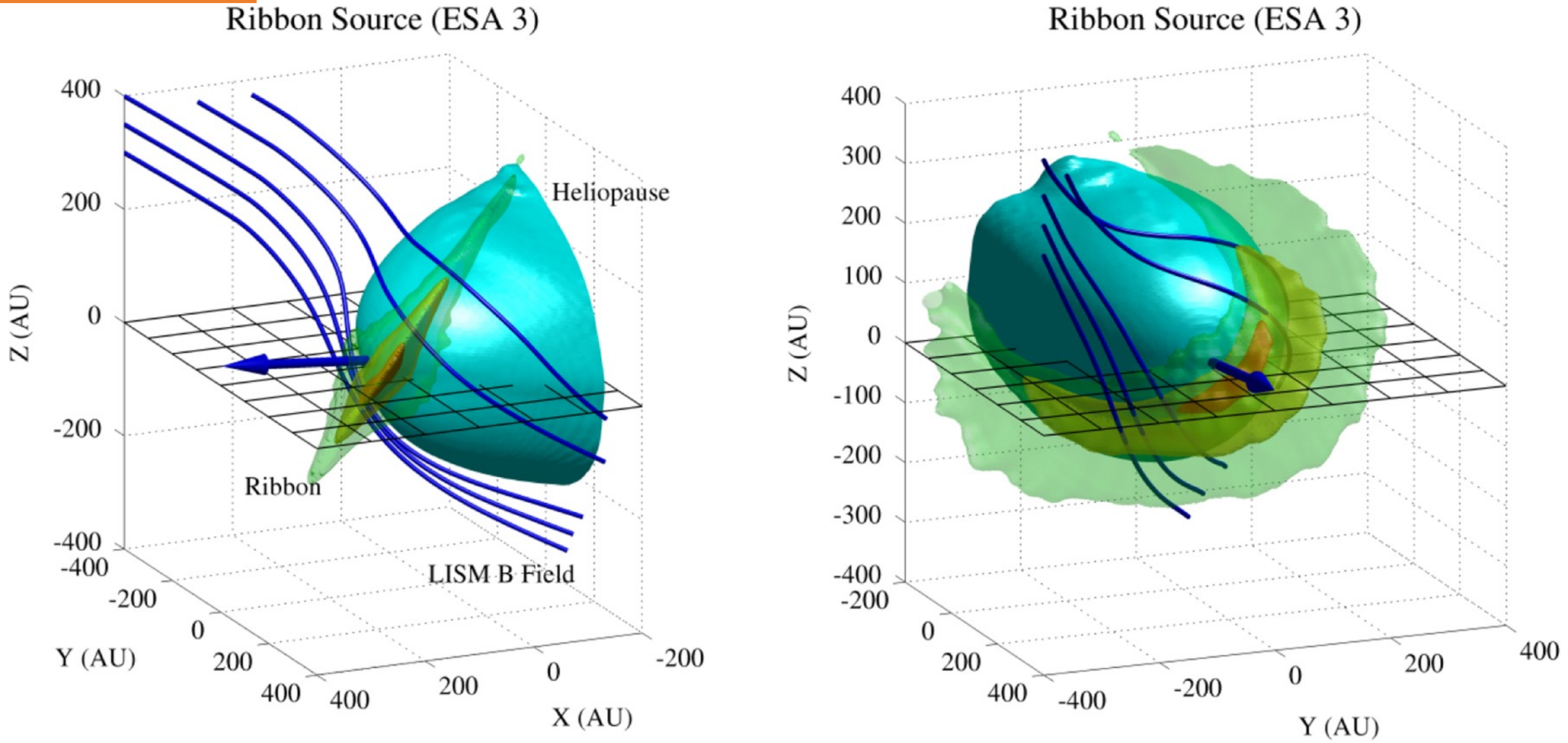
Zirnstein et al. (2015, ApJL)



- Polar cut of Ribbon production rate
  - Isocontours of ribbon: 70%, 25%, 10%
- Surface representing $\boldsymbol{B} \cdot \boldsymbol{r} = 0$ ($\boldsymbol{r}$ is IBEX line of sight, $\boldsymbol{B}$ is ISMF) is magenta curve
- Distance from heliopause at which 50% of Ribbon flux is accumulated is white curve
- Ribbon flux is concentrated near $\boldsymbol{B} \cdot \boldsymbol{r} = 0$, close to the heliopause
- $\boldsymbol{B} \cdot \boldsymbol{r} = 0$ surface is "warped" as a function of distance from the heliopause due to compression and draping of the ISMF

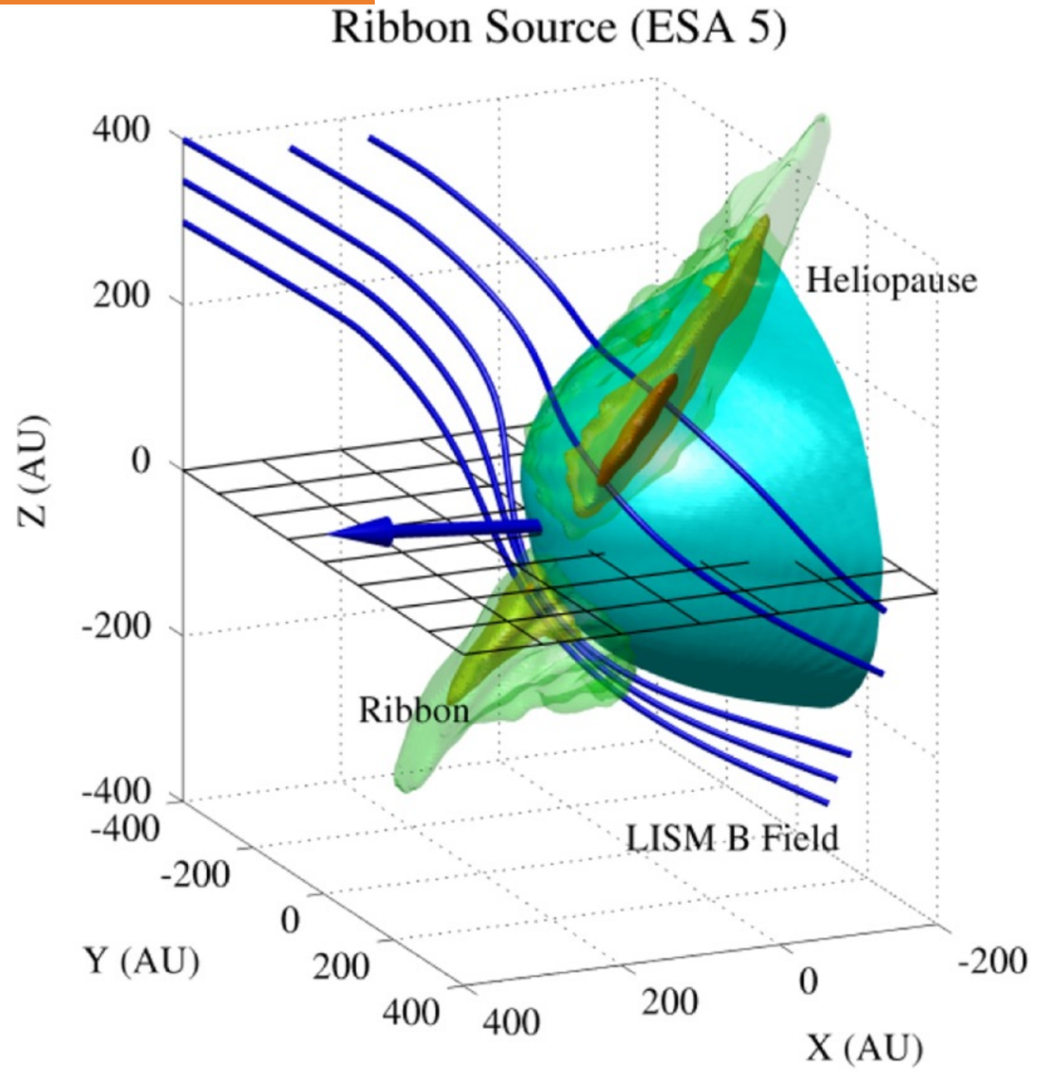
3D Ribbon Structure

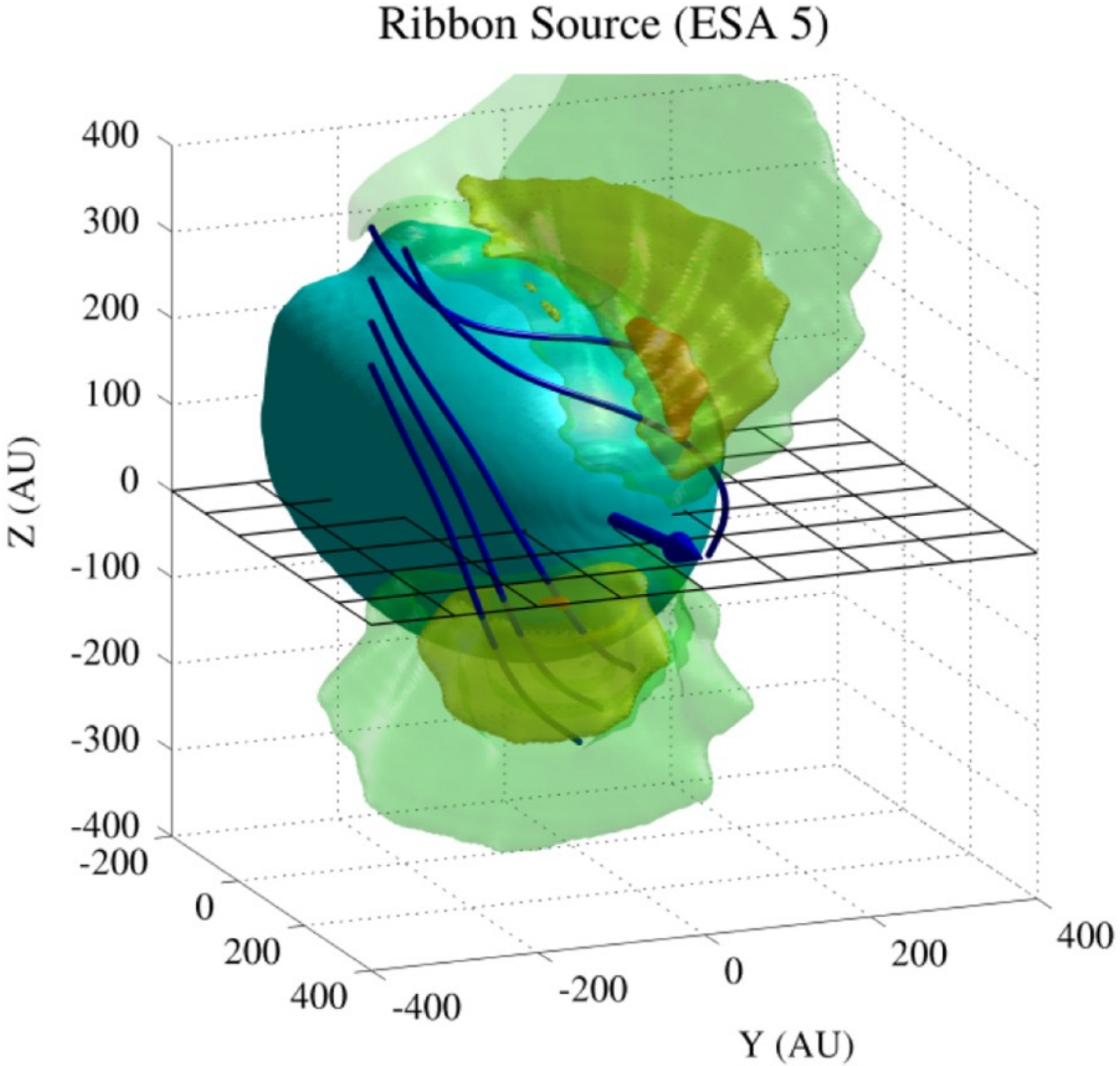
Zirnstein et al. (2015, ApJL)



3D Ribbon Structure

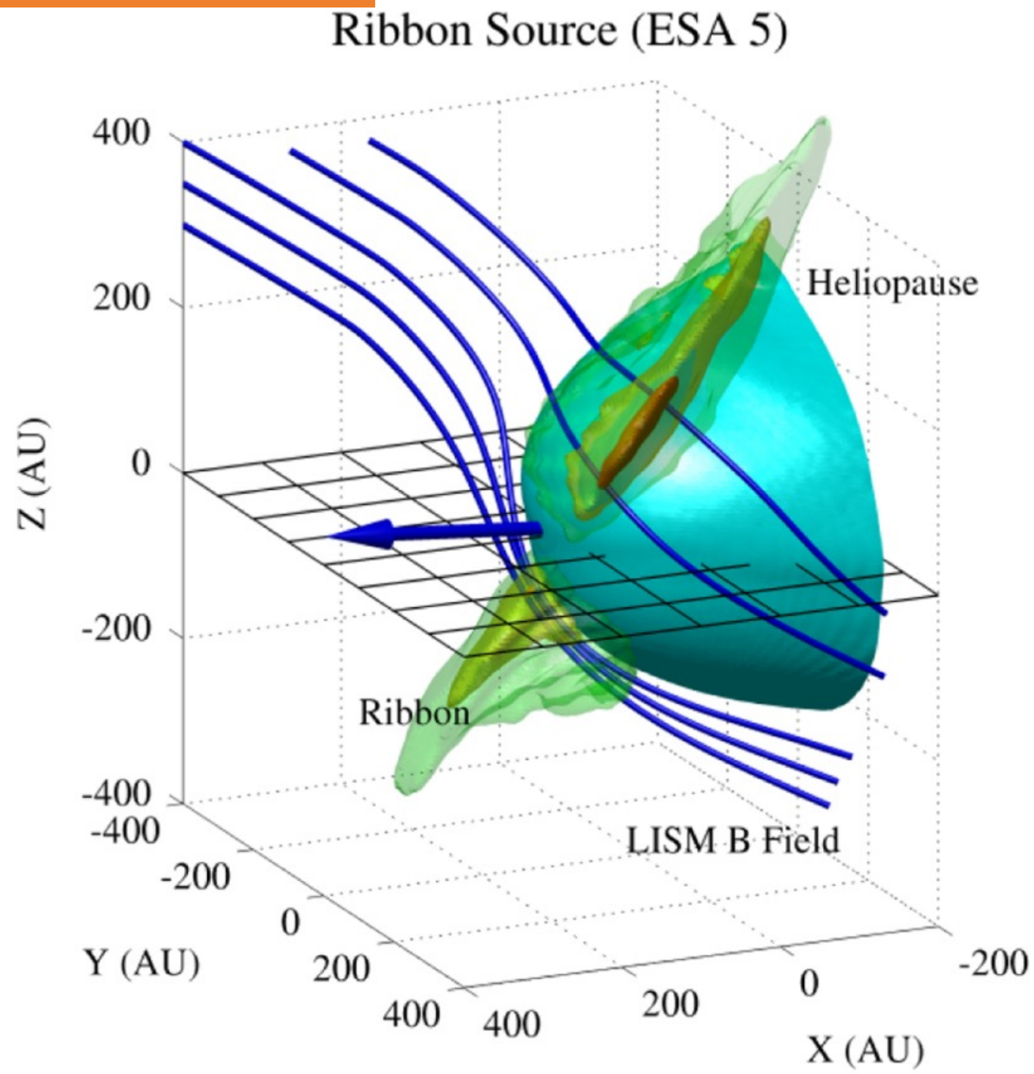
Zirnstein et al. (2015, ApJL)

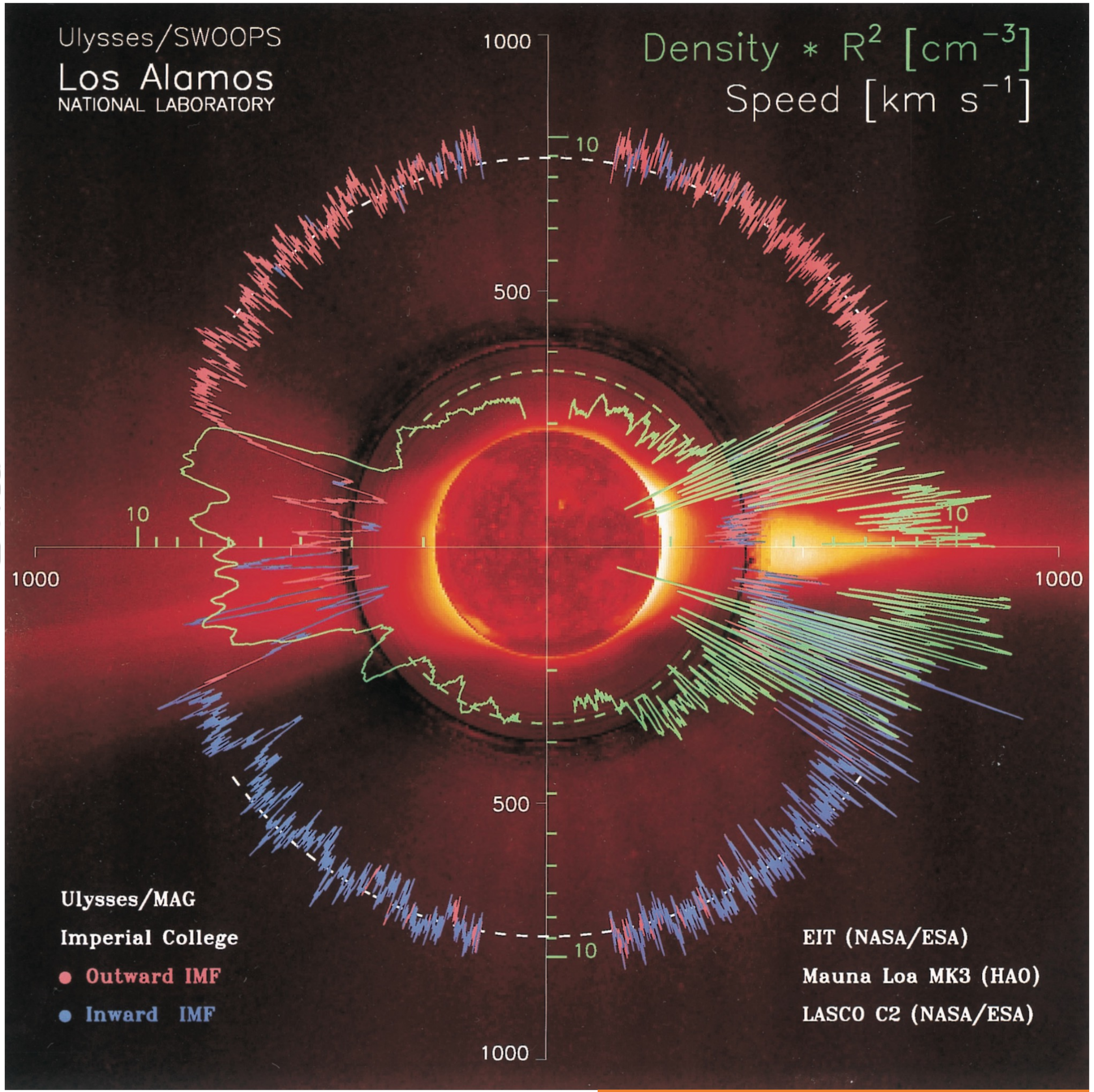




3D Ribbon Structure

Zirnstein et al. (2015, ApJL)

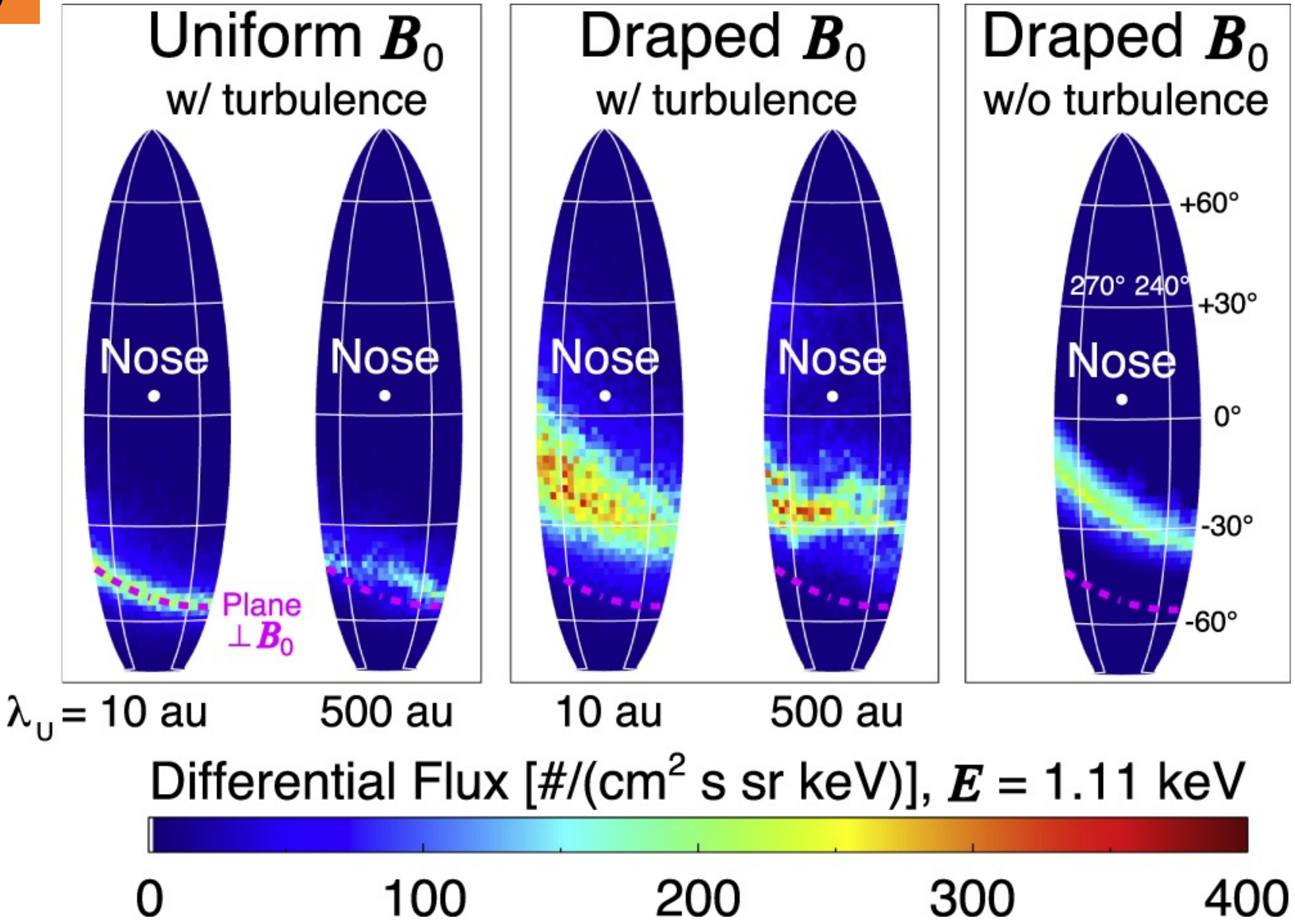




McComas et al. (2000, JGR)

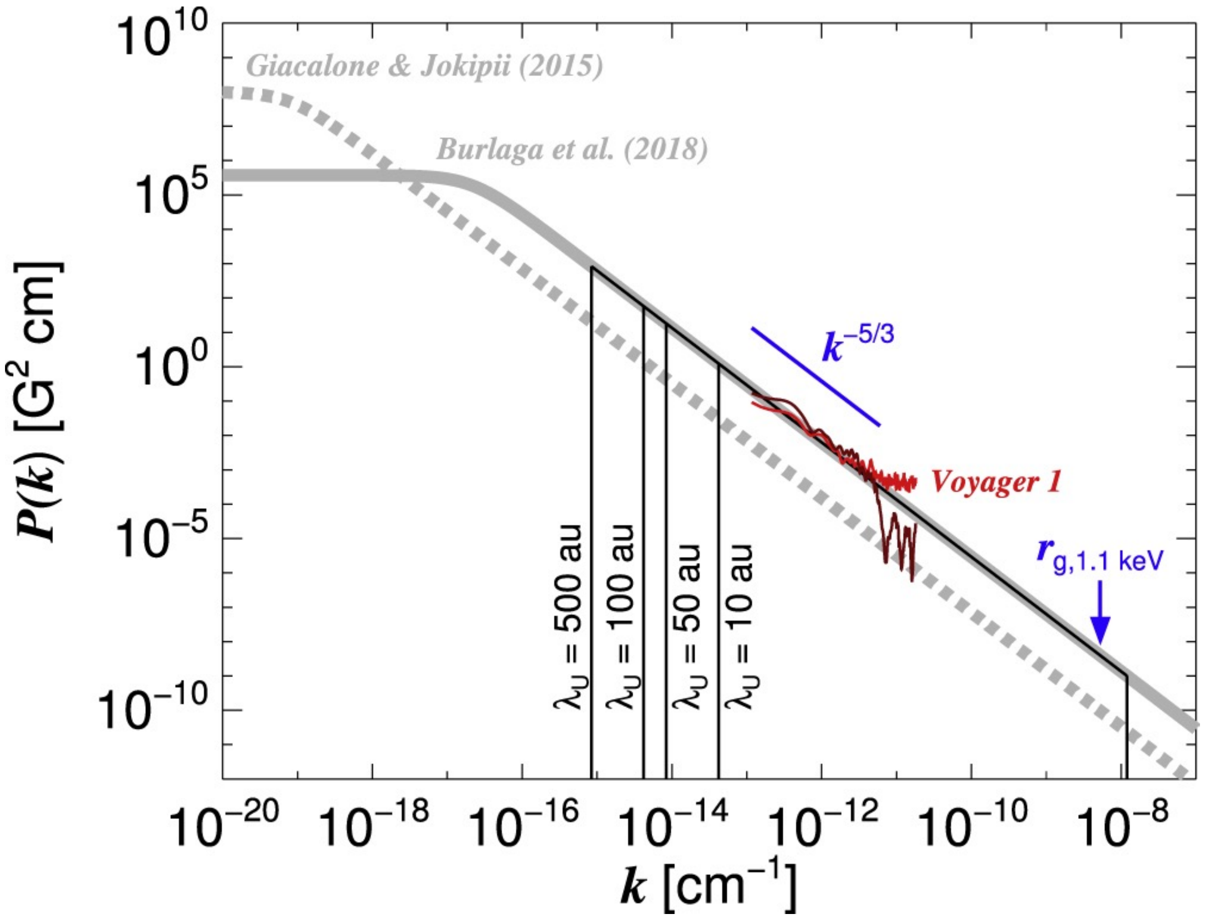
Draping of the ISMF and its Effects on the Ribbon

Zirnstein et al. (2020, ApJ)

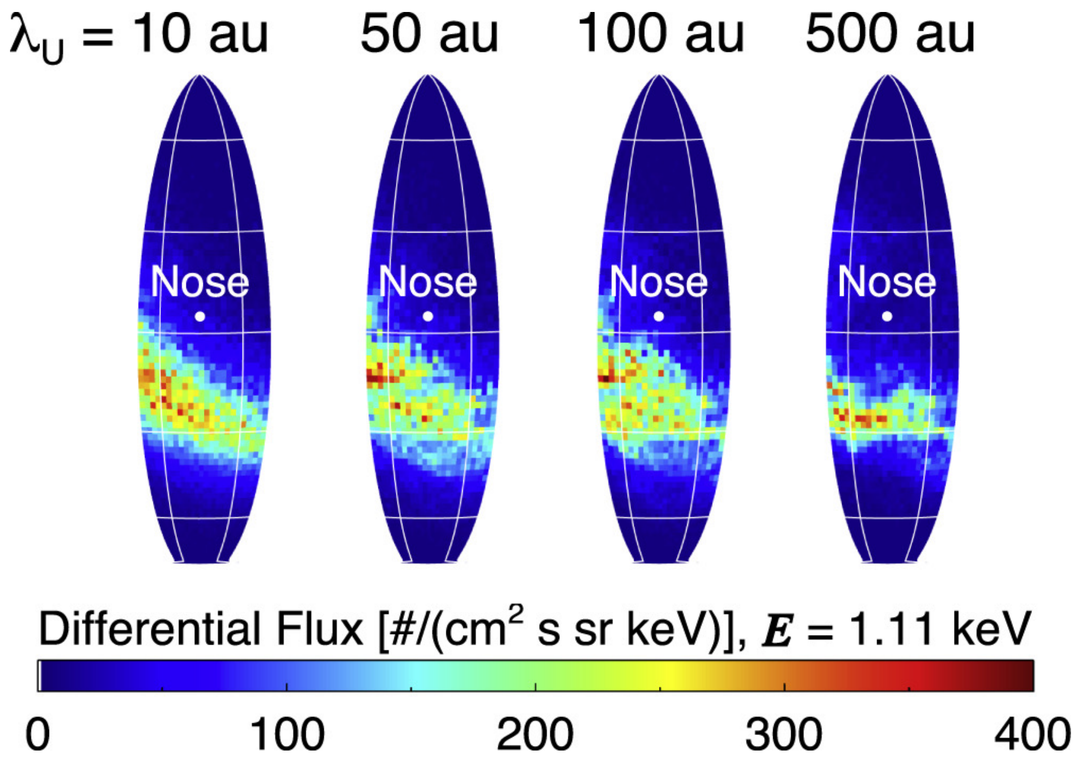


Ribbon Structure is Affected by Interstellar Turbulence

Zirnstein et al. (2020, ApJ)

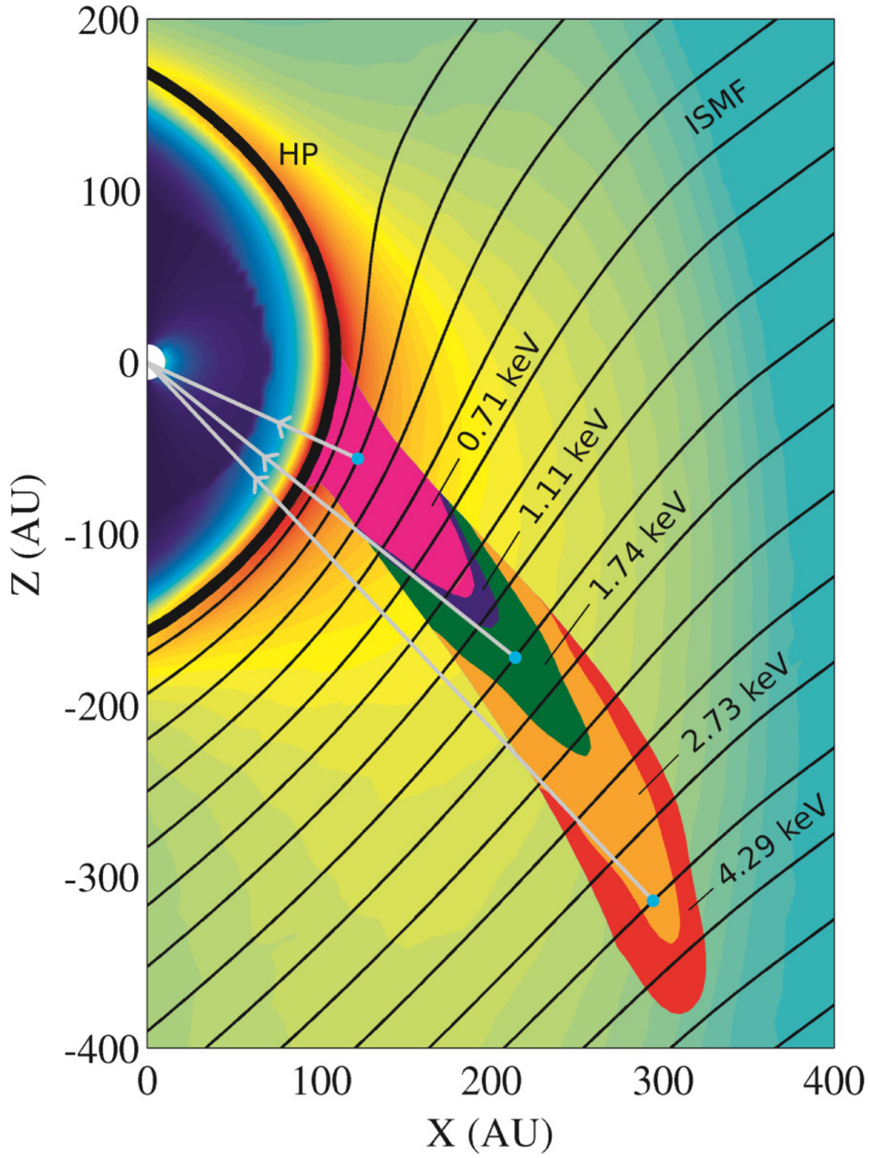


- The power level and correlation scale of turbulence in the interstellar medium may significantly affect the Ribbon's shape and position in the sky



Ribbon Position is Energy-dependent

Zirnstein et al. (2016, ApJL)

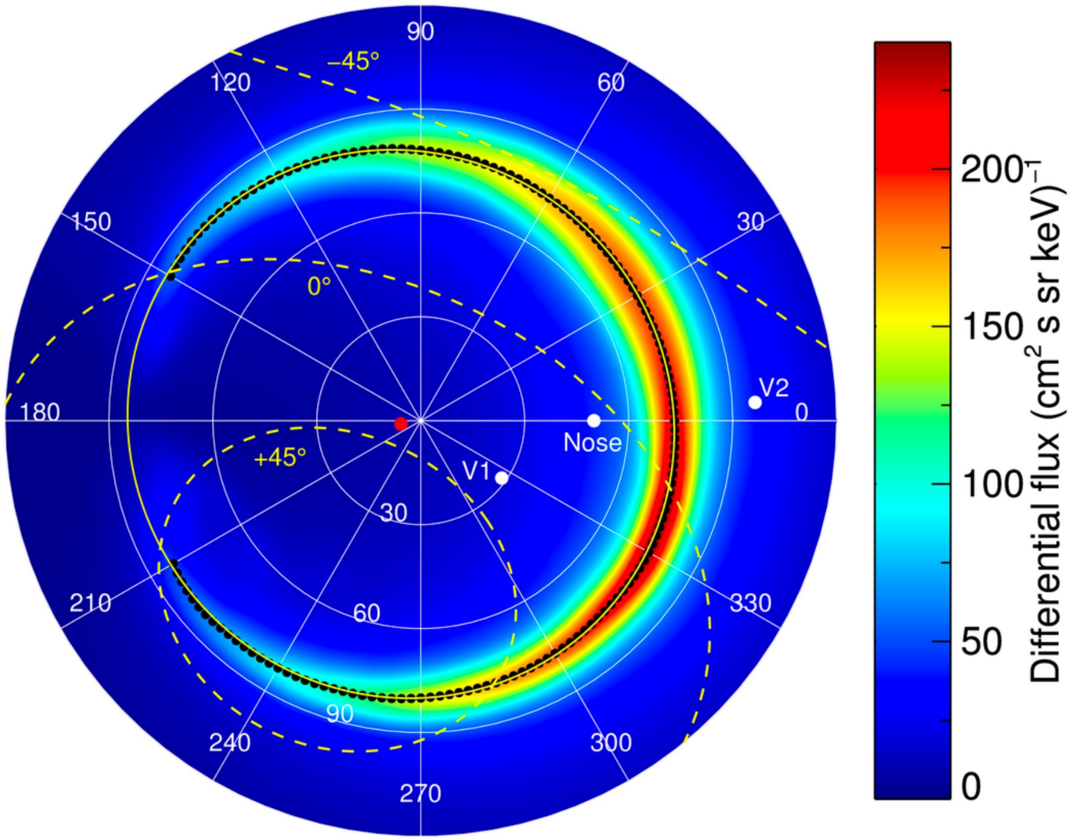


- Draping of the ISMF around the heliosphere creates spatially-changing Ribbon source
- Higher energy *secondary* (Ribbon) ENAs originate on average farther from the heliopause due to longer mean free path of *primary* ENAs
  - Causes Ribbon observed at higher energies (e.g., ESA 6) to appear to have a larger radius than at lower energies (e.g., ESA 2)
- Ribbon sources still overlap

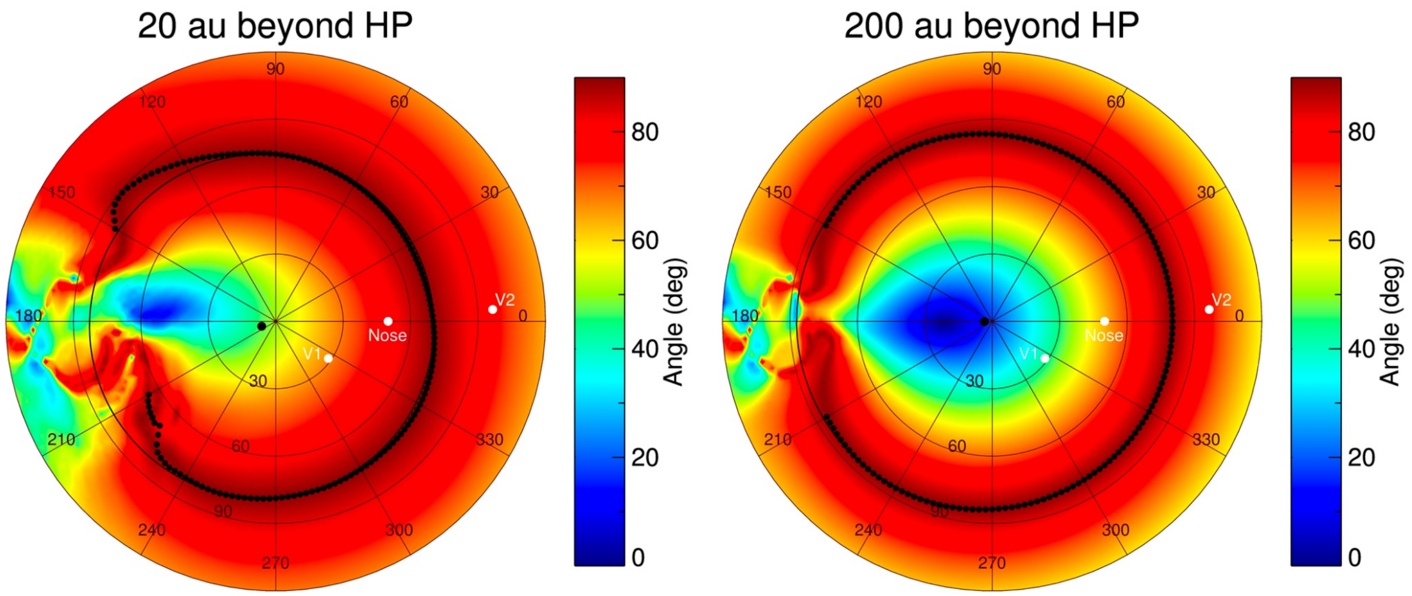
Ribbon Energy-dependent Circularity

Zirnstein et al. (2016, A&A)

Ribbon centered frame

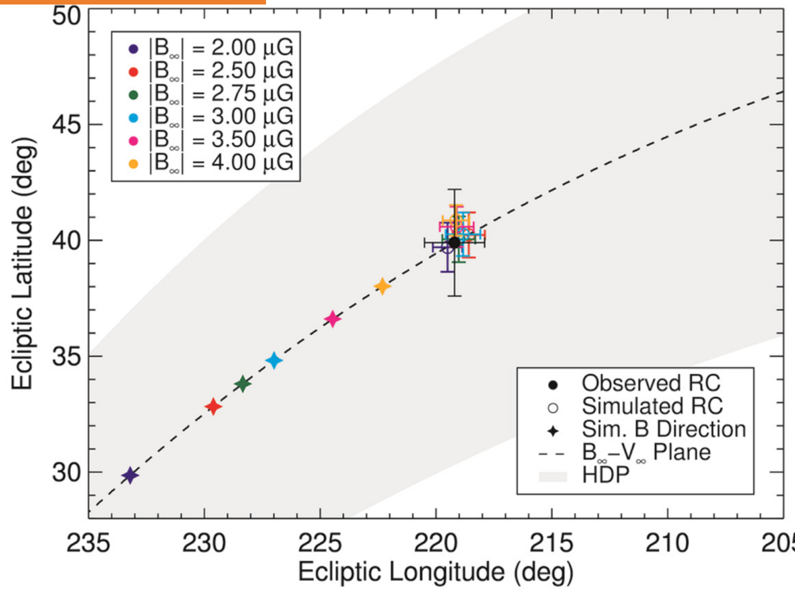


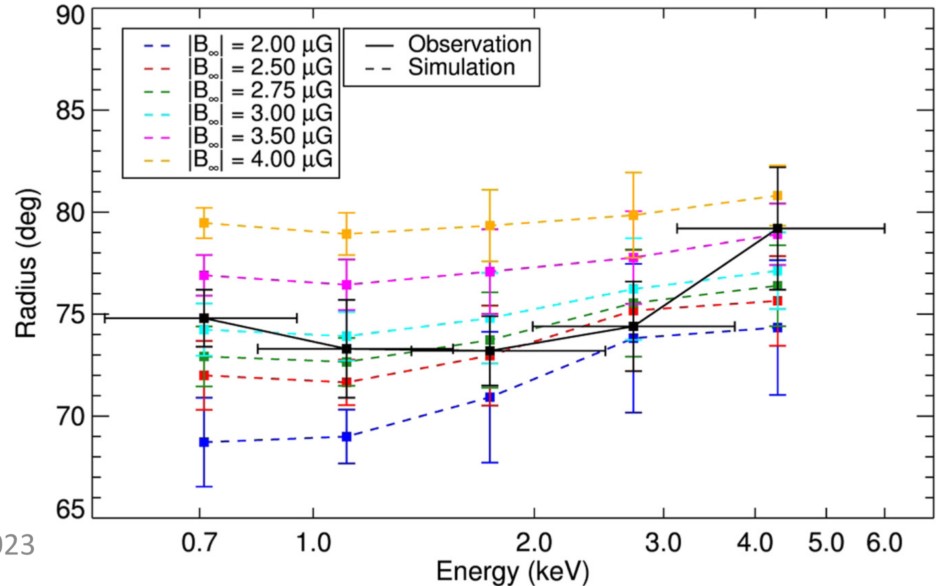
B · r angle



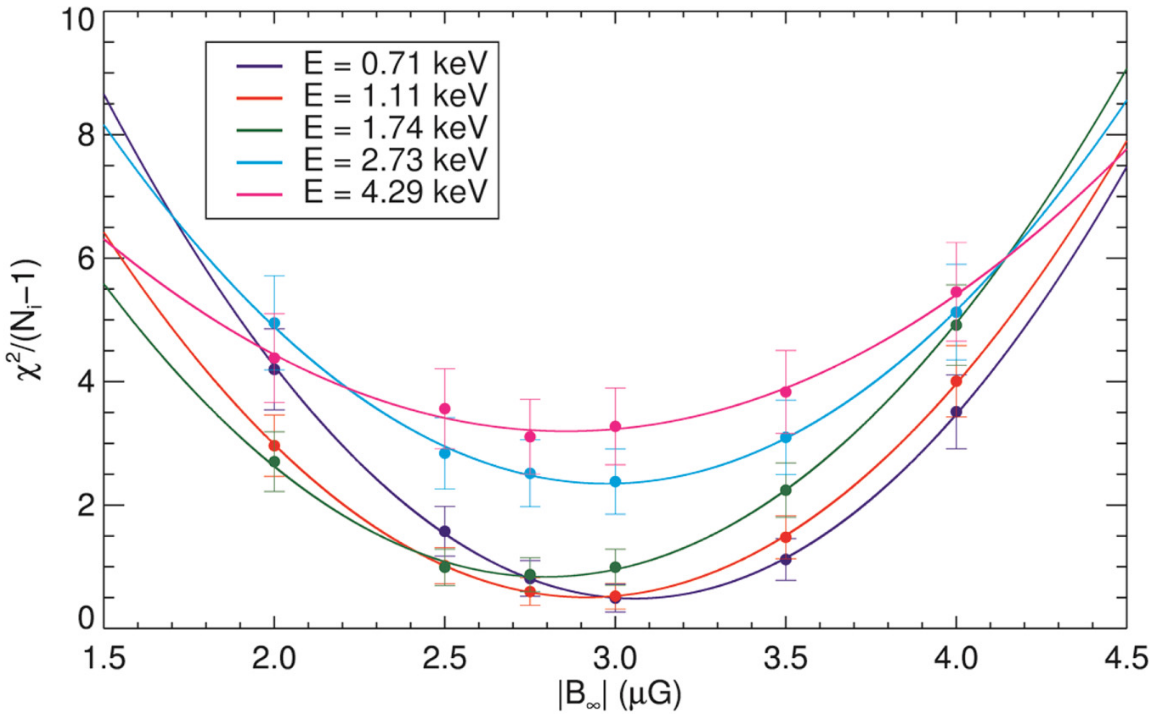
Ribbon Energy-dependent Circularity

Zirnstein et al. (2016, ApJL)



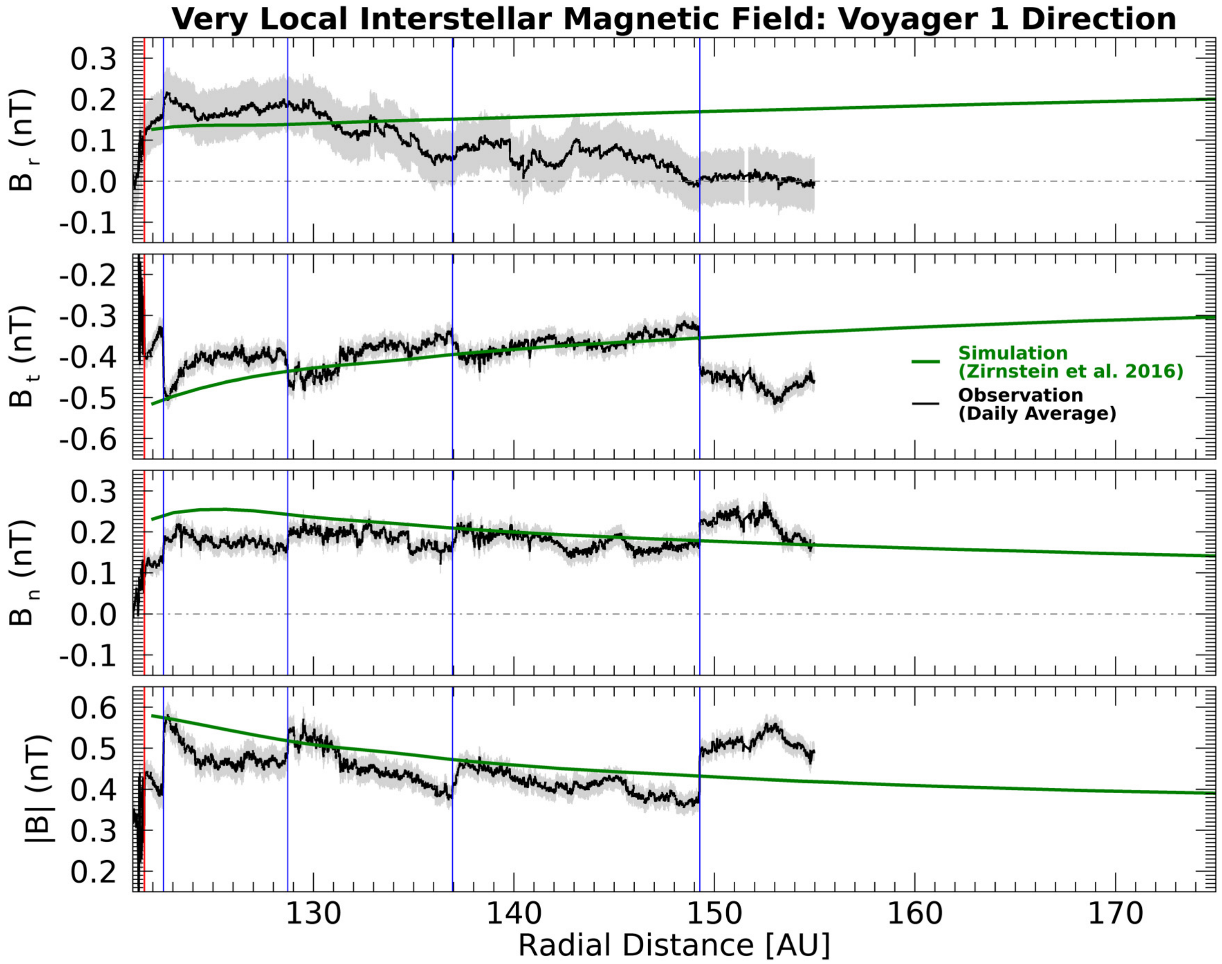


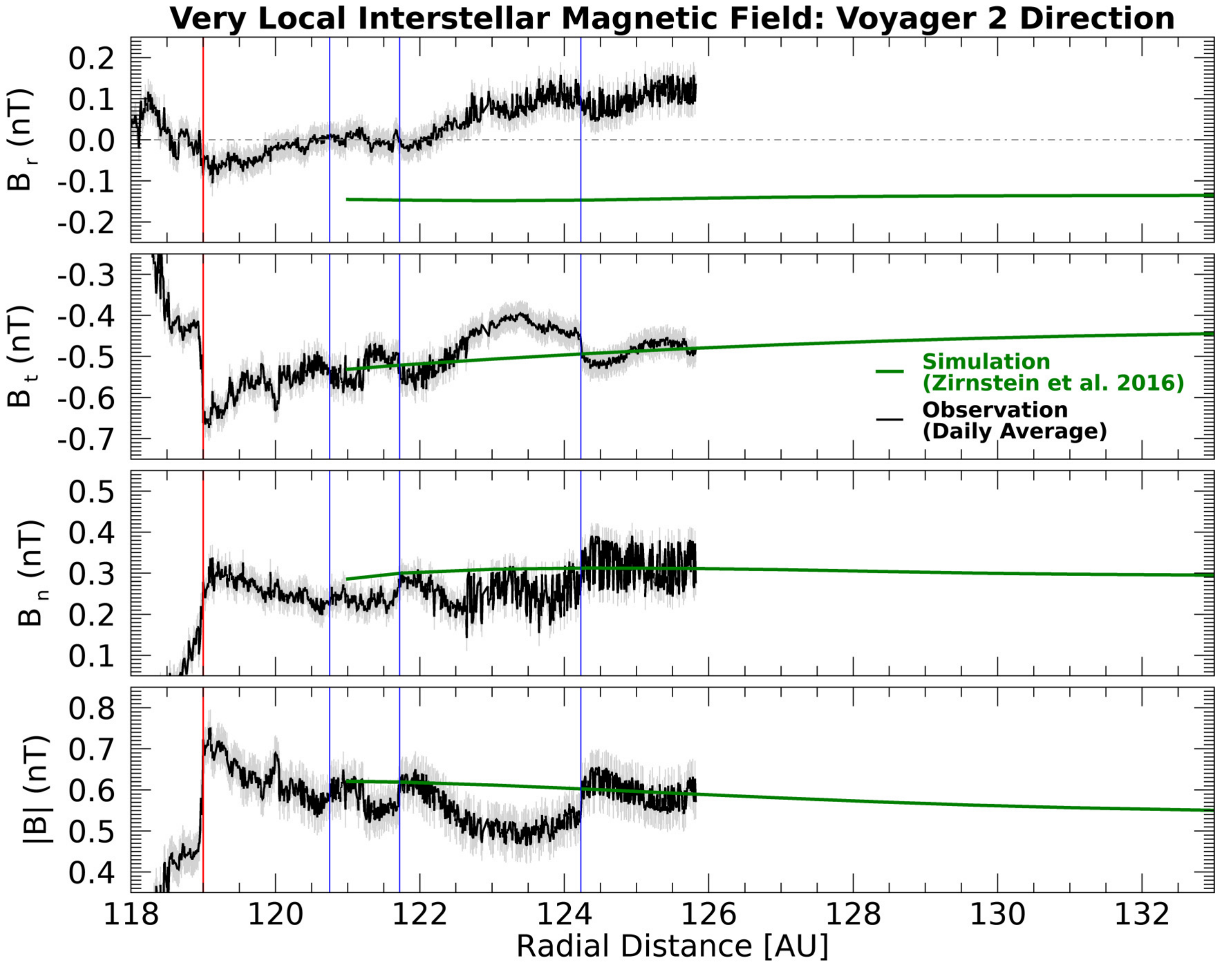
- Modeling the IBEX Ribbon at each ESA with different ISMF configurations (magnitude and direction) allows us to derive the most likely *pristine* ISMF outside our heliosphere



Comparison with Voyager Observations of ISMF

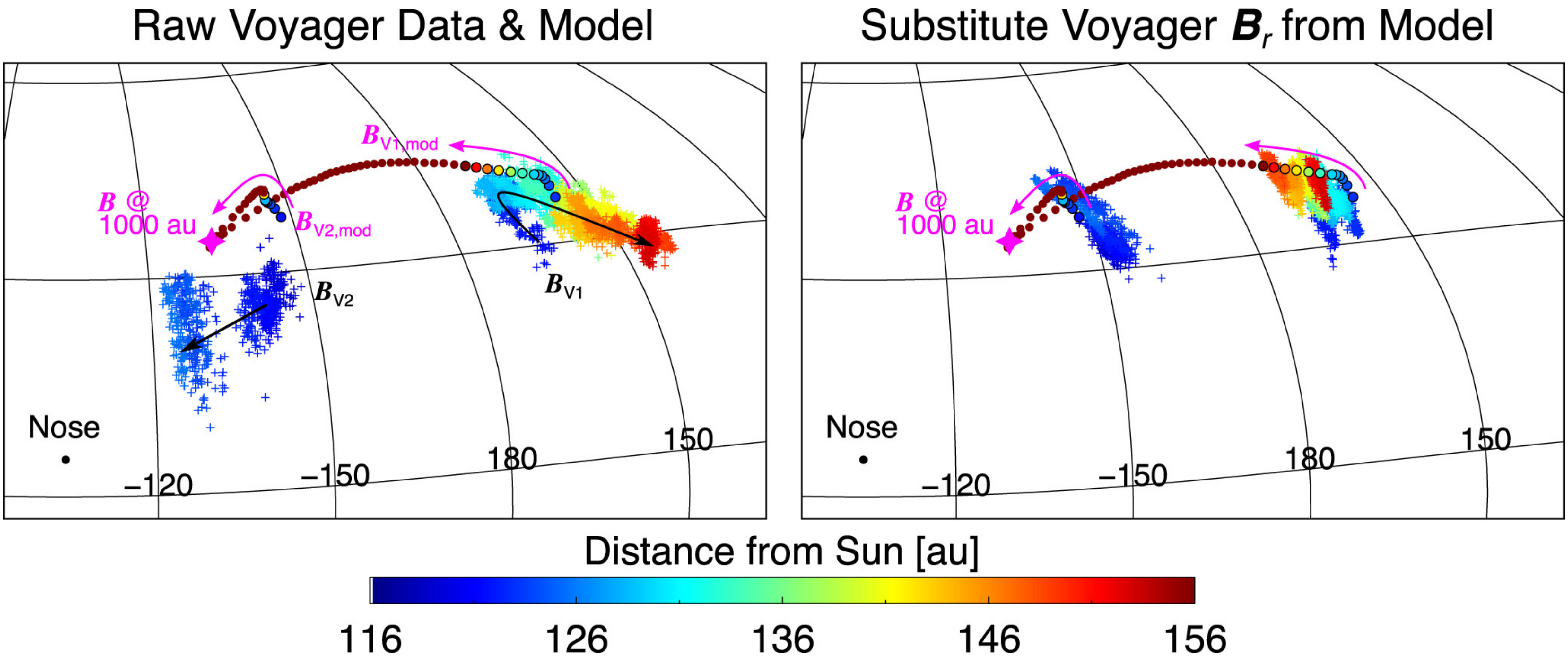
Rankin et al. (2023, ApJL)





Comparison with Voyager Observations of ISMF

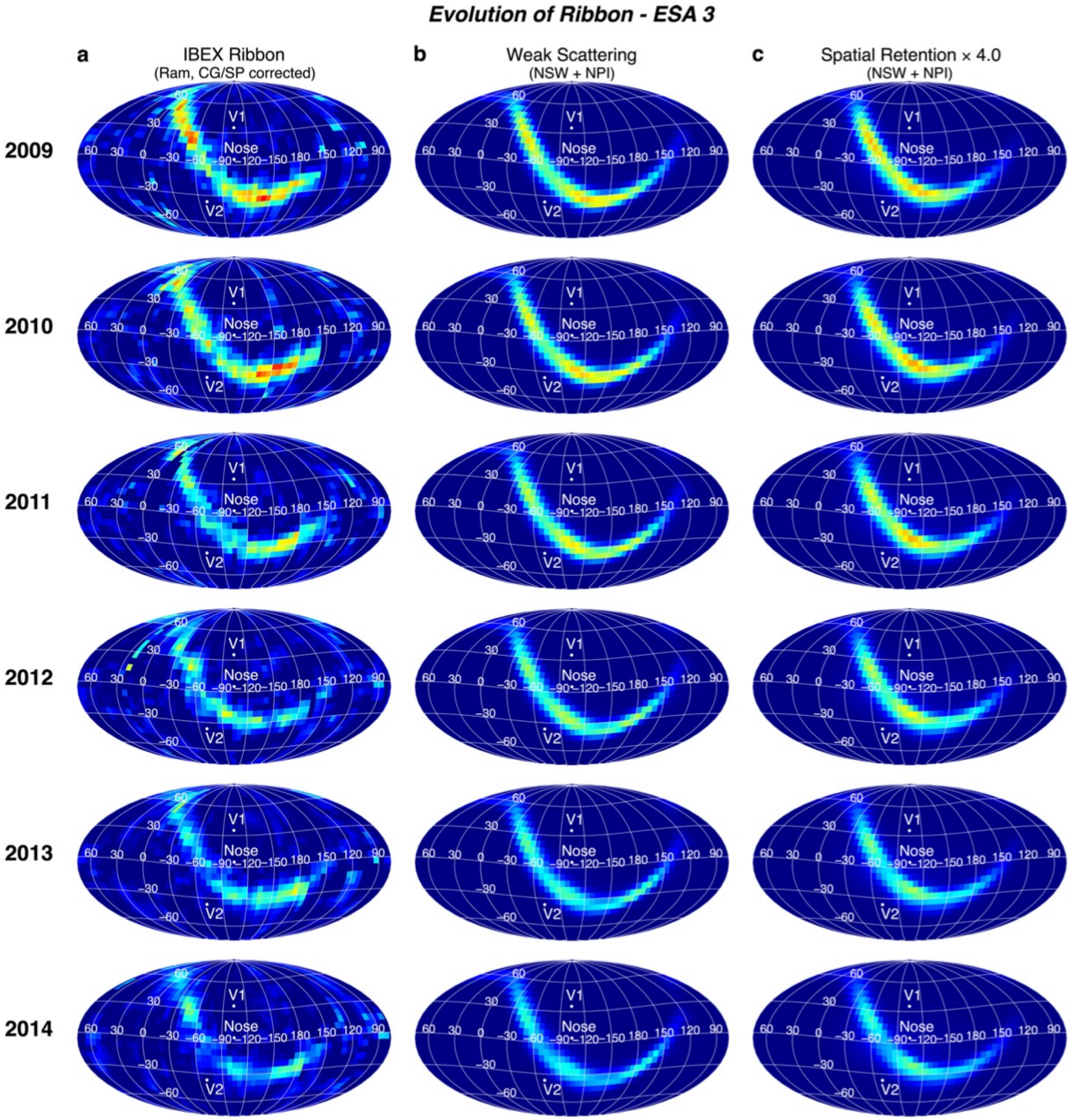
Rankin et al. (2023, ApJL)



Ribbon Evolution

Zirnstein et al. (2023, in press)

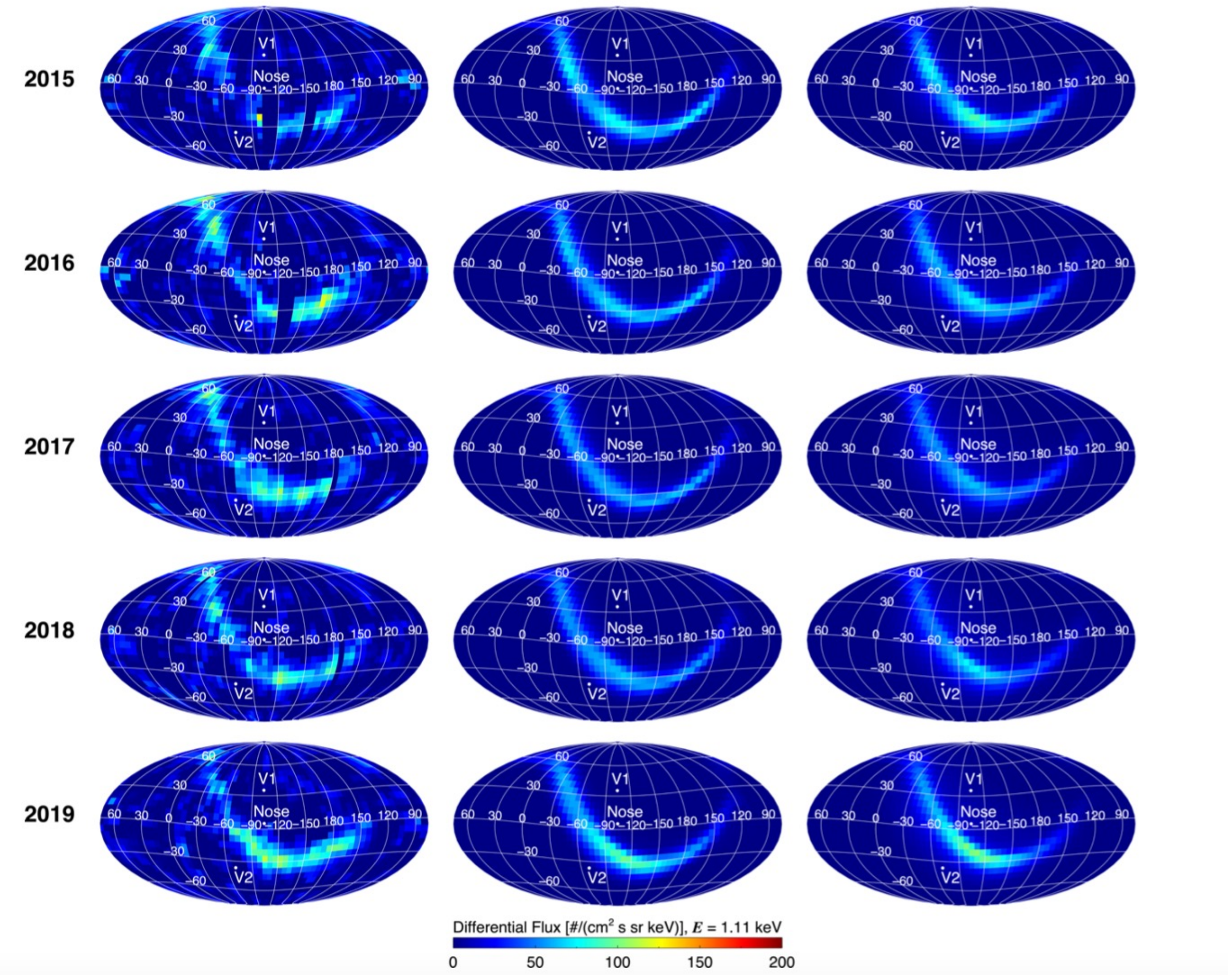
- Time-dependent results shown for ESA 3 from 2009-2014
  - *Again, spatial retention model is scaled up by factor of 4*
- Overall, there is a global decrease in ENA intensity at similar rates seen in the data and models
- Not much to distinguish between models



Ribbon Evolution

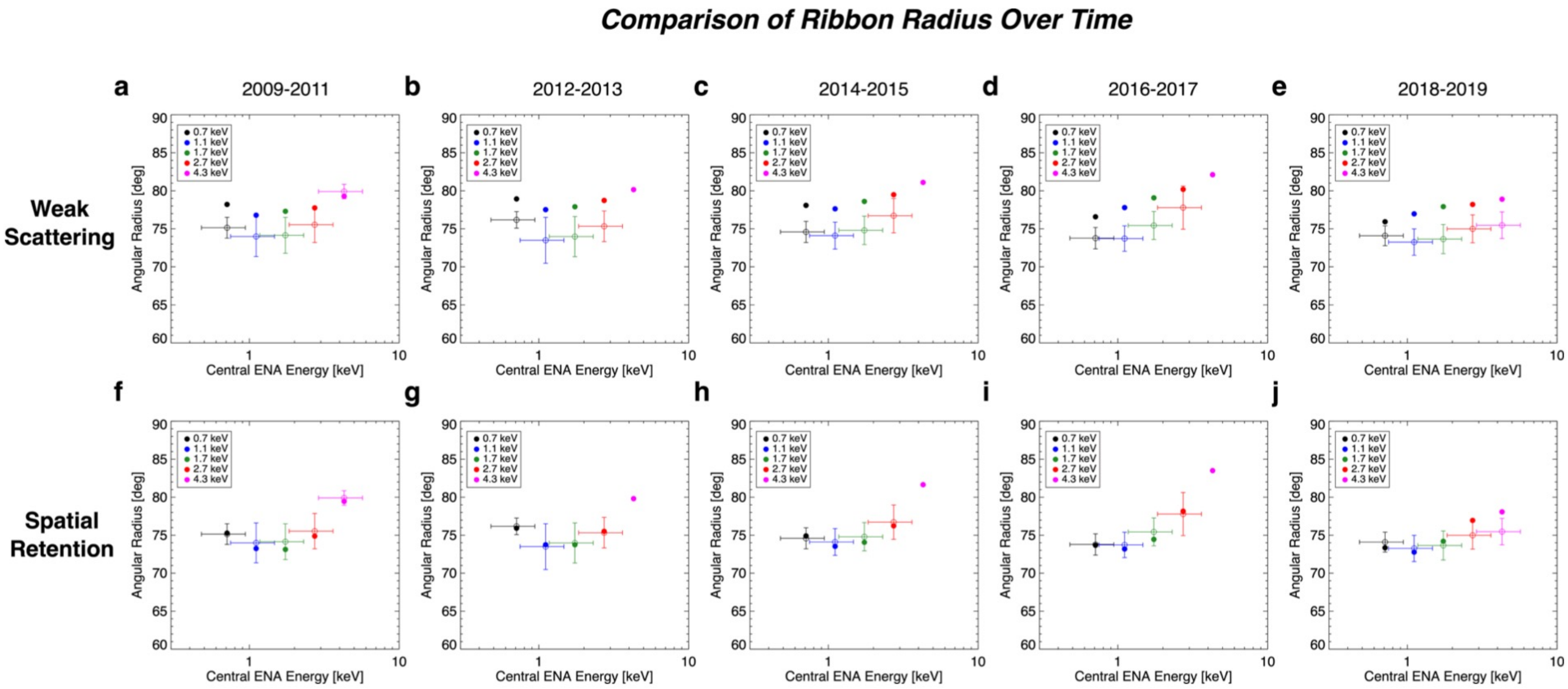
Zirnstein et al. (2023, in press)

- Time-dependent results shown for ESA 3 from 2015-2019
  - *Again, spatial retention model is scaled up by factor of 4*
- Fluxes decrease until ~2016, then start increasing in southern hemisphere in ~2019
- Again, not much to distinguish between models



Evolution of Ribbon Radii Over Time

Zirnstein et al. (2023, to be submitted)

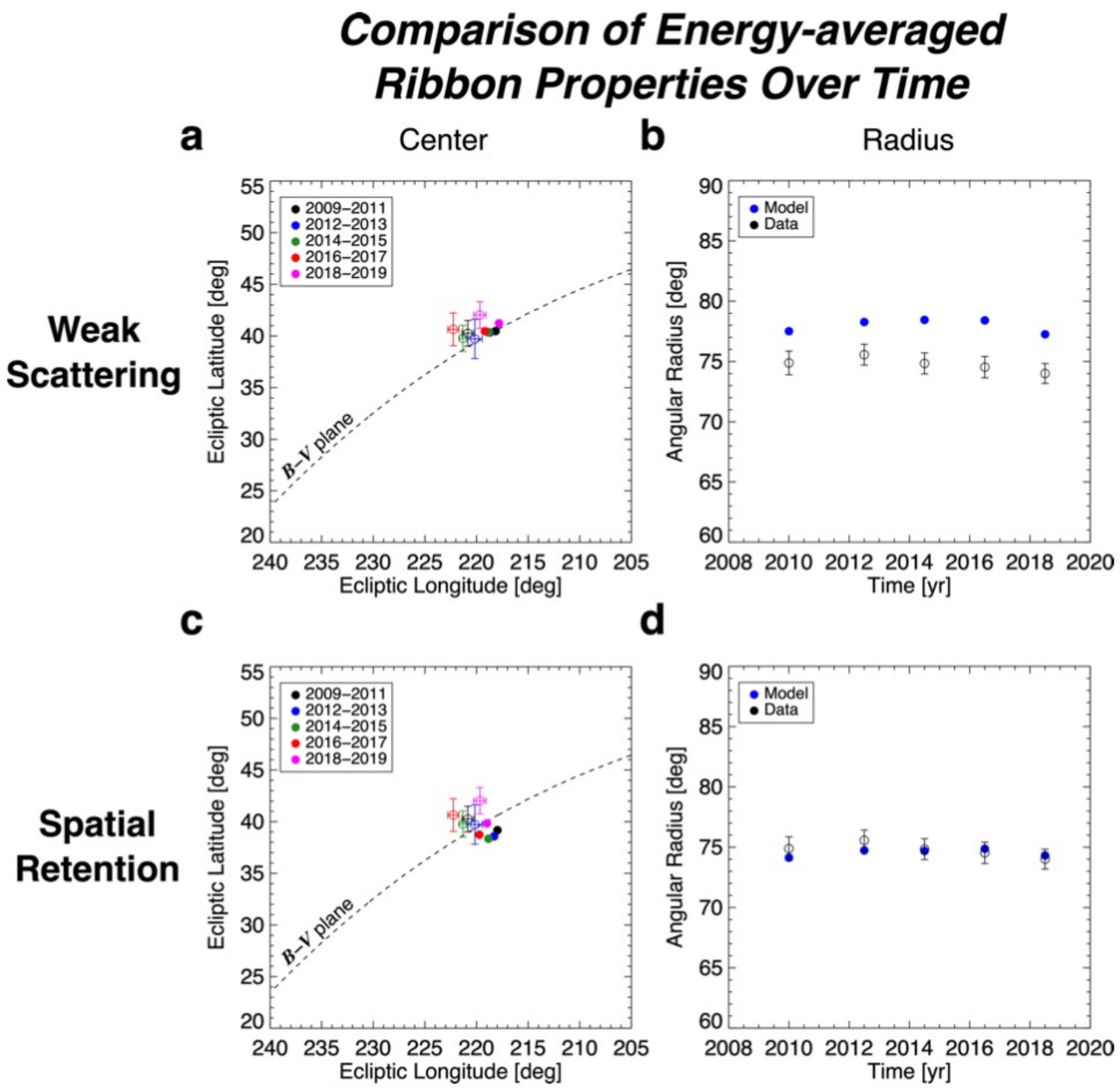


- Weak scattering results consistently overestimate ribbon radius (not new result; Zirnstein et al. 2021)
- Strong scattering results consistently match IBEX ribbon radius, though data uncertainties likely underestimated at ESA 5-6

Energy-averaged Centers and Radii

Zirnstein et al. (2023, to be submitted)

- Both data and model ribbon centers, averaged over energy, lie close to each other on the *B-V* plane
  - ***NOTE: We did not include ESA 6 in the average due to missing data and high systematic uncertainty unaccounted for***
  - Slight offset from data likely due to a few degree offset of the simulated interstellar magnetic field direction
- Ribbon centers do not appear to significantly change over time except from 2016 to 2019
- Ribbon radii do not appear to significantly change over time (in either model or data)
- Weak scattering radius overestimates data b/c ENA source is distributed much farther from heliosphere, reflecting closer to 'great circle'
- Strong scattering radius matches data within uncertainties, with not obvious trend over time



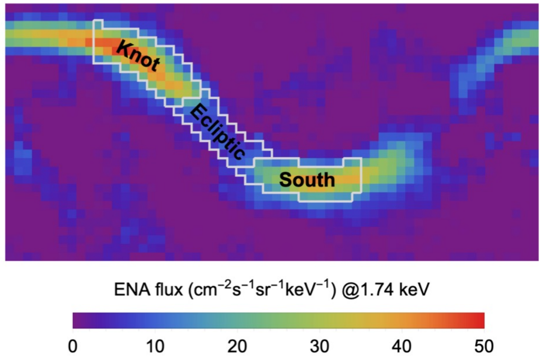
Conclusions

- *Ribbon shape, position, and intensity is strongly influenced by:*
  - *the draping of the ISMF around the heliosphere*
  - *the neutral SW/PUI distribution as a function of latitude and time*
  - *Small-scale PUI dynamics outside the heliopause*
- *Multiple "observables" are available to try to differentiate different Ribbon source models*
  - *Intensity, cross-section shape and width, position in the sky, circularity (radius, center location)*
- *Modeling ribbon to fit to IBEX observations allowed us to derive best-fit ISMF vector far from heliosphere*
  - *The results independently compare well to Voyager data, understanding that the measured* $\mathbf{B}_r$ *component has significant systematic uncertainties*
- *Ribbon evolution over the solar cycle is replicated well in both weak and spatial retention models, making them essentially indistinguishable*
  - *Largest difference between models is the low intensity of the spatial retention model, requiring at least factor of 4 increase to match data*
- *Ribbon centers and radii, however, do reveal noticeable differences between the models*
- *Based on our results, the spatial retention model is favored in reproducing the data as a function of time and geometry*
- *However, modifications to the spatial retention theory is required to fix the intensity problem*
  - *Scattering effects near* $\mathbf{B} \cdot \mathbf{r} = 0$ *amplifying distribution with pitch angles closer to 90° would increase ribbon flux at 1 au (Zirnstein et al. 2020)*

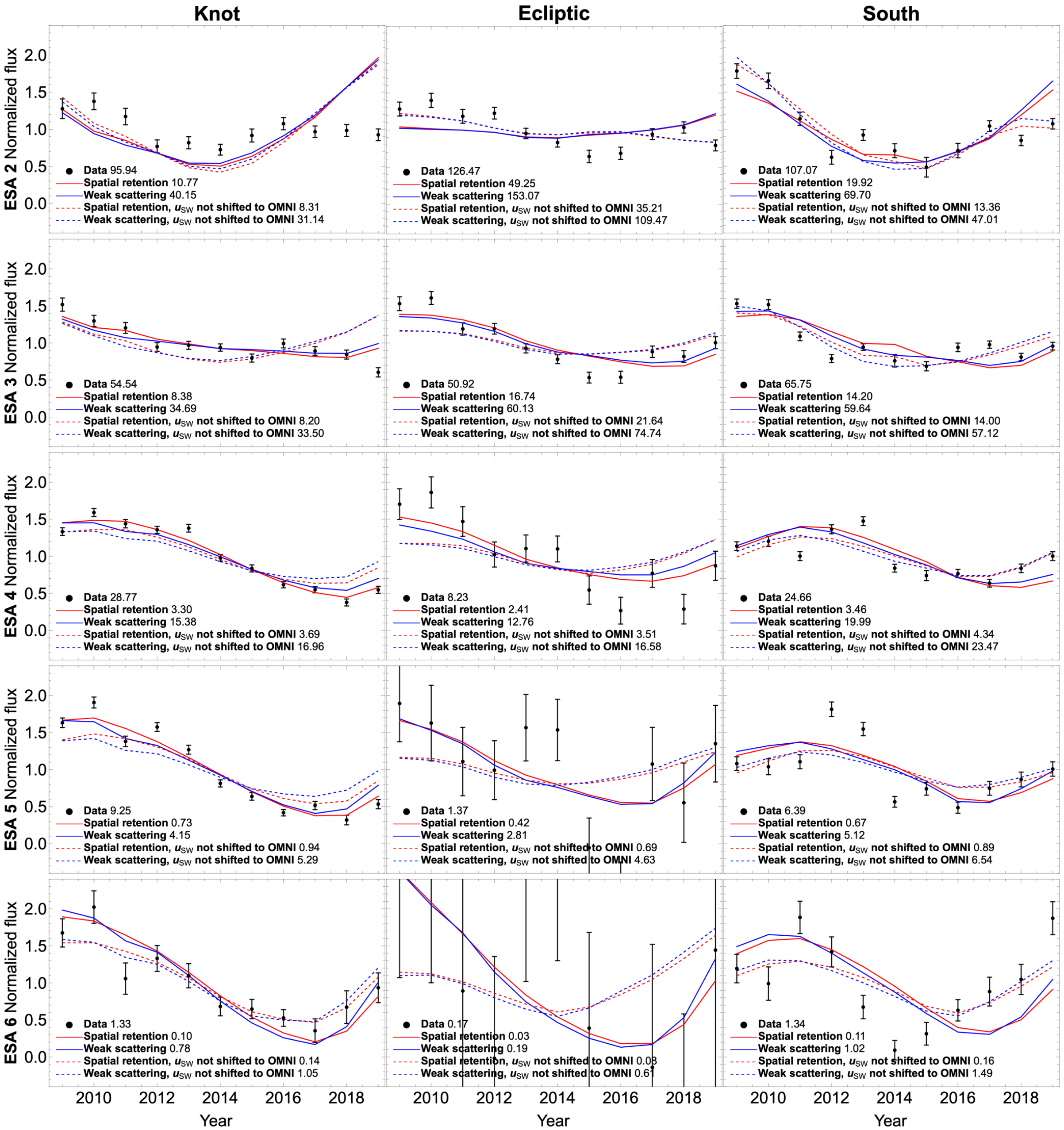
Extra Slides

Evolution over Sections of Sky

Zirnstein et al. (2023, in press)

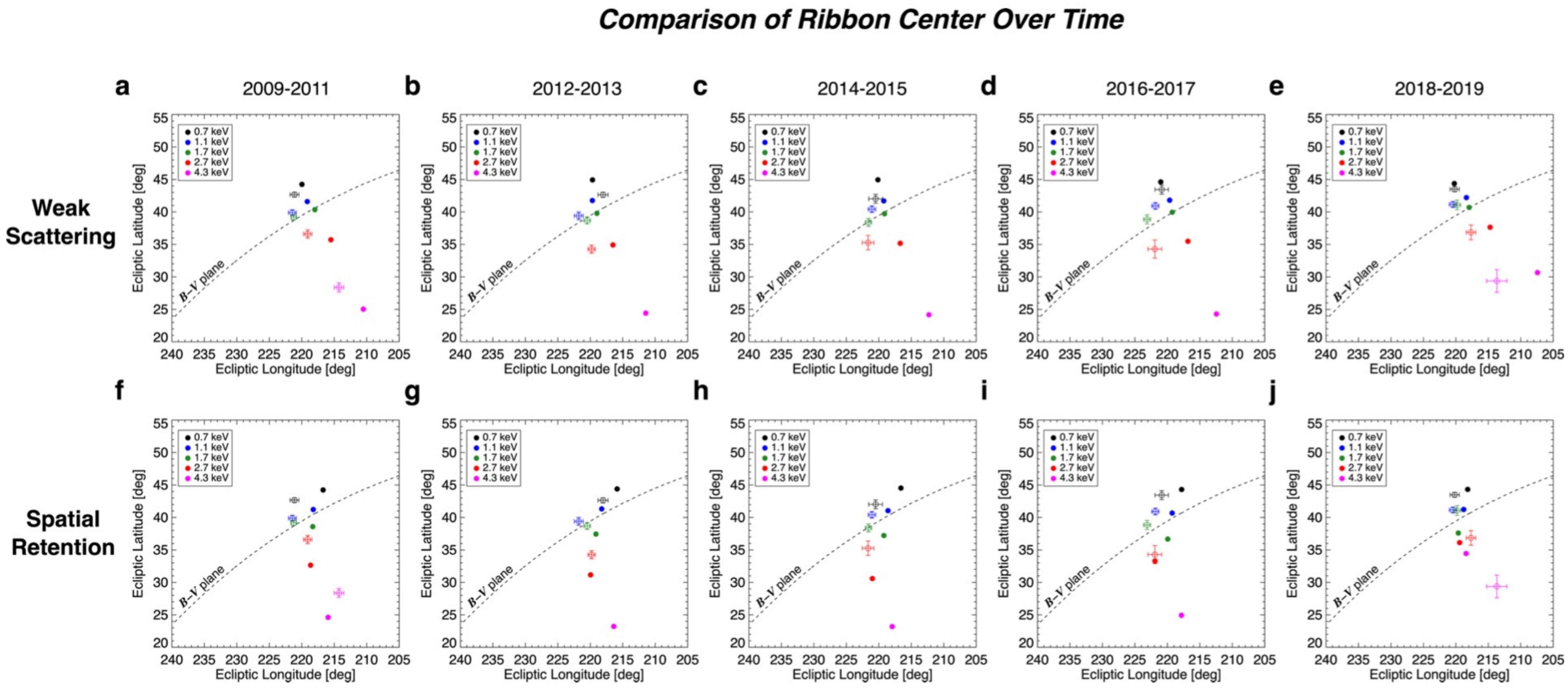


- We show results for **data**, **spatial retention model**, and **weak scattering model**
- Also show results where we scale IPS SW speeds to match OMNI (solid curves), and don't scale to OMNI (dashed curves)
- Numbers next to labels show factors used to scale the data/results such that the time-average equals 1



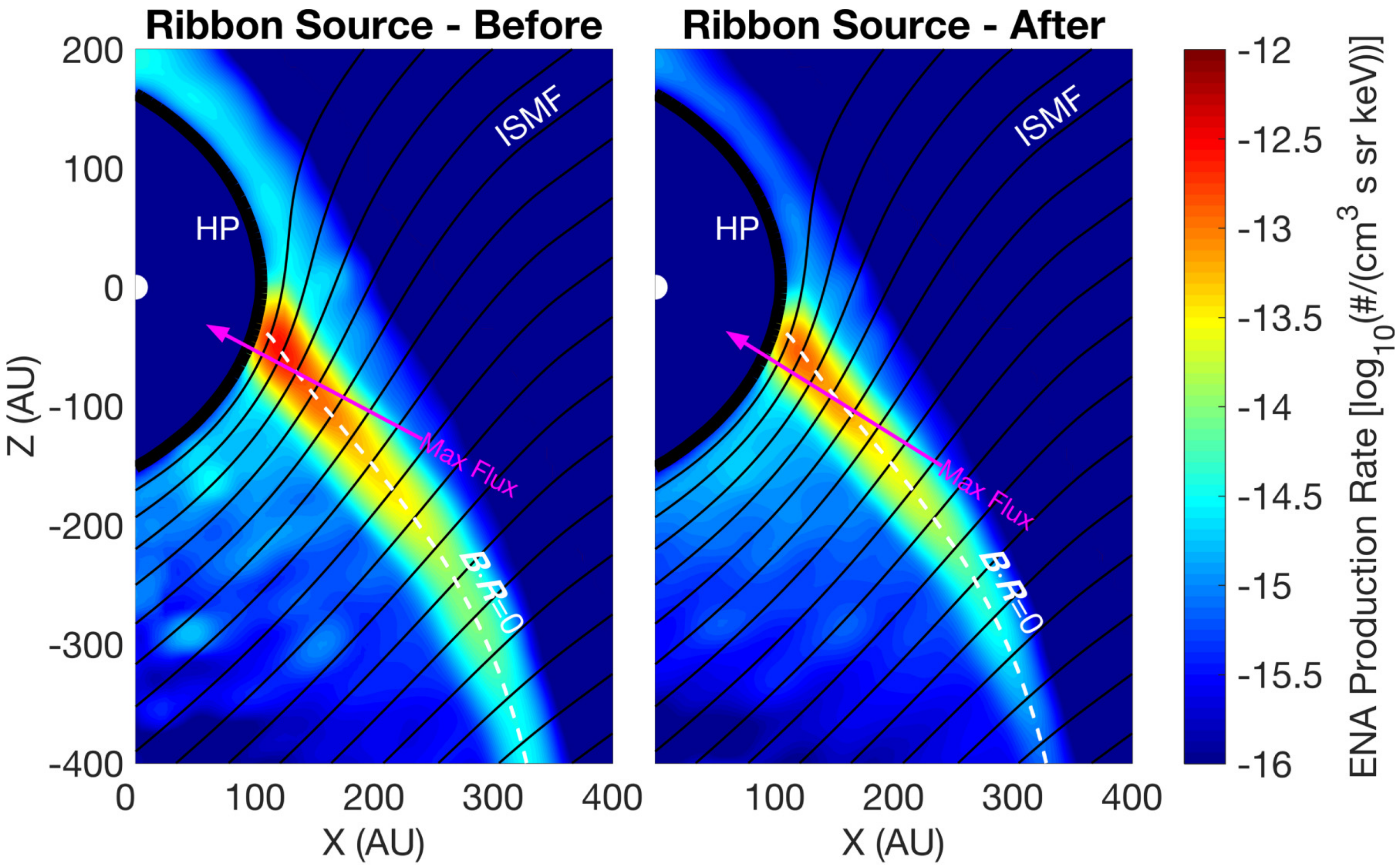
Evolution of Ribbon Centers Over Time

Zirnstein et al. (2023, in press)

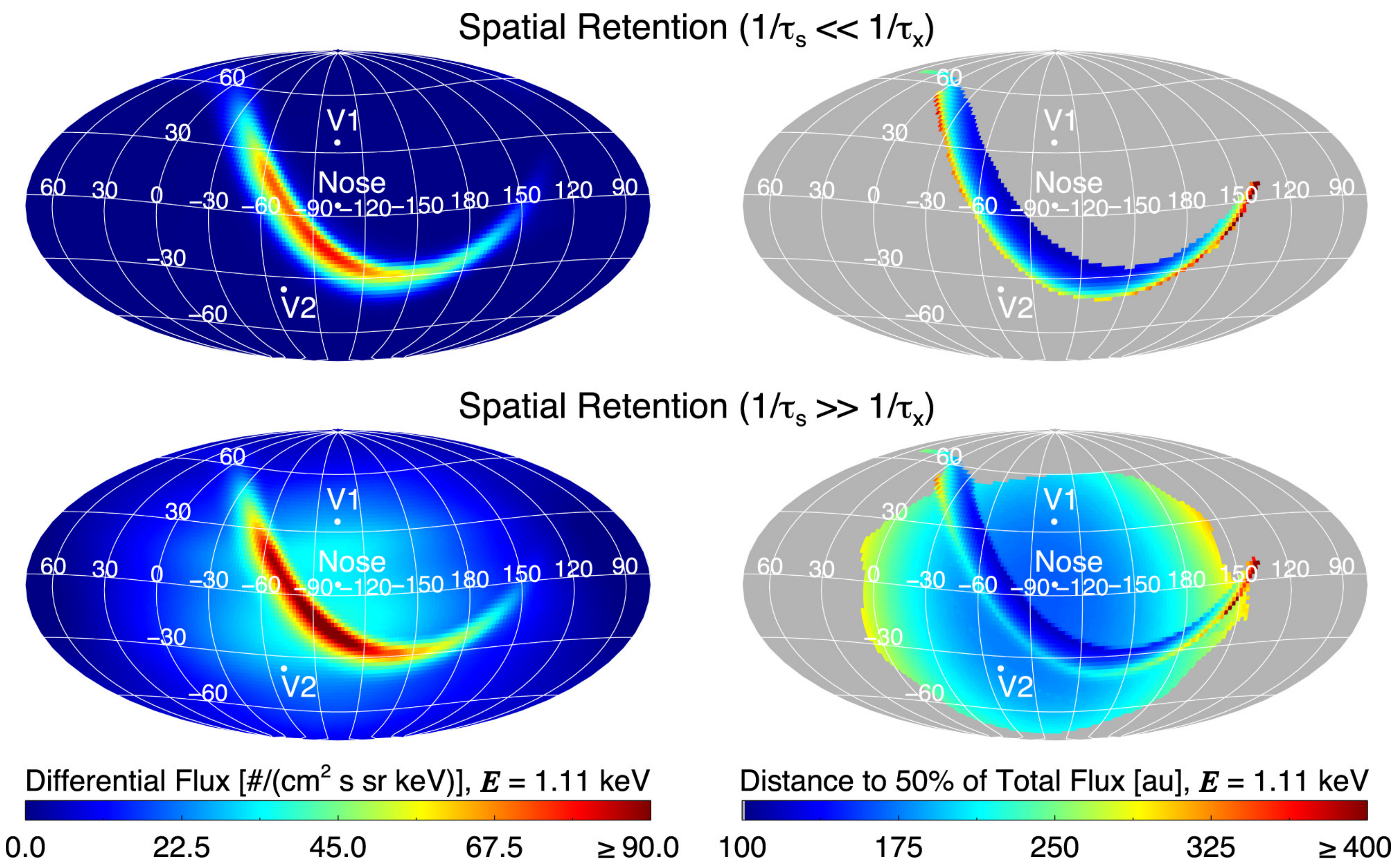


- While not overlapping exactly, the general trend in energy/latitude of ribbon centers is reproduced in the models
- The spatial retention model compares slightly better, particularly in 2014-2015 – just a systematic offset

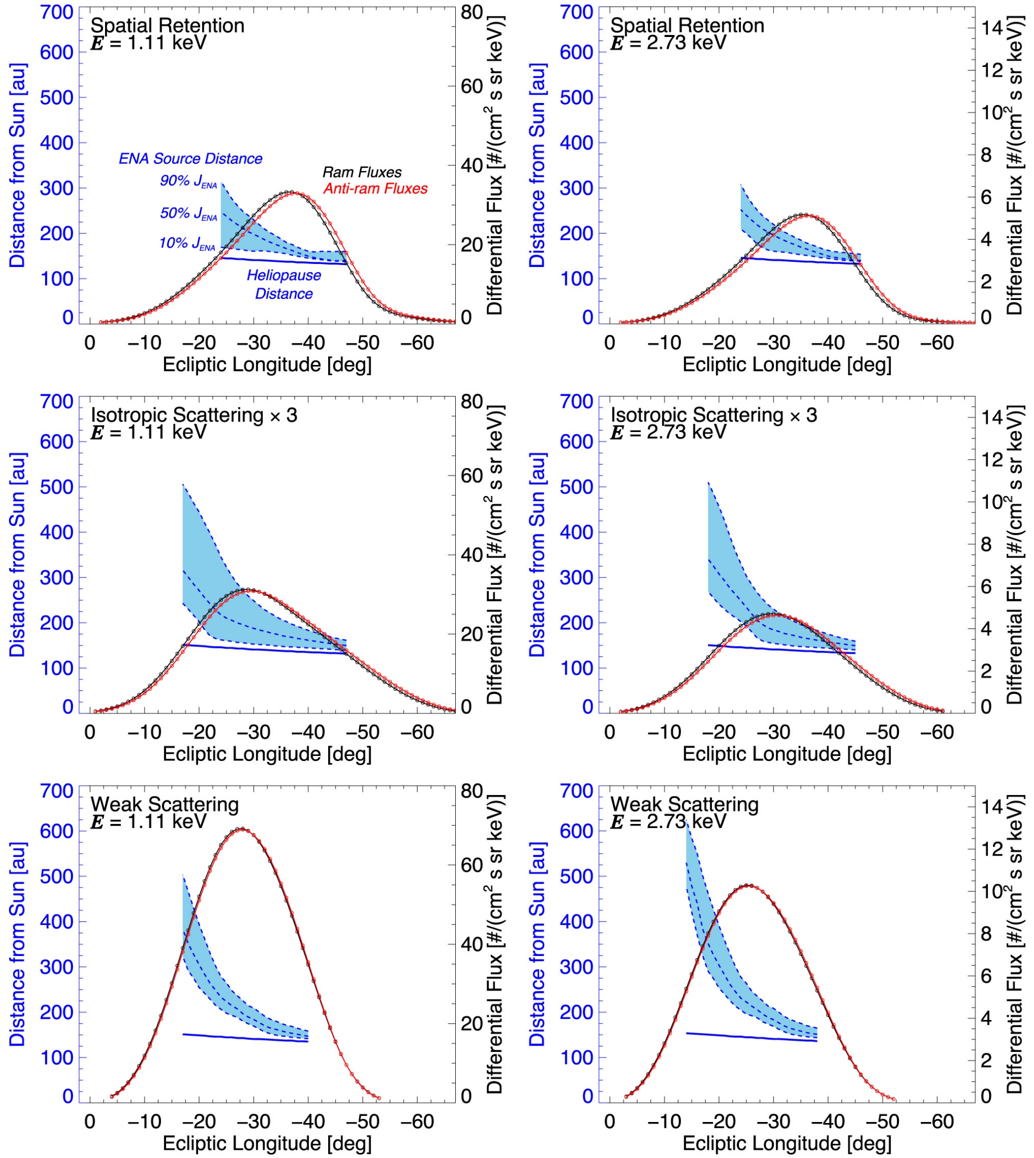
Ribbon Source in "Weak Scattering"



Distance to the Ribbon Source



Ribbon Cross-section Shape



- "Spatial retention" produces shape skewed away from Ribbon center (leftward)
- "Isotropic scattering" produces shape skewed towards Ribbon center (rightward)
- "Weak scattering" produces the most symmetric shape