The Science of the Global Heliosphere

in-situ ions from the Voyagers and remotely sensed ENAs from Cassini

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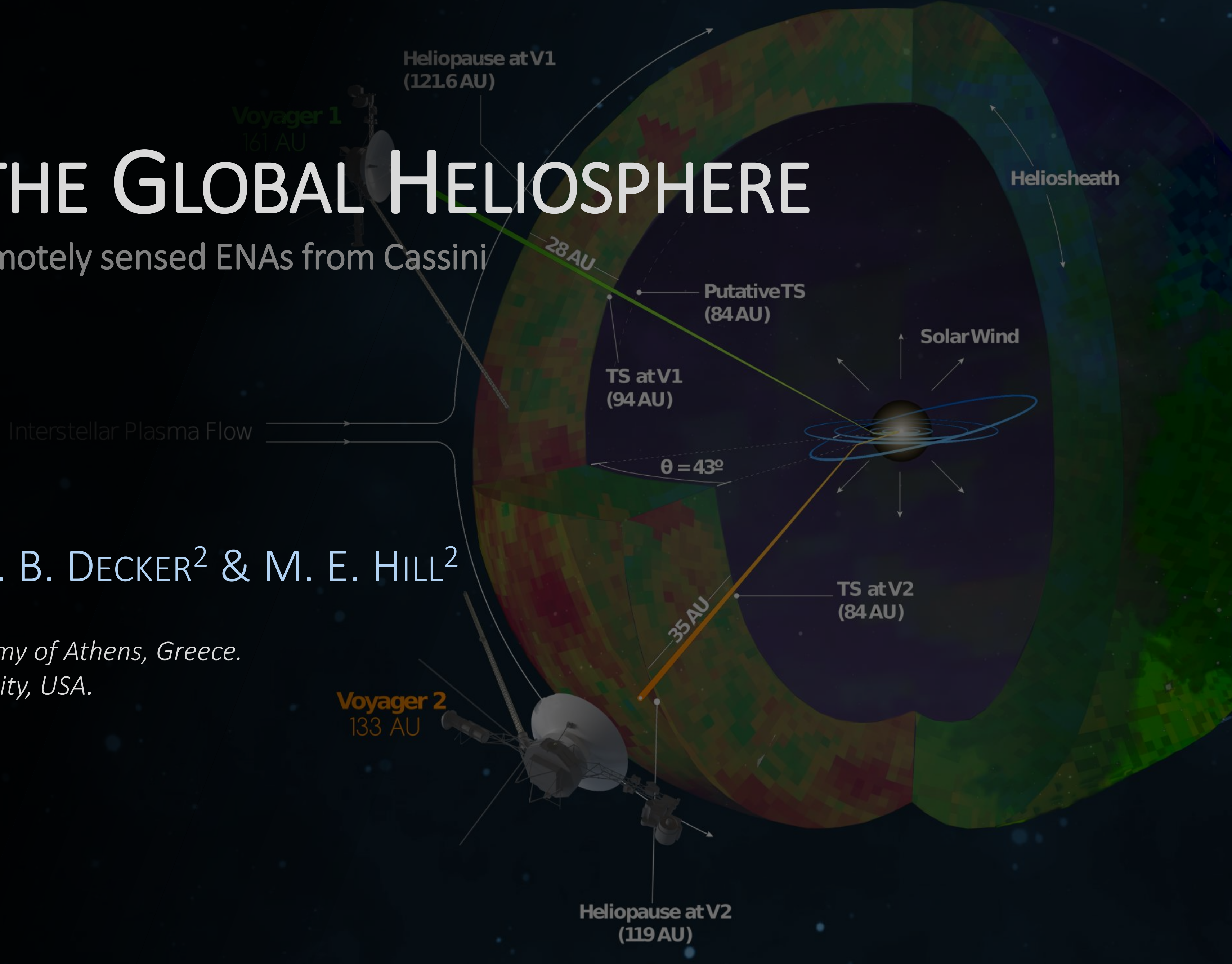
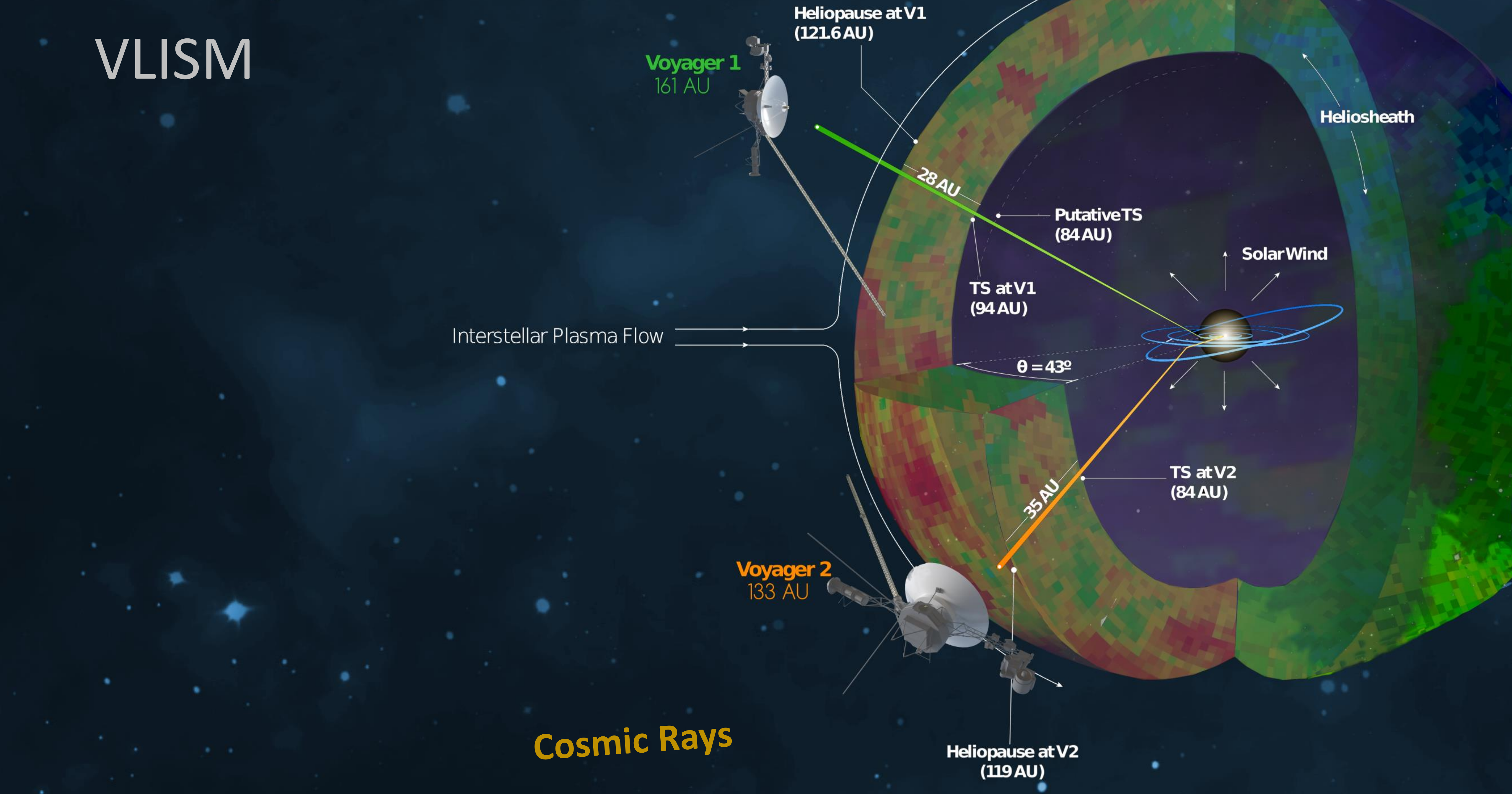


The Heliosphere // An Overview (Voyager 1 & 2, Cassini)



THE HELIOSPHERE // AN OVERVIEW (VOYAGER 1 & 2, CASSINI)

VLISM

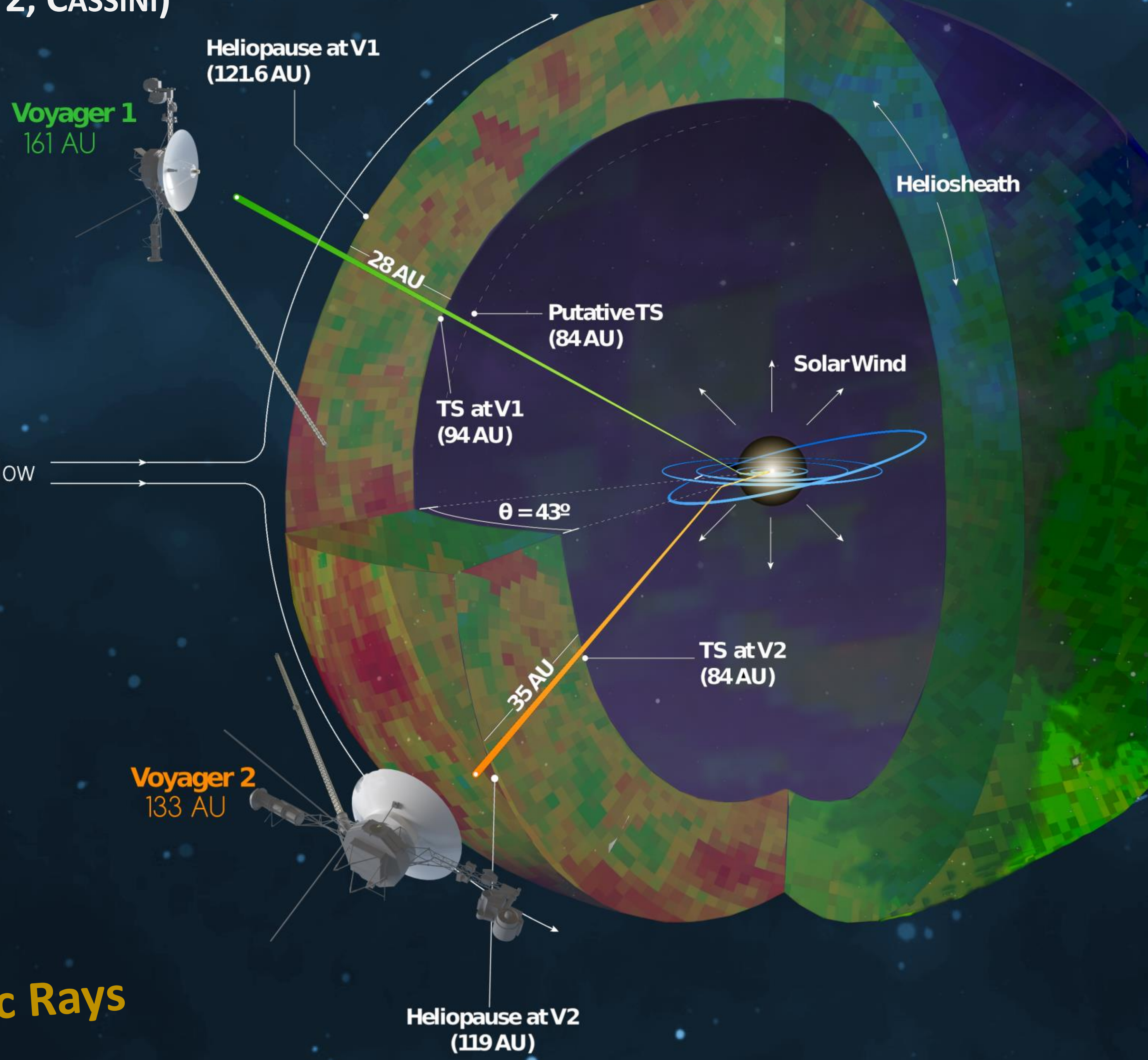
McComas+[2012]

Bow Shock?

Bow Wave?

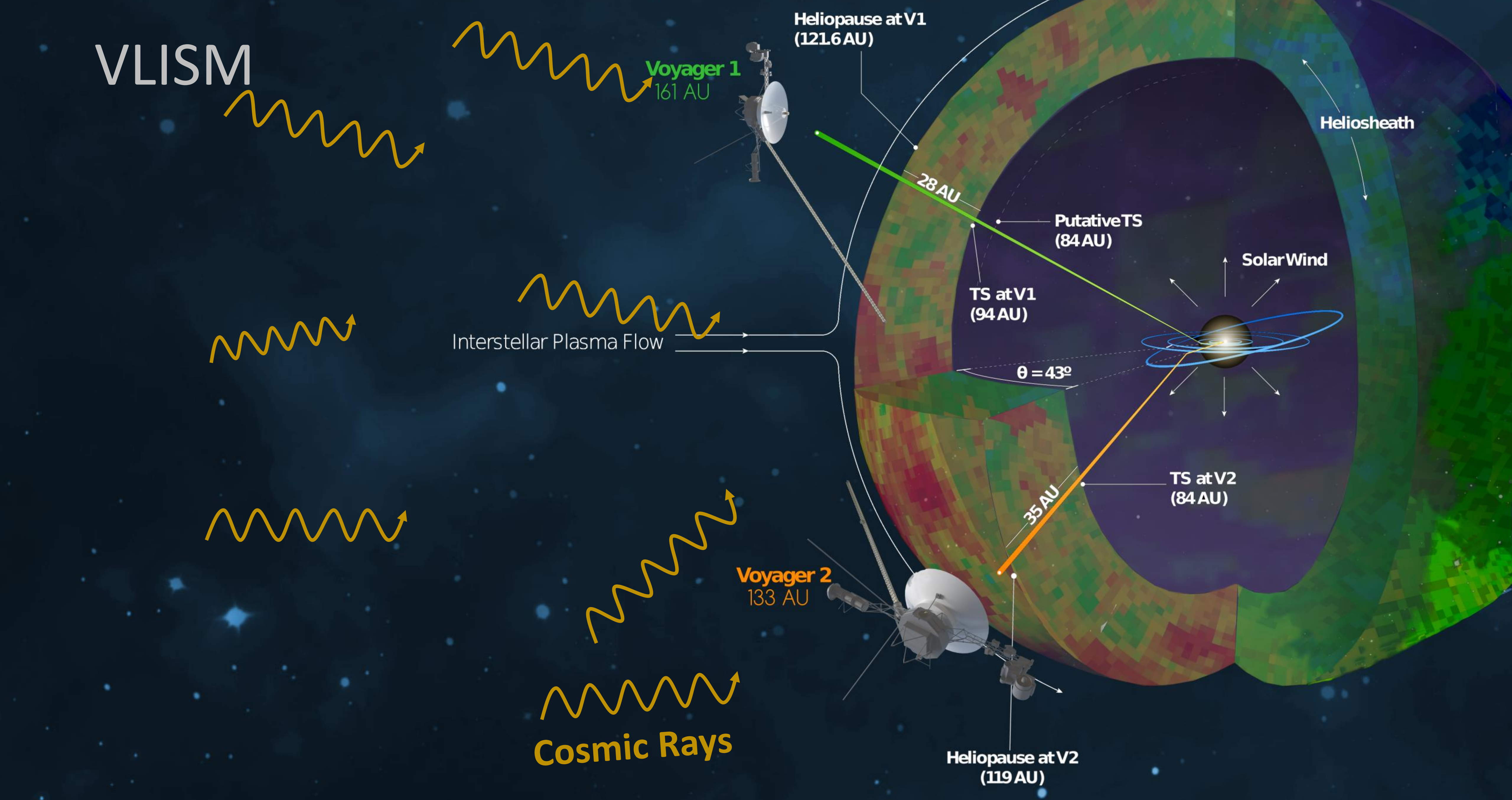
Scherer & Fichtner+[2014]

Interstellar Plasma Flow



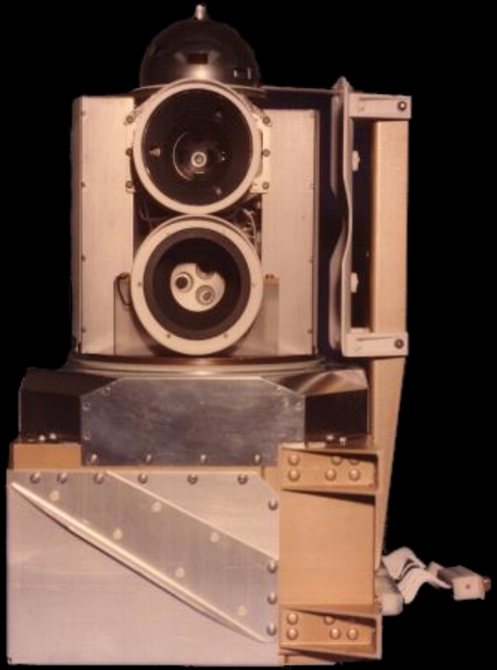
Cosmic Rays

THE HELIOSPHERE // AN OVERVIEW (VOYAGER 1 & 2, CASSINI)



INSTRUMENTATION // LECP on V1/V2 & MIMI/INCA on Cassini

LECP
Krimigis+[1977]

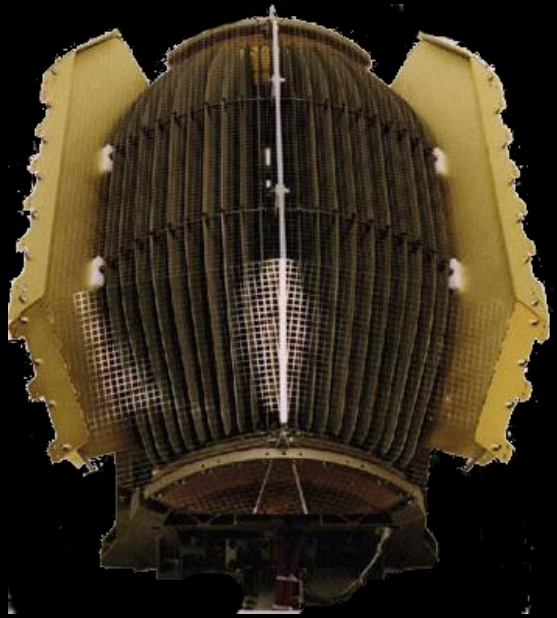


V1/LECP: ions ~40 keV to 60 MeV/Nuc and and electrons ~26 keV to >10 MeV, together with an integral ion measurement of > 211 MeV

V2/LECP: ions ~28 keV to ~60 MeV/Nuc and electrons ~22 keV to >10 MeV, along with an integral ion measurement of > 213 MeV.

The detectors are capable of providing angular information via a mechanically stepped platform.

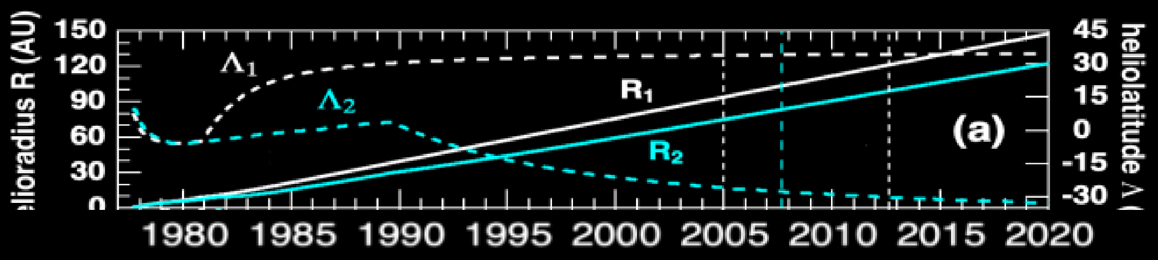
Cassini/INCA
Krimigis+[2004]



Geometry factor: ~2.4 cm^2 sr
Field of view (FOV): 90×120◦
Analyze: composition (H and O groups), velocity, and direction of the incident ENAs within 5.2-55 keV (TOF7-4: 5.2-13.5 keV, 13.5-24 keV, 24-35 keV, 35-55 keV)

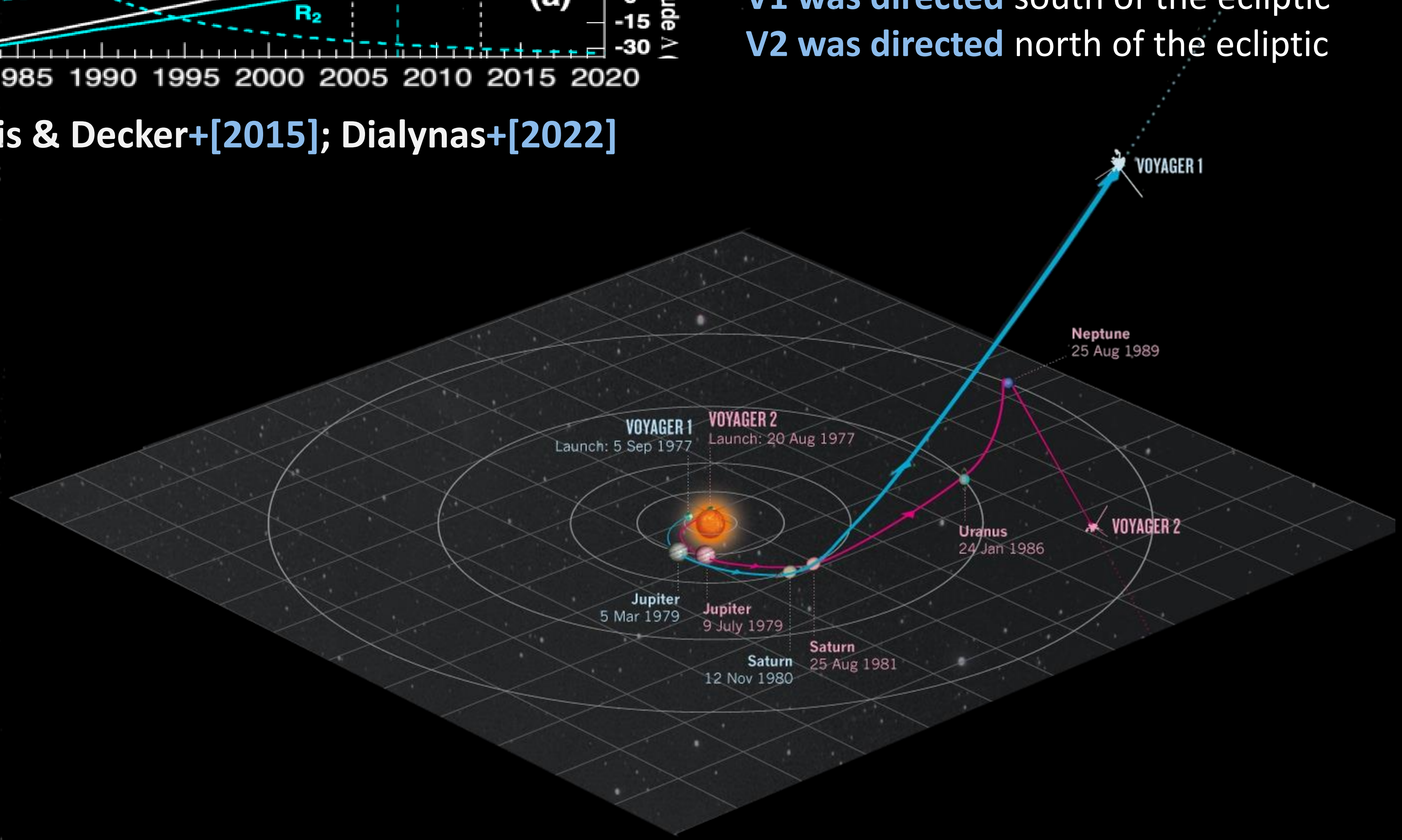
High sensitivity to detect very low ENA intensity events in the heliosphere and image large parts of the sky sphere.

IN-SITU ION MEASUREMENTS FROM V1 & V2 LECP // A 46 YEAR CRUISE THROUGH THE HELIOSPHERE



Krimigis & Decker+[2015]; Dialynas+[2022]

V1 was directed south of the ecliptic
V2 was directed north of the ecliptic



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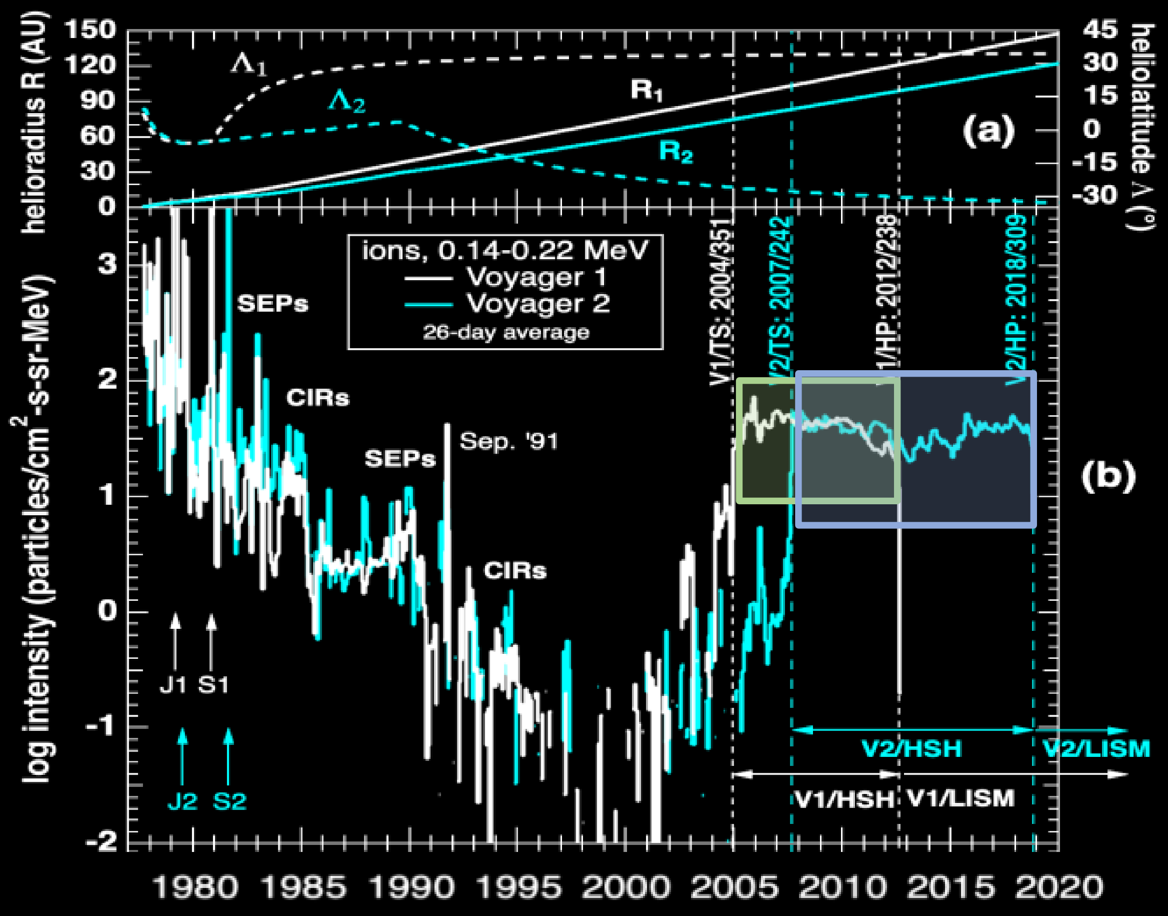
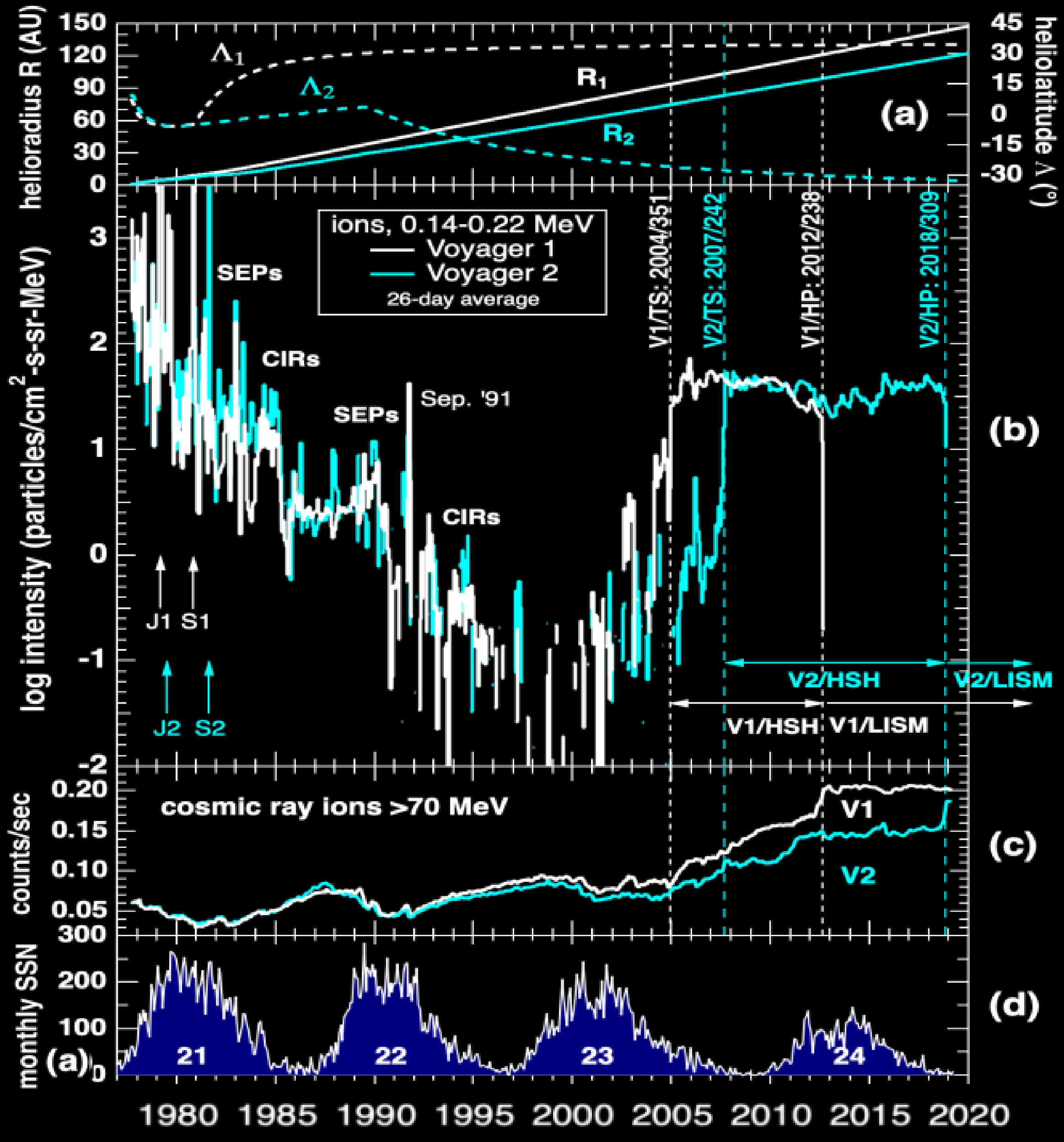


Krimigis & Decker+[2015]; Dialynas+[2022]

V1 was directed south of the ecliptic
V2 was directed north of the ecliptic

A general decrease in low energy ion intensities; a minimum at about the year 2000, followed by a gradual increase before reaching the TS.

IN-SITU ION MEASUREMENTS FROM V1 & V2 LECP // A 46 YEAR CRUISE THROUGH THE HELIOSPHERE



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V1 was directed south of the ecliptic
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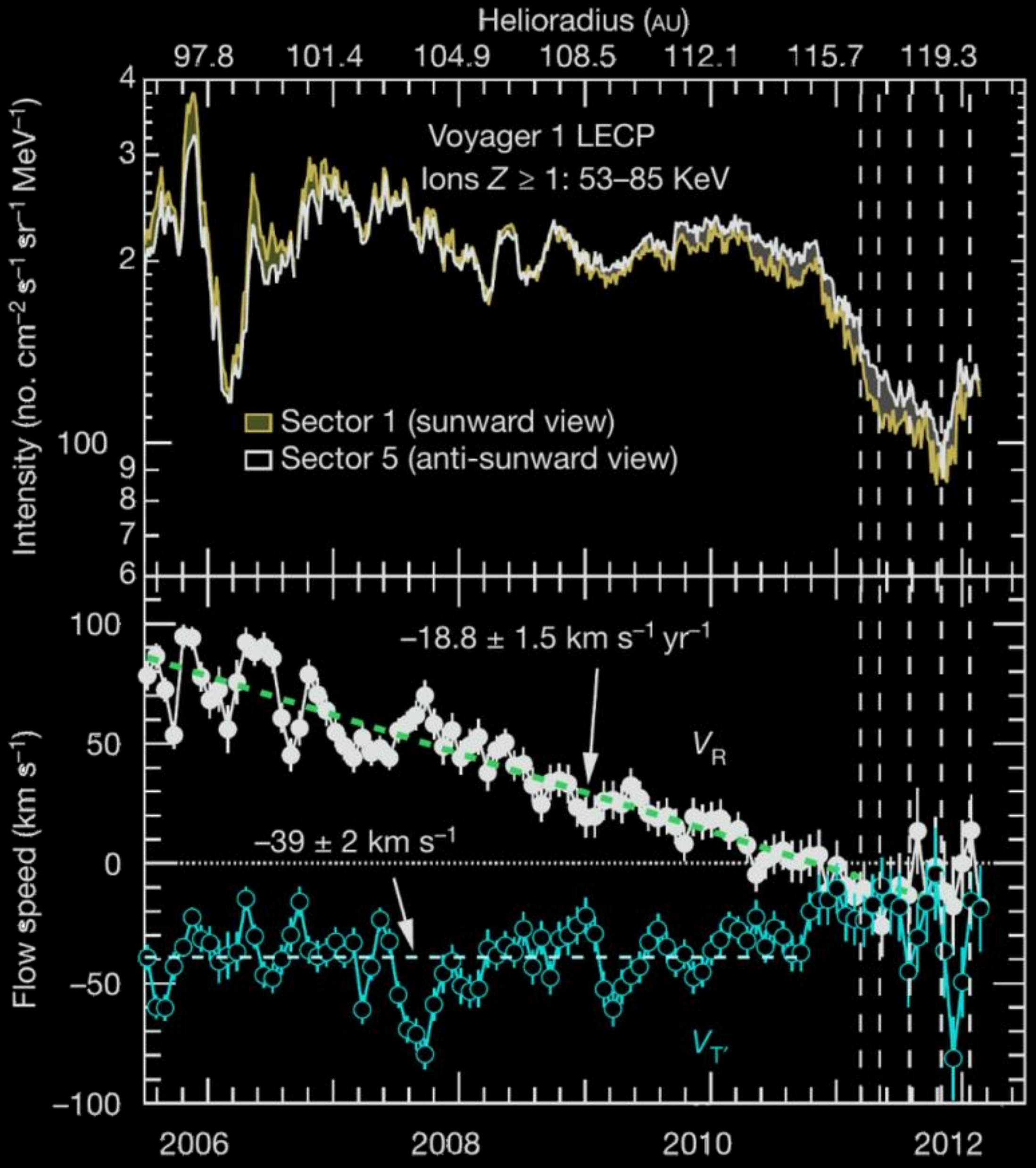
A general decrease in low energy ion intensities; a minimum at about the year 2000, followed by a gradual increase before reaching the TS.

A general increase of GCR intensity, with dropouts in anti-correlation with the solar activity over the solar cycle.

In-situ ion measurements from V1 & V2 LECP // THE HELIOSHEATH (IN BRIEF)



Decker+[2012]

V1 surveyed the HS for ~8 yrs (~28 AU past the TS)
V2 surveyed the HS for ~11 yrs (~35 AU past the TS)

The V1&V2/LECP ion intensities were very similar throughout the HS.

Gradual decrease of the radial velocities ~70 km/s to ~0 km/s at ~116 AU from the sun.

A finite transition layer of zero radial and meridional plasma flow velocity for several AU within the heliosheath.

Origin of Anomalous Cosmic Rays

Very Local Interstellar Medium

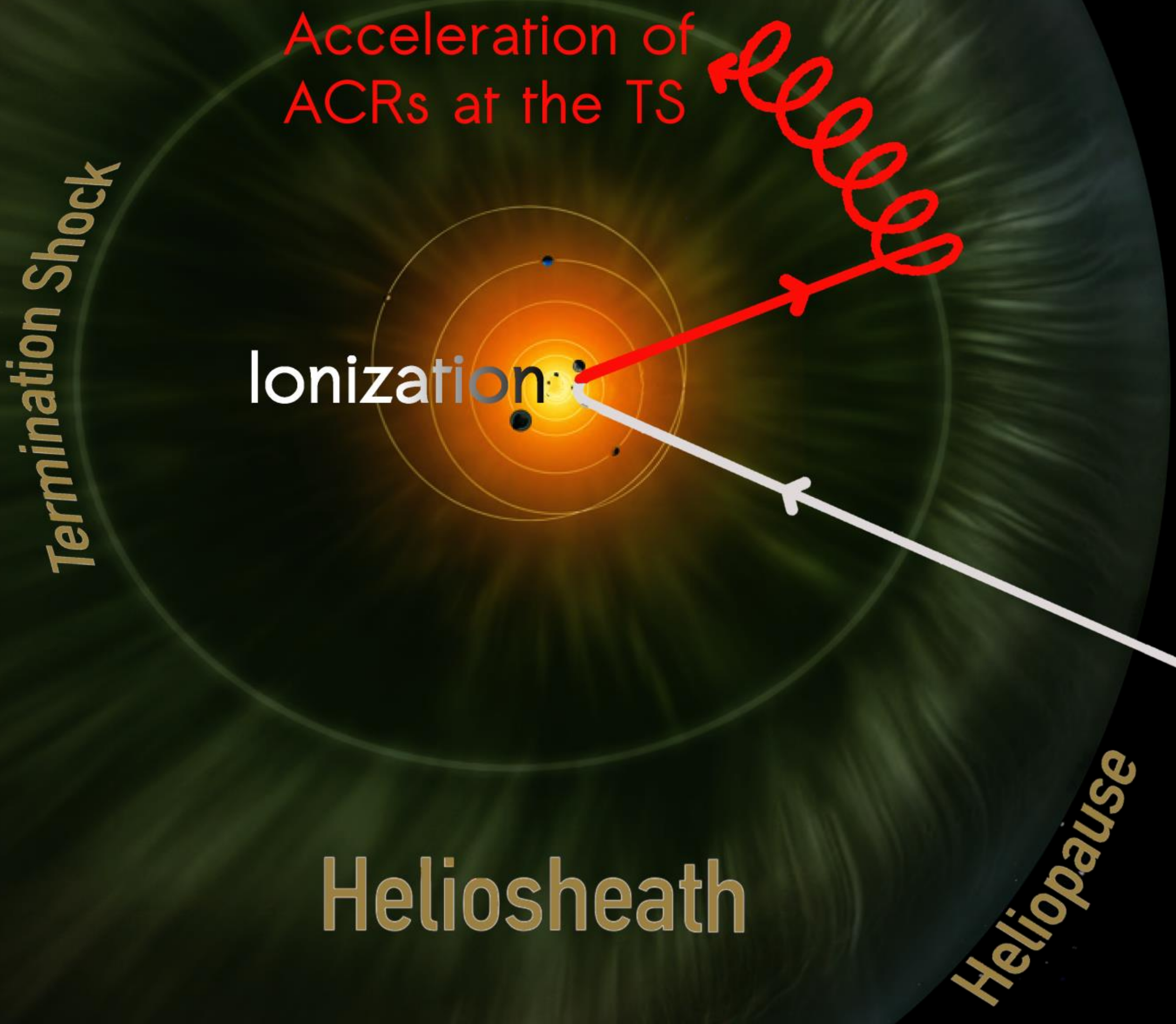
Voyager 1

Fisk+[1974]

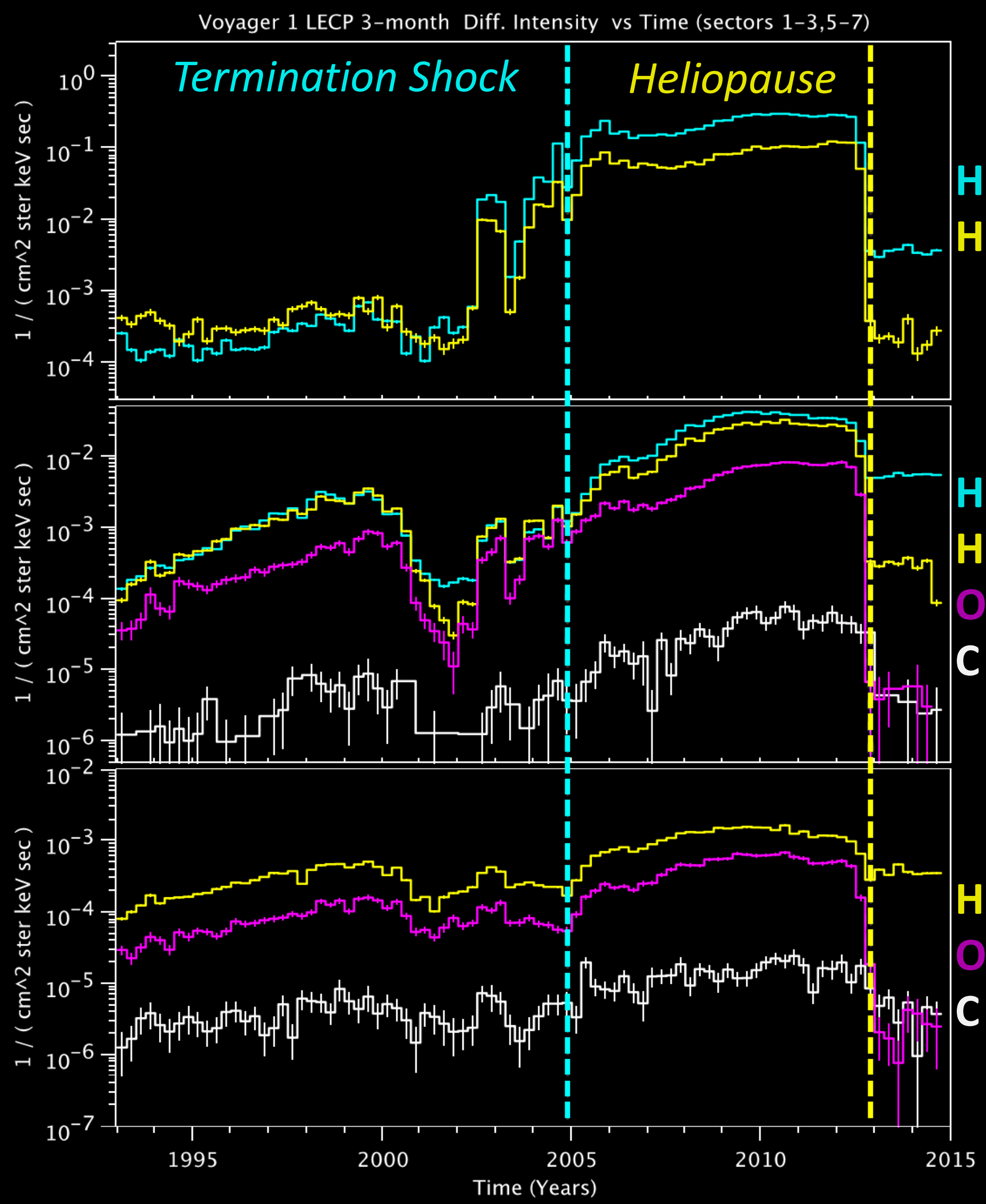
Solar wind acceleration to >10 Mev/nucleon

Pesses+[1981]

Acceleration at the Termination Shock



VGR1 ACR Histories for Groups of Species with same Total Energy/Charge



VGR1 Magnetic Field Measurements from the TS to the HP

VGR1 intensities are well-ordered by

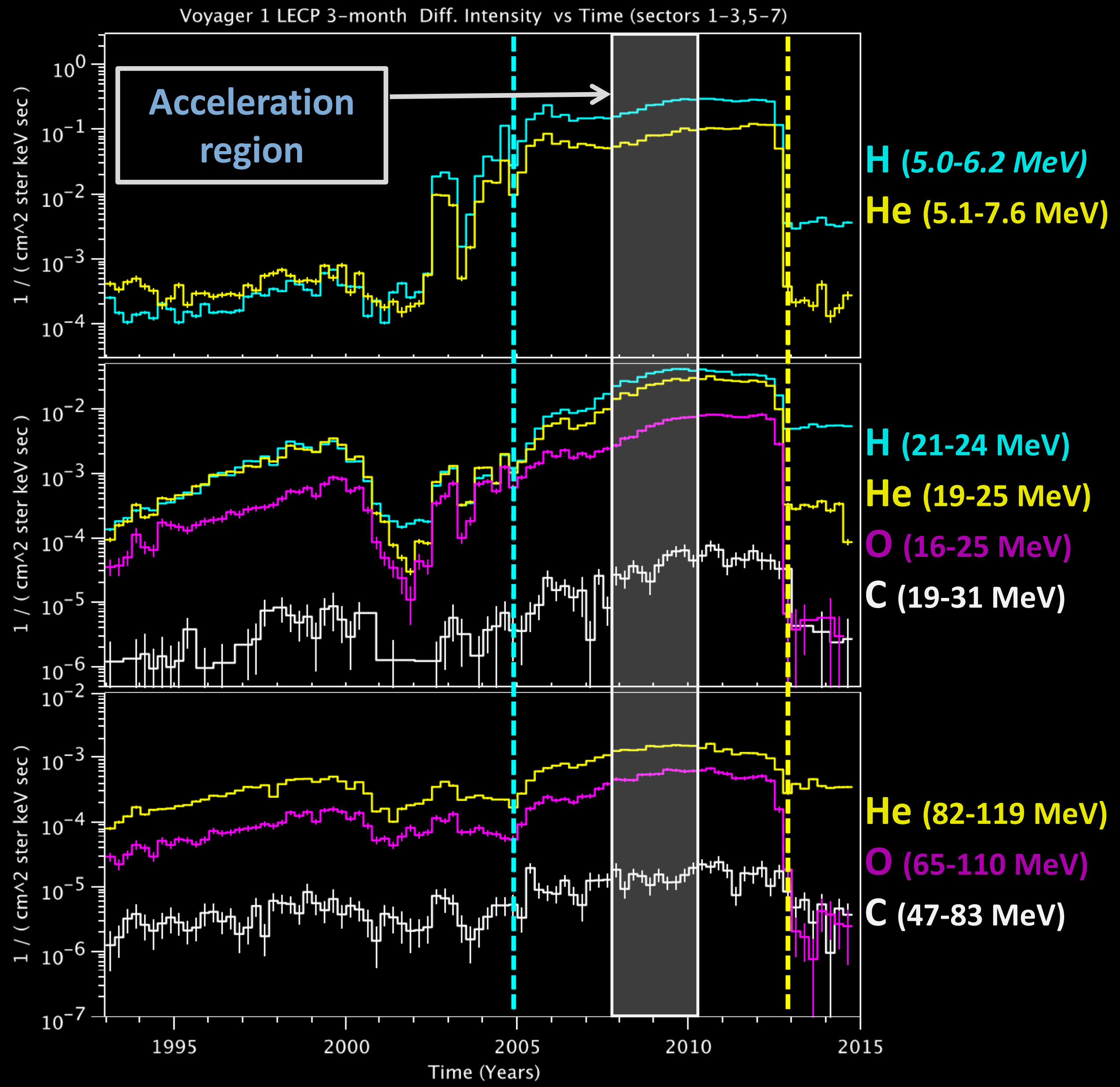
Total Energy/Charge

Implies *"common spectrum"* at any given time in HS

Krimigis+[2023]

(in preparation)

VGR1 ACR Histories for Groups of Species with same Total Energy/Charge



VGR1 Magnetic Field Measurements from the TS to the HP

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Implies *"common spectrum"* at any given time in HS

Krimigis+[2023]

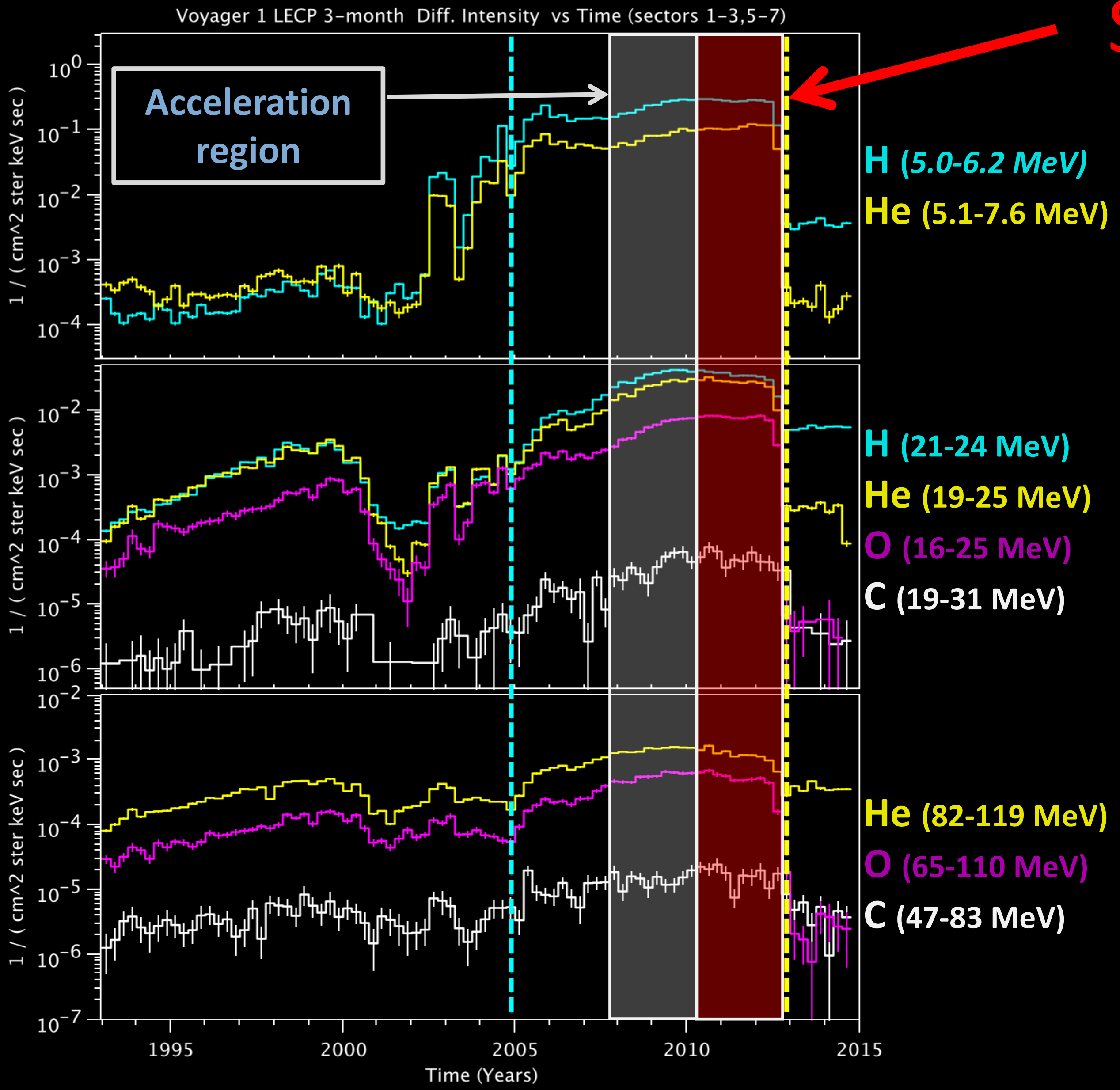
(in preparation)

ACR acceleration occurs inside the heliosheath

not at the nose or the flanks of the Termination Shock

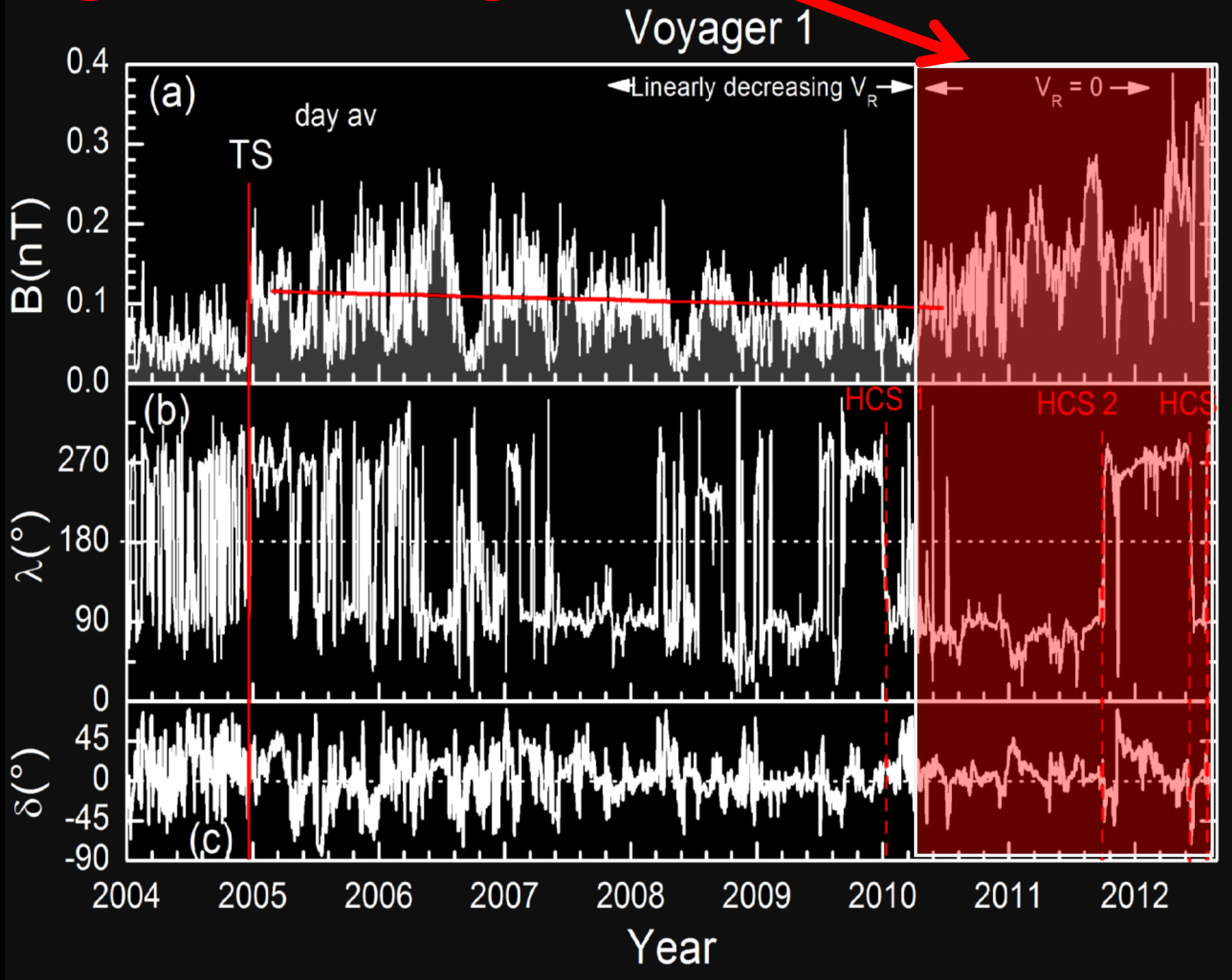
Krimigis+[2023]

(in preparation)



VGR1 Magnetic Field Measurements from the TS to the HP

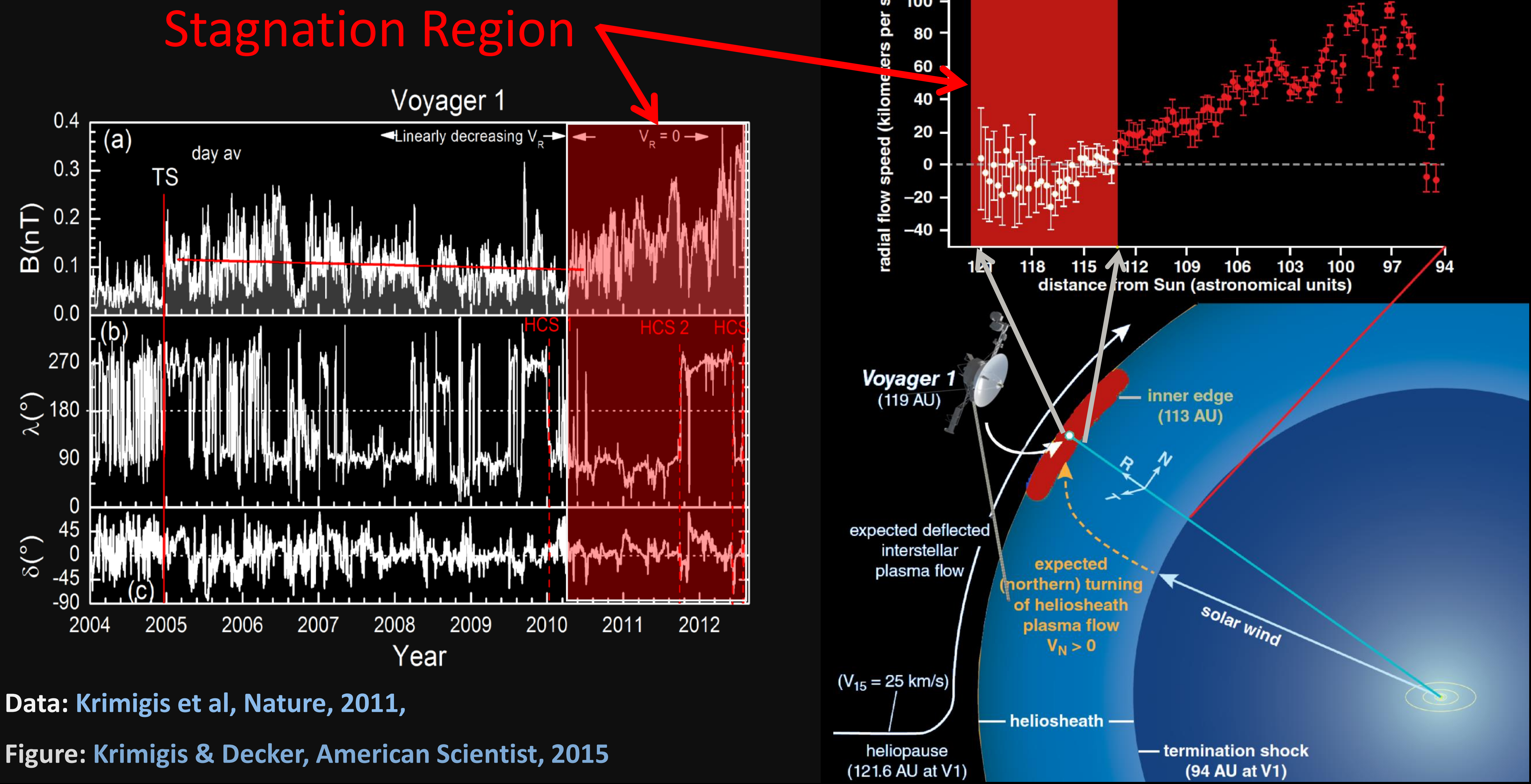
Stagnation Region



Burlaga & Ness

American Geophysical Union Dec. 2, 2012

Radial Plasma Flow in the Heliosheath

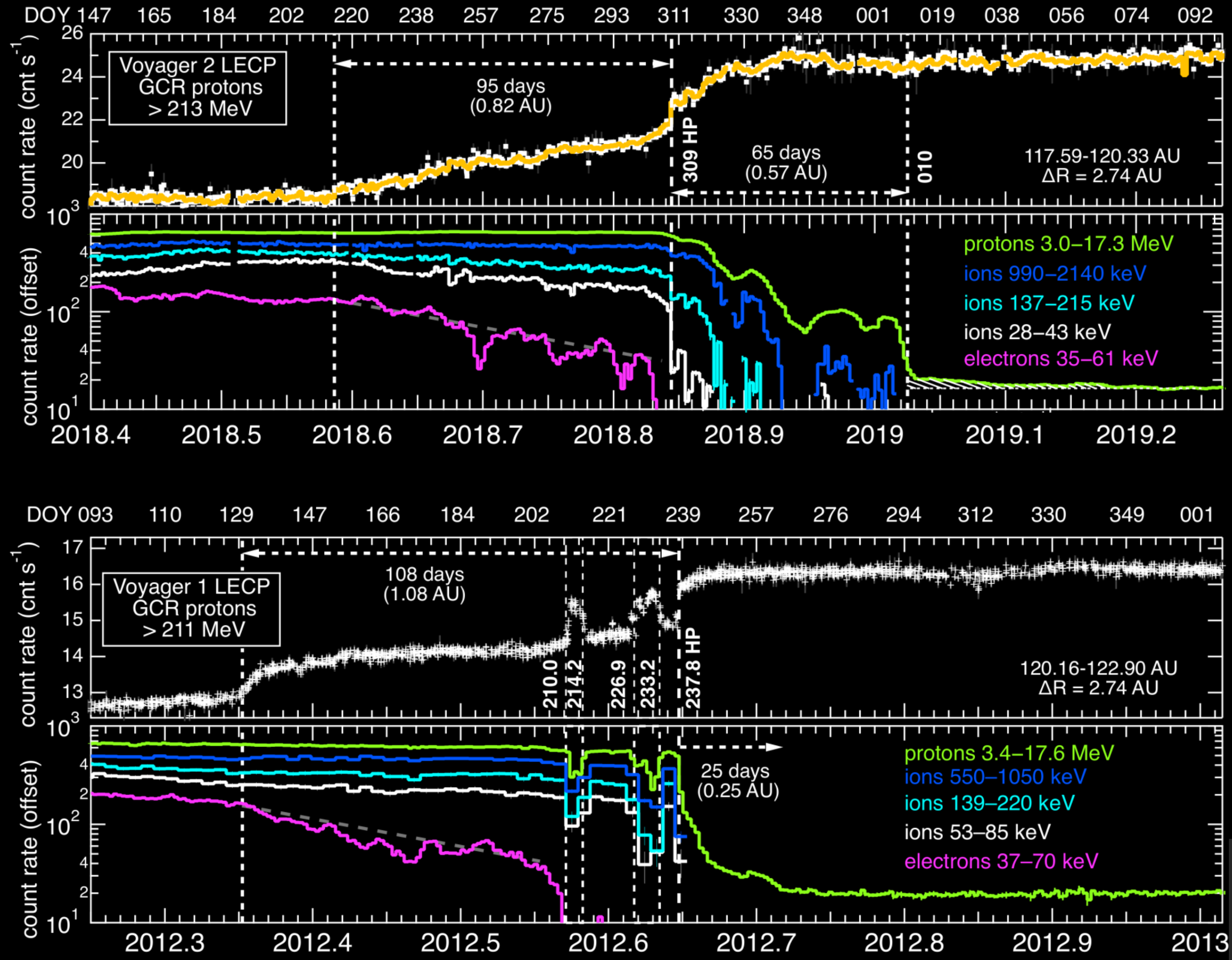


Data: Krimigis et al, Nature, 2011,

Figure: Krimigis & Decker, American Scientist, 2015

In-situ ion measurements from V1 & V2 LECP // The Heliopause

Krimigis +[2019]

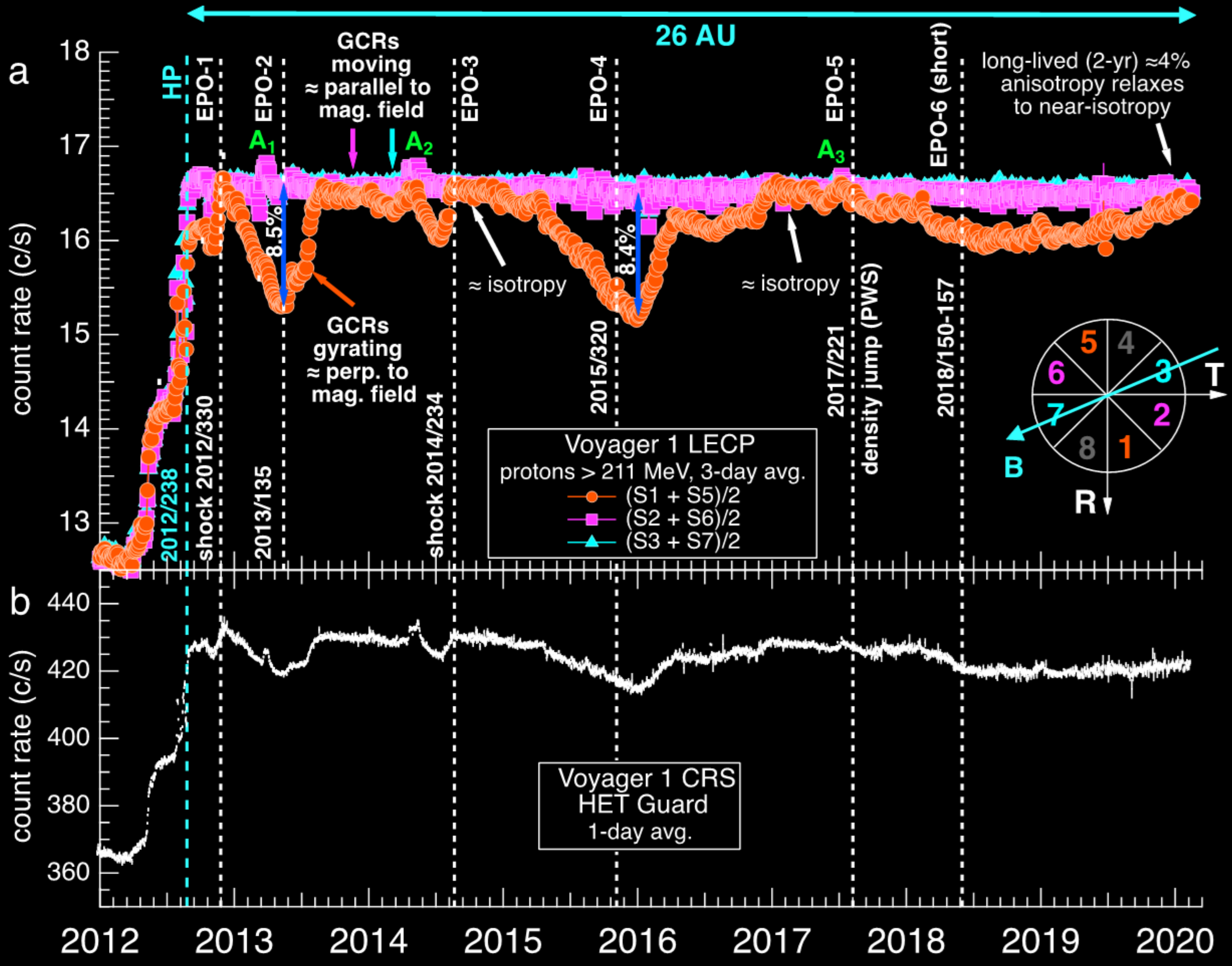


Comparison of GCR and HS particles at V1 and V2 over about the same distance scale of 2.74 AU.

- Virtual depletion of “solar” particles
- Abrupt increase of GCR
- Increase of B-field & plasma density
- Temperature in Voyager 2 was found substantially higher than expected

See also in *Nature Astronomy* 2019:
Richardson et al. (PLS), Stone et al. (CRS), Gurnett & Kurth (PWS), Burlaga et al. (MAG)

IN-SITU ION MEASUREMENTS FROM V1 & V2 LECP // THE VLISM



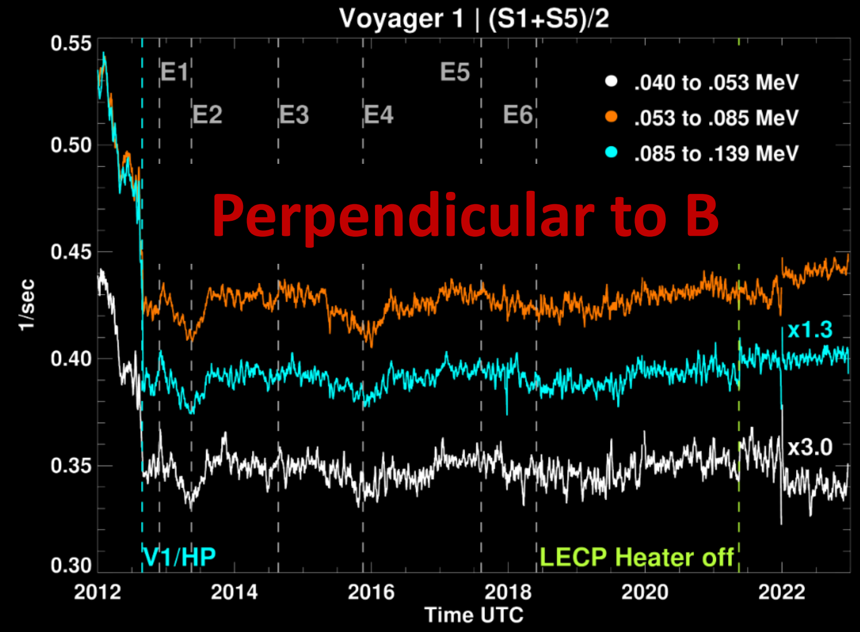
Krimigis+[2020]; Hill+[2020]

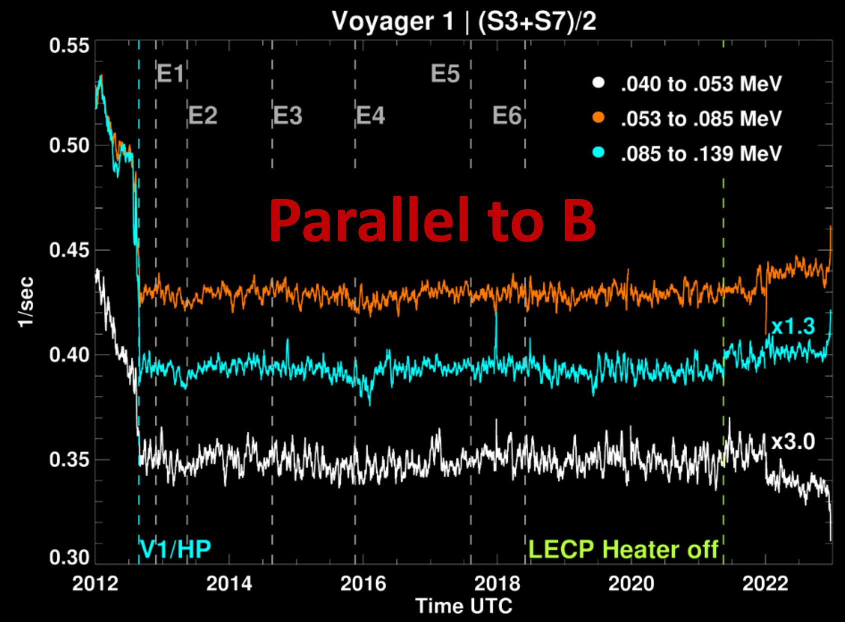
Intensity dropouts at nearly 90◦ pitch angle seen in the >211 MeV GCRs.

Gurnett+[2015; 2021]

Response to transient shocks and compressions

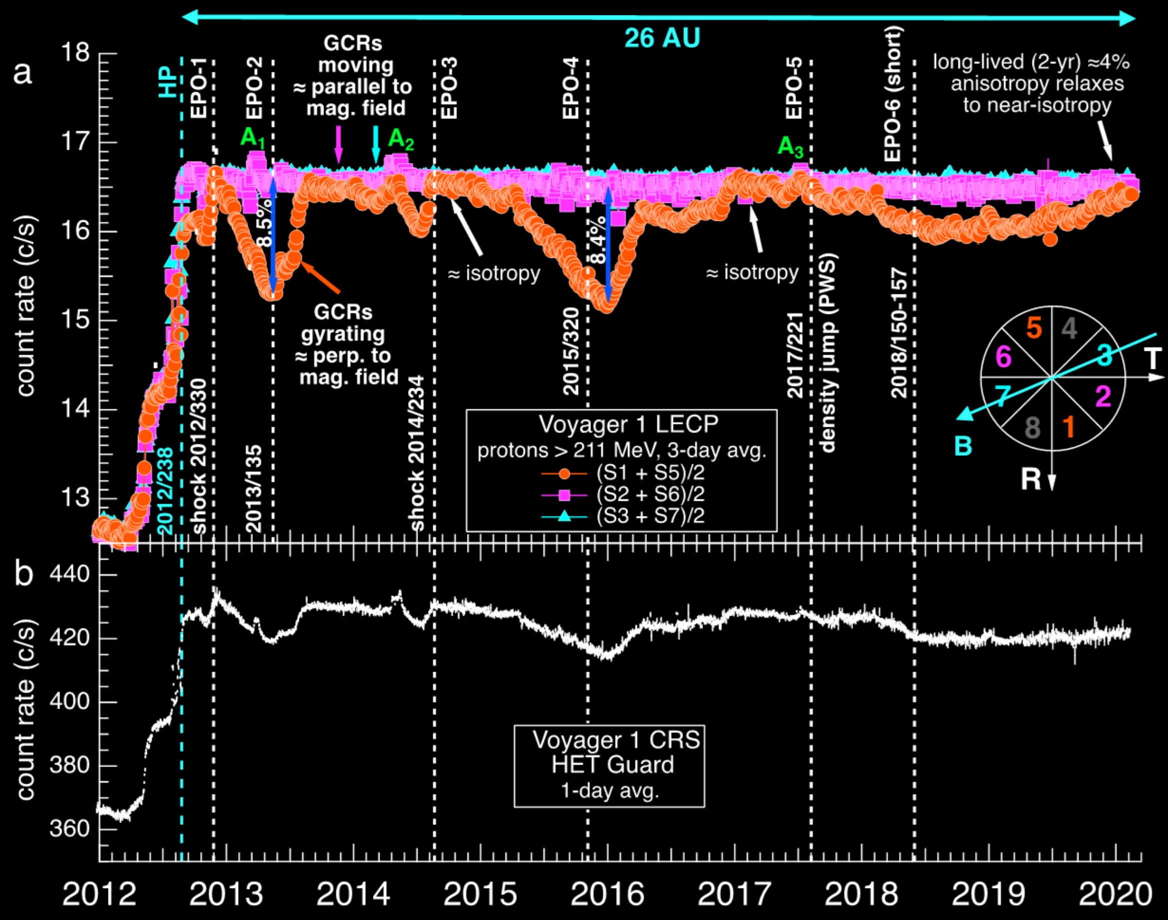
IN-SITU ION MEASUREMENTS FROM V1 & V2 LECP // THE VLISM





PL01-3

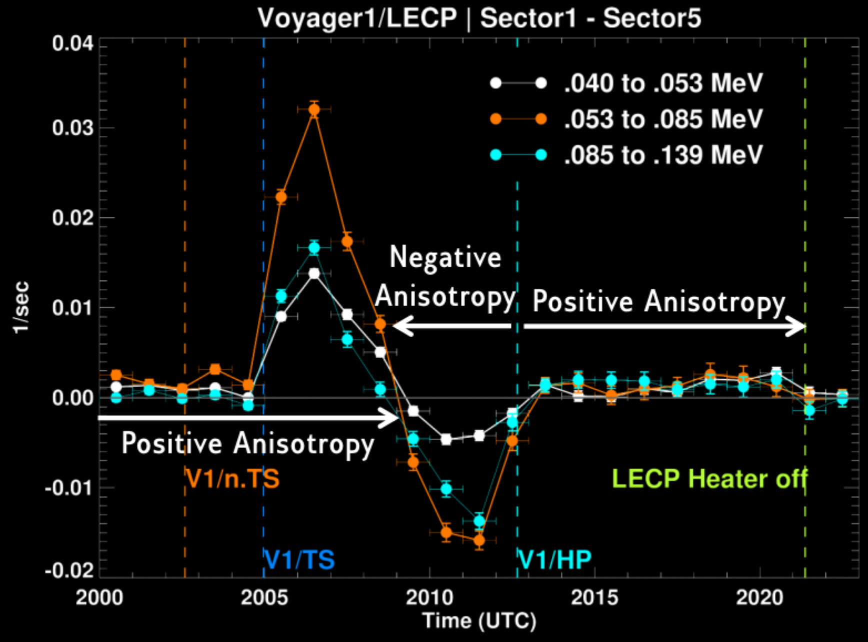
40-139 keV

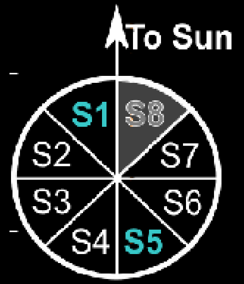


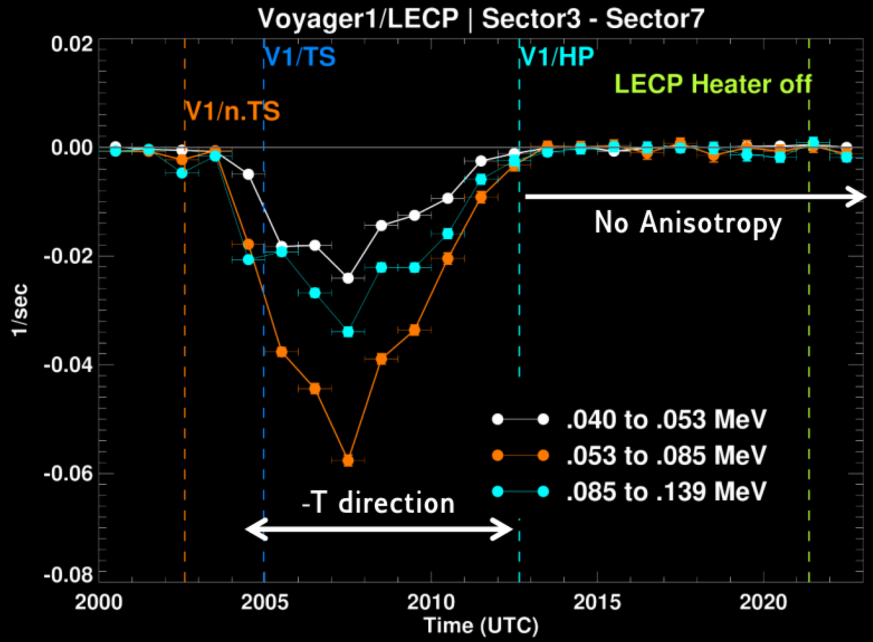
Dialynas+[2021]

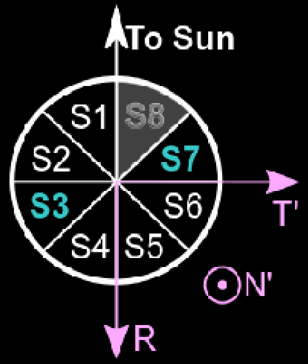
- Distinct Intensity dropouts in the S1 and S5 PL01-3 channel rates (Ei, i=1..6).
- The S3 and S7 PL01-3 channel rates remain stable.

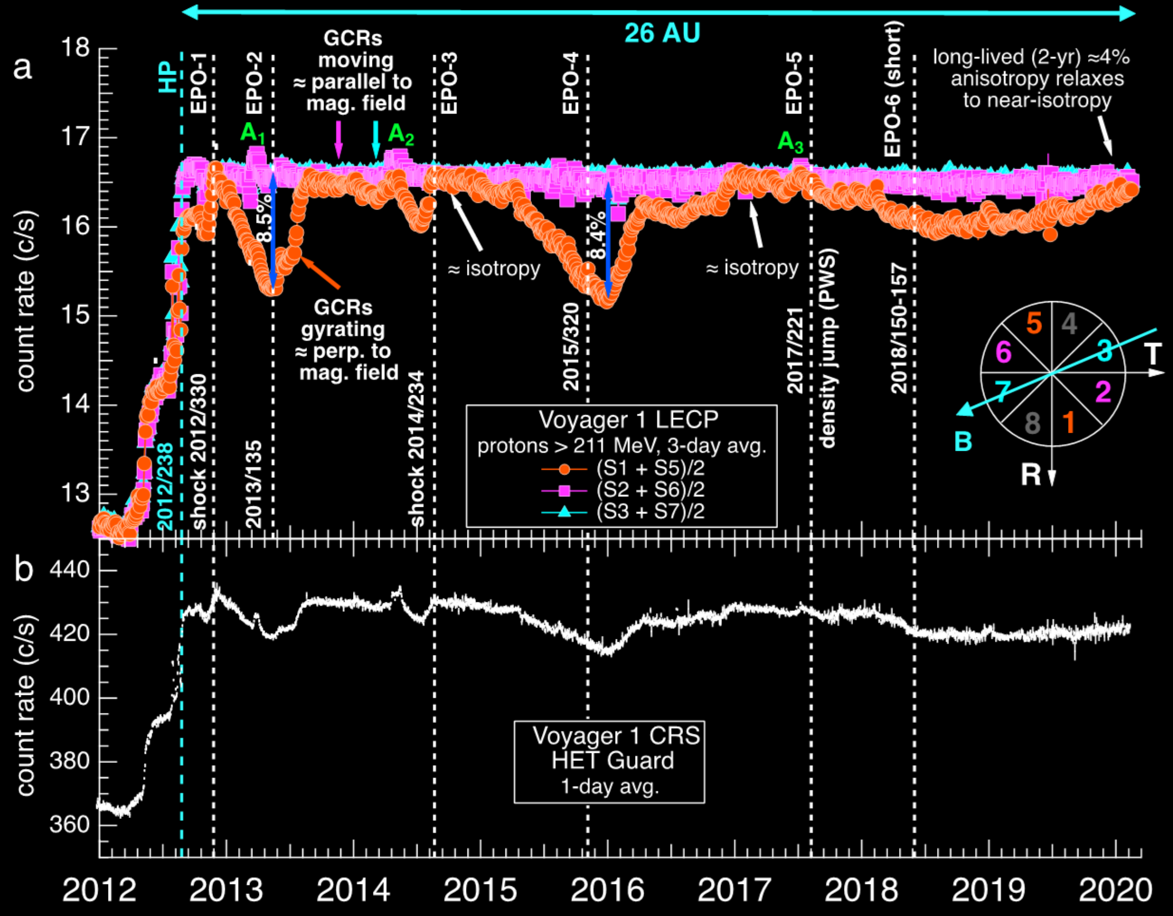
IN-SITU ION MEASUREMENTS FROM V1 & V2 LECP // THE VLISM





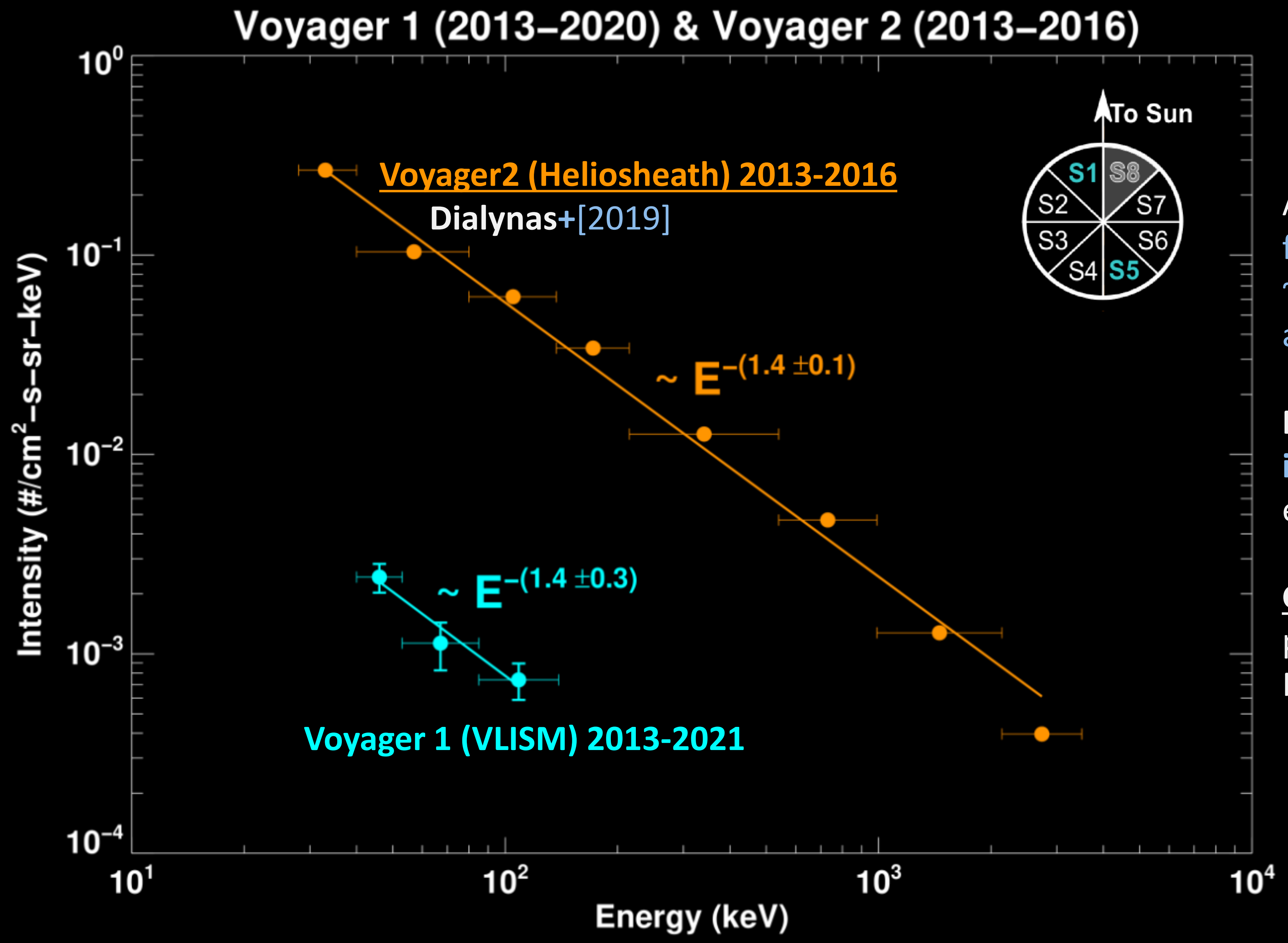






Dialynas+[2021]

- An inflow of 40-139 keV ions for ~9 AU before the HP
- An outflow of 40-139 keV ions for ~30 AU past the HP



Dialynas+[2023]

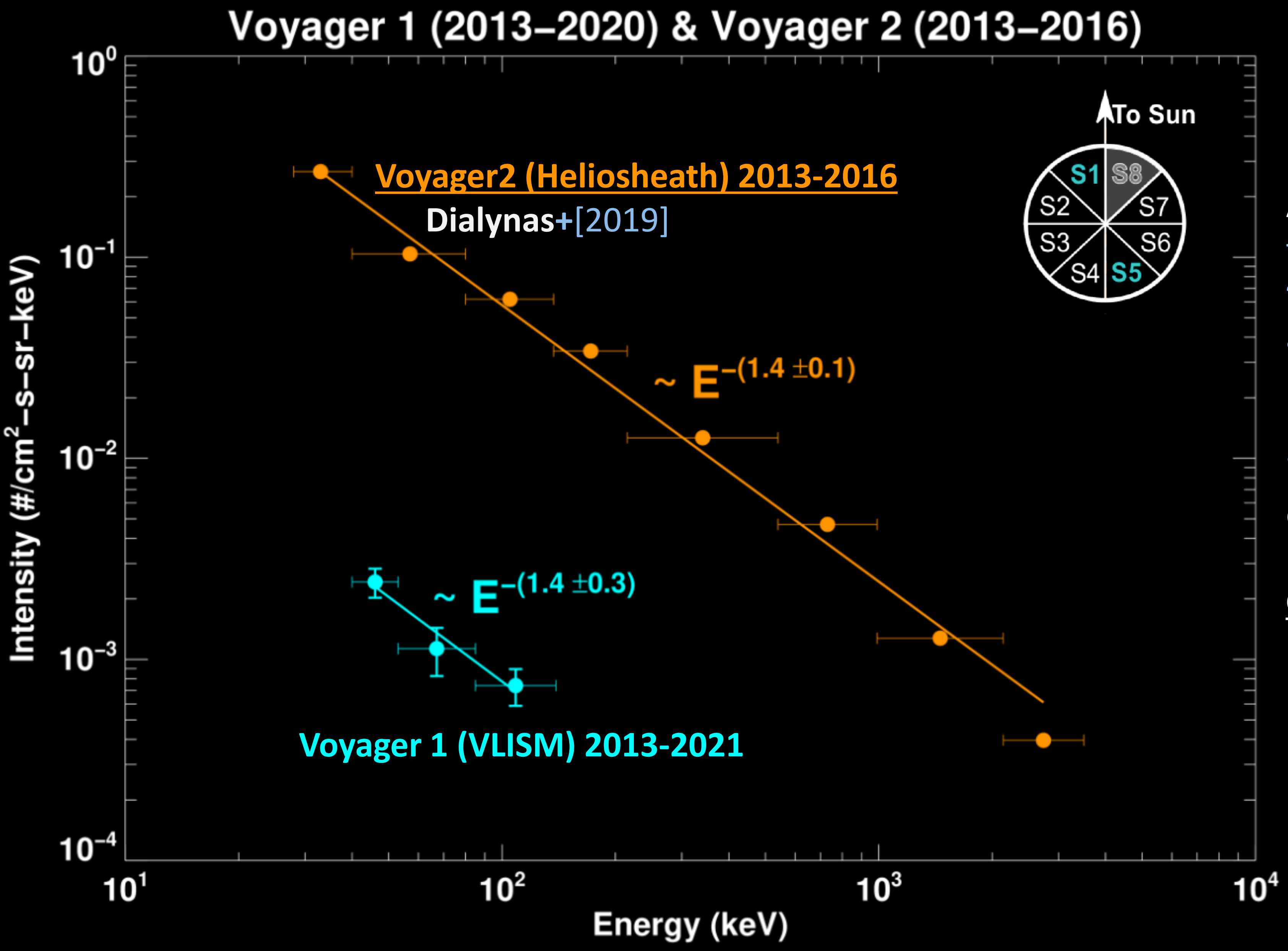
in preparation

A 40-139 keV ion population escaping from the HS radially outward, out ot ~30 AU past the HP, that has no azimuthal component.

Perhaps due to Flux Tube interchange instability at the HP, as explained by Florinski+[2015].

Gloeckler+[1997]: Superthermal particles that could play a role in the Pressure balance at the HP.

IN-SITU MEASUREMENTS // 40-139 KEV ION ANISOTROPIES IN THE HELIOSPHERE



Dialynas+[2023]

in preparation

A 40-139 keV ion population escaping from the HS radially outward, out ot ~33 AU past the HP, that has no azimuthal component.

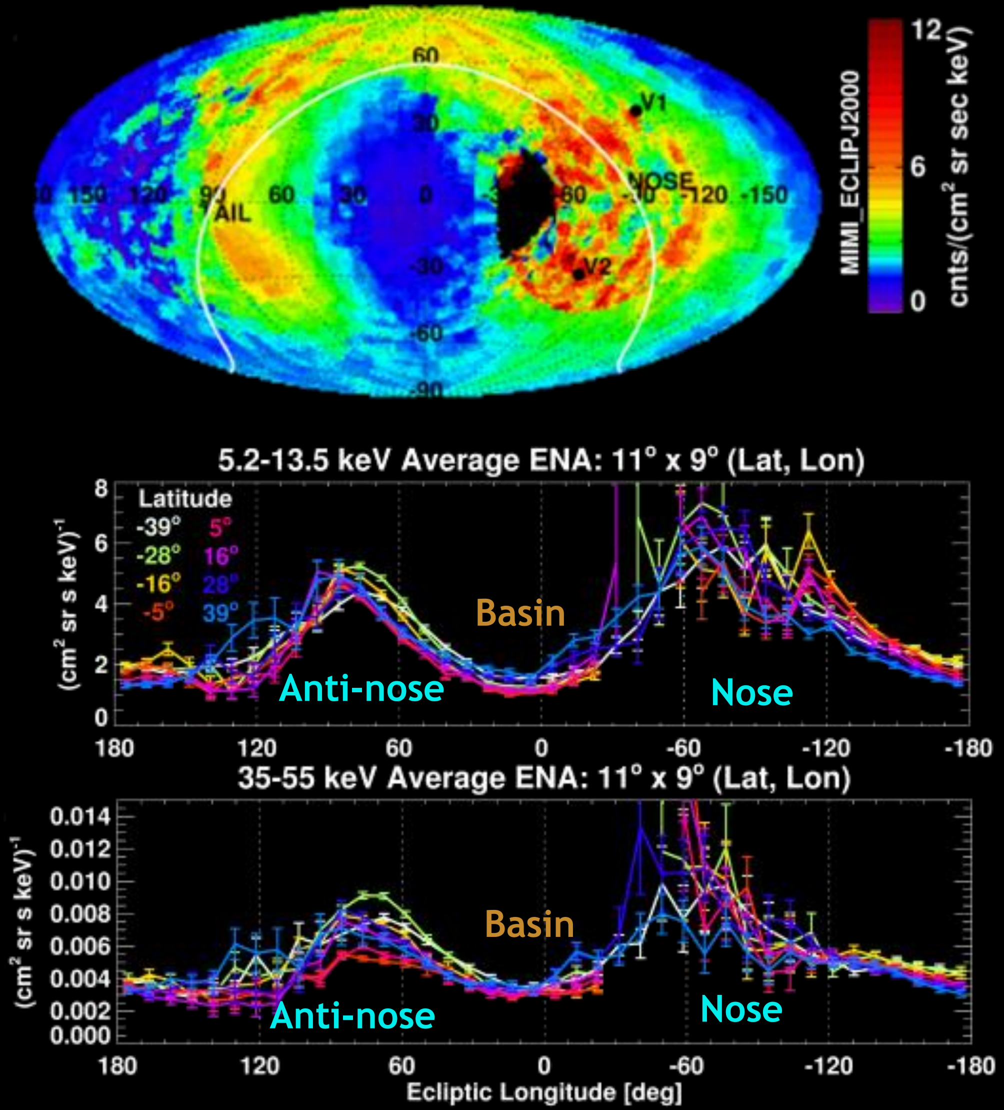
Perhaps due to Flux Tube interchange instability at the HP, as explained by Florinski+[2015].

Gloeckler+[1997]: Superthermal particles that could play a role in the Pressure balance at the HP.

Fisk & Gloeckler+[2022]

V1 did not cross the heliopause in 2012 and is not now in interstellar space.

REMOTELY SENSED ENAs FROM CASSINI // THE GLOBAL HELIOSPHERE (>5.2 KEV)

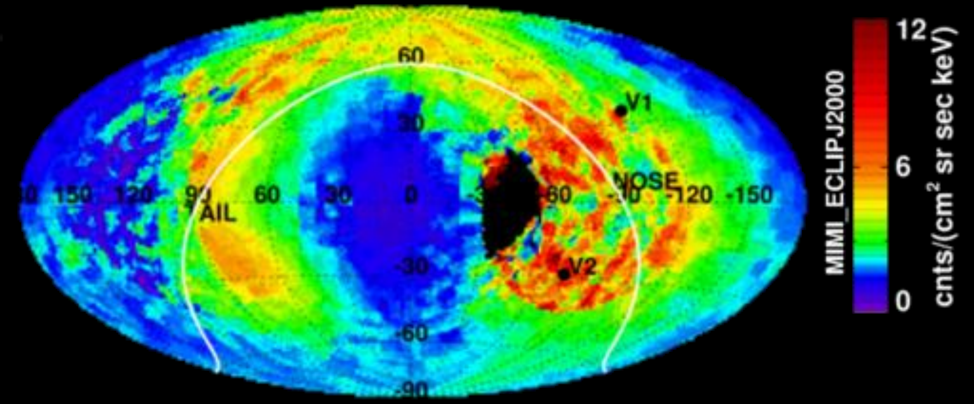


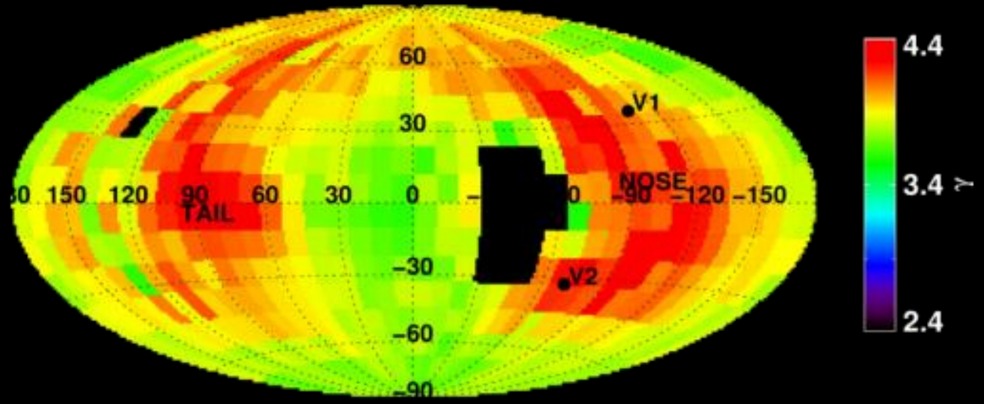
Dialynas+[2017b]
Dialynas+[2013]

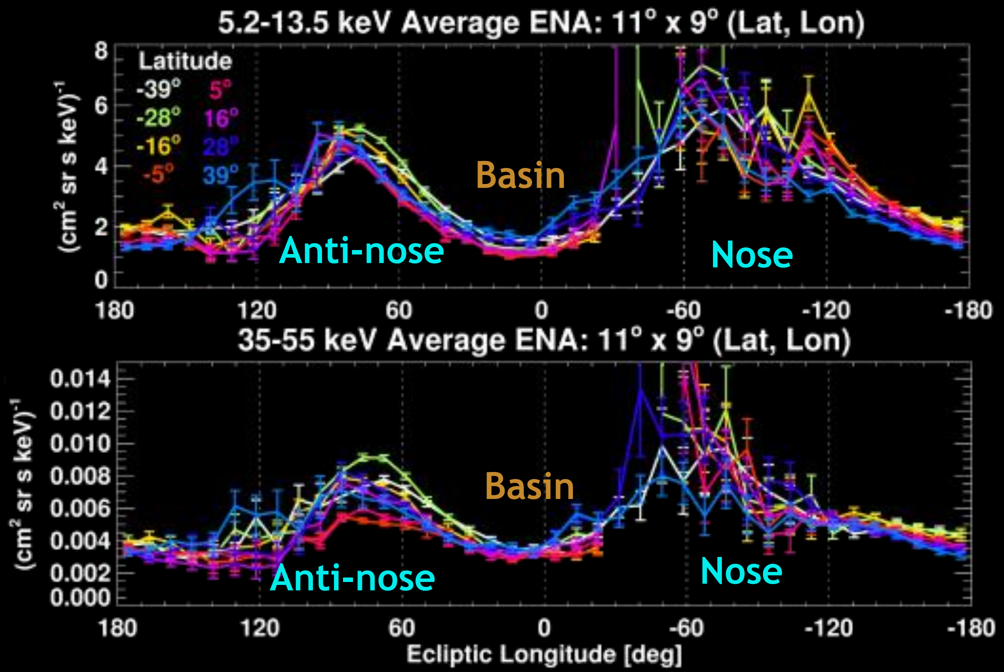
The INCA Belt is a broad band of emission in the sky *that corresponds to the reservoir of electrons and ions that constitute the heliosheath.*

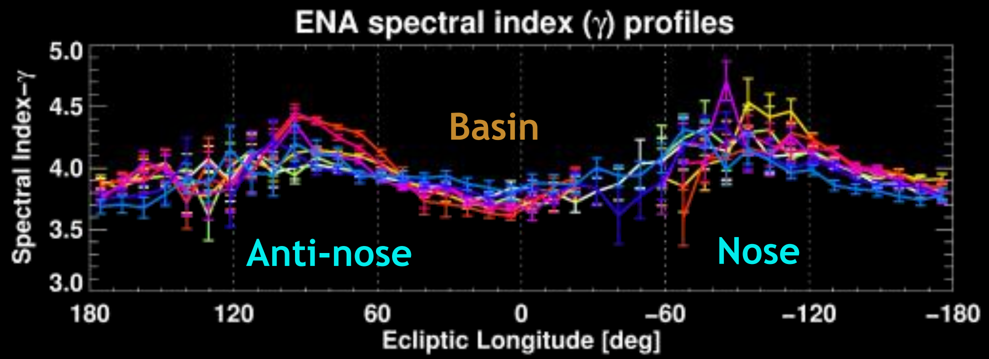
The INCA Basins are extended heliosphere lobes *where the ENA minima occur.*

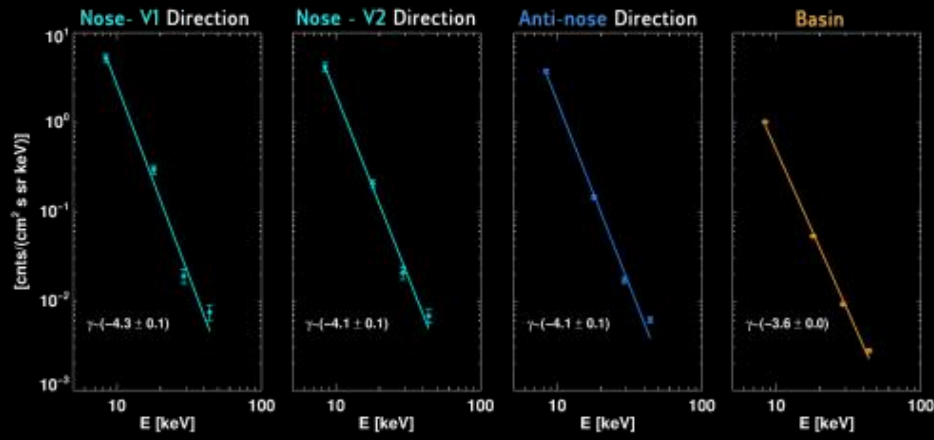
REMOTELY SENSED ENAs FROM CASSINI // THE GLOBAL HELIOSPHERE (>5.2 KEV)











ENA spectra show a power law form in energy and spectral properties follow the ENA intensity changes

Dialynas+[2017b]

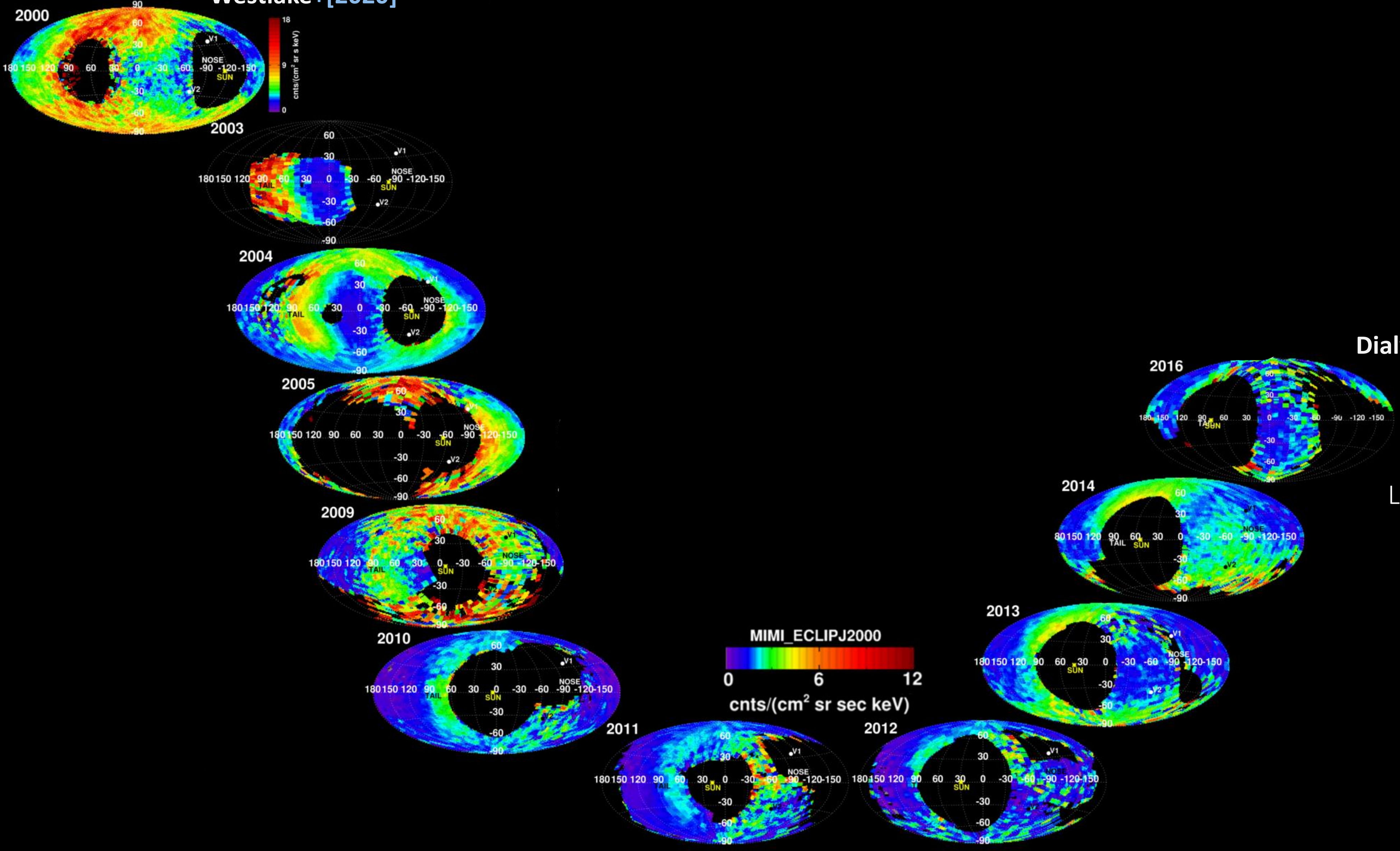
Dialynas+[2013]

Ground Truth from the Voyagers in the Heliosheath // ENA Maps Over SC23 & SC24 (2000-2017)

Dialynas+[2017]

Westlake+[2020]

Dialynas+[2019]



GLOBAL HS

>5.2 keV ENAs

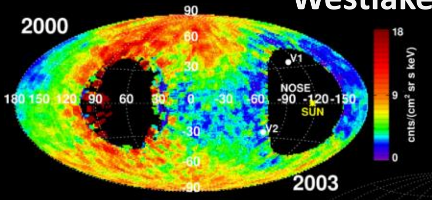
Decline (2000-2012).

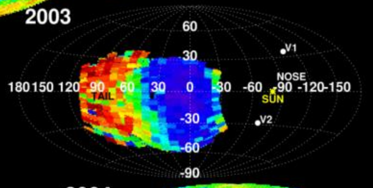
Local minimum at ~2012-2013.

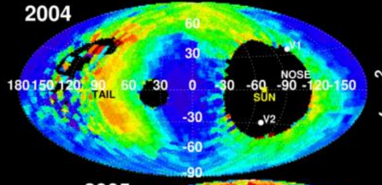
GROUND TRUTH FROM THE VOYAGERS IN THE HELIOSHEATH // ENA MAPS OVER SC23 & SC24 (2000-2017)

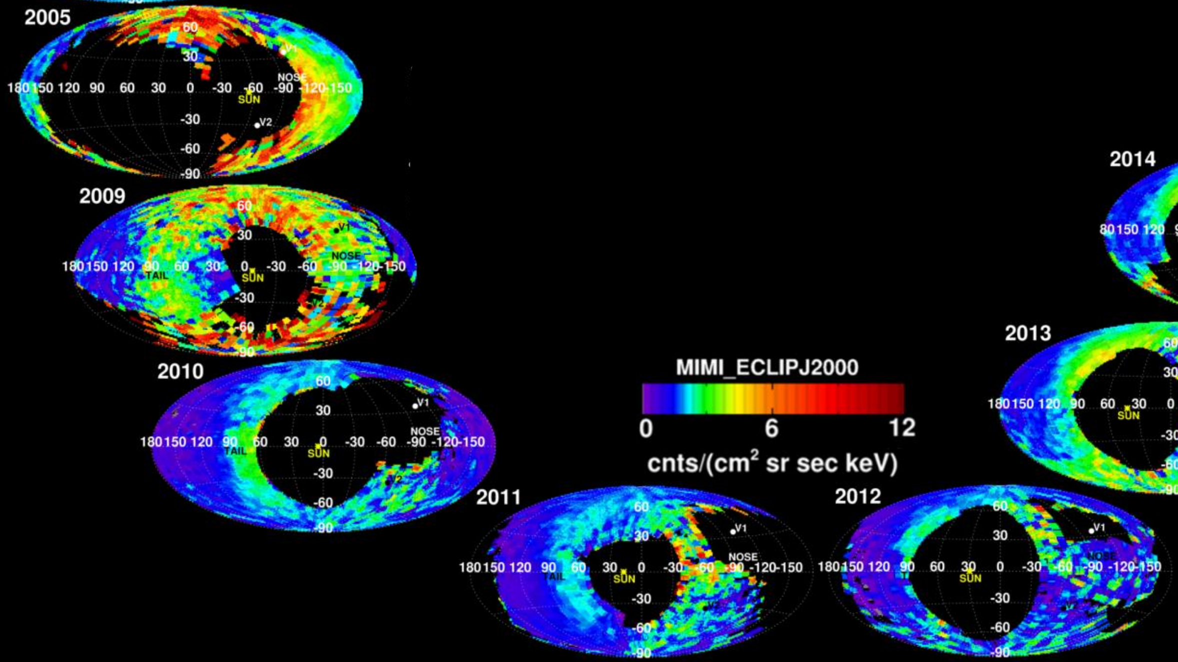
Dialynas+[2017]

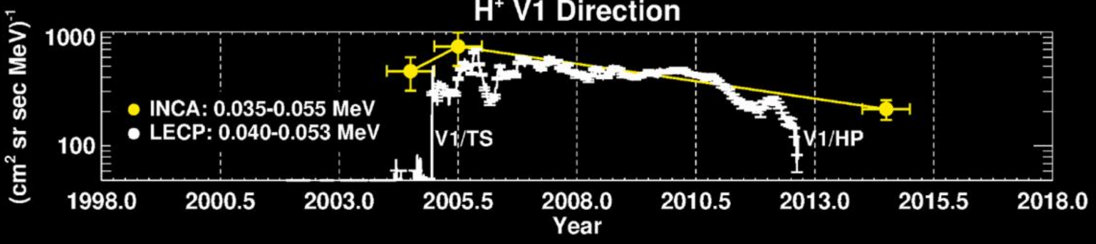
Westlake+[2020]

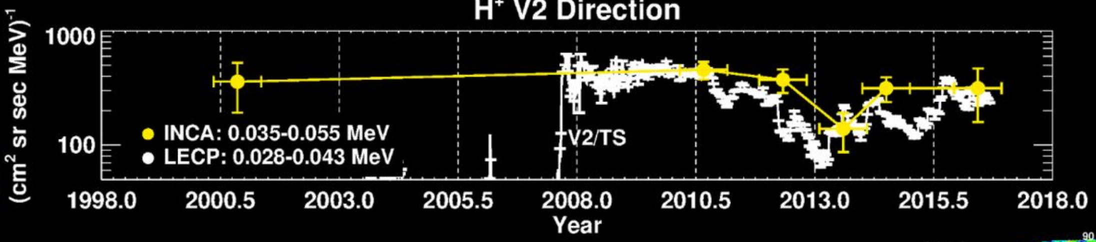




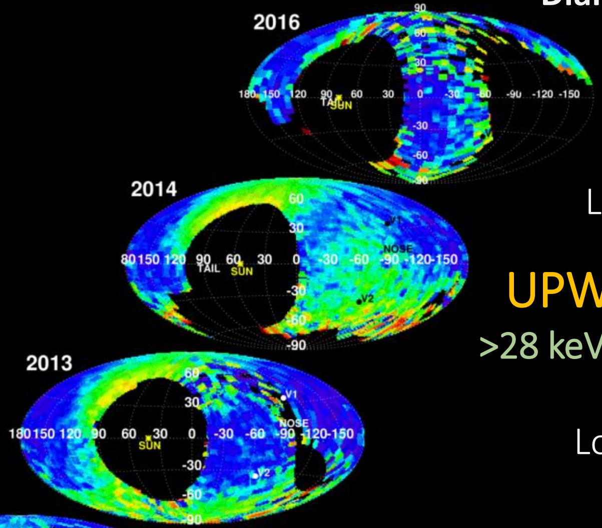








Dialynas+[2019]



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UPWIND (NOSE) HEMISPHERE

>28 keV ions & >24 keV ENA converted ions

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Local minimum at ~2012-2013.

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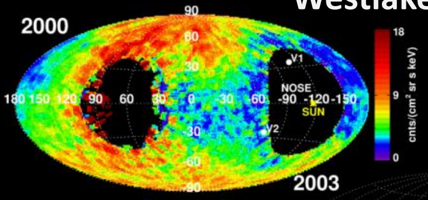
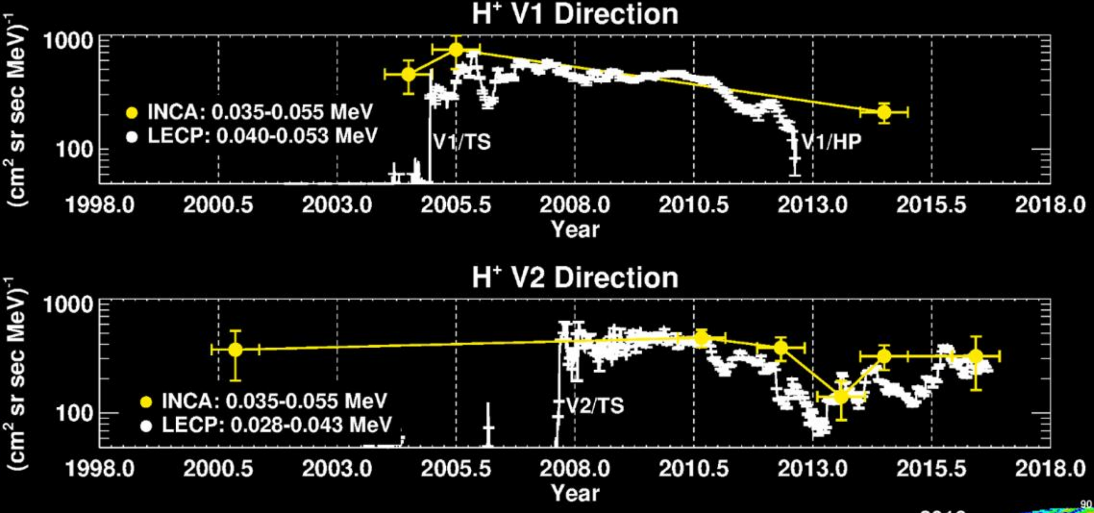
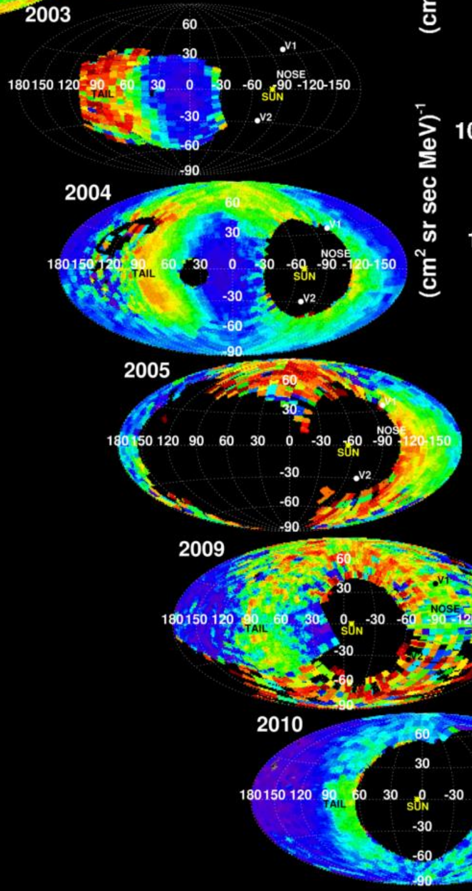
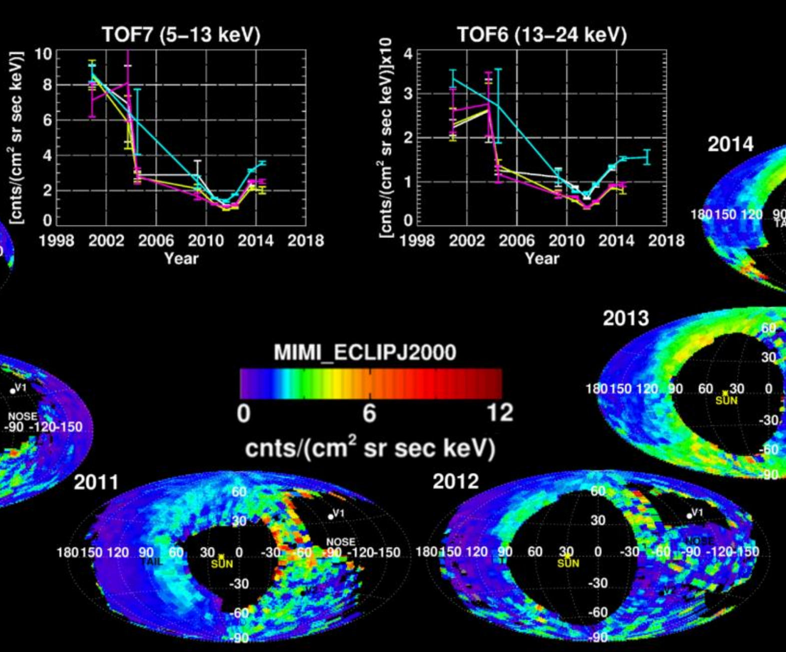
Dialynas+[2017]

Westlake+[2020]

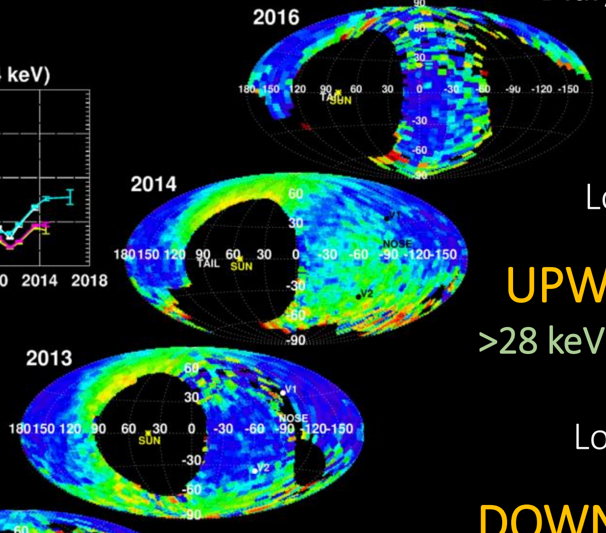








Dialynas+[2019]



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UPWIND (NOSE) HEMISPHERE

>28 keV ions & >24 keV ENA converted ions

Decline (2000-2012).

Local minimum at ~2012-2013.

DOWNWIND (TAIL) HEMISPHERE

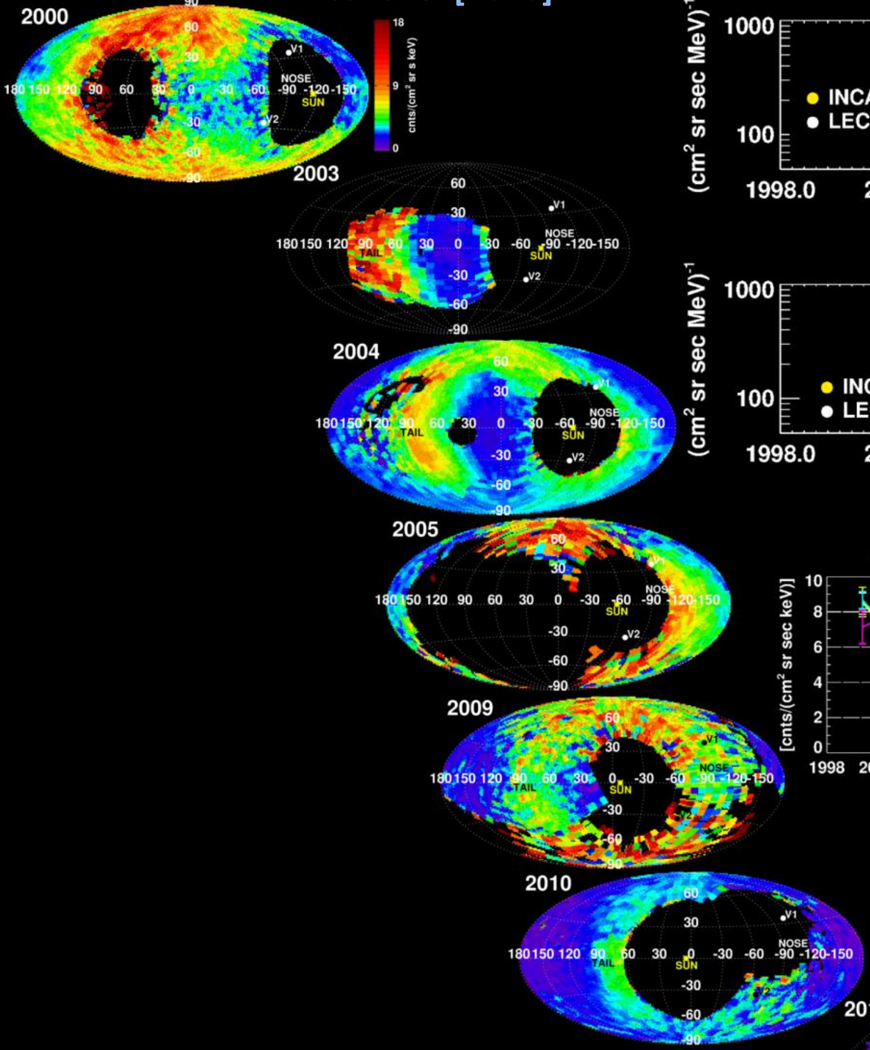
>5.2 keV ENAs

Decline (2000-2012).

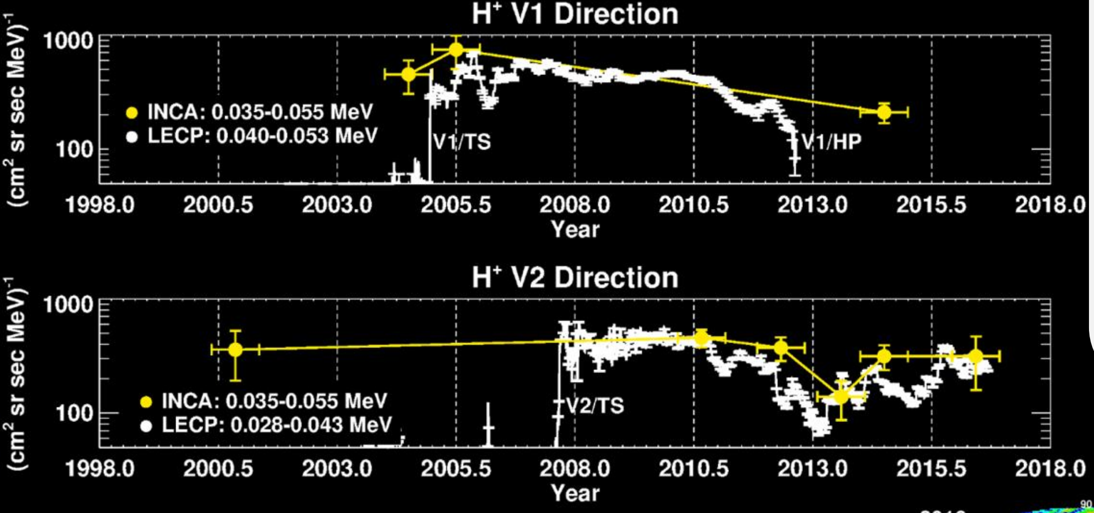
Local minimum at ~2011-2013.

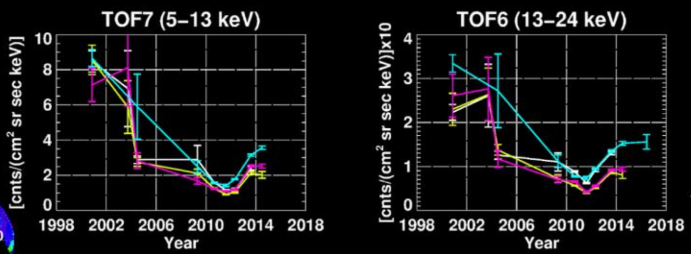
Ground Truth from the Voyagers in the Heliosheath // ENA Maps Over SC23 & SC24 (2000-2017)

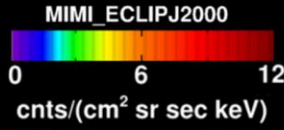
Westlake+[2020]

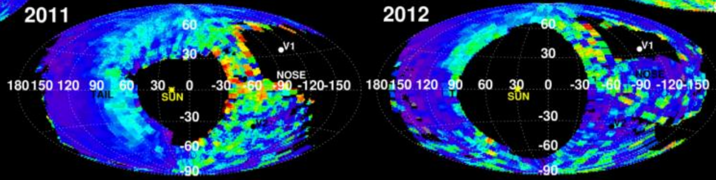


Dialynas+[2017]

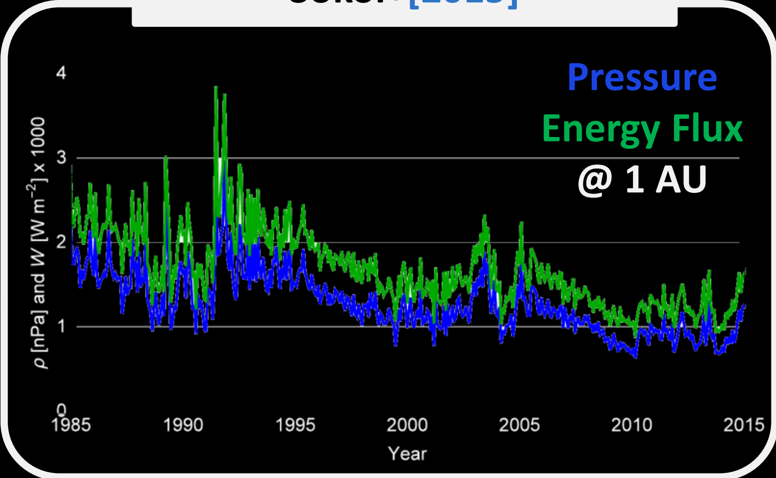




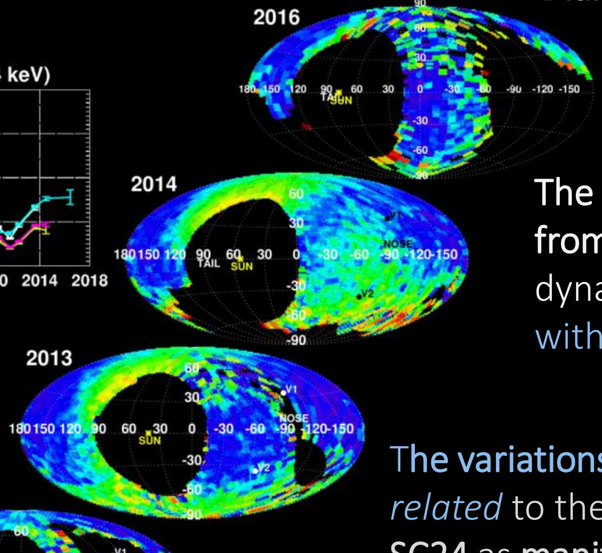




Sokol+[2015]



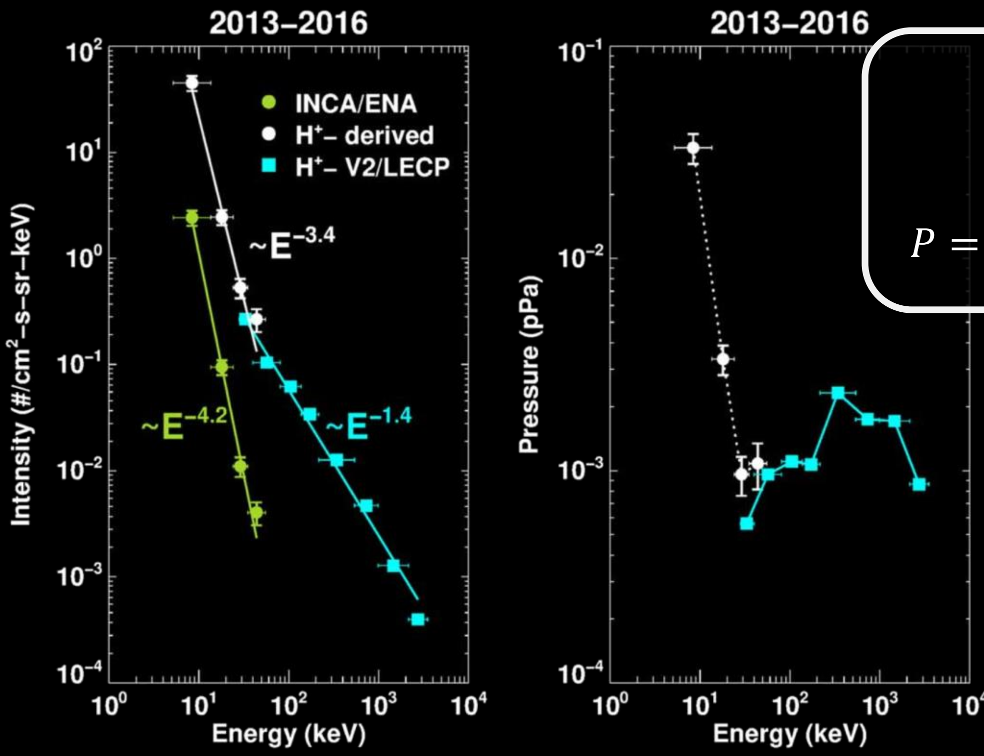
Dialynas+[2019]



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

COMBINED IN-SITU IONS & REMOTELY SENSED ENAs // >28 KEV IONS (VOYAGERS) & >5.2 KEV ENAs (CASSINI)



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

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

Dialynas+[2019]

- **Richardson+[2008]:** A substantial amount of the upstream energy density was transferred into heating the pickup ions and >15% being transferred to the >28 keV H^+

- **Giacalone & Decker [2010]; Giacalone+[2021]:** Accelerated “core” IS PUI distribution at the TS, through shock drift acceleration and particle scattering in the vicinity of the shock.

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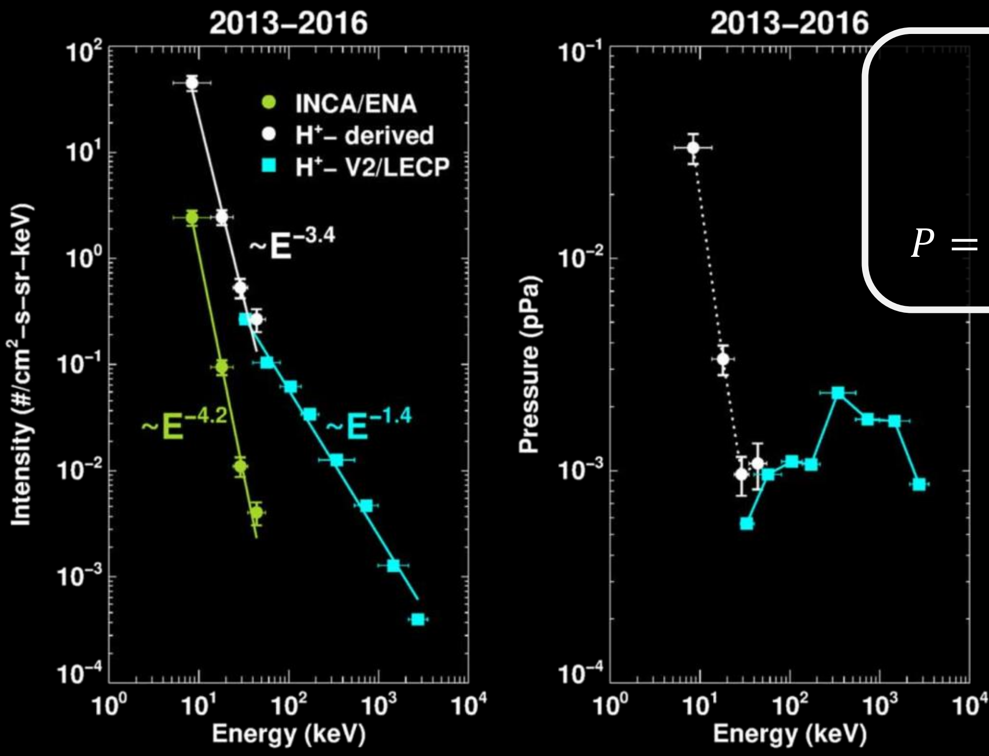

$$J_{ion} = \frac{J_{ENA}}{n_H \sigma L}$$

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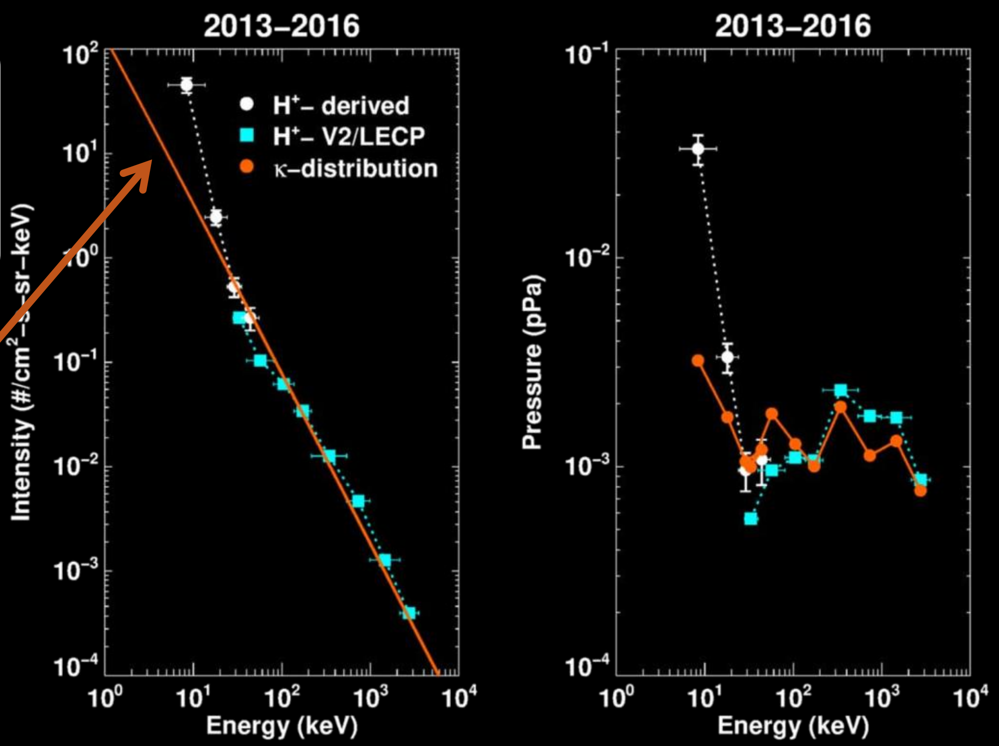
Modeled κ-distribution T=0.26 keV κ=1.63 and n=0.002 /cm³



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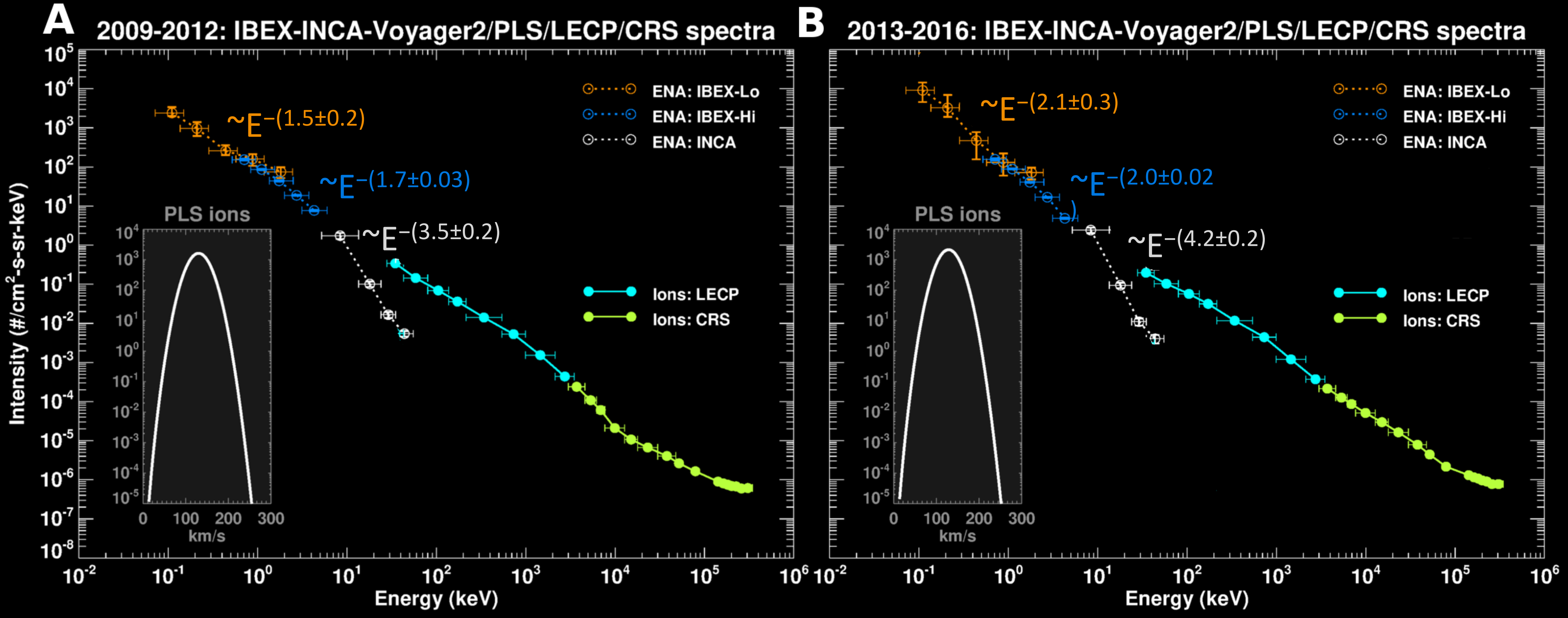
A single κ-distribution (or a single Maxwellian) would undershoot the 5.2 to 24-keV part of the H^+ distribution in both intensities and pressure.

THE SHAPE OF ENA & ION SPECTRA // INSIDE THE HELIOSHEATH (~10 eV to 344 MeV) keV ENA

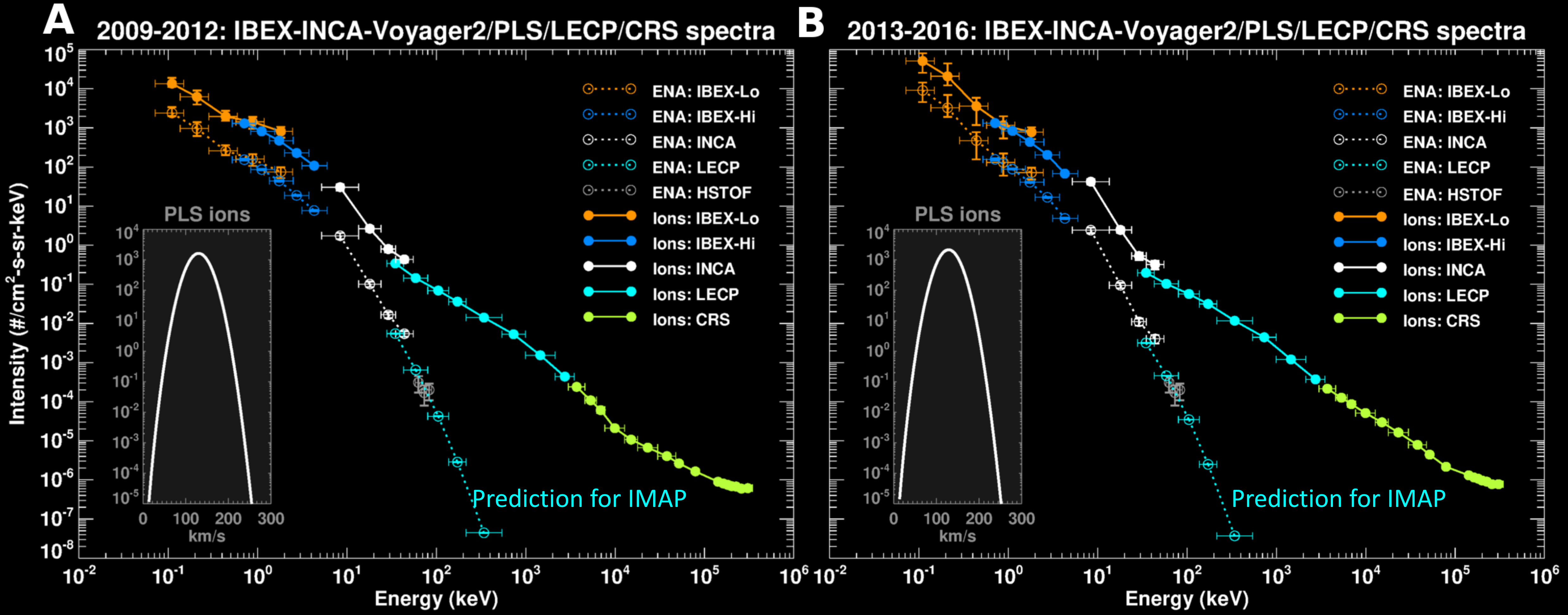
Dialynas+[2020]



SHIELD https://shielddrivecenter.com/

THE SHAPE OF ENA & ION SPECTRA // INSIDE THE HELIOSHEATH (~10 eV to 344 MeV) keV ENA

Dialynas+[2020]; Dialynas+[2022]

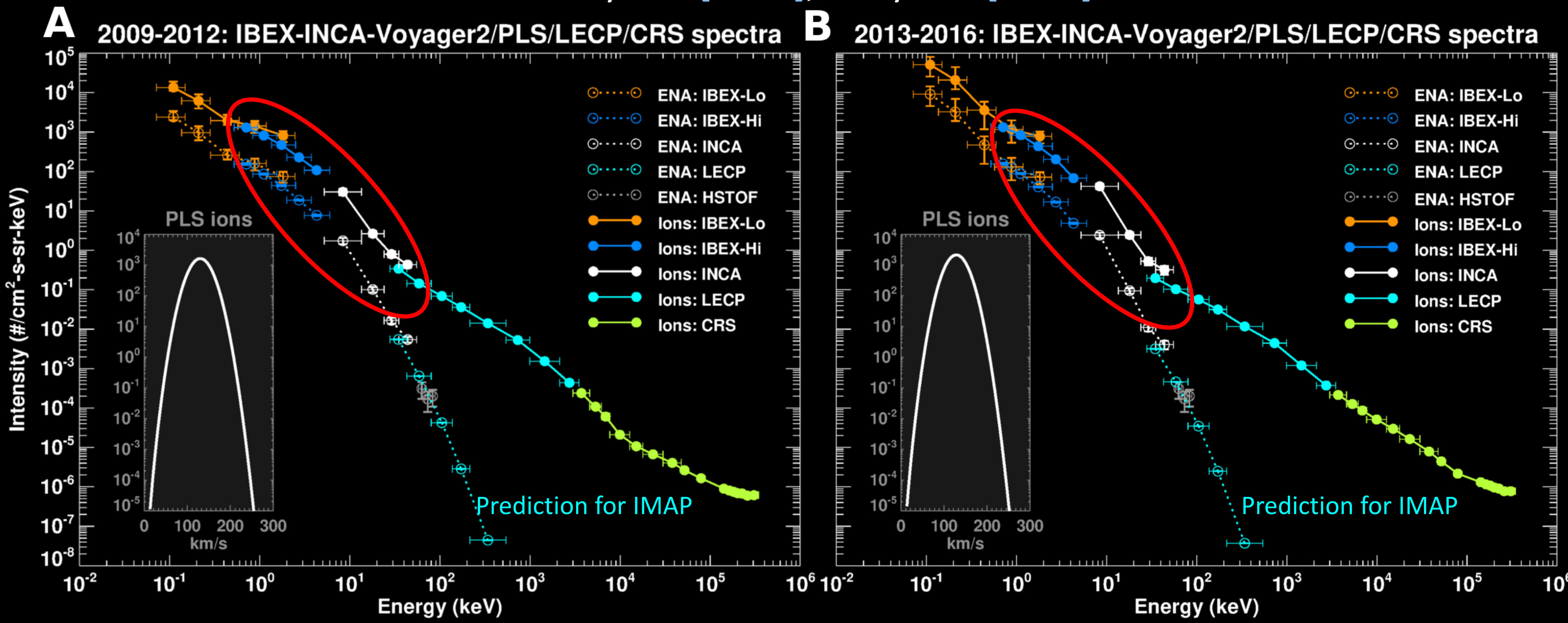


$n_H \sim 0.12\ cm^{-3}$ (Dialynas+2019; Swaczyna+2020)
L_{HS} = 35 AU (Krimigis+2019)

If IMAP-Ultra observed different energies, then we will need to search for an alternative source/mechanism(s).

THE SHAPE OF ENA & ION SPECTRA // INSIDE THE HELIOSHEATH (~10 eV to 344 MeV) keV ENA

Dialynas+[2020]; Dialynas+[2022]

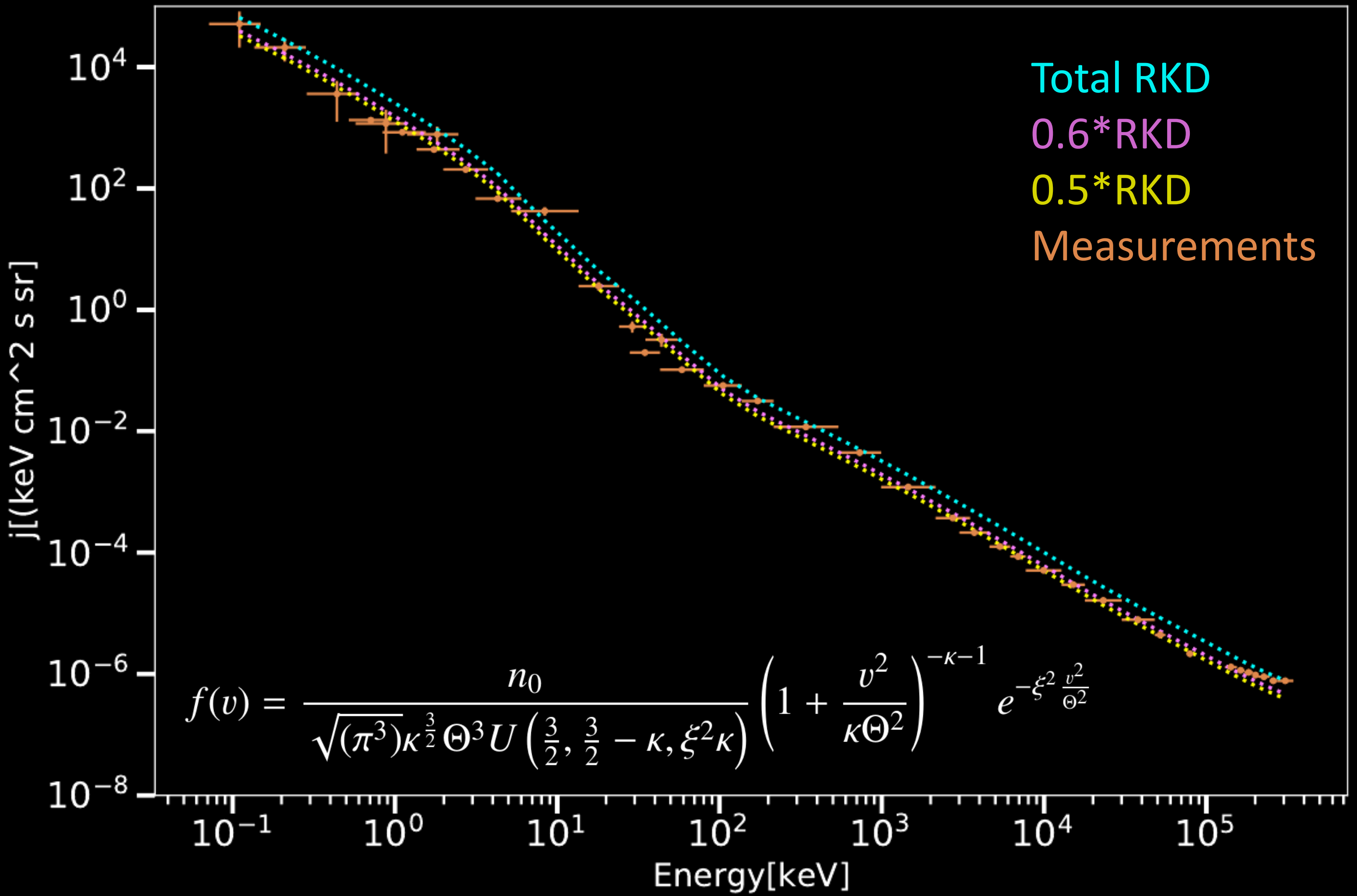


n_H ~ 0.12 cm^{-3} (Dialynas+2019; Swaczyna+2020)
L_{HS} = 35 AU (Krimigis+2019)

Sophisticated Heliosphere models underestimate the ENA (and ion) fluxes that correspond to the ~0.52 to 55 keV energies by ~1.5-4 (or more).

OBTAINING THE ENA & ION SPECTRA // SCHERER, DIALYNAS+2022

Scherer, Dialynas+[2022]



$$f(v) = \frac{n_0}{\sqrt{(\pi^3)}\kappa^{\frac{3}{2}}\Theta^3 U\left(\frac{3}{2}, \frac{3}{2} - \kappa, \xi^2\kappa\right)}\left(1 + \frac{v^2}{\kappa\Theta^2}\right)^{-\kappa-1} e^{-\xi^2 \frac{v^2}{\Theta^2}}$$

u = speed, *ϑ* = normalization speed, n_0 = number density, $\kappa > 0$, $\vartheta/c < \xi < 1$, *U(a,b,z)* = Kummer-U funct.

A very good agreement between the model and data for 2009-2013

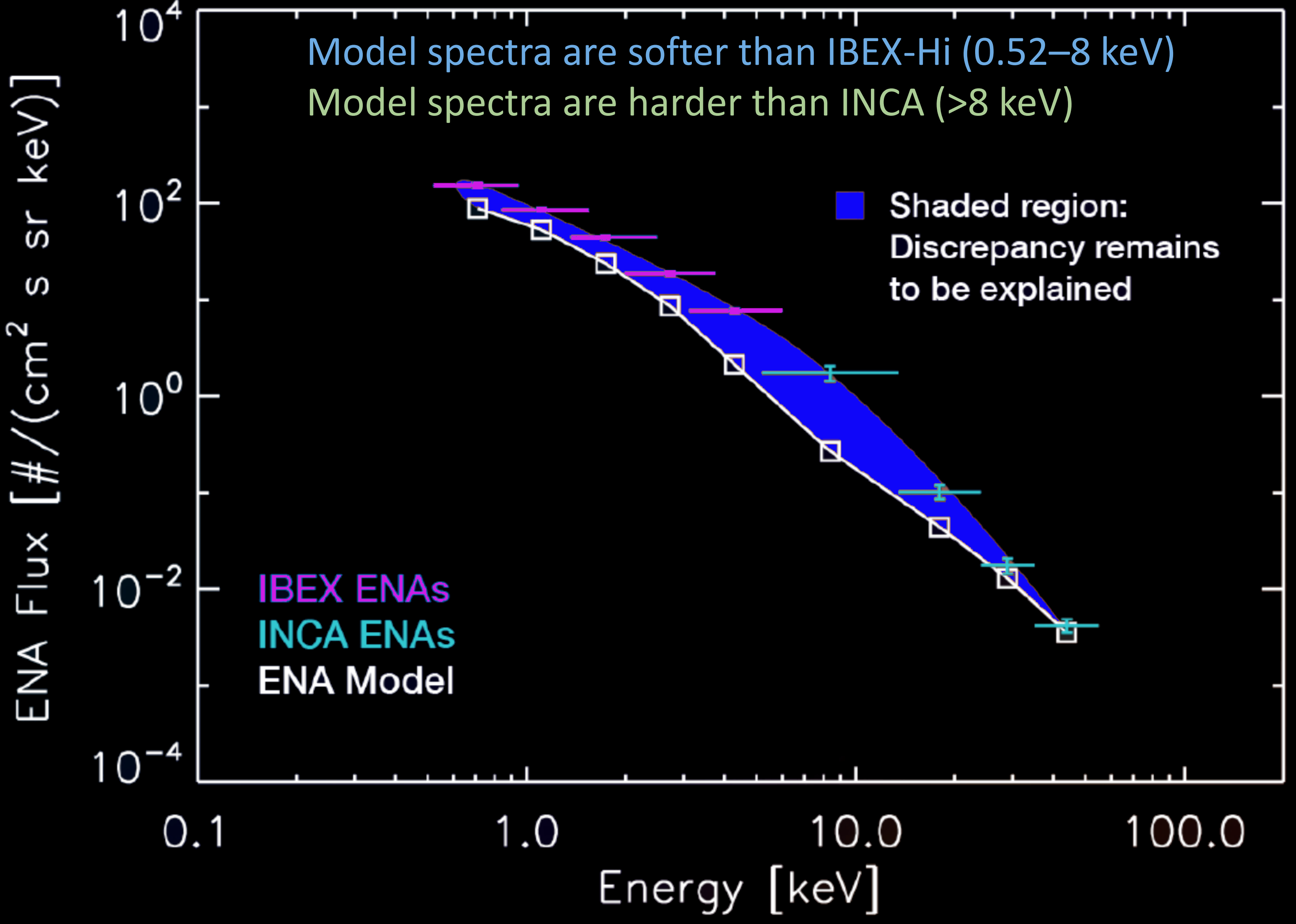
BUT

A factor of 0.5-0.6 difference between the model and data for 2013-2016.

Explanation:

- The ascending phase of SC24 (2013 to 2016) has not yet filled the entire IHS, and thus we have a combination of the proton fluxes from the previous cycle 23 and the ascending cycle 24.
- PUI and ACR shock accelerated particles that undergo additional acceleration inside the HS

Gkioulidou+[2022]



Giacalone+[2021]

Self-consistent, kinetic treatment of SW protons and pickup protons, showing high-energy tails for both the SW (~3 keV) & PUIs (~5 keV).

Kornbleuth+[2021]

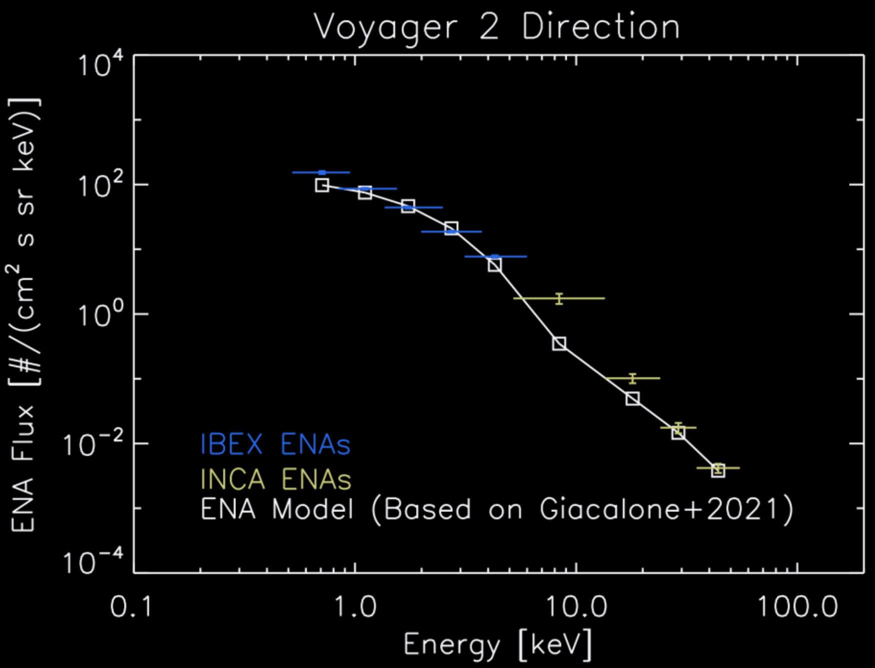
Partitioning of the plasma energy

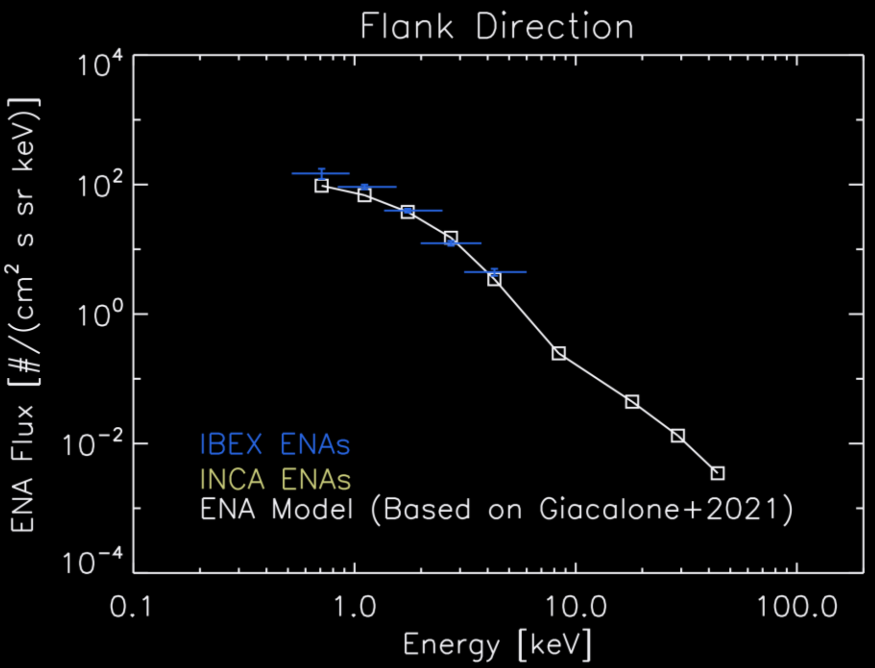
- Thermal SW protons,
- PUIs created in the supersonic SW; adiabatically transmitted across the TS
- PUIs being reflected at the TS.

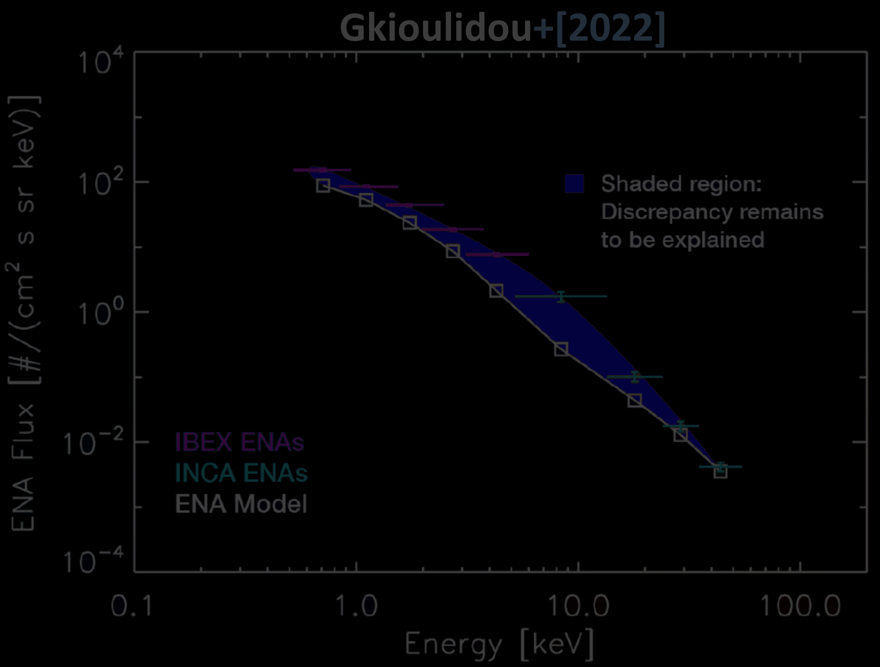
Fit the spectra with

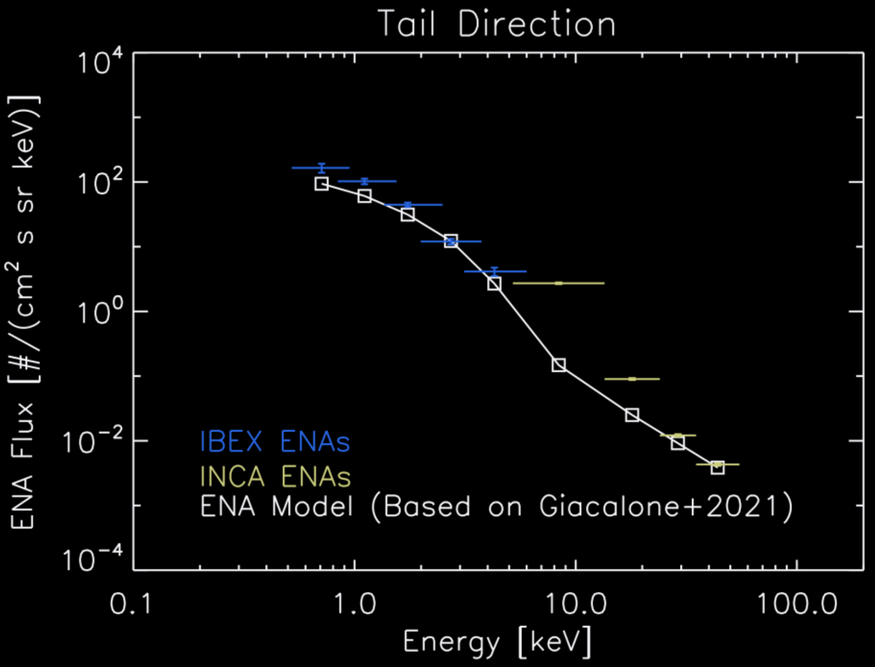
- Maxwellian distribution (cold SW protons)
- κ-Distributions (transmitted PUIs)

Obtaining The ENA & Ion Spectra // Kornbleuth+2023









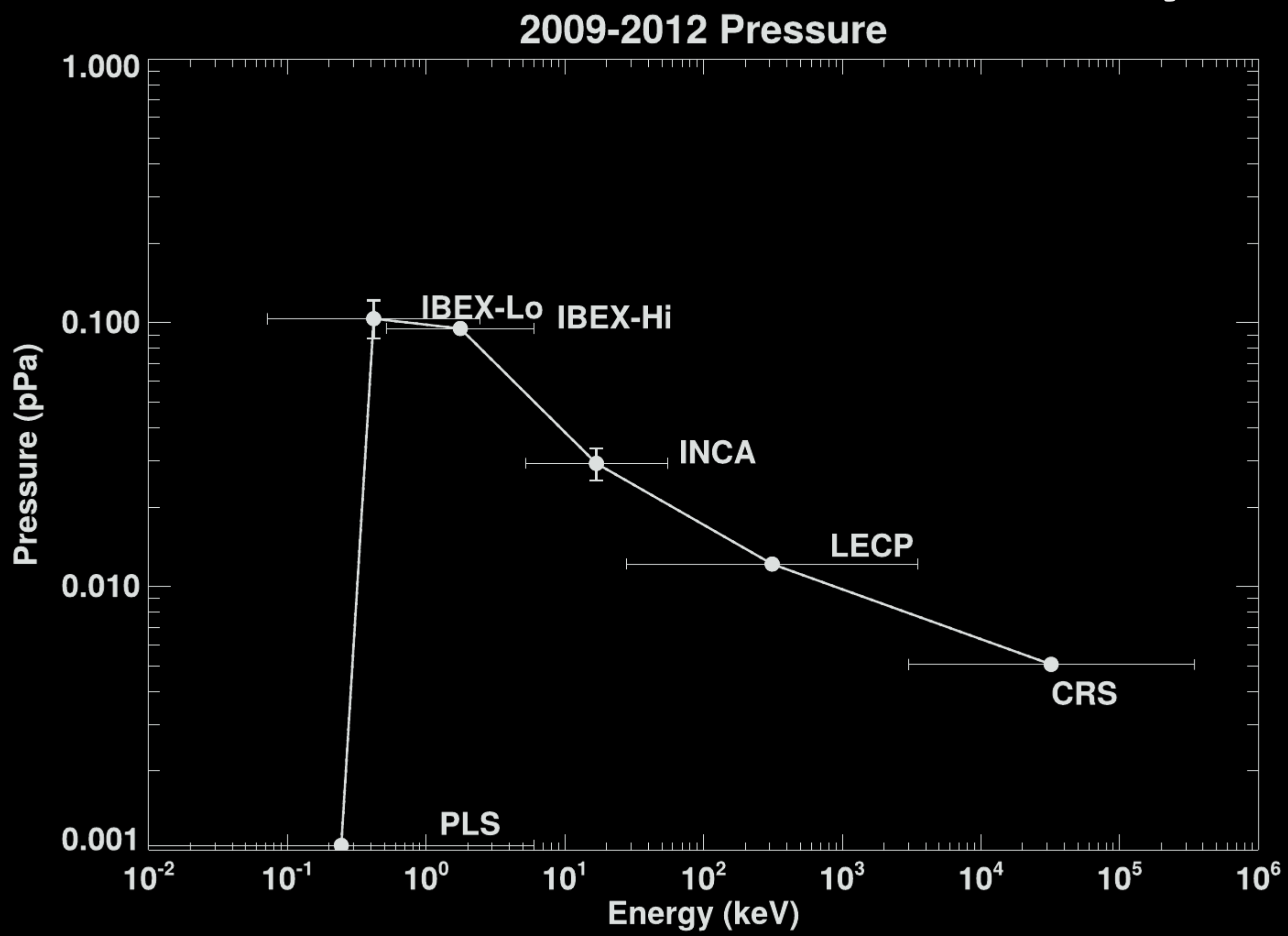
Kornbleuth+[2023]

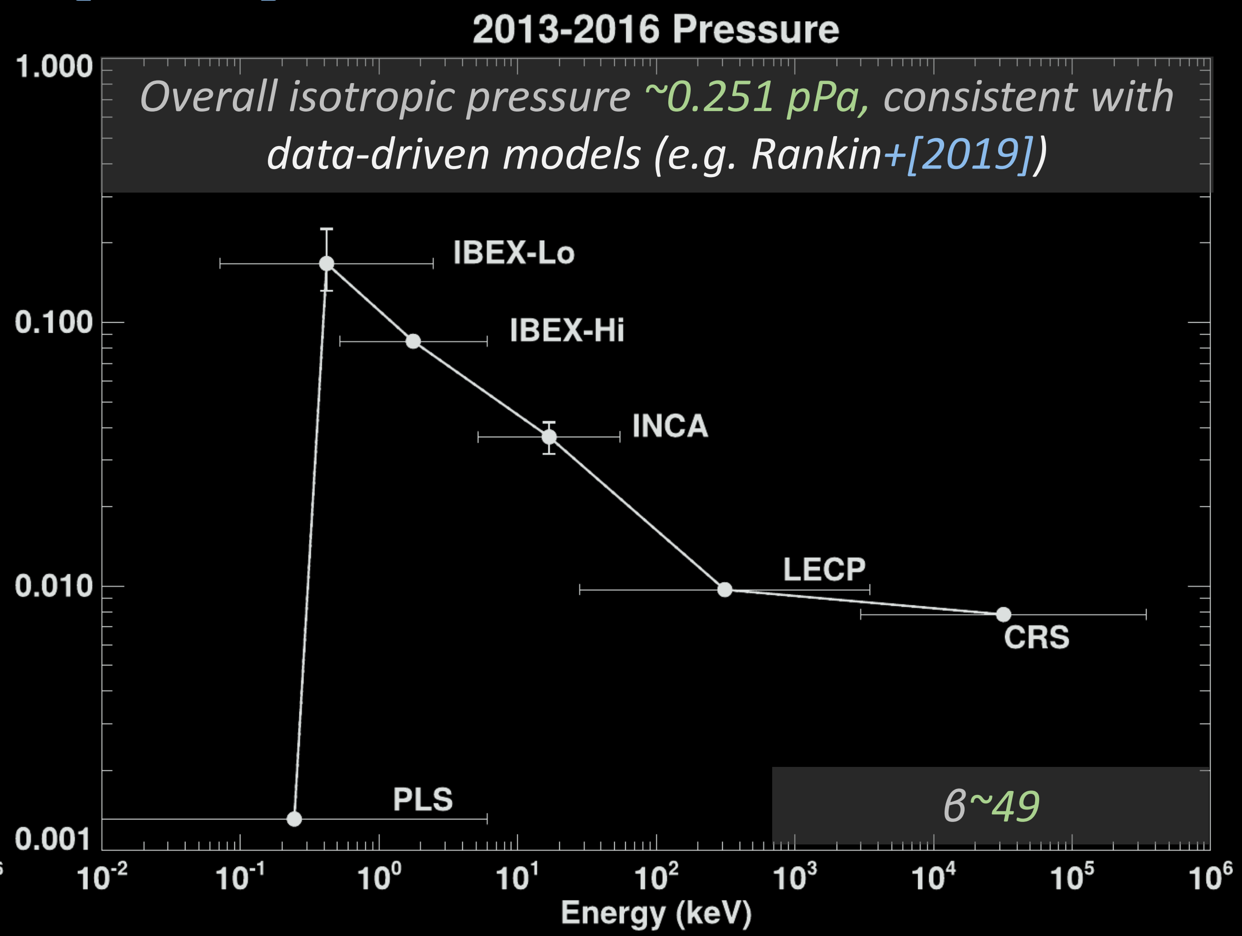
Provides an update to the Gkioulidou+[2022] model, by adding a PUI population that gets accelerated by Diffusive Shock Acceleration due to turbulence at the TS.

The 0.5-4 keV discrepancy is no longer there, but the discrepancy between 4-20 keV persists..

Further acceleration in the HS is needed.

Dialynas+[2020]

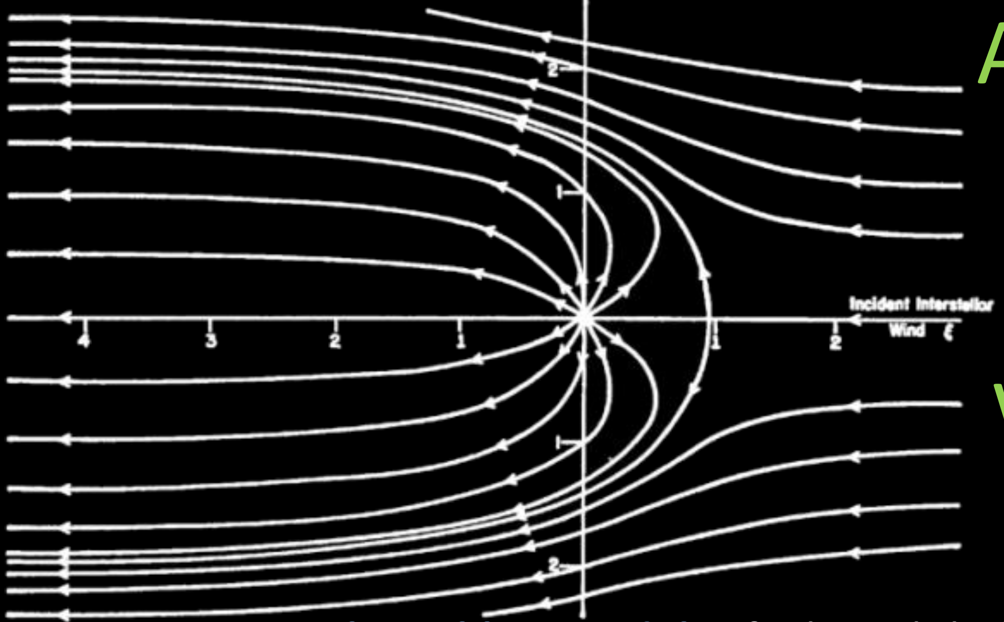




- V2 (Dialynas+2020): B required to balance the pressure from the HS ~0.67 nT (*Burlaga+[2019]; ~0.68 nT*).
- V1 (Krimigis+2010) : B required to balance the pressure from the HS <0.64 nT (Burlaga & Ness+[2016]; ~0.48 nT)

CONCENPTS OF THE GLOBAL HELIOSPHERE (1961) // PARKER, E.

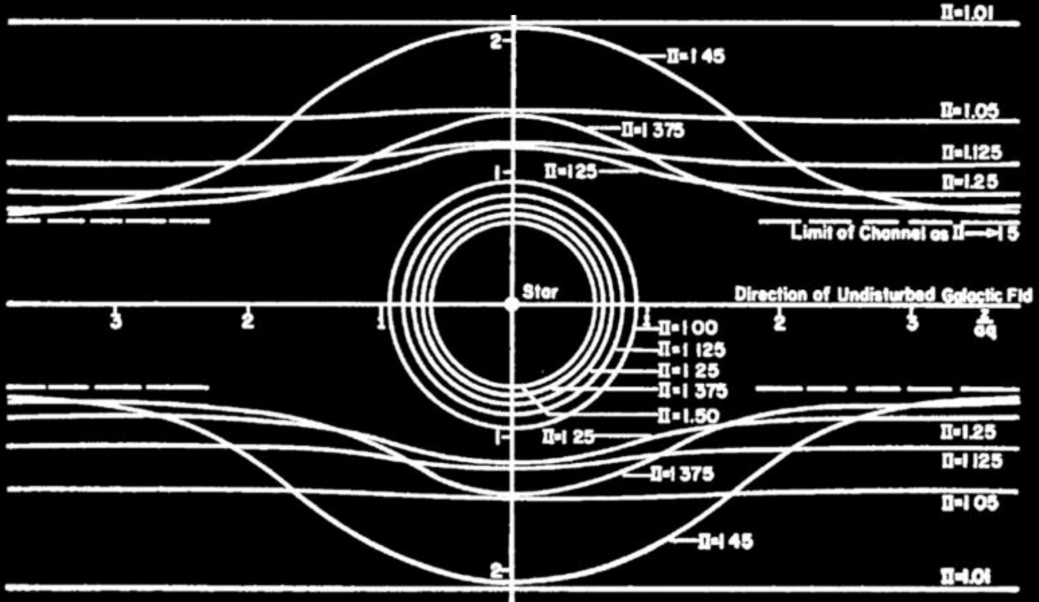
Parker, 1961 (A)



Adopted since 1961 without data

A ***magnetosphere-like model*** of the global Heliosphere, using a subsonic, incompressible hydrodynamic flow.

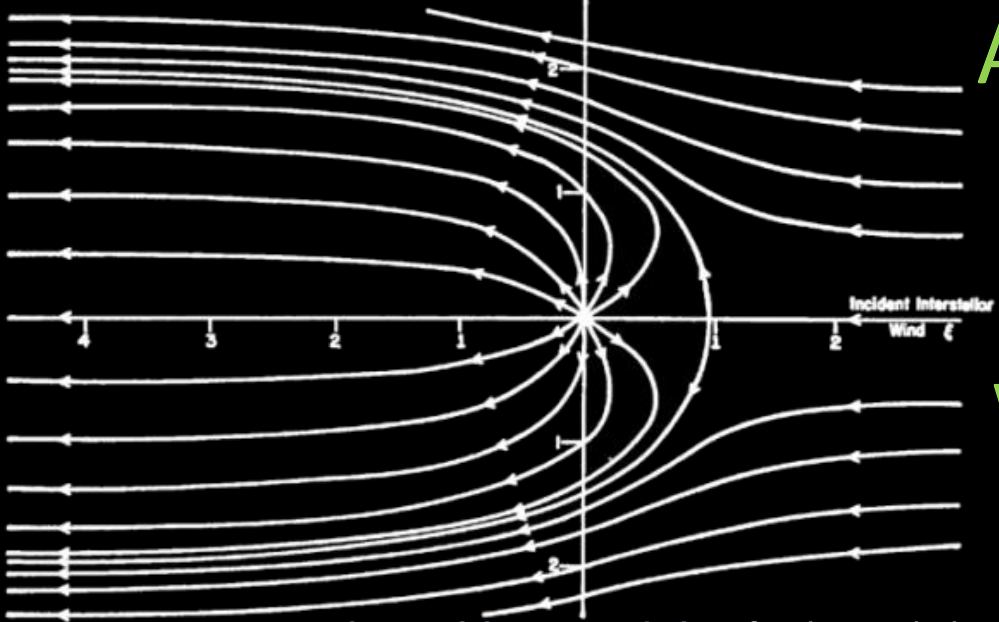
Parker, 1961 (B)



A ***tailless Heliosphere***, under the influence of a large scale ISMF.

Concenpts of the Global Heliosphere (1961) // Parker, E.

Parker, 1961 (A)



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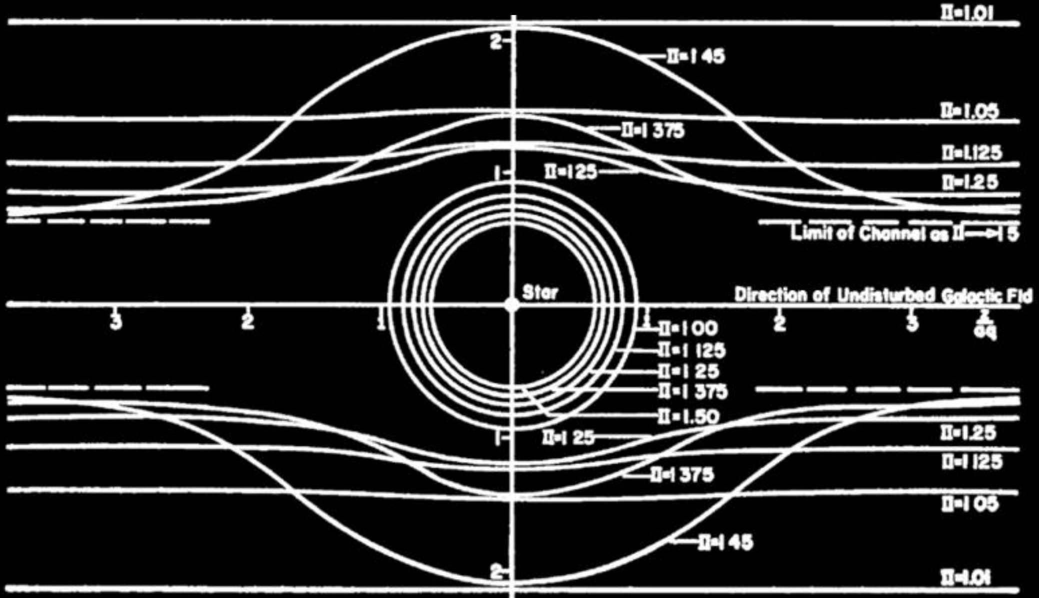


A ***tailless Heliosphere***, under the influence of a large scale ISMF.

a) **High Observed ISMF** V1 ~0.5 nT, V2 ~0.68 nT (**Burlaga+[2013; 2019]**).

b) **High B_{ISMF} pressure** $B^2/8\pi$ ~0.1 - 0.184 pPa.

c) **High HS pressure** P_{tot} ~ 0.230 - 0.267 pPa (**Krimigis+2010; Dialynas+2020; Rankin+2019**).

d) **High n_H** $n_H > 0.09 - 0.12\ cm^{-3}$ (**Gurnett+2013;2015, Kurth & Gurnett+2020, Dialynas+2019;2020, Swaczyna+2020**)

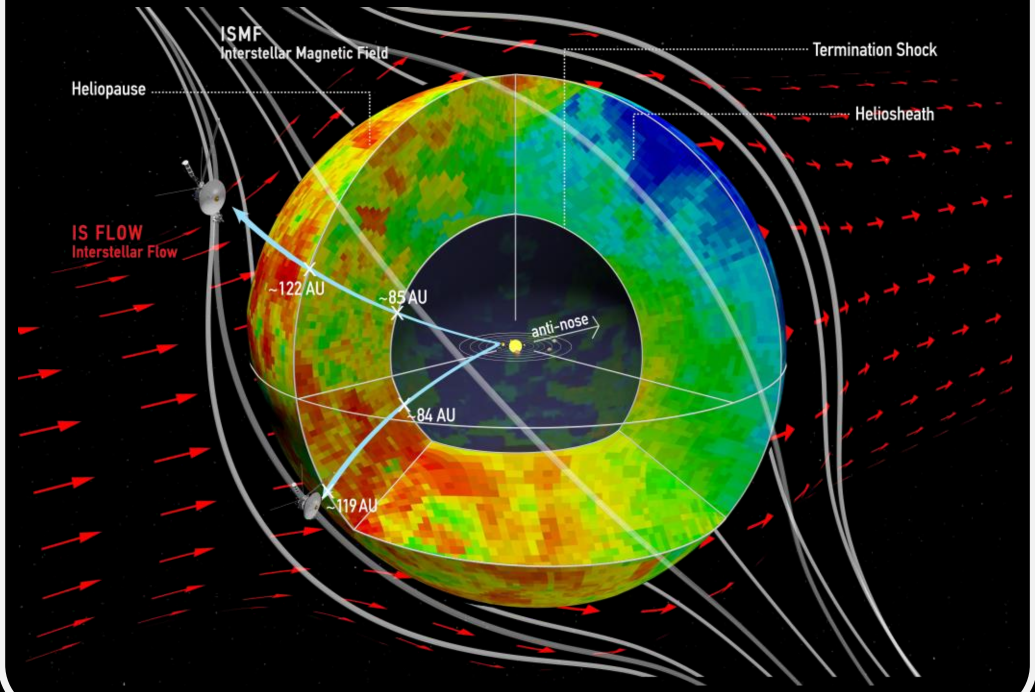
e) **High plasma beta** β > 10 on average (**Dialynas+2019;2020**)

f) **Low IS pressure** $P_{Stagn.}=\rho V^2/2$ ~ 0.056 pPa, $P_{thermal}$ = nkT ~0.010 pPa & P_{GCR} ~0.007 pPa (**Krimigis+2010; Dialynas+2020**)

g) **Resulting B_{ISMF}/P_S > 2 as opposed to the expected ~0.28-0.5.**

SHAPE OF THE GLOBAL HELIOSPHERE (1961-2022) // A ROUGH DIAMAGNETIC BUBBLE; A JETS STRUCTURE; A COMET...

Dialynas+[2017] (INCA & Voyager data)



Shape of the Global Heliosphere (1961-2022) // A rough diamagnetic bubble; a jets structure; a comet...

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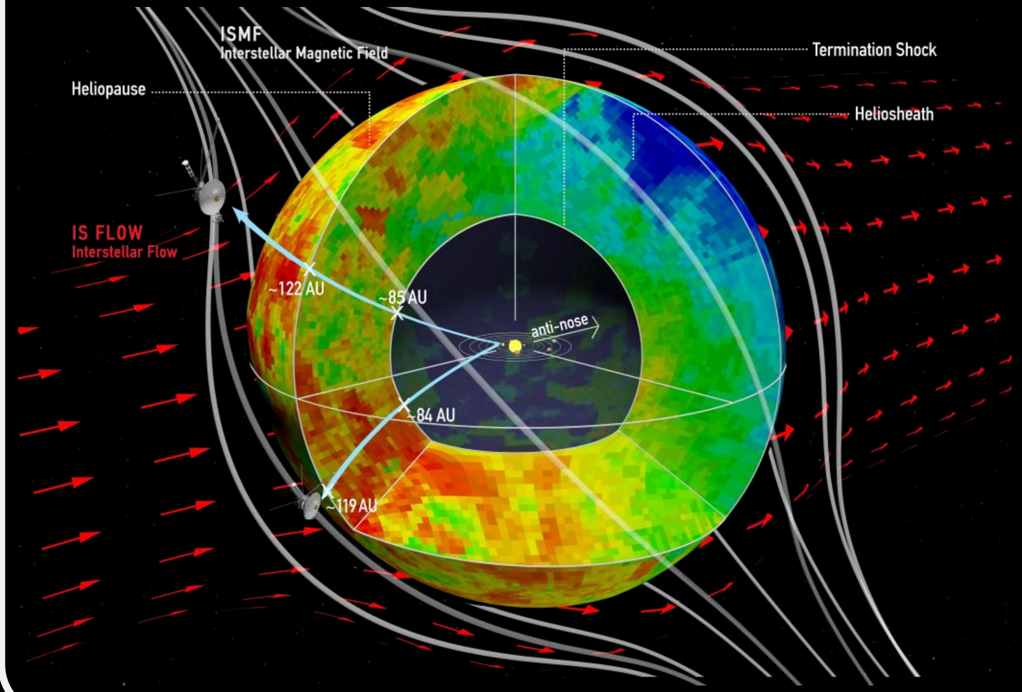
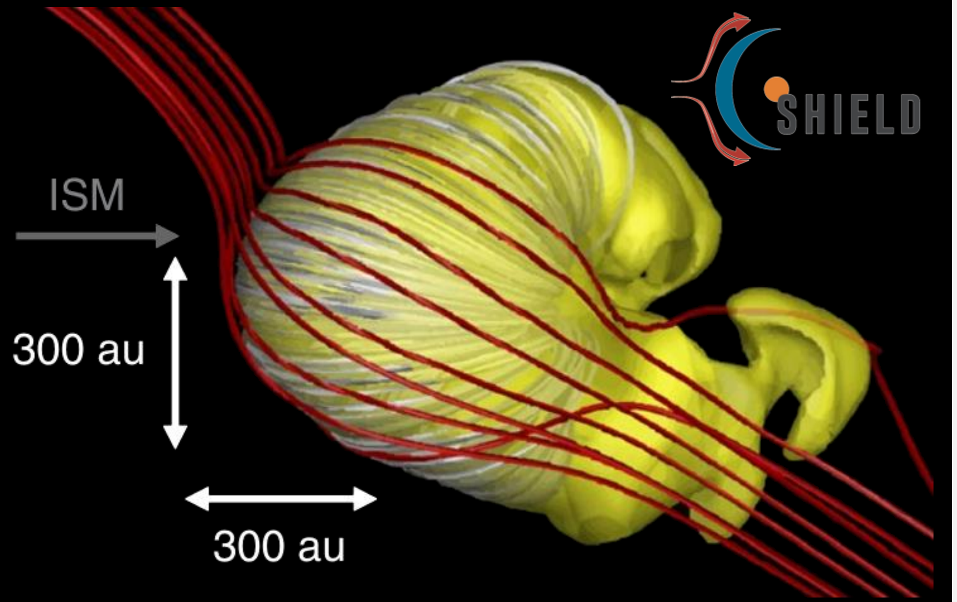


Opher+[2020] MHD modeling



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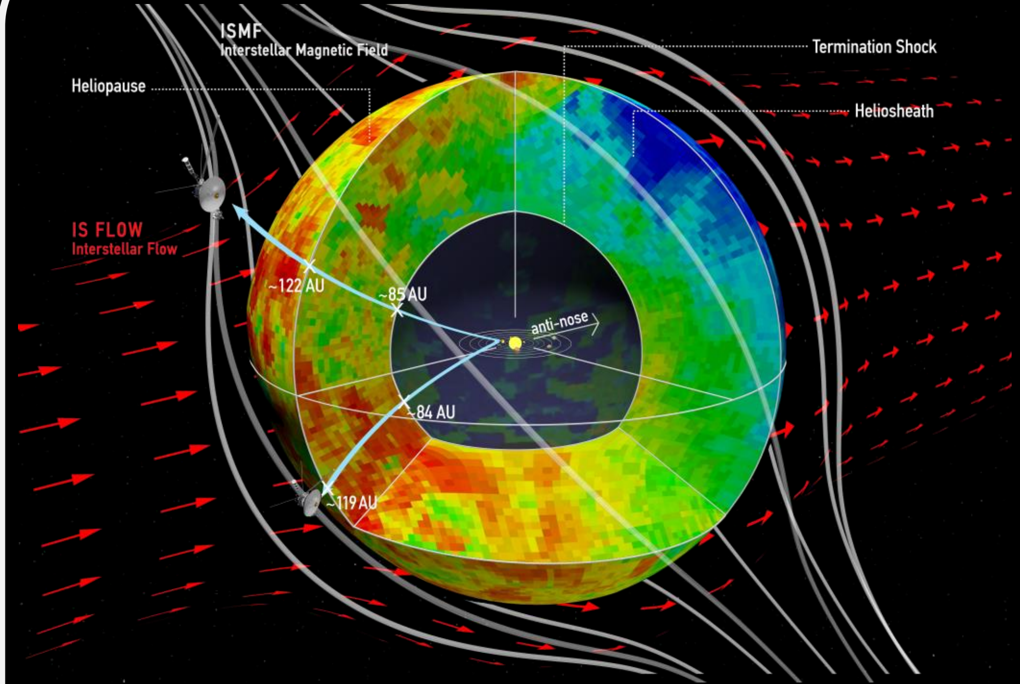

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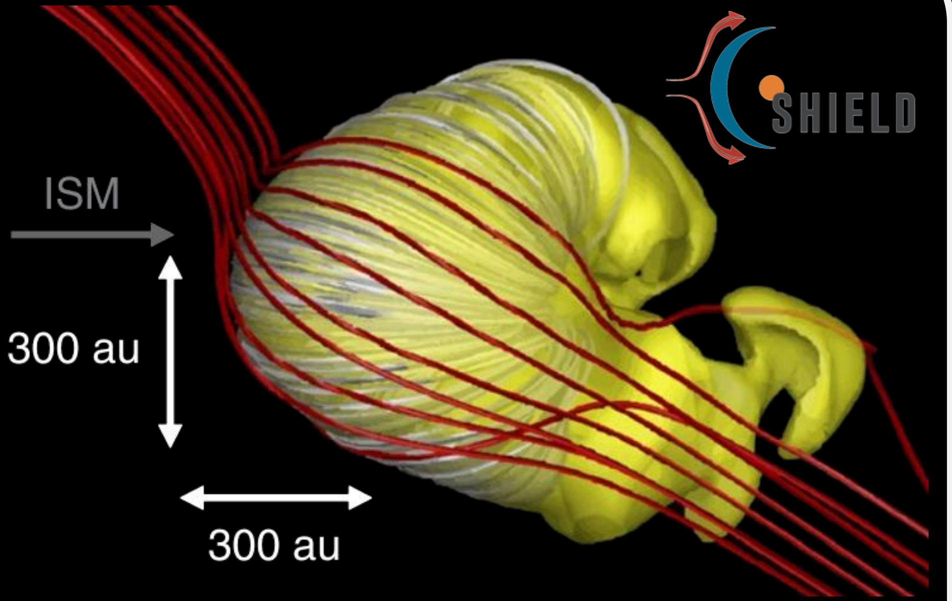


IBEX-Lo Data (Galli+[2016; 2017])

[…] typical thickness of HS in downwind
~(220±110) AU.

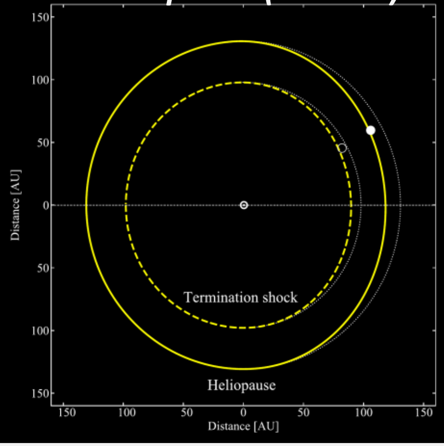
IBEX-Hi Data (Reisenfeld+[2016])

N. pole L_{HS}~210 AU || S. pole L_{HS}~160 AU

IBEX-Hi Data (Reisenfeld+[2021])

[…] heliosphere extends at least ~350 AU tailwards

Boschini+[2019]
Transport of GCRs through the heliosphere (HelMod).



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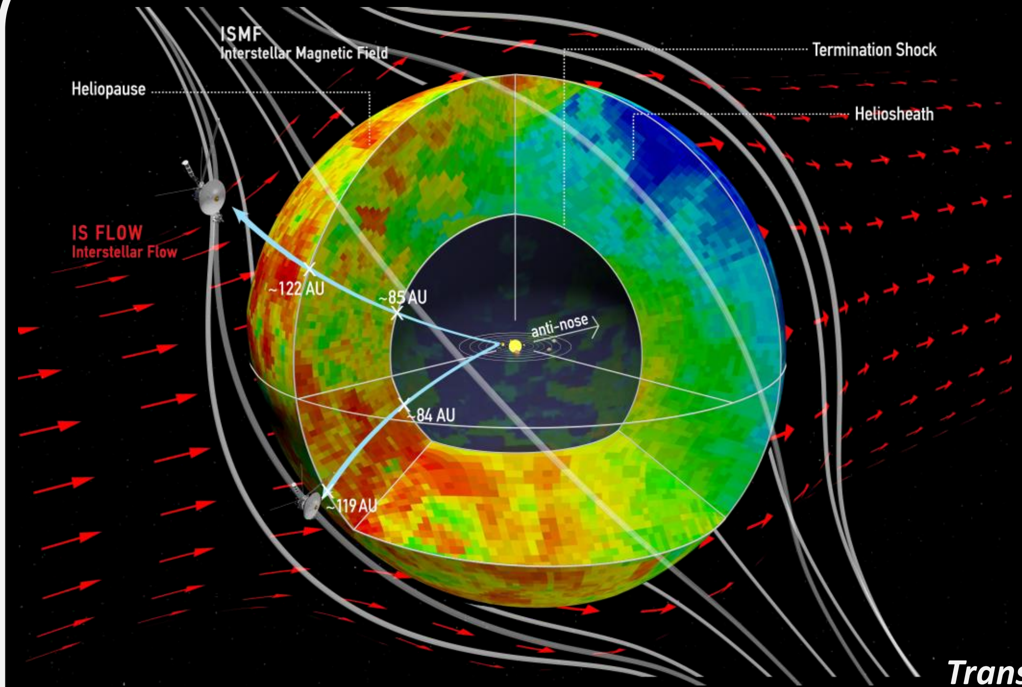

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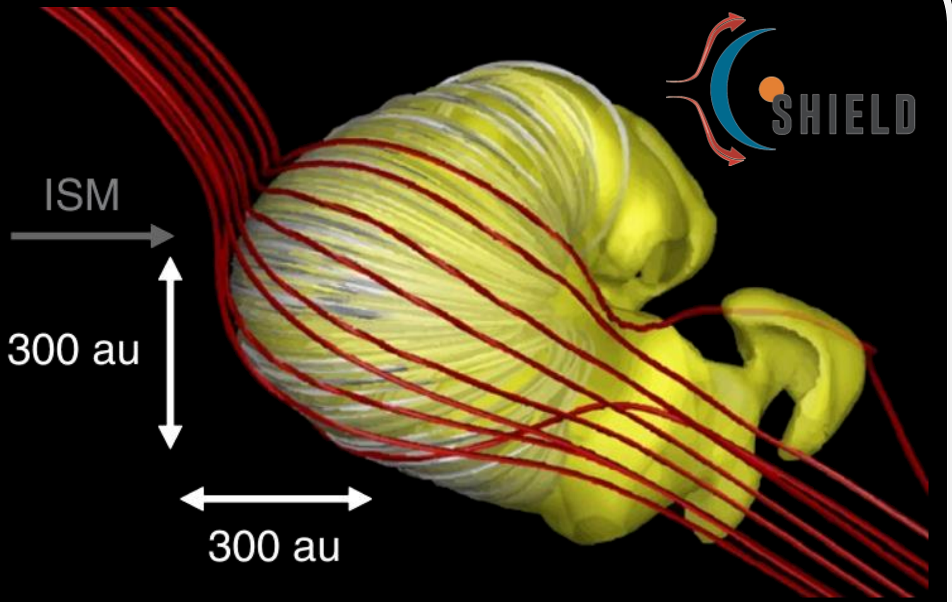

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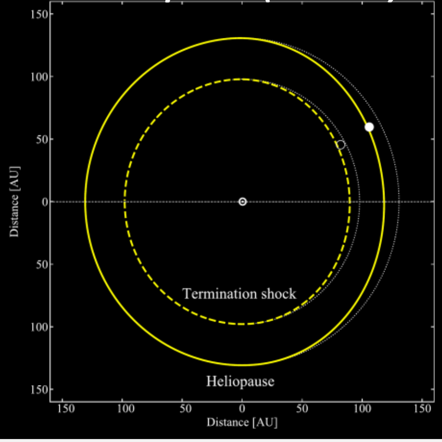
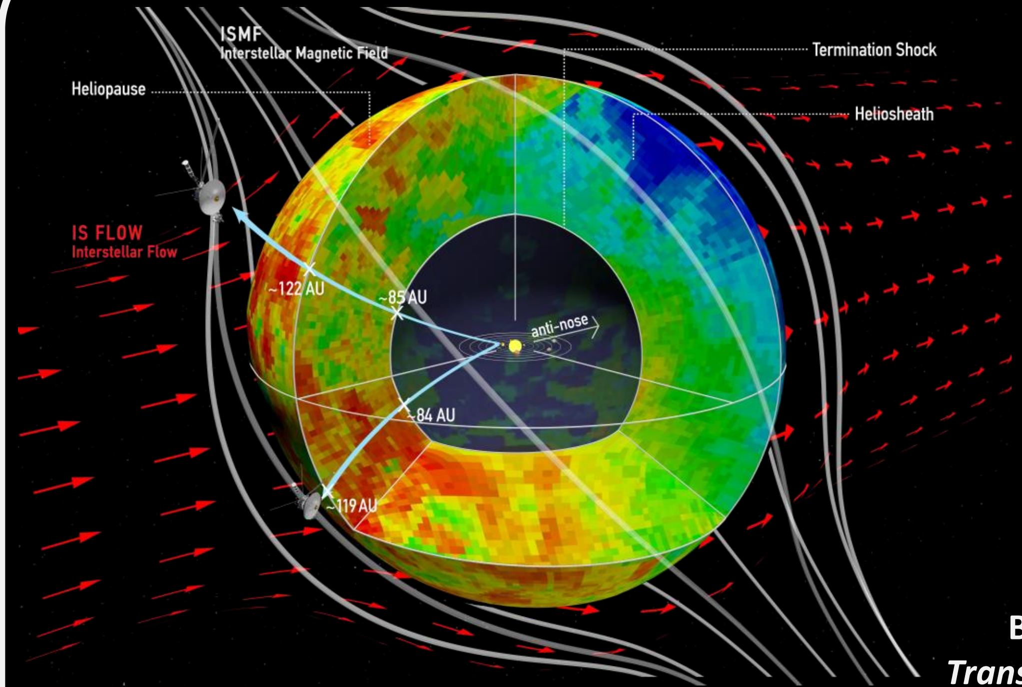


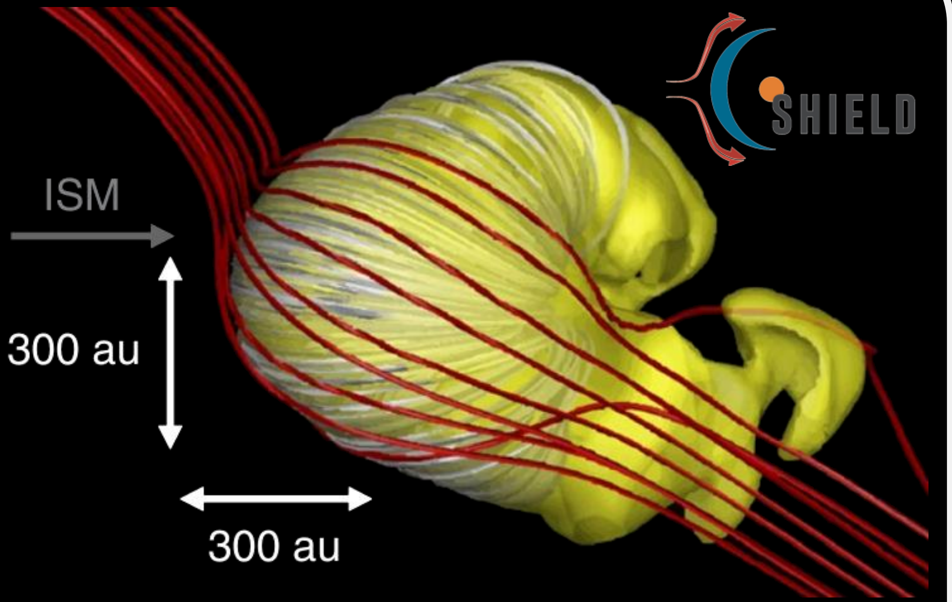
Czechowski+[2020]
Schwadron & Bzowski+[2018]
Pogorelov+[2015; 2017]

SHAPE OF THE GLOBAL HELIOSPHERE (1961-2022) // A ROUGH DIAMAGNETIC BUBBLE; A JETS STRUCTURE; A COMET...

Dialynas+[2017] (INCA & Voyager data)



Opher+[2020] MHD modeling



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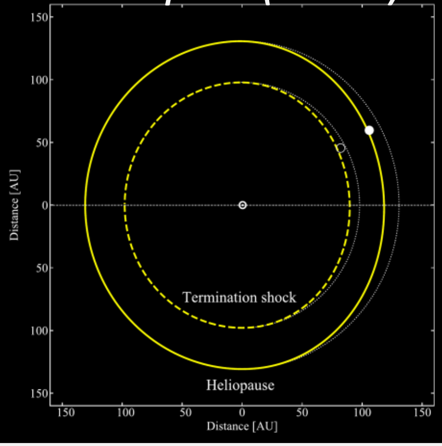
IBEX-Hi Data (Reisenfeld+[2021])

[…] heliosphere extends at least ***~350 AU*** *tailwards*

Boschini+[2019; 2020]

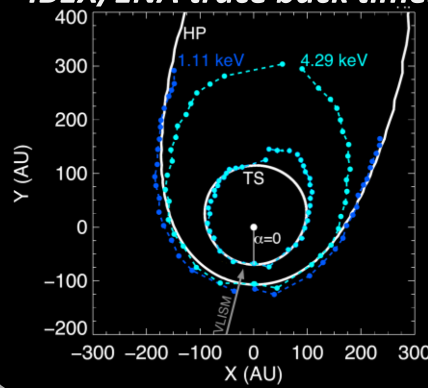
Transport of GCRs through the heliosphere (HELMOD).



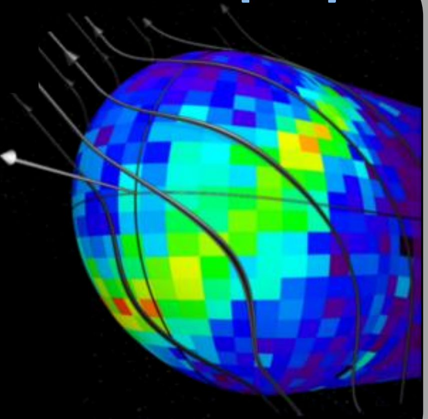
Intermediate Configuration

Zirnstein+[2018]

IBEX/ENA trace back times



McComas+[2013]



THE GLOBAL HELIOSPHERE A DATA-DRIVEN VIEW

Krimigis+[2019]

Combined data from V1, V2 and Cassini/INCA

Dialynas+[2022]

The heliosphere from the perspective of Cassini, HSTOF & Voyager measurements!

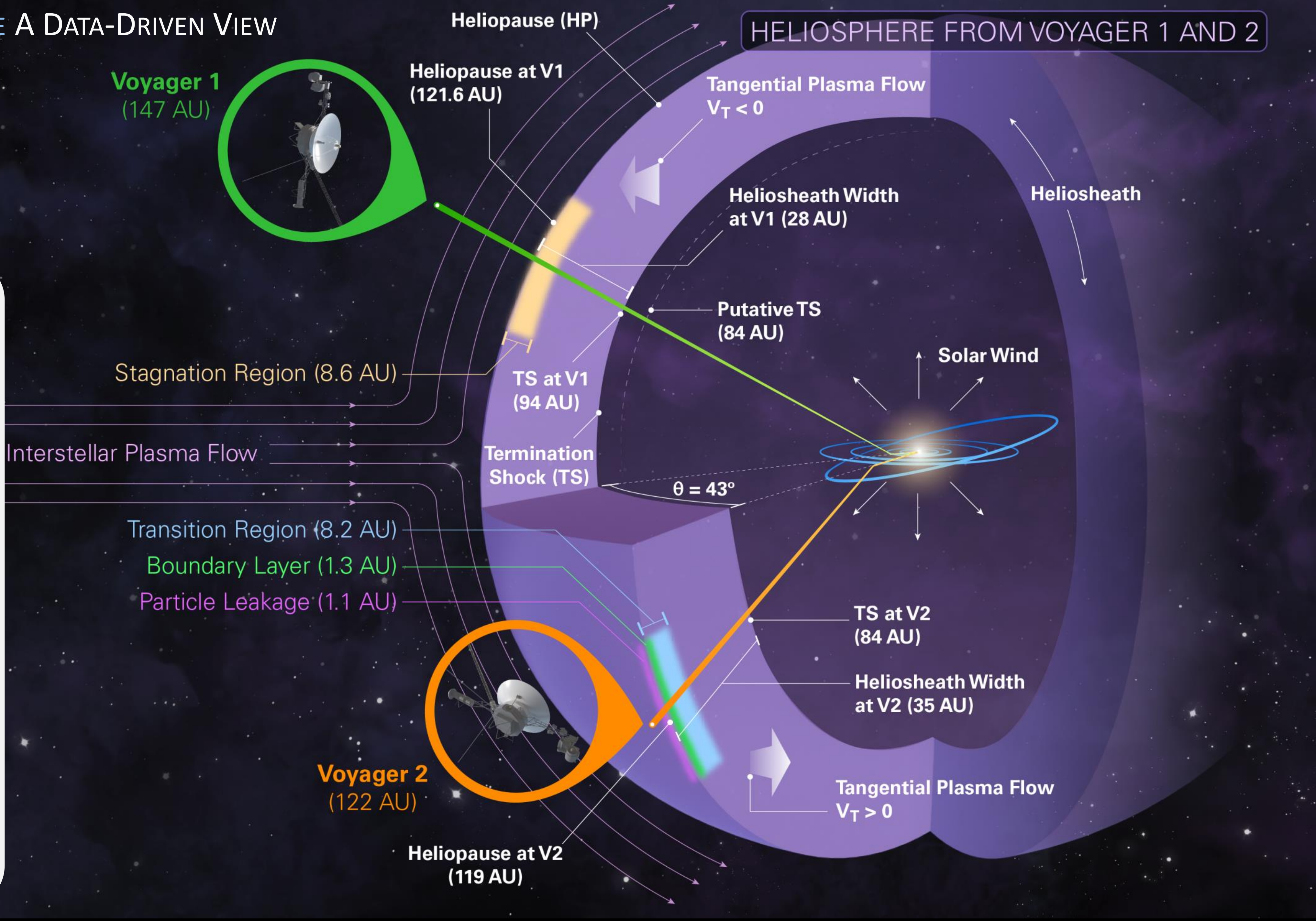
Kleimann+[2022]

The heliosphere from the perspective of the models and comparison of models with data!

SSRv 2022

The Heliosphere in the Local Interstellar Medium

Into the Unknown



Summary // Conclusions

We know that >5.2 keV ENAs are created in the HS

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

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 the particle spectrum inside the HS is complex

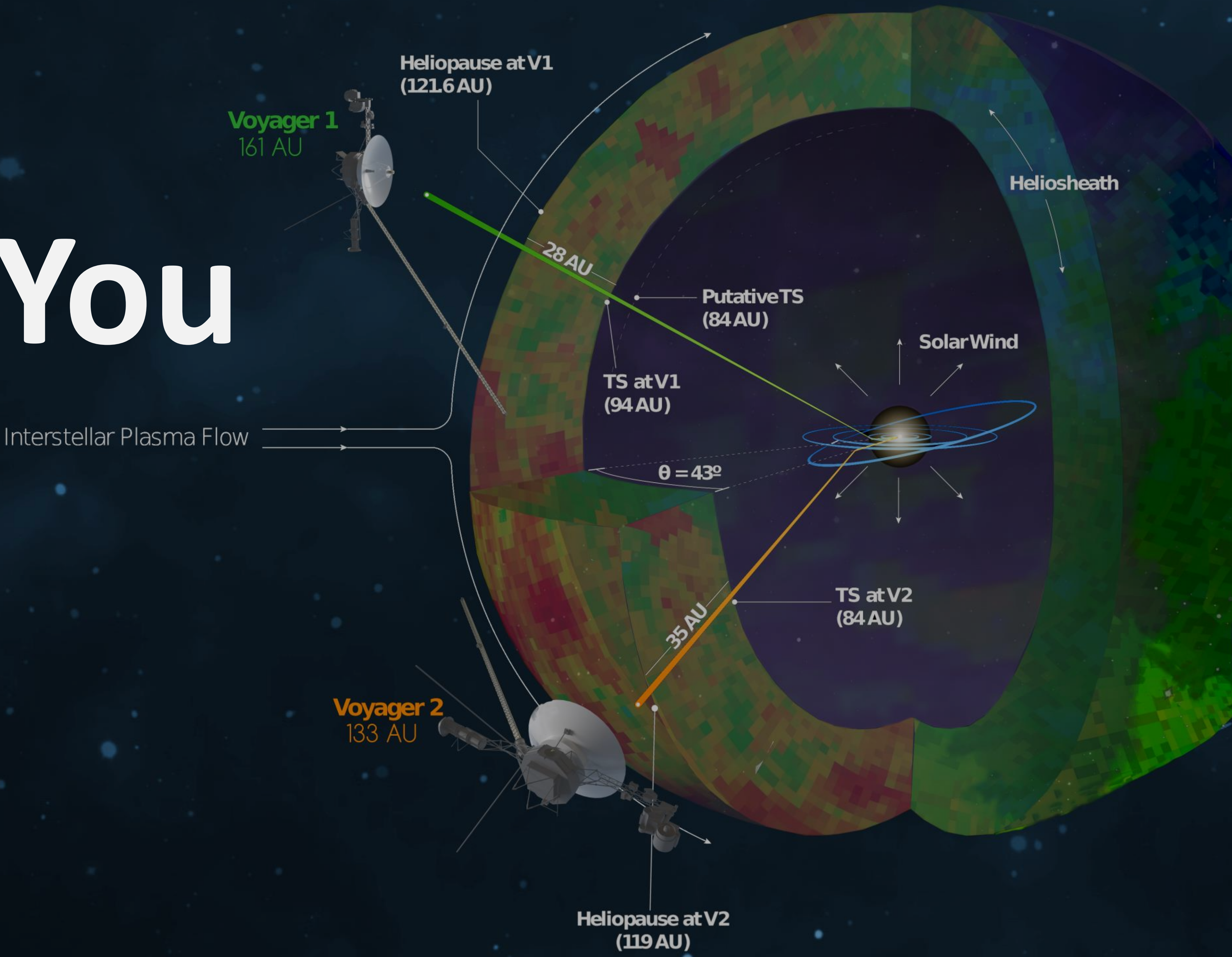
10 eV to 344 MeV ion spectra cannot be described by a single Maxwellian and/or a kappa-Distribution, but we cannot neglect any of these energies, otherwise we miss a substantial part of the processes that govern the ion energetics. Most models underestimate the ENA fluxes inside the HS by some factor of 1.5-4. *Plasma beta* is >>1 inside the HS. 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}!

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

Ion velocities decrease inside the HS and beyond 2010 we observe a reversal in the radial ion flow, in agreement with the previously identified flux tube interchange instability at the HP. 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.

The phenomenology of the heliosphere can only be addressed when taking all *in-situ* particle and field measurements into account (from eV to MeV energies), together with remotely sensed ENAs.

Thank You



Voyager 1
161 AU
Heliopause at V1
(121.6 AU)
28 AU
Putative TS
(84 AU)
Heliosheath
Solar Wind
TS at V1
(94 AU)
Interstellar Plasma Flow
θ = 43º
TS at V2
(84 AU)
35 AU
Voyager 2
133 AU
Heliopause at V2
(119 AU)