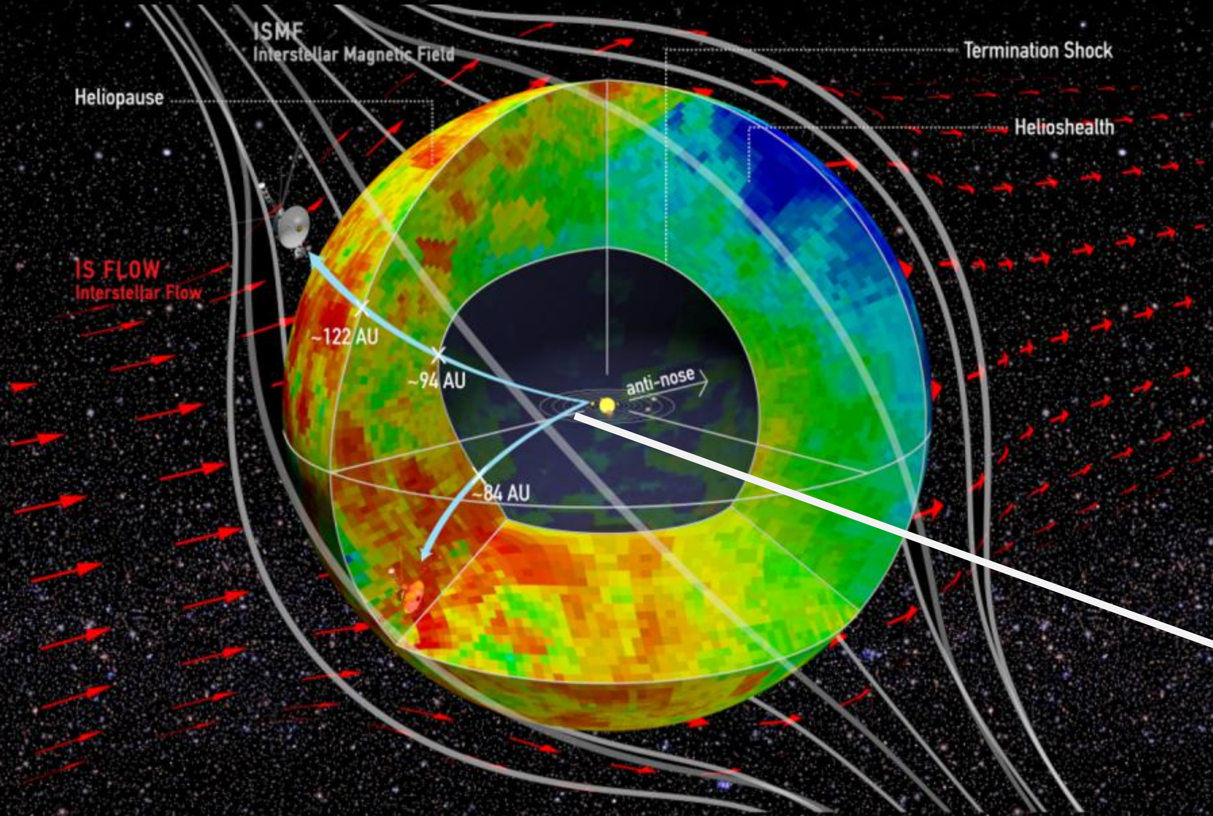
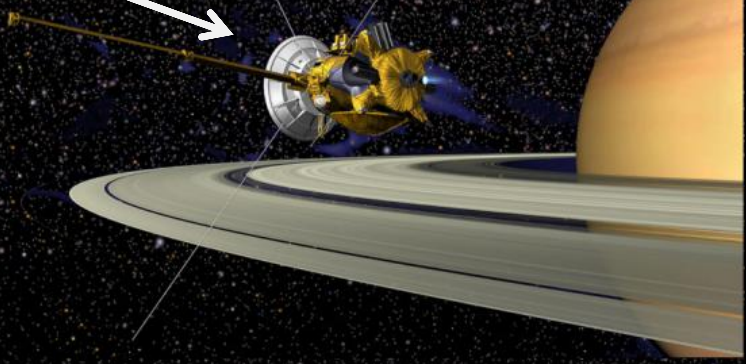


Dialynas et al, *Nature Astronomy*, [2017]

ION SPECTRA AND PRESSURES IN THE HELIOSHEATH

IN SITU IONS FROM THE VOYAGERS & ENA FROM CASSINI

CASSINI
GRAND FINALE
15-Sep.-2017

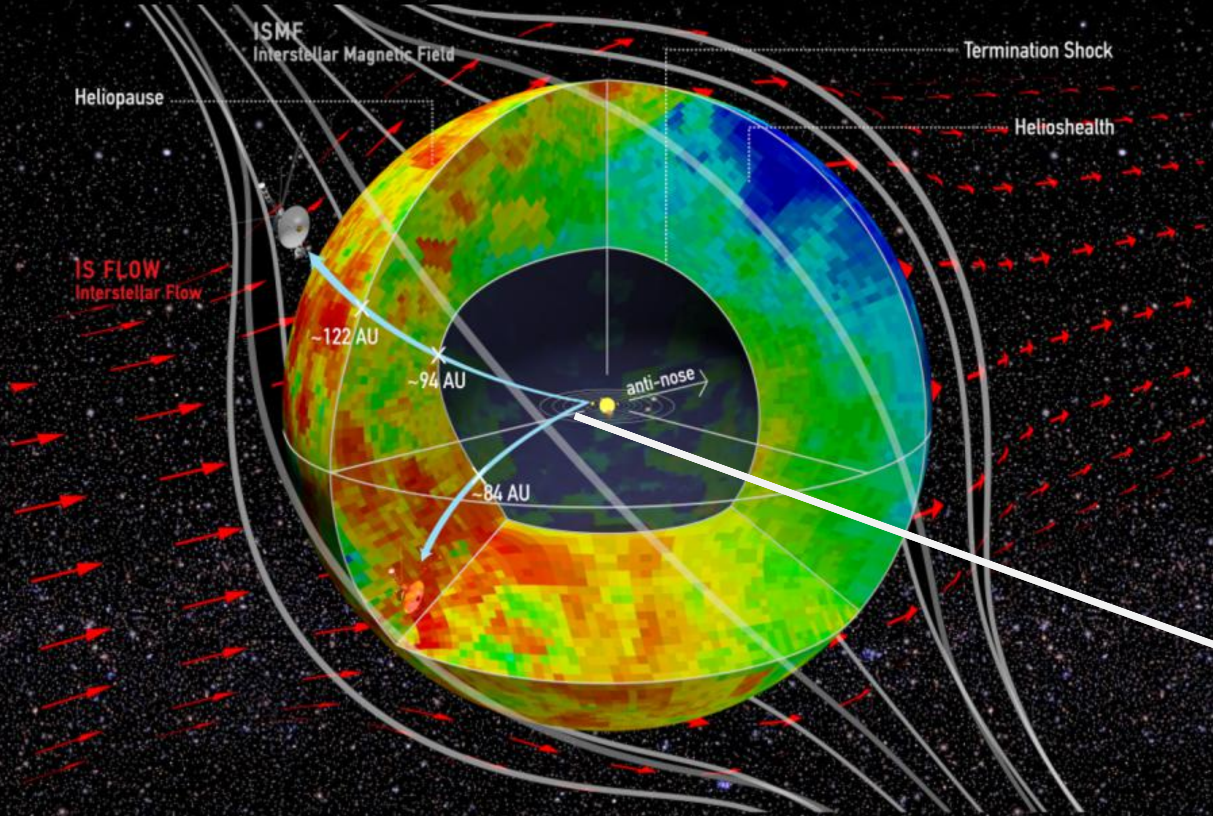


K. DIALYNAS[1], S. M. KRIMIGIS[1,2], R. B. DECKER[2] & D. G. MITCHELL[2]

[1]Office of Space Research & Technology, Academy of Athens, Greece.
[1]Johns Hopkins University, Applied Physics Laboratory, U.S.A.

Ion Spectra and Pressures in the Heliosheath

In Situ Ions From The Voyagers & ENA From Cassini



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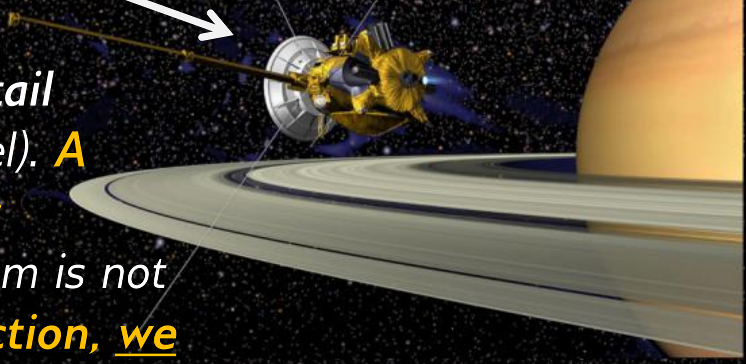
Cassini

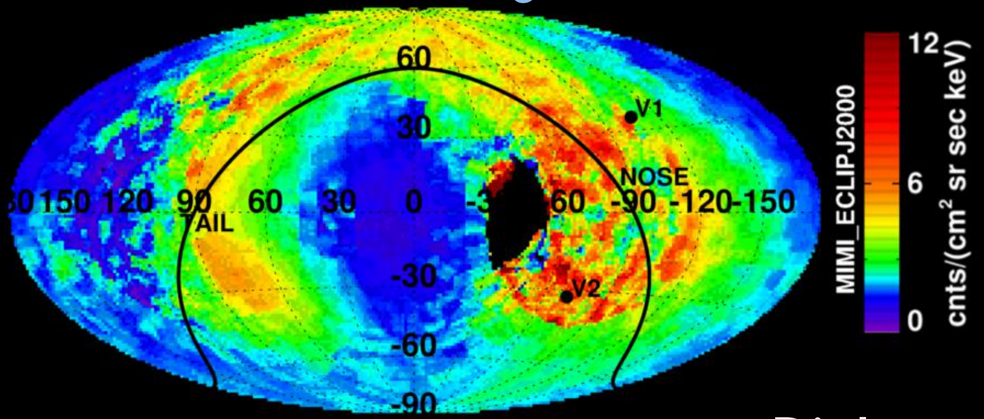
Grand Finale

15-Sep.-2017

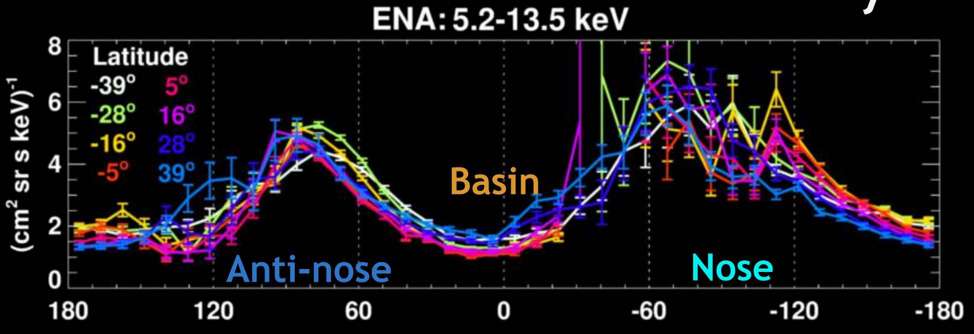


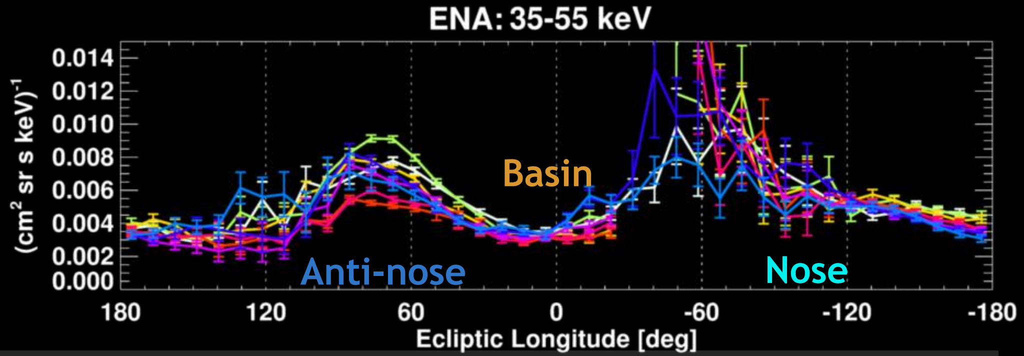
[...] The heliosphere bubble ***can inflate with time in either the anti-nose direction (tail models) or along the direction of the interstellar magnetic field*** *(the Parker 2 model).* ***A perfectly symmetric and stable heliosphere in time would not be possible and/or physically correct.*** *[...] Although the anisotropic ram pressure of the interstellar medium is not entirely negligible and* ***is expected to impose some distortion in the anti-nose direction, we stress that such distortion would differ substantially from any heliosheath structure that includes a very prolonged tail***[21]*. [...]*

Structure of >5.2 keV global ENA emissions // Morphology of the Belt



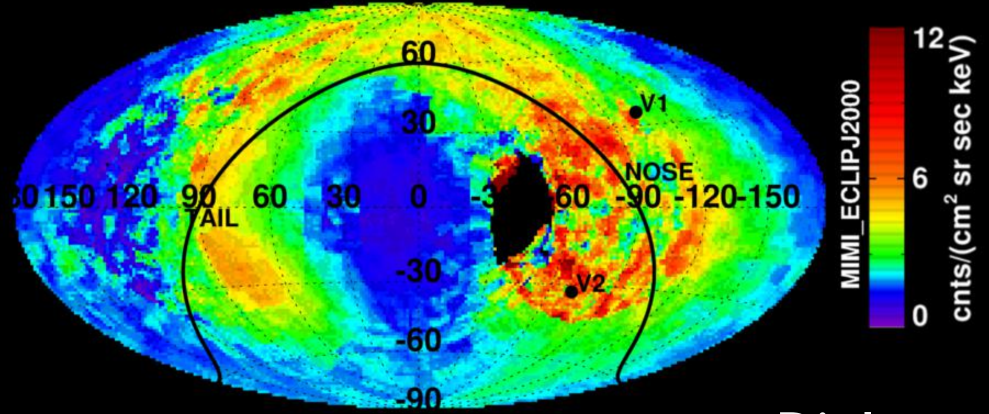
Dialynas et al. *J. Phys,* [2017b]

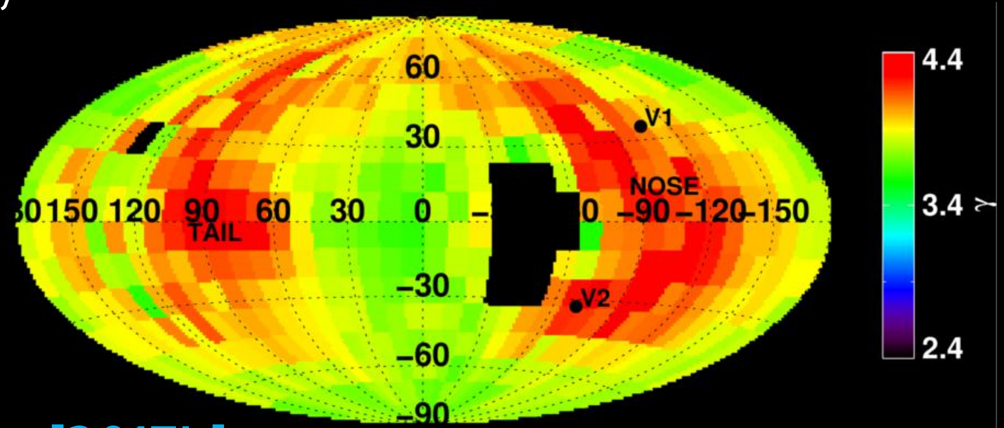




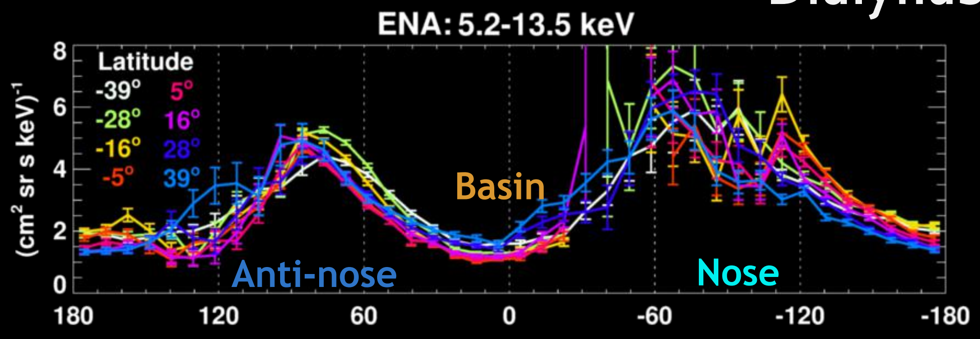
First >5.2 keV ENA image shown in Krimigis et al. *Science,* [2009]

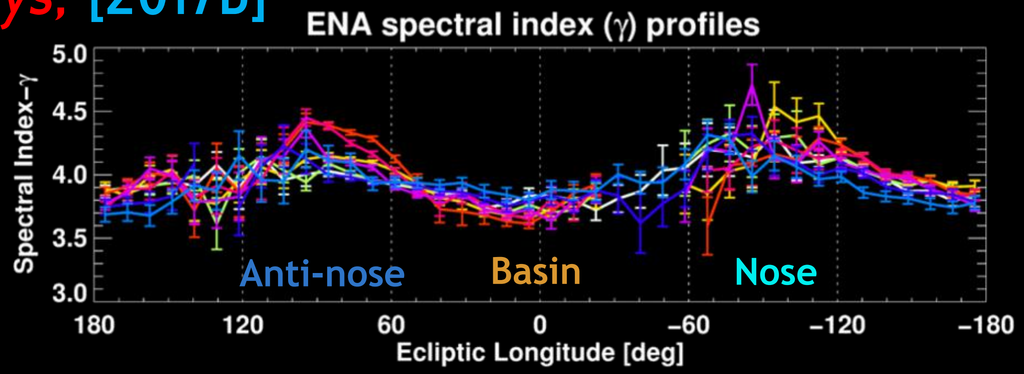
Structure of >5.2 keV global ENA emissions // Morphology of the Belt

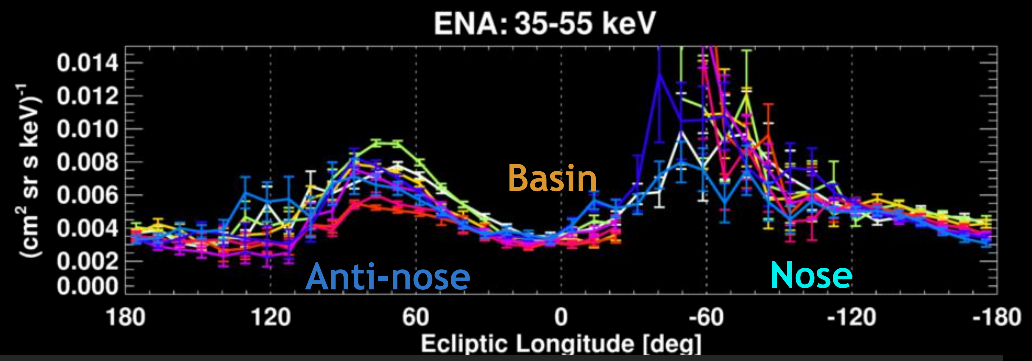


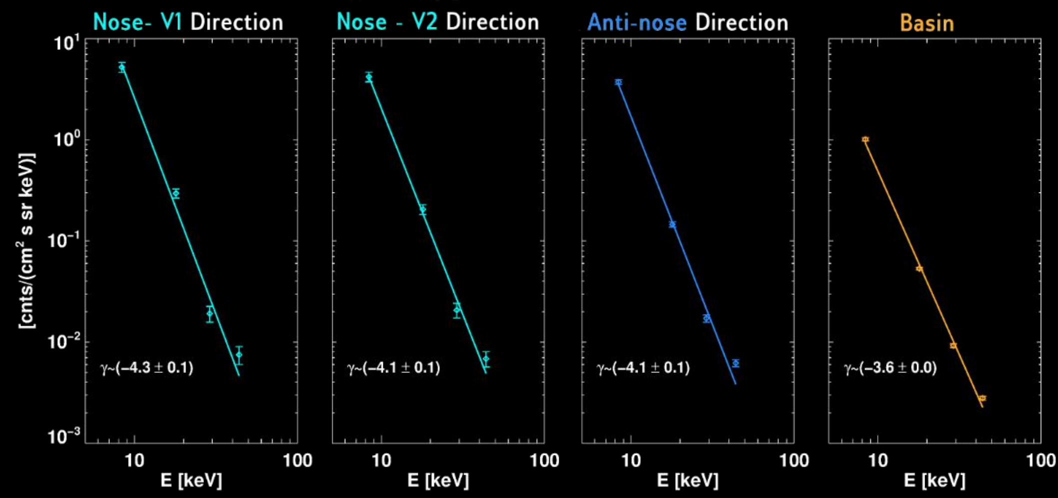


Dialynas et al. *J. Phys,* [2017b]









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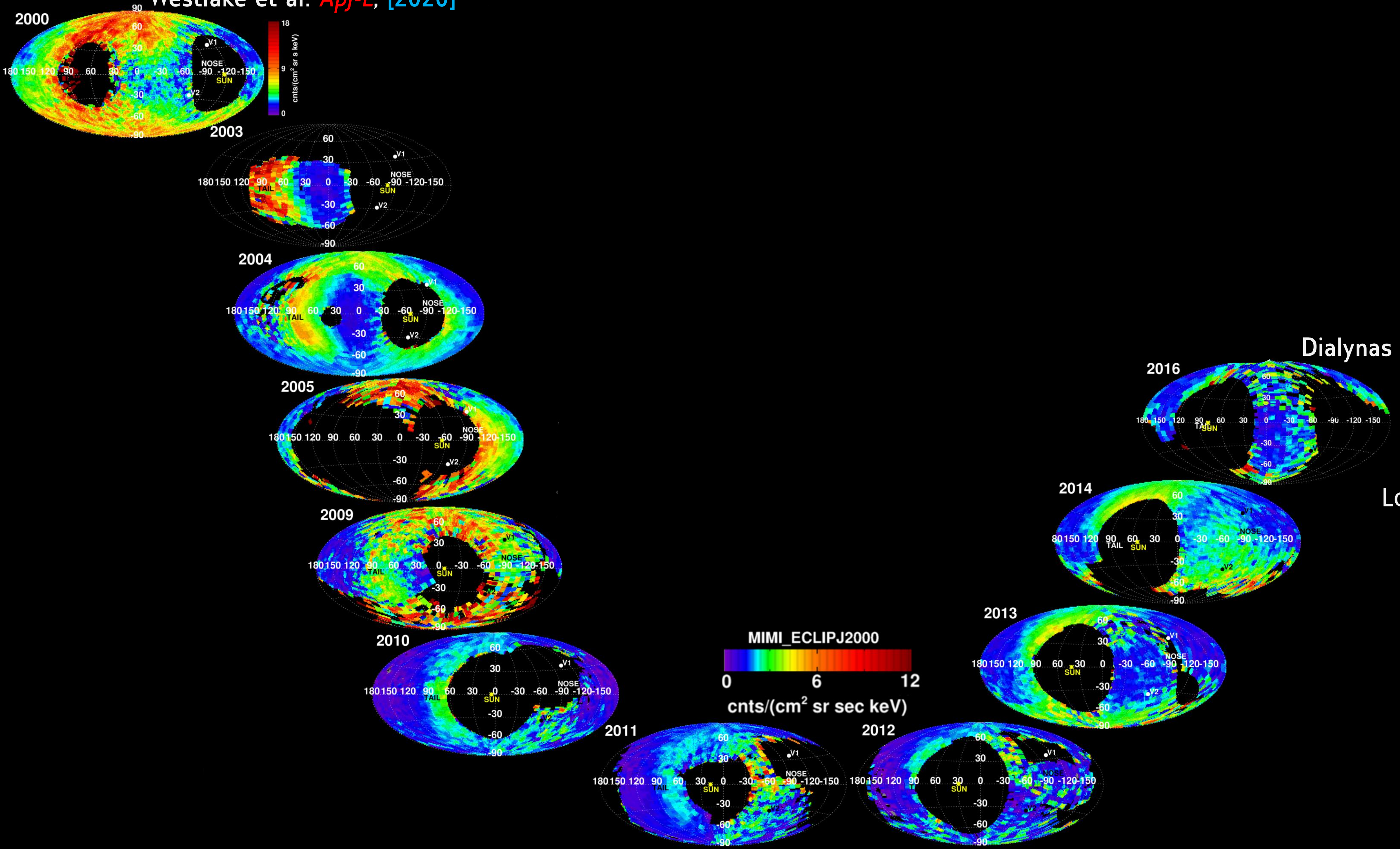
Ground Truth from the Voyagers in the HS & ENA Maps over SC23 & SC24 (2000 - 2017)

Dialynas et al. *Nat. Astron.* [2017]

Westlake et al. *ApJ-L*, [2020]



Dialynas et al. *GRL*, [2019]

GLOBAL HS

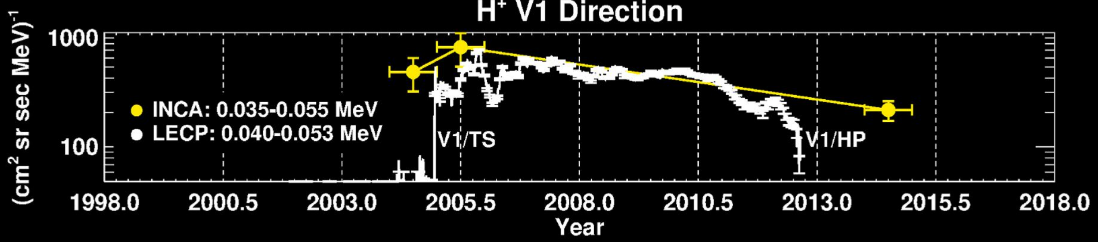
>5.2 keV ENAs

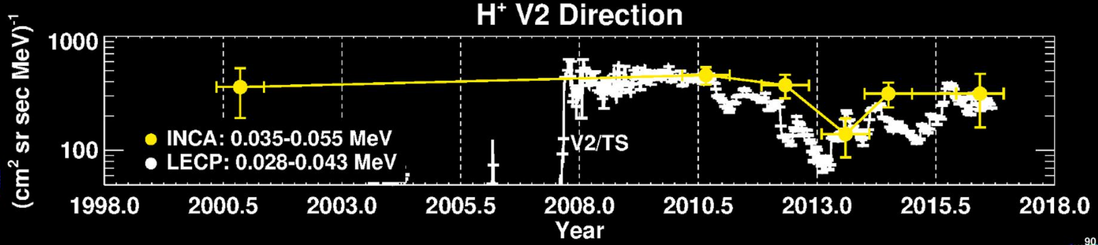
Decline (2000-2012).

Local minimum at ~2012-2013.

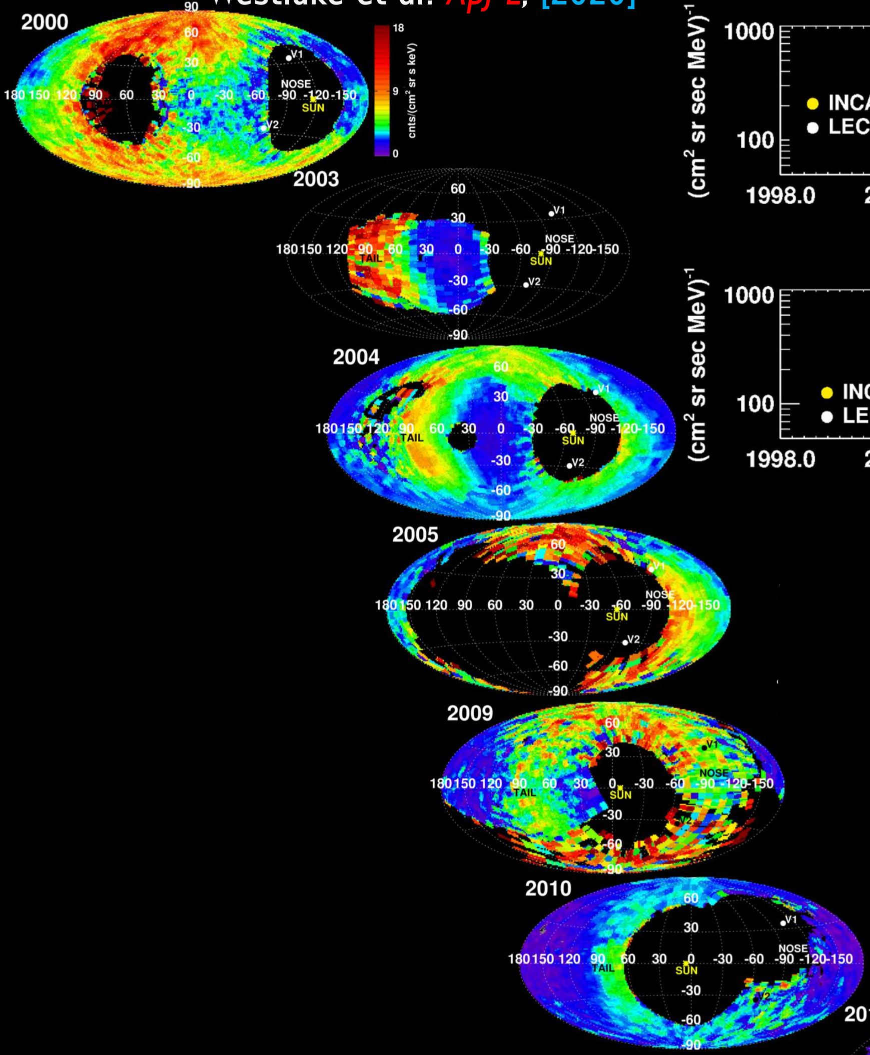
Ground Truth from the Voyagers in the HS & ENA Maps over SC23 & SC24 (2000 - 2017)

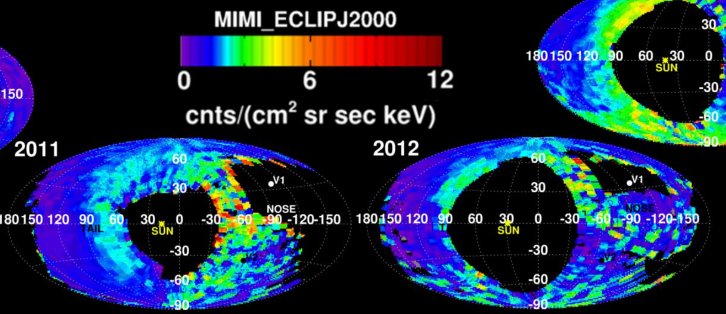
Dialynas et al. *Nat. Astron.* [2017]



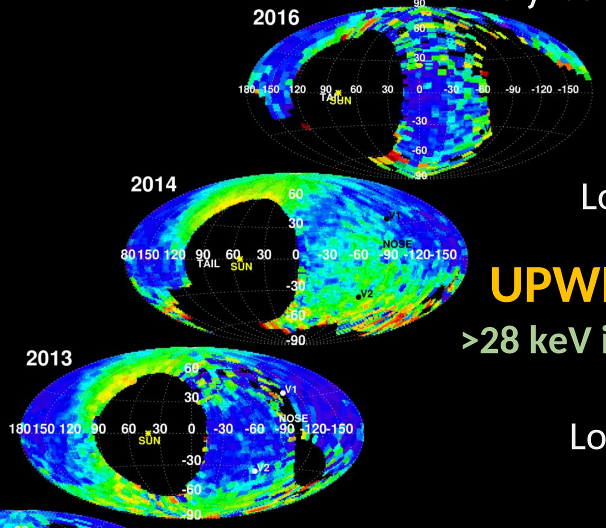


Westlake et al. *ApJ-L*, [2020]





Dialynas et al. *GRL*, [2019]



GLOBAL HS

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UPWIND (NOSE) HEMISPHERE

>28 keV ions & >24 keV ENA converted ions

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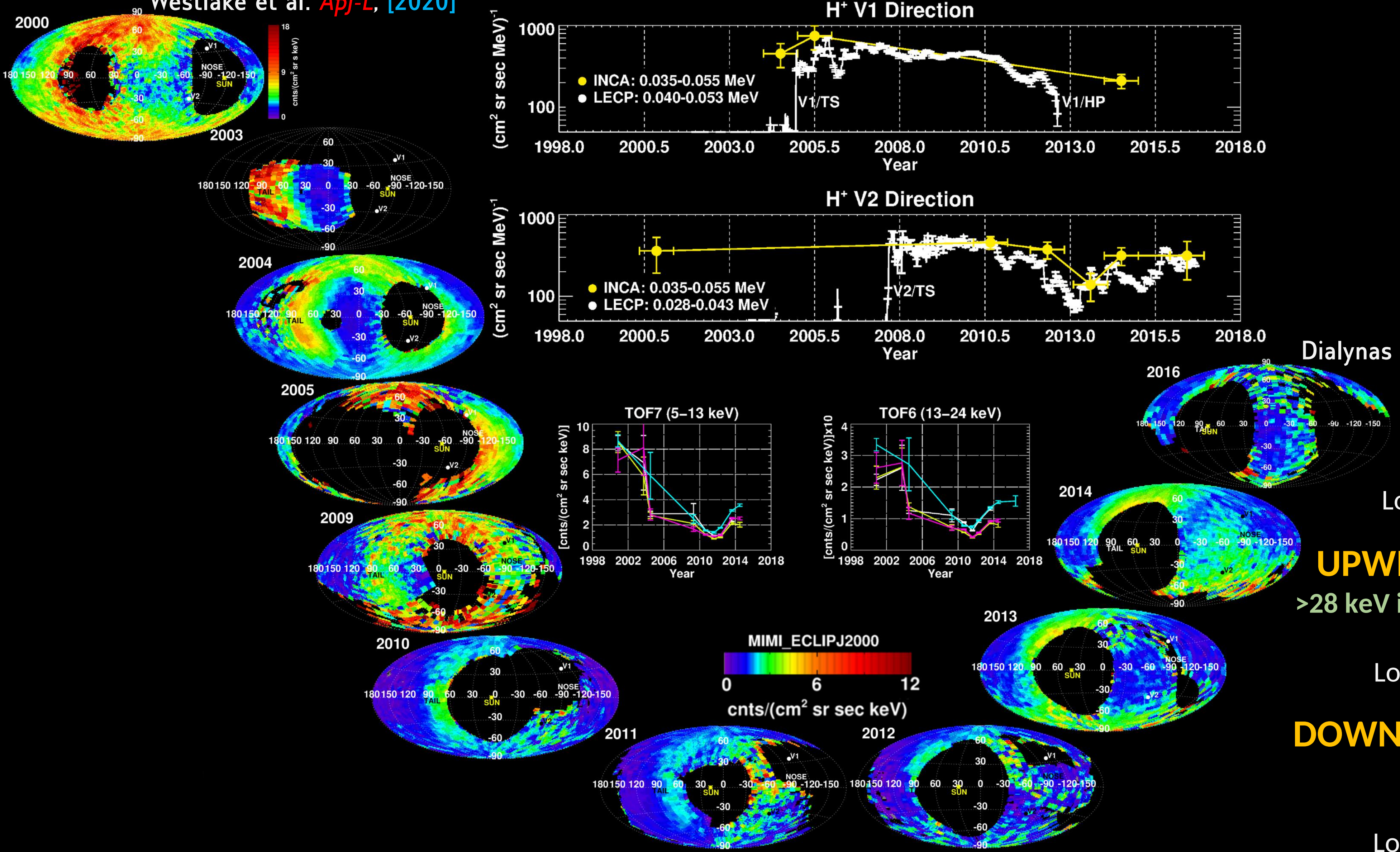


GLOBAL HS

>5.2 keV ENAs

Decline (2000-2012).

Local minimum at ~2012-2013.

UPWIND (NOSE) HEMISPHERE

>28 keV ions & >24 keV ENA converted ions

Decline (2000-2012).

Local minimum at ~2012-2013.

DOWNWIND (TAIL) HEMISPHERE

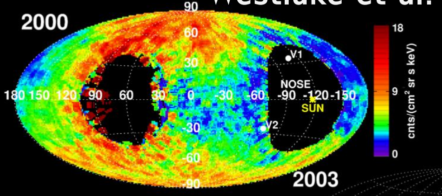
>5.2 keV ENAs

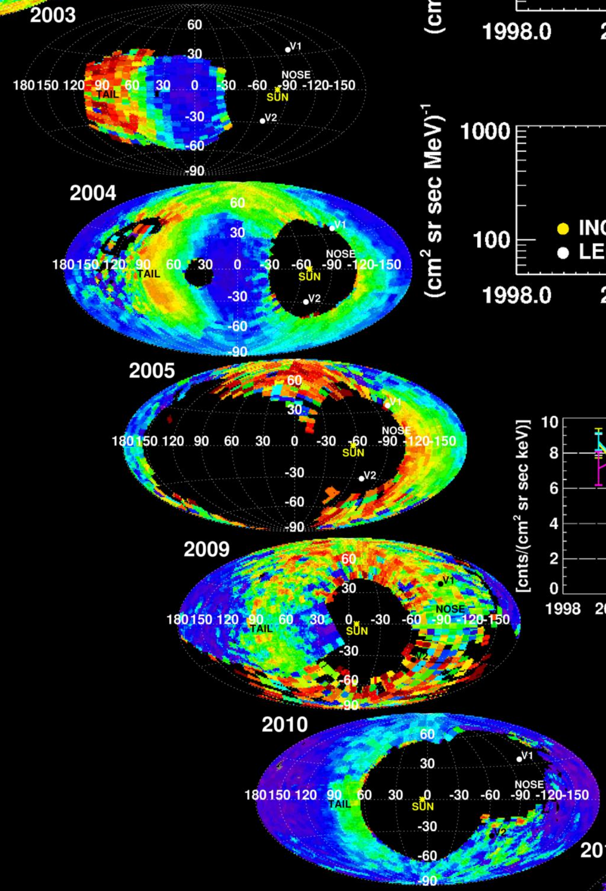
Decline (2000-2012).

Local minimum at ~2011-2013.

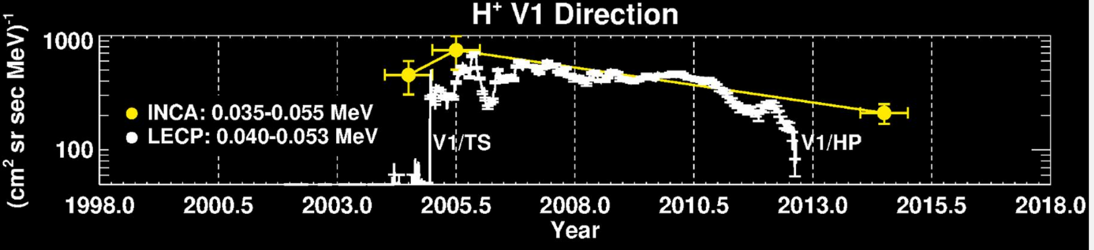
Ground Truth from the Voyagers in the HS & ENA Maps over SC23 & SC24 (2000 - 2017)

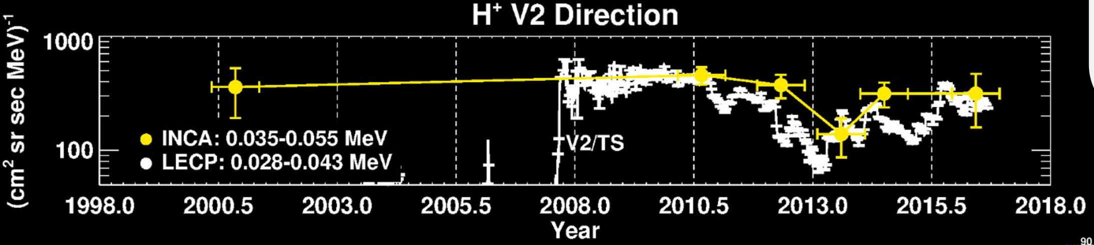
Westlake et al. *ApJ-L*, [2020]

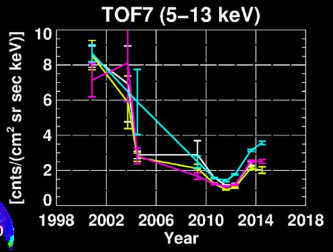


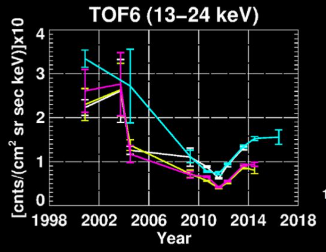


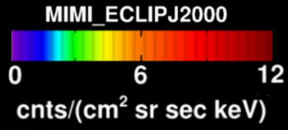
Dialynas et al. *Nat. Astron.* [2017]

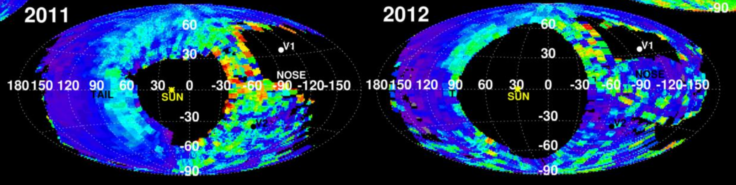


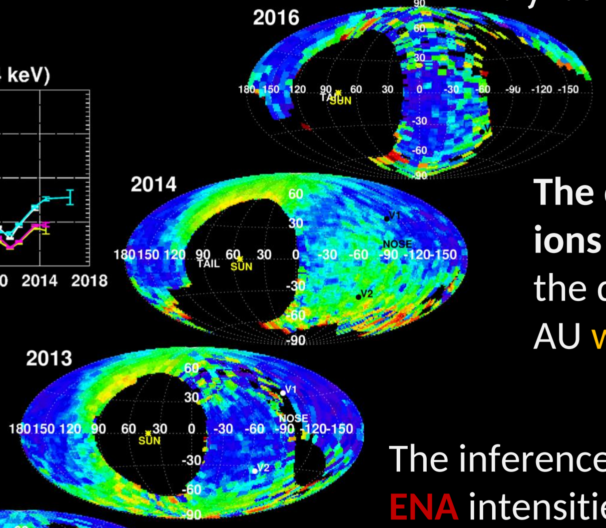




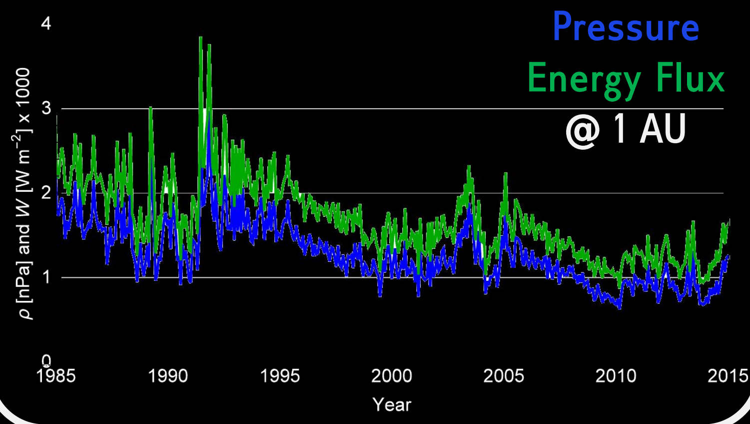








Sokol et al. *Sol. Phys.* [2015]

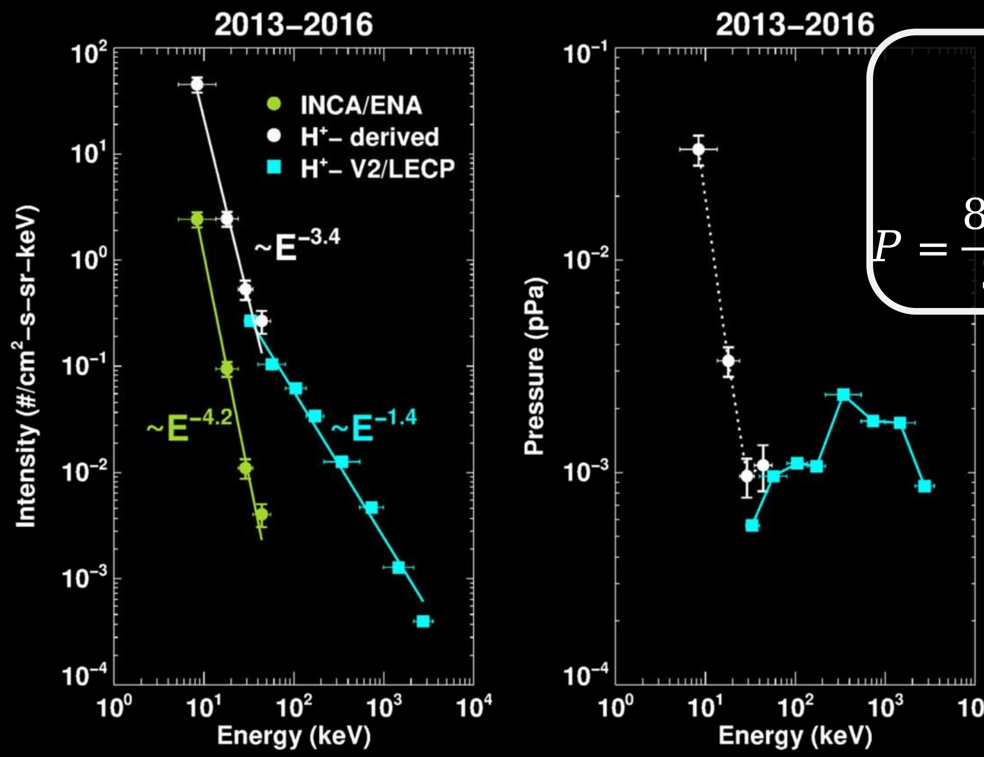


Dialynas et al. *GRL*, [2019]

The dynamic properties of ENAs and ions from the HS *are strongly related to* the dynamic properties of the SW at 1 AU with a time delay of >2.5 yrs.

The inference is that the variations in ion and ENA intensities *are related* to the declining phase of SC23 and rise of SC24 as manifested in the SW itself

Properties of the Heliosheath // ”Ground Truth” energy spectra & pressure



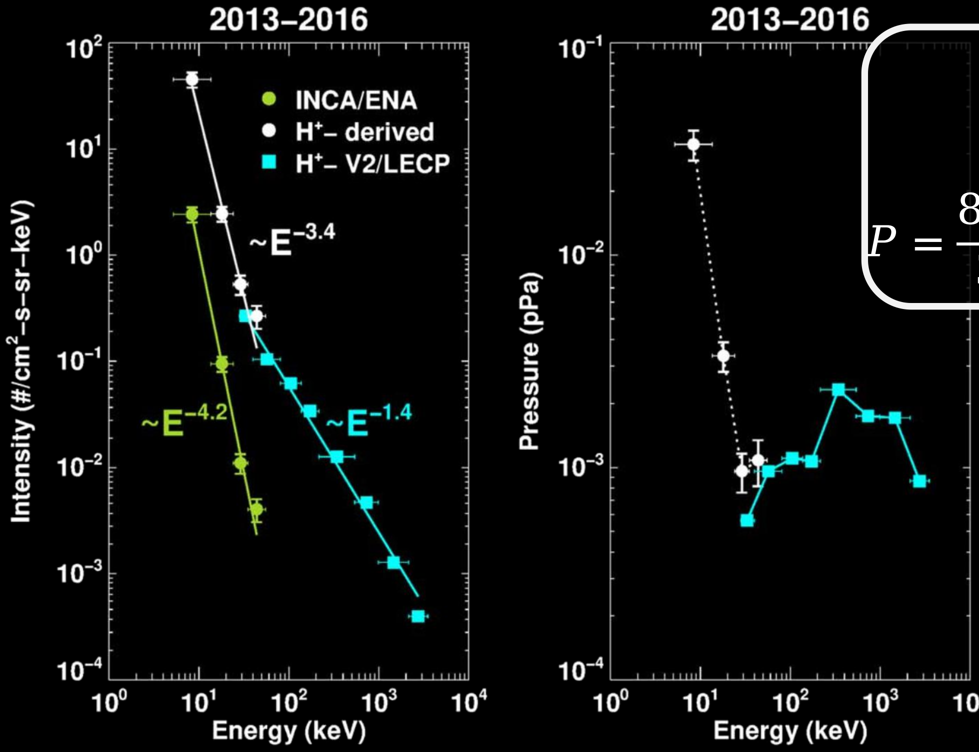
$$J_{ion} = \frac{J_{ENA}}{n_H \sigma L}$$

$$P = \frac{8\pi}{3}\left(\frac{m}{2}\right)^{1/2} J_{ion} E^{1/2} \Delta E$$

Dialynas et al. *GRL,* [2019]

- V2/HP @ 119.2 AU *(measured @ ~119 AU)*
- n_H~0.12 /cm³ *(Kurth & Gurnett 2020; Swaczyna et al. 2020)*

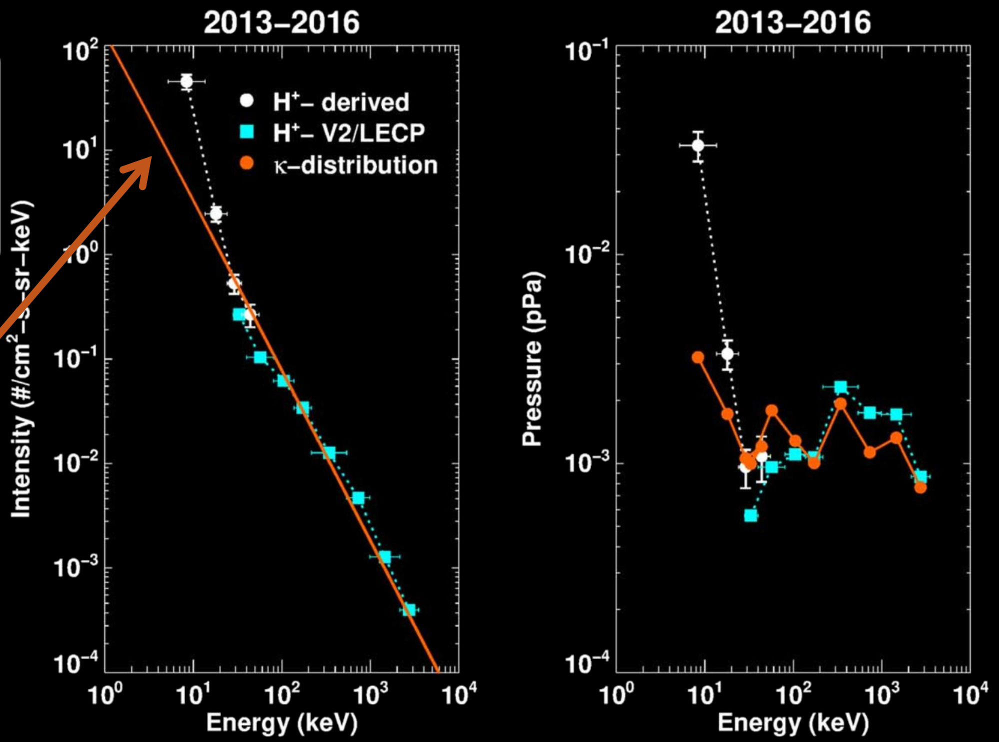
Properties of the Heliosheath // "Ground Truth" energy spectra & pressure



$$J_{ion} = \frac{J_{ENA}}{n_H \sigma L}$$

$$P = \frac{8\pi}{3}\left(\frac{m}{2}\right)^{1/2} J_{ion} E^{1/2} \Delta E$$

Modeled κ-distribution T=0.26 keV κ=1.63 and n=0.002 /cm^3



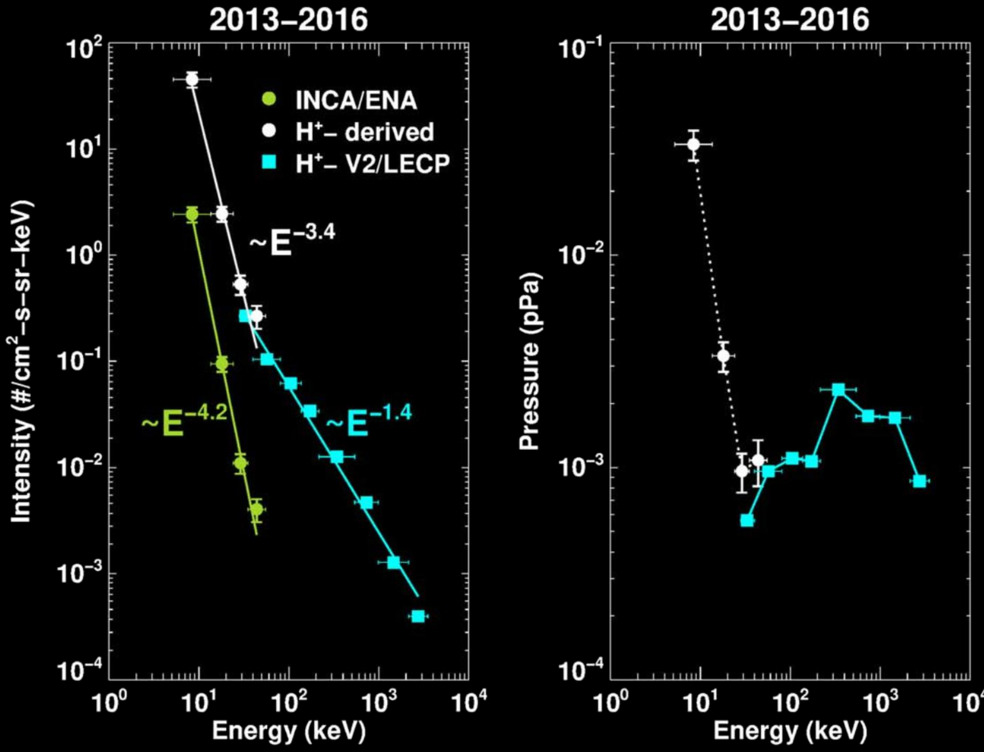
Dialynas et al. *GRL,* [2019]

- V2/HP @ 119.2 AU *(measured @ ~119 AU)*
- n_H~0.12 /cm^3 *(Kurth & Gurnett 2020; Swaczyna et al. 2020)*
- B_{ISM}>0.5nT *(measured ~0.68 nT; Burlaga et al. 2019)*

Krimgis et al. *Nature* [2011]: V1/HP @ 121 AU (~122 AU Krimigis et al. 2013; Stone et al. 2013)

Krimgis et al. *Jo. Plys.* [2010]: V1 B_{ISM} <0.64 nT (~0.48 nT Burlaga and Ness, [2016])

Properties of the Heliosheath // "Ground Truth" energy spectra & pressure



Dialynas et al. *GRL,* [2019]

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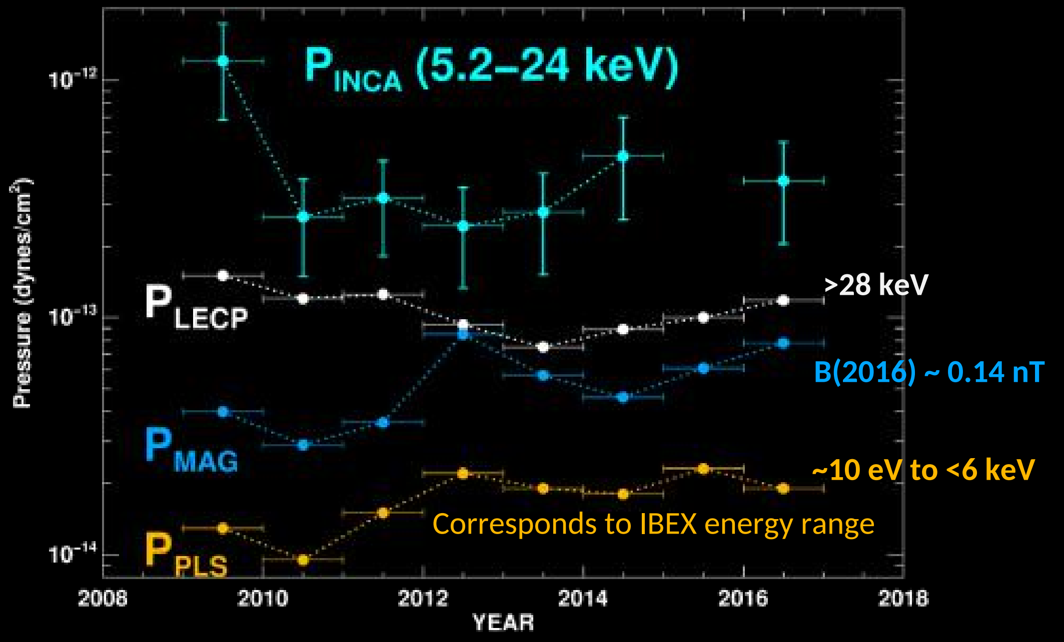
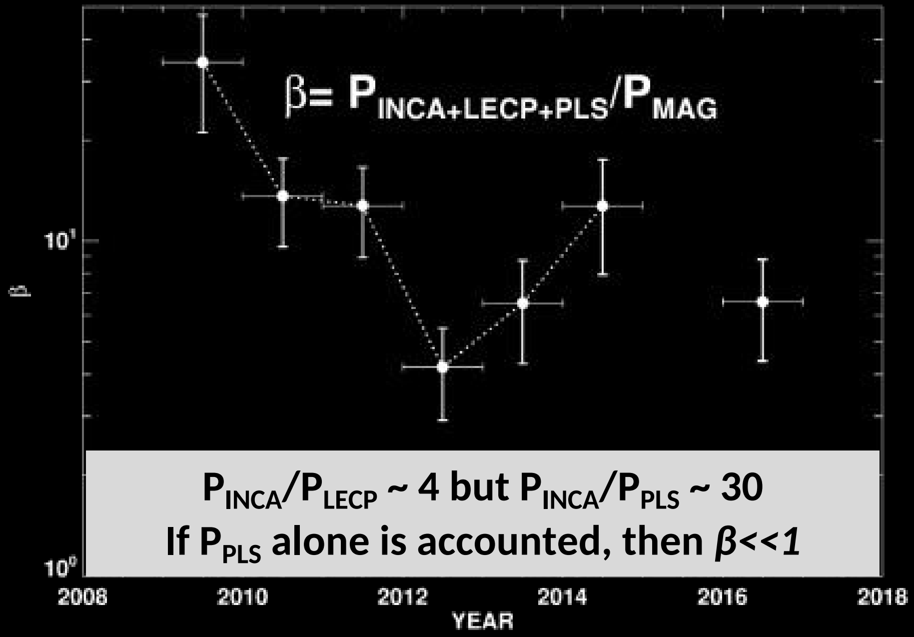




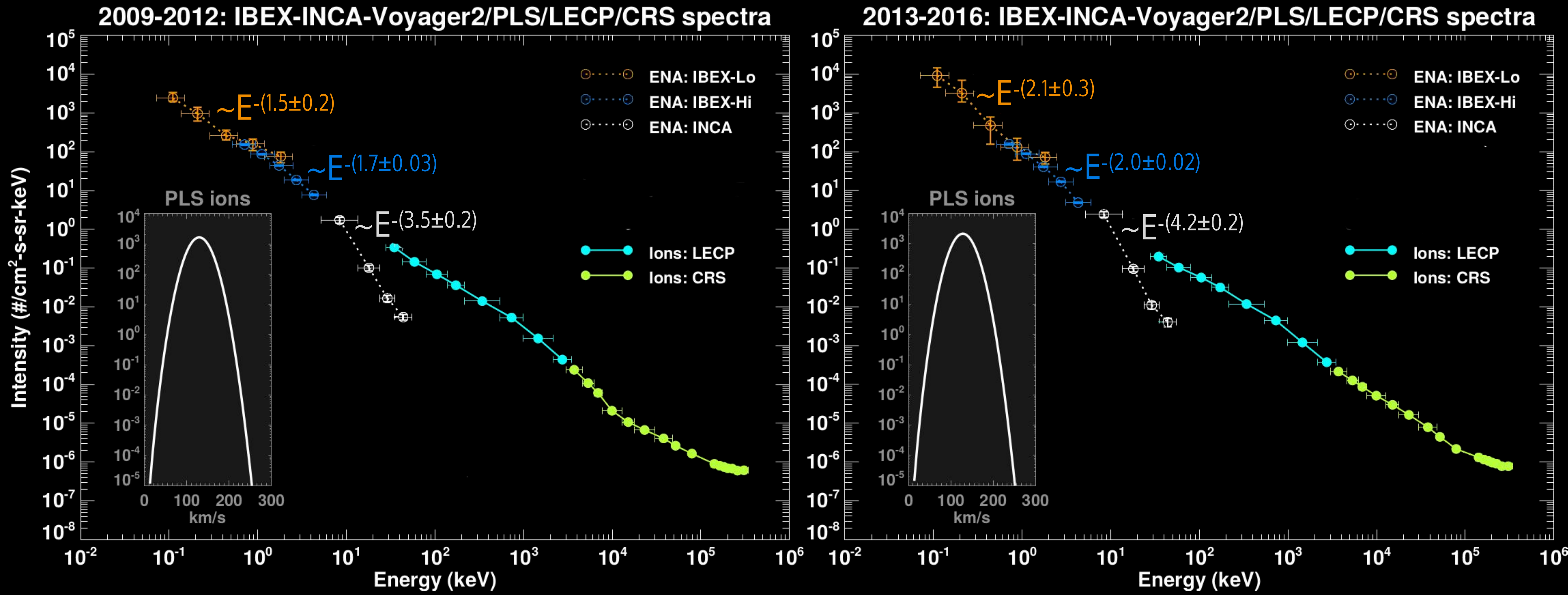
P_{INCA}/P_{LECP} ~ 4 but P_{INCA}/P_{PLS} ~ 30
If P_{PLS} alone is accounted, then *β<<1*

Krimgis et al. *Nature* [2011]: V1/HP @ 121 AU (~122 AU Krimigis et al. 2013; Stone et al. 2013)

Krimgis et al. *Jo. Plys.* [2010]: V1 B_{ISM} <0.64 nT (~0.48 nT Burlaga and Ness, [2016])

Properties of the Heliosheath // Combined ~10 eV to 344 MeV ENA and ion spectra in V2- direction

Dialynas et al. *ApJ-L*, [2020] (*BU SHIELD DRIVE Center* http://sites.bu.edu/shield-drive/)



<u>We know that</u>

- 0.52-6 keV GDF ENAs are *"largely produced in the HS"* (*McComas et al. [2017;2020]*) & 5.2-55 keV ENAs are produced in the HS (*Dialynas et al. [2017]*)
- 0.028-3.5 MeV spectra (LECP) show a κ-index of ~-1.63 (*Decker et al. (2005); Dialynas et al. (2019)*)
- The observed hardening break at >100 MeV (CRS) is most likely due to GCR.

Properties of the Heliosheath // Combined ~10 eV to 344 MeV ENA and ion spectra in V2- direction

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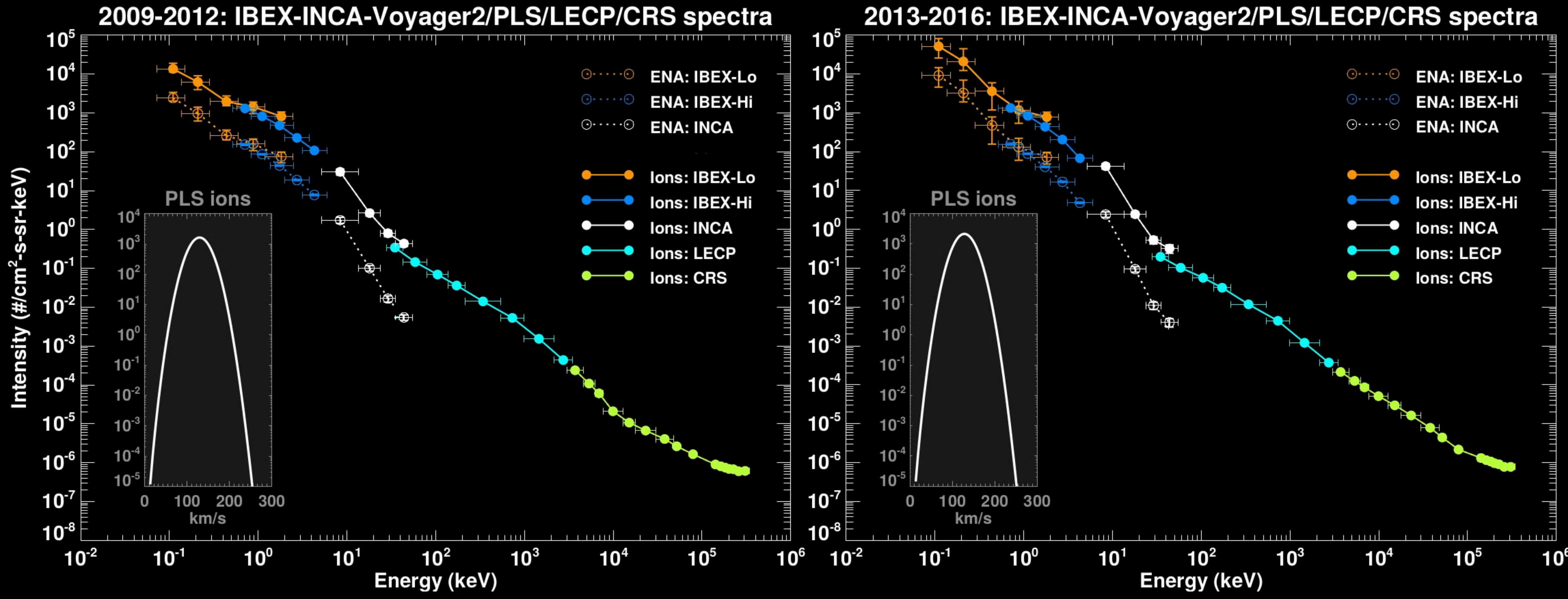

We assume that

- All ENAs are due to CE interactions between HS ions and IS neutrals
- The thickness of the HS in V2 direction is L~35 AU (*Krimigis et al. (2019); Dialynas et al. (2019*)
- The IS neutral H density is n_H~0.12 /cm³ (*Dialynas et al. [2019], Swaczyna et al. [2020]*, measured indirectly from PWS: e.g. *Kurth & Gurnett [2020]*).

Properties of the Heliosheath // Combined ~10 eV to 344 MeV ENA and ion spectra in V2- direction

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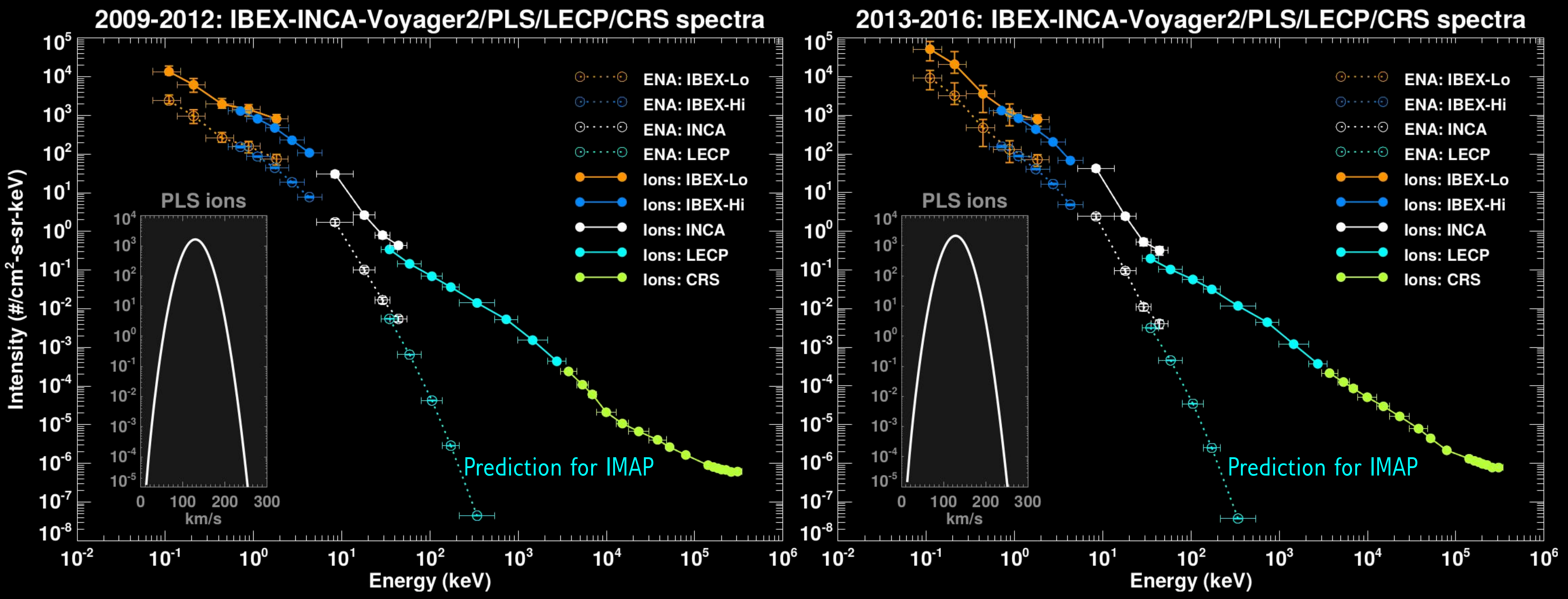

With the same assumptions we

- predict ENA spectra of 28-540 keV (converted from in-situ LECP); fit smoothly to 5.2-55 keV INCA/ENAs; *(prediction for IMAP; McComas et al. [2018])*

Properties of the Heliosheath // Combined ~10 eV to 344 MeV ENA and ion spectra in V2- direction

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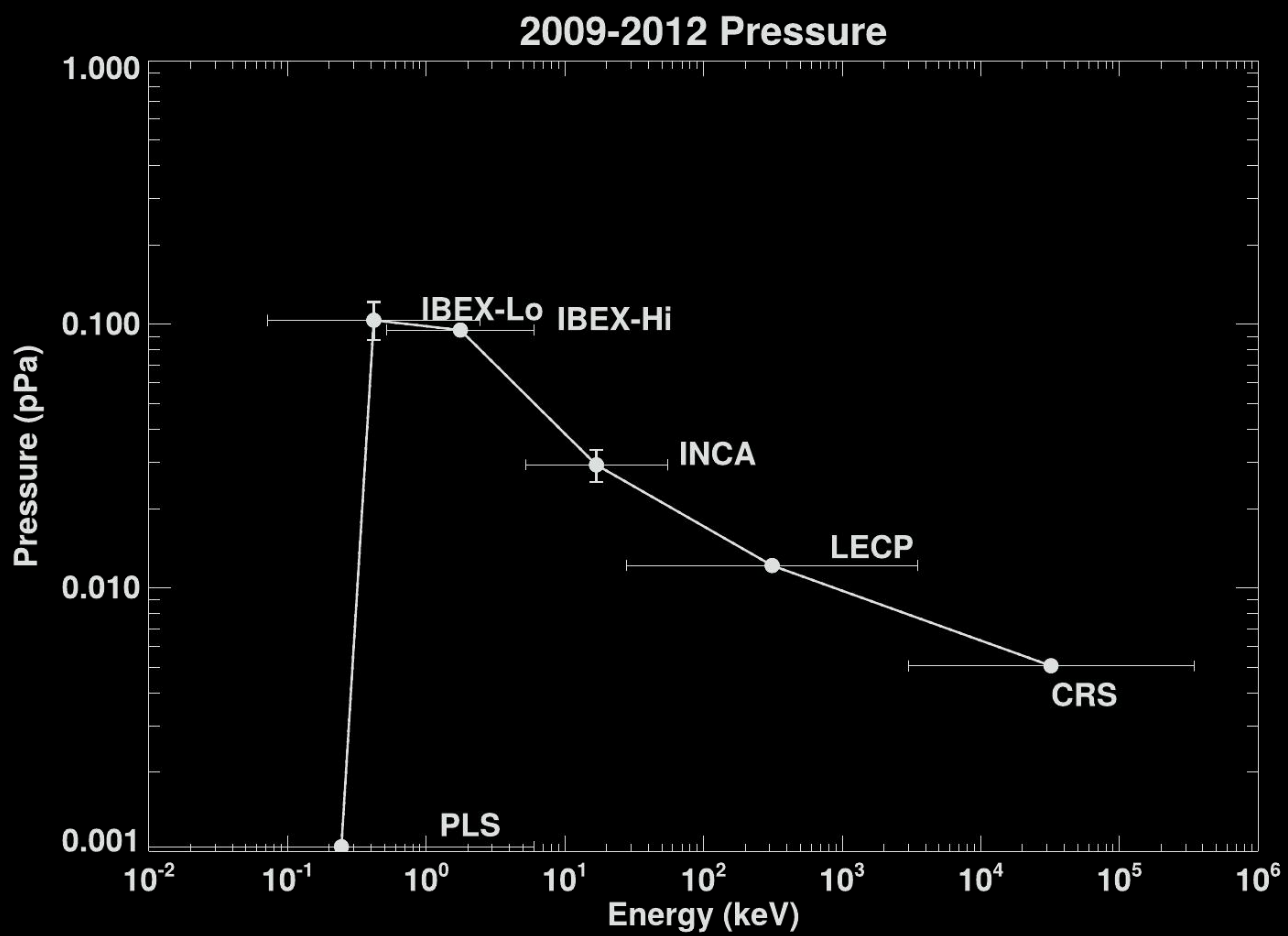

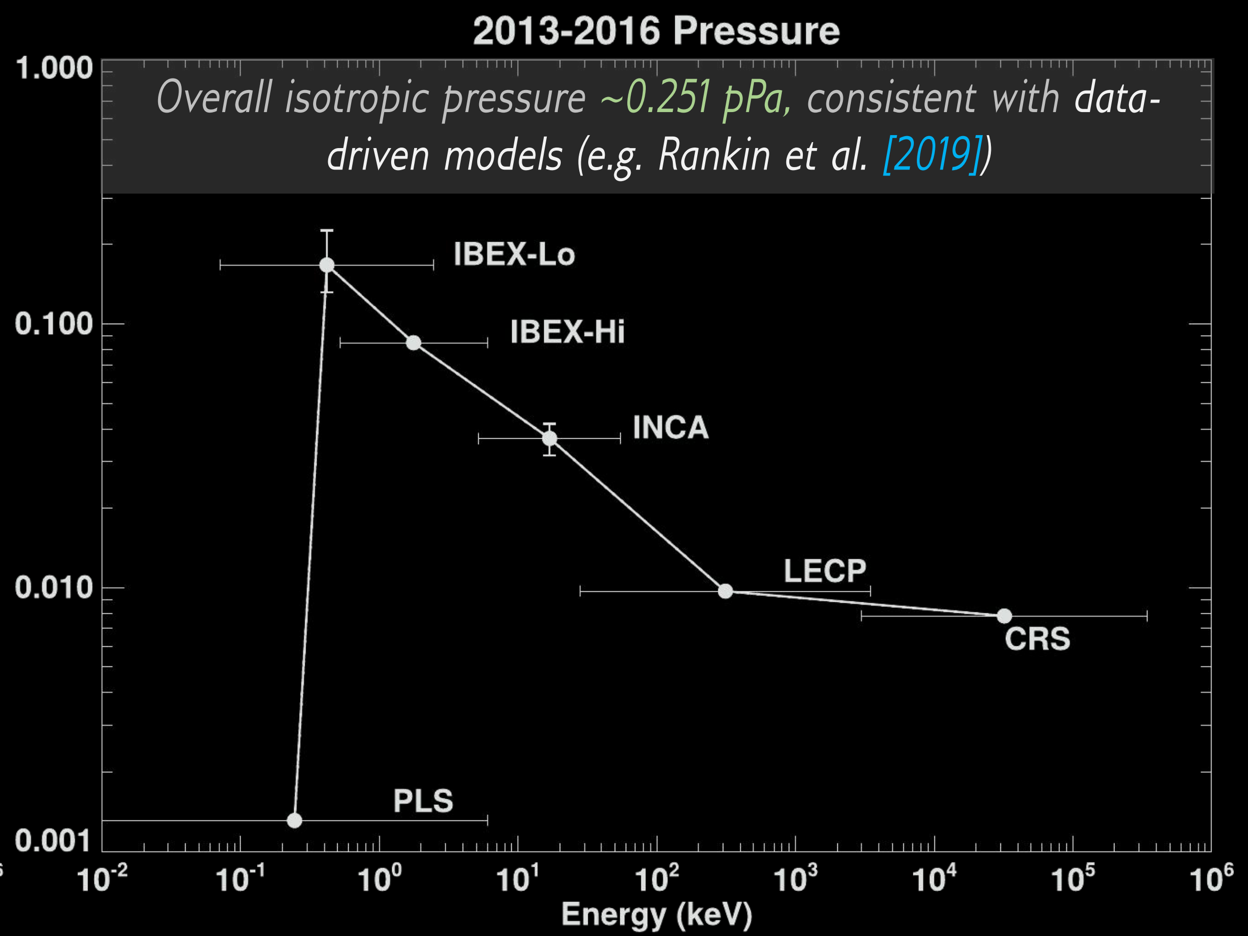

Overall isotropic pressure ~0.251 pPa, consistent with data-driven models (e.g. Rankin et al. [2019])

- The <6 keV PUIs dominate the total pressure in the HS, but the >5.2 keV suprathermal particles provide a significant contribution **that cannot be neglected**.
- B upstream at the HP required to balance the pressure from the HS in V2 direction is ~0.67 nT, as measured (*Burlaga et al. [2019]*).

Properties of the Heliosheath // Combined ~10 eV to 344 MeV ENA and ion spectra in V2- direction

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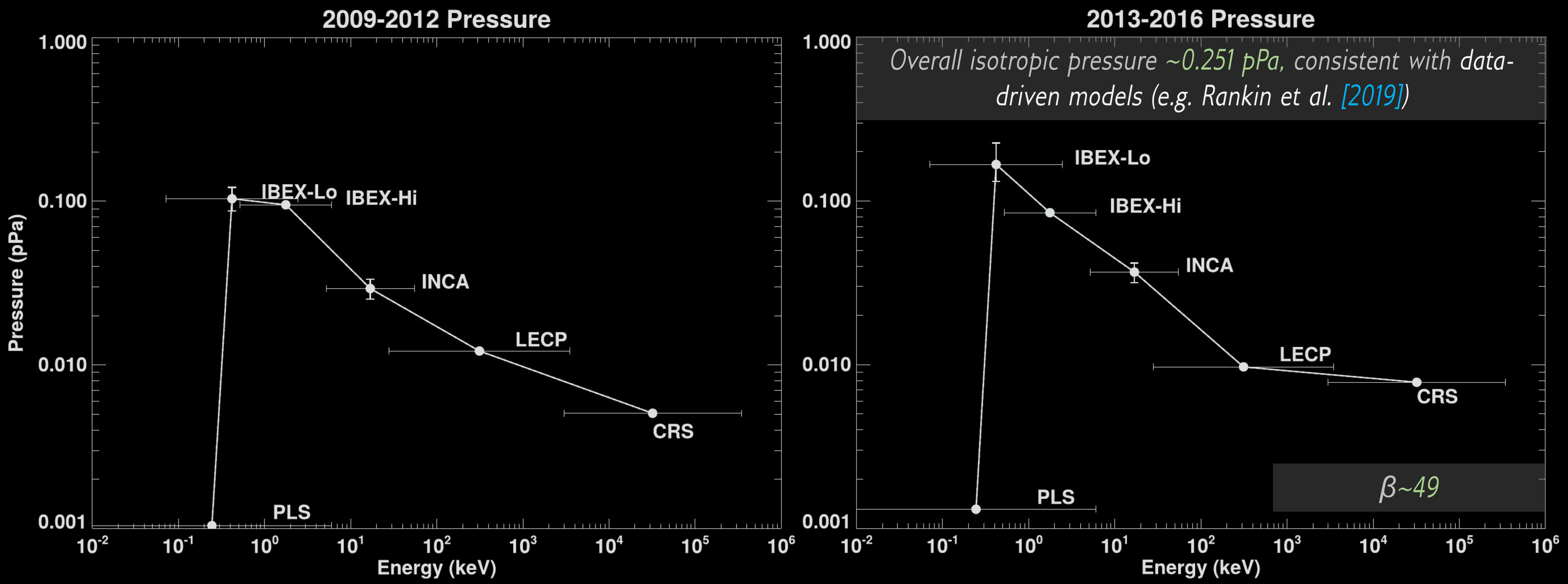

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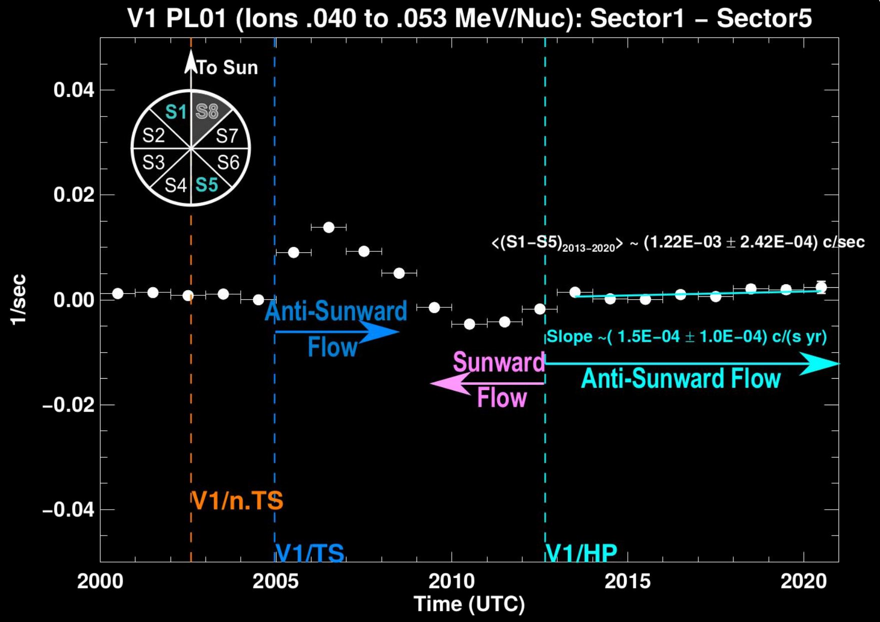
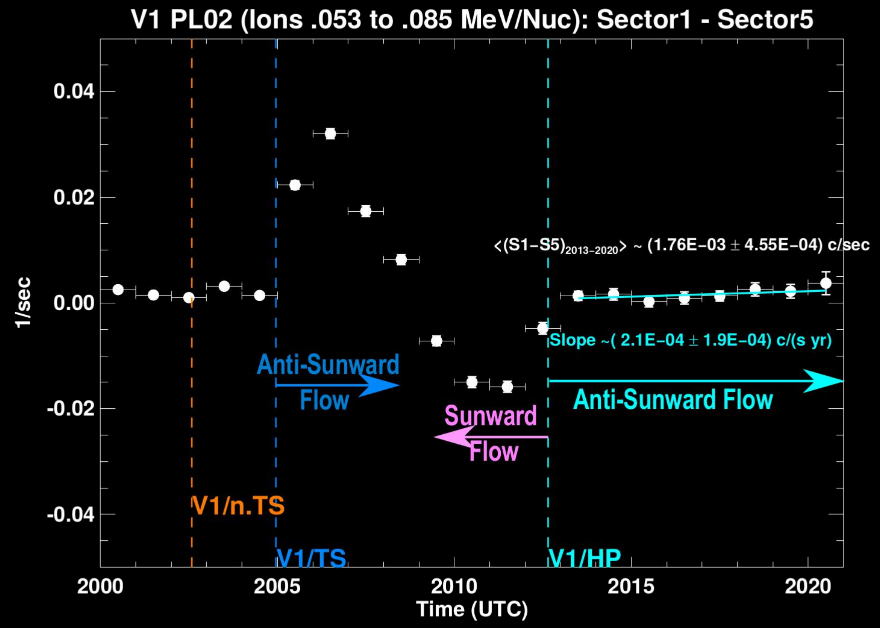
- B upstream at the HP required to balance the pressure from the HS in V2 direction is ~0.67 nT, as measured (*Burlaga et al. [2019]*).
- Strong B_{IS} interacts directly with high beta plasma HS (Krimigis et al. *Science,* [2009])

V1 & V2 HP crossings // A 40-139 keV ion population leaking from the HS to the VLISM

Dialynas et al. *ApJ*, [2021]--In Press





Dec. 2004

Outflow

until ~2009-2010.

>2009

Inflow

Decker et al. *Nature*, 2012

(*Radial plasma V*).

Krimigis et al. *Science* 2013

(*Interchange instability*)

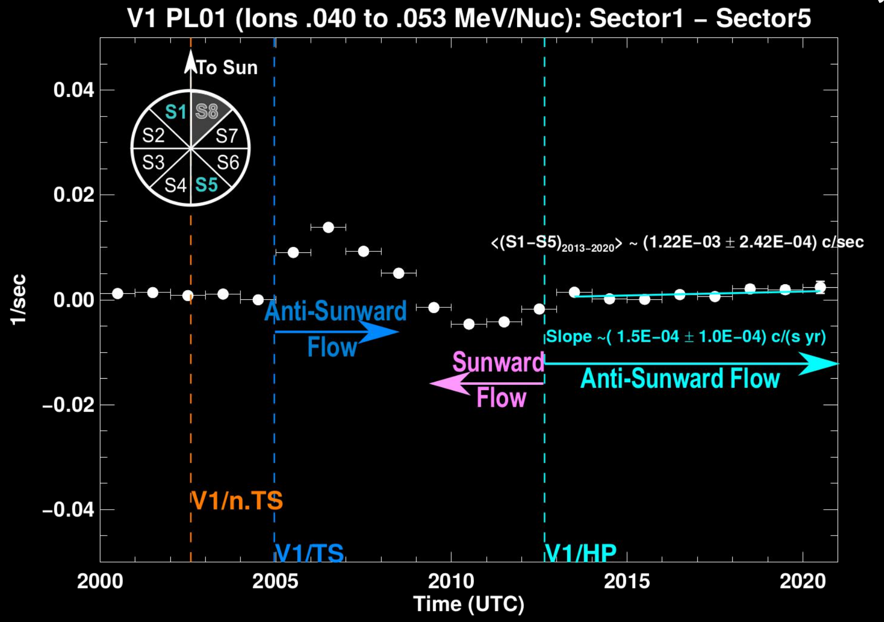
>2013:

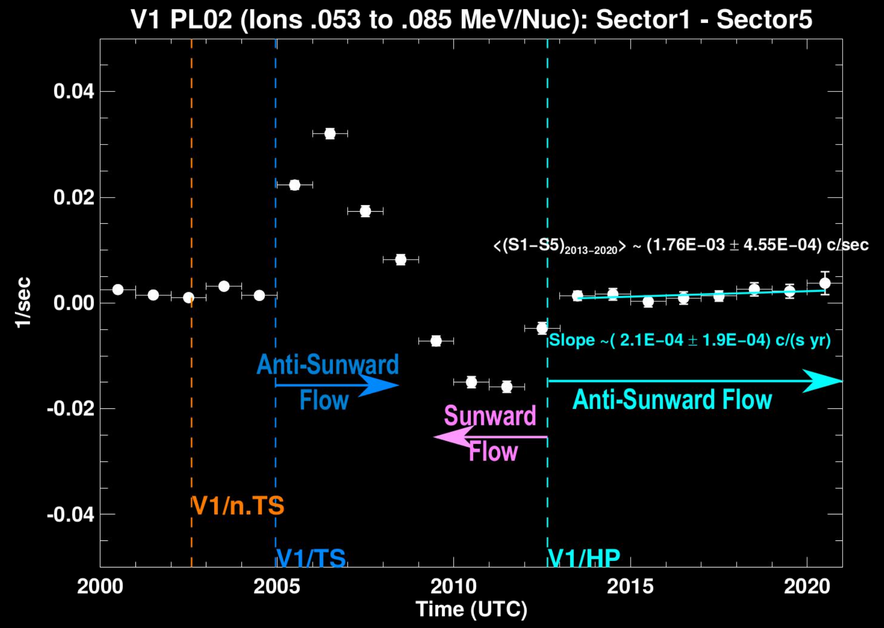
Outflow

Upstream of the HP (~28 AU)

V1 & V2 HP crossings // A 40-139 keV ion population leaking from the HS to the VLISM

Dialynas et al. *ApJ*, [2021]--In Press





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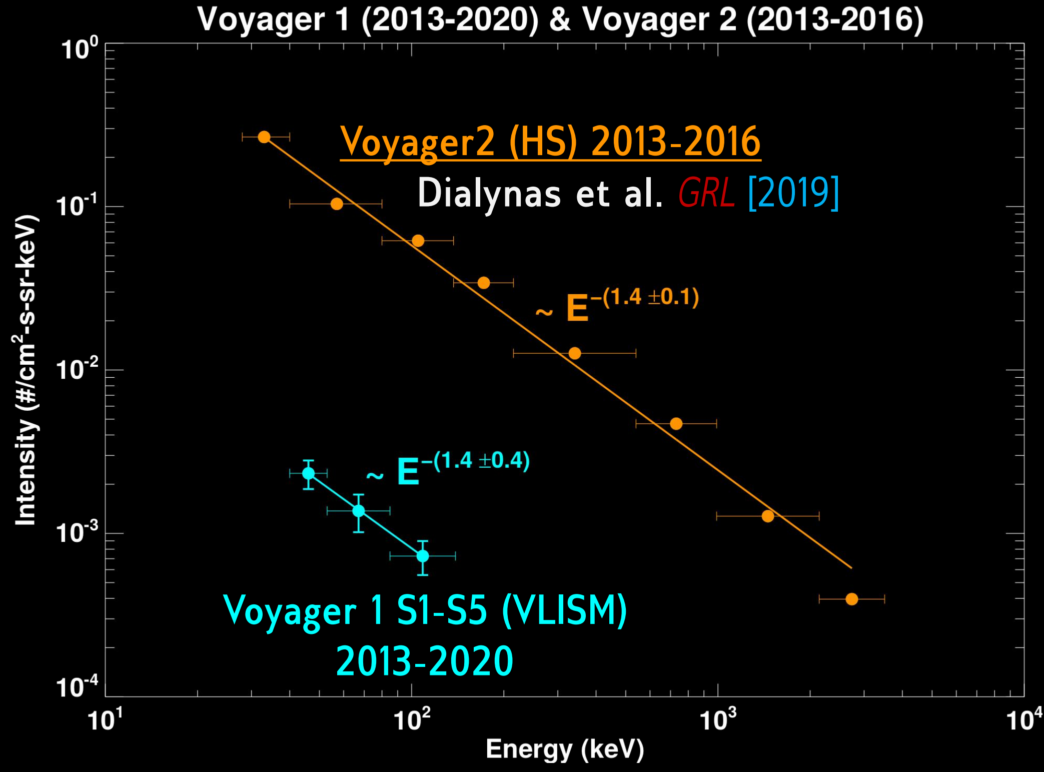

40-139 keV: escaping the HS (~28 AU past the HP).

FT interchange instability: Florinski, *ApJ*, [2015]

Gloeckler et al. *Nature*, [1997]: Superthermal particles that could play a role in the Pressure balance at the HP.

Summary // Conclusions

We know that >5.2 keV ENAs are created in the HS (GROUND TRUTH)

ENA (>5.2 keV) decrease during the declining phase of SC23 but recover through 2014-2016 (SC24) in agreement with the V1,2/LECP ion intensities (>28 keV) measured ***in situ*** inside the HS. The global HS responds promptly (within >2.5 yrs) to outward-propagating solar wind changes throughout the SC.

We know how many ions it takes to make one ENA in the HS at a given energy and velocity direction corresponding to the integration along LOS (GROUND TRUTH).

The width of the HS at V1 & V2 as ~27 AU & ~35.2 AU. The ISMF magnitude as 0.48-0.68 nT. The IS neutral H density as 0.12/cm^3

We know that suprathermal particles are important towards estimating the pressure balance in the HS.

$P_{>5.2\ keV}/P_{>28\ keV}$ ~4 & $P_{>5.2\ keV}/P_{>10\ eV}$ ~30 **(on average)**, while $\beta>>1$ inside the HS (at least at the upwind hemisphere). **Neglecting the suprathermal ions from 5.2 keV to MeV** energies **underestimates** **the ion pressure in the HS, leading to underestimating the β, that leads to erroneous pressure balance in the HS and wrong B_{ISM}! The phenomenology of the heliosphere can only be addressed when taking all measurements into acount, from eV to MeV energies.**

We know that there is communication between the HS and the LISM

40-139 keV ions propagate outwards since the TS crossing (2004), but in ~2009 we observe **a reversal in the radial ion flow**, in agreement with the previously identified flux tube interchange instability, where cold, high-magnetic field flux tubes invade the heliosheath. Our data imply that this process occurs in **larger spatial scales than previously thought (~10 AU)**. The crossing of V1 (>2013) from the **HP is associated with a 40-139 keV ion population that leaks from the heliosheath**, over a spatial range of ~28 AU from the HP; pre-accelerated ions from the parent heliosheath exiting into IS space through the flux tube interchange instability mechanism at the HP.

Thank You!