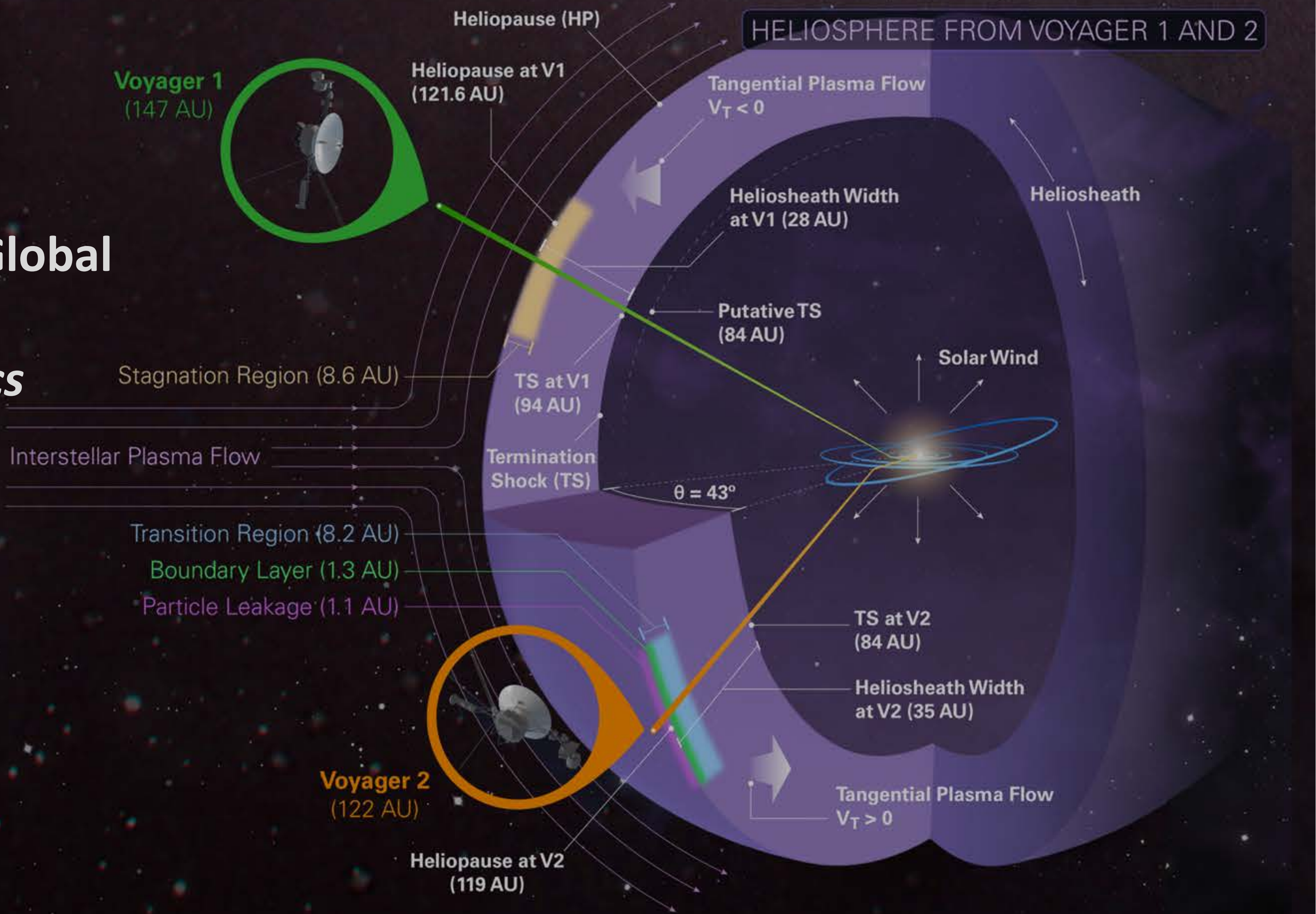
# In-situ Hot Plasma Ion Measurements by Voyagers in Heliosheath and Galaxy, and Global ENA Images by Cassini/INCA: *Shape, Pressures and Dynamics*


**S. M. Krimigis[1,2],** R. B. Decker[1], K. Dialynas[2],

M. Hill[1], D. G. Mitchell[1], & E. C. Roelof[1]

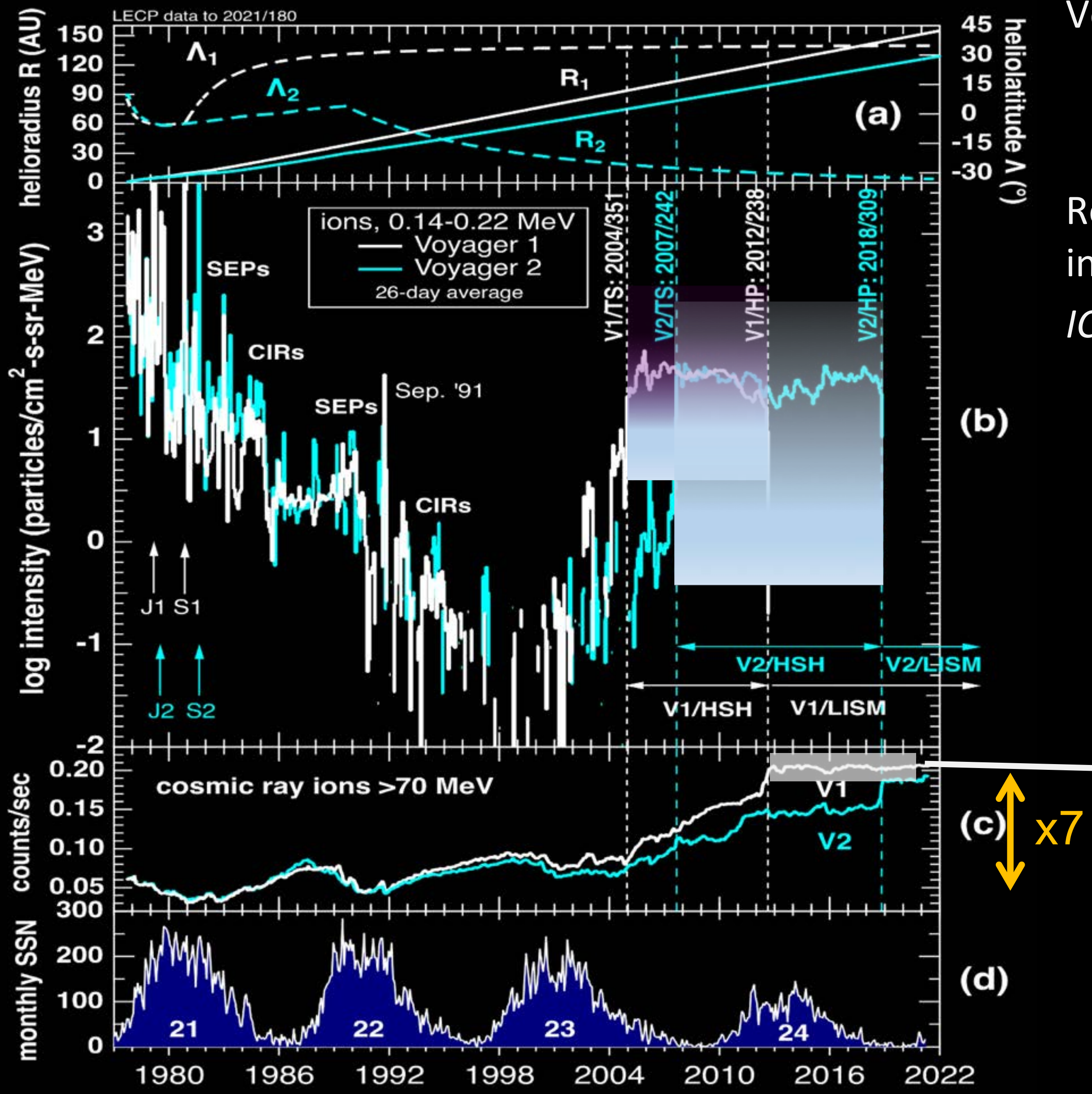
*[1]Johns Hopkins University Applied Physics Laboratory, USA*

*[2]Academy of Athens, Greece*


**Krimigis et al.** ***Nature Astronomy,*** **[2019]**

# Voyager Mission // 43 year cruise through the Heliosphere



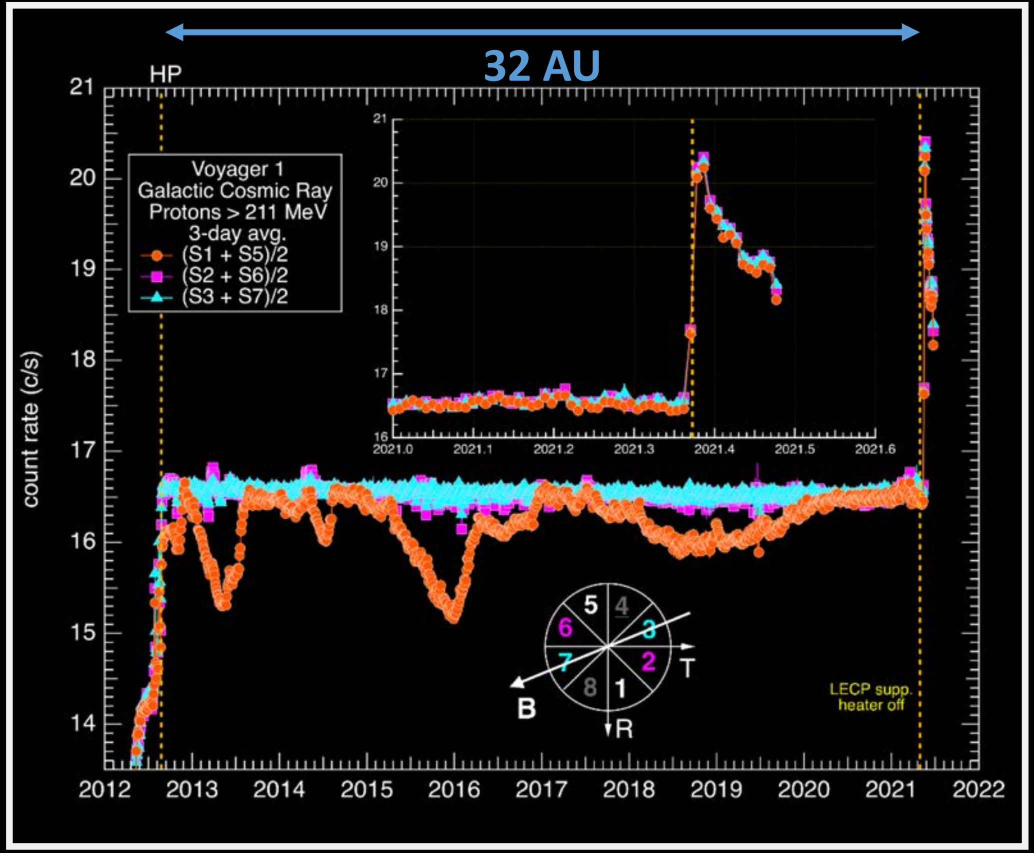

Voyager 1: 1977.7-2020.3

Ions140-220 keV, & >70 MeV

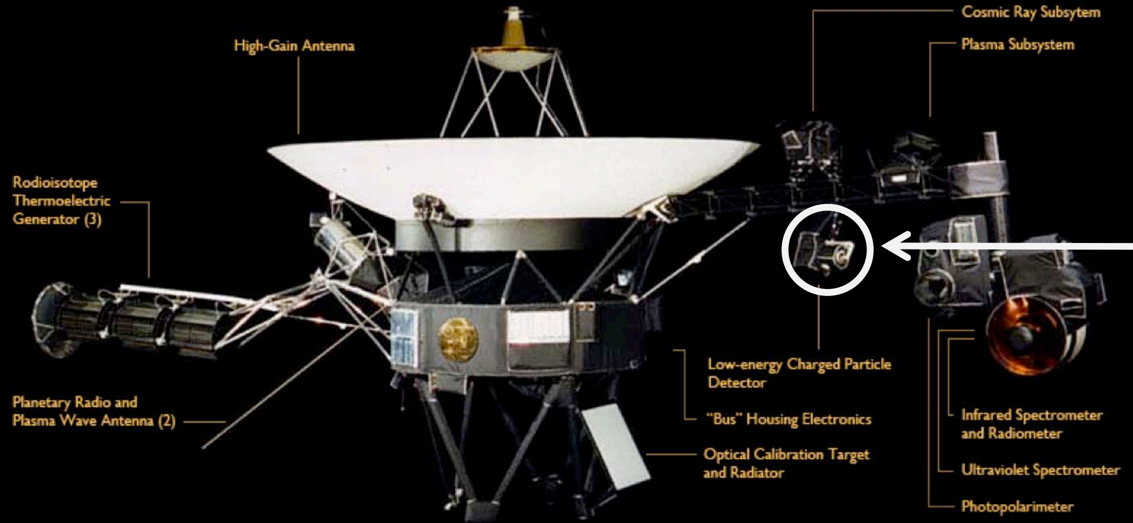
**Note**: *Very low intensities during 1995-2000*

Relatively slow S/C speed ≈0.01 AU/day gives in-depth view of solar-interplanetary phenomena

*ICMEs, SEPs, CIRs, CMIRs, MIRs, GMIRs, TSPs, TS, HSH, ACRs, GCRs …*



# Low Energy Charged Particle (LECP) instrument // Voyager 1 & 2



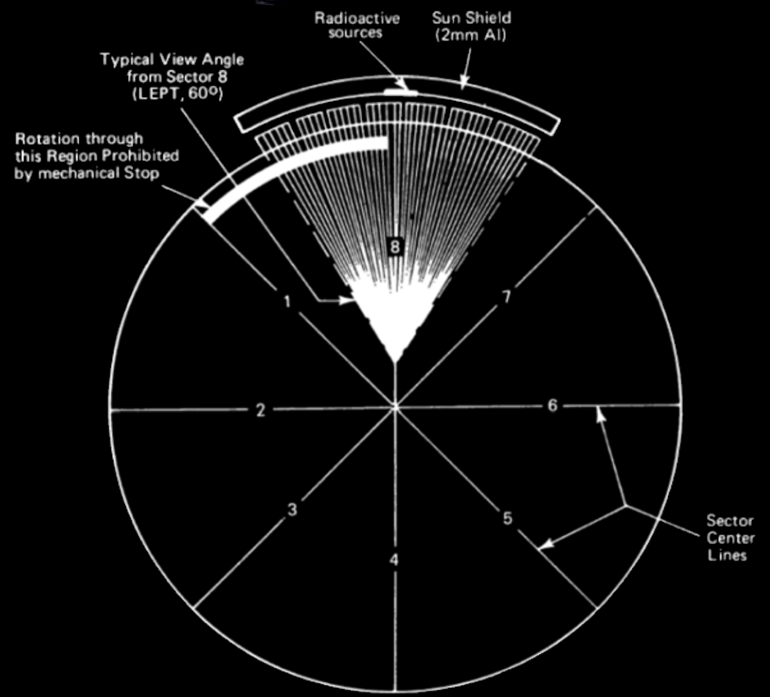
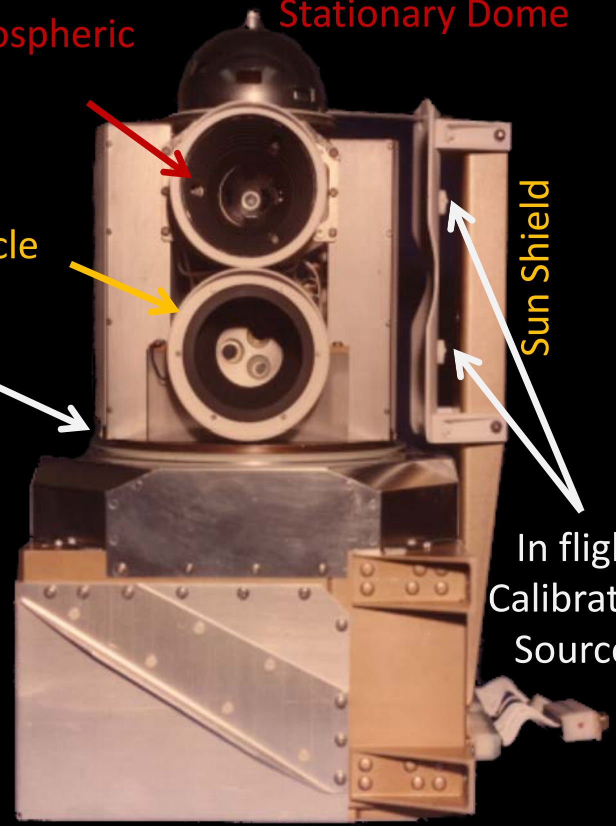



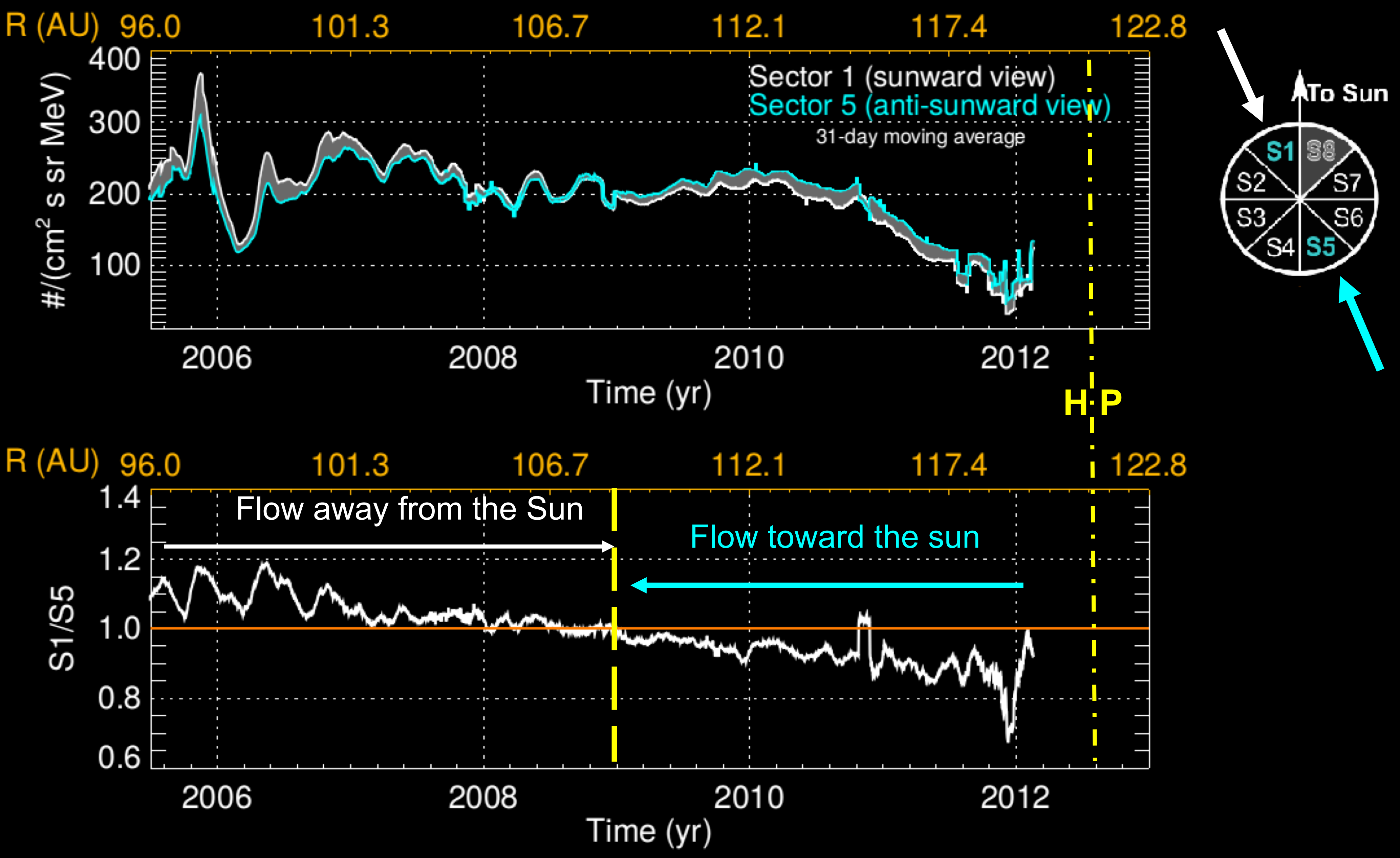

Fig. 9. Sectoring scheme for the LECP experiment detector assemblies. The sequence is 8-7-6-5-4-3-2-1-1-2-3-4-5-6-7-8-8-7- . . . . Radioactive calibration sources for both LEPT and LEMPA are mounted inside the sun shield.

## LECP Proposal team in 1970

T. P. Armstrong* (UoK) , W. I. Axford* (UCSD), C. O. Bostrom (APL), G. Gloeckler (UoMD), C. Y. Fan* (UoA), S. M.Krimigis (APL-PI), L. J. Lanzerotti (BellLabs)



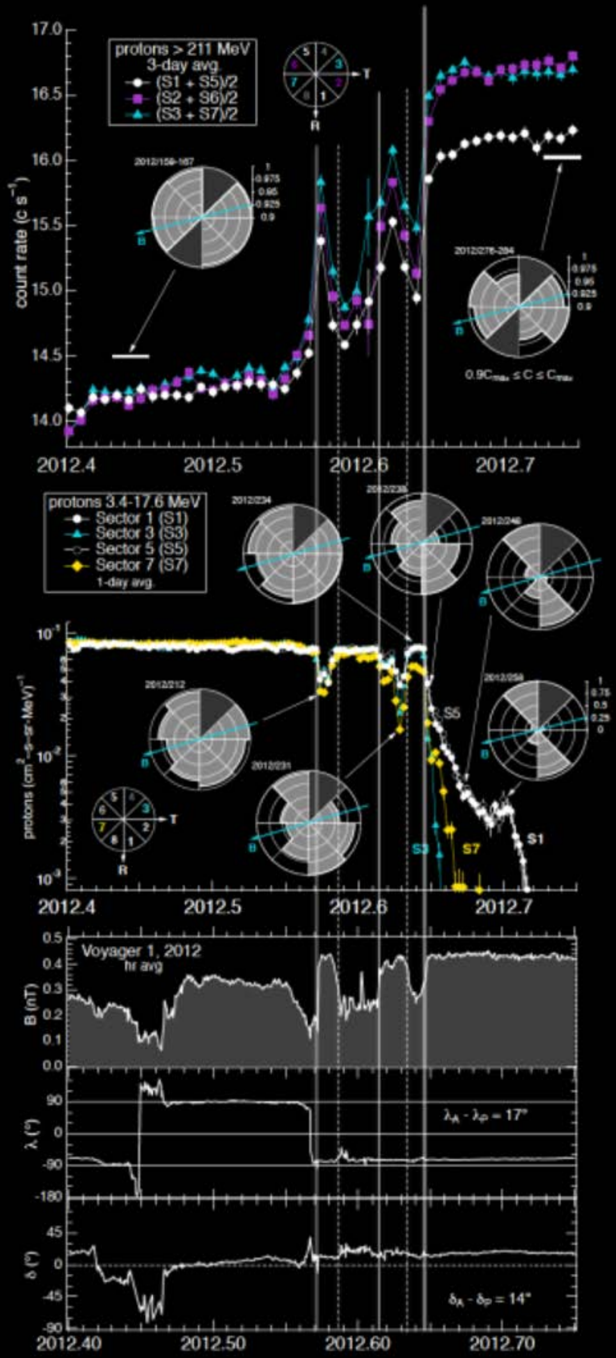
## Voyager 1 // Krimigis et al. *Science,* [2013]-Anti-sunward plasma flow inside the HP

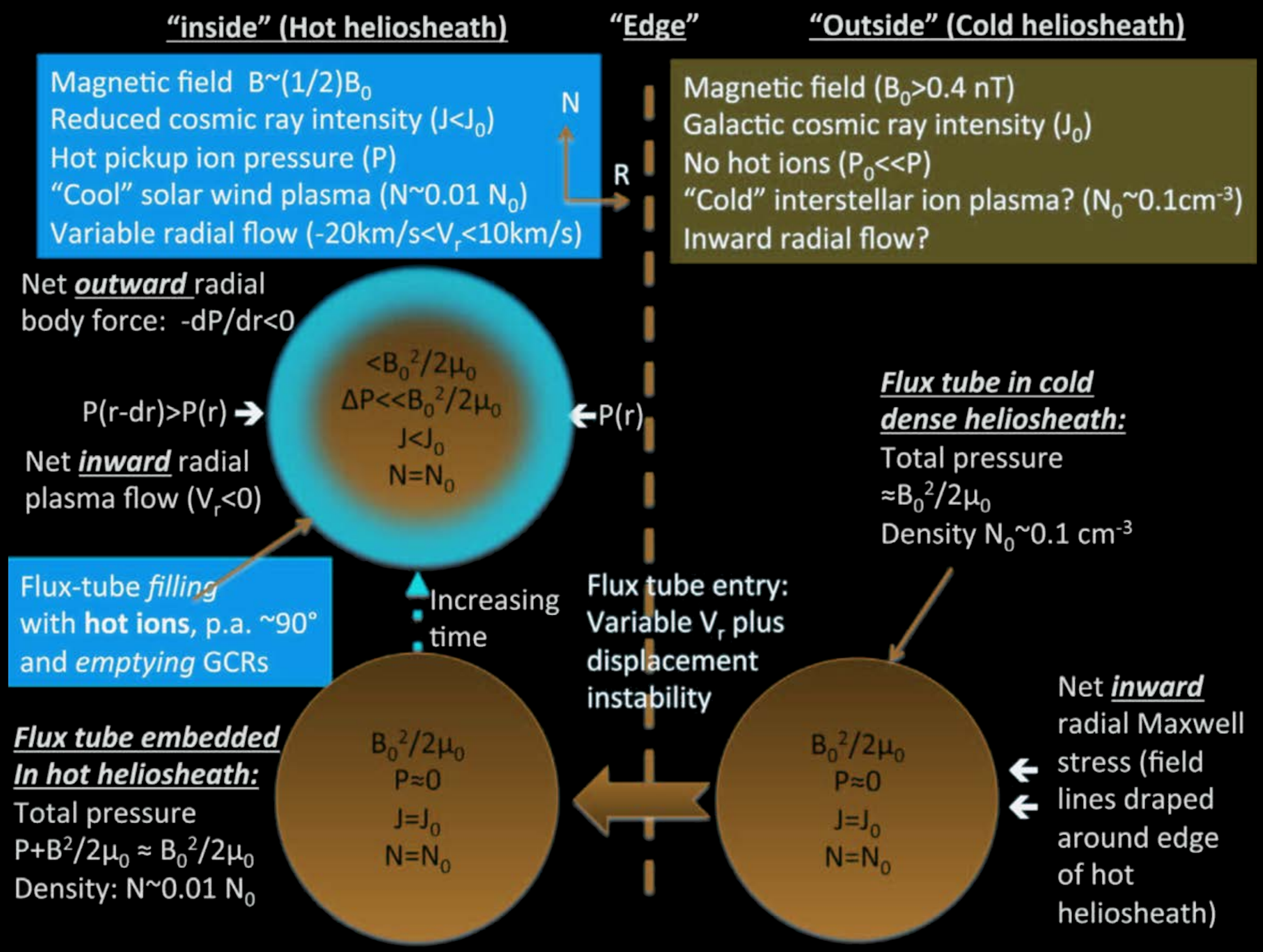


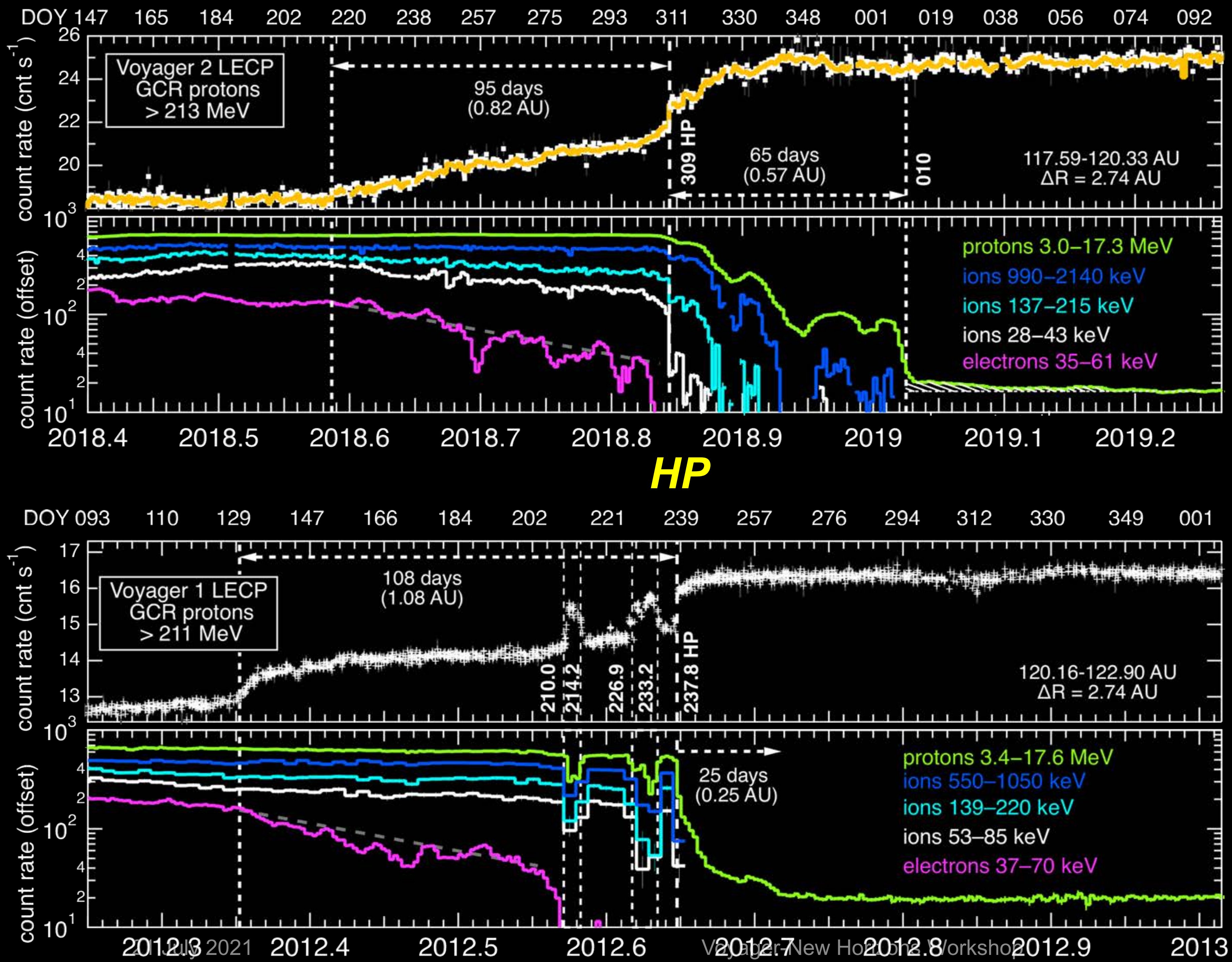
# Physical parameters in the "Hot" and "Cold" Heliosheath

## ***A flux interchange instability?*** (Gurnett & Bhattacharjee, Cambridge, 2005)

**Krimigis et al, *Science,* [2013]**






# Comparison of GCR and HS particles at V1 and V2 over about the same distance scale of 2.74 AU surrounding the respective HP crossings

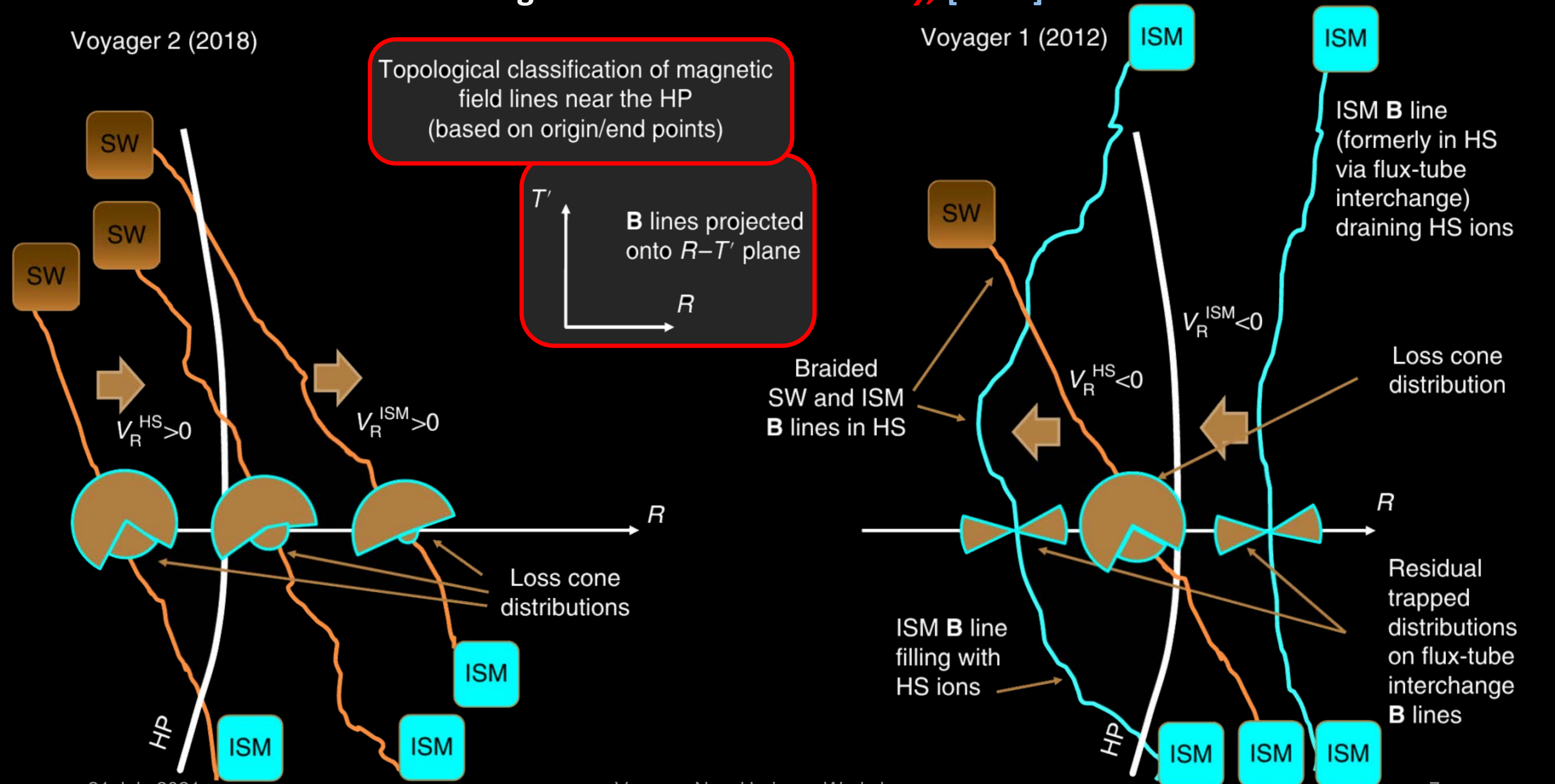
**Krimigis et al, *Nature Asttronomy,*** [2019]

**See also in *Nature Astronomy* 2019**

Richardson et al. (PLS), Stone et al. (CRS), Gurnett & Kurth (PWS), Burlaga et al. (MAG)

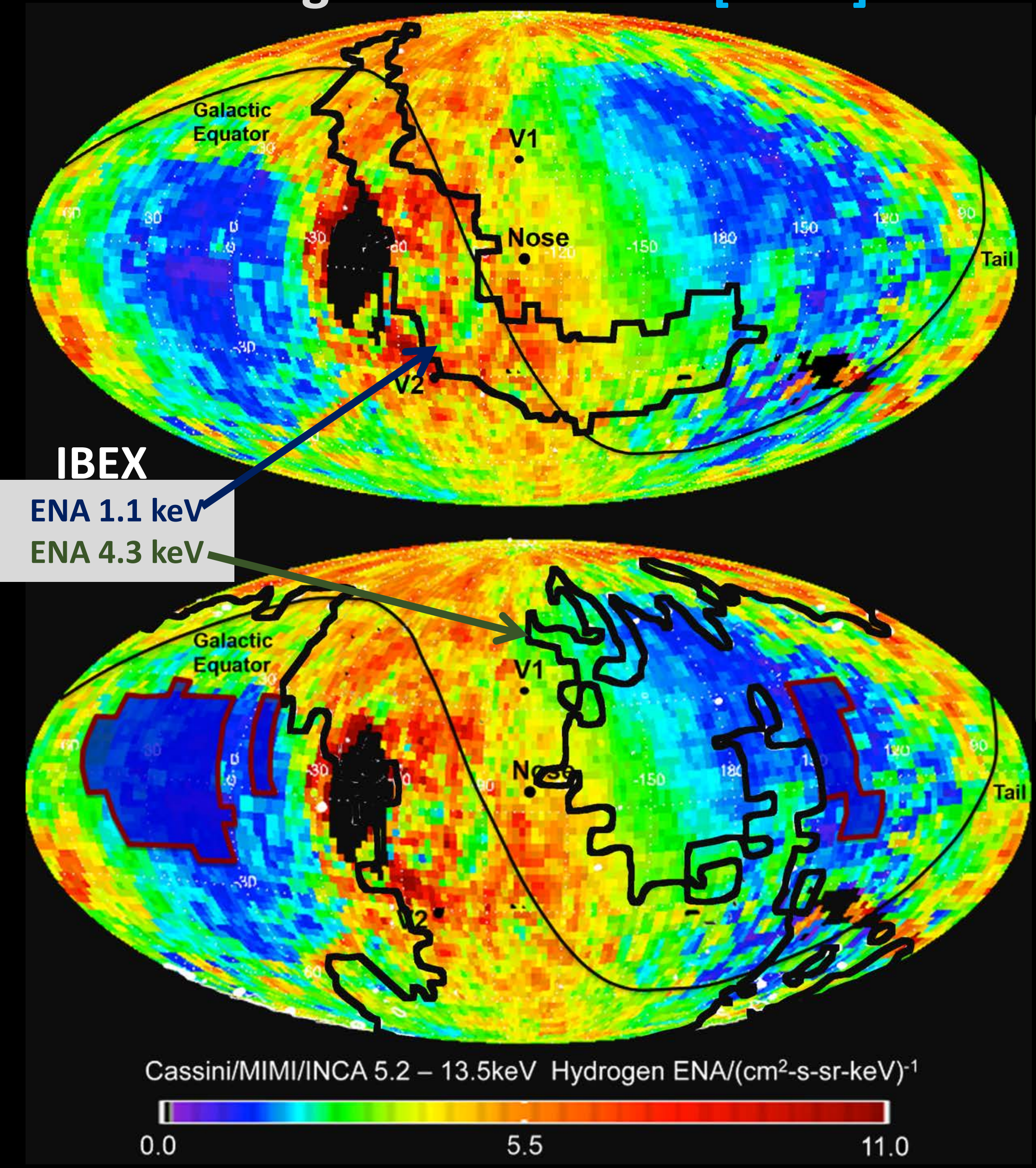
# Schematic view of hot plasma anisotropies // within the HS and upstream from the HP at V1 and V2

**Krimigis et al.** ***Nature Astronomy,*** **[2019]**



# First images of the global heliosphere // 5.2-55 keV ENA @ 10 AU (Cassini/INCA)

**Krimigis et al. *Science* [2009]**




**Our current understanding of the "ENA Heliosphere"**
Are the "Ribbon" and the "Belt" different?

## Dialynas et al. *ApJ*, [2013] *(>5.2 keV $H_{ENA}$)*

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

**Basins** *extended heliosphere lobes where the ENA minima occur.*

**Comparison of 5-55keV ENAs with >28 keV LECP ions**

$L_{V1}$**~27(-11,+26) AU: Krimigis et al.,** *Nature,* [2011] & $0.5<B_{IS}<0.64$ nT
Krimigis et al., *JoPhy,* [2010].

$L_{V2}$~35 AU: **Krimigis et al.,** *Nature Astronomy,* [2019] & **$0.5<B_{IS}<0.67$ nT**, Dialynas et al. *GRL* [2019], Dialynas et al. *ApJL*, [2020].

## In brief

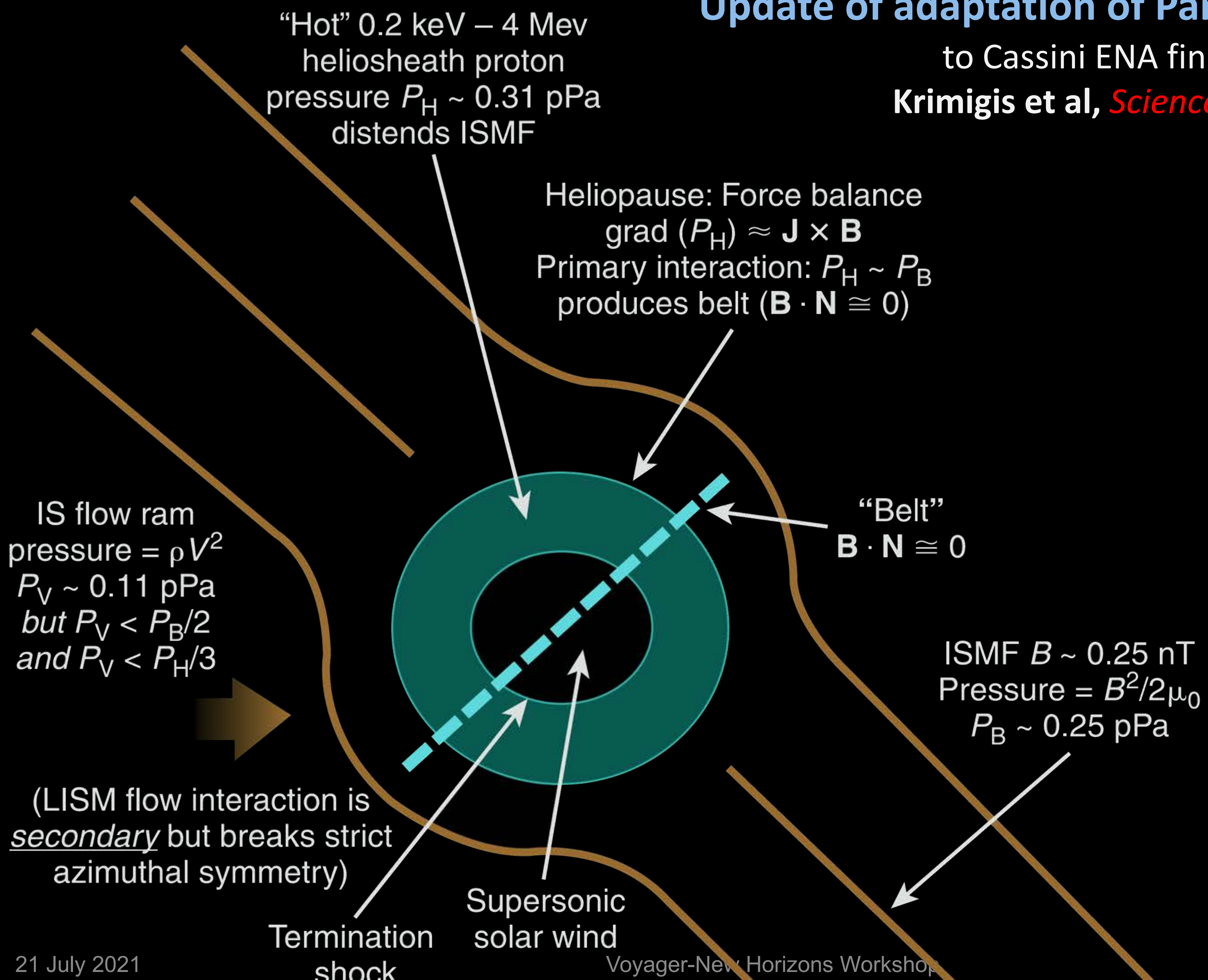
The ENAs detected by INCA originate in the HS, and the heliosphere resembles a roughly symmetric (diamagnetic) bubble .

"GROUND TRUTH"-V1, V2 & Solar Cycle (SC) dependence!

# Update of adaptation of Parker (1961) model

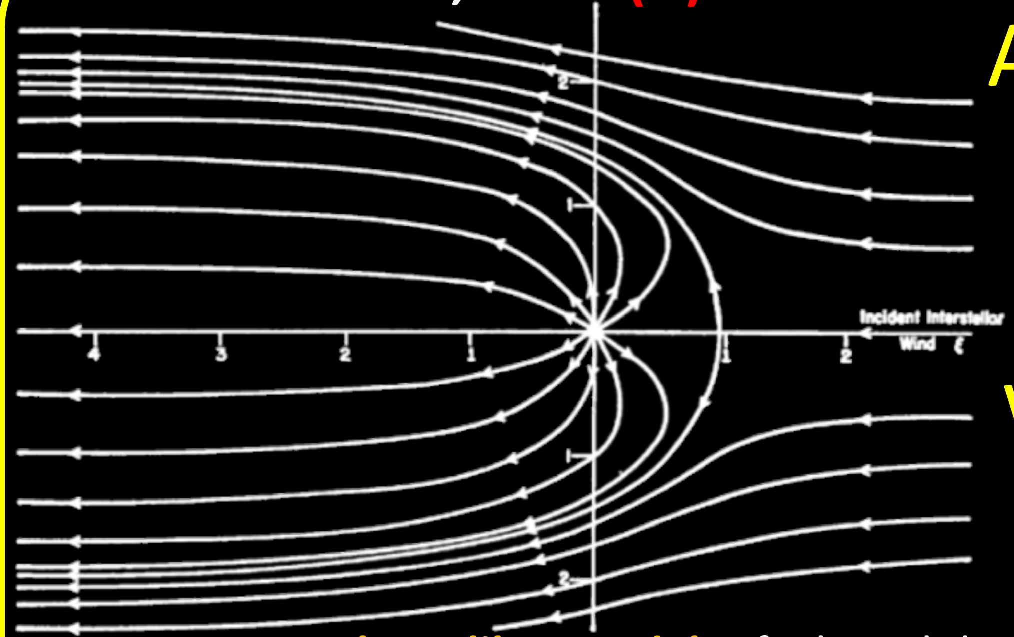
to Cassini ENA findings

**Krimigis et al,** *Science,* [2009]



# Concepts of the Global Heliosphere 1961-2016

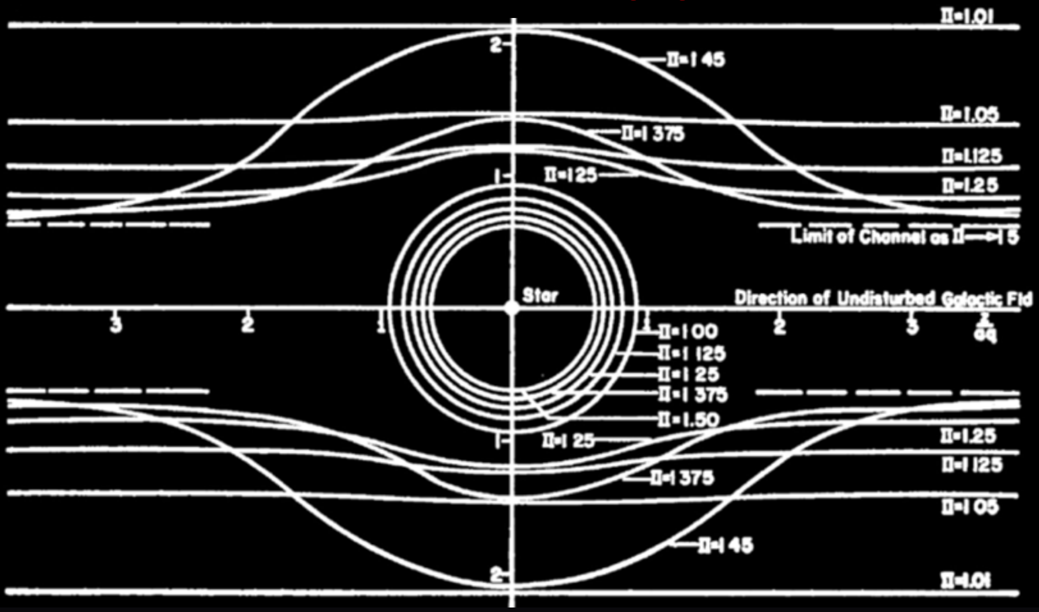
**Parker, 1961 (A)**




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.

**HOWEVER**

a) Observed ISMF from V1 **~0.5 nT** (**Burlaga et al,** 2013), and from V2 ~0.68 nT (**Burlaga et al,** 2019), contrary to the expected ~0.2-0.3 nT.

b) ***Total*** *estimated* ***HS pressure*** *downstream of the TS is* $P_{tot}$ ***~ 0.230 pPa*** *(Krimigis et al, 2010) to* $P_{tot}$***~0.251 pPa*** *(Dialynas et al. 2020)*

c) IS plasma stagnation pressure is $P_S=\rho V^2/2$ ***~ 0.056 pPa.***

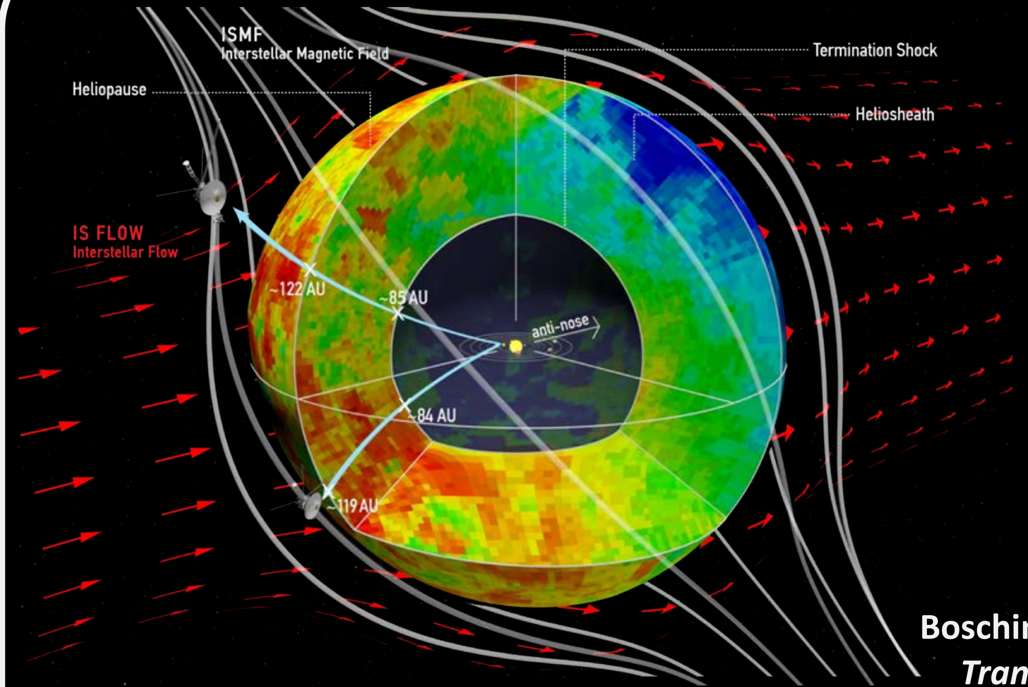
d) IS thermal pressure is $P_{th}=nkT$ ***~0.010 pPa*** **& the GCR Pressure is** ***~0.007 pPa.***

e) ISMF (observed) Magnetic pressure is $B^2/8\pi$ ***~0.1 to 0.184 pPa.***

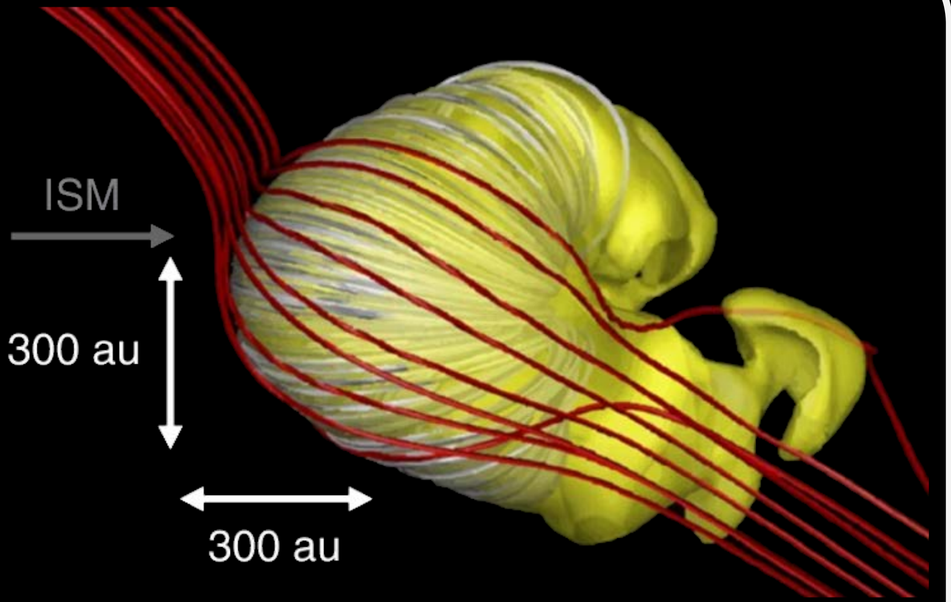
f) The resulting $B_{ISMF}/P_S$ **> 2 as opposed to the expected ~0.28-0.5**

# The Global Heliosphere // A rough diamagnetic bubble; a jets structure; a comet…

**Dialynas et al., *Nat. Astron,* [2017]-*INCA & Voyager data***




**Opher et al., *Nat. Astron,* [2020]-*MHD modeling***




**IBEX-Lo Data (Galli et al. *ApJ,* [2016; 2017])**

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

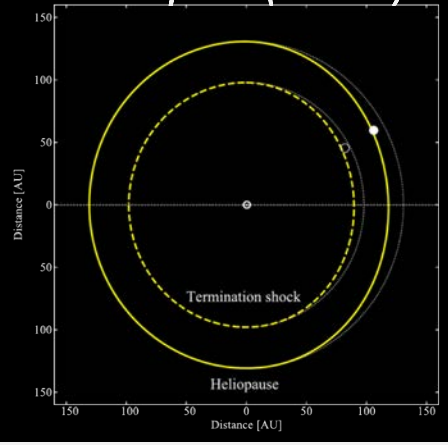
**IBEX-Hi Data (Reisenfeld et al. *ApJ,* [2016])**

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

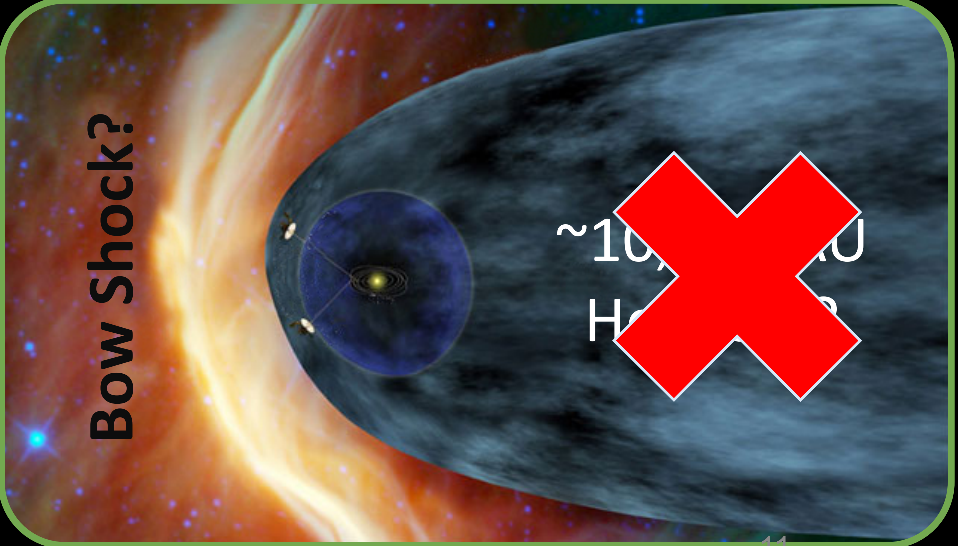
**IBEX-Hi Data (Reisenfeld et al. *ApJ-S,* [2021])**

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

**Boschini et al., *Adv. Sp. Res,* [2019]**
***Transport of GCRs through the heliosphere (HELMOD).***




**Comet-type Heliosphere**



## **Theory vs Observations //** In interaction with the LISM

| | Pre-Voyager Predictions | Voyager *in-situ* Observations |
|---|---|---|
| **ISMF magnitude** | 0.2-0.3 nT | ~0.5 nT (V1) & ~0.7 nT (V2) |
| **Anomalous Cosmic Rays** | Accelerated at the Termination Shock (TS) | Accelerated in Heliosheath |
| **Heliosheath Pressure** | Heated Solar Wind dominates pressure in Heliosheath | Suprathermal ions dominate Pressure in Heliosheath |
| **Galactic Cosmic Rays** | Fully isotropic in LISM | Long-term episodes of reduced GCR perpendicular to B |
| **Shape of the global Heliosphere** | Resembles magnetospheres | Heliosphere is more like a rough "Bubble" with a ~120 AU radius (no tail) |

# Summary // Conclusions

## Crossings of the HP

Voyager 1 and 2 crossed the Heliopause (HP) at nearly the same radius (~ 120 AU), while the 2 S/C were separated by ~170 AU. Further, V1 crossed at solar minimum but V2 at solar maximum

## Pressure Balance

Most of the pressure in the HS resides in superthermal ions and pressure balance predicts a strong ISMF, as observed

## Interstellar Magnetic Field

The ISMF at ≈ 0.5-0.7nT is stronger than predicted (~ 0.2nT) and its direction remains close to the Parker spiral of the heliosphere

## GCR anisotropies

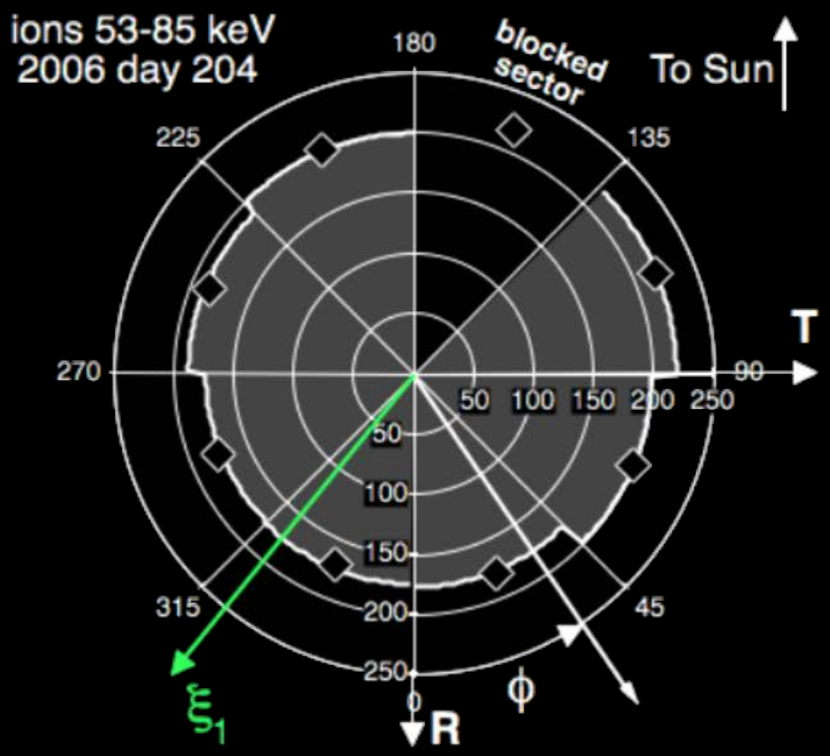
The GCR intensity is unmodulated overall, but exhibits long periods of anisotropy with decreased intensities perpendicular to ISMF to distances >28 AU upstream of HS

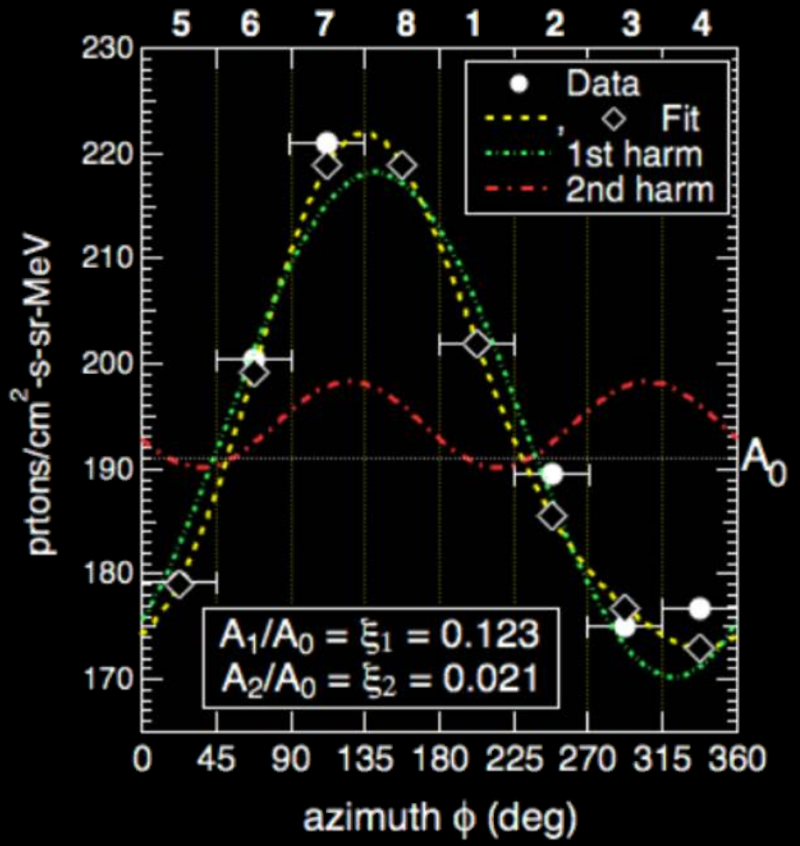
## The phenomenology of the heliosphere

The combination of "ground truth" ion measurements by the Voyagers in the HS and the resulting ENAs through charge exchange imaged by Cassini/MIMI show the global heliosphere to be a <u>rougly symmetric "bubble"</u> traveling through strong ISMF flux tubes, i. e. not much evidence of a comet-like tail

# BACKUP SLIDES

# **Flow Velocity //** Compton-Getting anisotropy




Fourier fits, through 2$^{nd}$ harmonic in azimuth angle ϕ, to angular distributions of low-energy Heliosheath ions

Least-squares fit to 7 of 8, 45° sectors

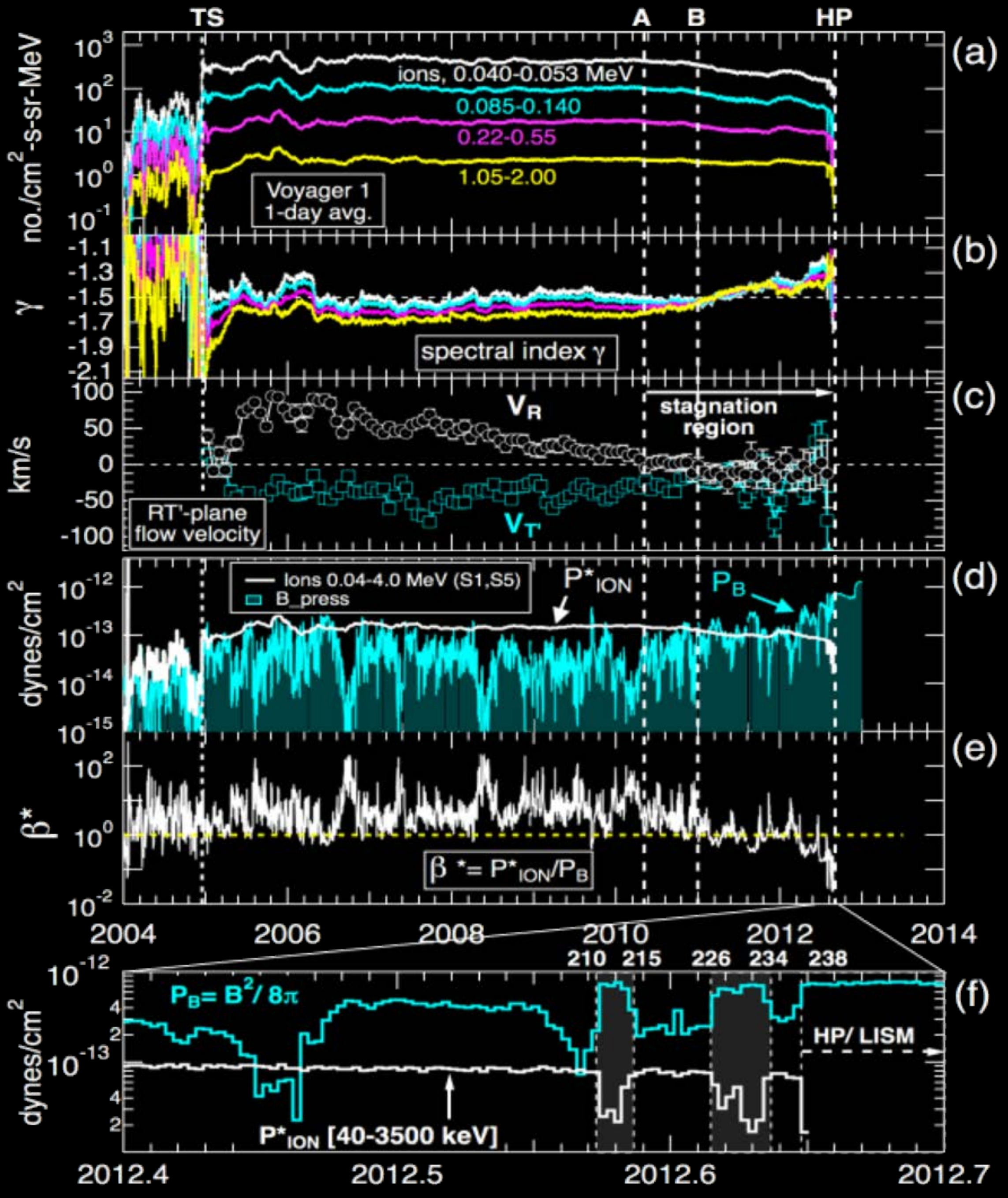
$$j(\phi) = A_0 + A_1 sin(\phi - \phi_1) + A_2 sin[2(\phi - \phi_2)]$$

yields 5 fit parameters $[A_0, (A_1, \phi_1), (A_2, \phi_2)] = [A_0, \xi_1, \xi_2]$

For $\xi_2 << \xi_1$ and $(V/v)^2 << 1$, $\xi_1 \cong 2(\gamma + 1)(V/v) \longrightarrow$ **$V \cong v\xi_1/2(\gamma + 1)$**

$v$ = ion speed, $\gamma$ = ion energy spectrum slope

# Voyager 1 // Traversal of the Heliosheath




1. ***Decreasing radial velocity until Stagnation Region***

2. ***Near constant tangential flow***

3. ***High beta (>1) plasma***

4. ***Diamagnetic "holes" before Heliopause crossing***