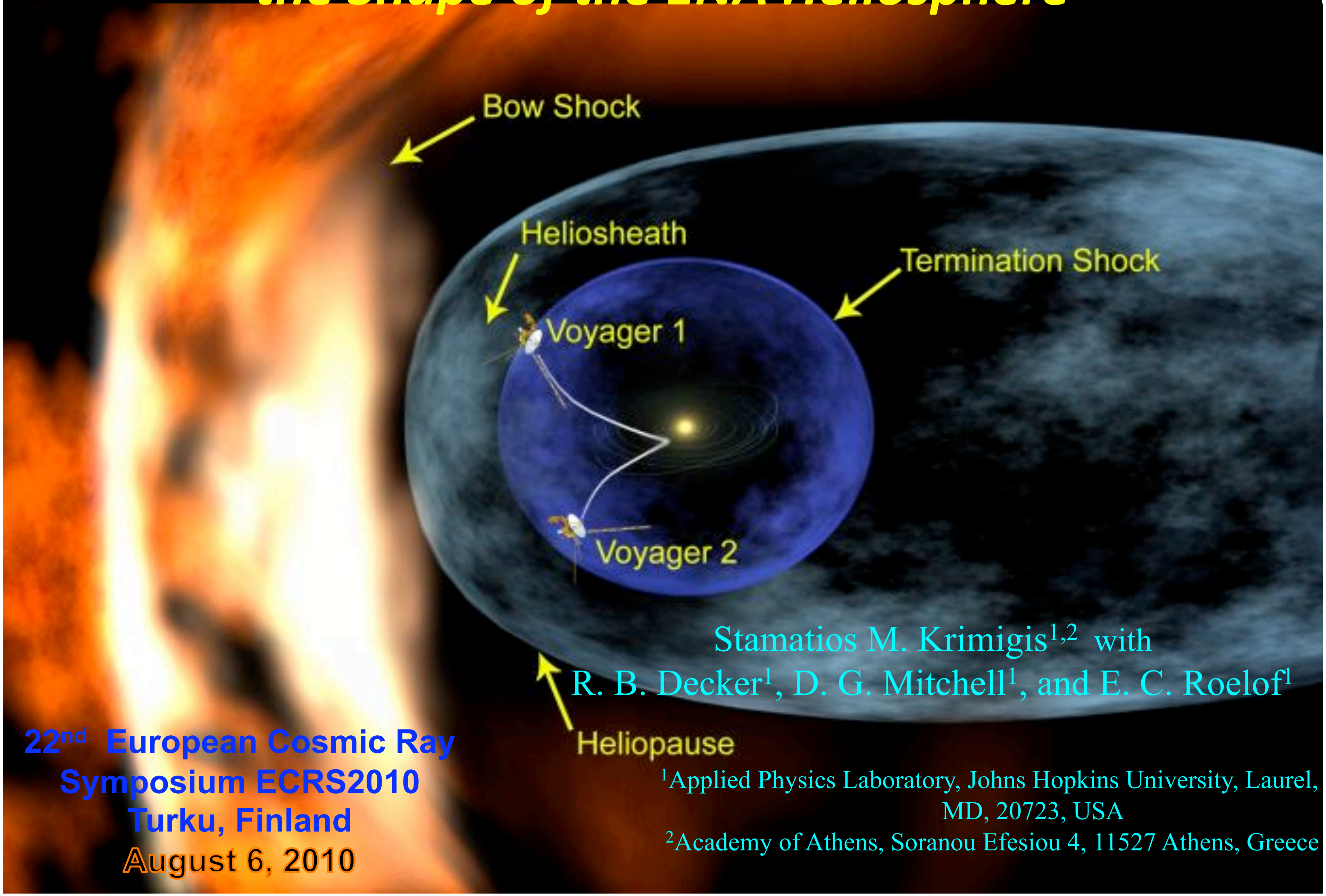
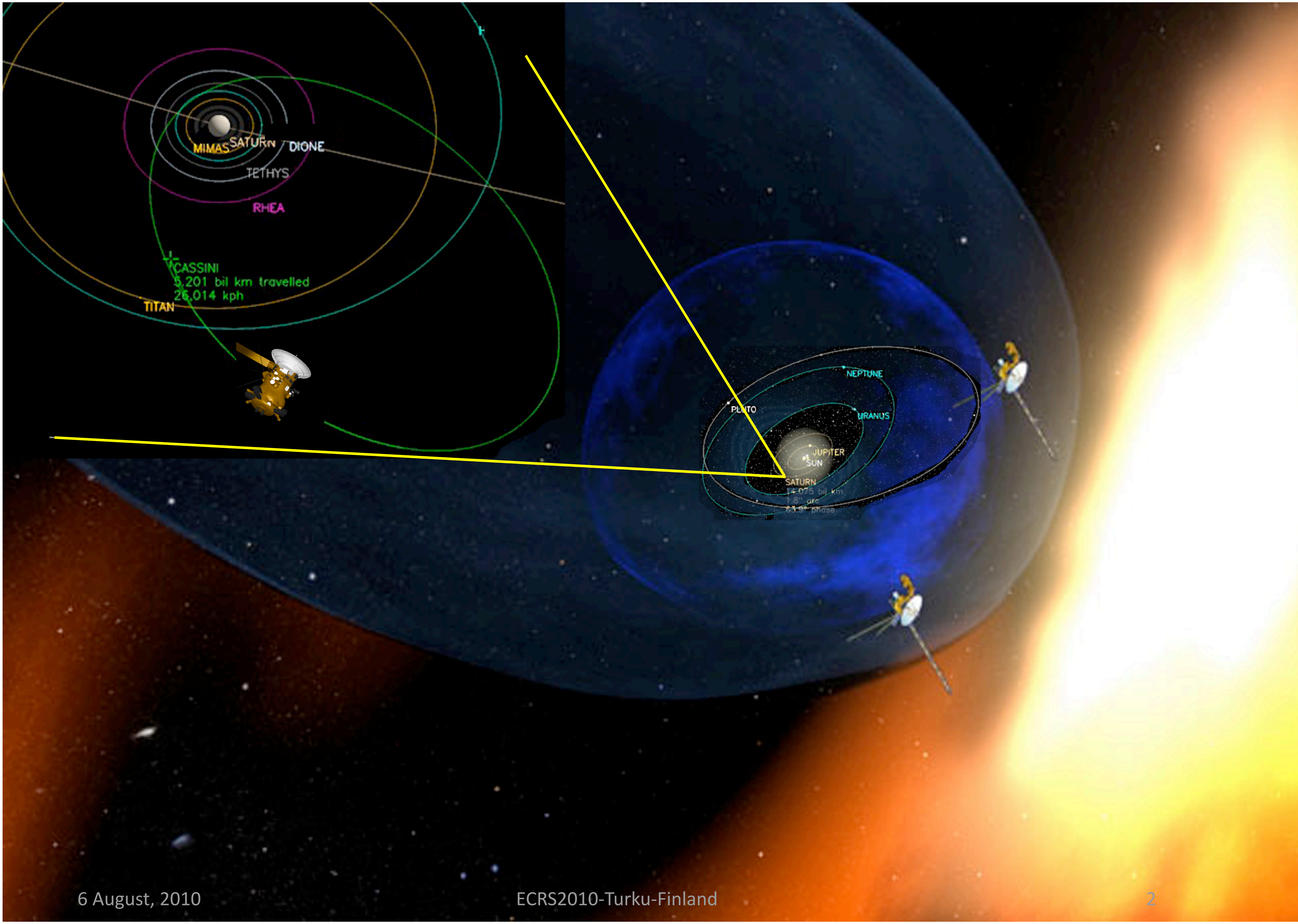
The Voyagers' View of Cosmic Rays in the Heliosheath and the Shape of the ENA Heliosphere



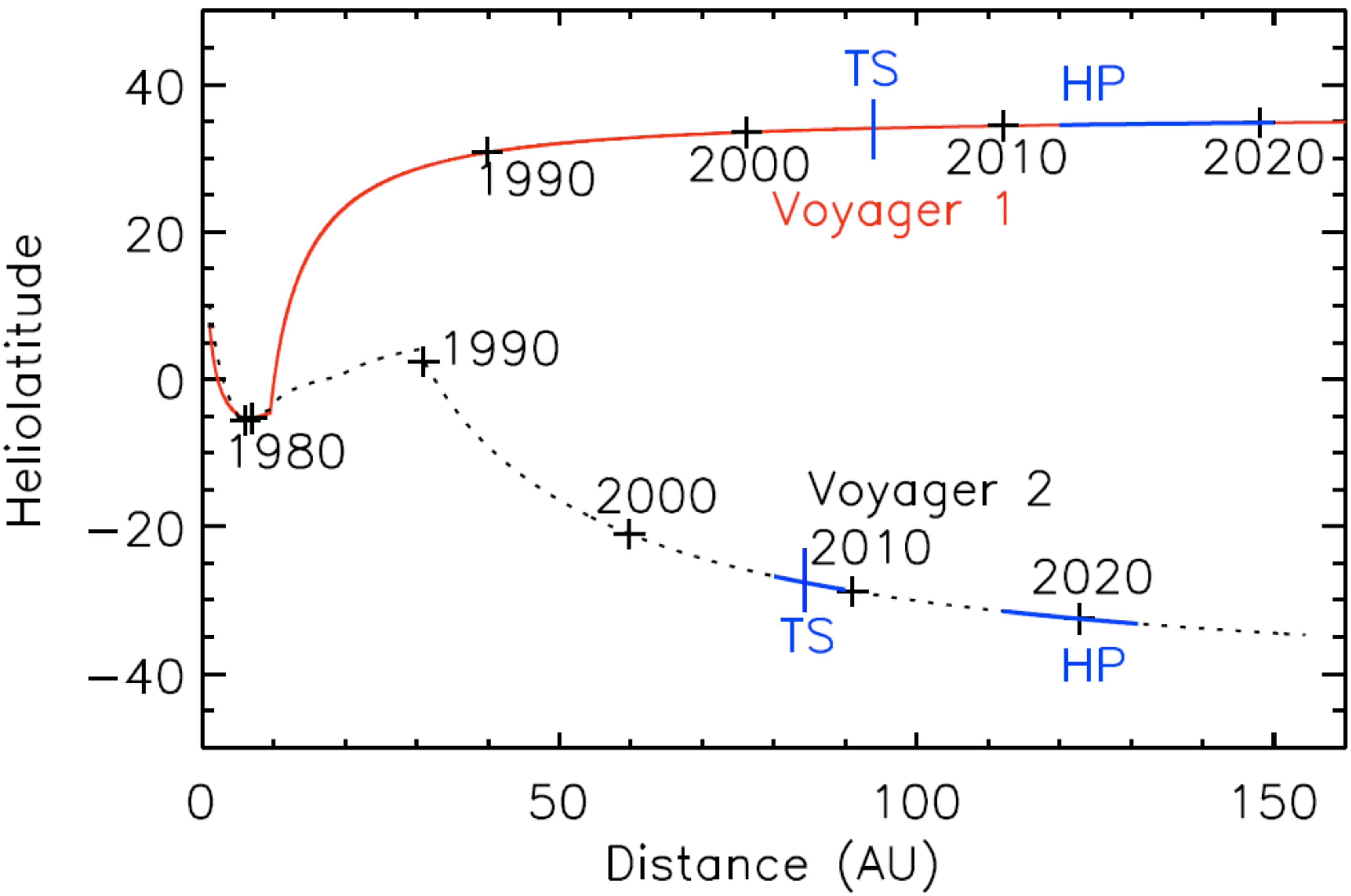
Stamatios M. Krimigis[1,2] with
R. B. Decker[1], D. G. Mitchell[1], and E. C. Roelof[1]

[1]Applied Physics Laboratory, Johns Hopkins University, Laurel, MD, 20723, USA
[2]Academy of Athens, Soranou Efesiou 4, 11527 Athens, Greece

22nd European Cosmic Ray Symposium ECRS2010
Turku, Finland
August 6, 2010

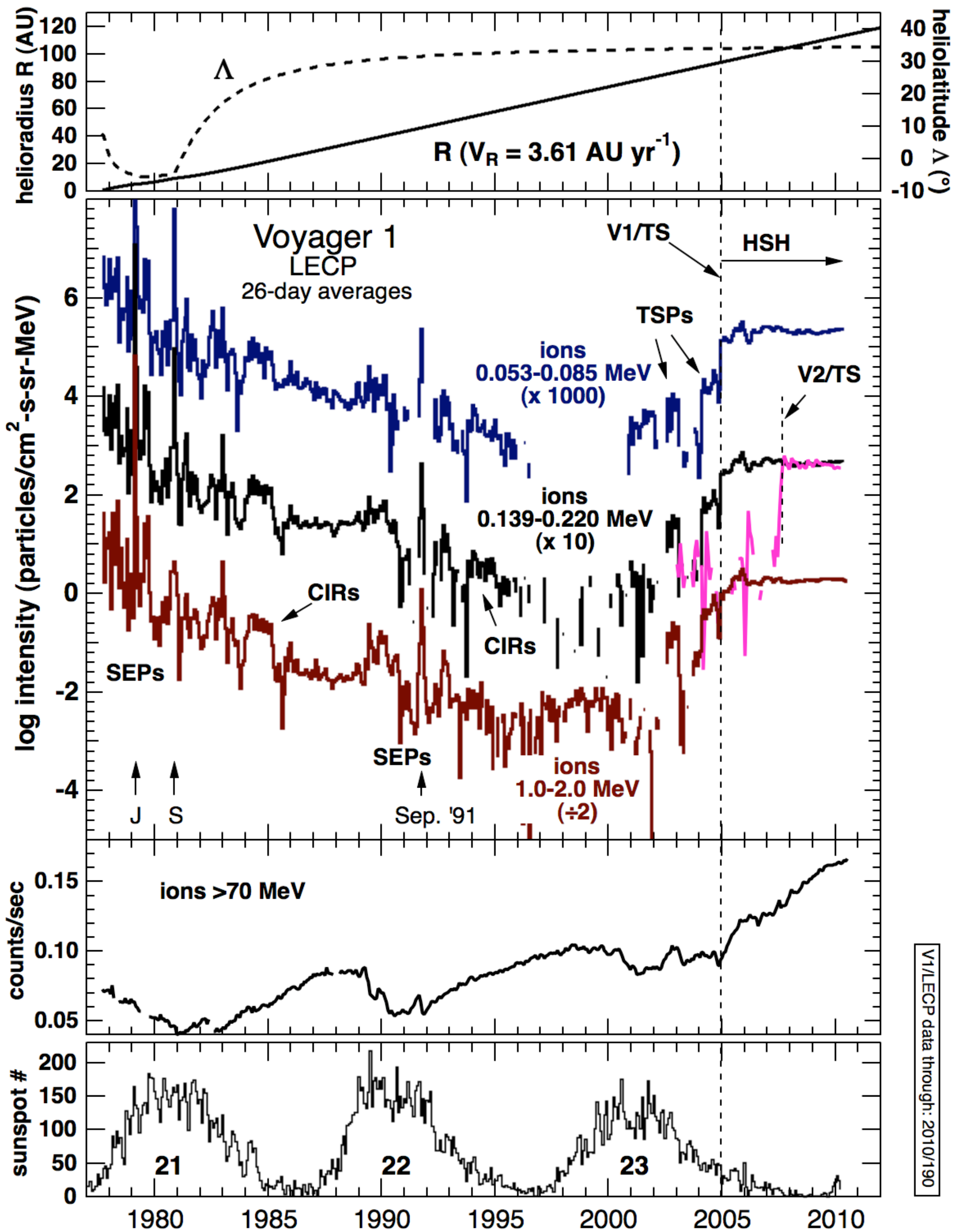

MIMAS
SATURN
DIONE
TETHYS
RHEA
CASSINI
5.201 bil km travelled
26.014 kph
TITAN
NEPTUNE
PLUTO
URANUS
JUPITER
SUN
SATURN

Voyager 1/2: Termination shock (TS) encounters & heliopause (HP) estimates



Outline

- Voyagers 1, 2 Termination Shock (TS) crossing and Galactic Cosmic Rays (GCR) in Heliosheath
- Anomalous Cosmic Rays (ACR), Termination Shock Particle (TSP) spectra, and plasma flows in Heliosheath
- ENA Heliosphere: Cassini-Belt, IBEX-Ribbon, ENA spectra and Voyager 1,2 "ground truth" measurements in the heliosheath (LECP)
- Ion pressures at the Voyagers and in the Heliosheath
- Consequences for the ISMF magnitude and direction
- Shape of the Heliosphere

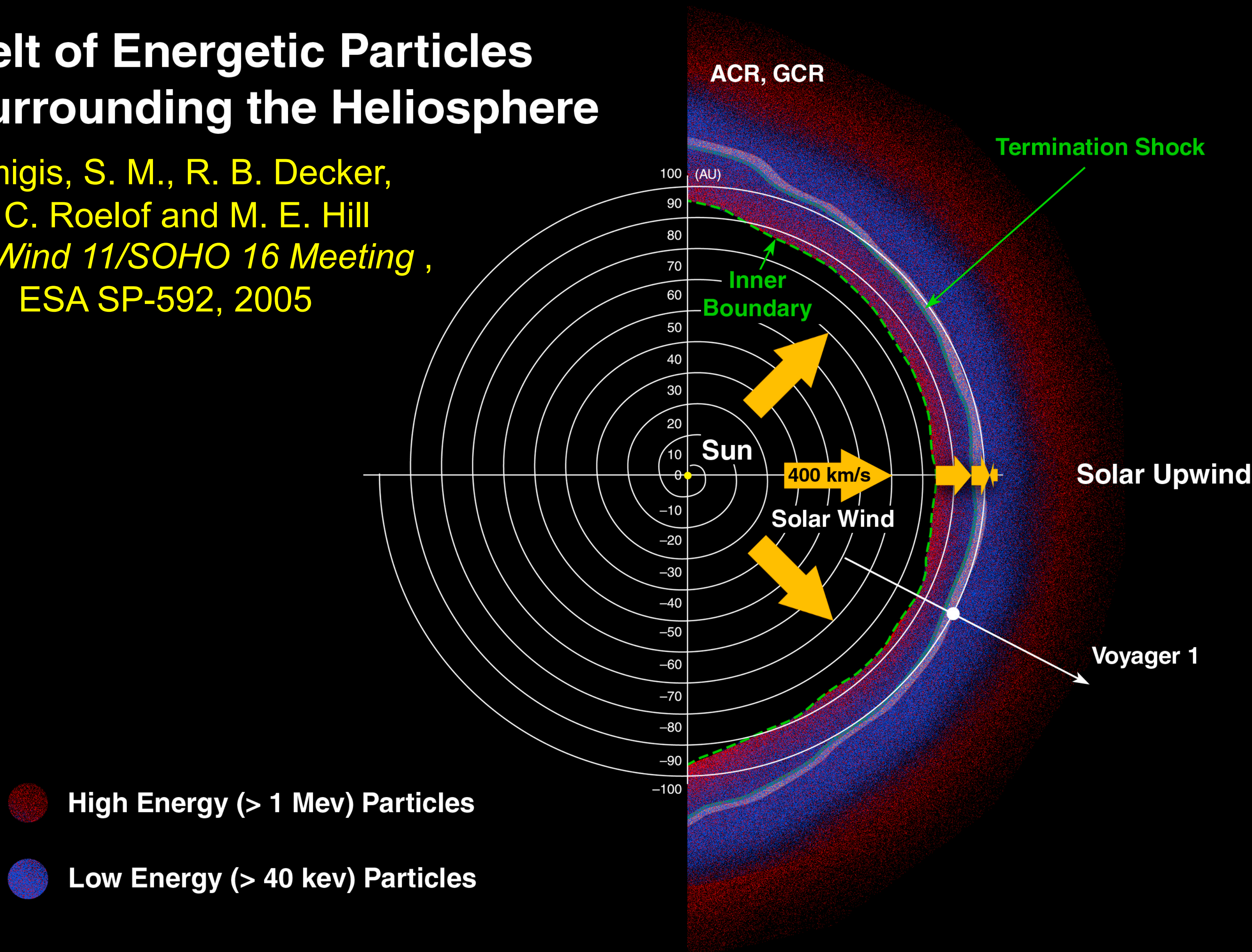


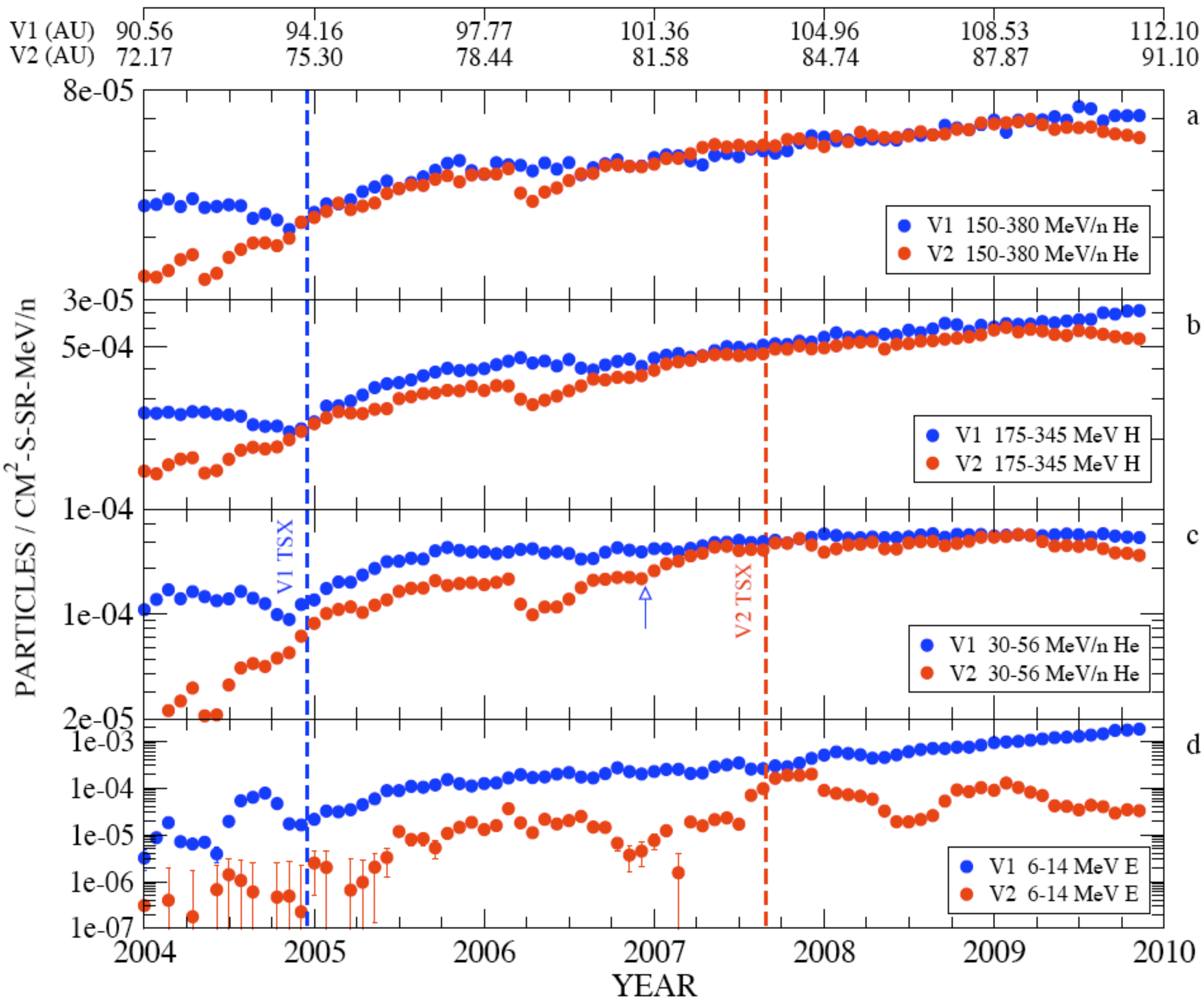
Voyager Mission: 33-year cruise through the heliosphere

- *Voyager 1, 1977.7-2010.6*
  - *Trajectory*
  - *Ions 53-85 keV*
  - *Ions 140-220 keV*
  - *Protons 0.6-1.8 MeV*
  - *Protons >70 MeV*
  - *Sunspot number*
- *Relatively slow S/C speed ≈0.01 AU/day gives in-depth look at solar phenomena* (*ICMEs, SEPs, CIRs, CMIRs, MIRs, GMIRs, TSPs, TS, HSH, ACRs, GCRs …*)

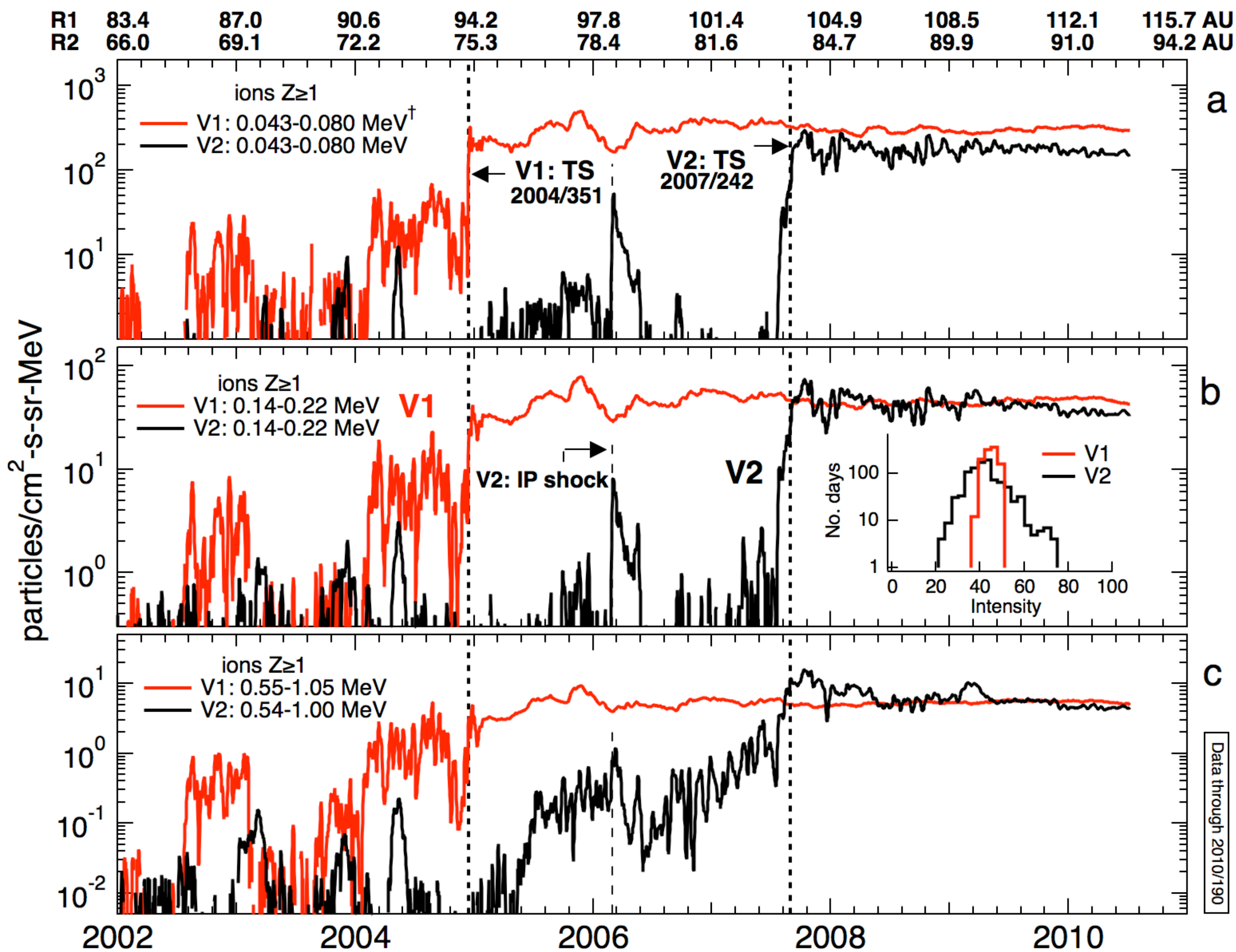
Belt of Energetic Particles Surrounding the Heliosphere

Krimigis, S. M., R. B. Decker,
E. C. Roelof and M. E. Hill
Solar Wind 11/SOHO 16 Meeting ,
ESA SP-592, 2005

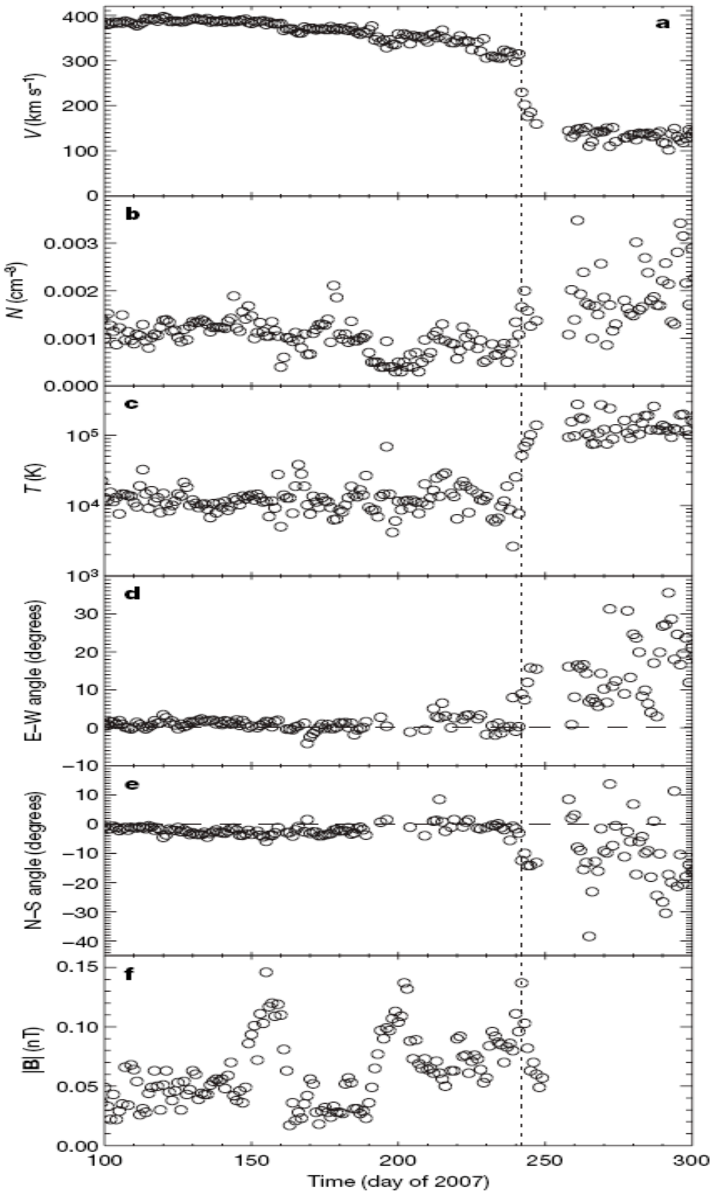



V1 (AU) 90.56 94.16 97.77 101.36 104.96 108.53 112.10
V2 (AU) 72.17 75.30 78.44 81.58 84.74 87.87 91.10
PARTICLES / CM^2-S-SR-MeV/n
a
V1 150-380 MeV/n He
V2 150-380 MeV/n He
b
V1 175-345 MeV H
V2 175-345 MeV H
c
V1 TSX
V2 TSX
V1 30-56 MeV/n He
V2 30-56 MeV/n He
d
V1 6-14 MeV E
V2 6-14 MeV E
YEAR
2004 2005 2006 2007 2008 2009 2010

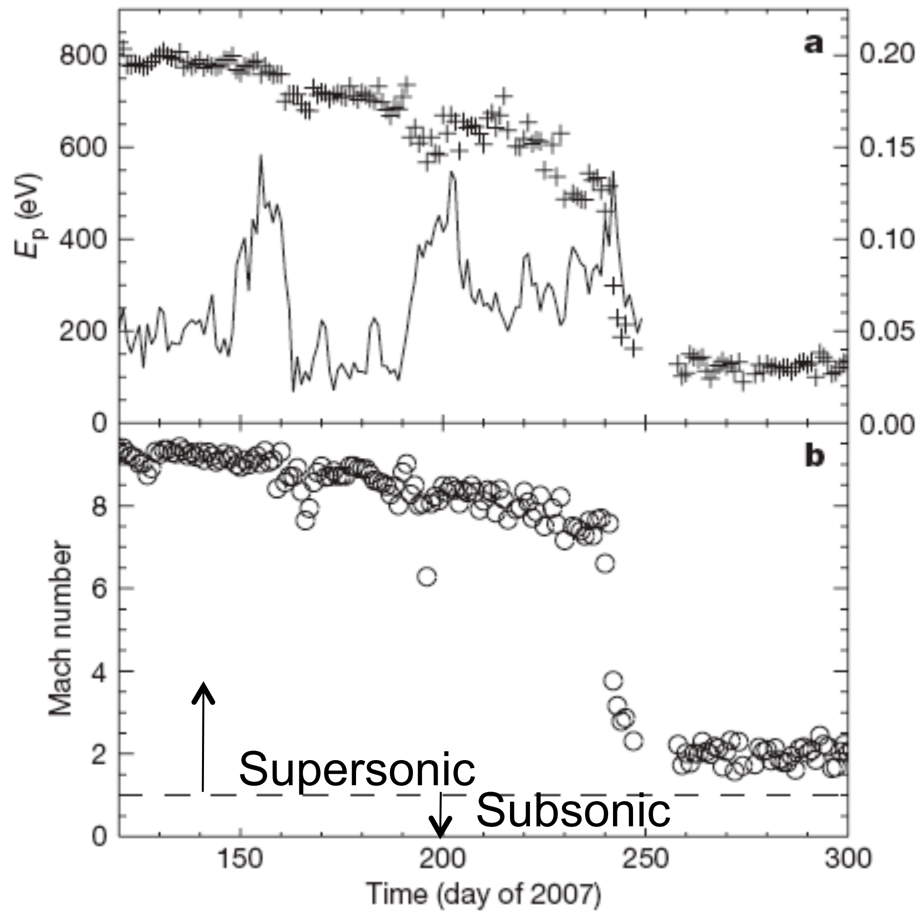
Low-energy ions >40 keV at TS/HSH, 2002-on



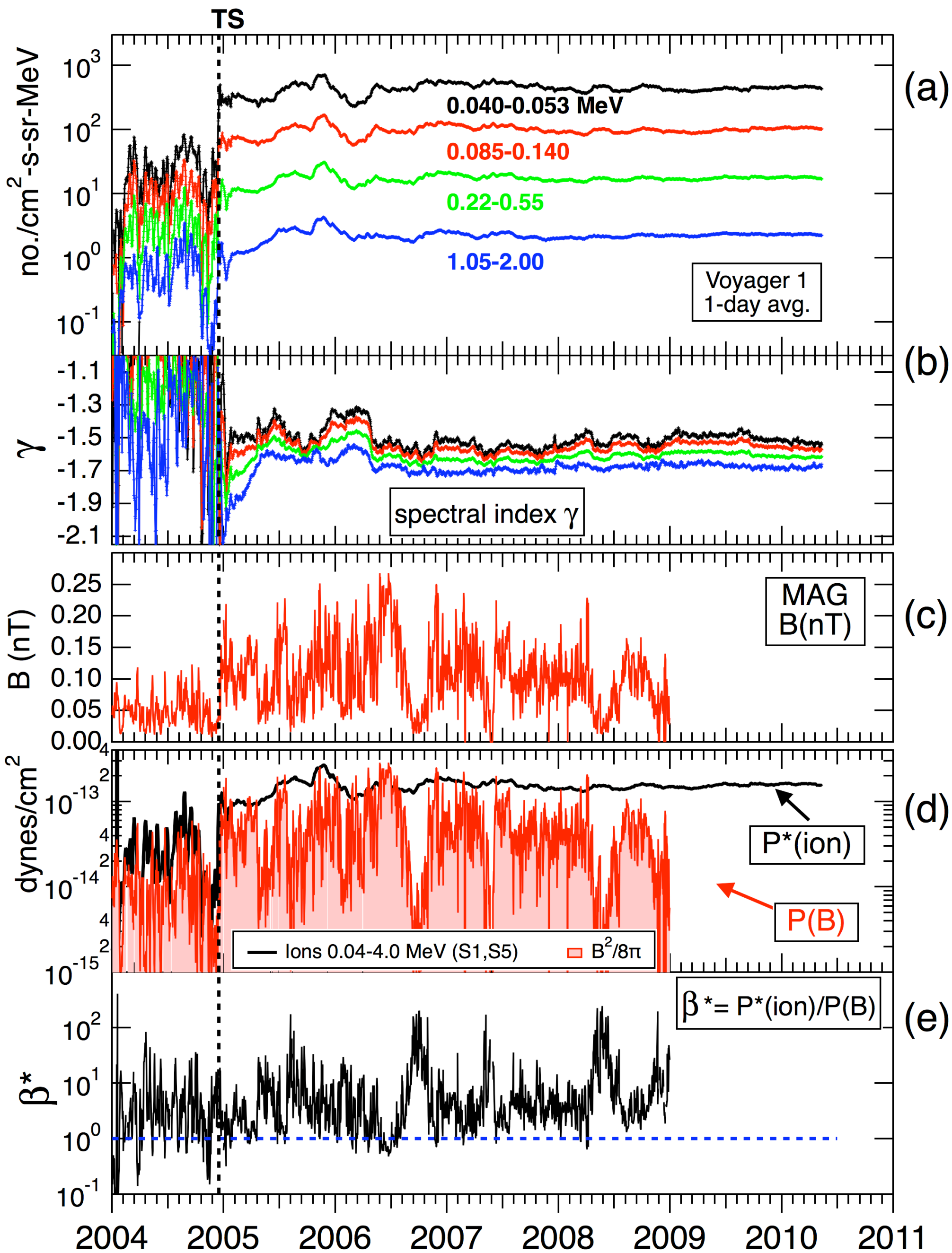
Voyager 2 TS crossing: plasma and magnetic field measurements



Richardson et al, *Nature*, *454*, 63, 2008



Only ~ 20% of the solar wind flow energy went into thermal plasma heating in the heliosheath!



Low-energy ion pressure in HSH: Voyager 1

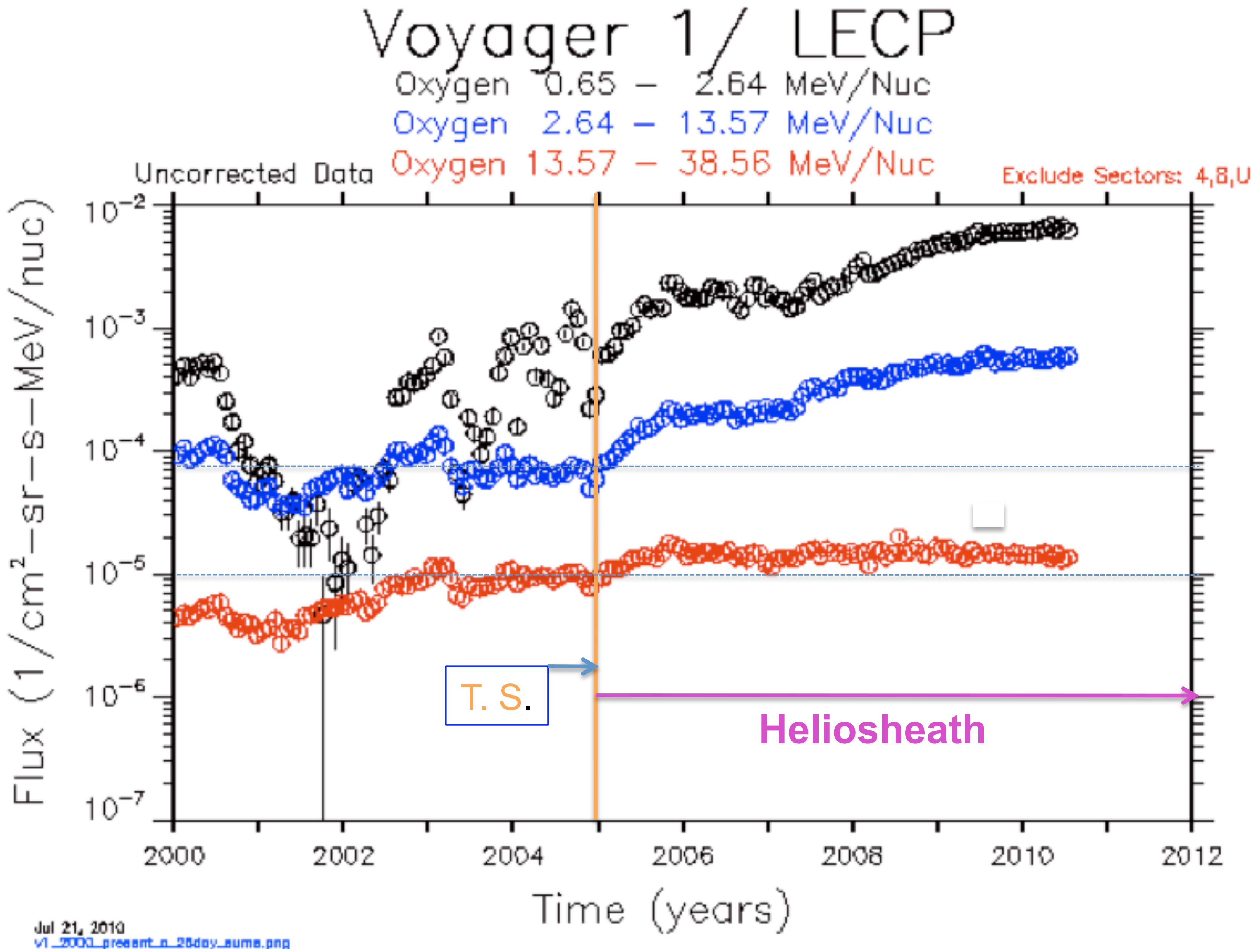
- Ions 0.04-4.0 MeV at V1 during 2004-2010.3
- Spectral index γ
- B during 2004-2009.0
- Ion partial pressure P* (a lower-limit) compared to $P_B=B^2/8\pi$
- $\beta^*= P^*/P_B$ often >1 in HS

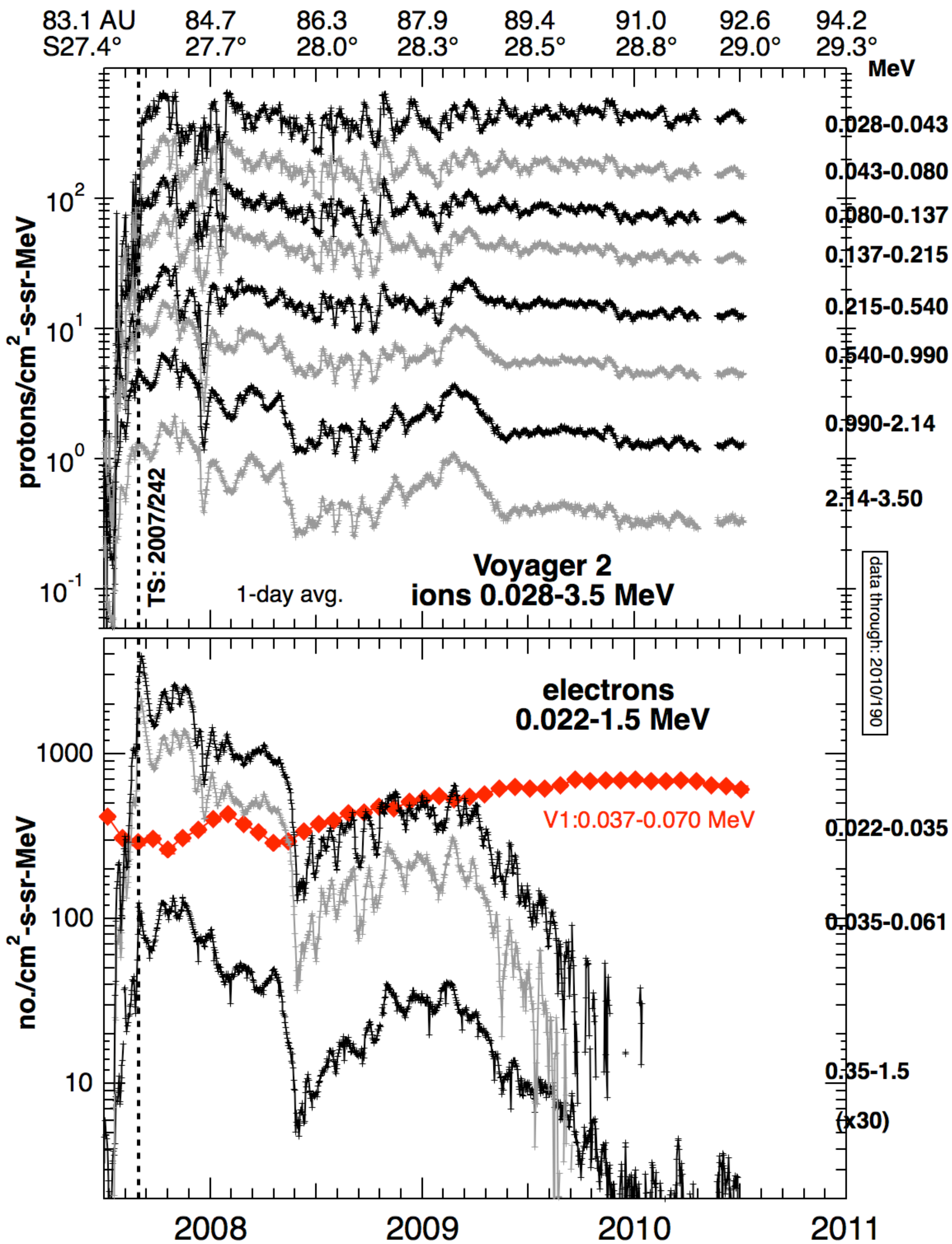
Outline

- Voyagers 1, 2 Termination Shock (TS) crossing and Galactic Cosmic Rays (GCR) in Heliosheath
- Anomalous Cosmic Rays (ACR), Termination Shock Particle (TSP) spectra, and plasma flows in Heliosheath
- ENA Heliosphere: Cassini-Belt, IBEX-Ribbon, ENA spectra and Voyager 1,2 “ground truth” measurements in the heliosheath (LECP)
- Ion pressures at the Voyagers and in the Heliosheath
- Consequences for the ISMF magnitude and direction
- Shape of the Heliosphere

TSP & ACR Oxygen at Voyager 1

(Hill, Hamilton et al, 2010)

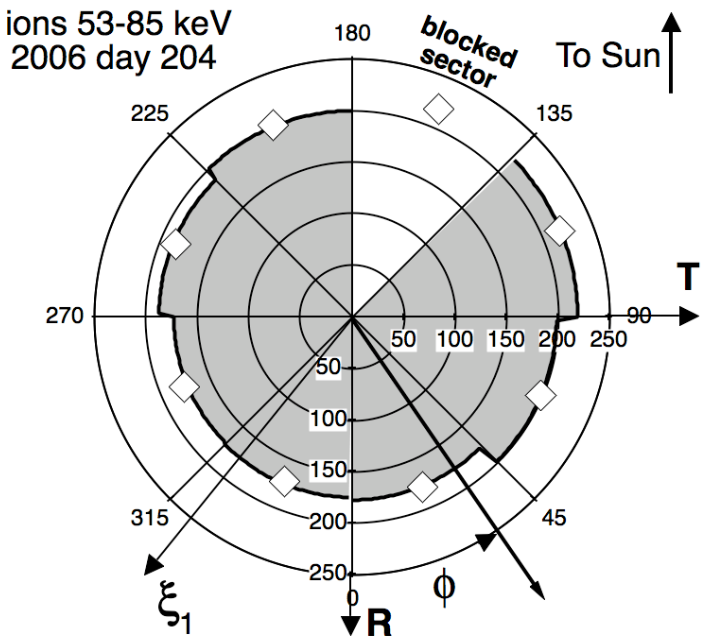


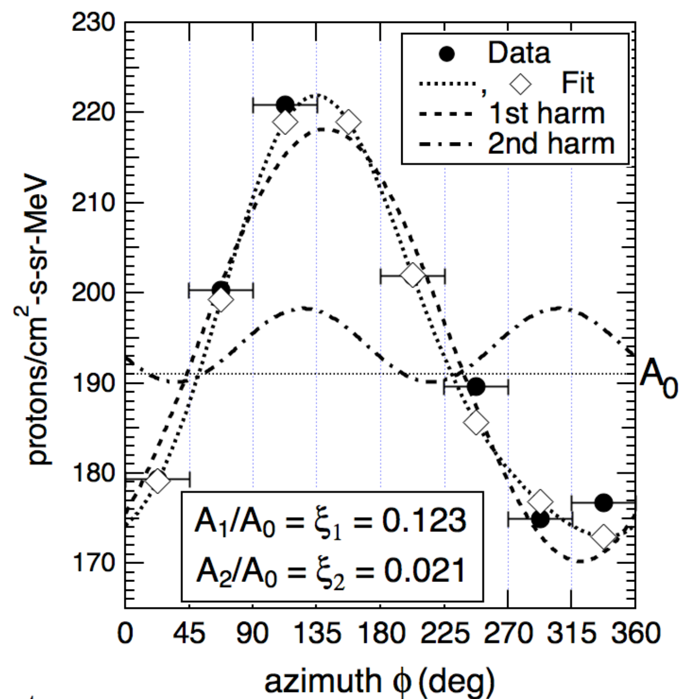


Low-energy ion and electron intensities at V2 in HSH

- Reduction of ion intensity variations since mid-2009 consistent with evolution of southern polar coronal holes ~1 year earlier [Roelof et al., 2009]
- Starting ~2009.30 low-energy electron intensities began to decline, reaching detection background in 2010
- V1 electron intensities do not show similar decrease

Perform Fourier fits, though 2^{nd} harmonic in azimuth angle ϕ to angular distributions of low-energy HSH ions





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

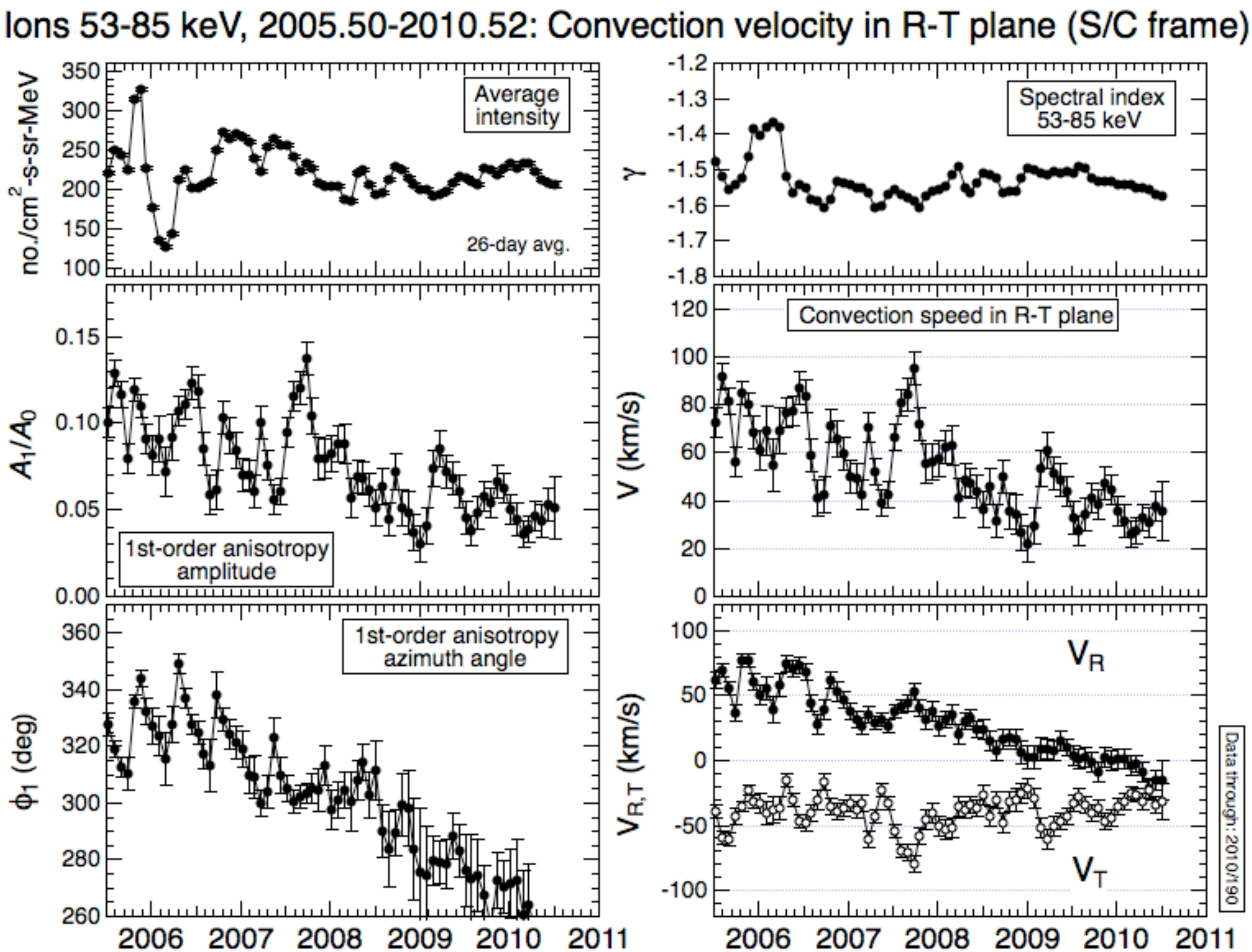
$$j(\phi) = A_0 + A_1 sin(\phi - \phi_1) + A_2 sin[2(\phi - \phi_2)]$$

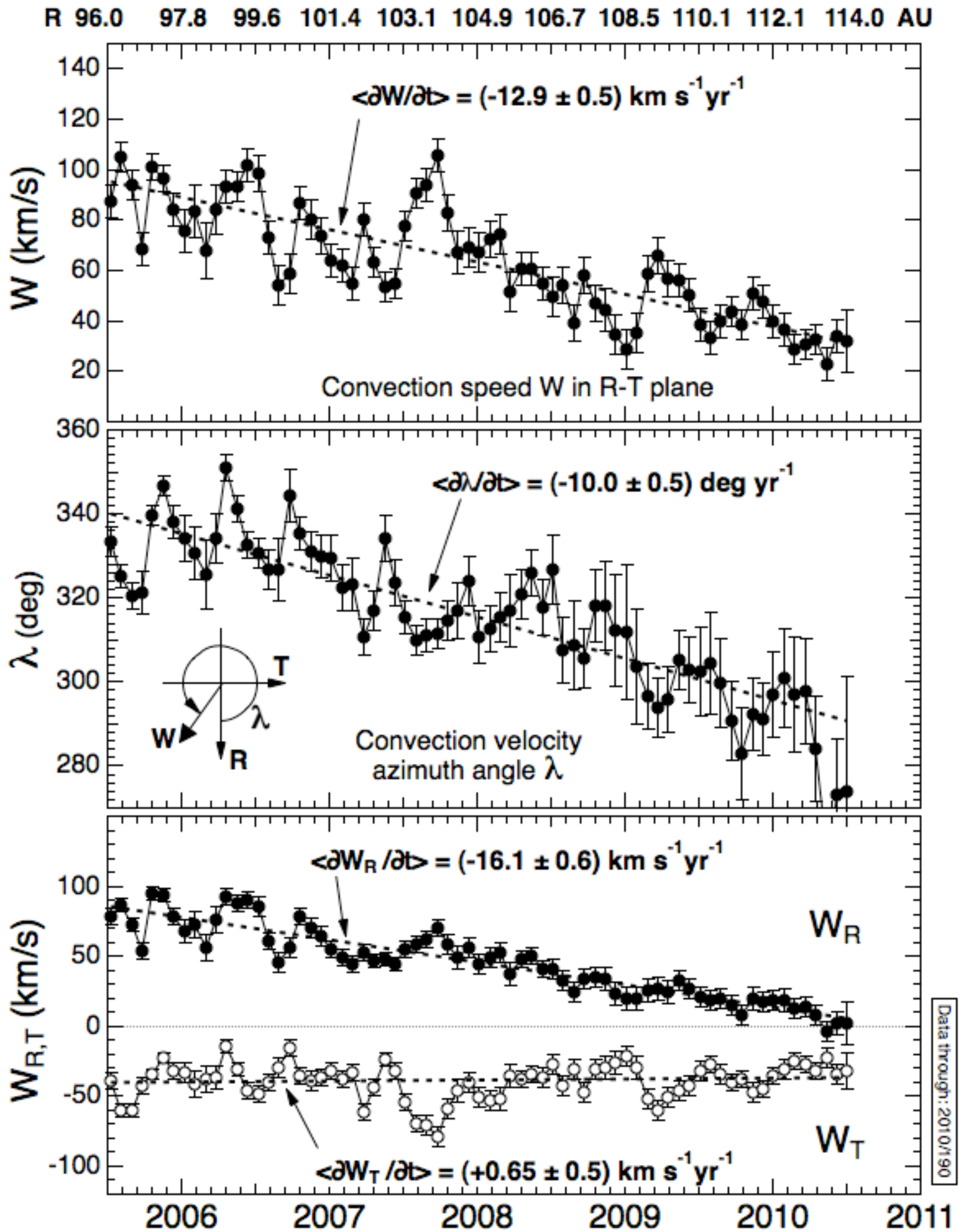
yields 5 fit parameters $[A_0, (A_1, \phi_1), (A_2, \phi_2)] = [A_0, \xi_1, \xi_2]$

(2) For $\xi_2 << \xi_1$ and $(V/v)^2 << 1$, $\xi_1 \cong 2(\gamma + 1)(V/v) \Rightarrow \mathbf{V} \cong v\xi_1/2(\gamma + 1)$

v = ion speed, γ = ion energy spectrum slope

Estimates of HSH plasma flow in R-T plane at V1



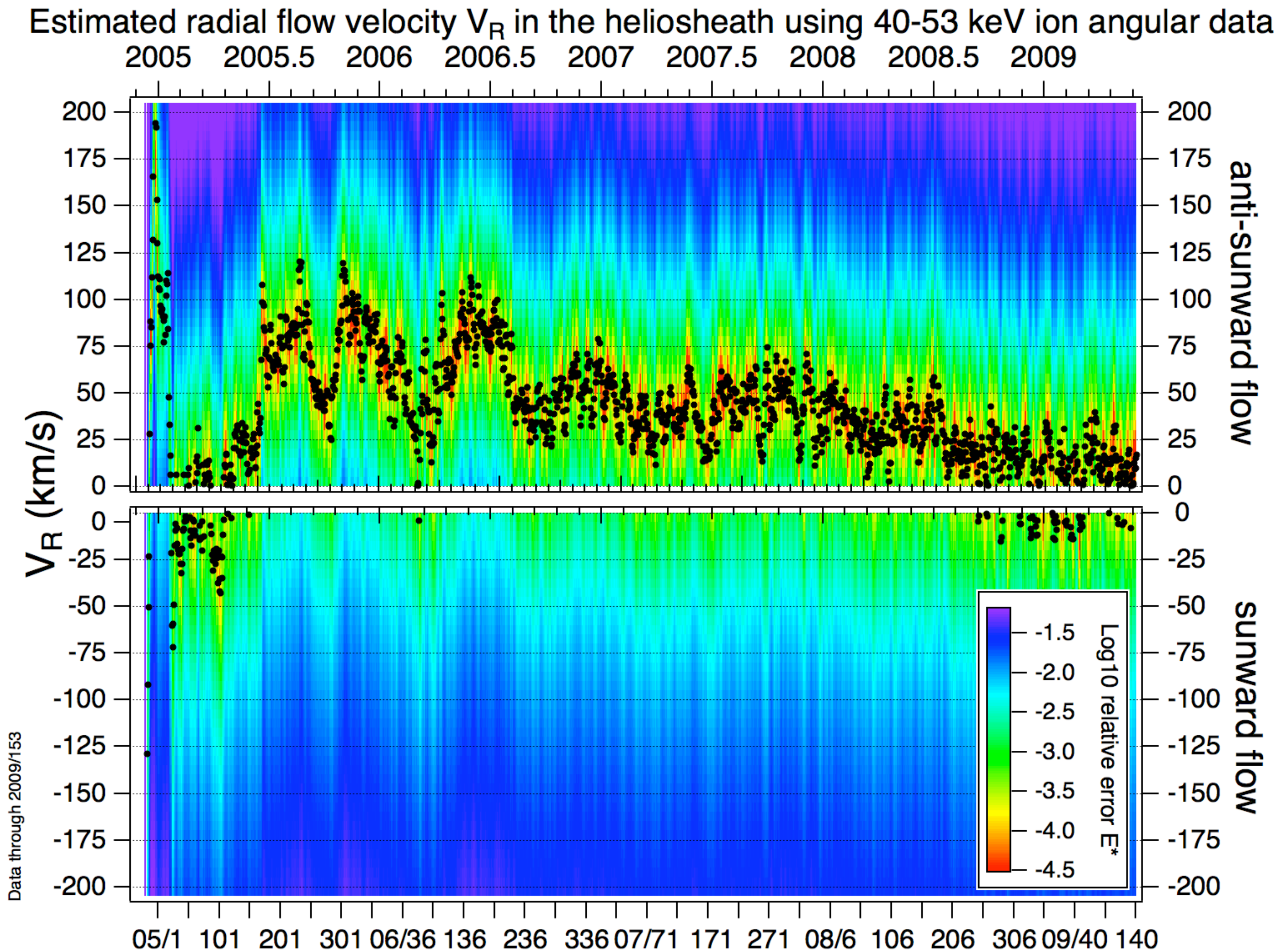


Voyager 1 53-85 keV ion angular dists., 2005.50-2010.52

<= Remove S/C radial velocity to express final results in sun-fixed inertial frame

$W_R \approx 0$
$W_T \approx -40$ km/s ~ constant

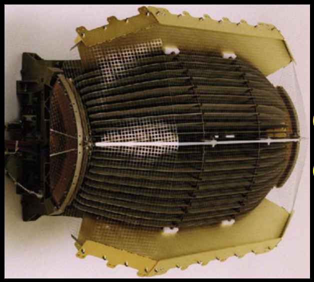
Voyager 1 plasma velocities in HS

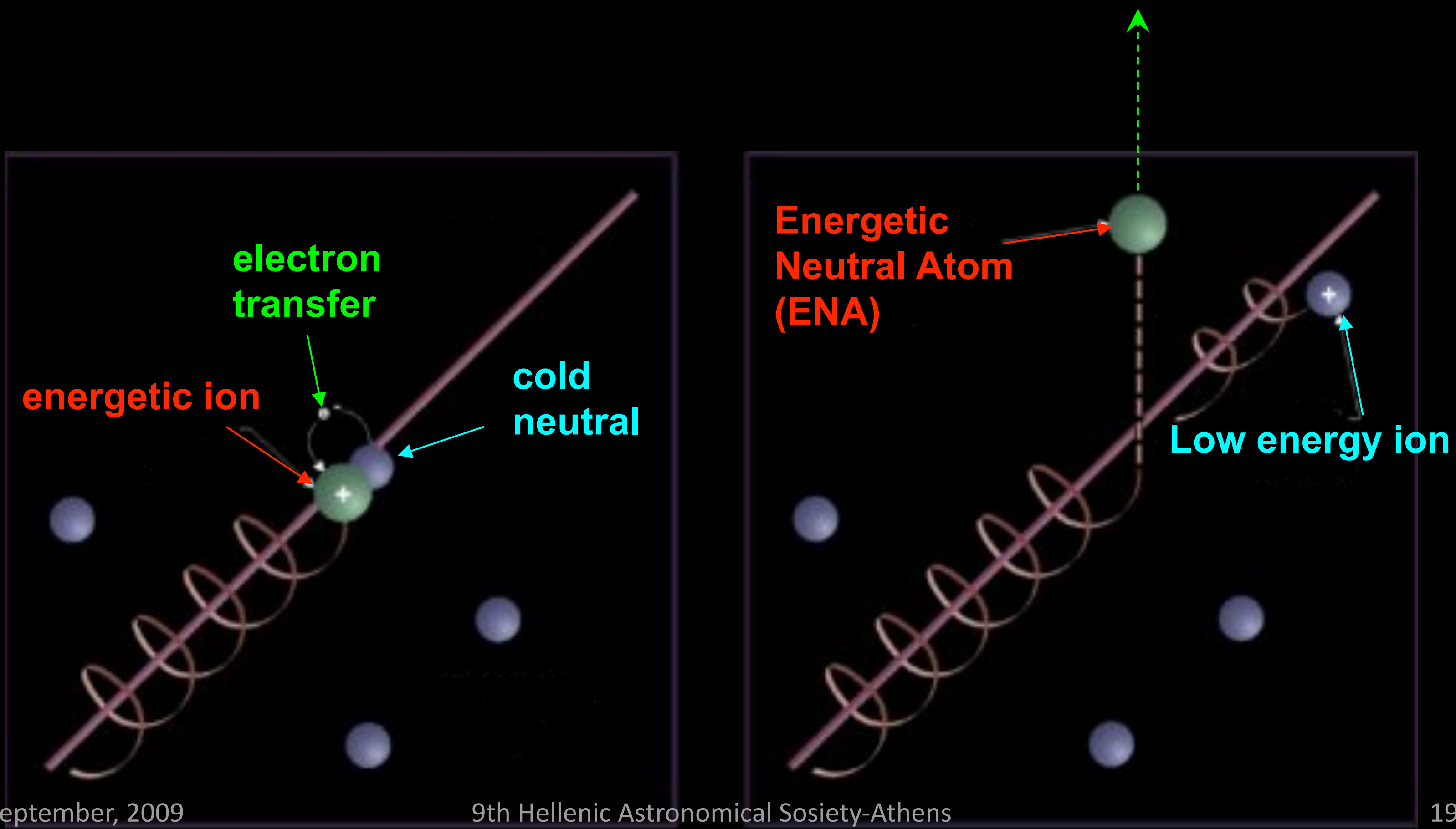


Outline

- Voyagers 1, 2 Termination Shock (TS) crossing and Galactic Cosmic Rays (GCR) in Heliosheath
- Anomalous Cosmic Rays (ACR), Termination Shock Particle (TSP) spectra, and plasma flows in Heliosheath
- ENA Heliosphere: Cassini-Belt, IBEX-Ribbon, ENA spectra and Voyager 1,2 "ground truth" measurements in the heliosheath (LECP)
- Ion pressures at the Voyagers and in the Heliosheath
- Consequences for the ISMF magnitude and direction
- Shape of the Heliosphere

Visualizing the "invisible": Energetic Neutral Atoms (ENA)





ENA (Energetic Neutral Atoms) production principle

For a singly-charged energetic ion species interacting with a cold neutral gas along a line of sight ($0<s<\infty$) from the imager:

$$j_{ENA}(E) = \sigma(E) \int_0^{\infty} ds\, n(s)\, j_{ION}(s) \exp[-\tau(s)]$$

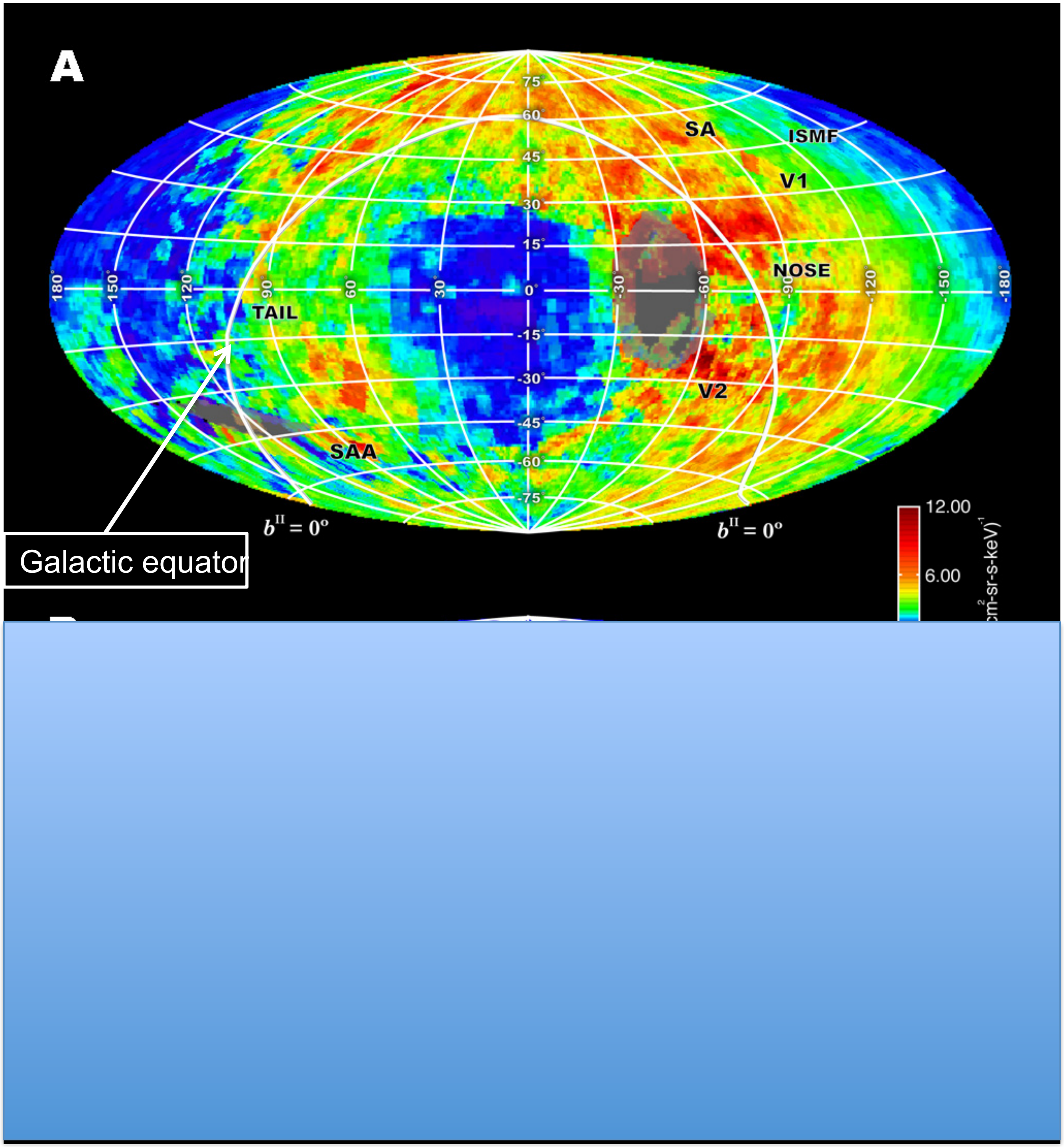
$j_{ENA}(E)$ = ENA intensity ($cm^2 srskeV$)

$j_{ION}(E)$ = Energetic ion intensity ($cm^2 srskeV$)

$\sigma(E)$ = Charge-exchange cross section (cm^2)

$n(s)$ = Cold neutral gas density (cm^{-3})

$\tau(s)$ = "Optical depth" for ionization of ENA *en route* to imager



ENA map, 5.2-13.5 keV
2003 d265 to 2009 d184

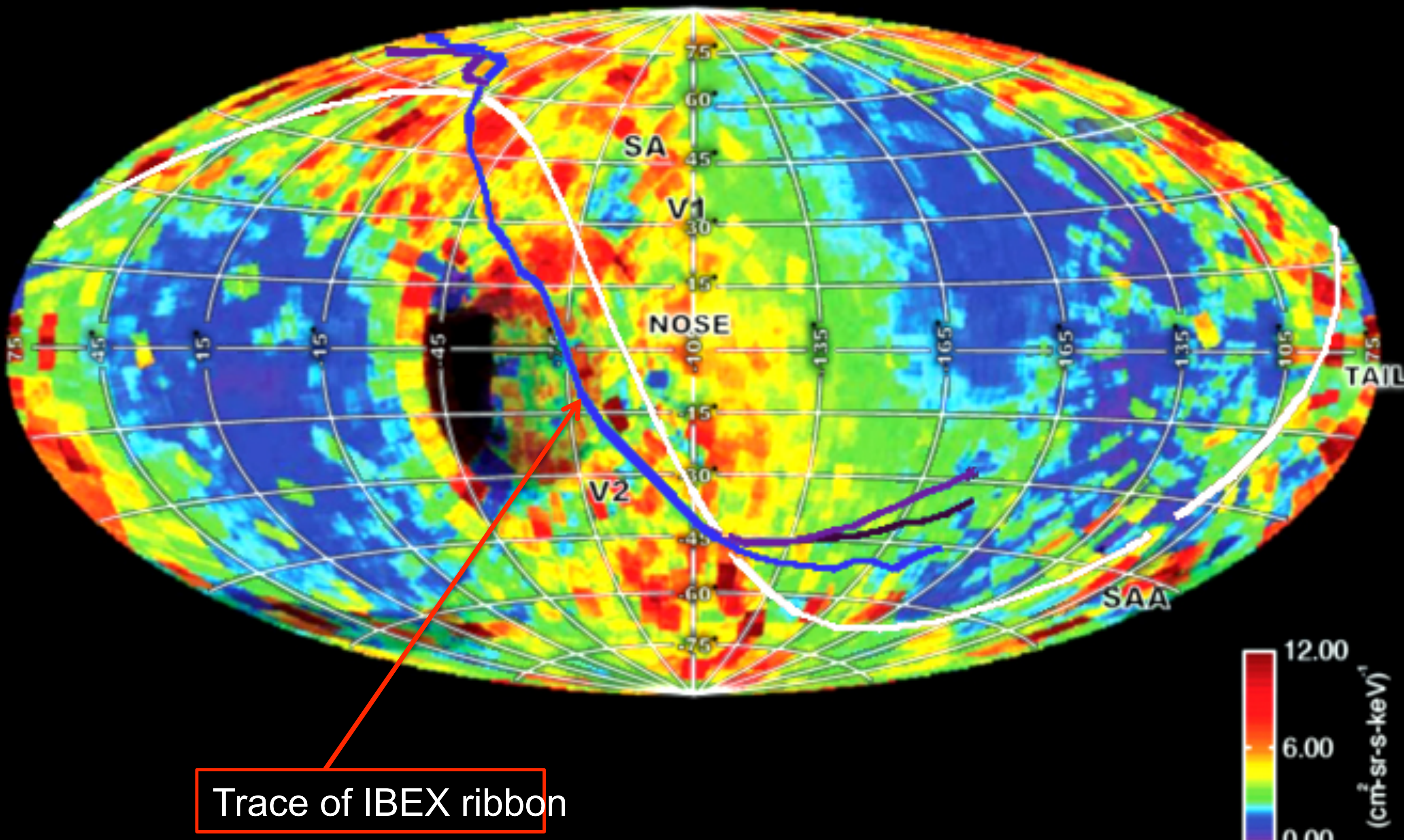
A.
Ecliptic coordinates

Belt!

B.
Galactic coordinates

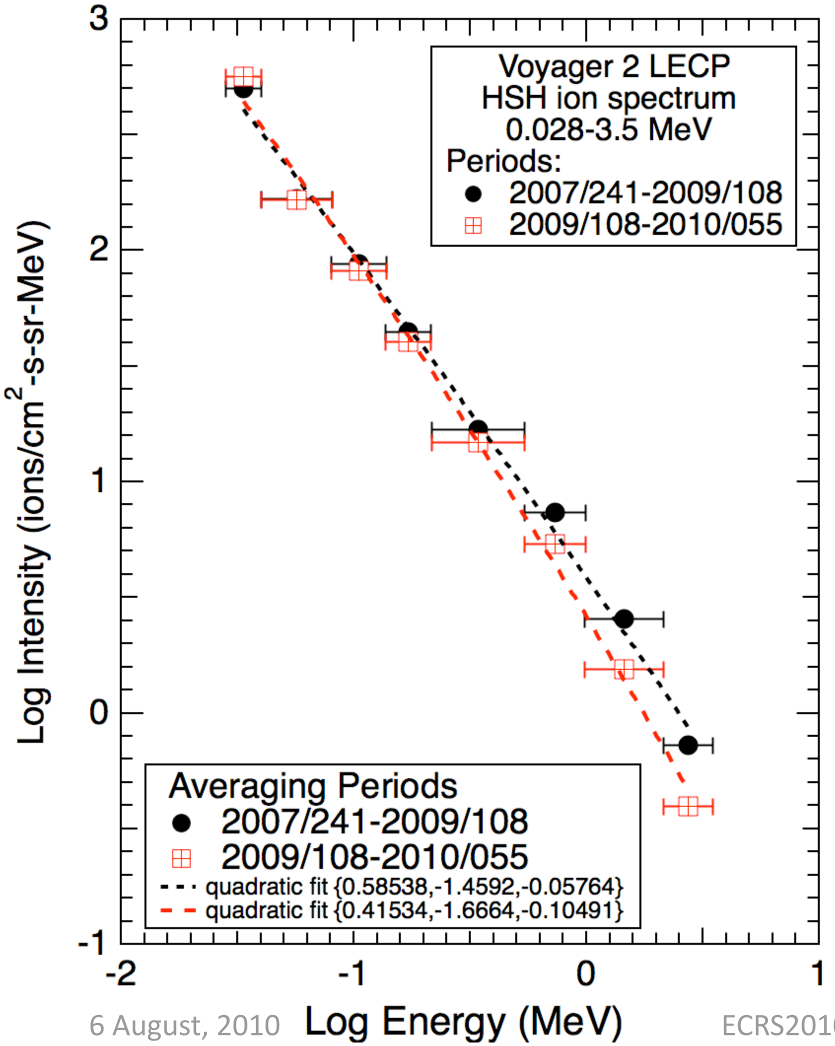
{Krimigis, Mitchell, Roelof, Hsieh, McComas, *Science Express*
(online, October 15, 2009)}

Cassini/MIMI/INCA 5.2 – 13.5keV Hydrogen ENA/(cm²-s-sr-keV)⁻¹

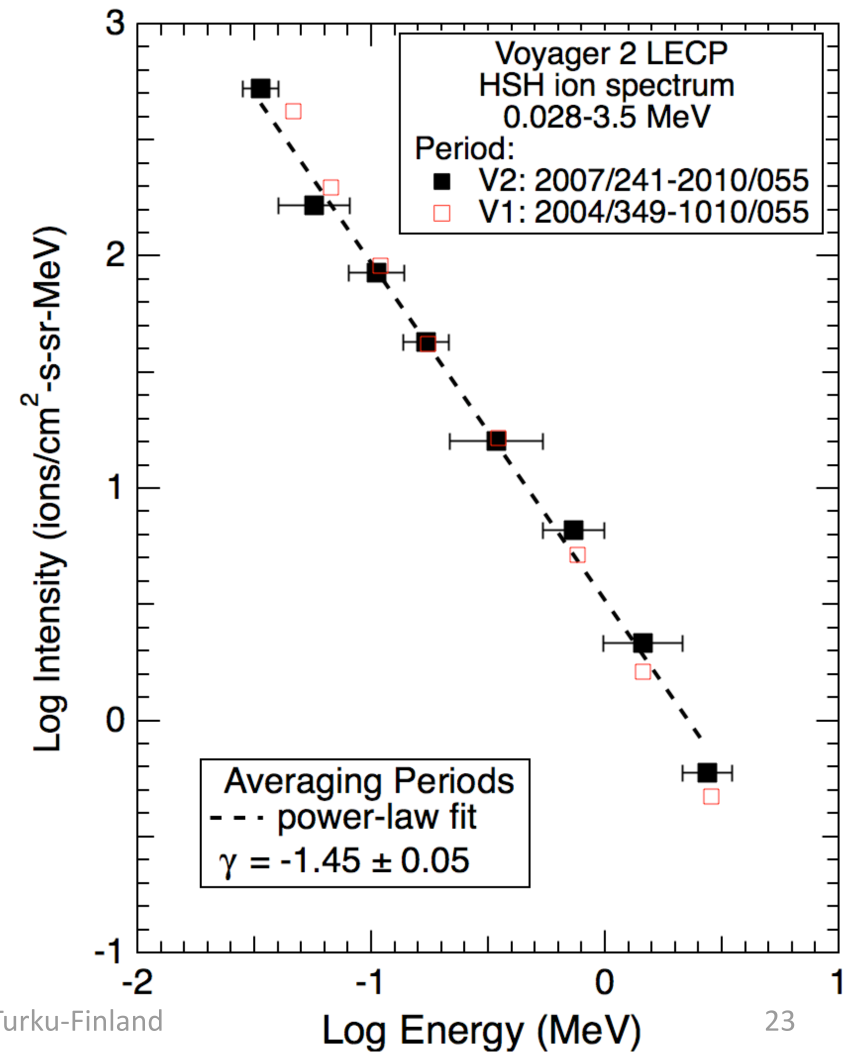


Energy spectra of ions 28 keV - 3.5 MeV at V2 in the HSH

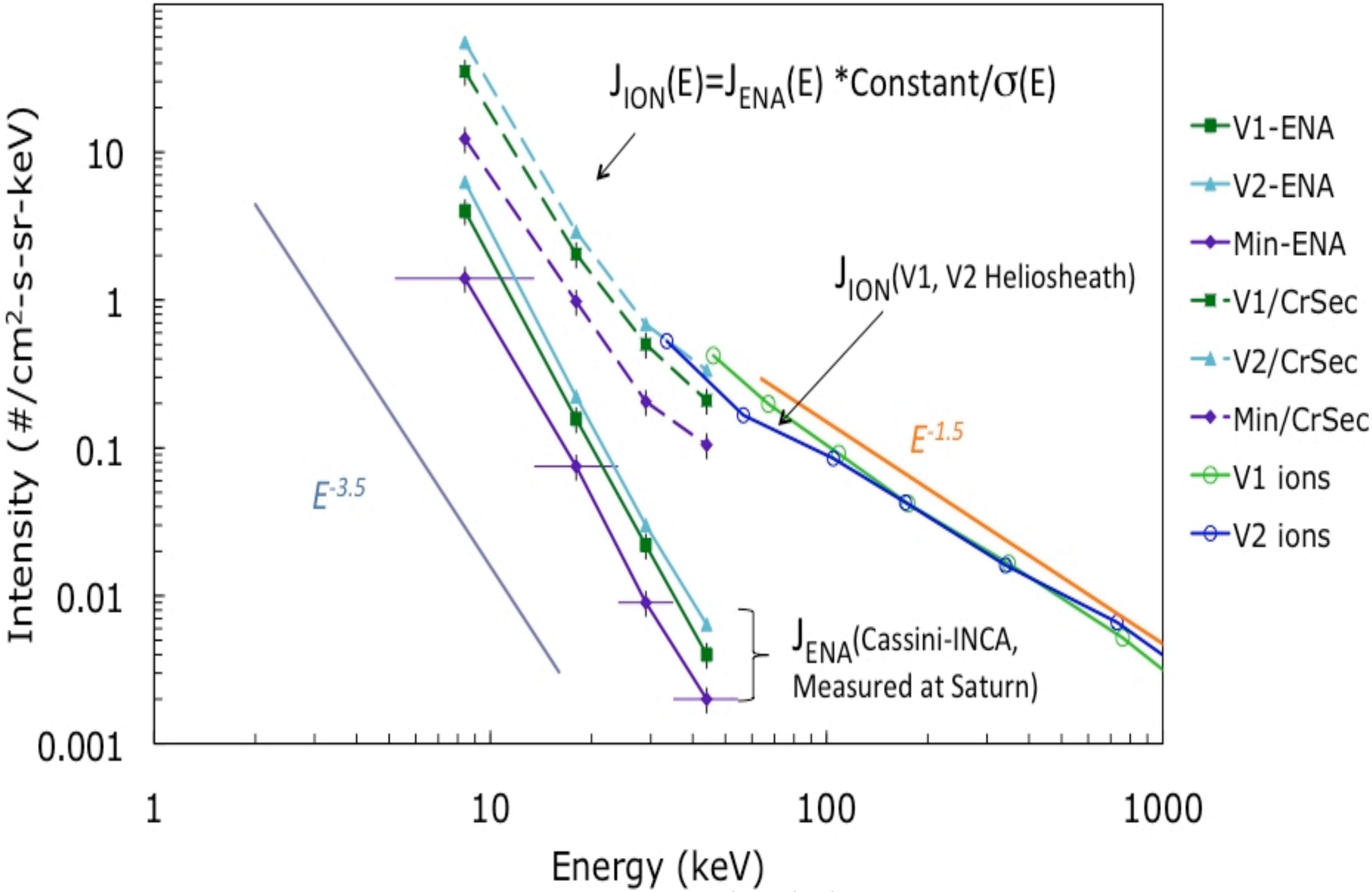
Energy spectrum before (black) and after (red) onset of large, steady, low-energy ion anisotropy on ~2009.3



Energy spectrum in HSH 2007/241 - 2010/055



ENA spectra at Cassini and "ground truth" ion intensities at Voyagers



Voyager 2 in situ measurement in the same energy band (~ 44 keV) enables estimation of Heliosheath Thickness L

$$J_{ion=} J_{ENA}/n_H \, \sigma \, L \approx (80 \pm 30) \, J_{ENA}$$

(Spectrum normalization with Voyager 2)

$$L \approx 1/80 \, \sigma \, n_H$$

For $n_H = 0.1 \text{ cm}^{-3}$
and for $\sigma = 1.53 \text{x} 10^{-16} \text{ cm}^2$ (± 20%)
(compilation by Lindsay & Stebbings, 2005)

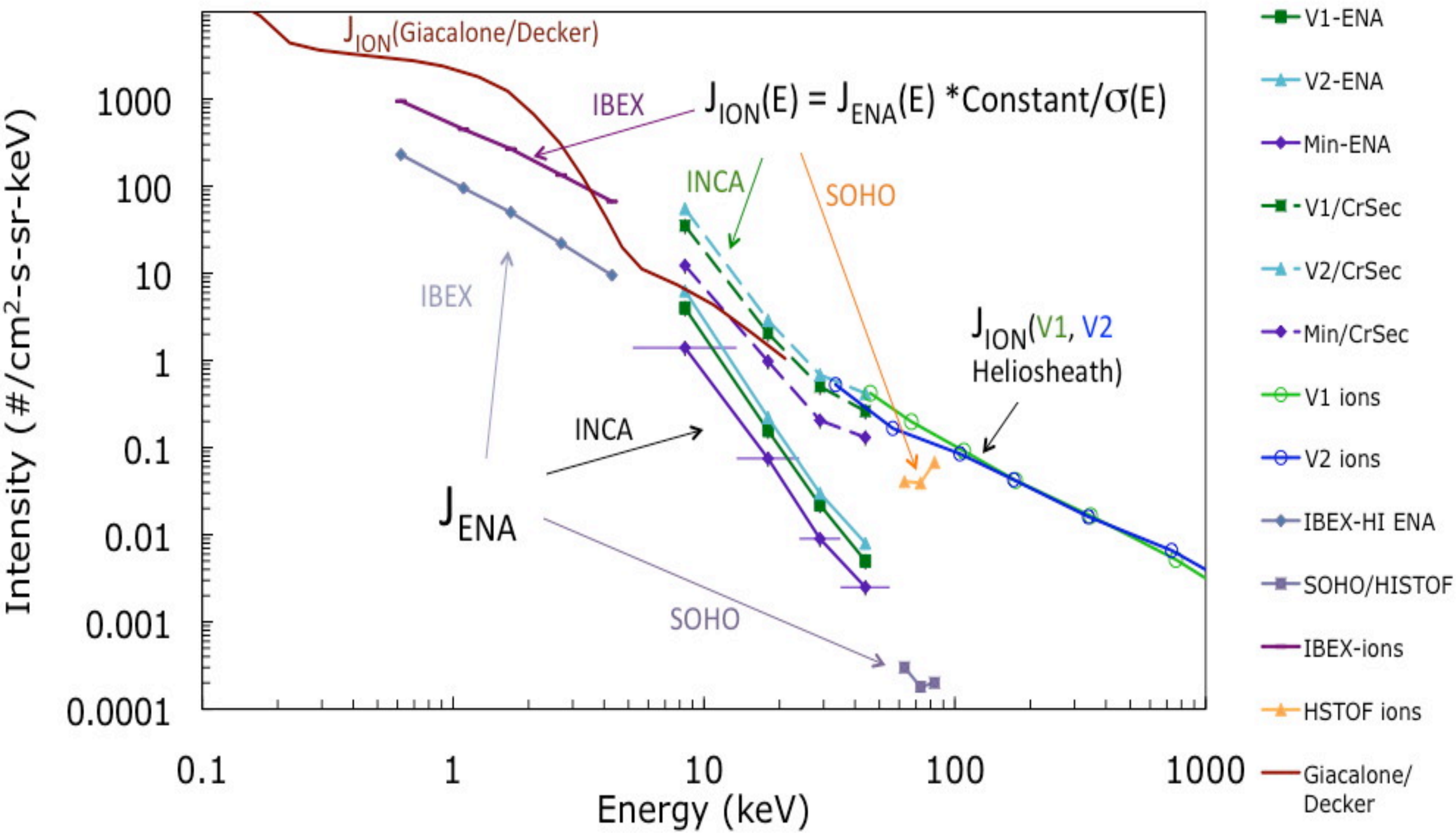
$L = 54 \, (+30, -15)$ AU

We adopt 50 AU as a nominal value for Heliosheath thickness

Outline

- Voyagers 1, 2 Termination Shock (TS) crossing and Galactic Cosmic Rays (GCR) in Heliosheath
- Anomalous Cosmic Rays (ACR), Termination Shock Particle (TSP) spectra, and plasma flows in Heliosheath
- ENA Heliosphere: Cassini-Belt, IBEX-Ribbon, ENA spectra and Voyager 1,2 “ground truth” measurements in the heliosheath (LECP)
- Ion pressures at the Voyagers and in the Heliosheath
- Consequences for the ISMF magnitude and direction
- Shape of the Heliosphere

Extended Spectra with inclusion of IBEX at < 6 keV (McComas et al. 2009) and HSTOF at > 59 keV (Hilchenbach et al, 2008)



Summary of Relevant Pressures (pPa) at VGR 2 in Heliosheath and Local Interstellar (IS) Plasma (Krimigis et al, AIP Proc. in press, 2010)

- Thermal pressure (nkT) ~ 0.005
- Hot protons (0.2 - ~6 keV) ~ 0.121^{+} (was 0.20 in Science 326, 2009)
- Hot protons (5 - 55 keV), Cassini ~ 0.077* (was 0.09 in Science 326, 2009)
- Voyager 2 protons, 28 keV - 4 Mev ~ 0.023
- Magnetic pressure ($B^2/8\pi$) ~ 0.004
- ***Total HS pressure downstream TS (P_{tot}) ~ 0.230 (was 0.310 in Science 326, 2009)***
- IS plasma stagnation pressure ($P_S=\rho V^2/2$) ~ 0.056 (was 0.11 in Science 325, 2009)
- IS thermal pressure ($P_{th}=nkT$) ~ 0.010
- IS magnetic pressure (P_B) ***

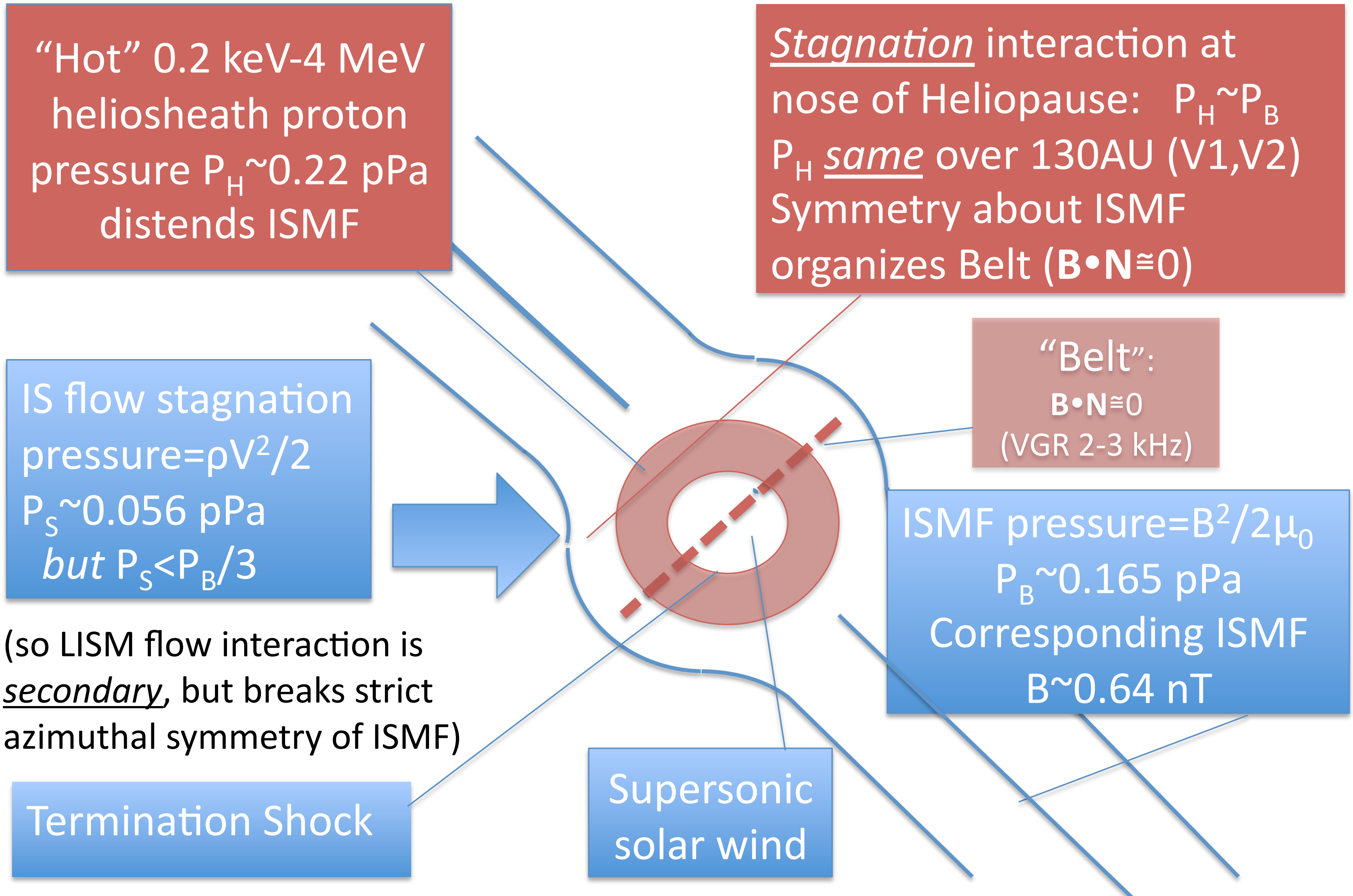
+ *Estimated from simulation (Giacalone & Decker) at Voyager 2 TS crossing; consistent with IBEX if L~50AU*
- *Assumes Cassini ENAs are generated over L~50 AU LOS normalized to Voyager 2 in situ*

*******The total HS pressure at the Nose needs to be balanced by the sum of the IS thermal pressure (P_{th}), plasma stagnation pressure (P_S), and LISM B-field pressure (P_B), so that:***

LISM B-field needed for balance: $P_B = P_{tot} - P_s - P_{th} \sim 0.165$ ➔ $B_{IS} \leq 0.64$ nT

Cox, D. & Helenius, L., Astrophys. J. 583, 205–228 (2003) estimate 0.7nT; Opher et al, Nature,2009, estimate 0.35- 0.55nT max. Pogorelov, et al, ApJ. 695, L31, (2009), estimate ~0.4nT

Update of adaptation of Parker (1961) model to Cassini ENA findings (adapted from Krimigis *et al*, 2009)



Parker (1961)original —*TWO MODELS!*

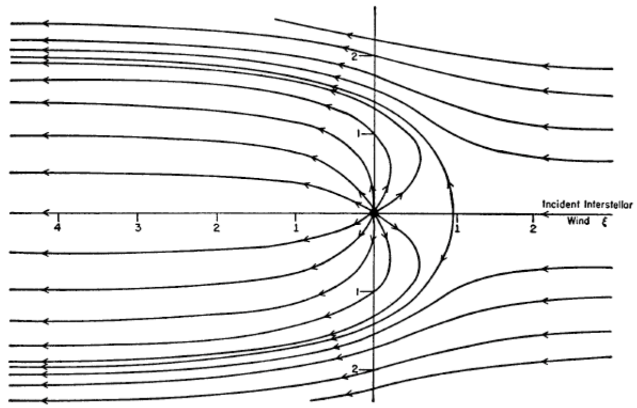


FIG. 1.—The streamlines of the subsonic, nearly incompressible, hydrodynamic flow of a stellar wind beyond the shock transition ($r = R$) in the presence of a subsonic interstellar wind carrying no significant magnetic field.

Subsonic **heliosheath** flow
(beyond SW termination shock)
Subsonic interstellar wind
Negligible interstellar magnetic field

"Comet" interaction with "tail"

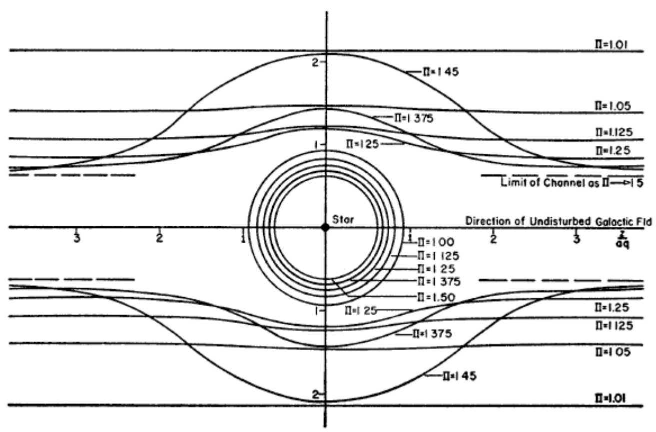
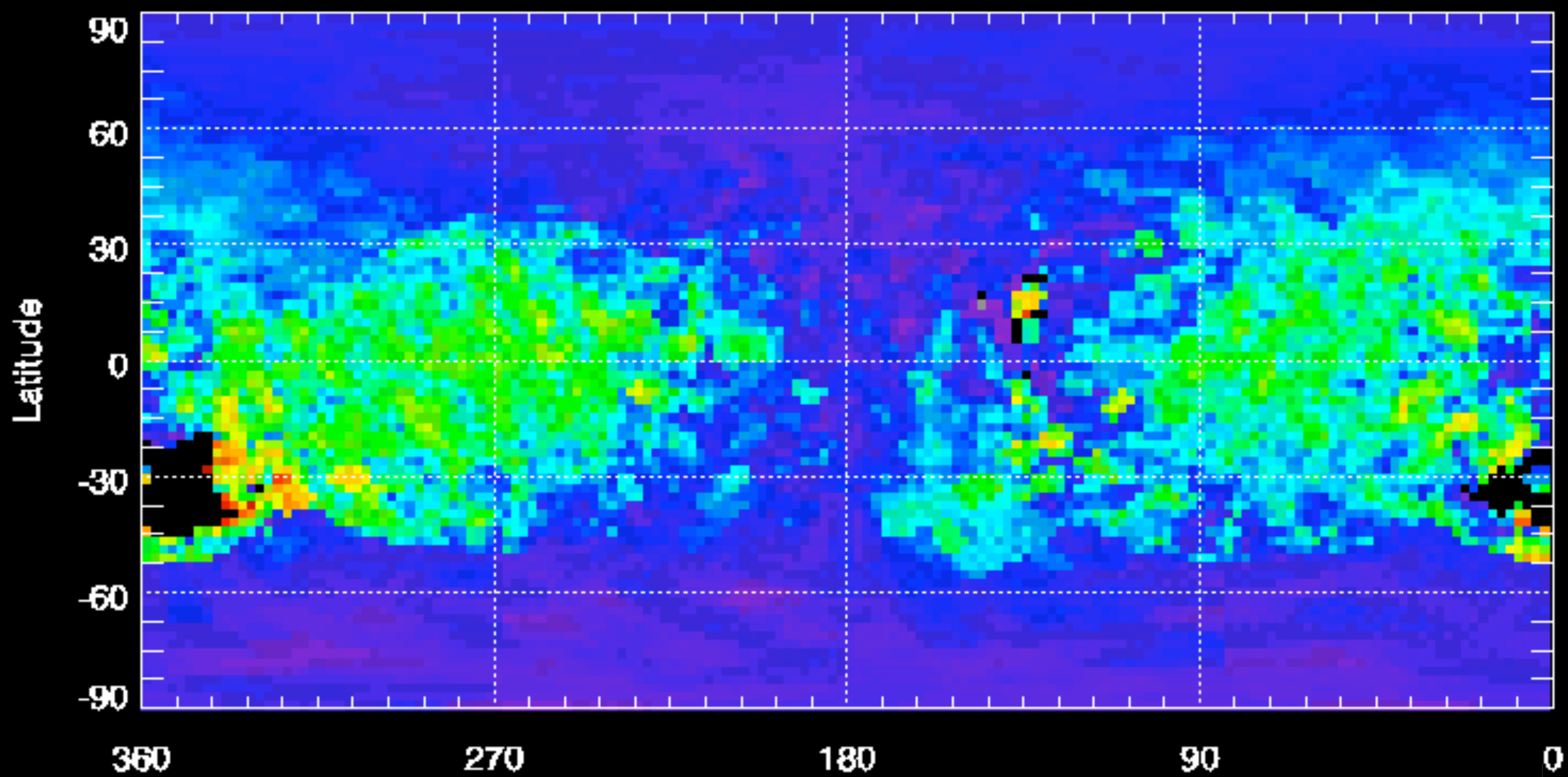


FIG 3 —The shock transition $r = R$, shown by the concentric circles, and the outer boundary of the stellar-wind region in the presence of a large-scale interstellar magnetic field, for various values of the stagnation pressure at infinity.

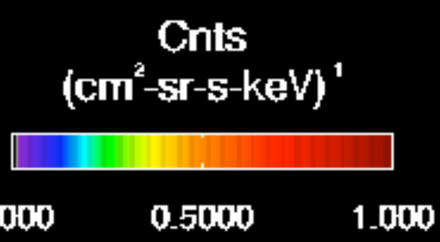
Outer boundary of **heliosheath**
(beyond SW termination shock)
Large-scale interstellar magnetic field

"Bubble": Exhaust flows, no "tail"

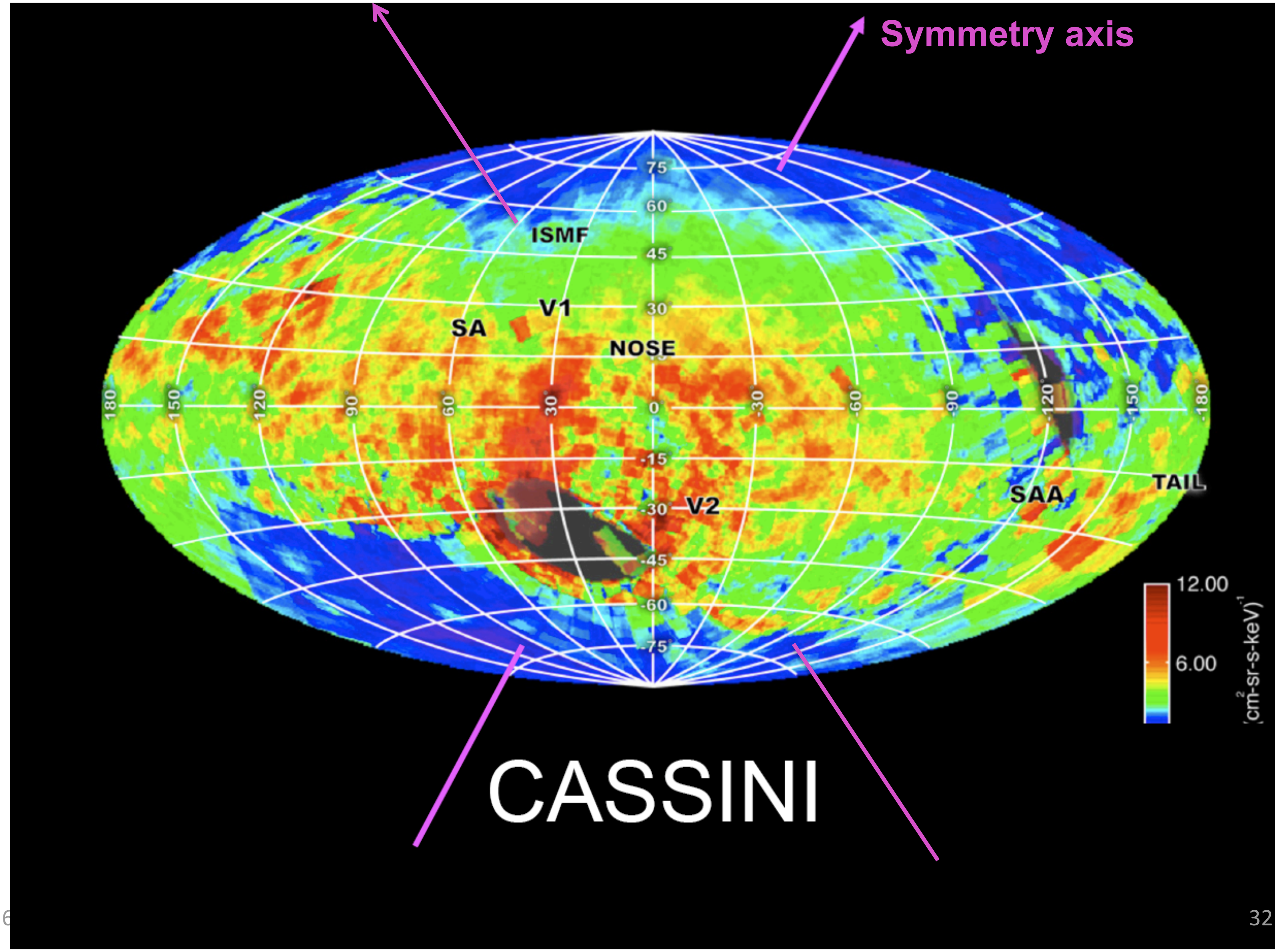
INCA 13.5 - 24 keV Hydrogen, 2003 - 2009



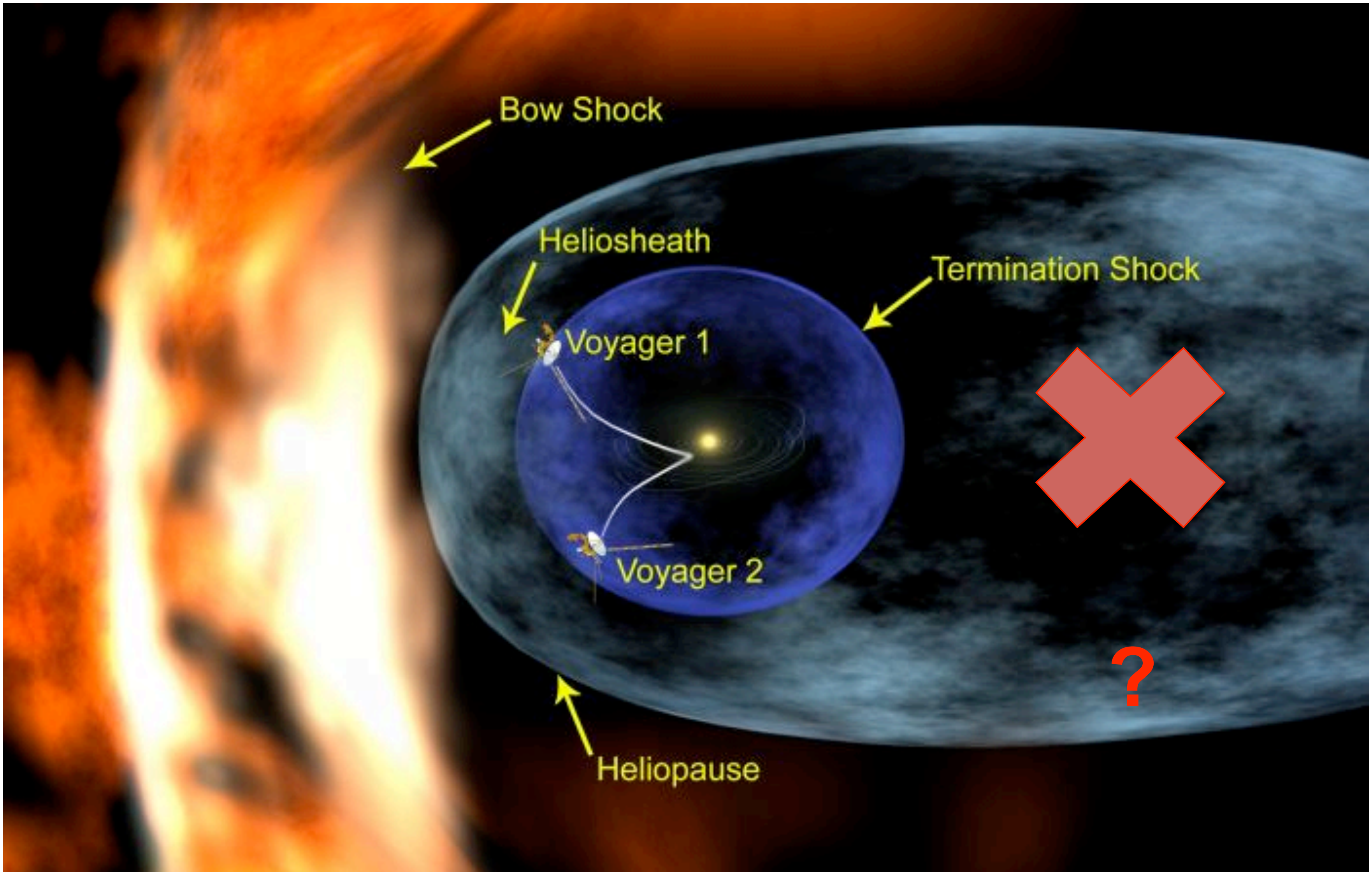
IF B•n =0,
what should the Rotation angle of B to minimize deviation from equator?
North Pole at 190, 15 Ecliptic (compare IBEX-Hi 221, 39)



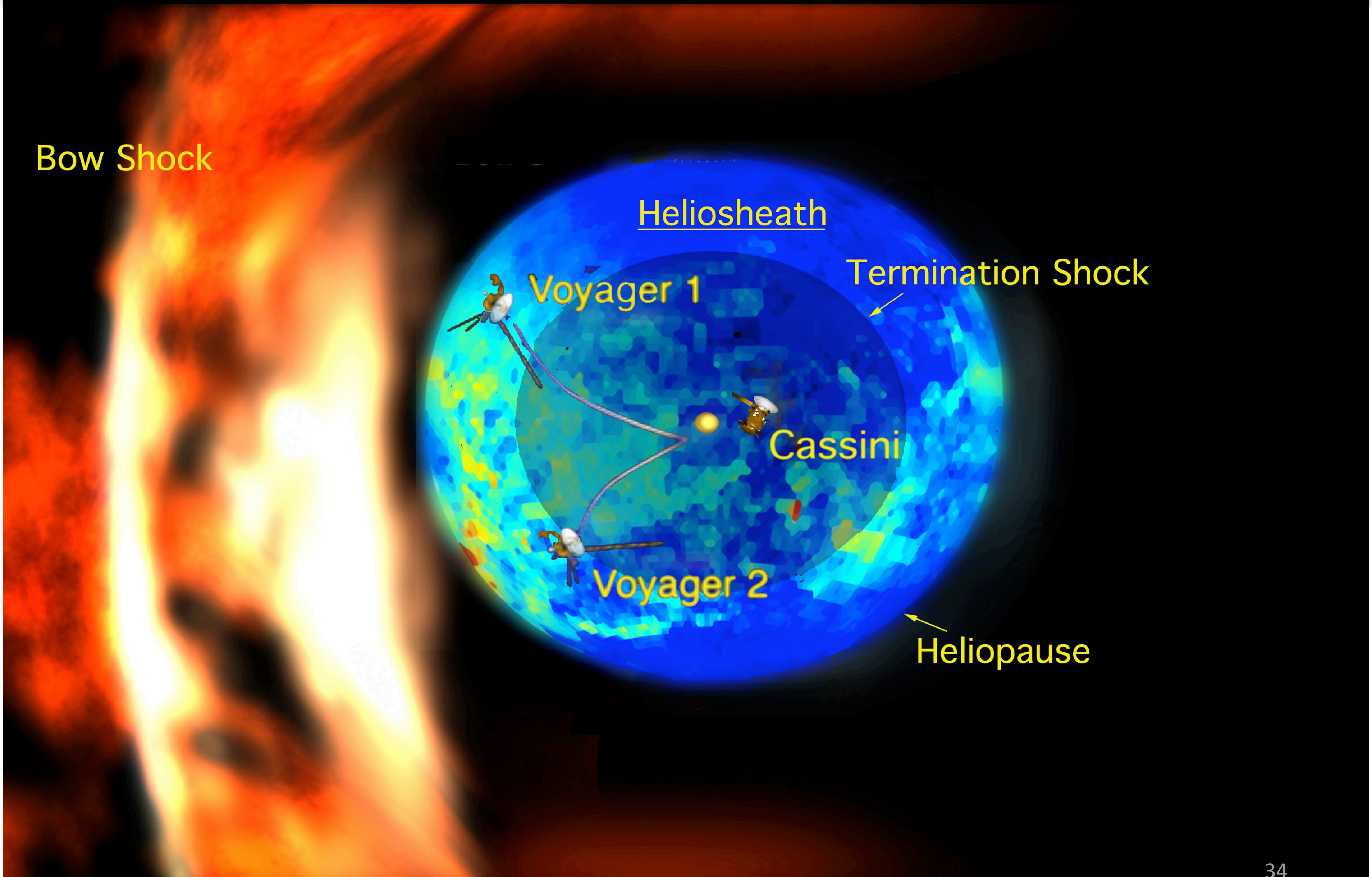
What is the direction of the ISMF? Estimate from the MIMI/INCA data Require that Belt be symmetric, i.e.(Lon -95°, Lat 70°, galactic))



Artist's Concept of Heliosphere and Trajectories of Voyagers 1, 2: Still the same?



A more plausible concept of the Heliosphere



Summary and Conclusions

- The Heliosheath (HS) is a reservoir of energetic particles (E > 28 keV) with steady-state intensities similar to those seen near 1 AU in 77-79. The proton spectra at the two Voyagers are nearly identical, even though V1, V2 are separated by ~ 126 AU
- Galactic cosmic rays (GCR) are apparently not modulated in the HS
- Anomalous cosmic ray (ACR) acceleration site is not at the TS, since intensities did not peak there and continue to increase as V1 moves deeper into the HS, suggesting a source distributed over the HS and closer to the heliopause (HP)
- The radial component of HS plasma $V_R \approx 0$ at V1, while the tangential component $V_T \approx -50$ km/s is constant
- Using the ENA "Belt" discovered by Cassini/INCA at E > 5 keV, HS proton spectra (5 < E < 55 keV) in absolute physical units are determined from overlapping energy channels with in situ measurements (E > 28 keV) from Voyagers 1, 2
- Concomitant estimate of heliosheath thickness based on Voyager "ground truth" measurements (no assumptions) is ~ 50 AU, for interstellar hydrogen densities of ~ 0.1 cm^{-3}
- Pressure at TS crossing of Voyager 2 is dominated by accelerated PUIs, with comparable contributions above and below ~ 5 keV
- PUI pressure is probably balanced by the local interstellar magnetic field at a value < 0.64nT. The local interstellar plasma flow is likely of lesser importance, since there is no obvious spatial signature
- Consequently, the shape of the heliosphere overall is not comet-like but more like a bubble (Parker, 1961)