Observation of suprathermal neutral atom fluxes with SOHO/CELIAS and the thickness of the heliosheath

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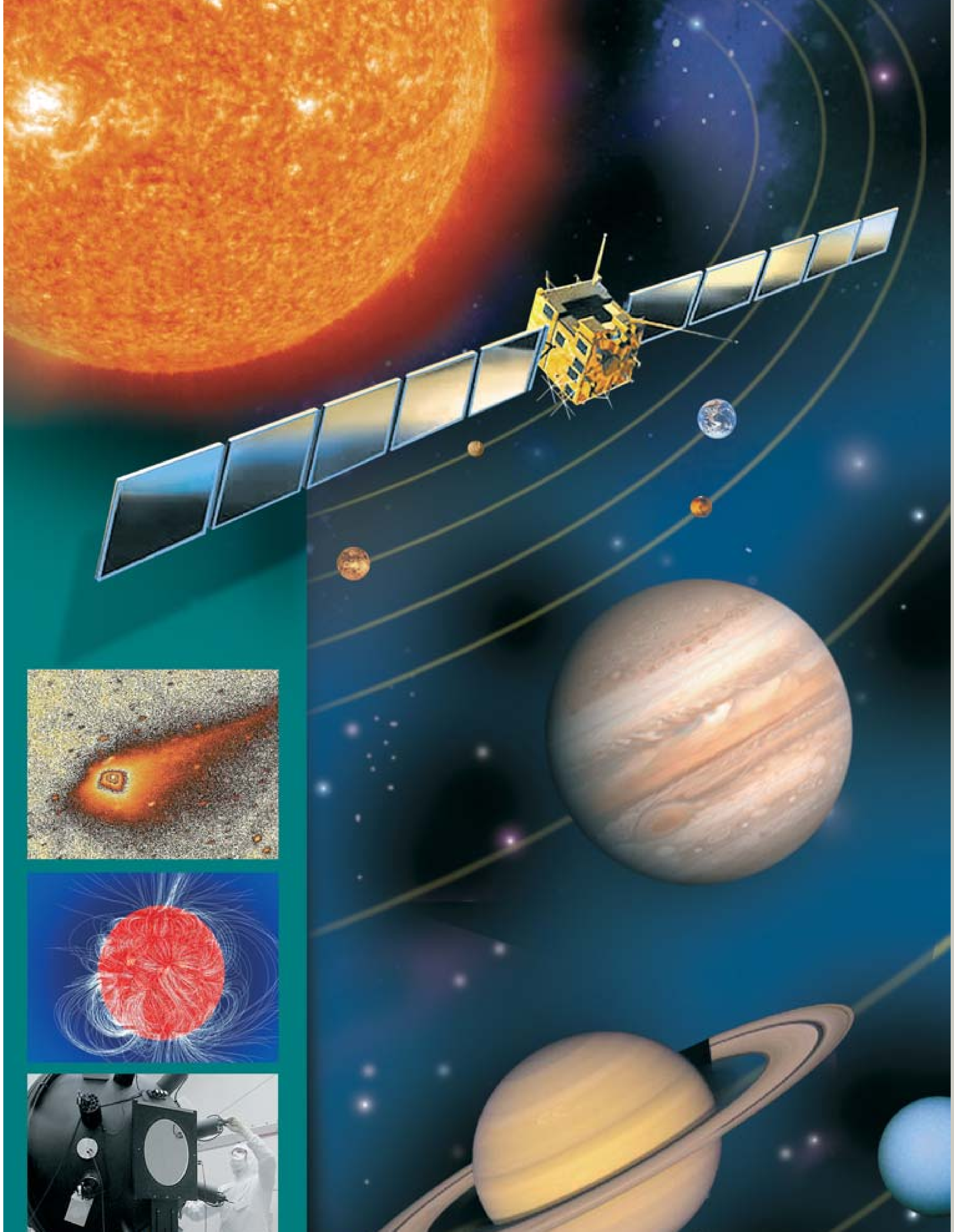

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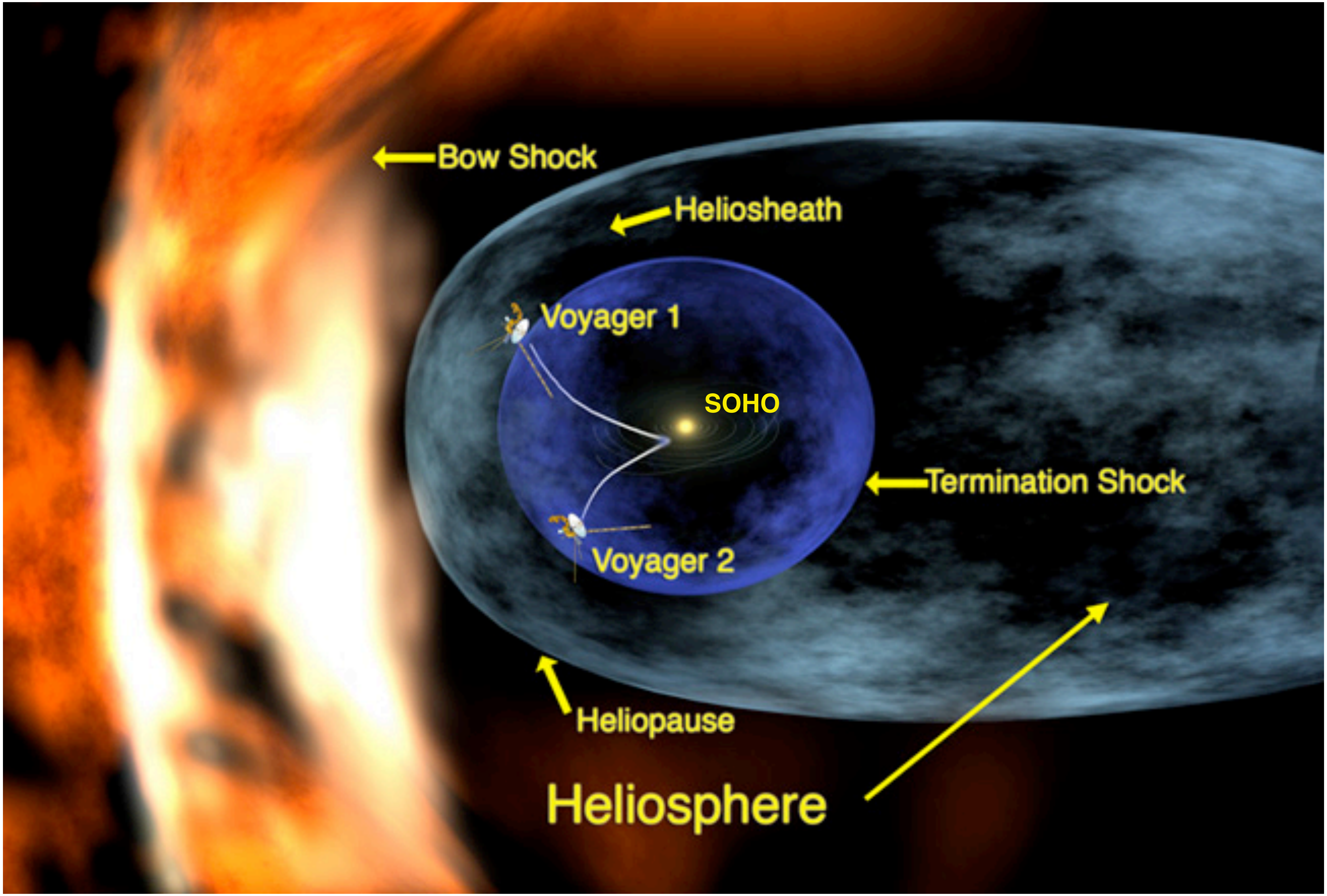
Bow Shock
Heliosheath
Voyager 1
SOHO
Termination Shock
Voyager 2
Heliopause
Heliosphere

Overview

- The local environment of the solar system
- Suprathermal energetic ions and neutral atoms in the inner and outer heliosphere
- CELIAS/HSTOF: an in-situ particle instrument onboard SOHO
- Energetic neutral atoms observed in the inner heliosphere
- Thickness of the heliosheath
- Actual Voyager V1 data
- Within and beyond the heliopause: Comets and the heliosphere

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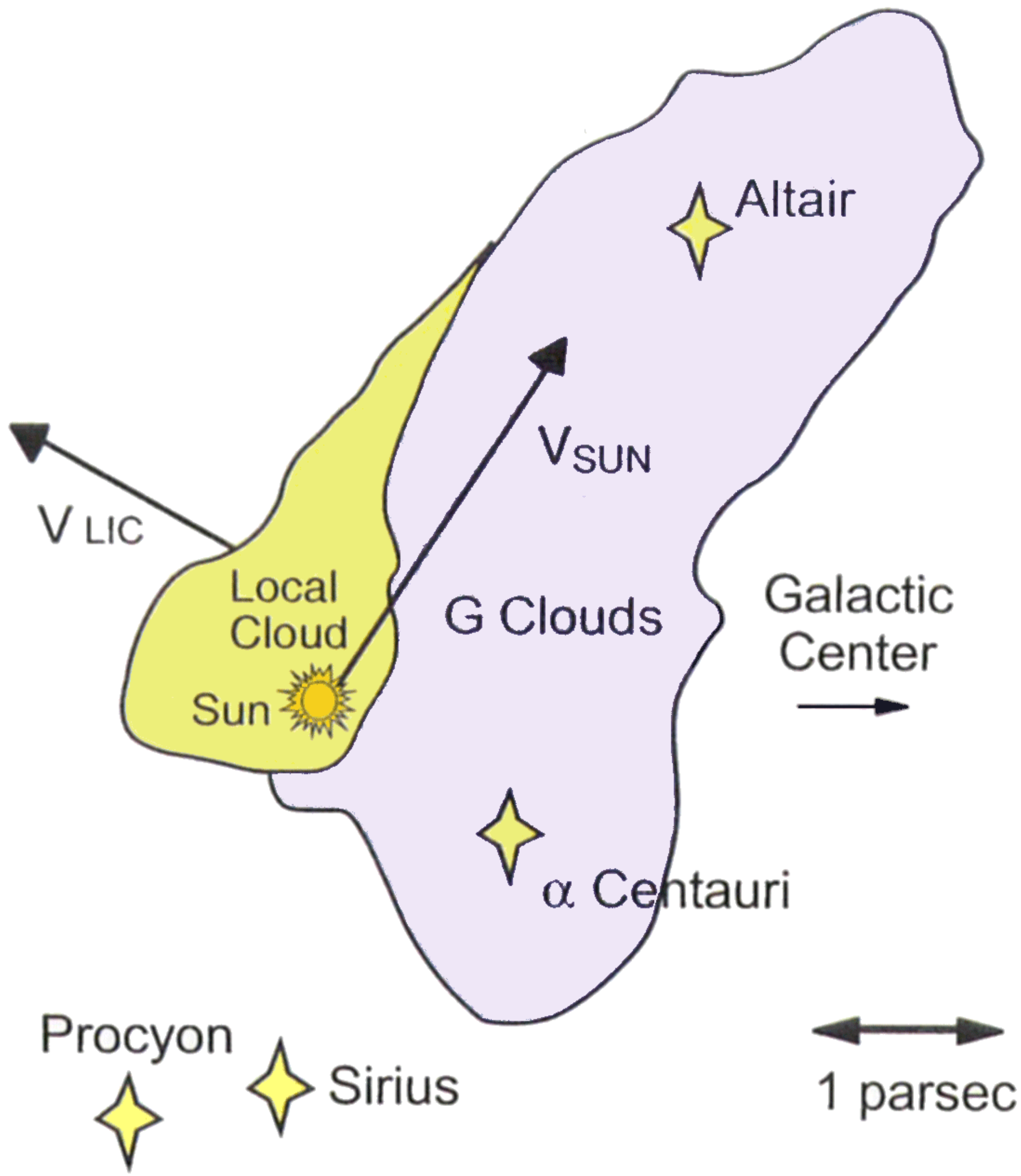
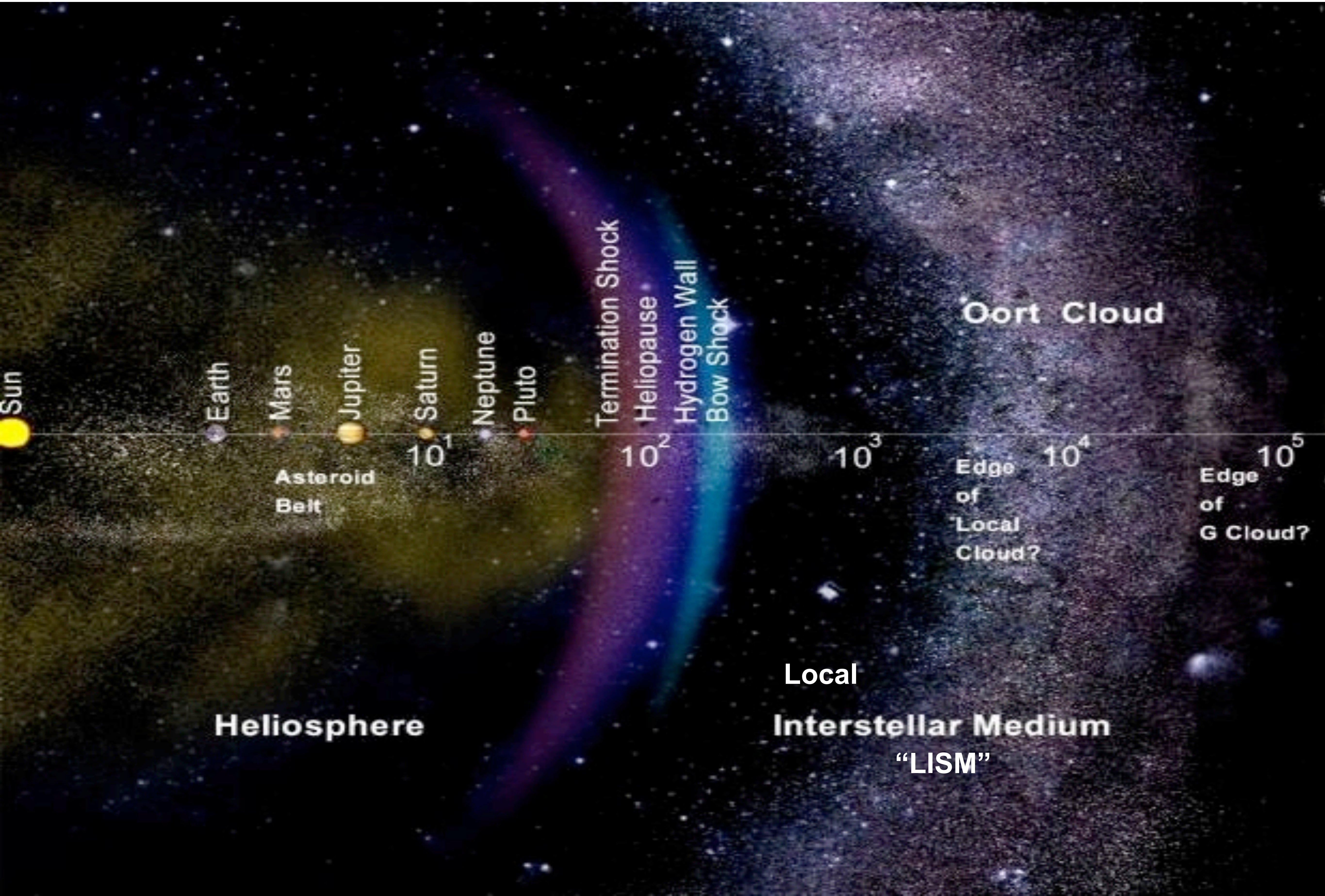
Map of the Local Interstellar Cloud

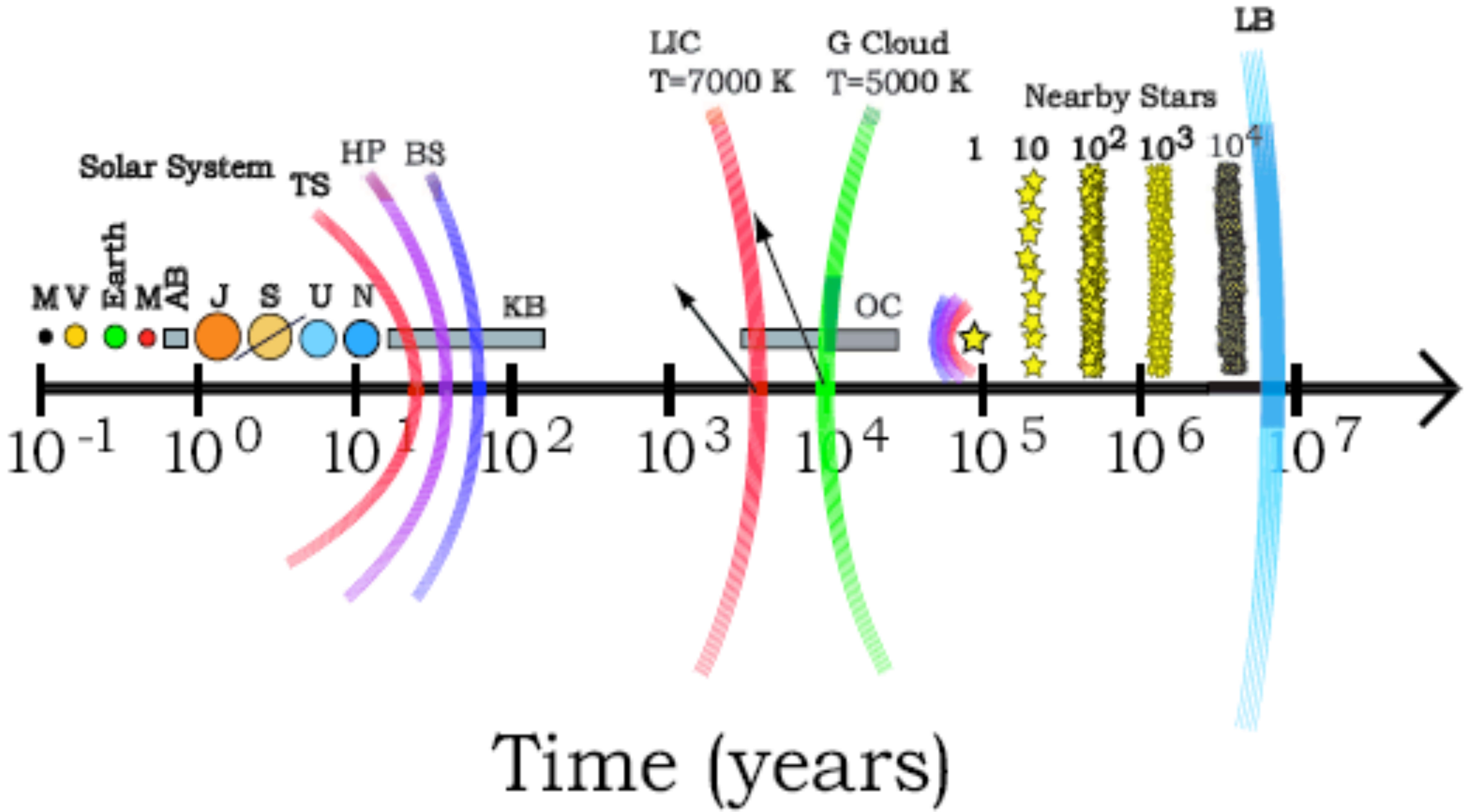


Frisch 1998

Solar system regions



Local environment in time frame



Redfield 1998

History: Passages of solar system through ISM

Table 1: Solar movement in the ISM

Time (yBP)(a) Start	End	dT (y)	Region	Den. (cm^{-3}) (Temp (K))	Comments(b)
0	$1.0\ 10^4$	$1.0\ 10^4$	fluff	0.08 (7000)	Size 5 pc, From SCA, moving in orthogonal direction to Sun 20 km/s B= 1.5 μG. Highly Inhomogeneous (1
$1.0\ 10^5$ (a)	$3.1\ 10^5$	$6.0\ 10^3$	SN(?)	4 (104)	Geminga? (2,3)
$1.0\ 10^4$	$1.0\ 10^5$	$(0.1\text{-}1)10^5$	bubble	0.04 (106)	Expanding bubble from SCA. Age 15 My vel $\approx 4\ 10^4$ km s^{-1} orthogonal to Sun B 1.5 μ G crossed the Sun 250,000to 400,000 y ago (1,3,4,5)
$1.0\ 10^5$	$1.0\ 10^7$	$(0.01\text{-}1)\ 10^7$	Inter-arm	0.0005 (100)	(1,6)
$1.0\ 10^7$(a)	$2.5\ 10^7$	$3.0\ 10^6$	HI shock	4 (10^4)	From Gould belt (7). Duration is taken as that for the earlier SN.(3,6)
$2.5\ 10^7$(a)	$4.0\ 10^7$	$5.0\ 10^5$	Orion belt	10^4 (10)	Size 5pc, Sun must have 5 10^5taken yrs to cross at current velocity (7,8)
$4.0\ 10^7$	$5.0\ 10^7$	$(2.5\text{-}4)10^7$	inter-arm	0.005 (10)	(6)
$5.0\ 10^7$	$6.0\ 10^7$	$(4\text{-}5)10^7$	Persius arm	1 (1000)	Duration uncertain(6)
$\leq 6\ 10^7$					(9)

(a) For SN the start and end time are the interval between which the SN spike crossed the earth (b) Bracket numbers in comments refer to notes.

References: 1 Frisch (1995); 2 Ramadurai(1993); 3 Sabalska et al(1991) 4 Egger et al(1996) 5 Van der Walt and Wolfendale (1988) 6 Bash (1987) 7 Clube and Nupier (1984)

Vahia 2004

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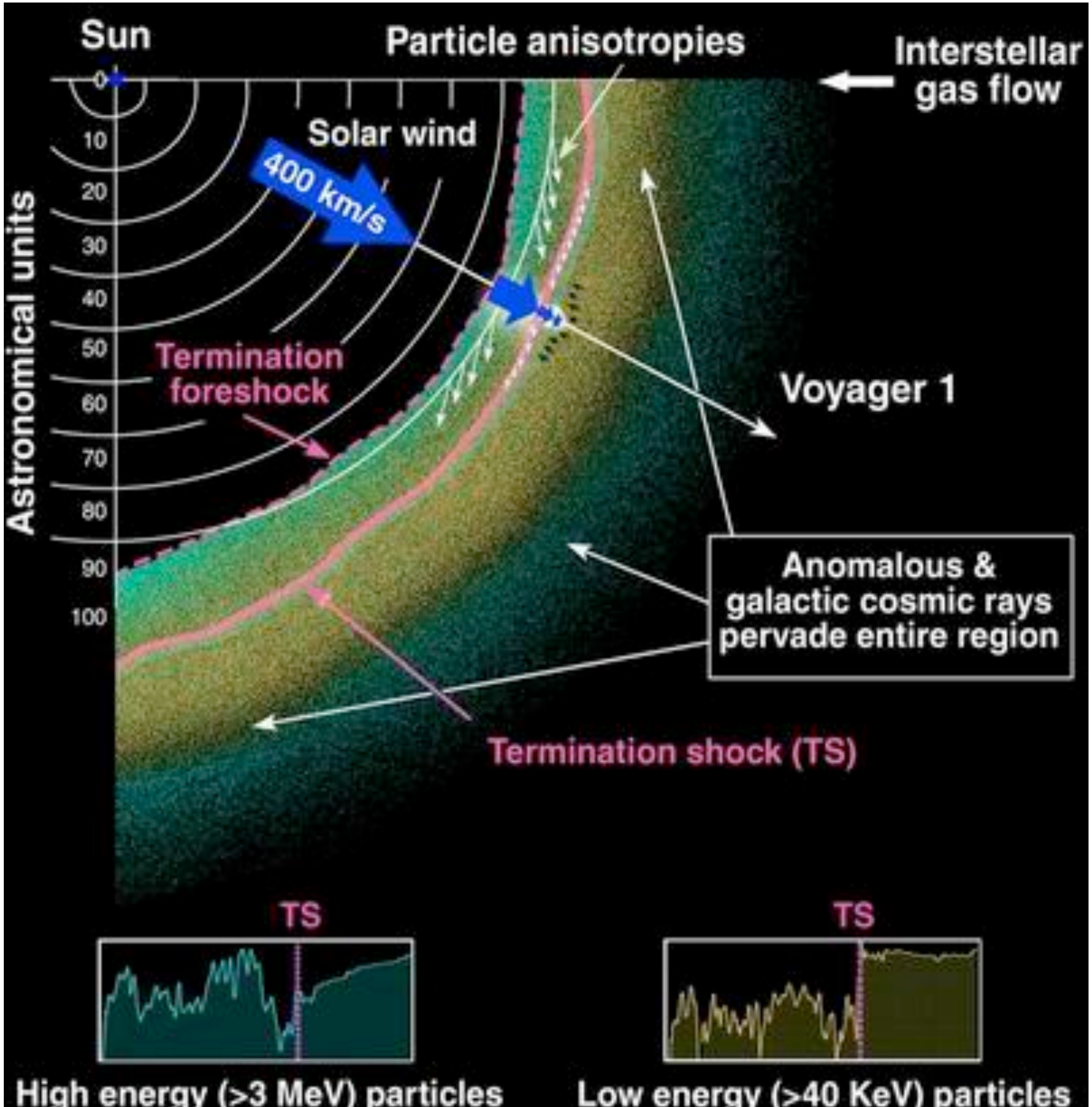
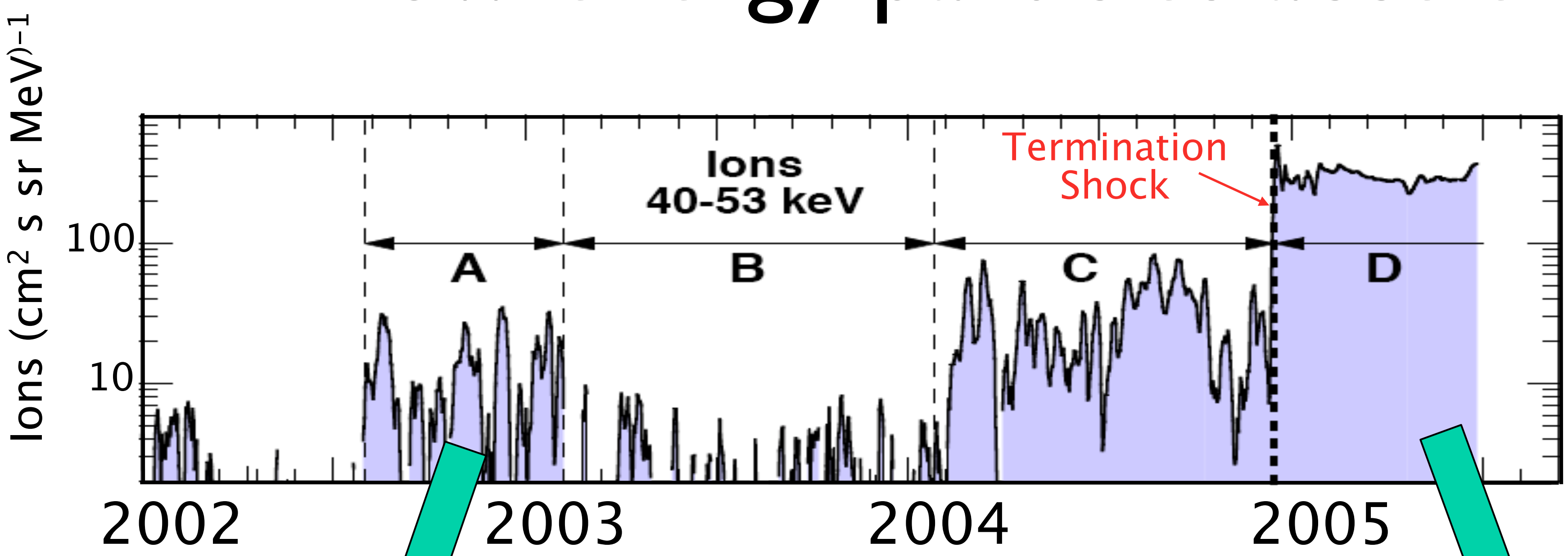
Voyage to the edge of heliosphere ...

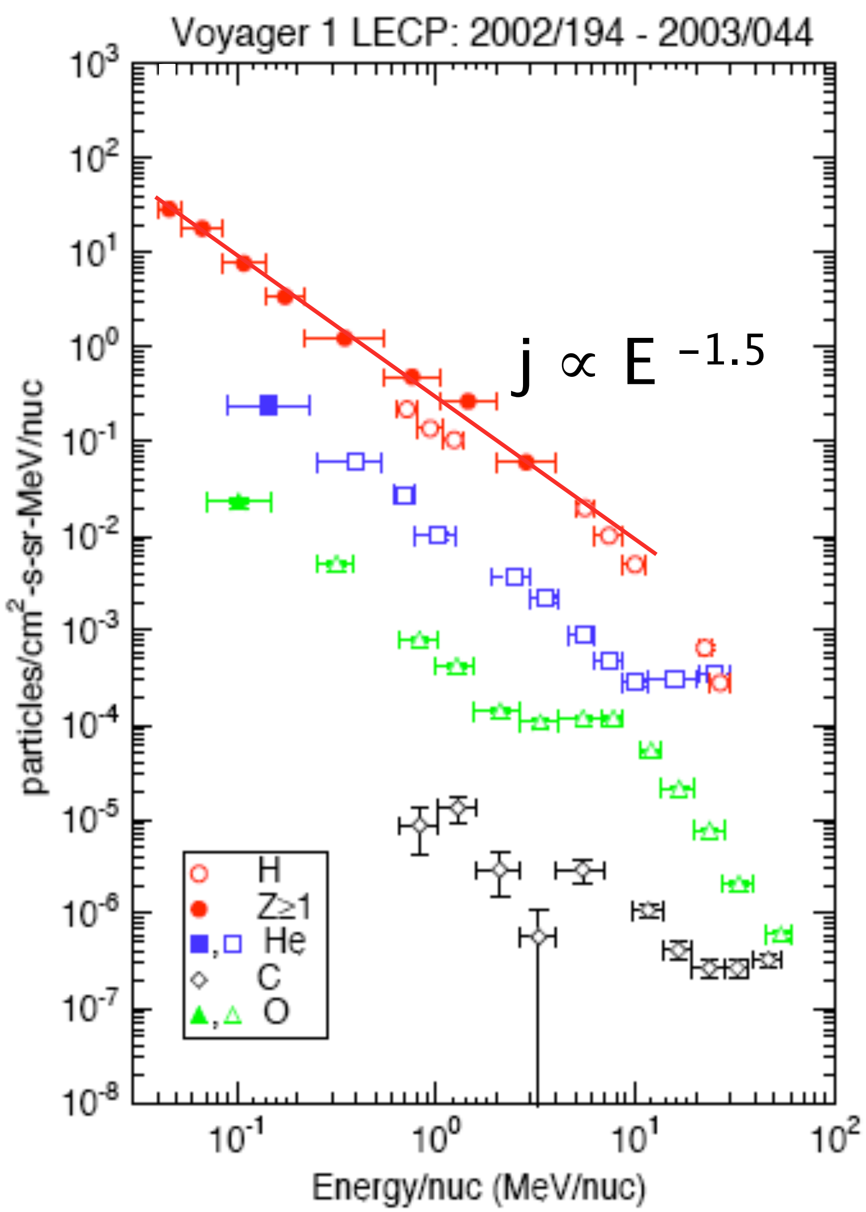


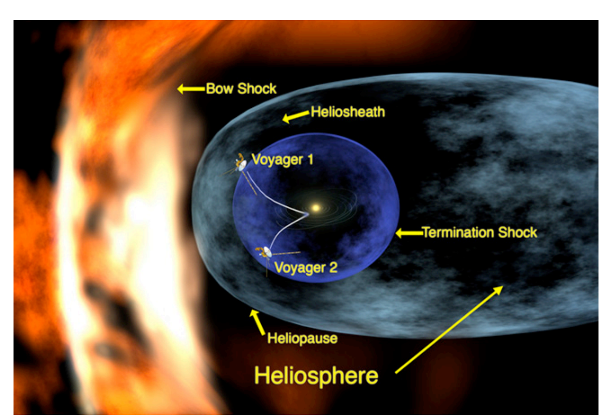
Decker 2005

Low-energy particles accelerated at TS

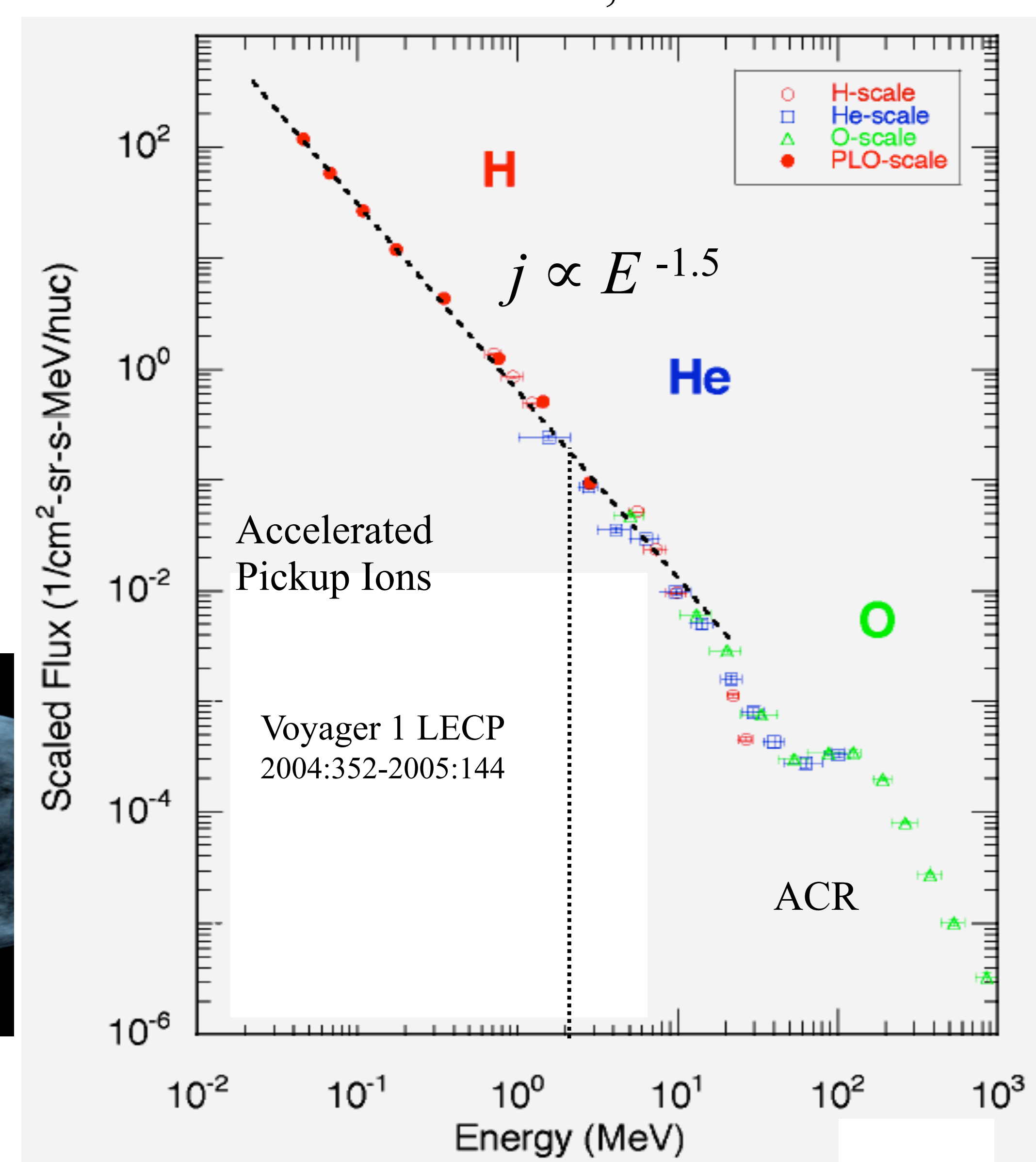


Anomalous Cosmic Rays are not accelerated at the Termination shock where Voyager 1 crossed it

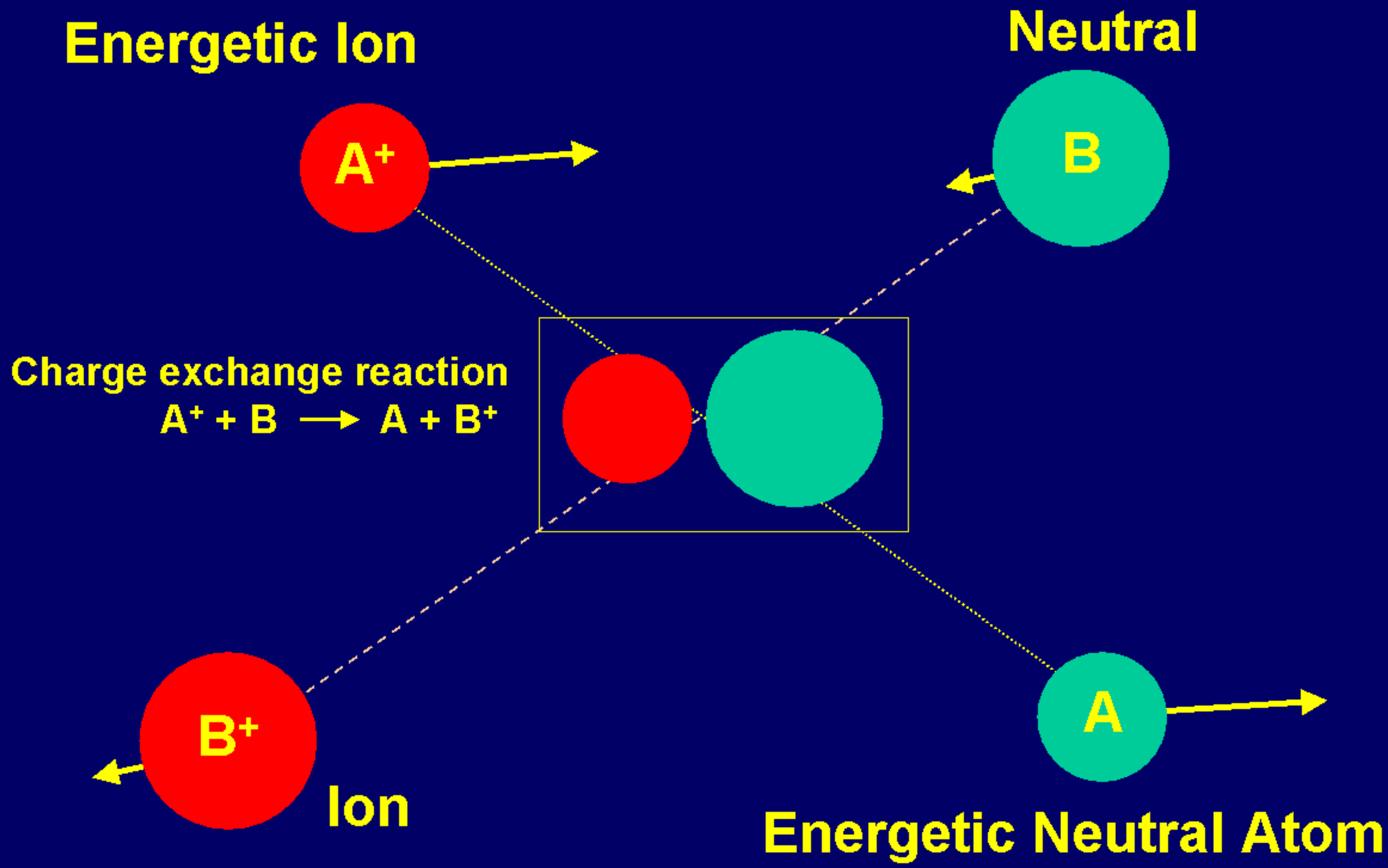




Decker et al., 2005

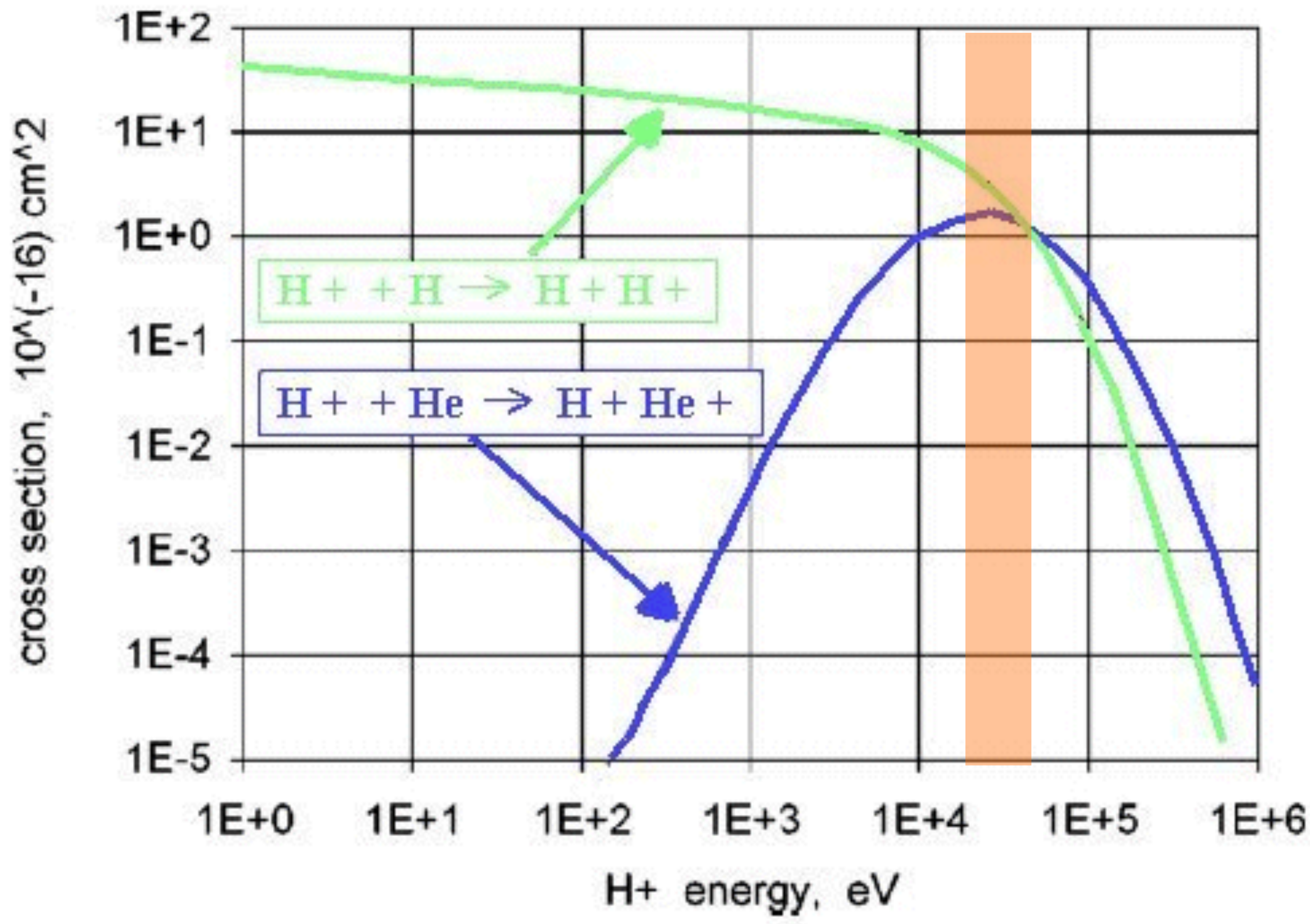


Origin of energetic neutral atoms



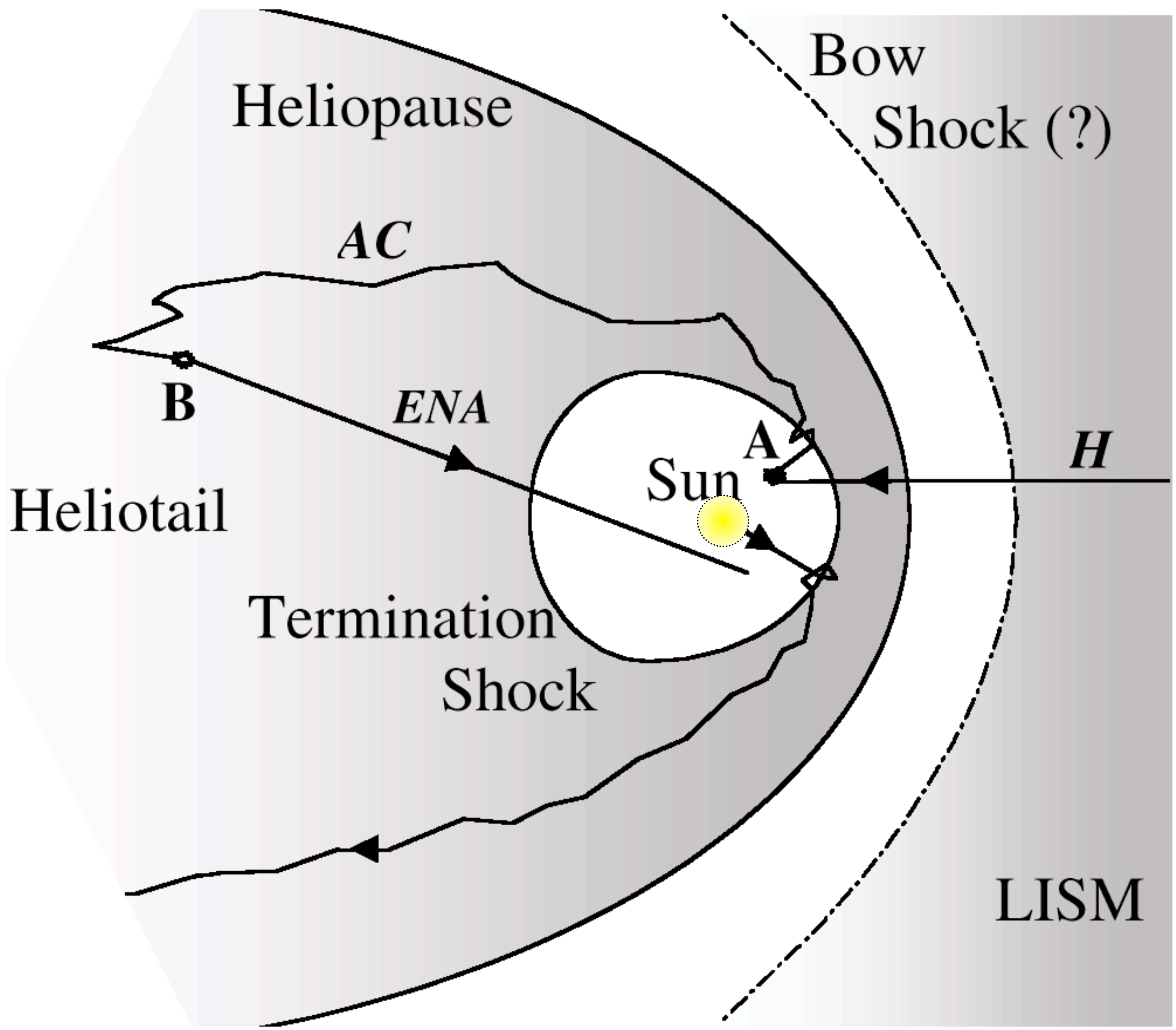
H^+ Charge Exchange Cross Sections

In the energy region of interest - 58 to 88 keV - the cross sections of protons with hydrogen and helium are very similar!

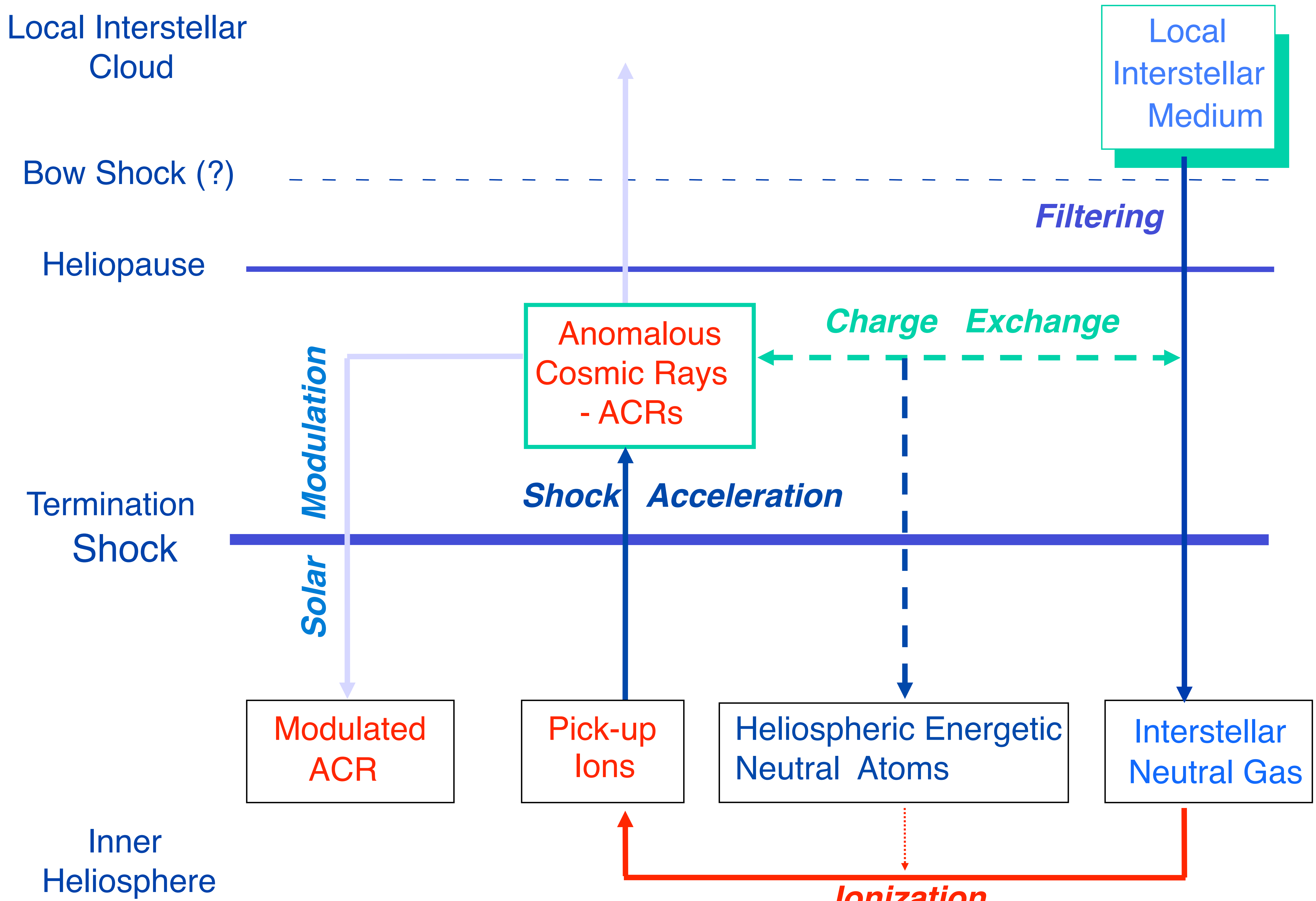


Gruntman 1997

Energetc neutal atoms (ENA) and the Heliosphere



Solar Neighborhood Recycling of Particles



Hsieh 2002

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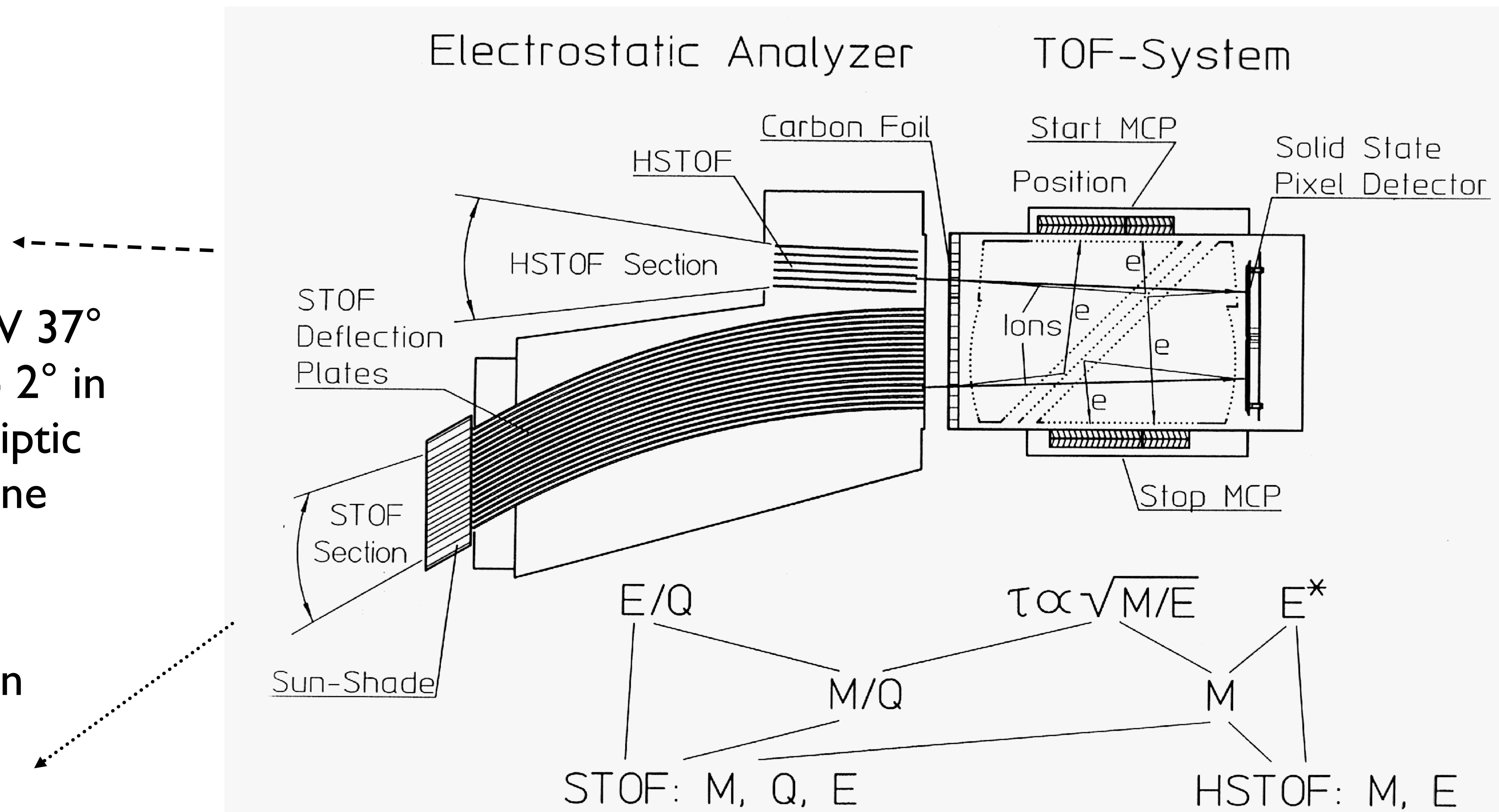
View of heliospheric research about 250 years ago

SOHO/CELIAS/HSTOF instrumentation

FOV +/- 17° out of ecliptic plane

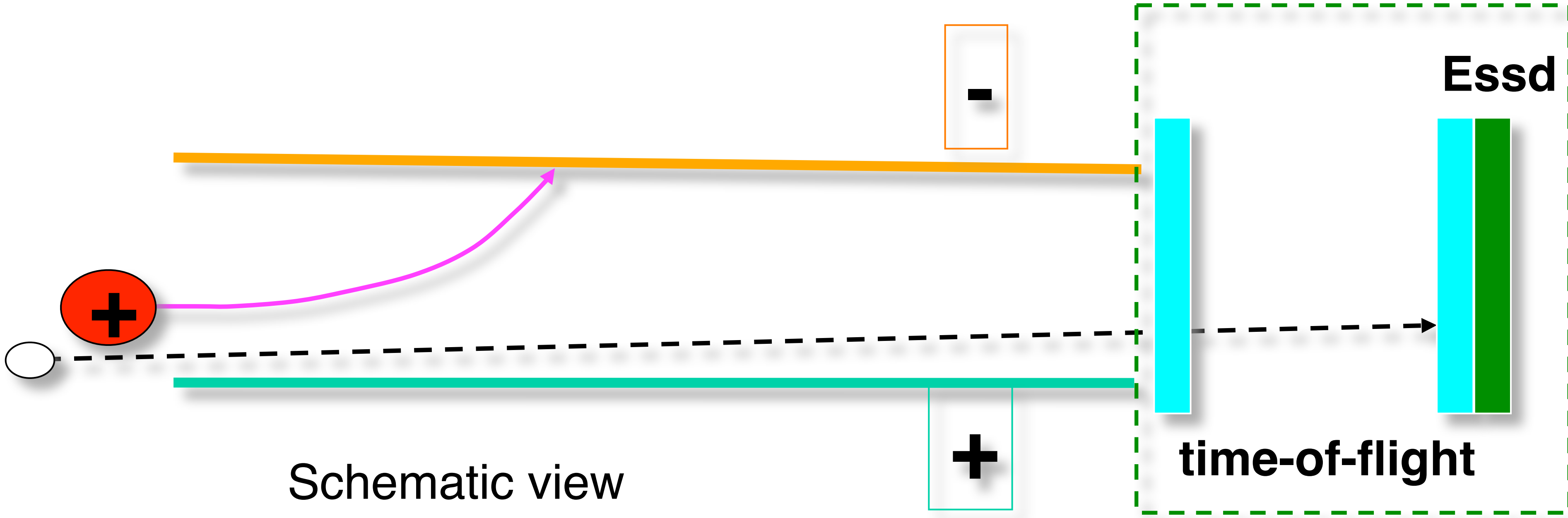
FoV 37° +/- 2° in ecliptic plane

Sun



Hovestadt et al 1995

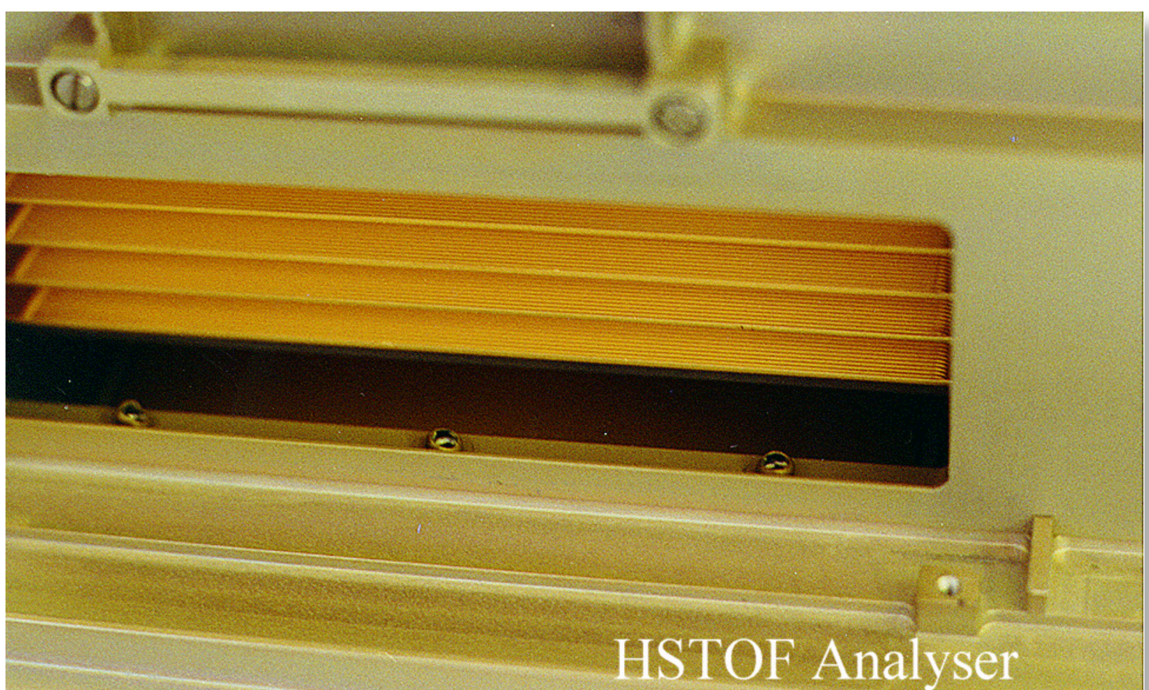
Observation of ENAs



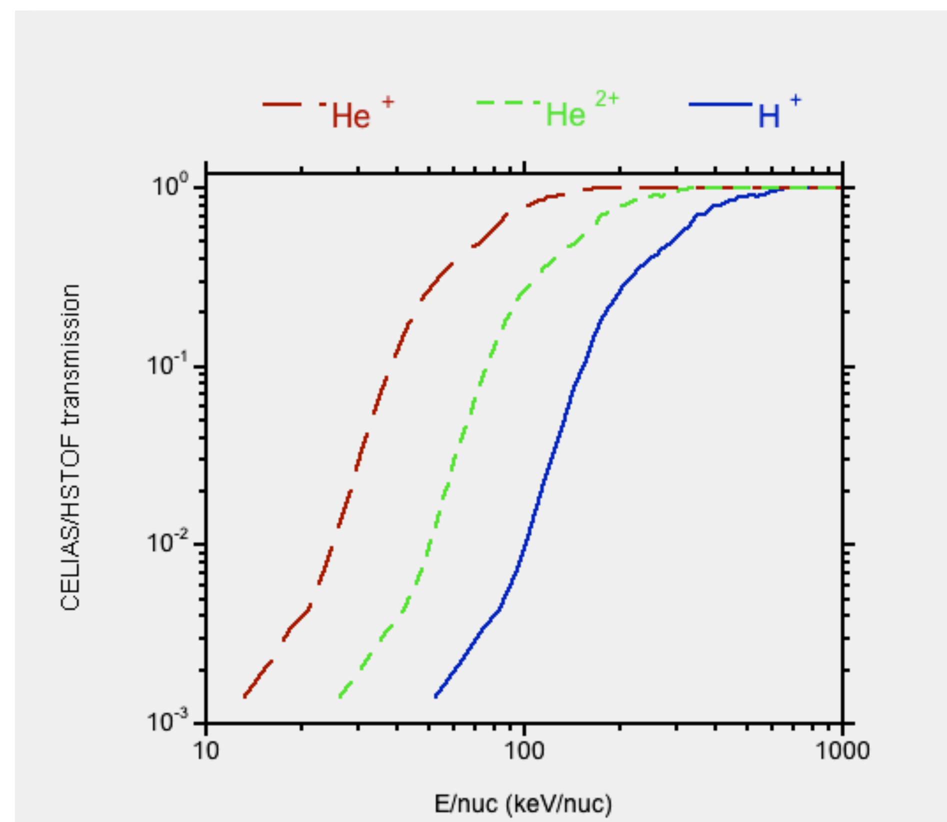
Schematic view

Separation of ions and neutral particles with a transmissionsfilter (E/q filter),

triple coincidence measurement



Picture of CELIAS/HSTOF filter



CELIAS/HSTOF Transmission from in-flight data

Energetic Proton Quiet Time Fluxes

TABLE 2

QUIET-TIME SPECTRA FOR <10 MeV PER NUCLEON IONS: $dJ/dE \sim E^{\gamma}$

Source	γ(Proton)	γ(He)	Year(s)
This work	−2.5	−3.0	1978–1984
This work	−3.1	−2.6	1984–1987
Wenzel *et al.* 1990	−2.4 ± 0.1	...	1978–1981
Mason *et al.* 1979	−3.2, −4	−2.6	1977
Krimigis *et al.* 1977	−2.3 ± 0.3	...	1975
Gloeckler *et al.* 1975	−1.8	...	1974
Krimigis *et al.* 1975	−3.1 ± 0.2	...	1973
Mewaldt *et al.* 1975	−4	−3.6	1972–1973
Zamow 1975	−(2.2–3.3)	−(1.9–3.2)	1964–1972
Simpson and Tuzzolino 1973 ...	−3.0 ± 0.3	−3.0 ± 0.3	1972–1973
Fan *et al.* 1970	−1.6	−2.1	1964–1967
Fan *et al.* 1968	−2.4	−2.4	1964–1965

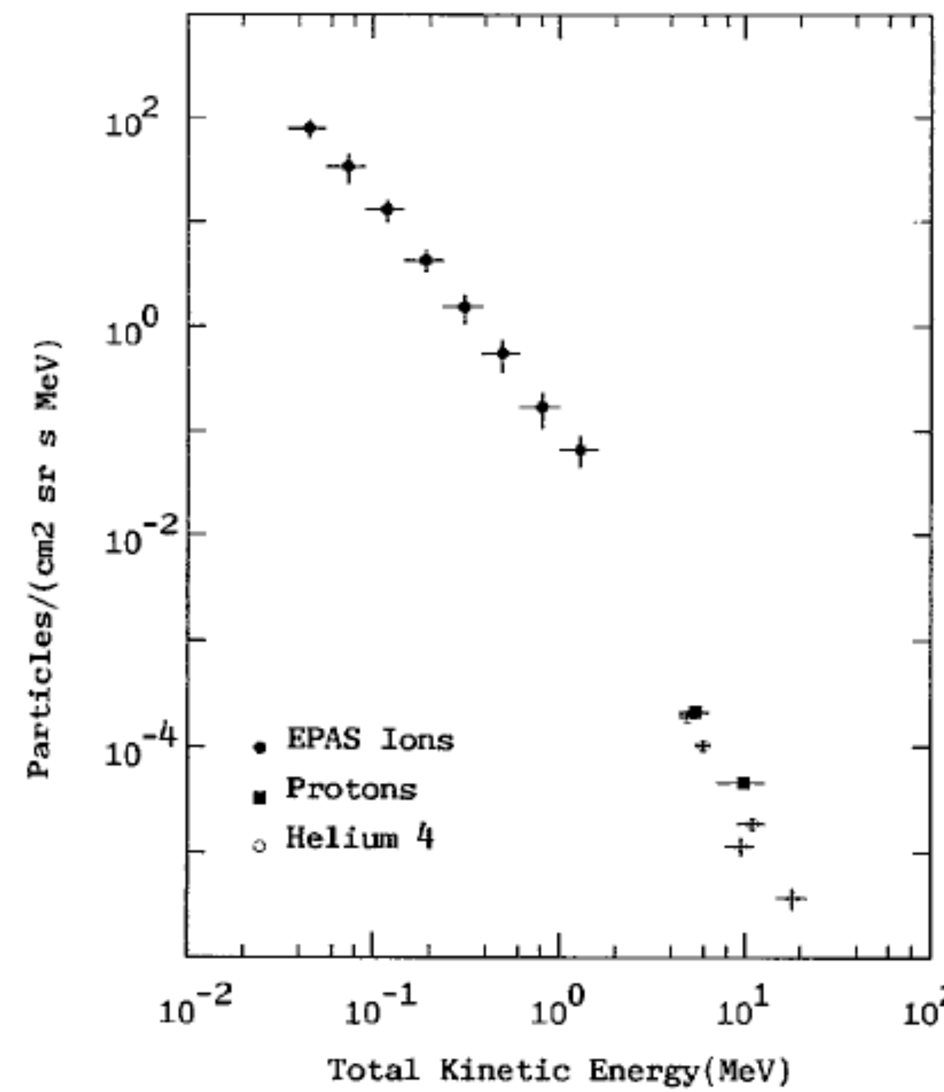
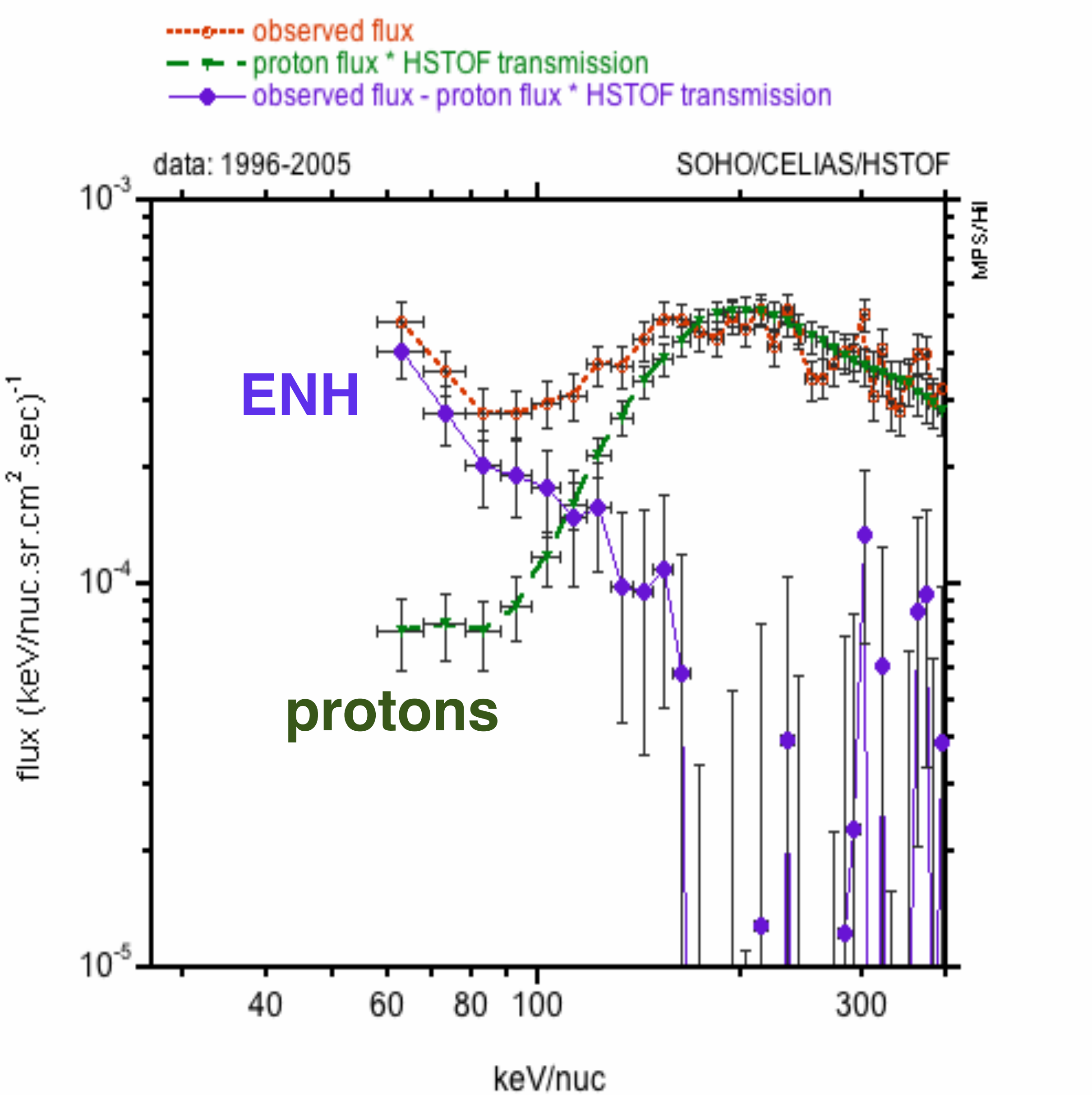


FIG. 3.—Comparison of solar maximum 35–1600 keV ion spectrum (a
'enzel *et al.* 1990) with ≤20 MeV proton and ^{4}He spectra plotted in term
ıtal kinetic energy. While the low-energy and MeV ion spectra are reasona
ınsistent, the similar MeV proton and ^{4}He fluxes suggest that ^{4}He may b
gnificant contributor to the lower energy spectrum in addition to protons.

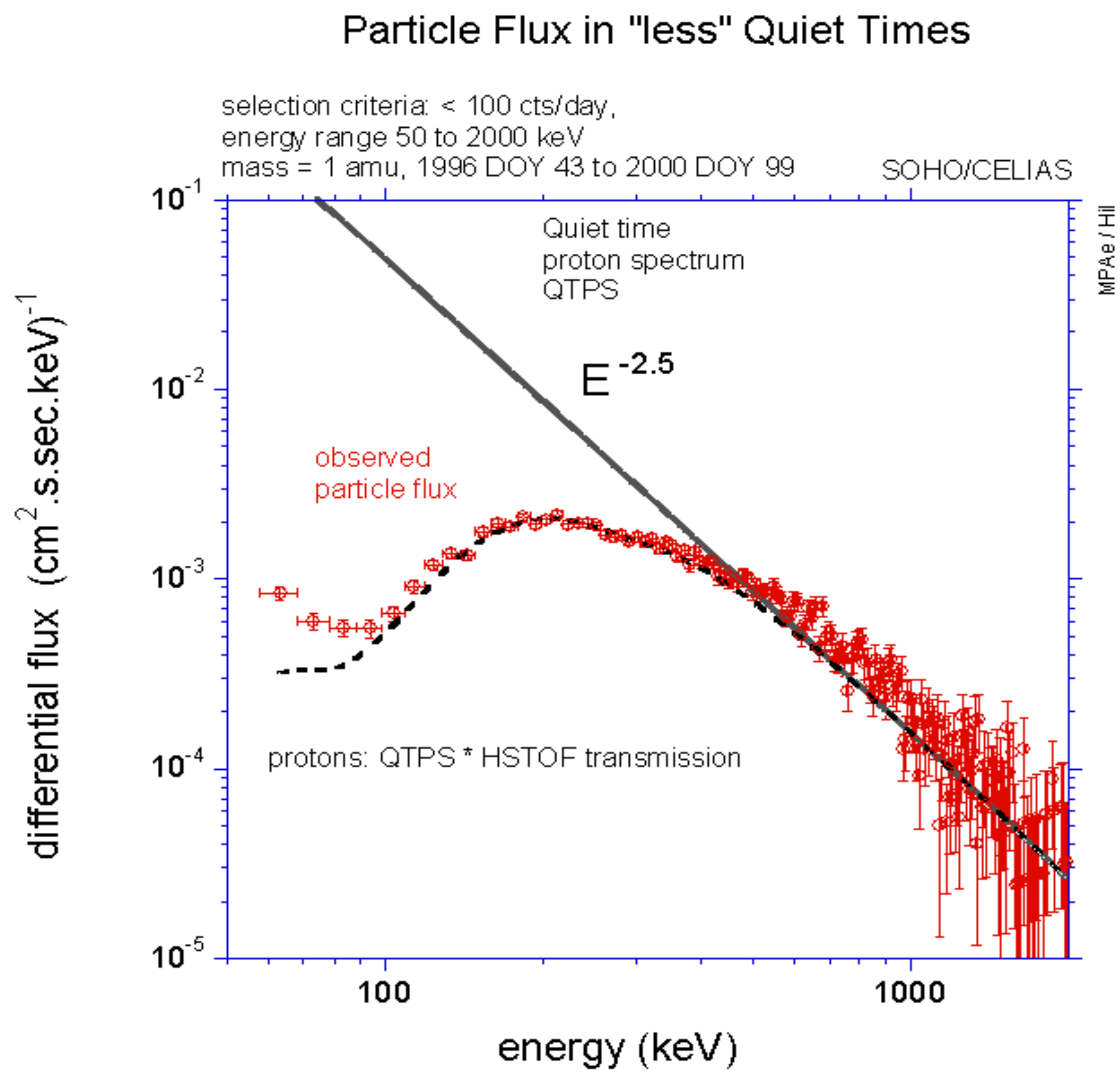
Richardson 1990

SOHO/CELIAS/HSTOF
"Quiet time" energy spectra

ENH and protons

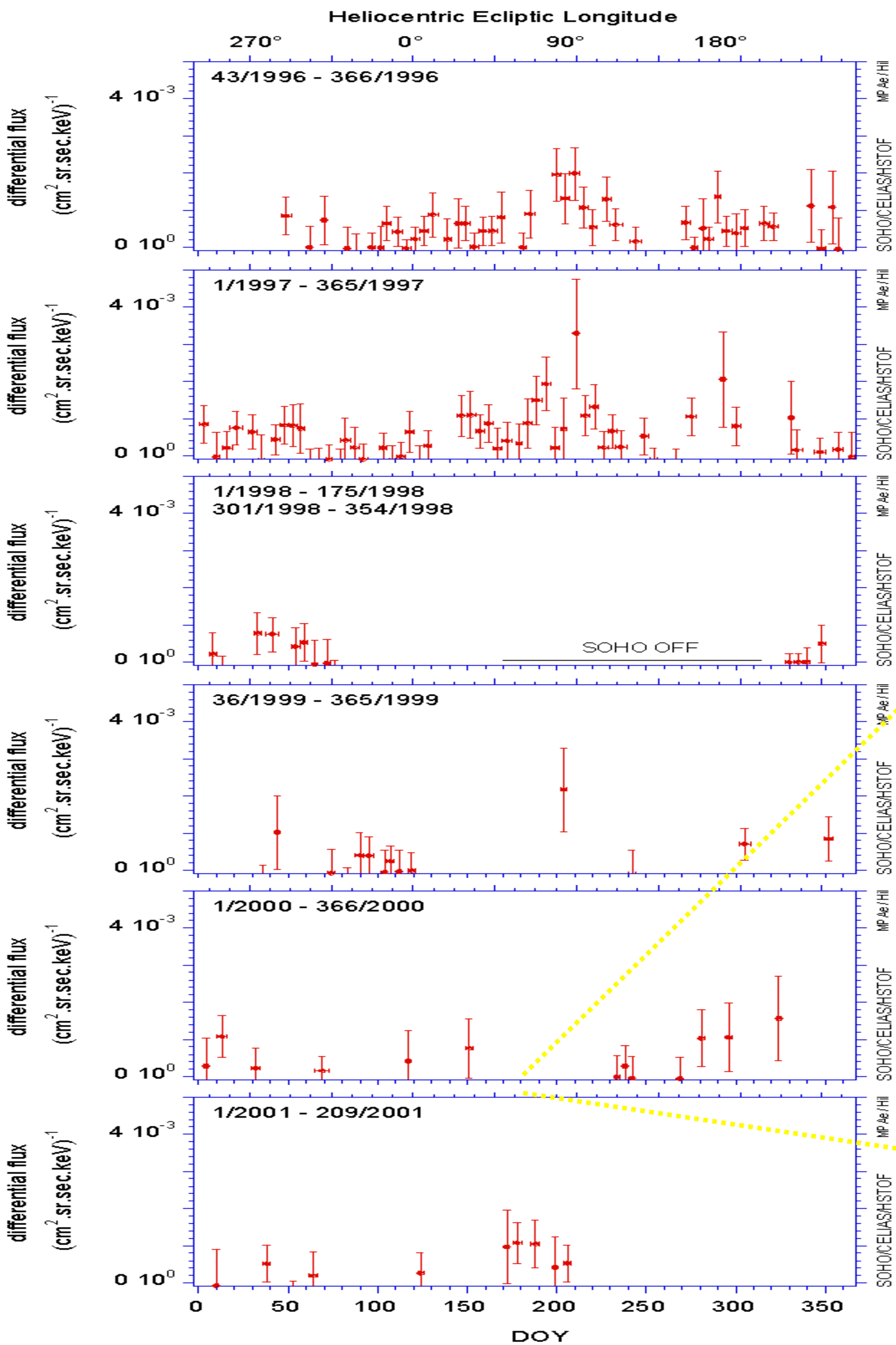


ENH: 58 - 88 keV/n

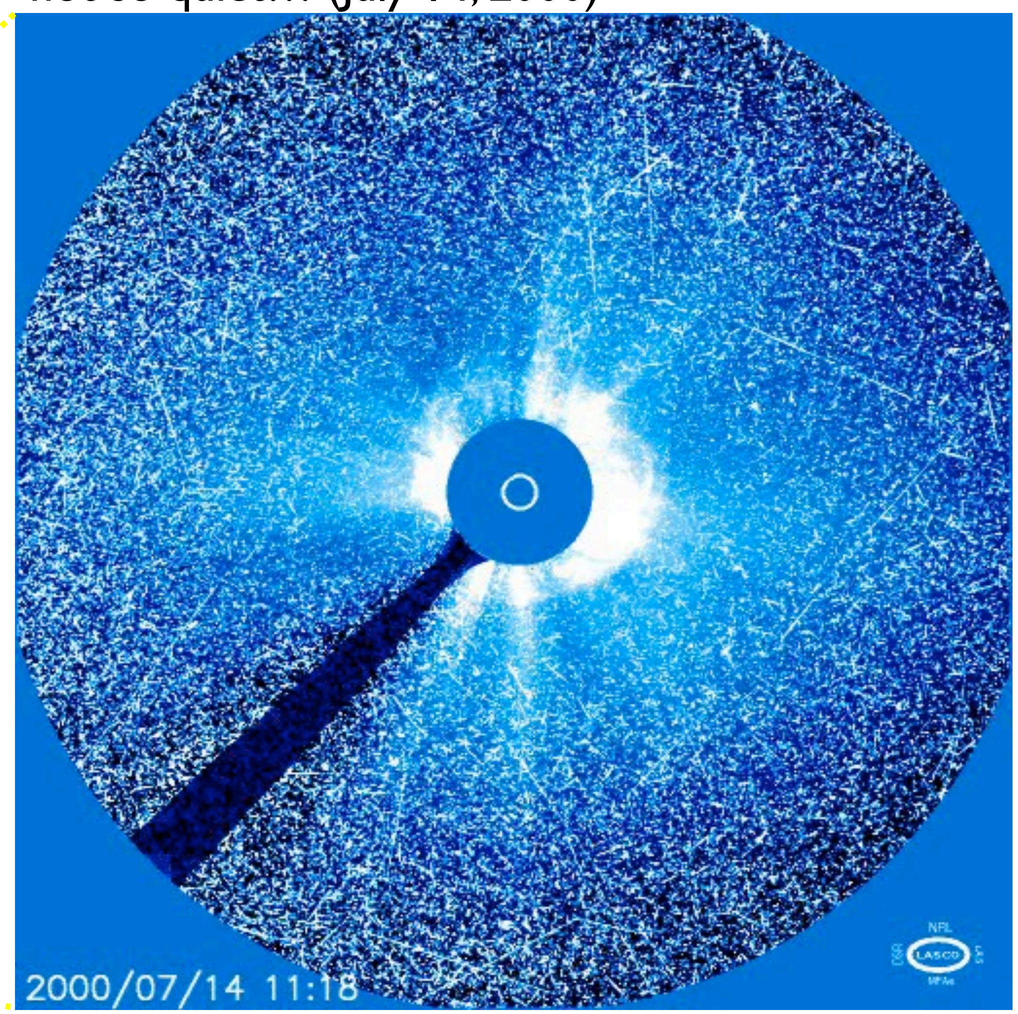


Hilchenbach 2000

Quiet time energetic neutral hydrogen atom (EHA) flux 1996-2001

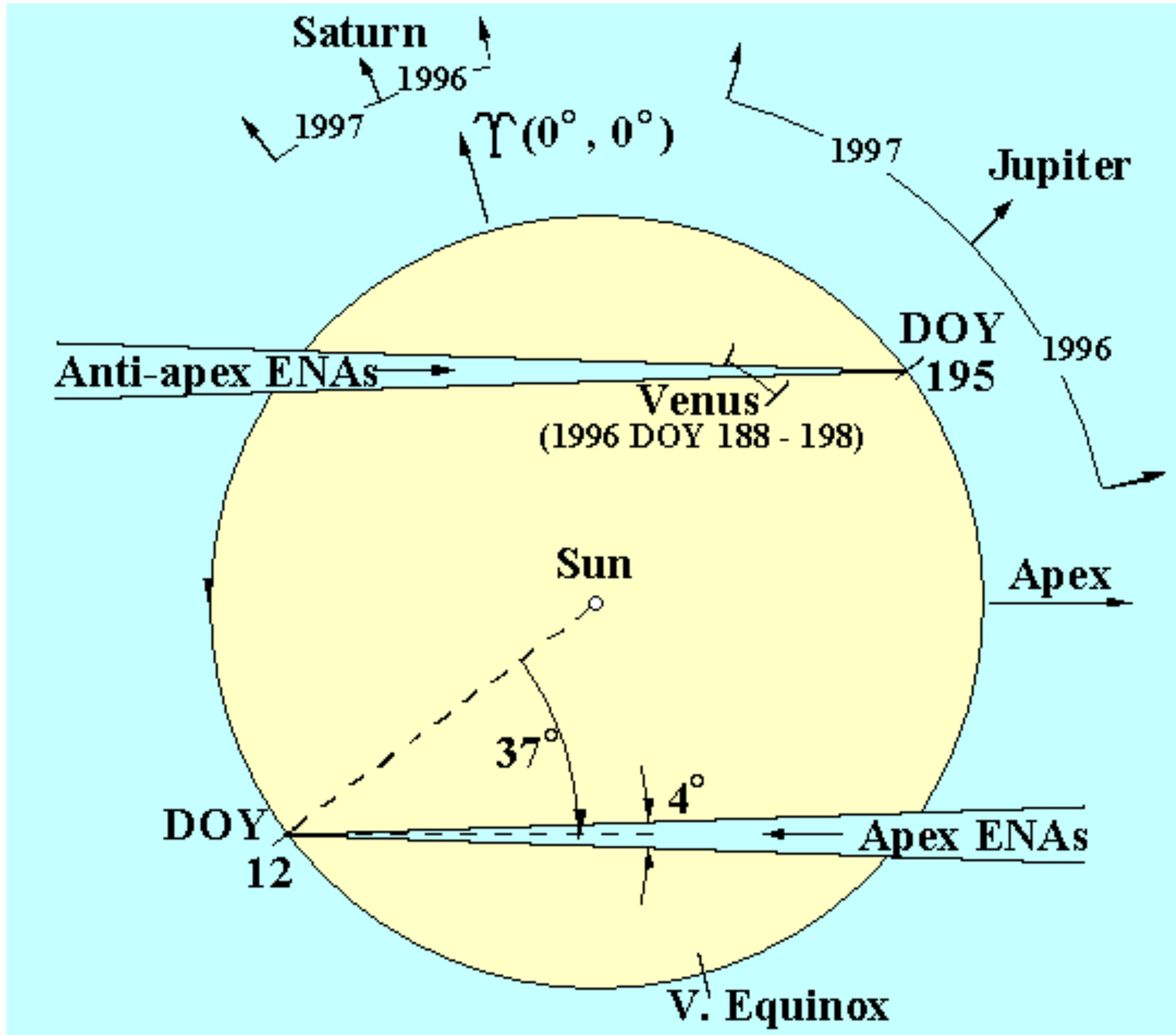


not so quiet… (July 14, 2000)



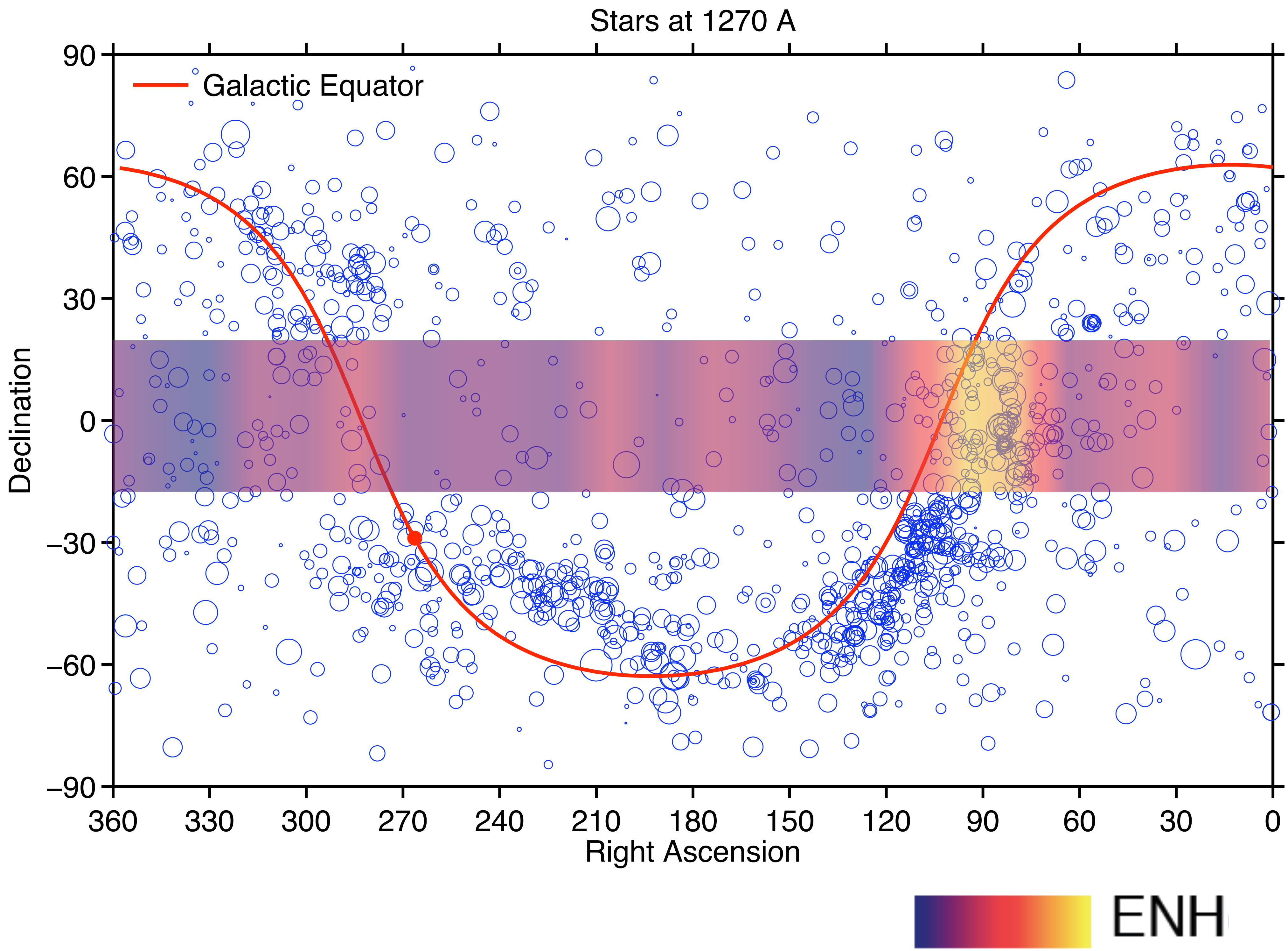
SOHO
LASCO
C3

SOHO/CELIAS/HSTOF "field of view"



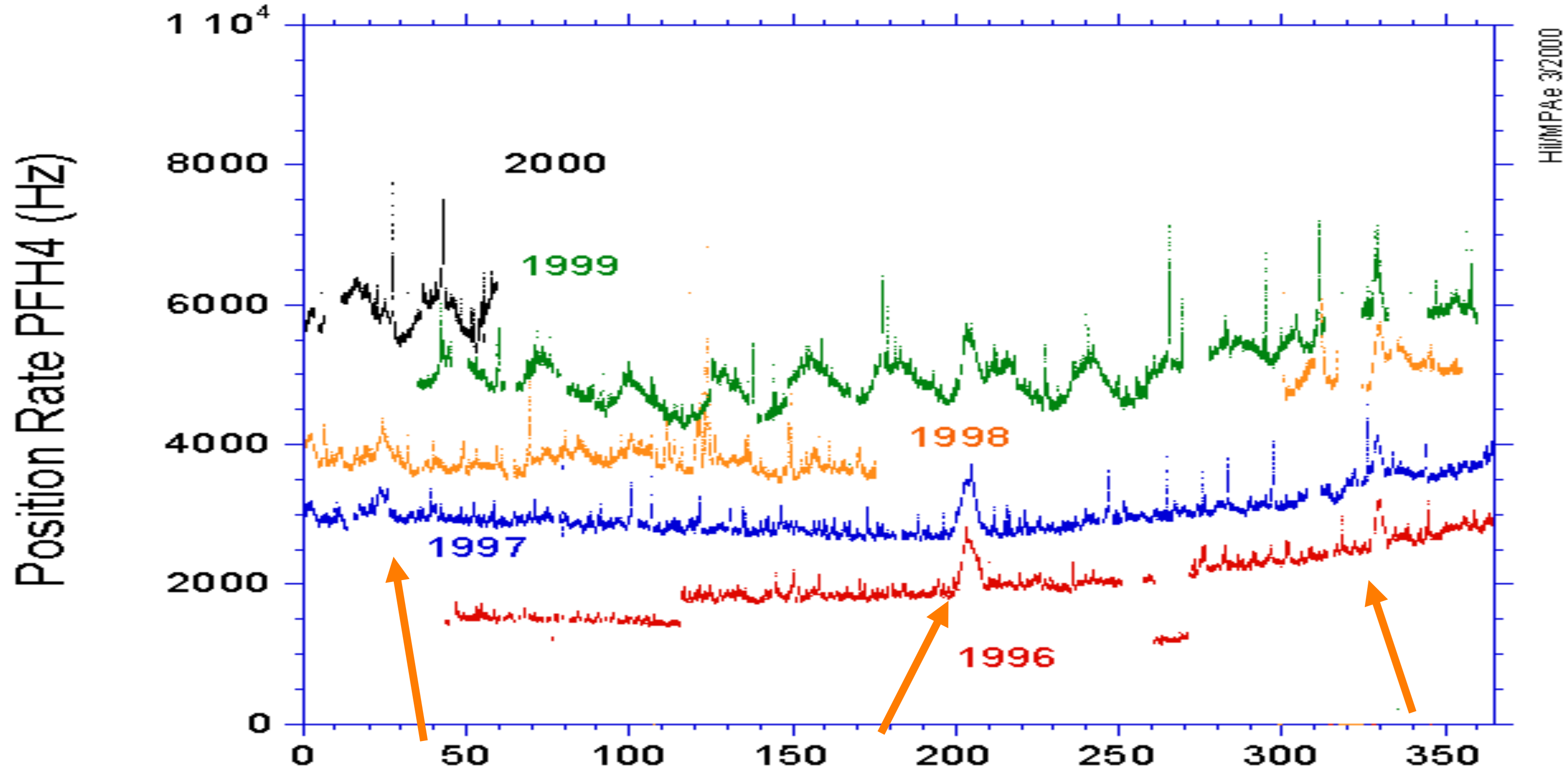
SOHO/CELIAS/HSTOF
Observational field of view in the ecliptic plane

UV Stars - Background?

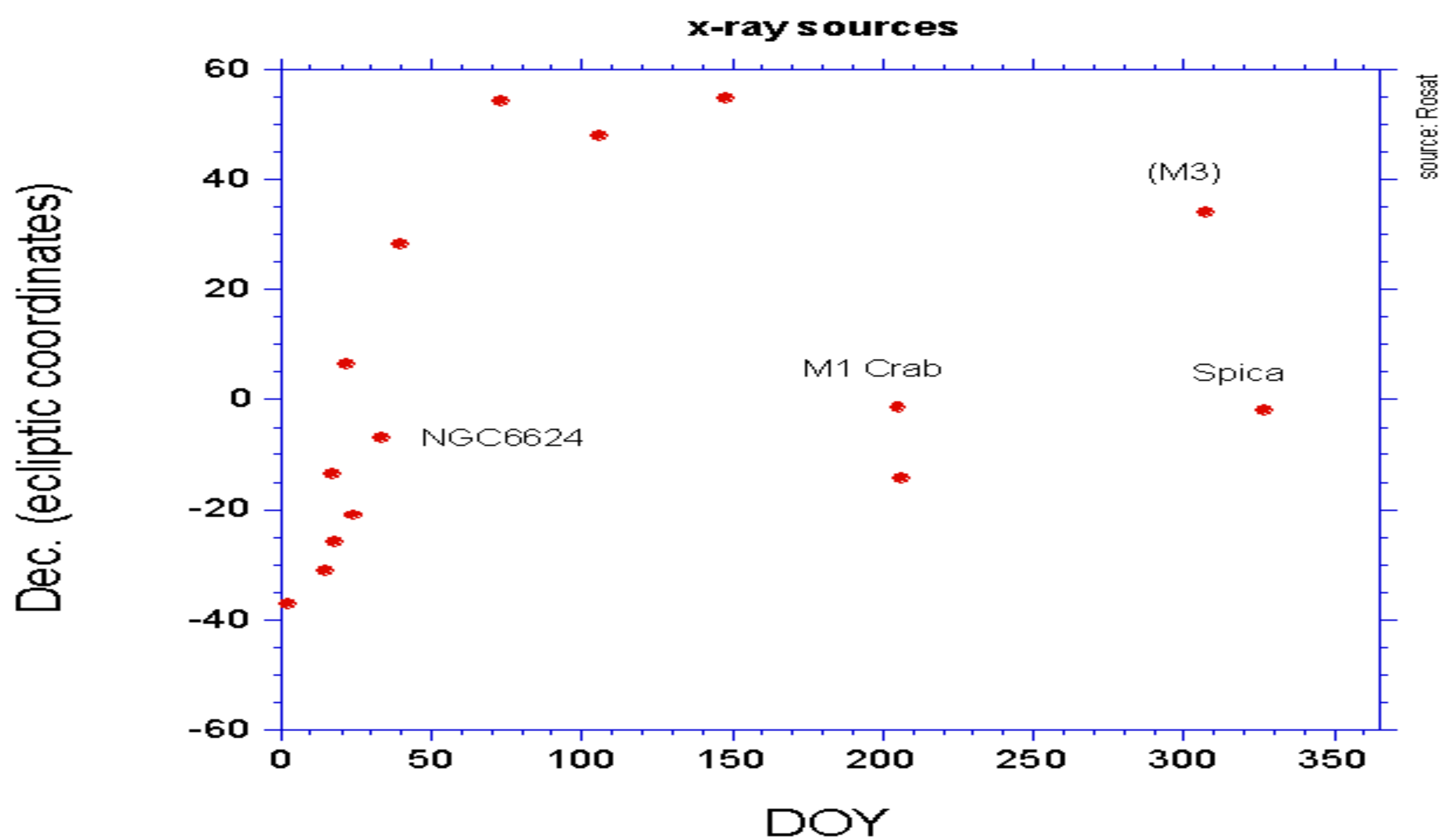


Sandel
2010

HSTOF Position Single Rate



X-ray souces (Rosat)



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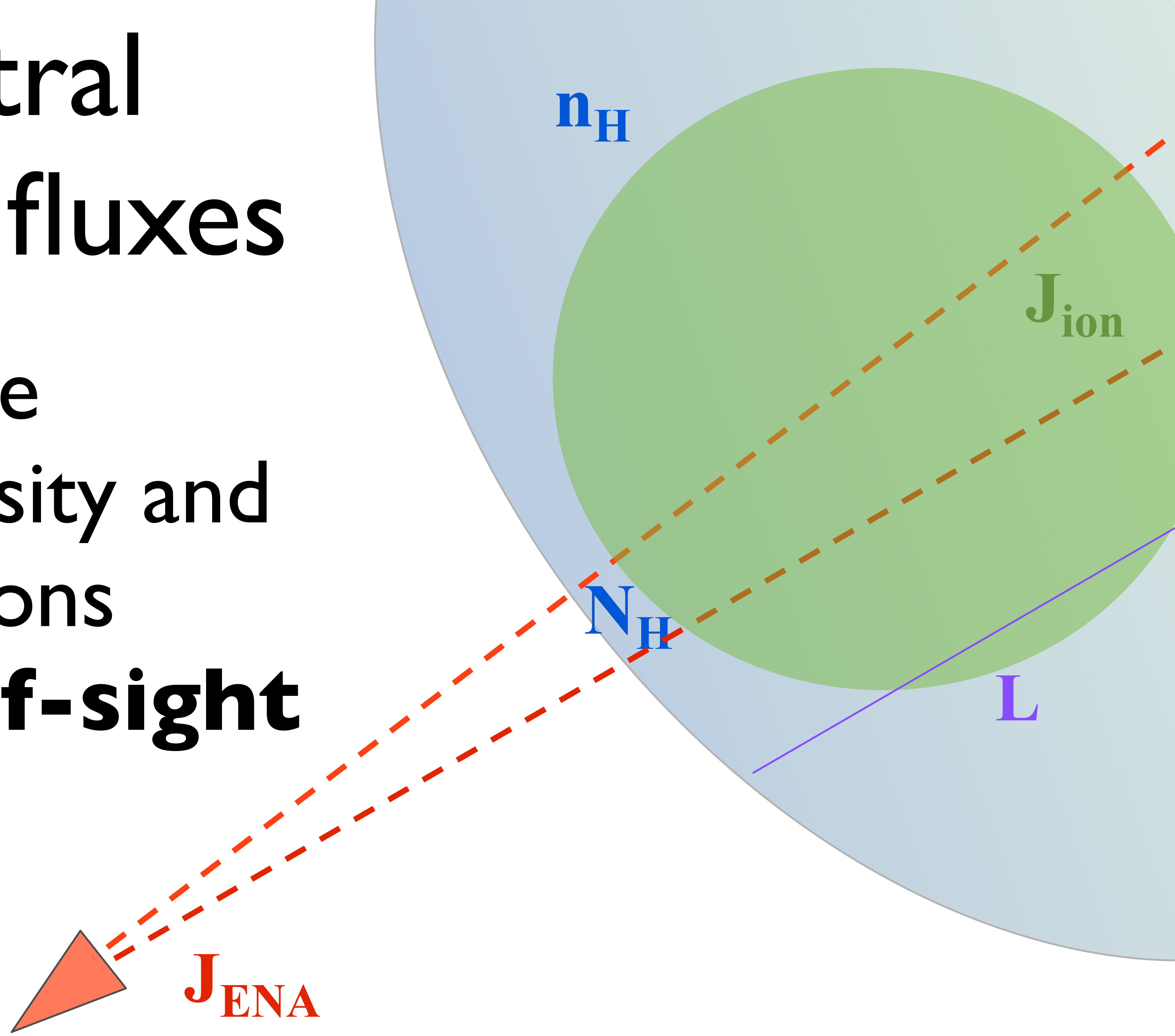
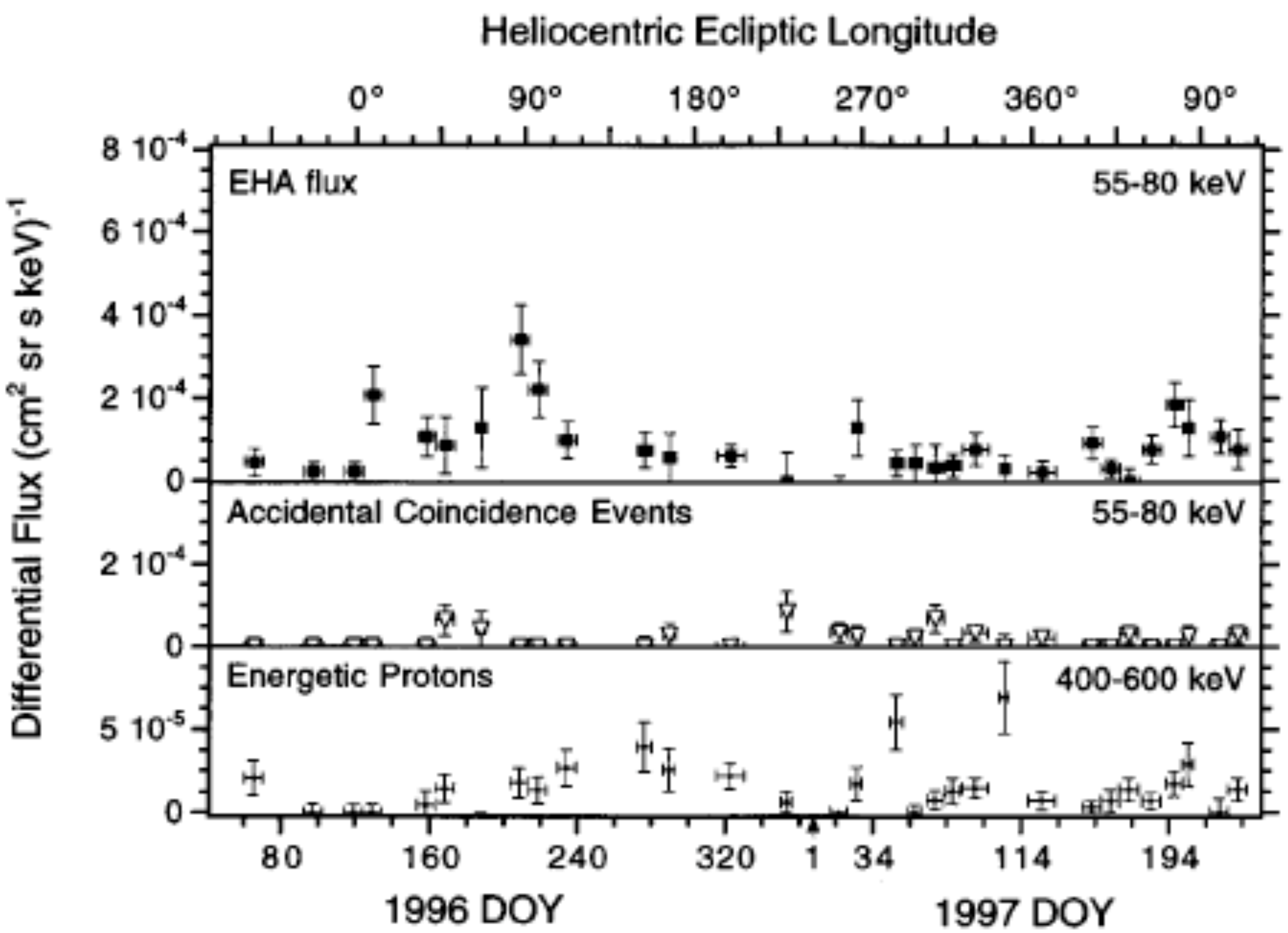
Energetic Neutral Atom - ENA - fluxes

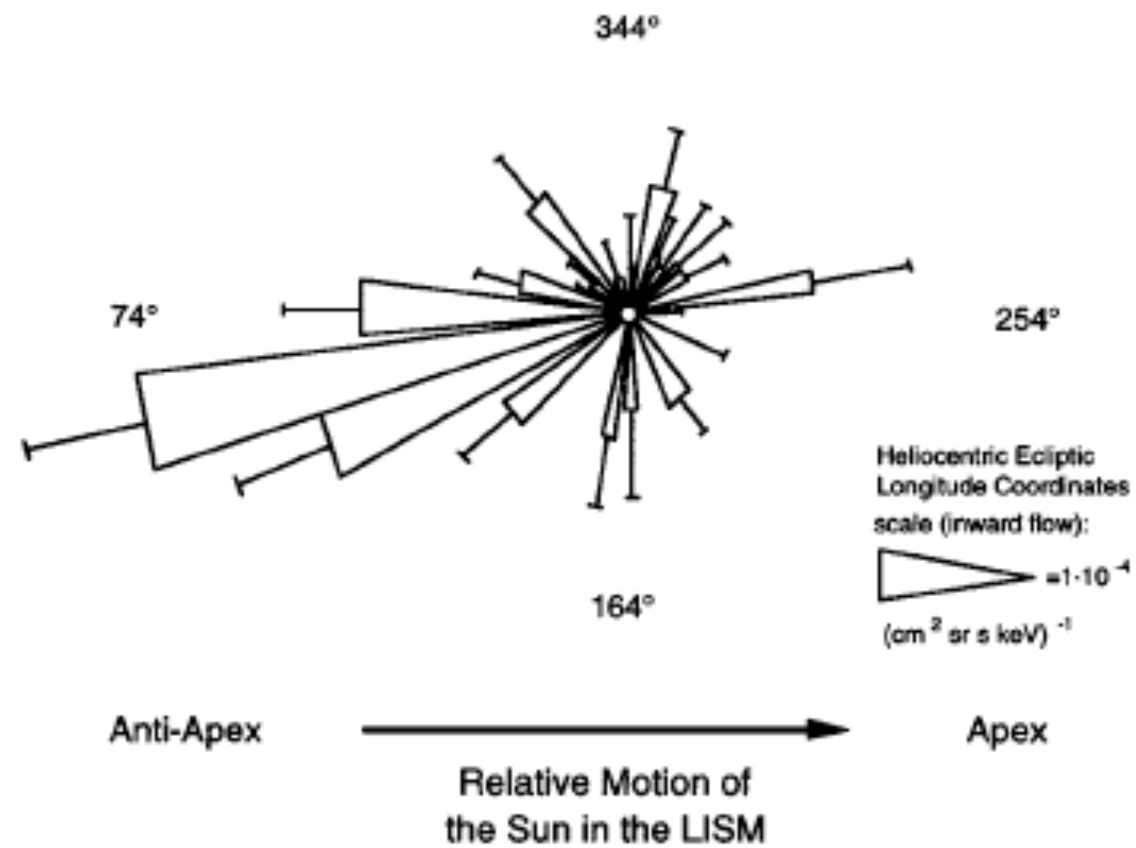
Projections of the neutral column density and plasma ion populations **along the line-of-sight**



1) $J_{ion}(E)$ (observed by V1/ V2 in apex, but not in tail region of heliosphere)
2) J_{ENA} (e.g. SOHO at 1 AU)
3) $J_{ENA}(E)$ and $J_{ion}(E)$ flux measurement yields the neutral column densities along the field-of-view
$J_{ENA,H}(E) / (J_{ion}(E) * \sigma_{ex}) = N_H$
4) from the column density N_H and the ISM density n_H, one can calculate the extension L of the source region $N_H / n_H = L$

SOHO: First suprathermal neutral hydrogen (ENH) observations





Hilchenbach 1998

A potential explanation of the SOHO ENH heliotail observations

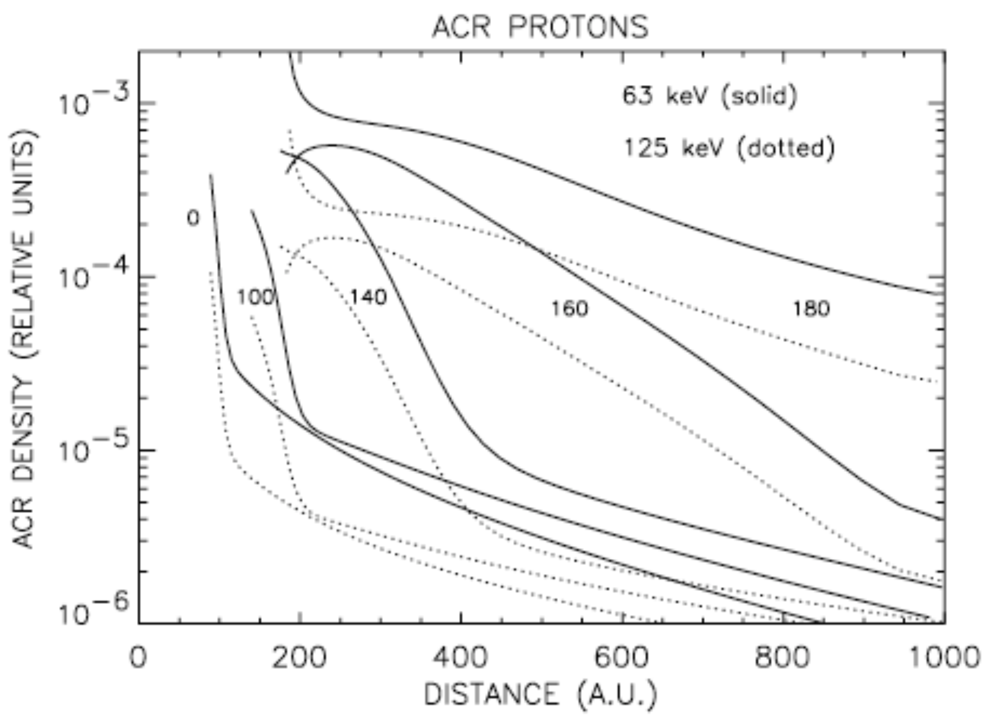


Figure 2: ACR proton distribution presented as constant θ (angle from the apex) density profiles plotted against distance from the Sun, for $\theta = 0, 100, 140, 160$ and 180 deg.

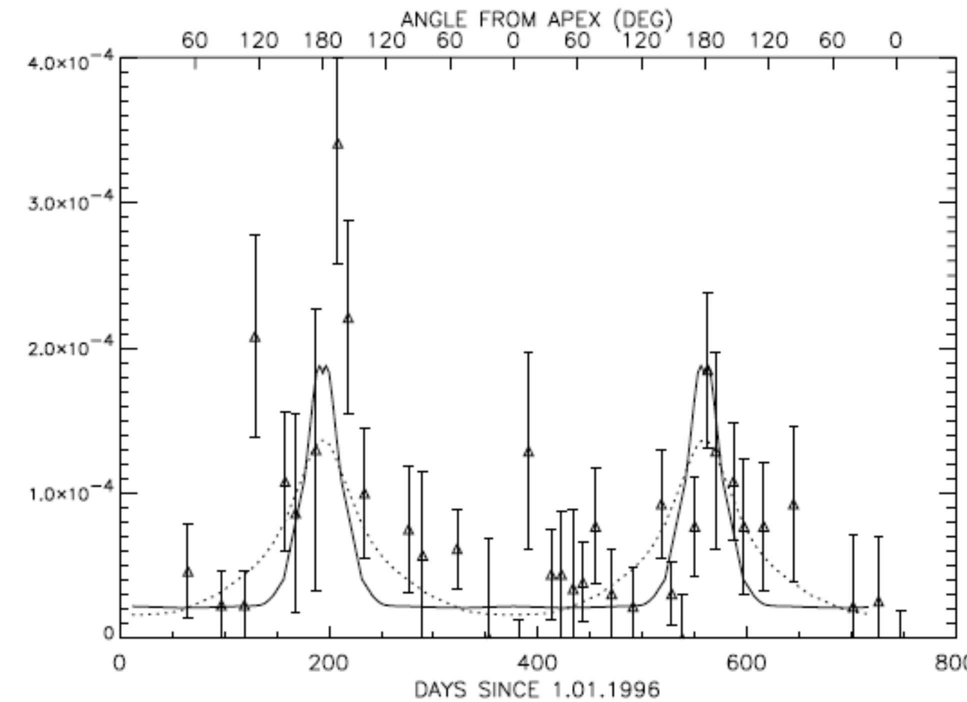


Figure 3: ENA flux: the data points show the flux (units $(cm^2\ s\ sr\ keV)^{-1}$) of mass=1 particles in low energy channels (~55-80 keV) observed during quiet times (low ion flux) by CELIAS/HSTOF instrument. The calculated flux of 63 keV hydrogen ENA from ACR transcharging in the field of view of the instrument is shown for the cases of Kausch's (solid line) and Parker's (dotted) models of the heliosphere.

Due to convection and diffusion, the ACR density and consequently the ENA flux along the line-of-sight could be increased.

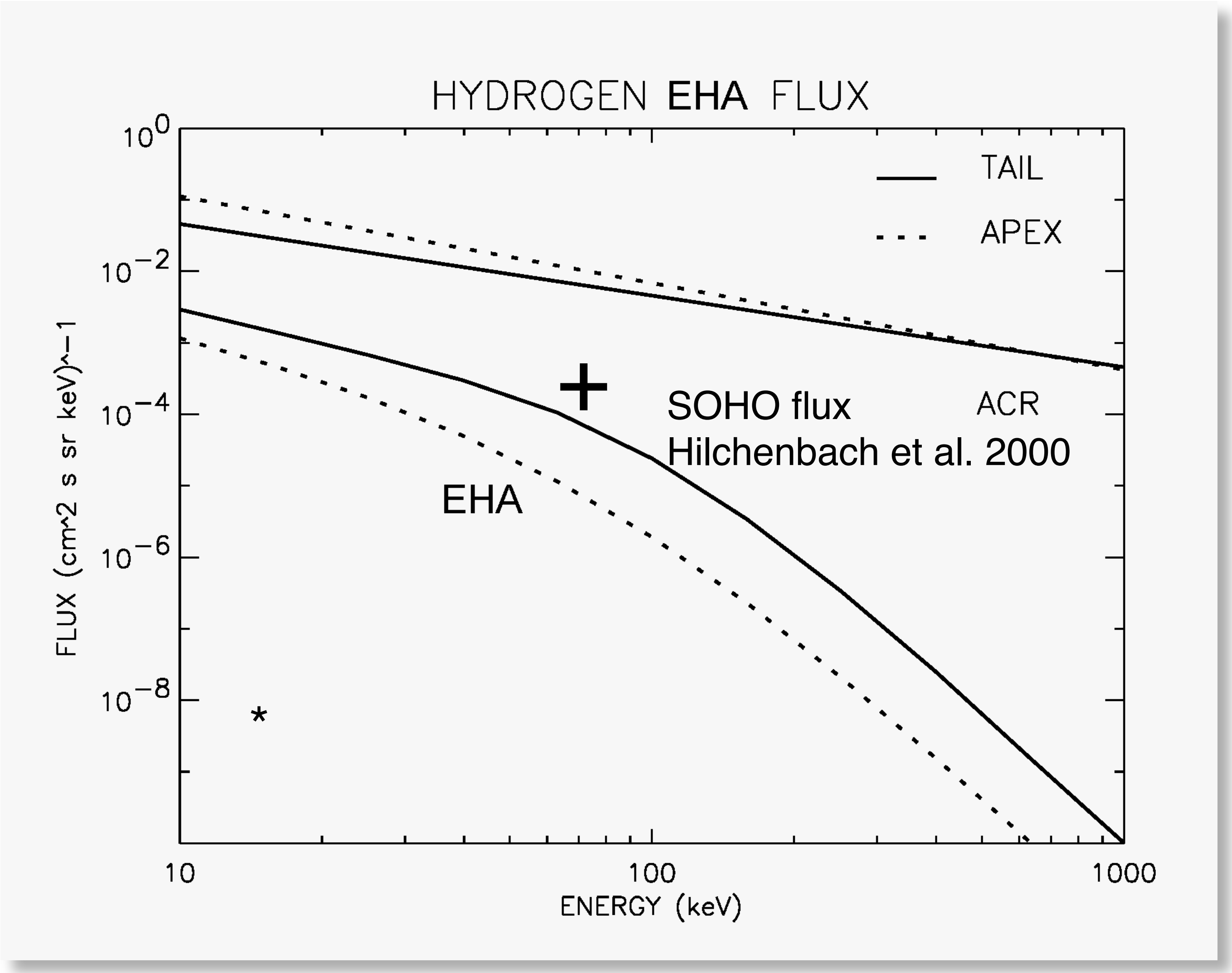
Grzedzielski 1993

Czechowski 1995, 1999

ENH in the inner and outer heliosphere:

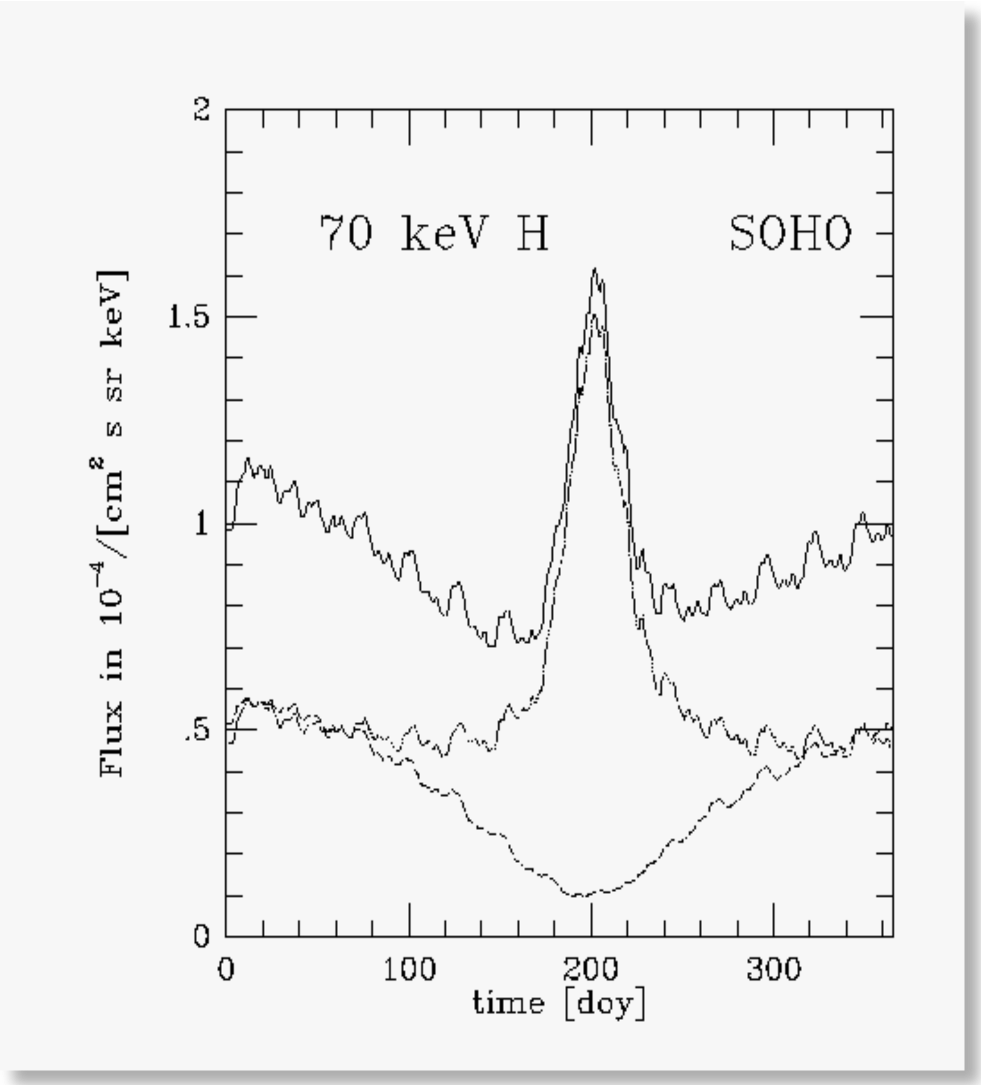
ENH sources and expected ENH flux and flux anistropy

ACRs



Czechowski et al. 2001 (based on Kausch's model)

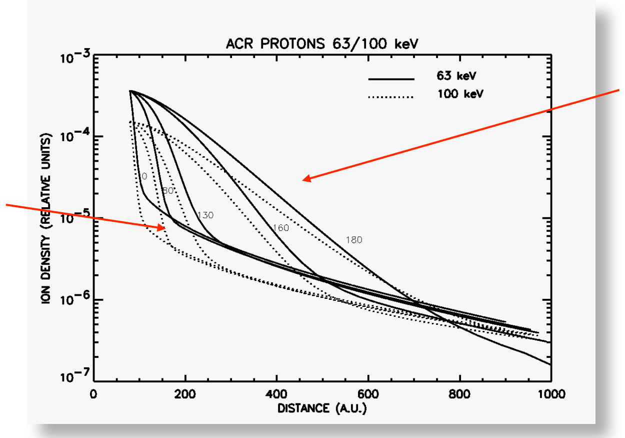
CIRs



Kota and Hsieh 1999, 2001

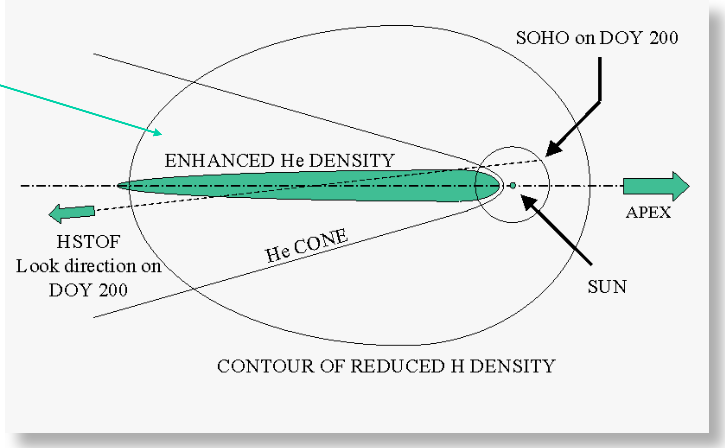
Apex region

ACR density

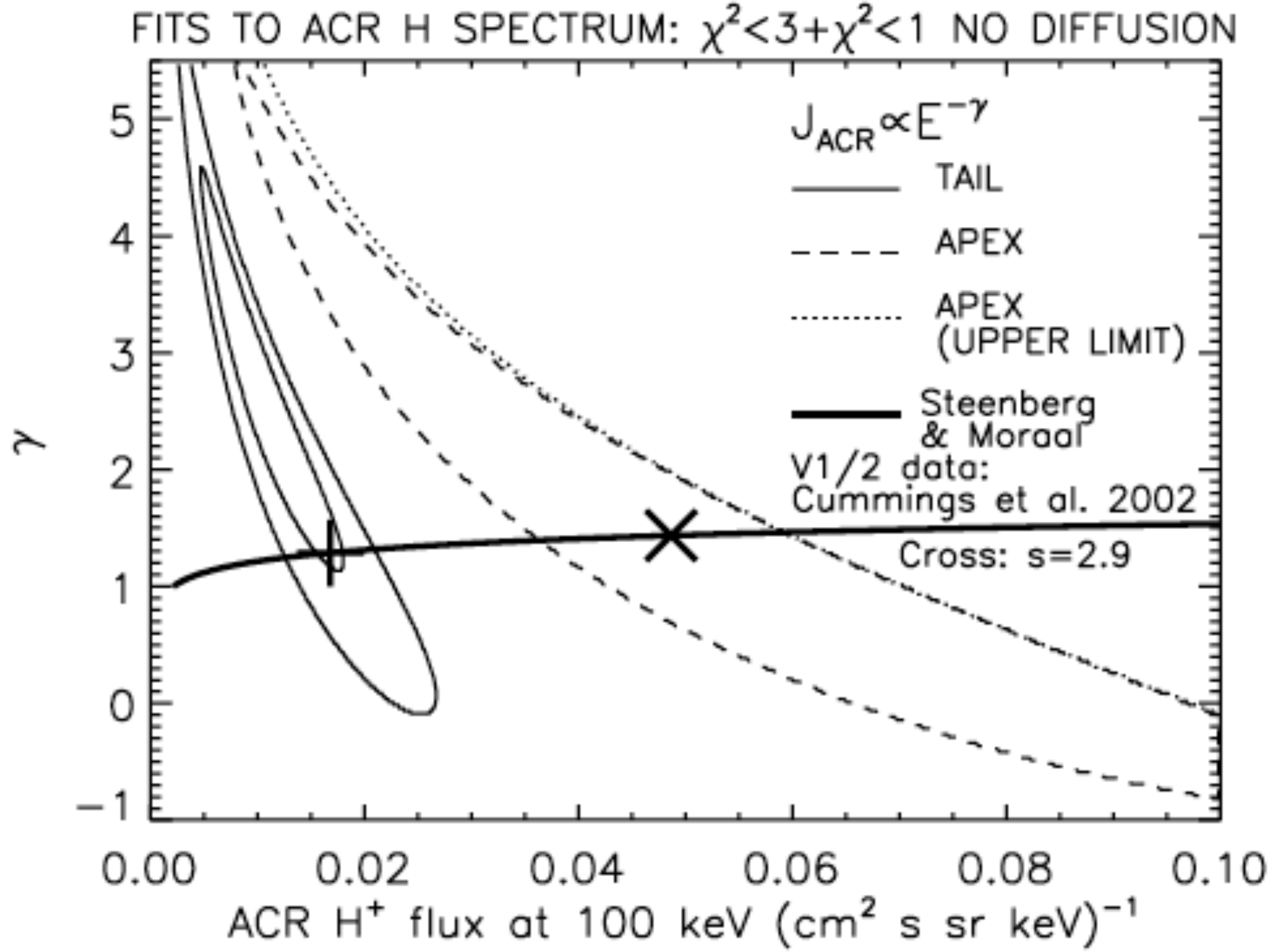


Anti-Apex or tail region

LISM - Helium Cone

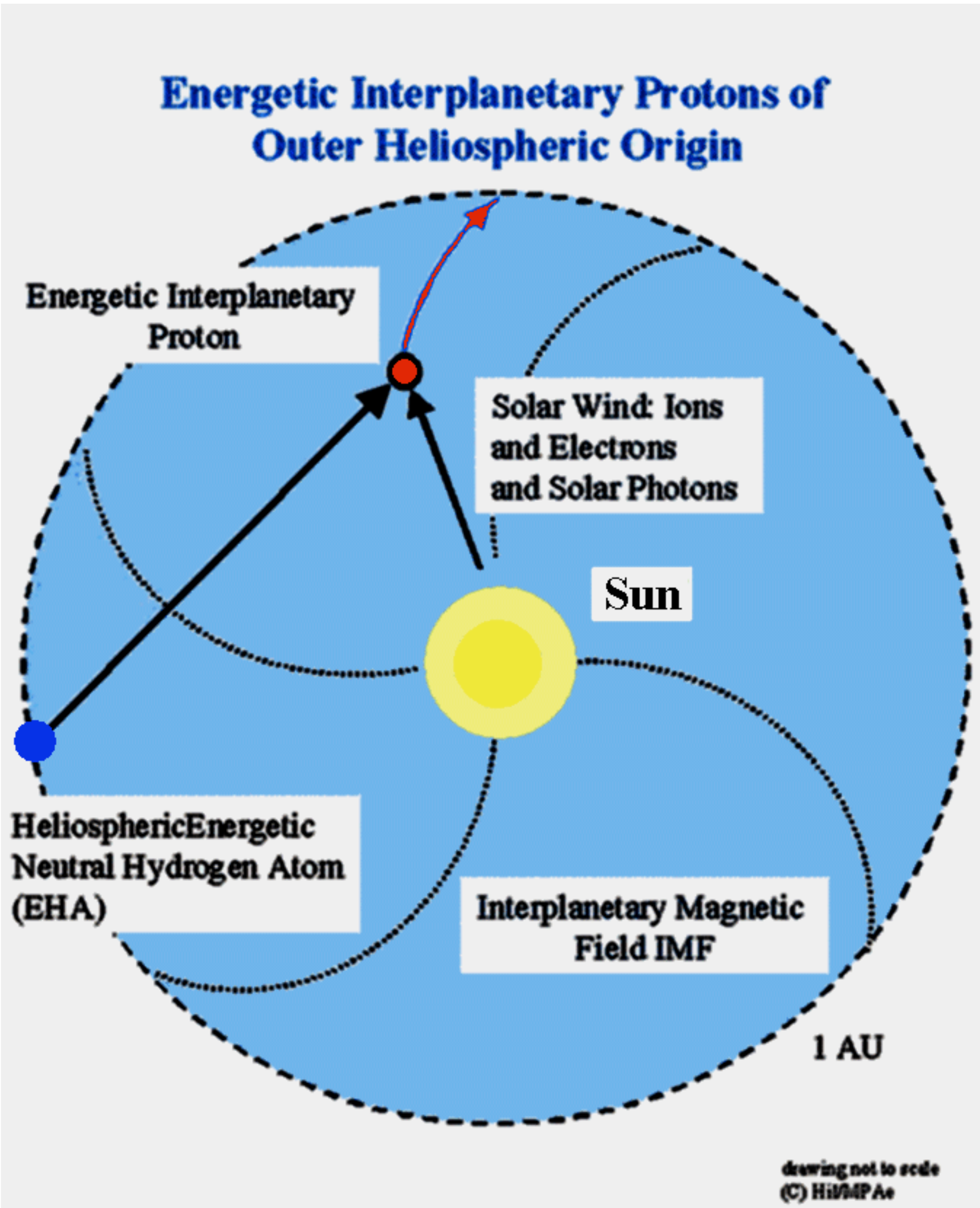


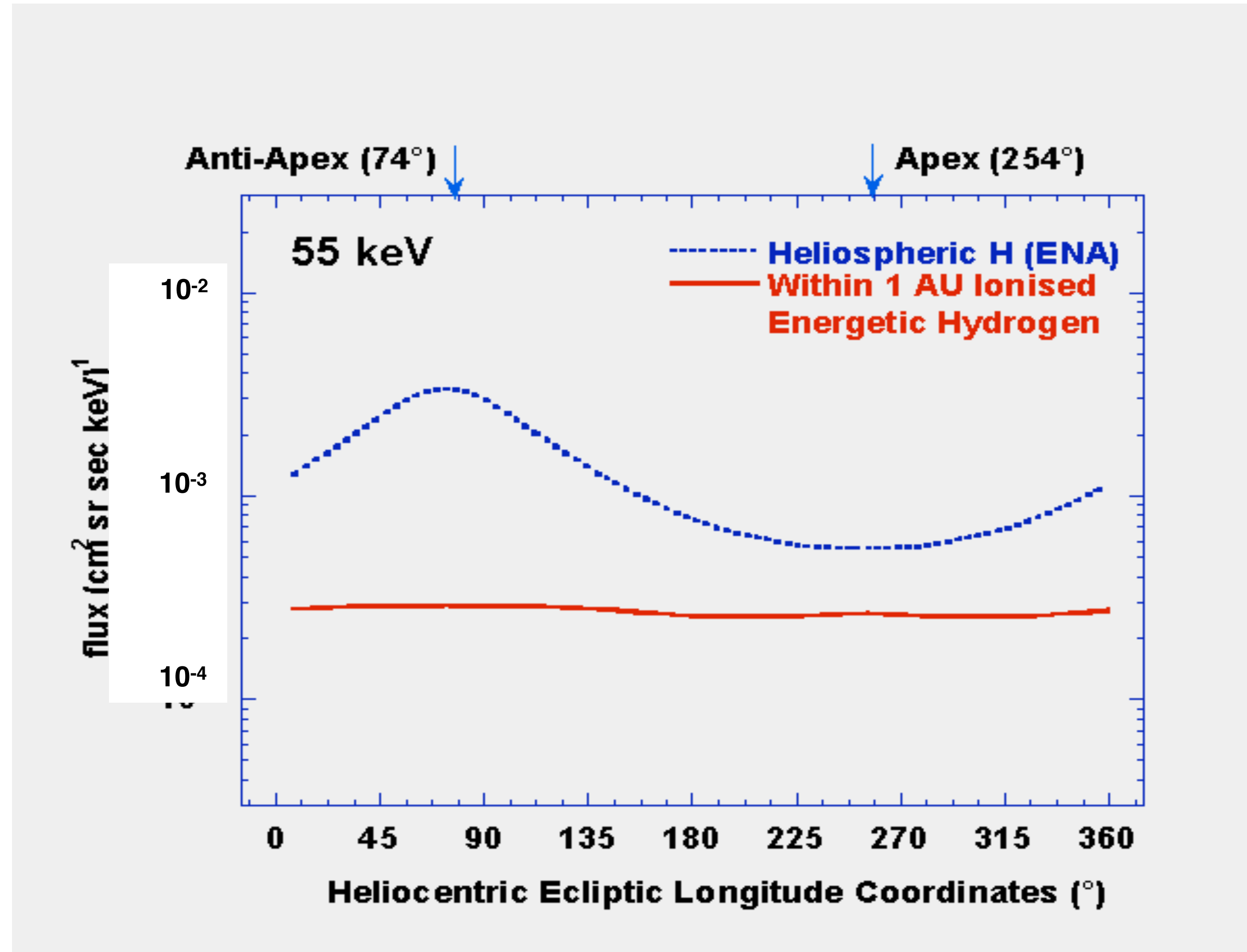
ENH and the Termination Shock



Czechowski 2005

Are EHAs a source of the quiet time energetic proton flux in the inner heliosphere ?



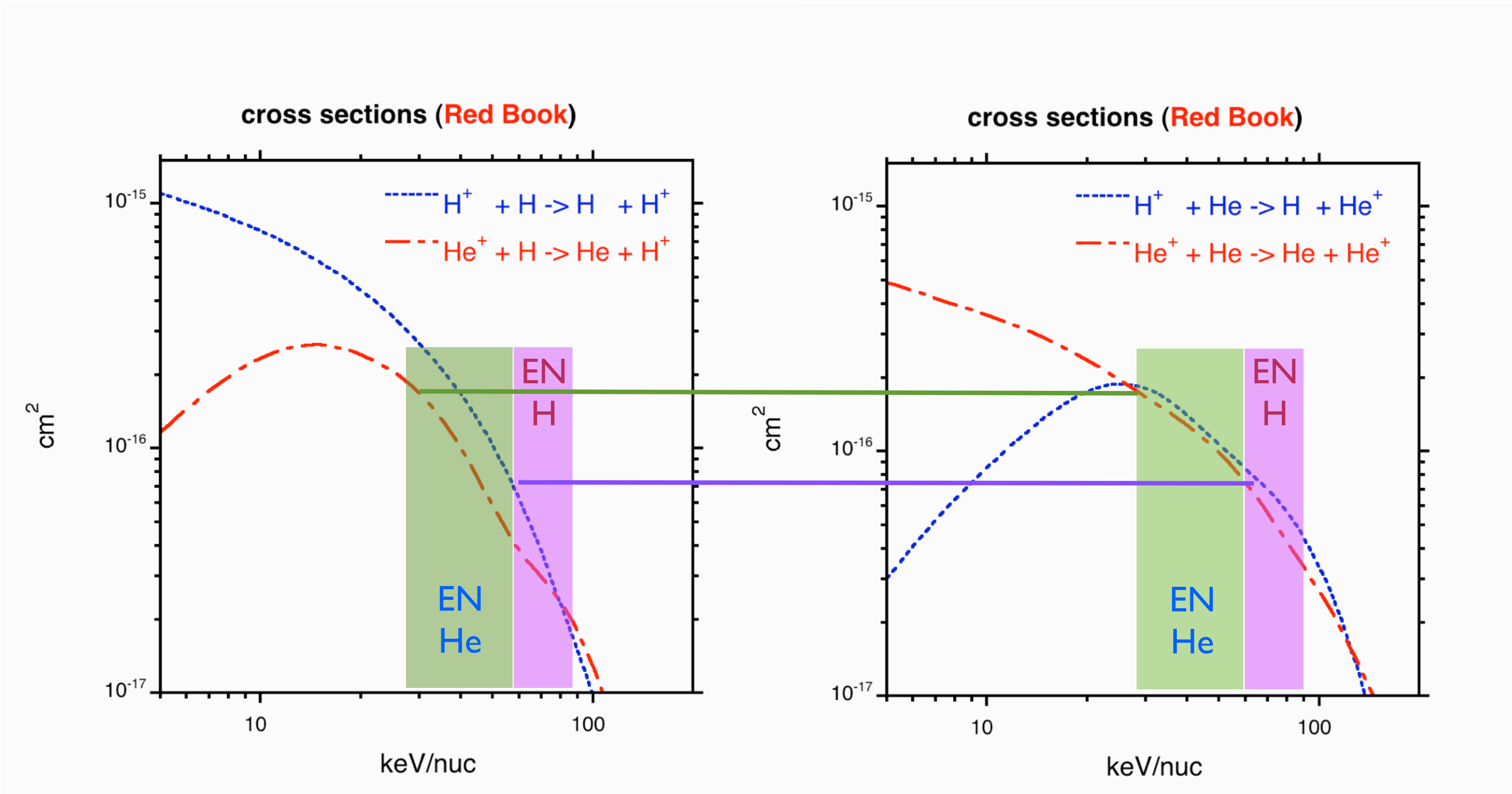


adapted from Hilchenbach et al. 1999

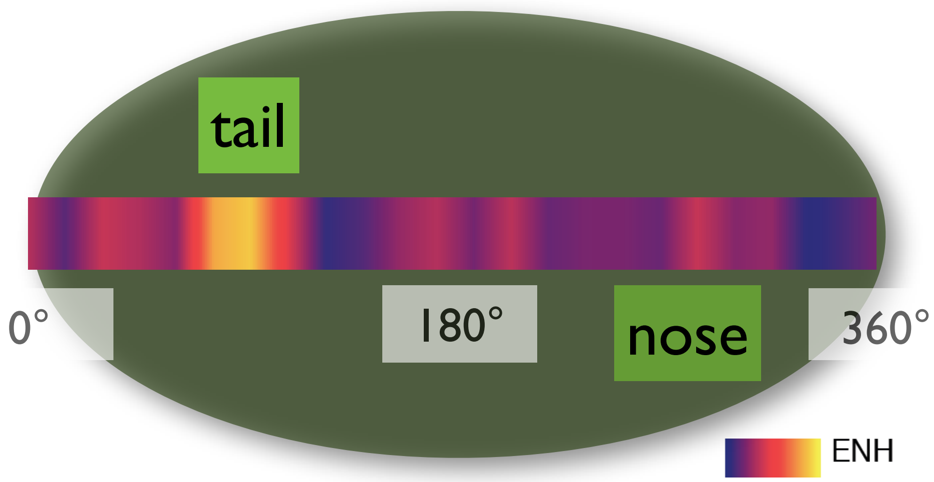
Estimated proton flux of EHA origin at 1 AU: ~ 10^{-4} $(cm^2.sec.sr.keV)^{-1}$

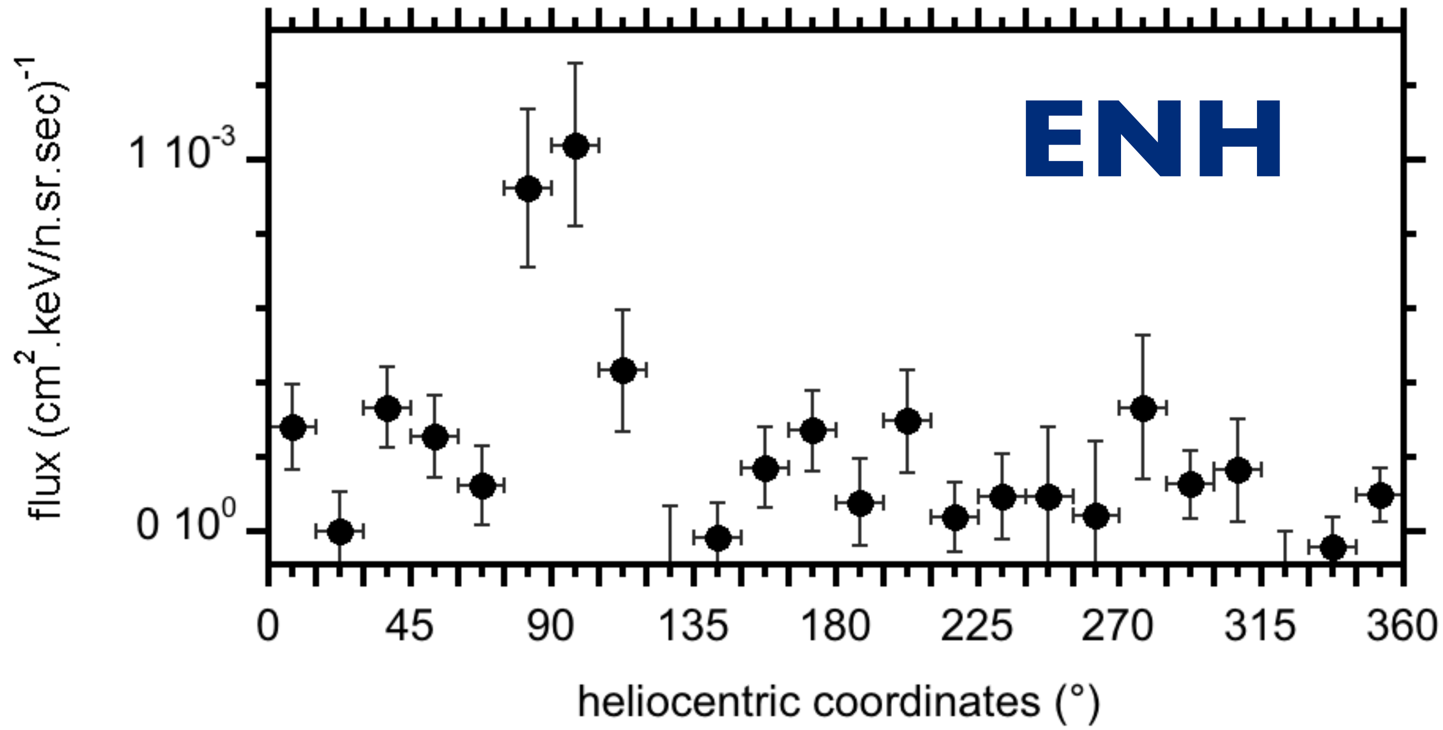
(Energy range: 58 to 88 keV)

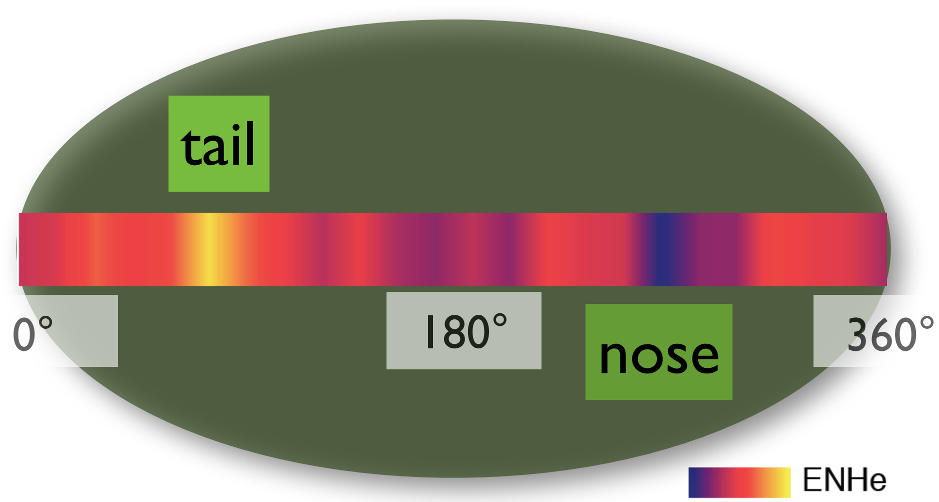
H^+ and He^+ Charge Exchange Cross Sections

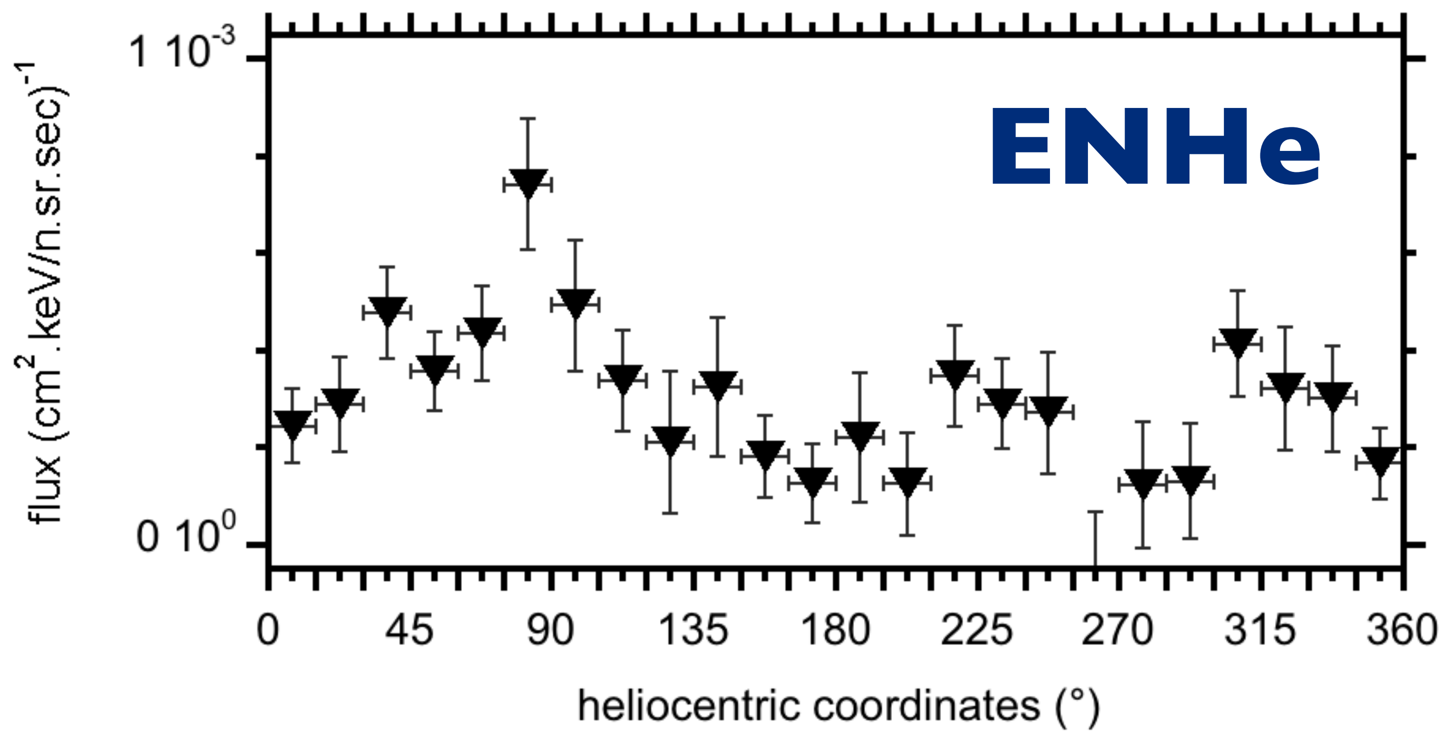


SOHO/CELIAS: Averaged neutral energetic hydrogen **(ENH)** and helium **(ENHe)** fluxes (time interval 1996-2006 *)



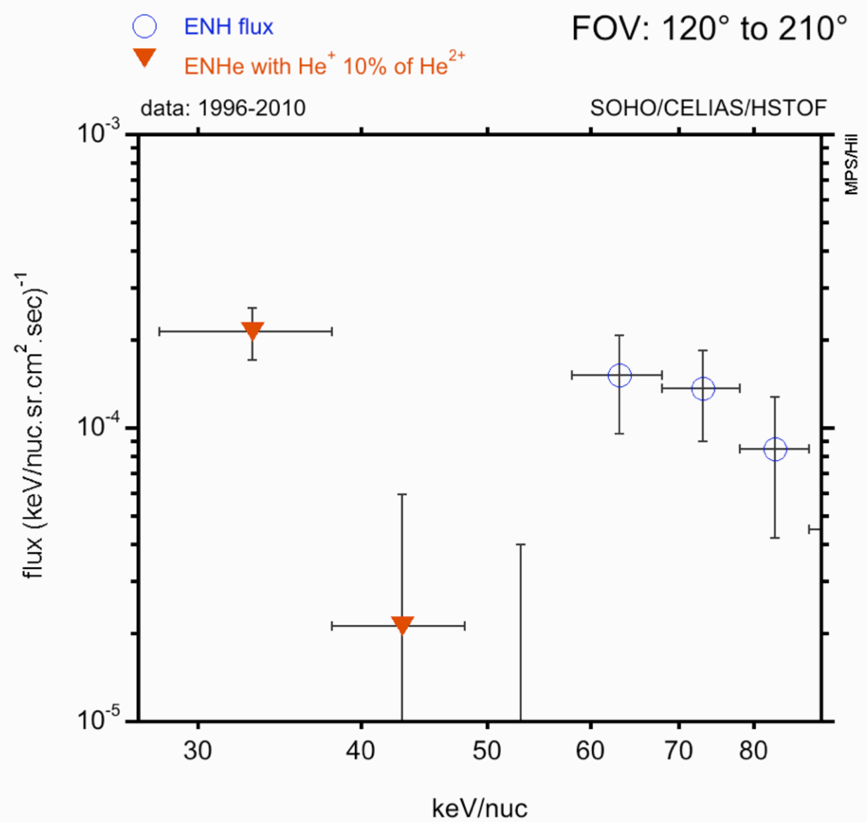


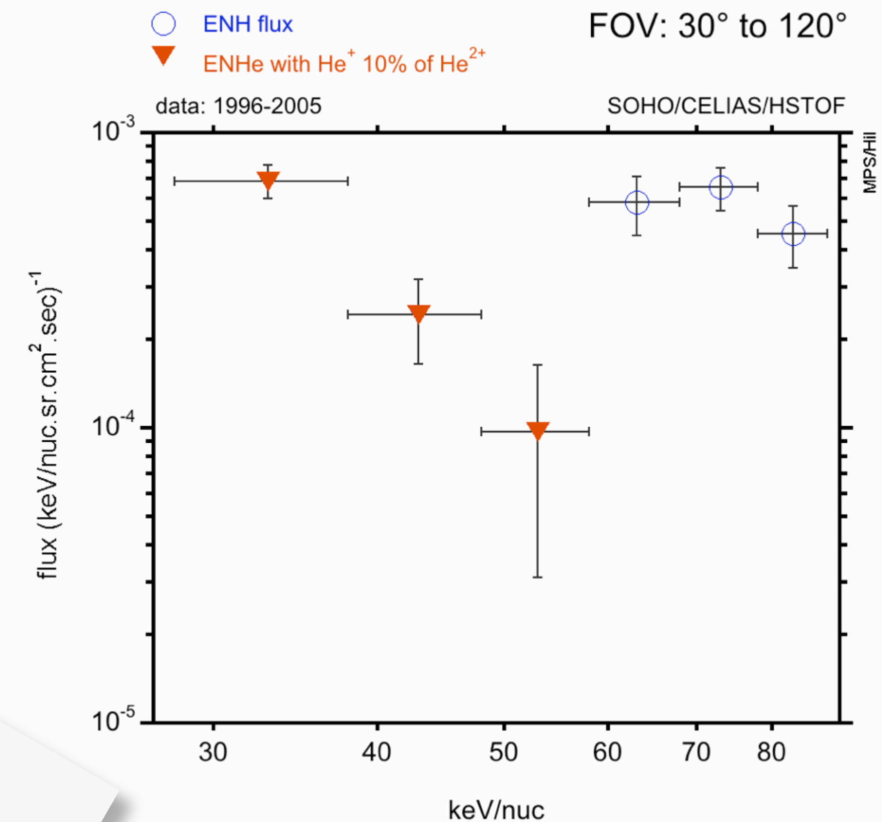




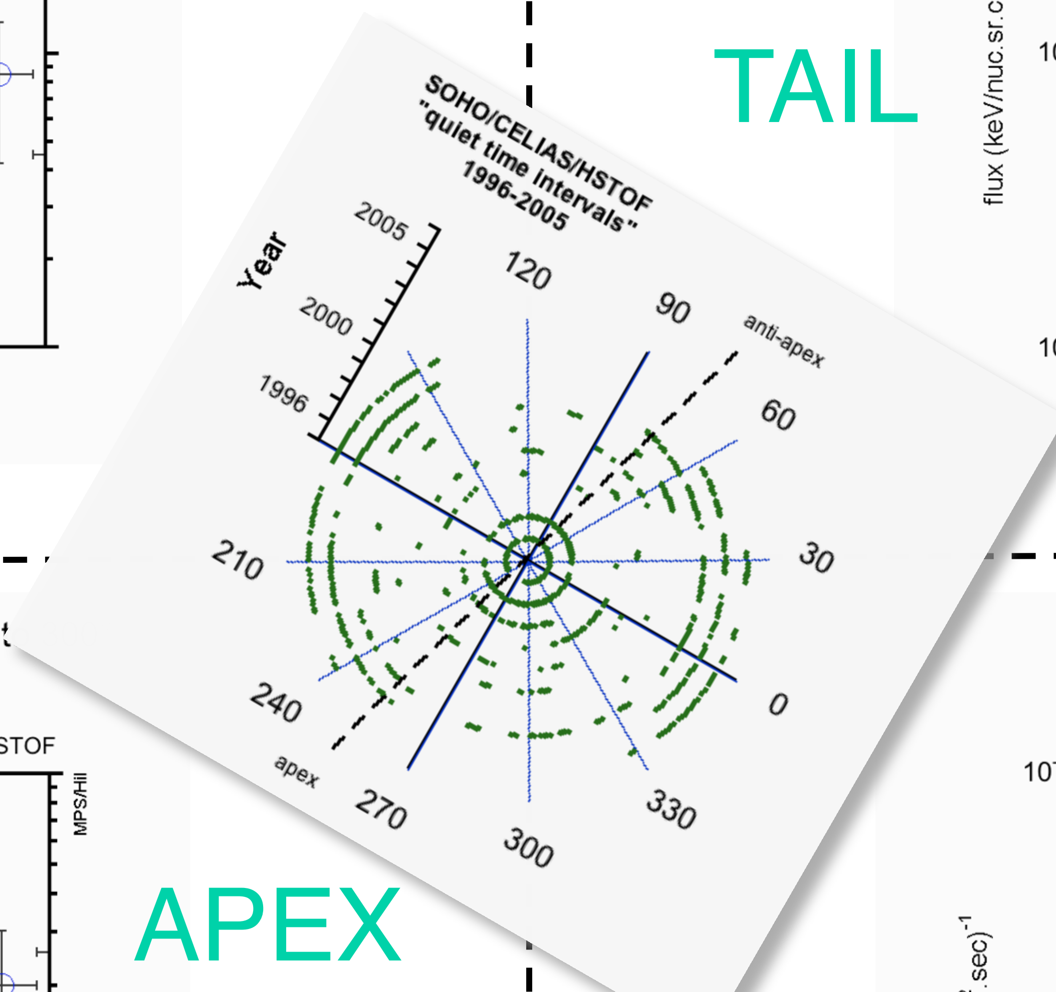
*further onwards, the tail and apex directions are not scanned anymore by SOHO/CELIAS field-of view due to a SOHO onboard antenna motor failure in 2003.

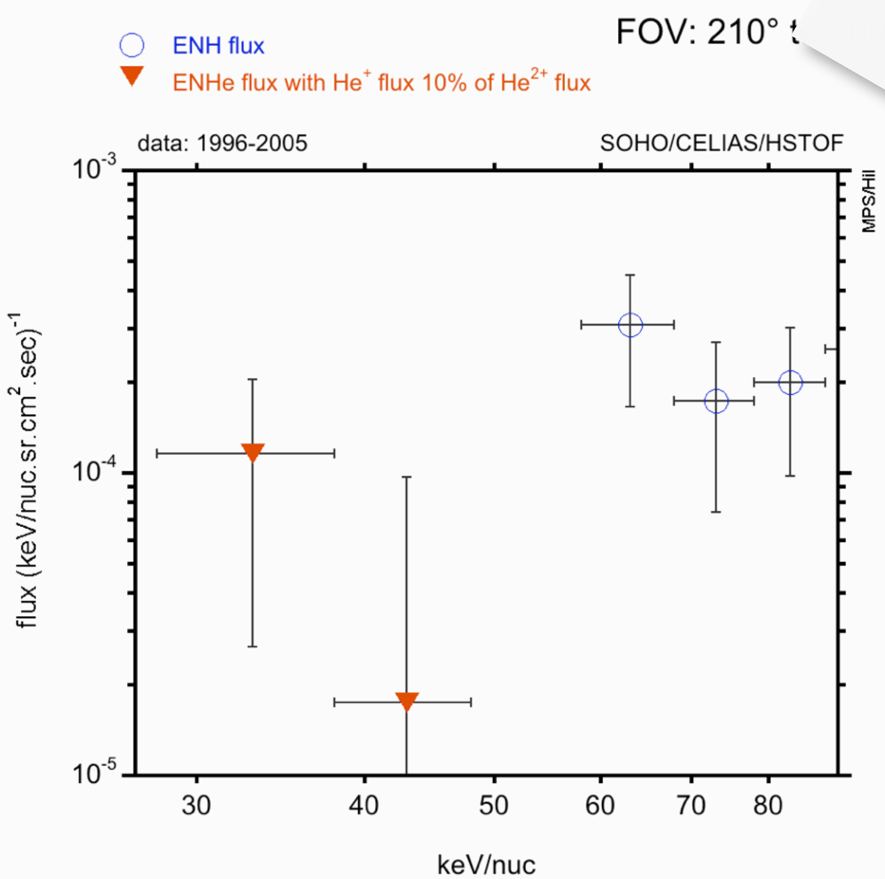
ENH and ENHe energy spectra: FOV direction





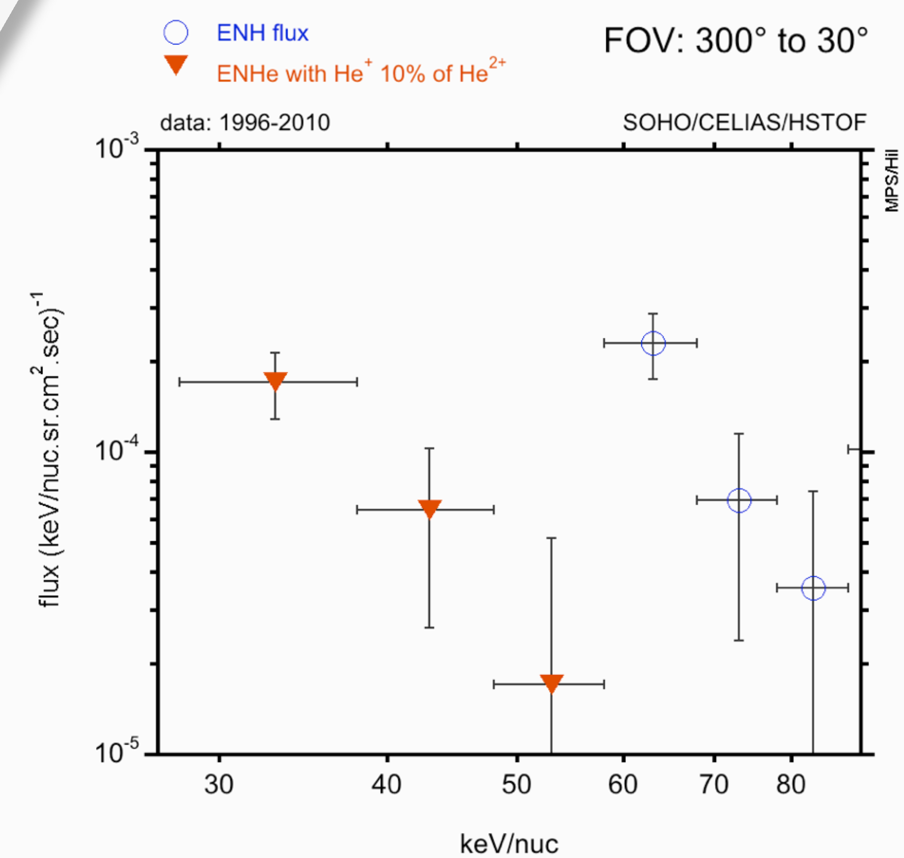
TAIL





APEX

Sector	H^+/He^+
1996–2005	
210°–300°	28.6 ± 24.1
300°–30°	12.8 ± 6.1
120°–210°	16.0 ± 7.0
30°–120°	10.6 ± 1.8
1996–2010	
300°–30°	9.9 ± 3.2
120°–210°	9.0 ± 2.9



Hilchenbach 2011, Czechowski 2012

Anomalous Cosmic Ray Helium Ions as Source of ENHe in the Outer Heliosphere

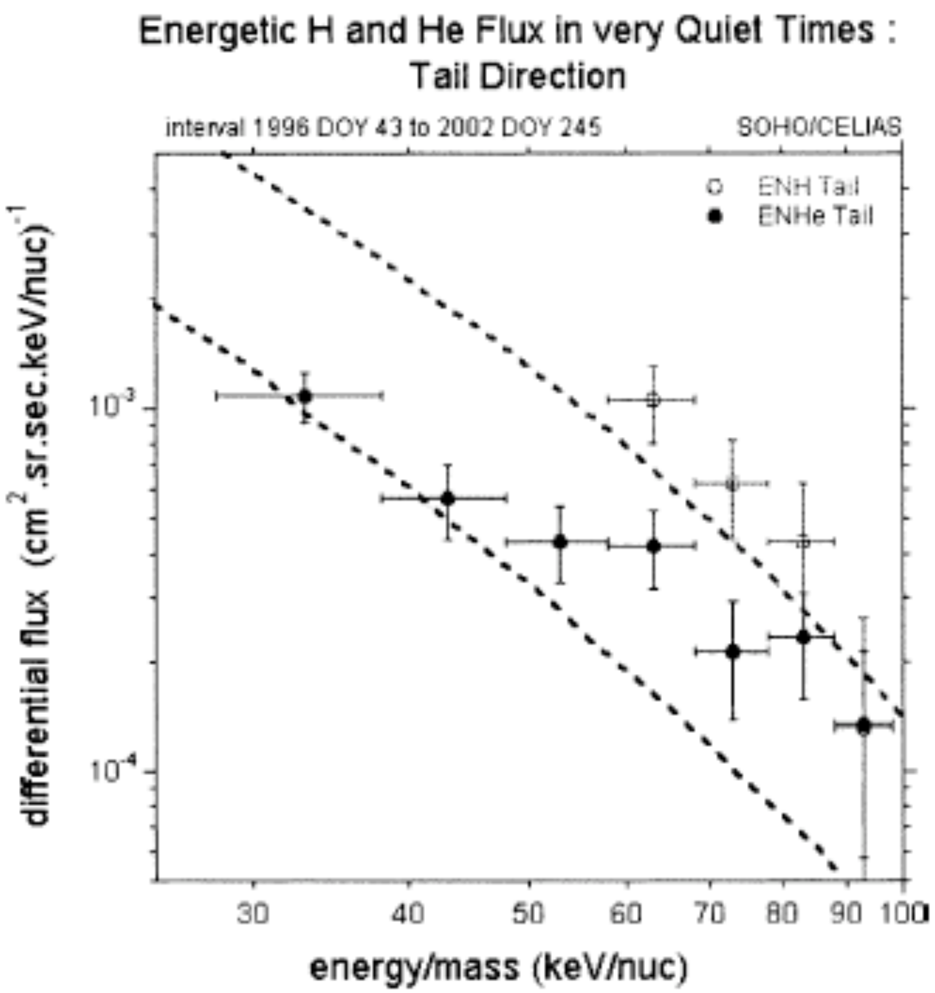


Fig. 5. H and He ENA spectrum from the heliotail direction compared with the ACR ENA model (dotted lines, the lower one for helium).

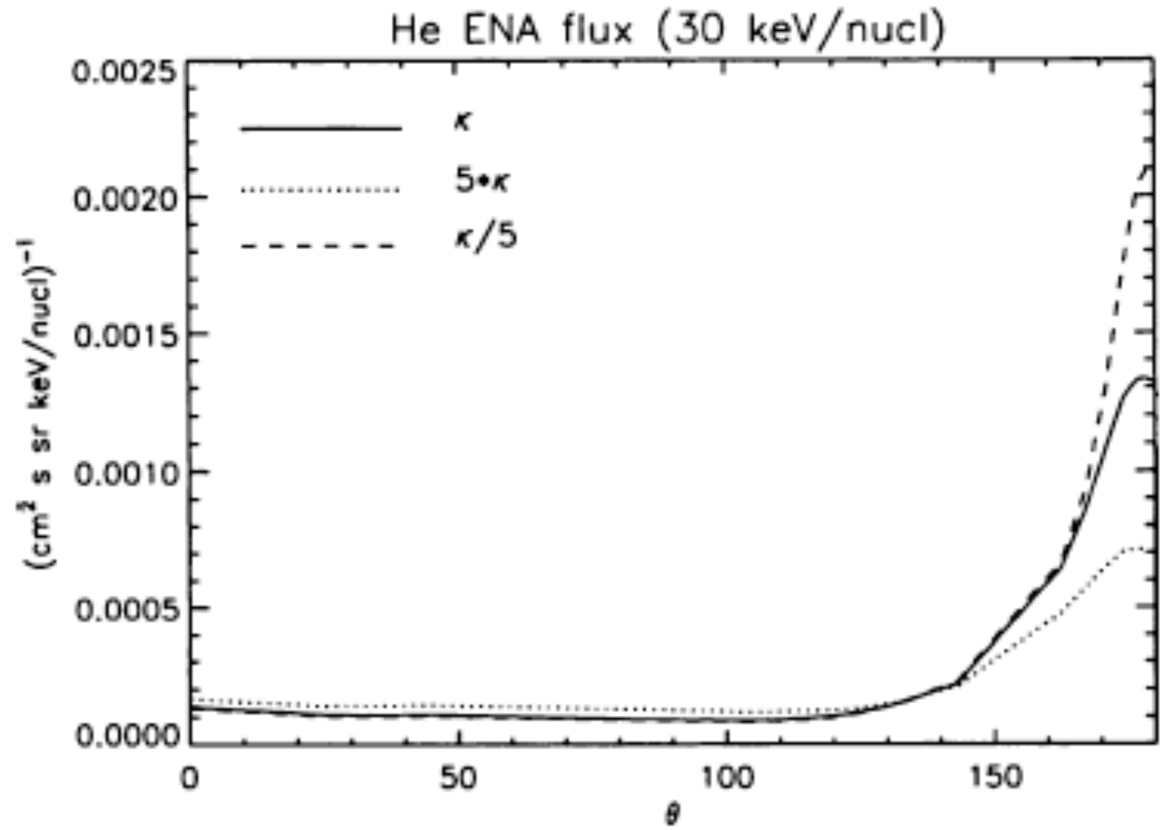
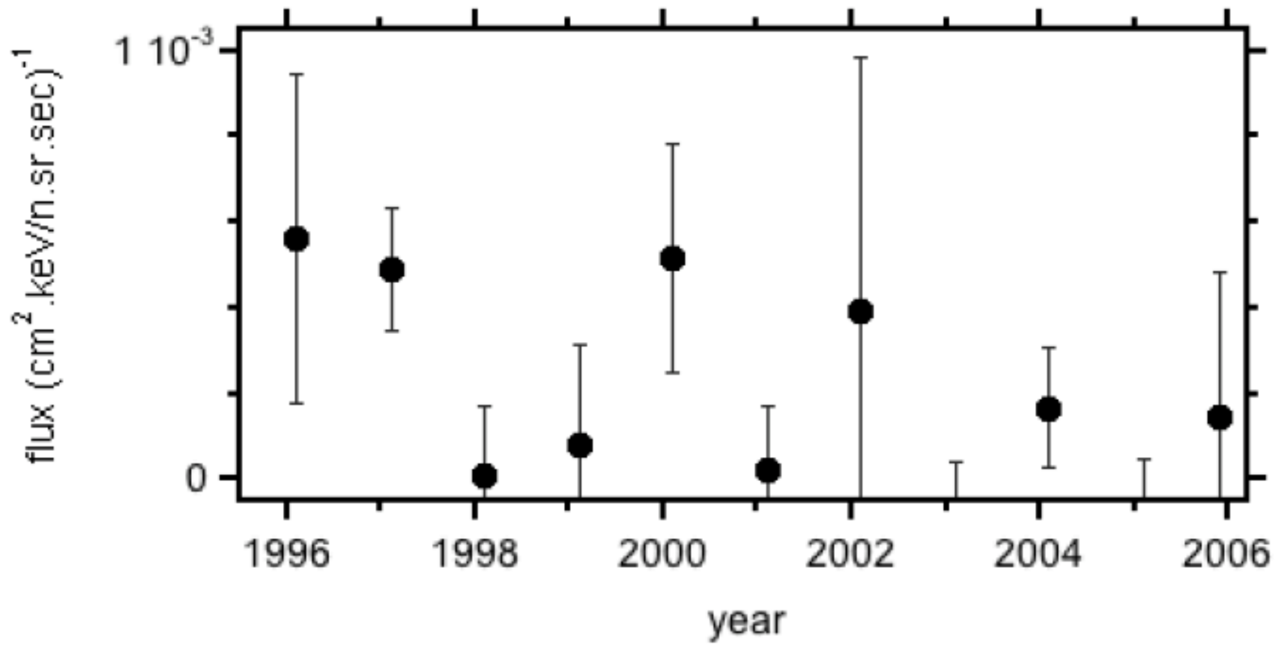


Fig. 4. Calculated He ENA flux in the inner heliosphere as a function of direction. The angle θ is counted from the LISM apex direction, $\theta = 180°$ corresponds to the flux from the heliotail. The dashed (dotted) curve corresponds to the ACR diffusion coefficient increased (decreased) by a factor of five. The anisotropy is much reduced if a higher value of the diffusion coefficient κ is assumed.

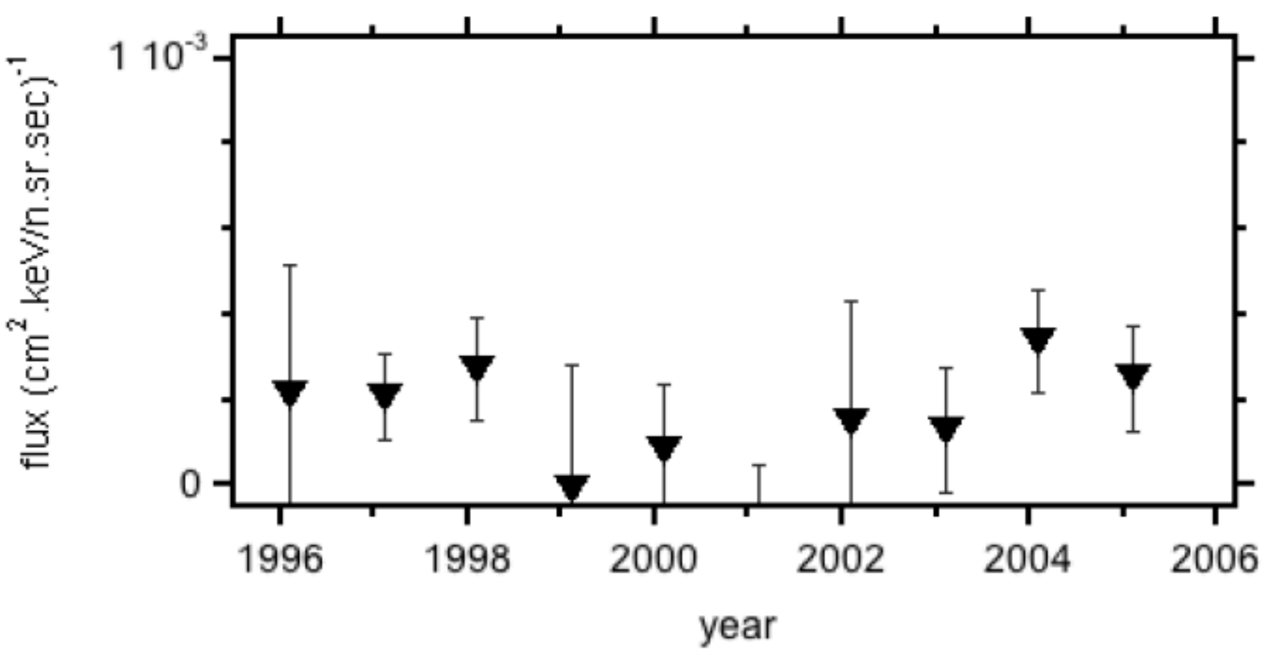
Czechowski 2004

ENH and ENHe Fluxes 1996-2005

Fluxes from apex direction of heliosphere



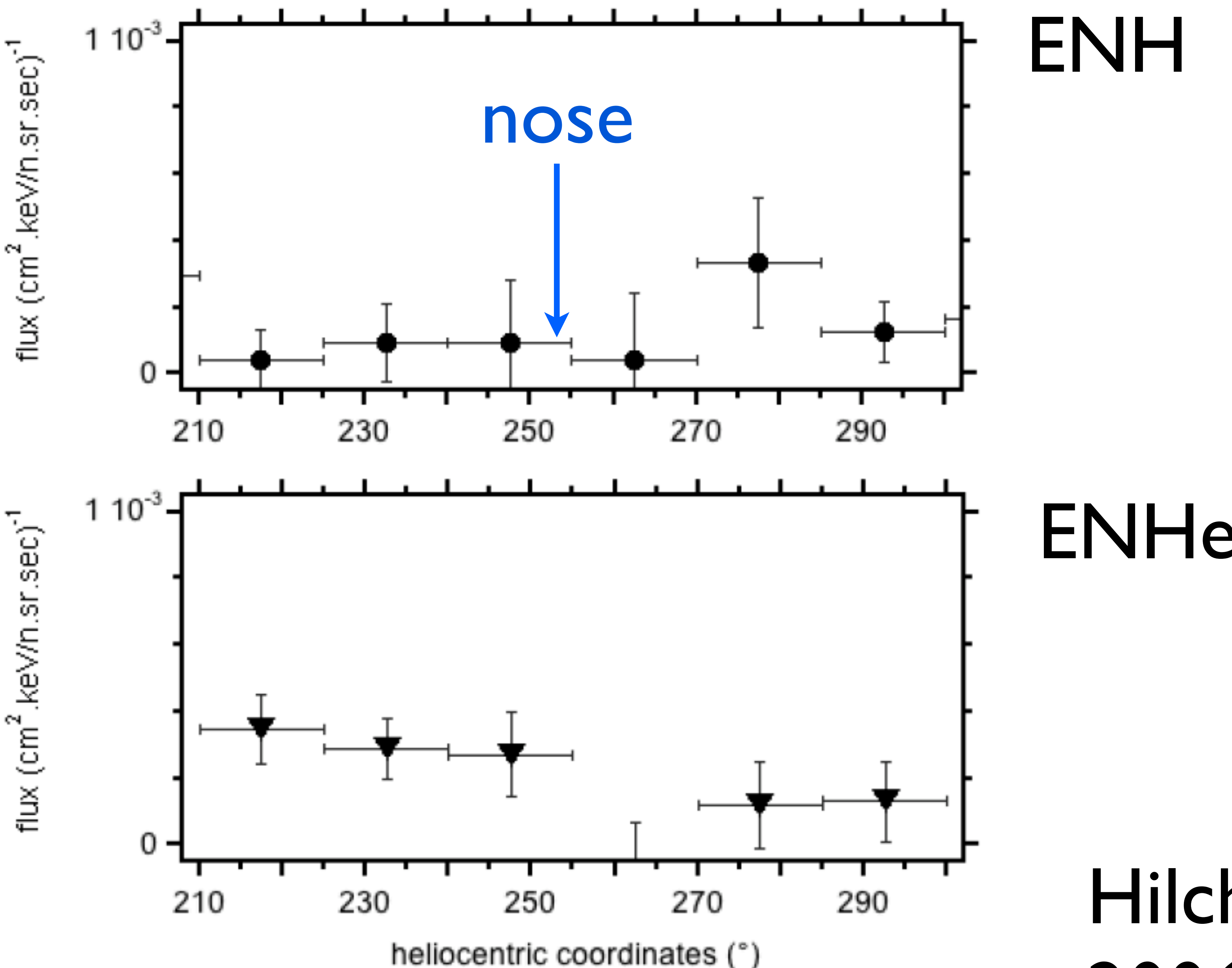
ENH



ENHe

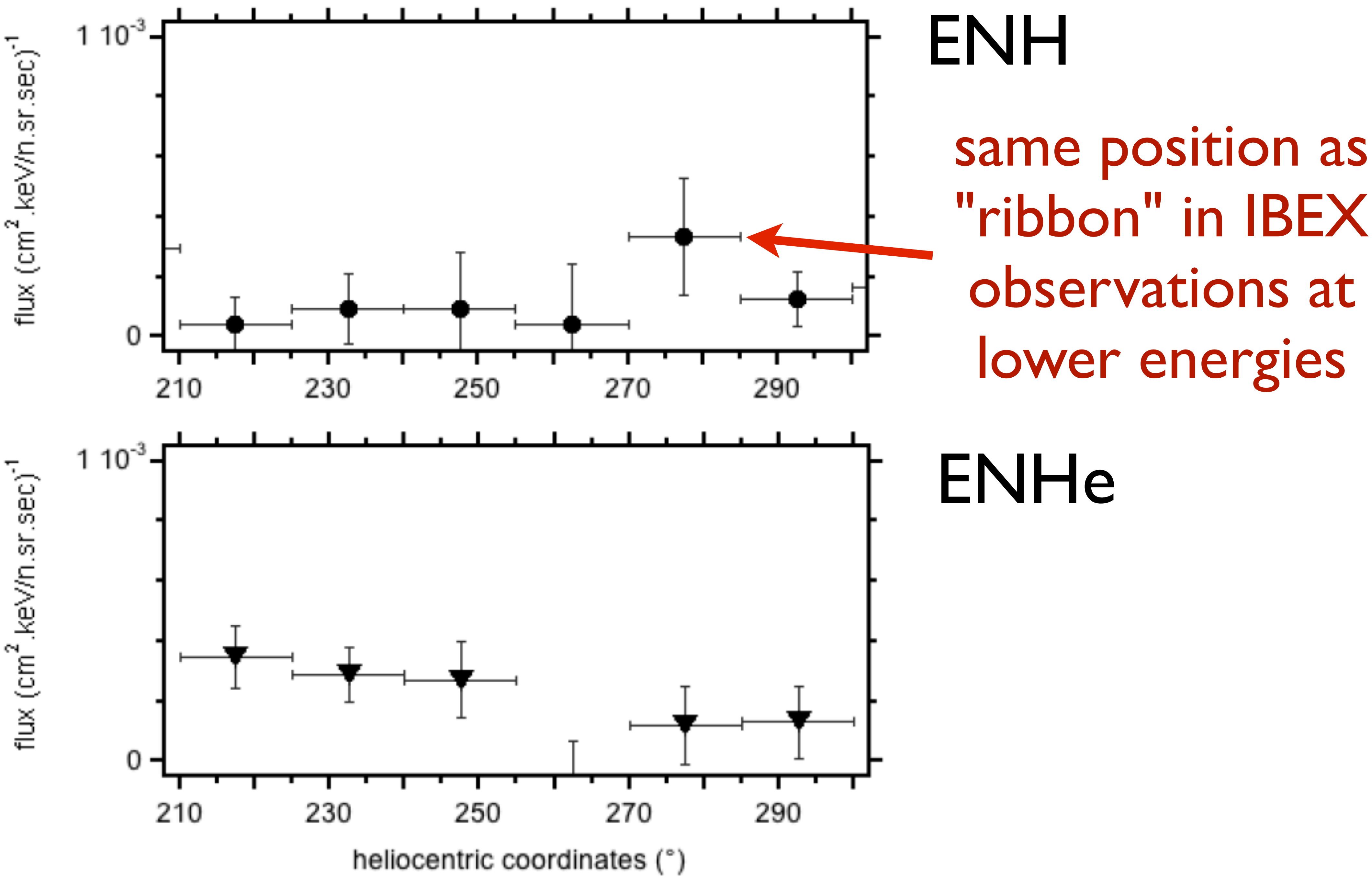
Hilchenbach 2006

ENH and ENHe Fluxes 1996-2005 in the apex-sector of the heliosphere



Hilchenbach 2006

ENH and ENHe Fluxes 1996-2005 in the apex-sector of the heliosphere



Hilchenbach 2006

ENH Fluxes and a Time-Dependent Heliosphere

Assumptions: No diffusion, only convection and no loss processes ...

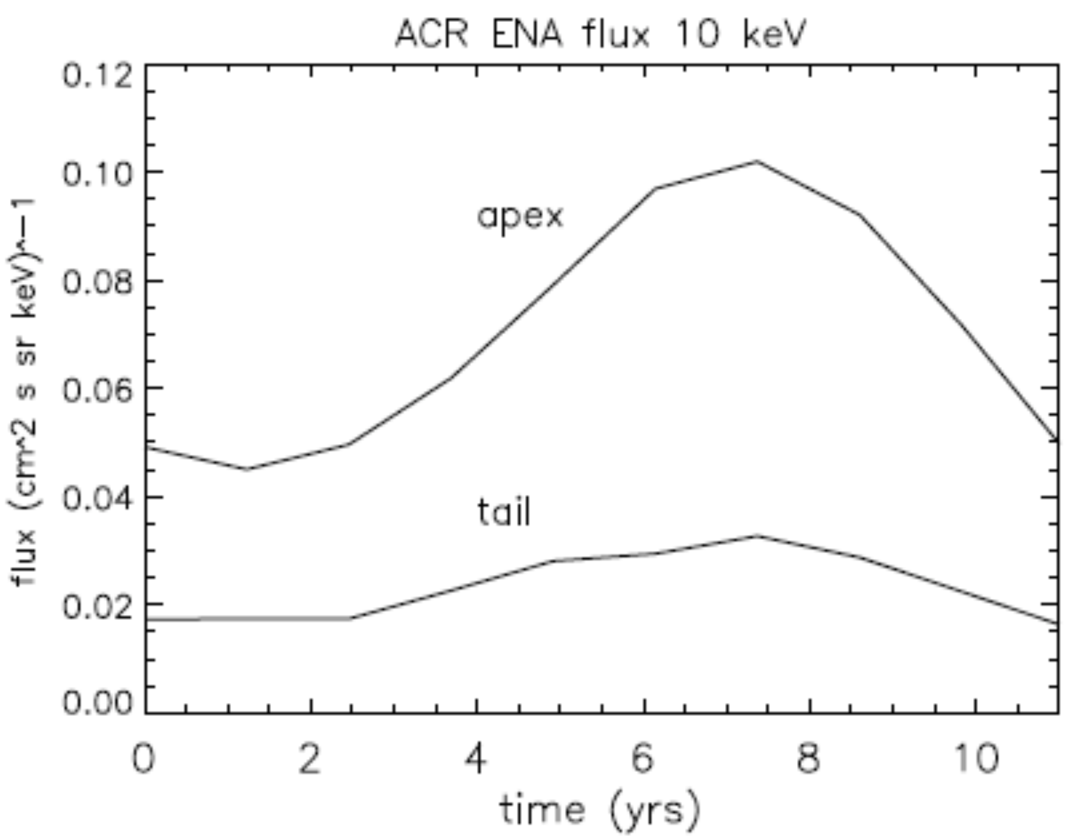


Figure 8. Energetic neutral hydrogen flux at 10 keV from the apex and the heliotail directions as a function of time. The peak of the flux occurs near "solar maximum".

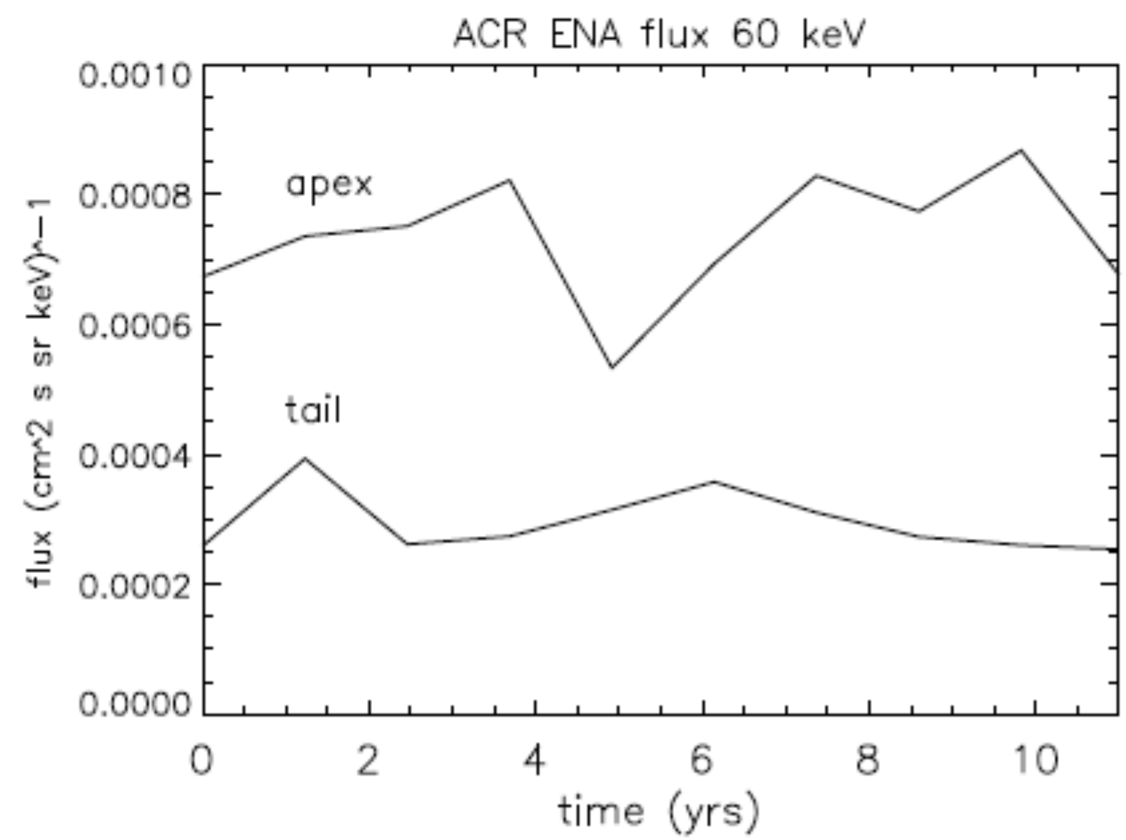


Figure 9. Energetic neutral hydrogen flux at 60 keV from the apex and the heliotail directions as a function of time. There is no peak at the "solar maximum".

Time variations of the ENA fluxes should show up more pronounced in the energy region < 10 keV.
Furthermore, the model parameters applied in these calculations led to an increased ENA flux from the apex region.

Hilchenbach 2005
Scherer 2005

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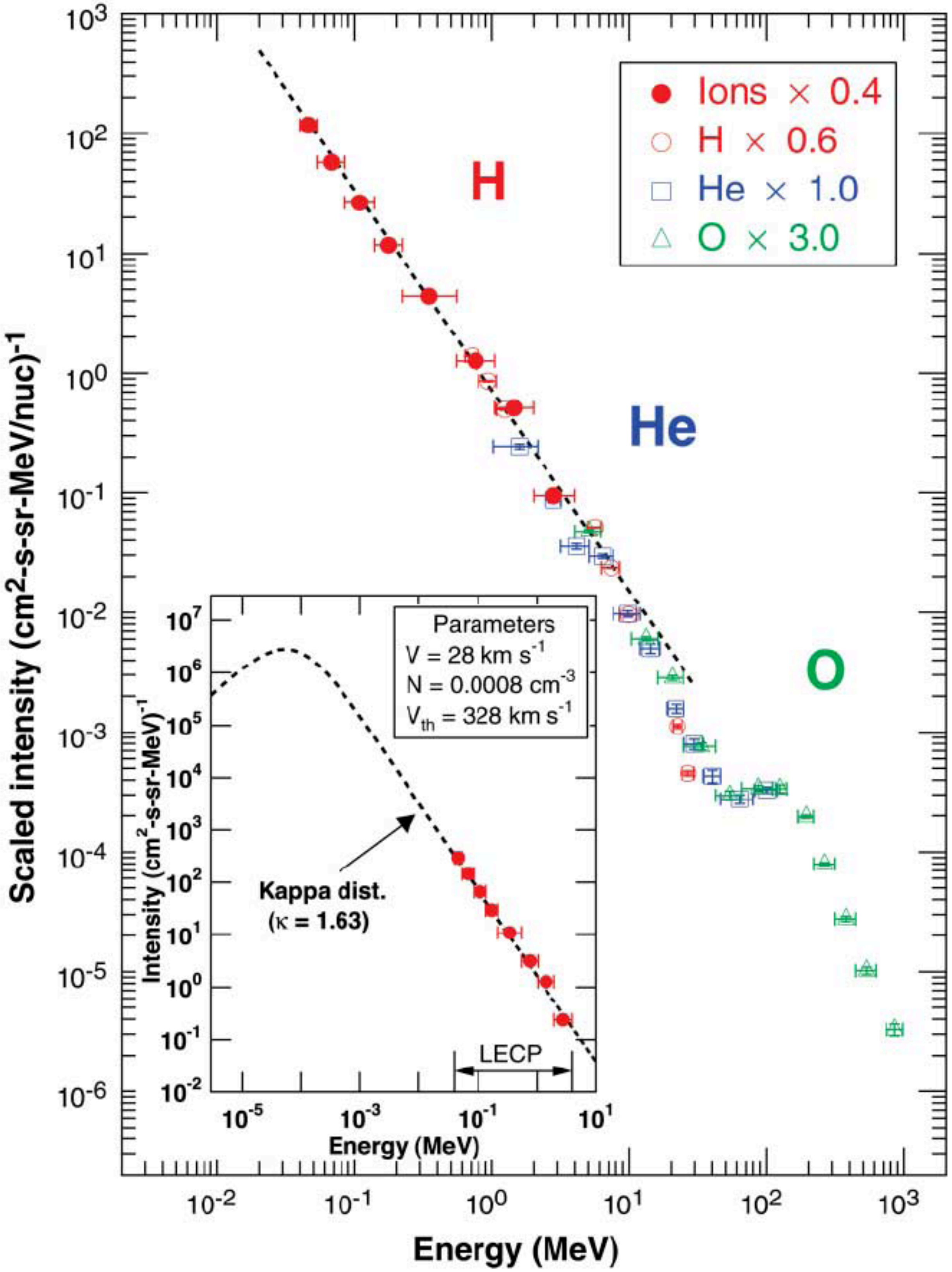
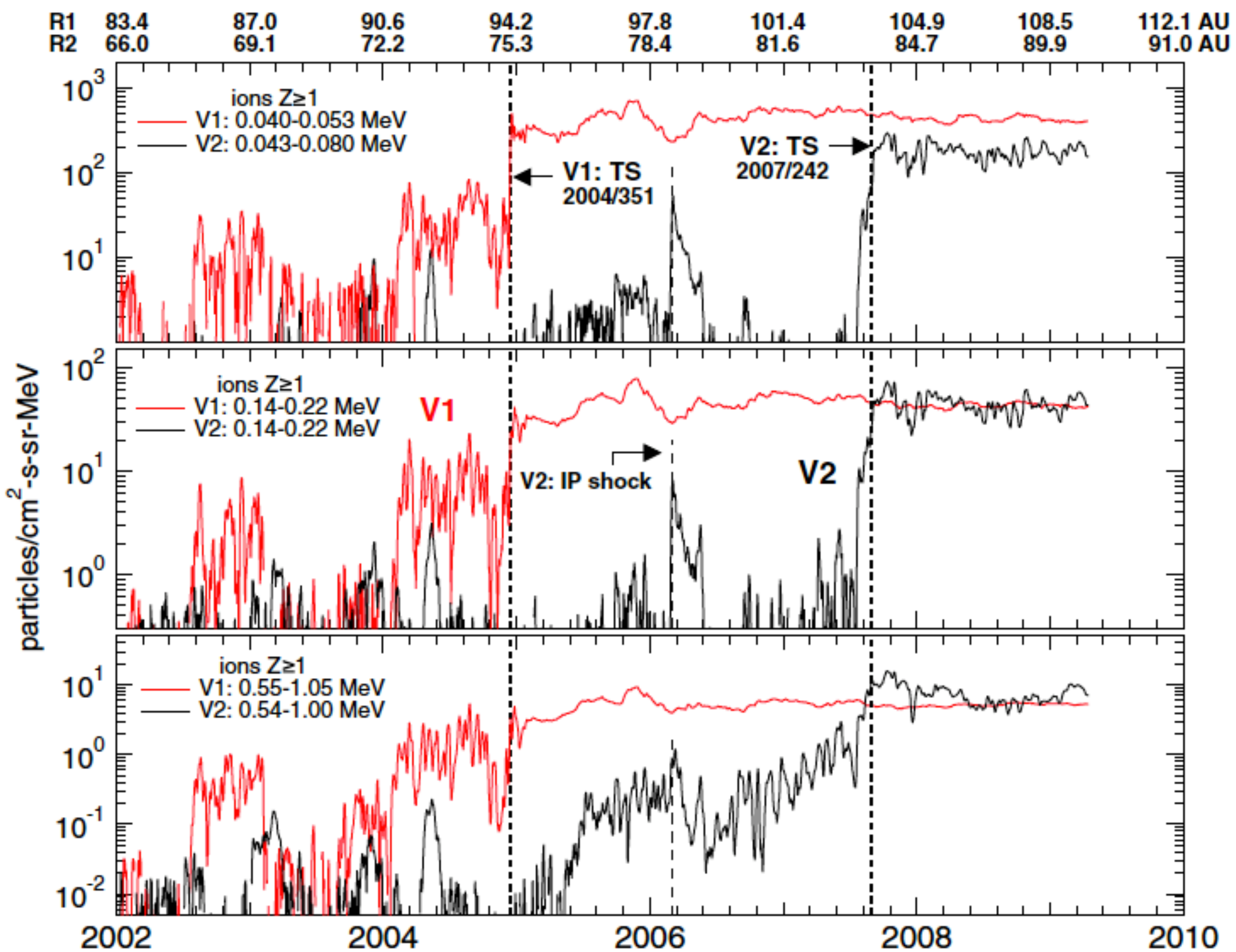
- Within and beyond the heliopause: Comets and the heliosphere


SMITH-CORONA

Energetic ions of the Heliosheath

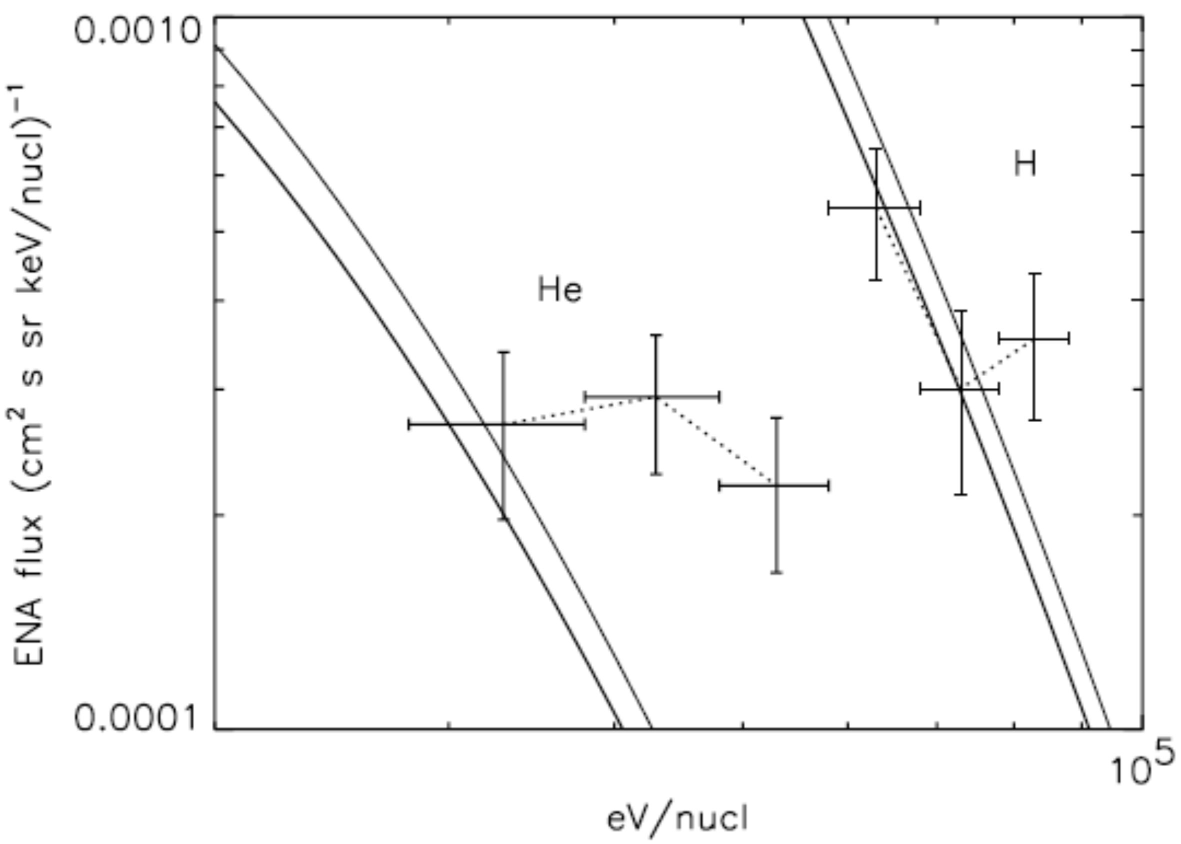




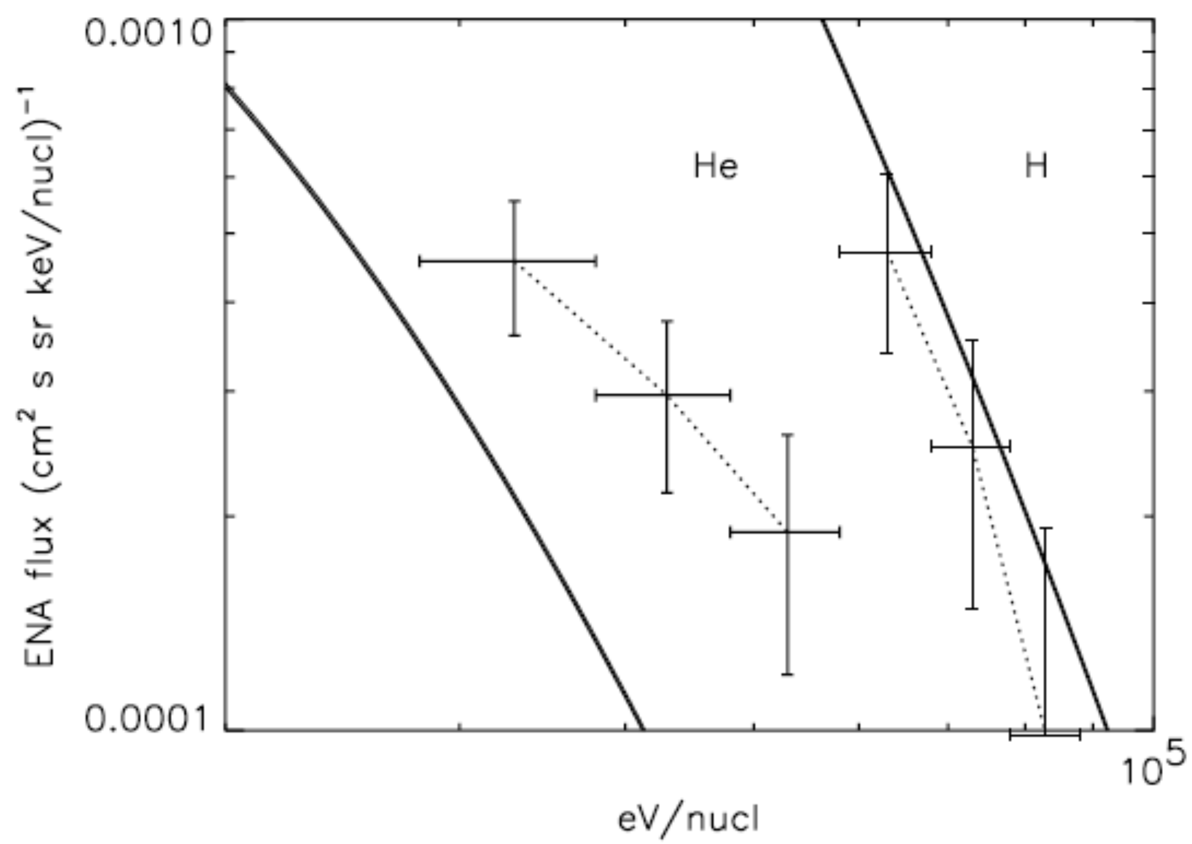
Decker 2005

Decker 2009

Thickness of the heliosheath in apex direction (SOHO/CELIAS/HSTOF and Voyager 1)



1996-1997



1998-2003

->Average thickness of heliosheath L (n_H about 0.1 cm^{-3}): about 75 AU -> in apex direction ("nose") about 30 AU....

Czechowski 2006

Thickness of the Heliosheath

Table 2. Results from numerical models.

Model	$n_{\mathrm{p,LISM}}$ ($\mathrm{cm^{-3}}$)	$n_{\mathrm{H,LISM}}$ ($\mathrm{cm^{-3}}$)	L(apex) (AU)	N_{H}(apex) ($\mathrm{cm^{-2}}$)
1[a]	0.1	0.1	39	0.36×10^{14}
2[a]	0.04	0.2	45	1.1×10^{14}
3[b]	0.04	0.24	47	1.1×10^{14}
4[b]	0.1	0.1	33	0.23×10^{14}
5[b]	0.1	0.14	25	0.21×10^{14}
6[b]	0.1	0.24	27	0.44×10^{14}
7[c]	0.1	0.2	55	0.9×10^{14}
8[c]	0.07	0.2	75	1.3×10^{14}
9[c]	0.04	0.2	85	1.6×10^{14}

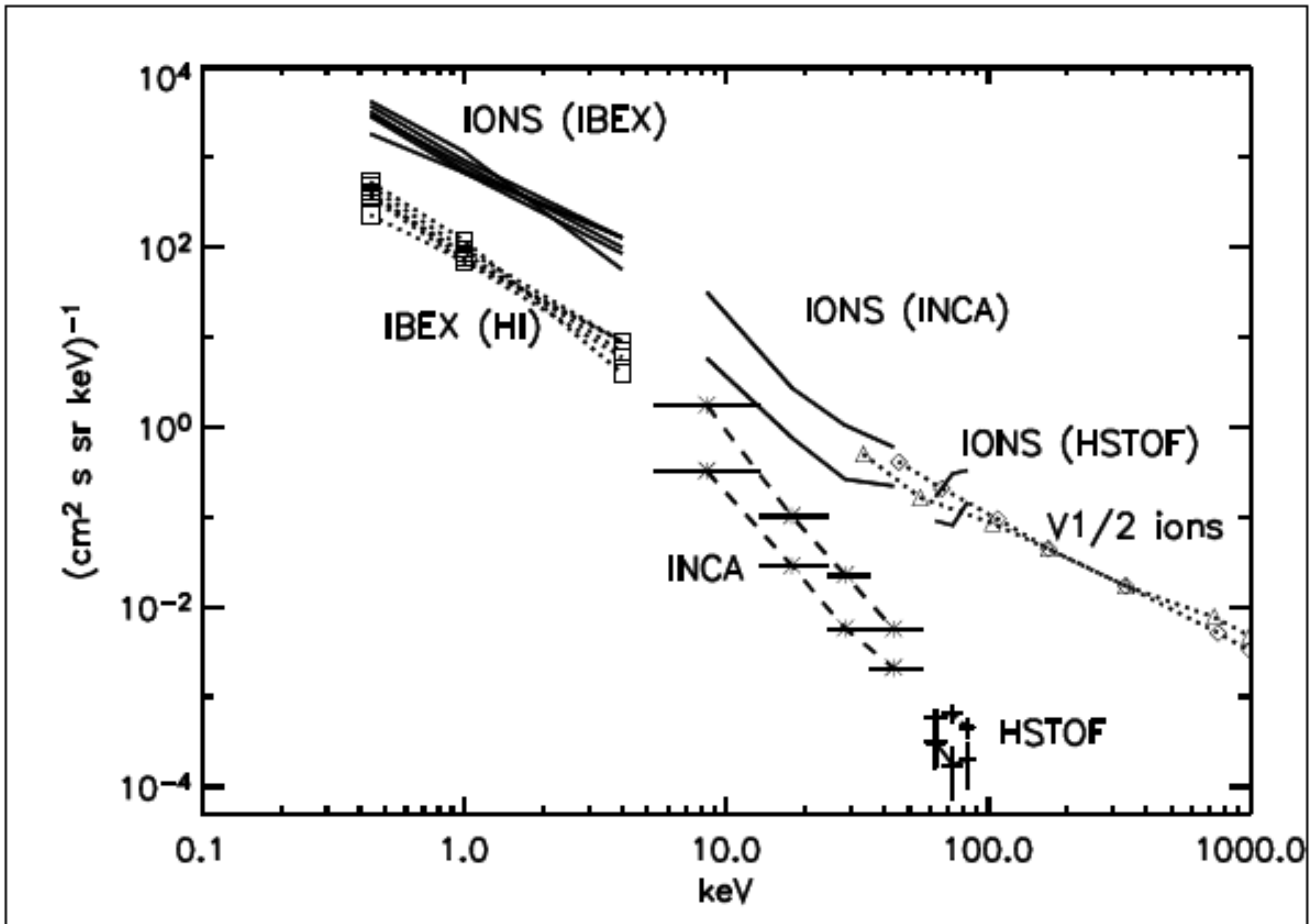
[a] Bonn model: Fahr et al. (2000); [b] multifluid: Müller et al. (2006); [c] kinetic: Izmodenov et al. (1999).

Estimate of L based on SOHO/CELIAS/STOF ENH, ENHe and VOYAGER 1 LECP data
N_H = (0.63 +/- 0.19) x 10^{14} $\mathrm{cm^{-2}}$
corresponding to a thickness of the heliosheath
L = 42 +/- 12 AU with n_H = 0.1 $\mathrm{cm^{-3}}$.

Czechowski 2008

How SOHO/HSTOF data fit into the global picture of neutral and charged particle observations

(IBEX, CASSINI-INCA, SOHO-CELIAS-HSOTF, VOYAGER-LECP)



Thickness of the Heliosheath

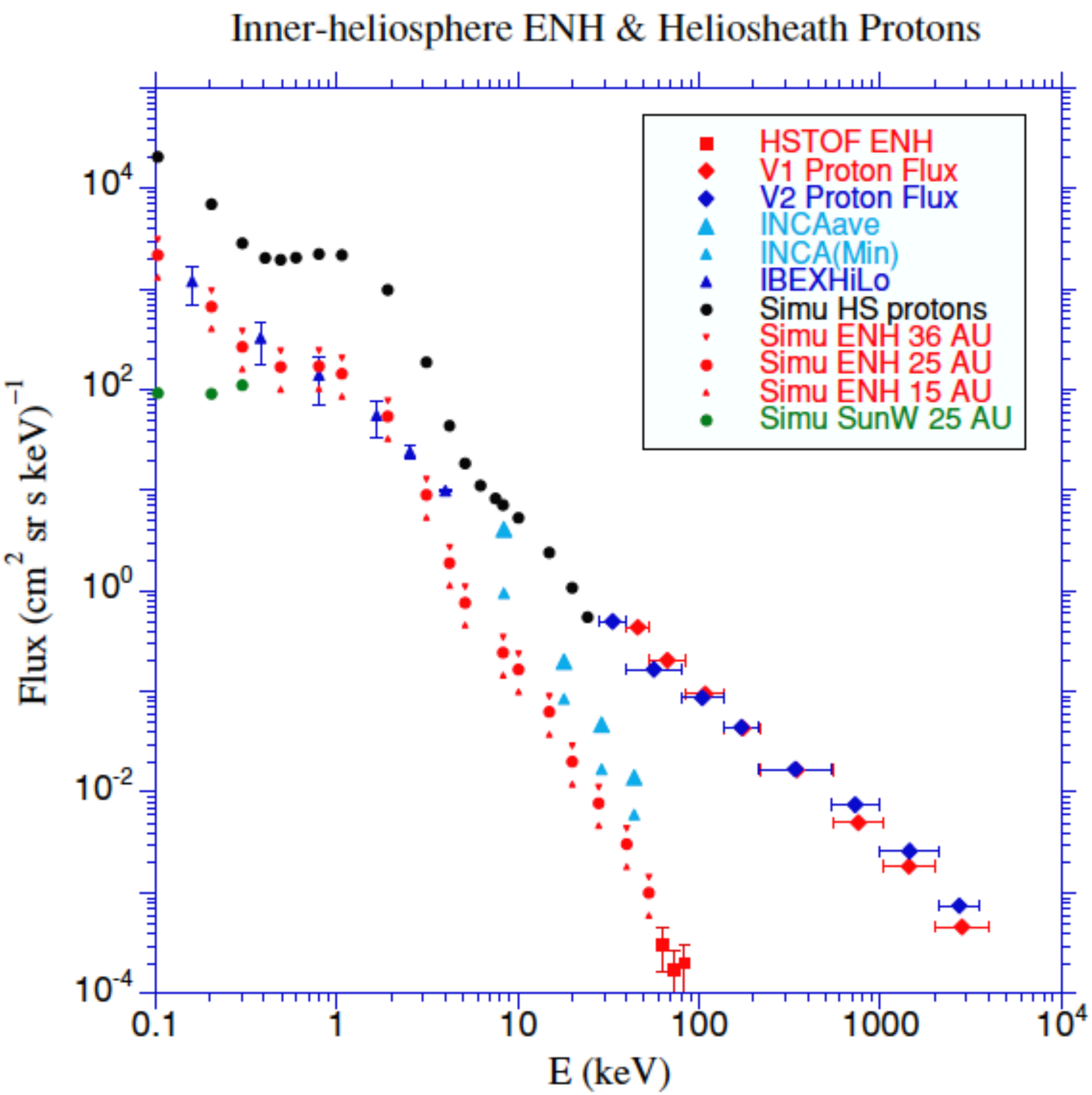
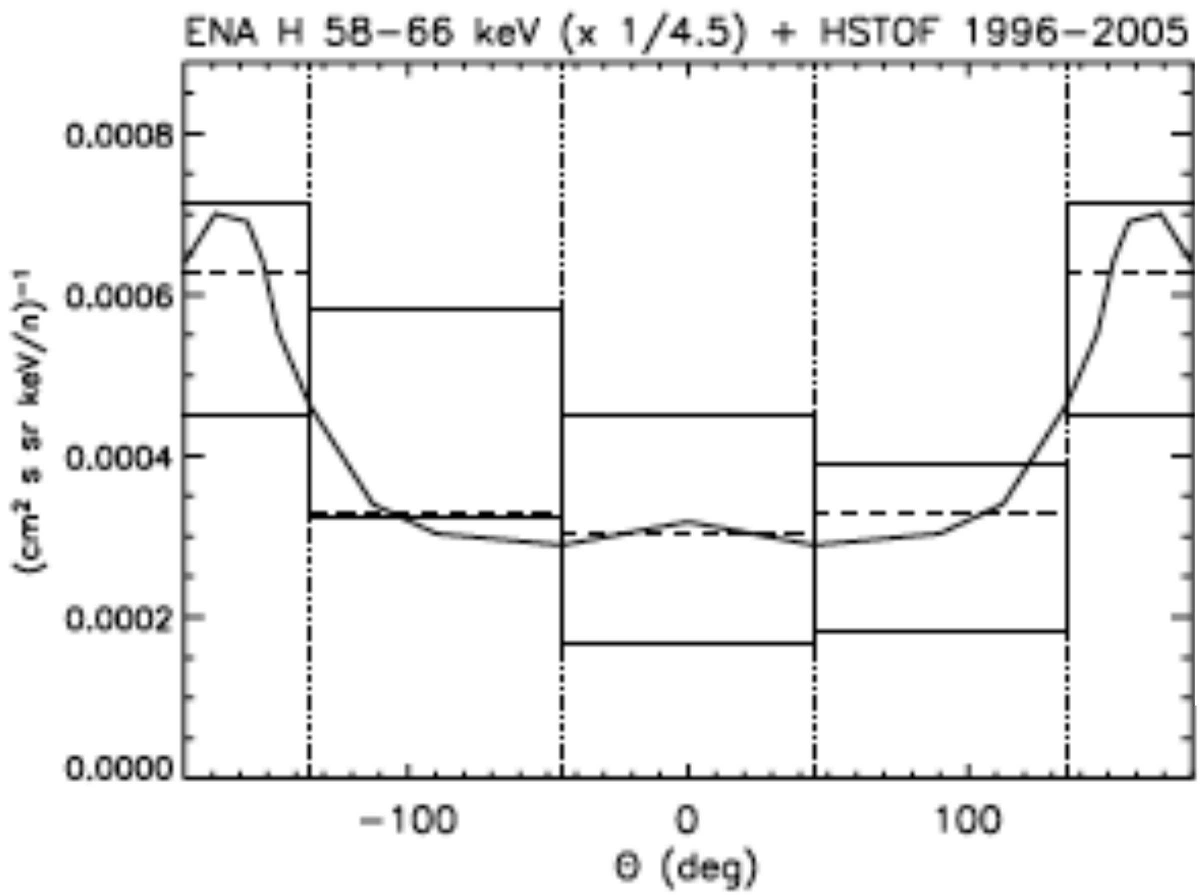


Table 1.
Estimated Characteristic Thickness of the Frontal Lobe of HS

Proton Spectrum	A	γ	L (AU)	ΔL(AU)
V1	183.5	1.60	21	6
V2	57.5	1.39	28	8
Combined	99.3	1.49	25	8

Hsieh 2010

Thickness of the Lobes of the Heliosheath



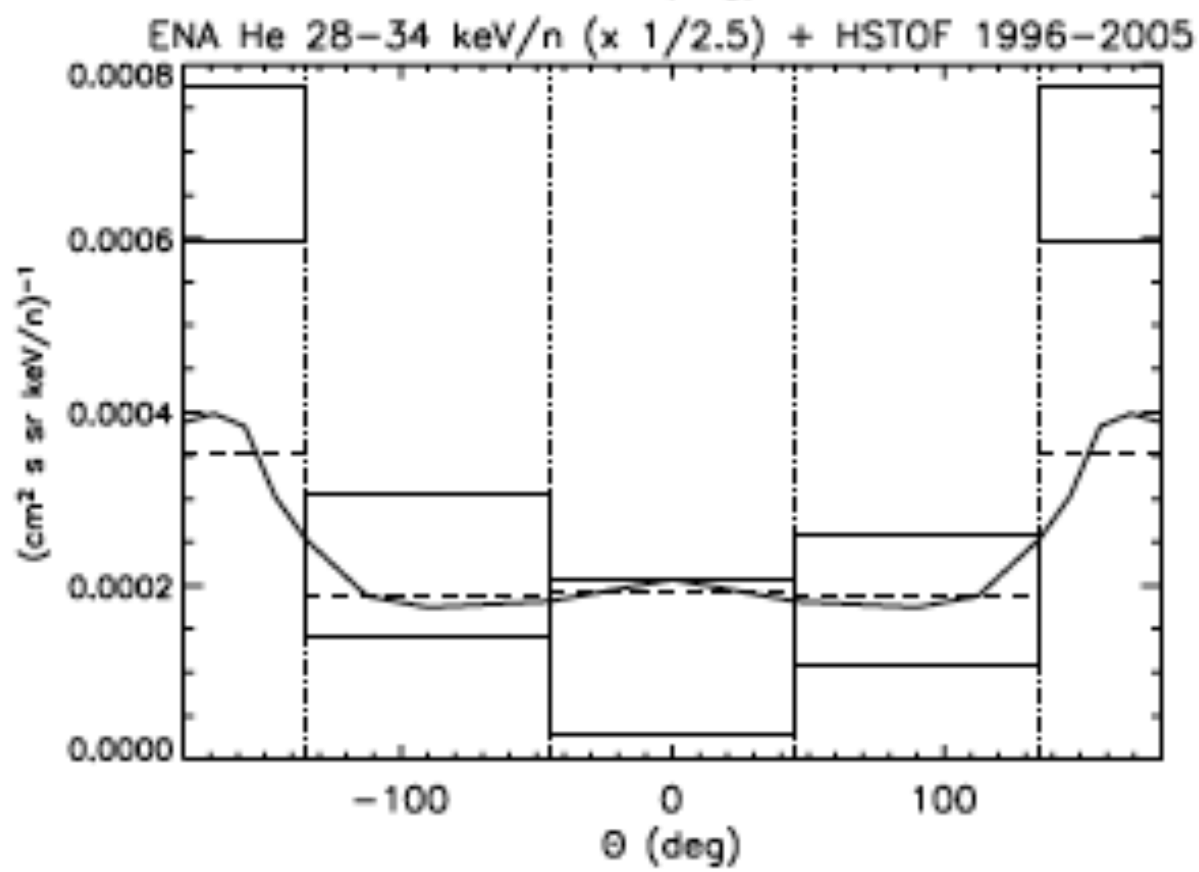
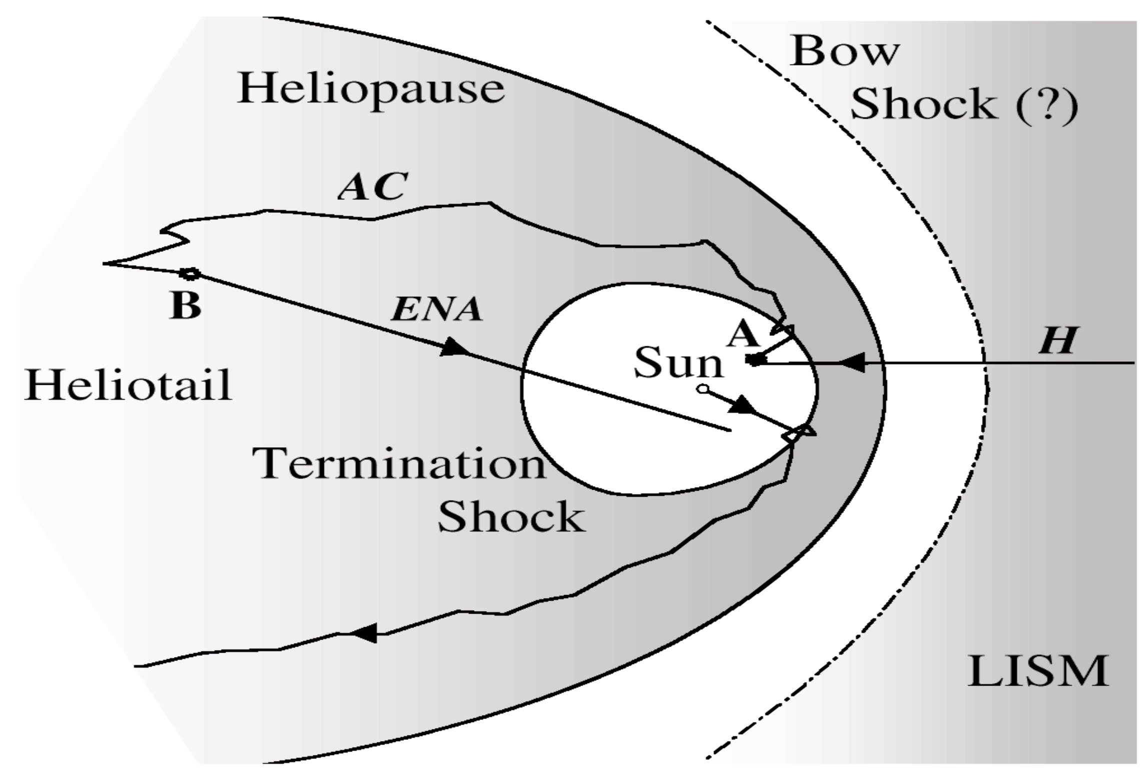


Table 2. L_{eff} derived from observations (HSTOF ENA and Voyager ion data).

Sector	L_{eff} (V1) (AU)	L_{eff} (V2) (AU)
1996–2005		
210°–300°	19.9 ± 6.2	31.0 ± 9.5
300°–30°	13.8 ± 4.7	20.8 ± 7.3
120°–210°	24.2 ± 5.7	37.3 ± 8.7
1996–2010		
300°–30°	11.2 ± 2.5	17.0 ± 3.9
120°–210°	10.2 ± 2.6	16.1 ± 4.0



Czechowski 2012

Conclusion

ENH and ENHe fluxes from apex direction observed by SOHO/HSTOF are consistent with a heliosheath thickness of **25 +/- 8 AU**

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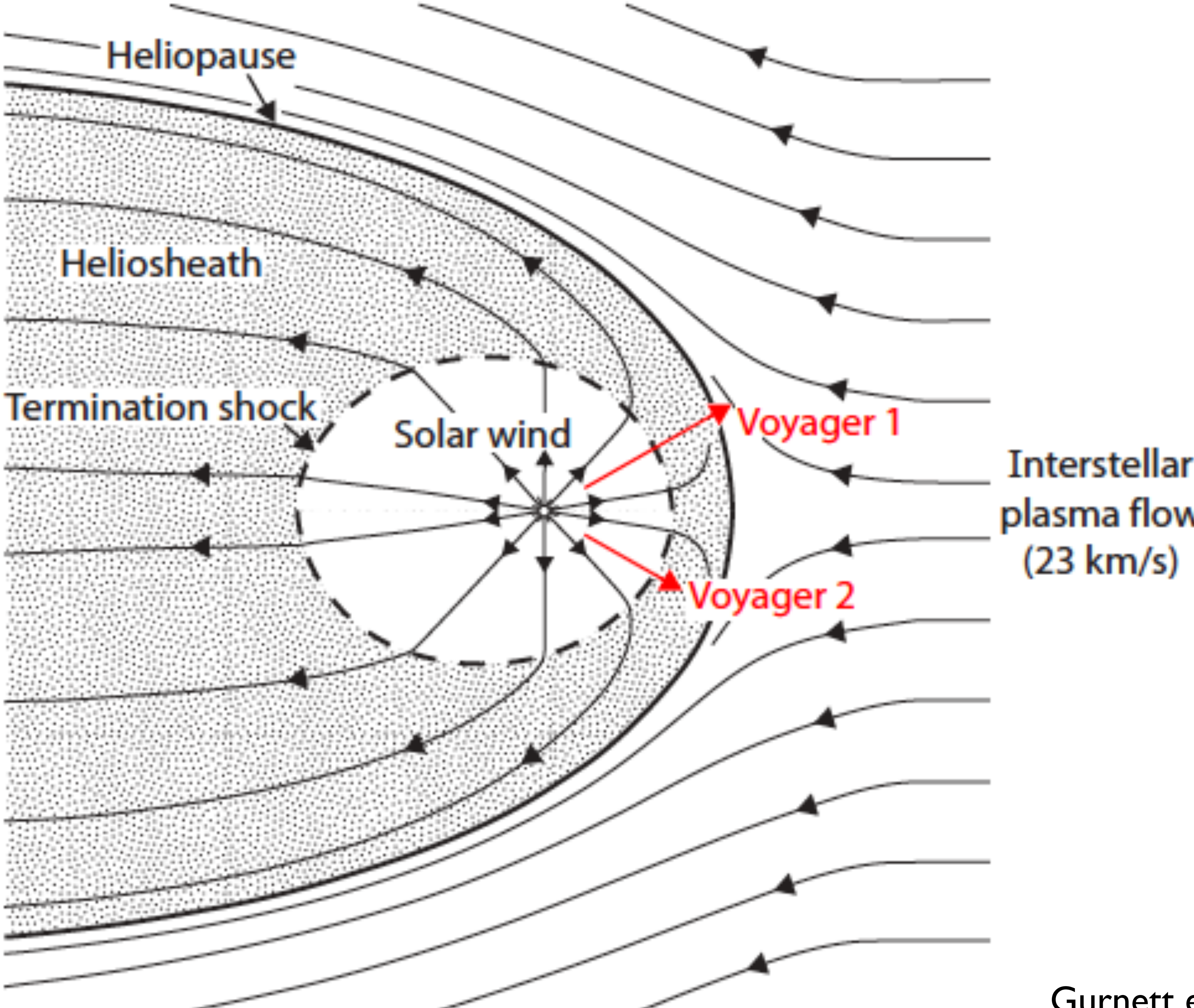
- Within and beyond the heliopause: Comets and the heliosphere

Shigeo Fukuda:

Projection of a piano ...

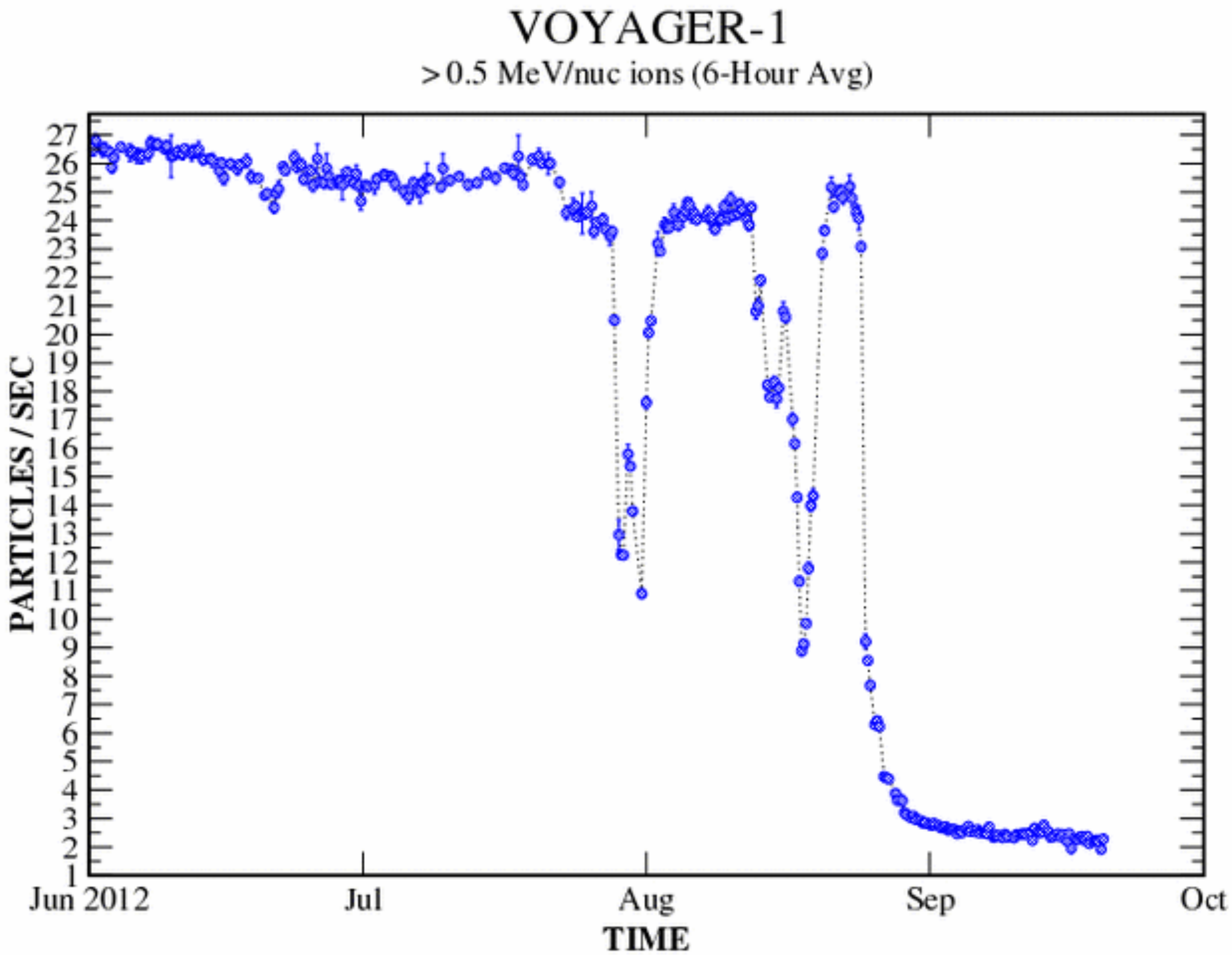
... and the full view

Voyager 1 and Voyager2

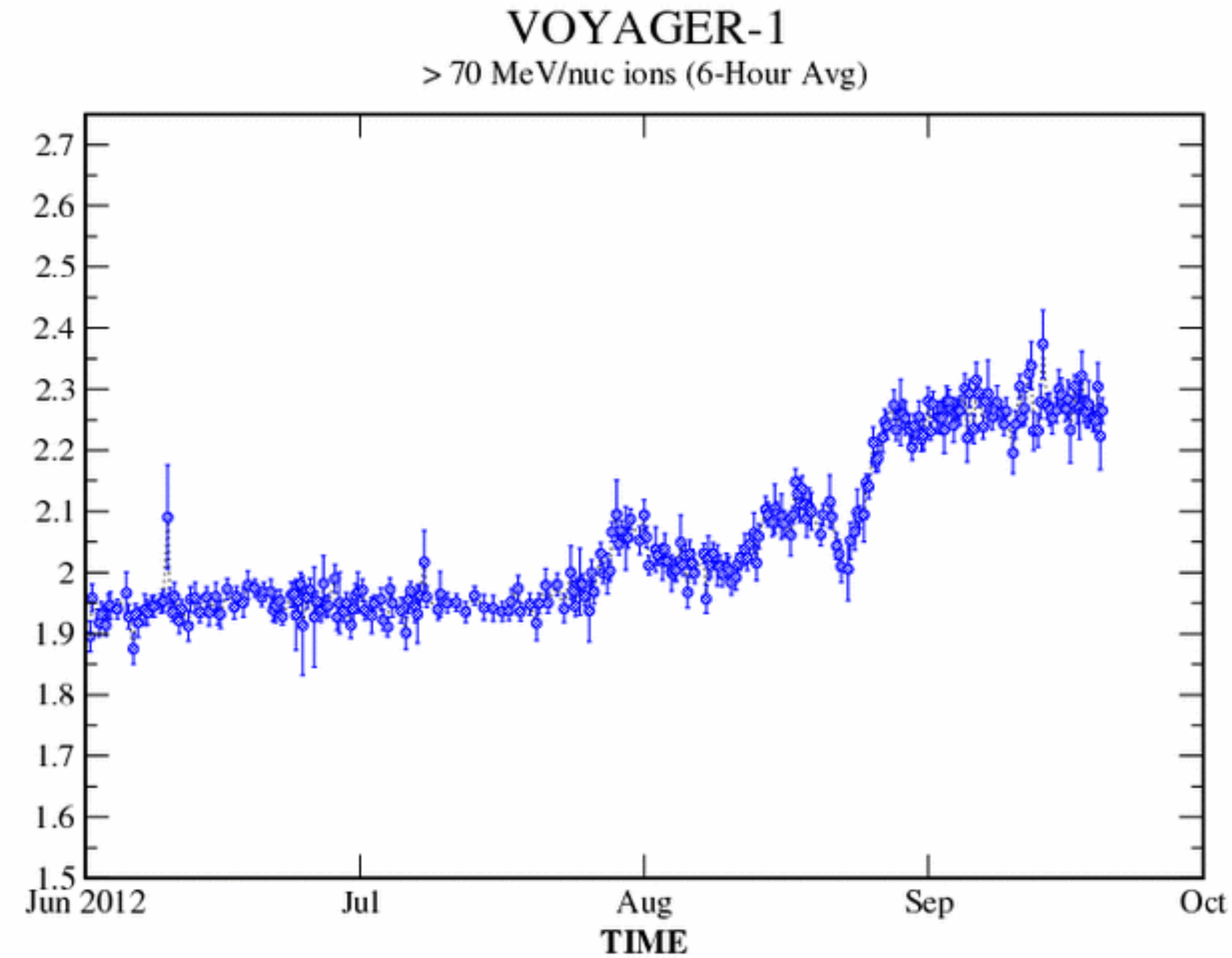


Gurnett et al 2013

Voyager 1 at 121.94 AU (archive data...): Has Voyager 1 crossed into the heliopause?

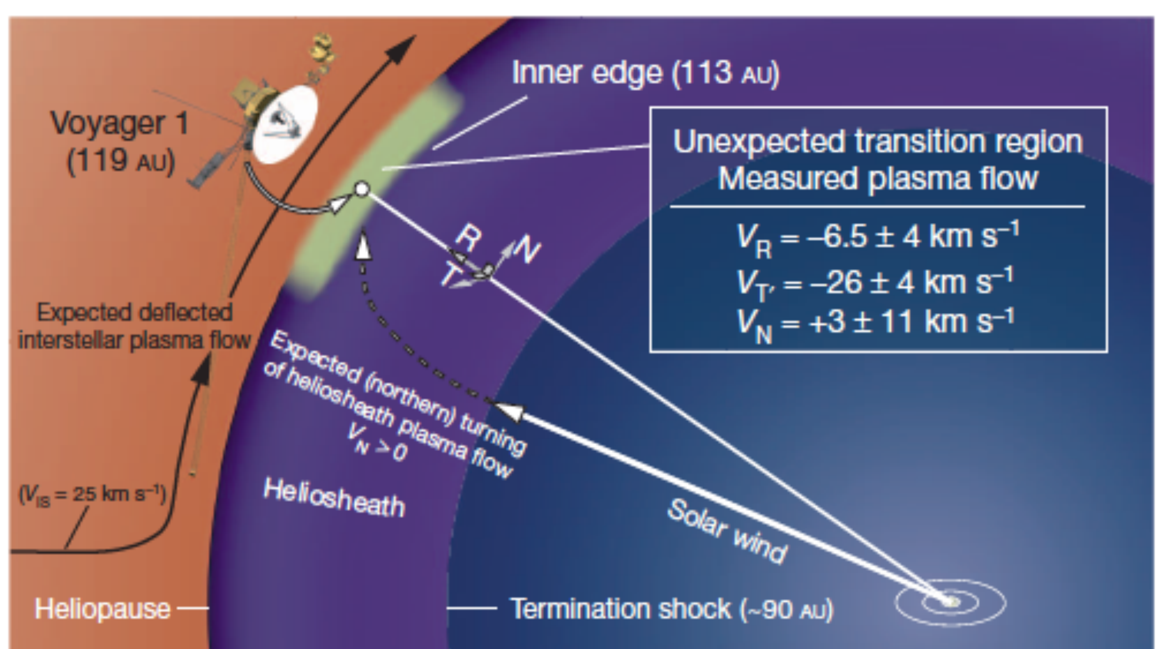


Generated:
Thu Sep 20 21:31:19 2012



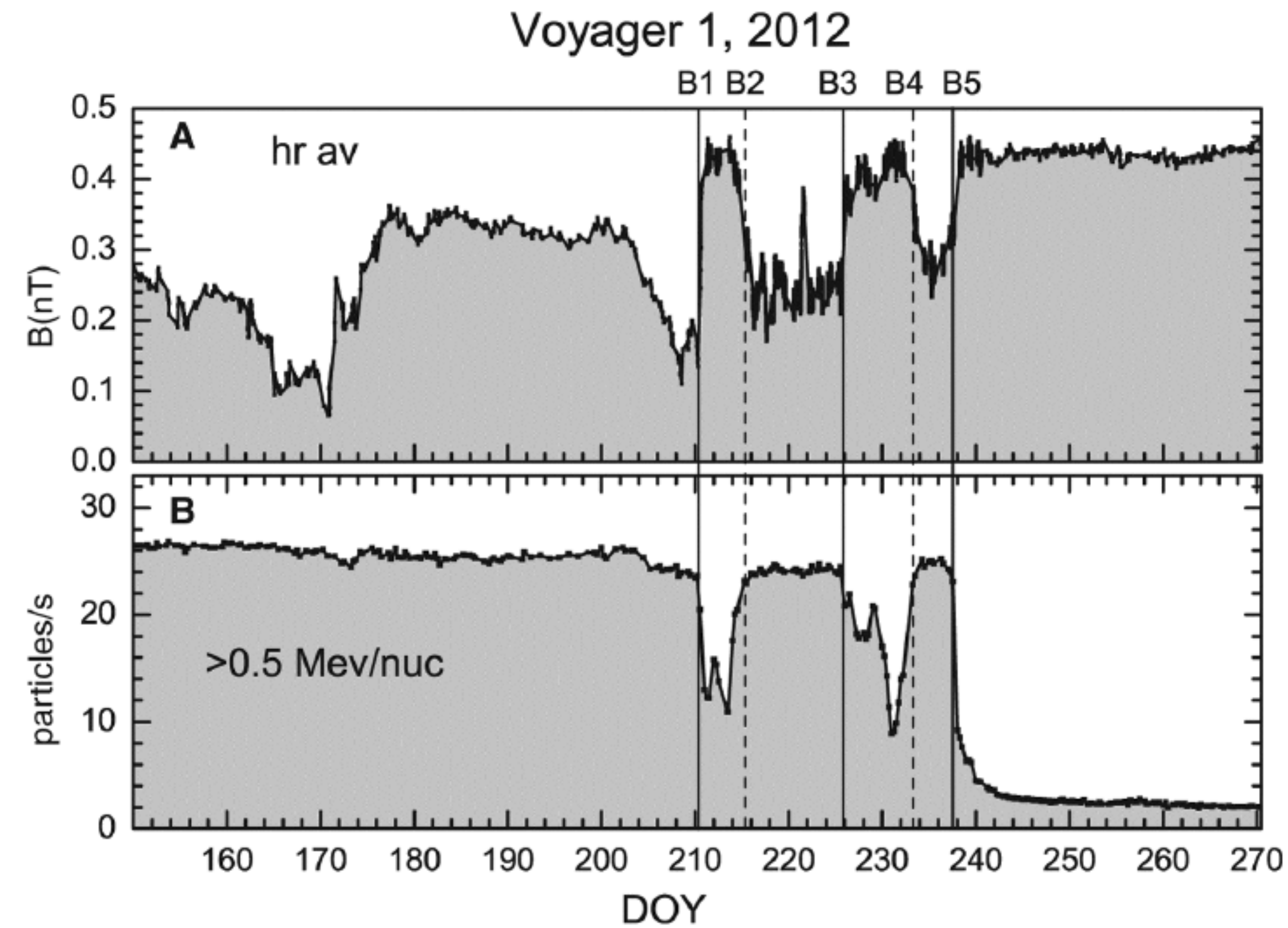
rated:
Sep 20 21:31:18 2012

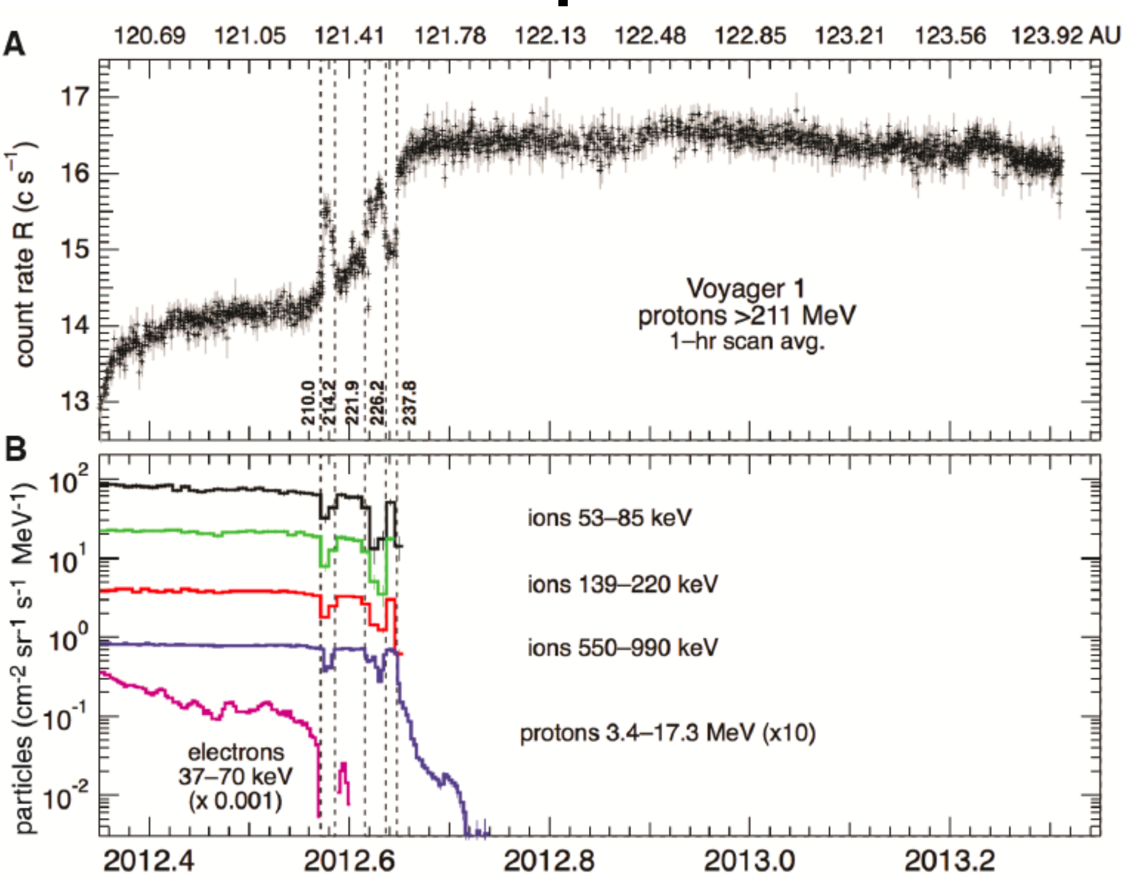
Voyager Data Archive Sep 2012



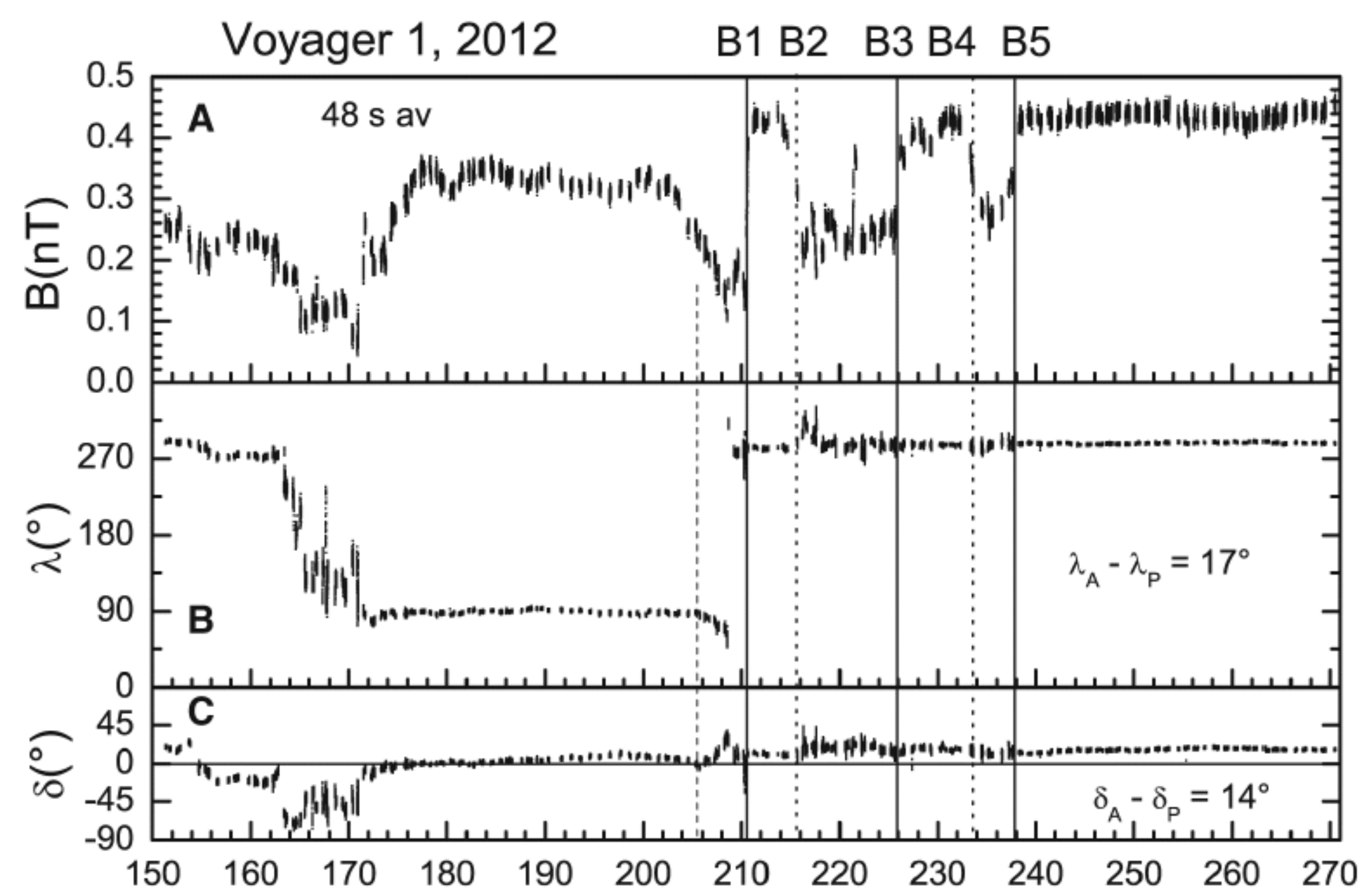
Decker 2012

Suprathermal energetic particles declined, galactic cosmic rays - GCRs -increased and <u>magnetic field</u> increased, <u>but still aligned along Parker's spiral.</u>



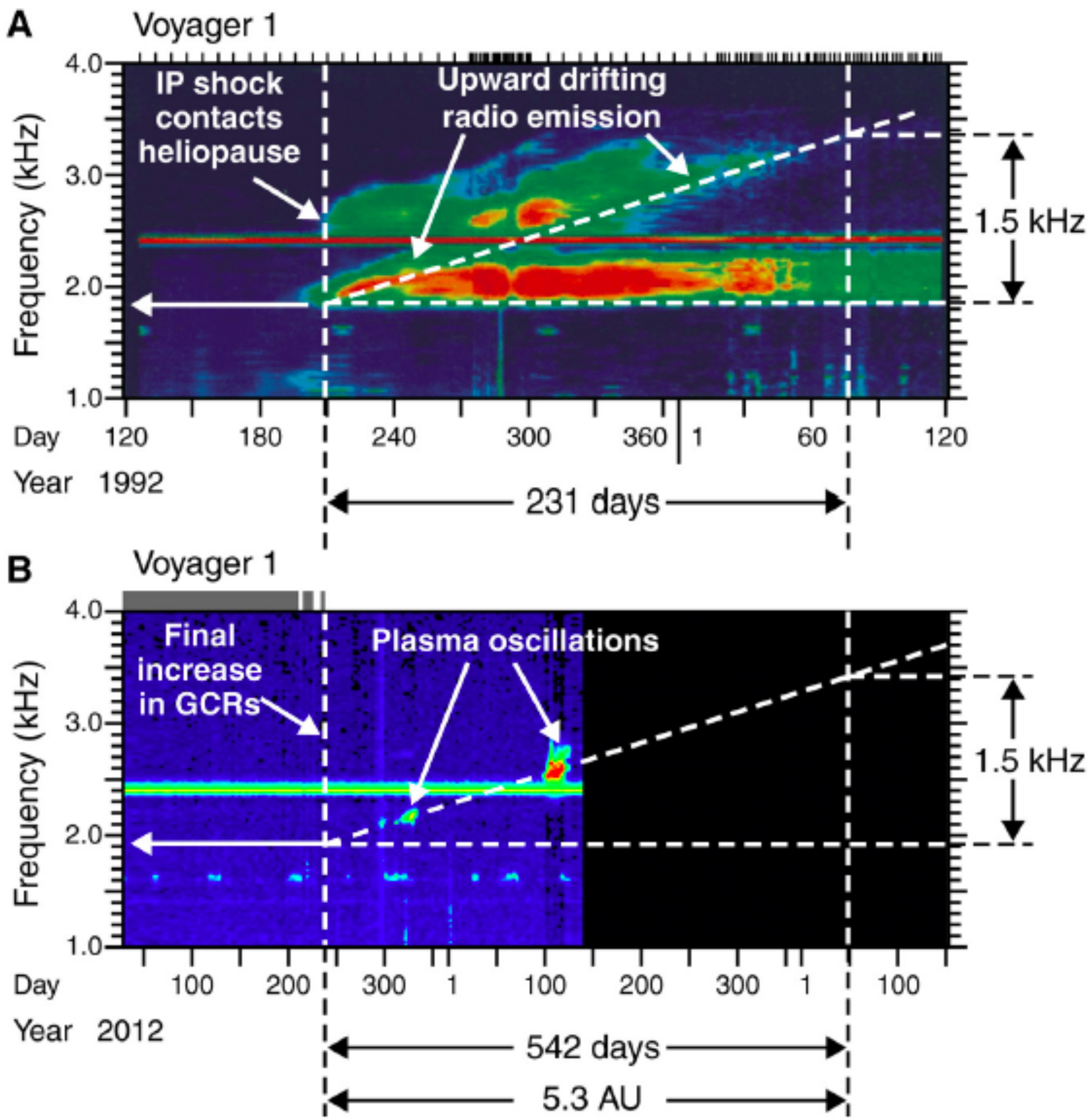


Krimigis et al 2013



Burlaga et al 2013

Plasma density increased - Voyager 1 crossed the heliopause into the interstellar plasma on or about August 25, 2012.



Gurnett et al 2013

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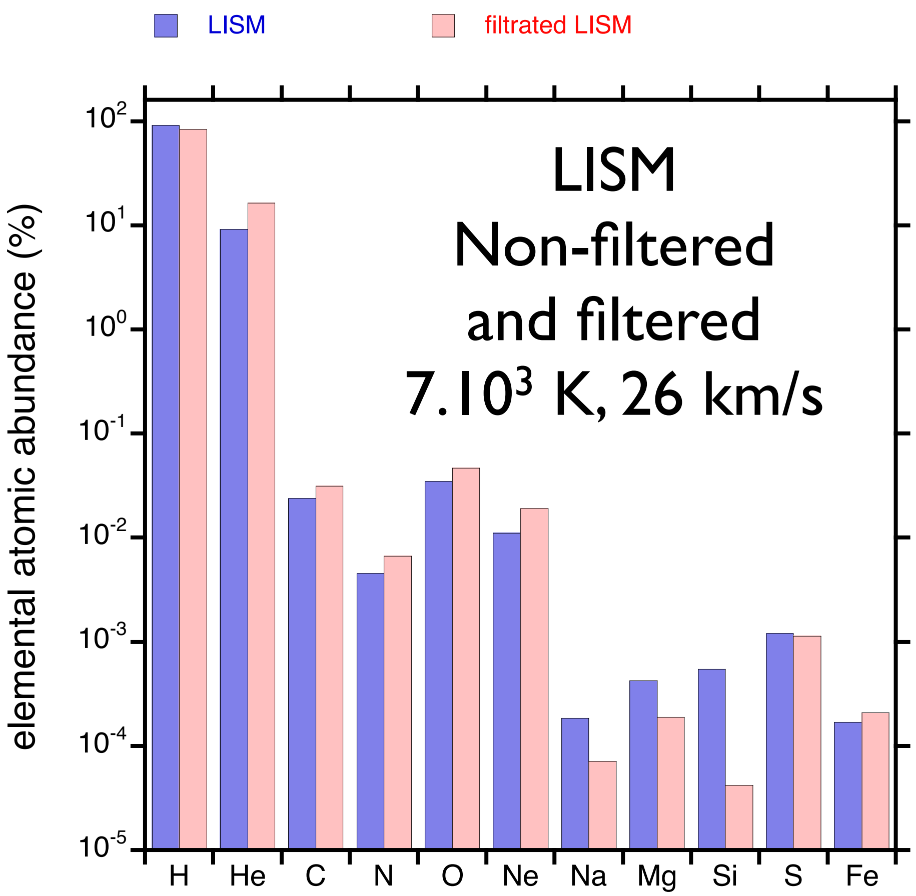
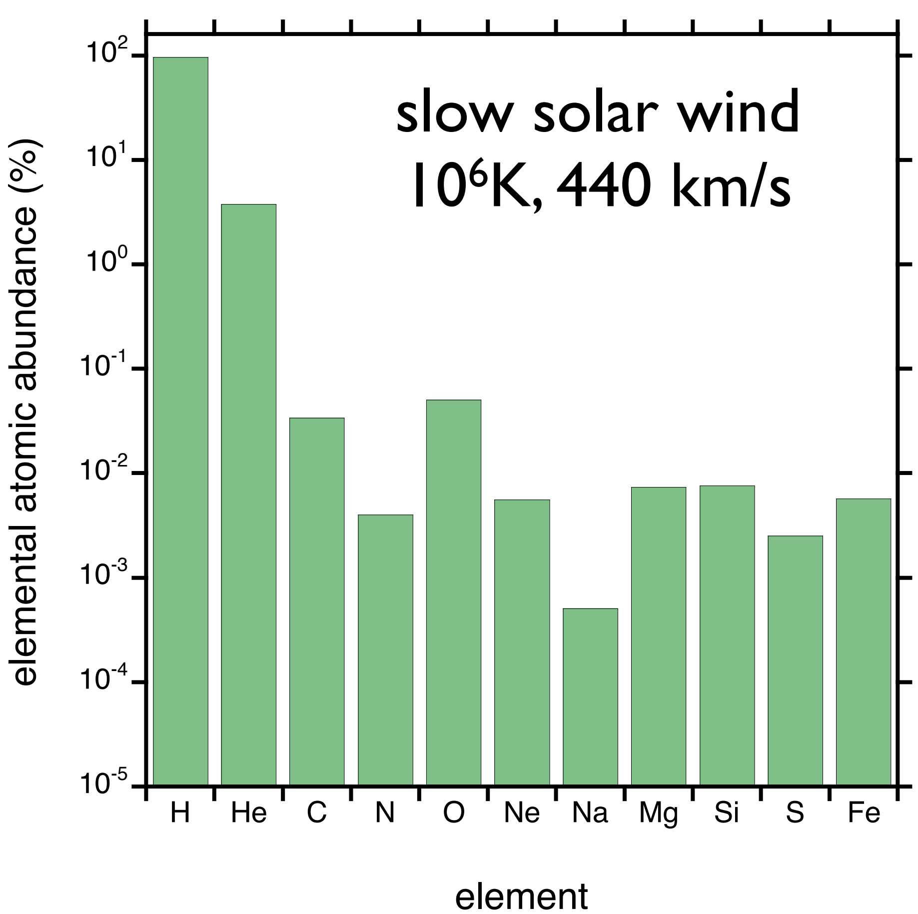
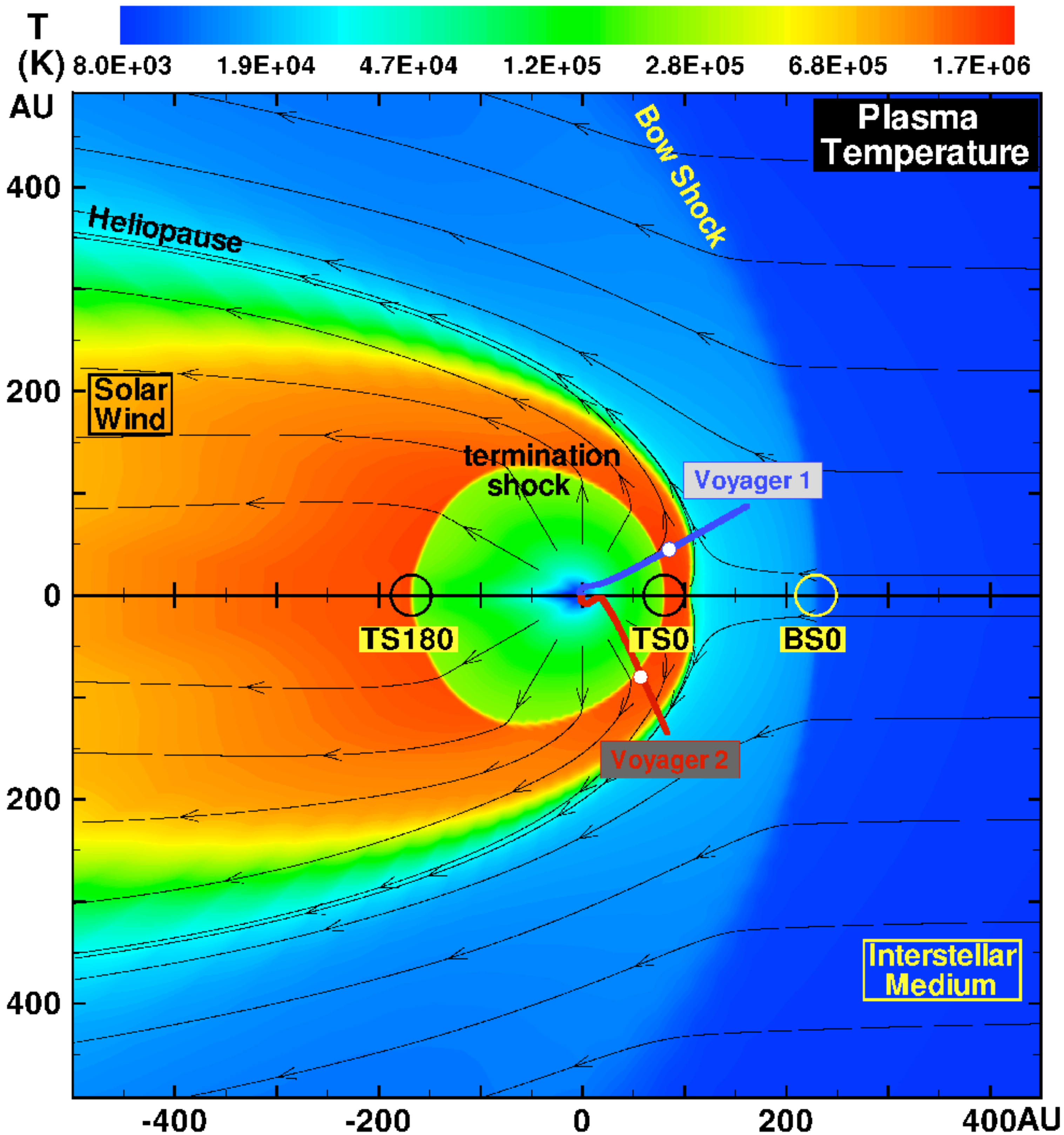
Rosetta lander Philae
Nov 2014

Heliospheric gas and plasma

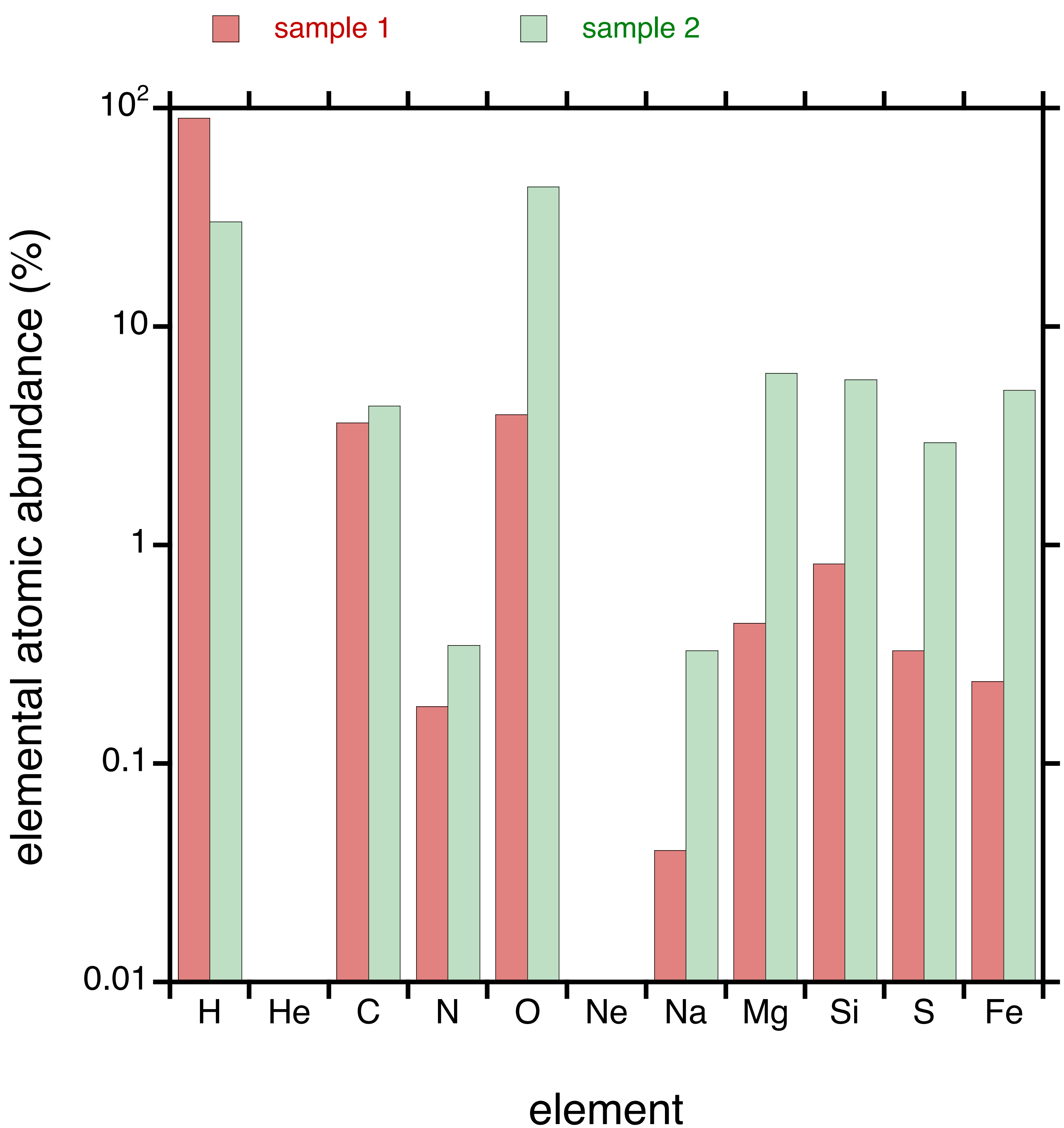






Müller
2006

Selected samples



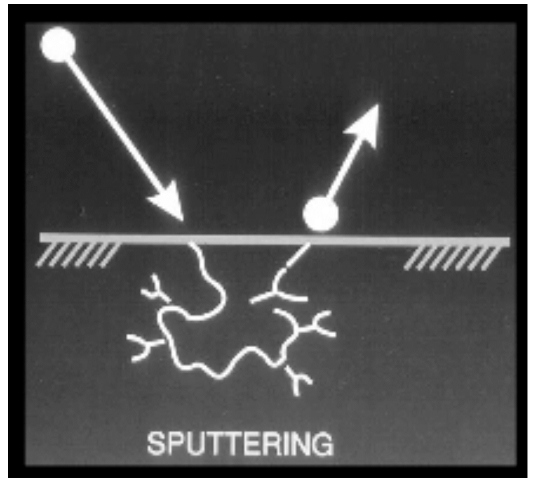
composition:
cometary (1) and
chondritic (2)

based on Jessberger 1988

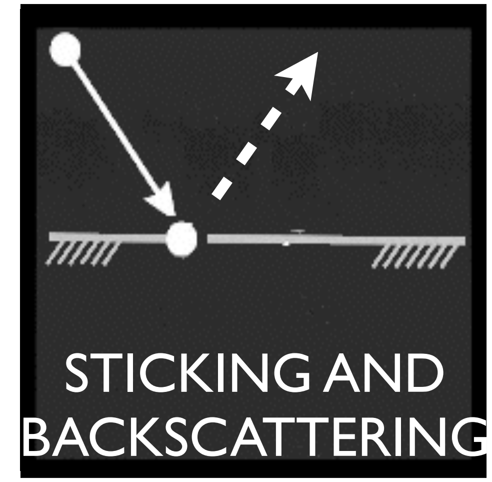
Weathering and matter

projectile

interaction region

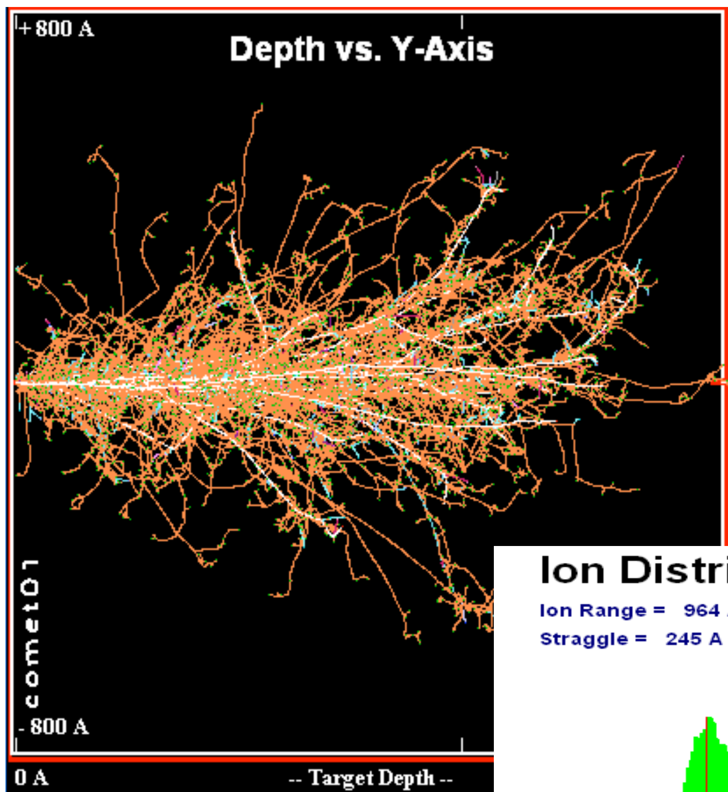


sputtered particles

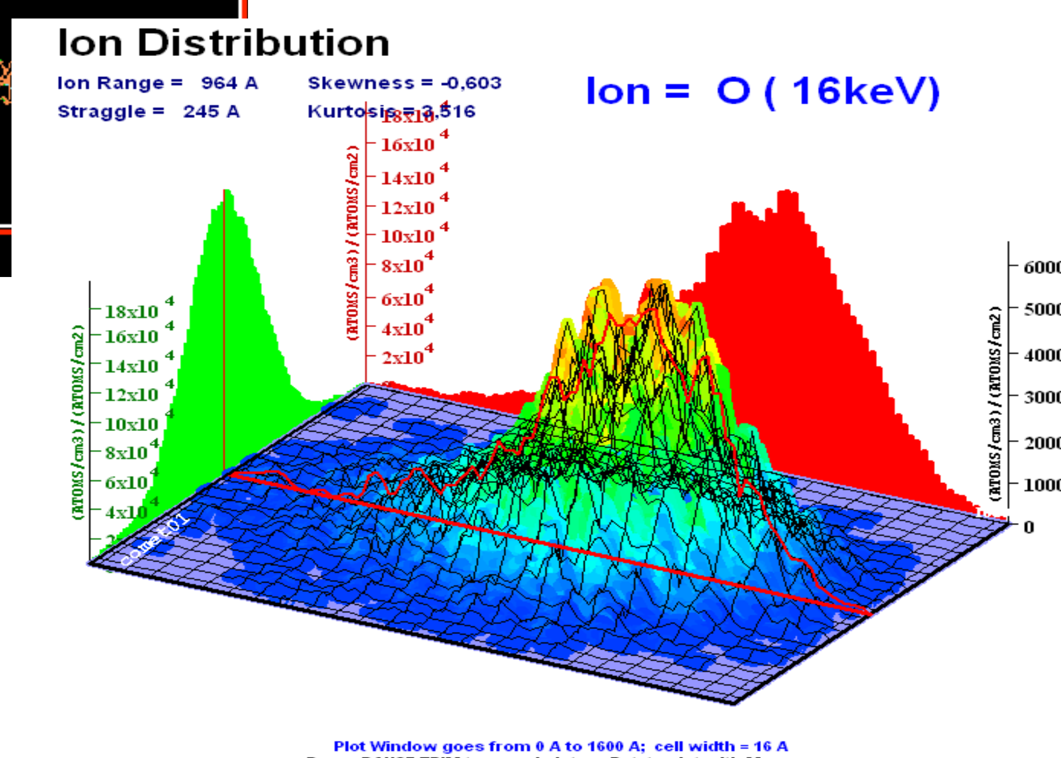


back scattered projectile

sticking projectiles

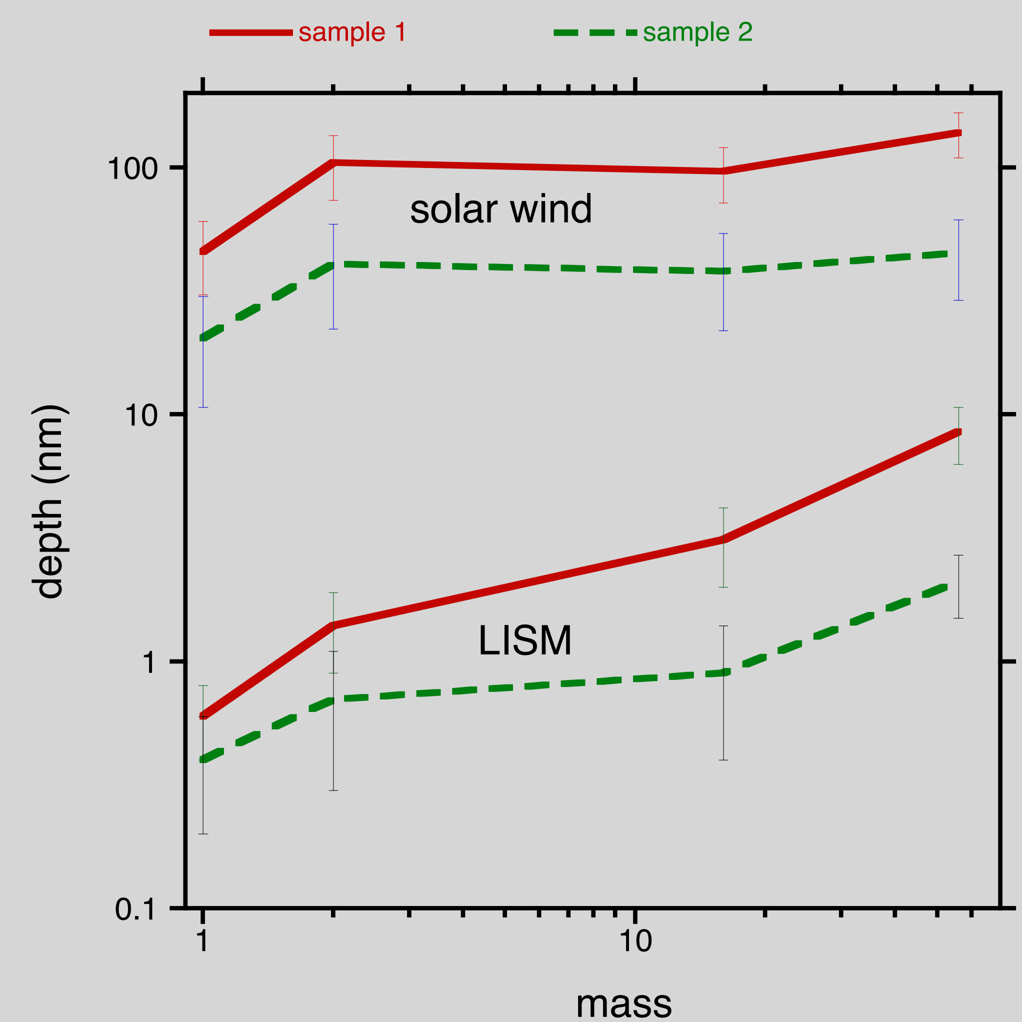


TRIM simulations



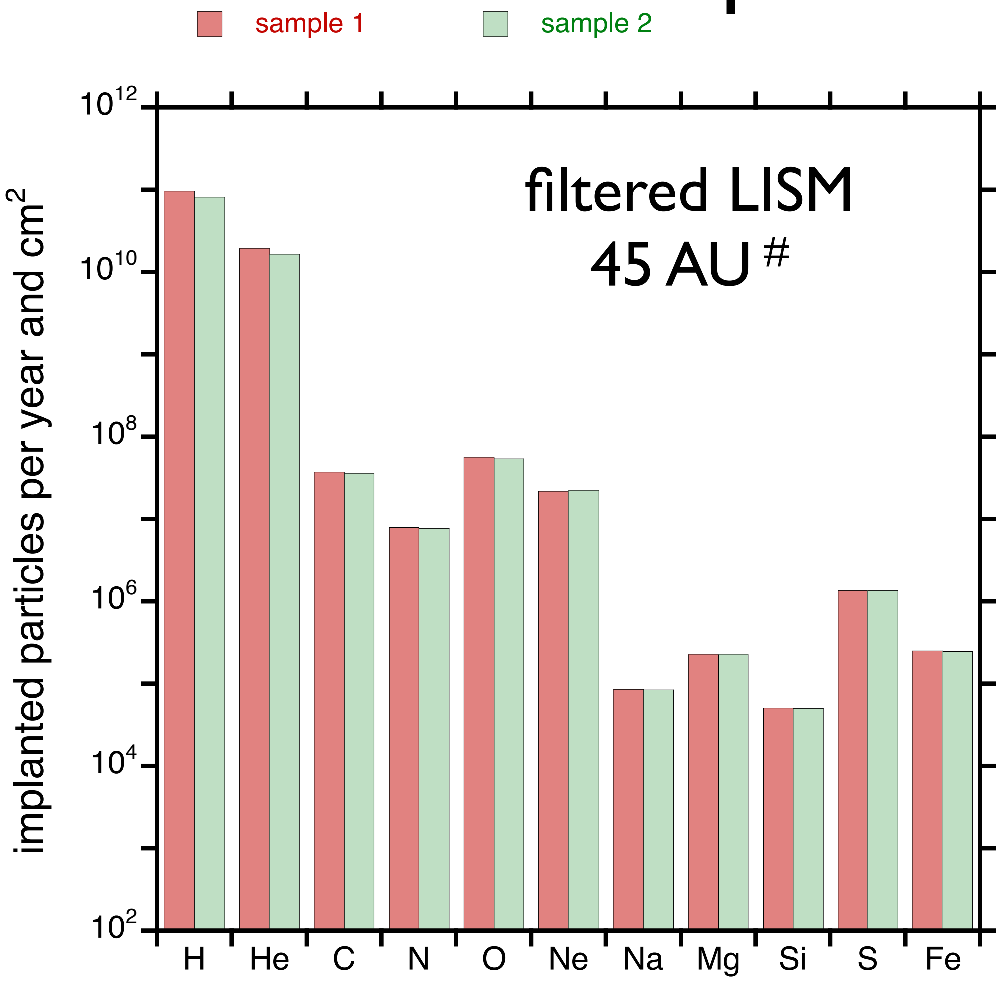
TRIM software: Ziegler 2011

Implantation depth

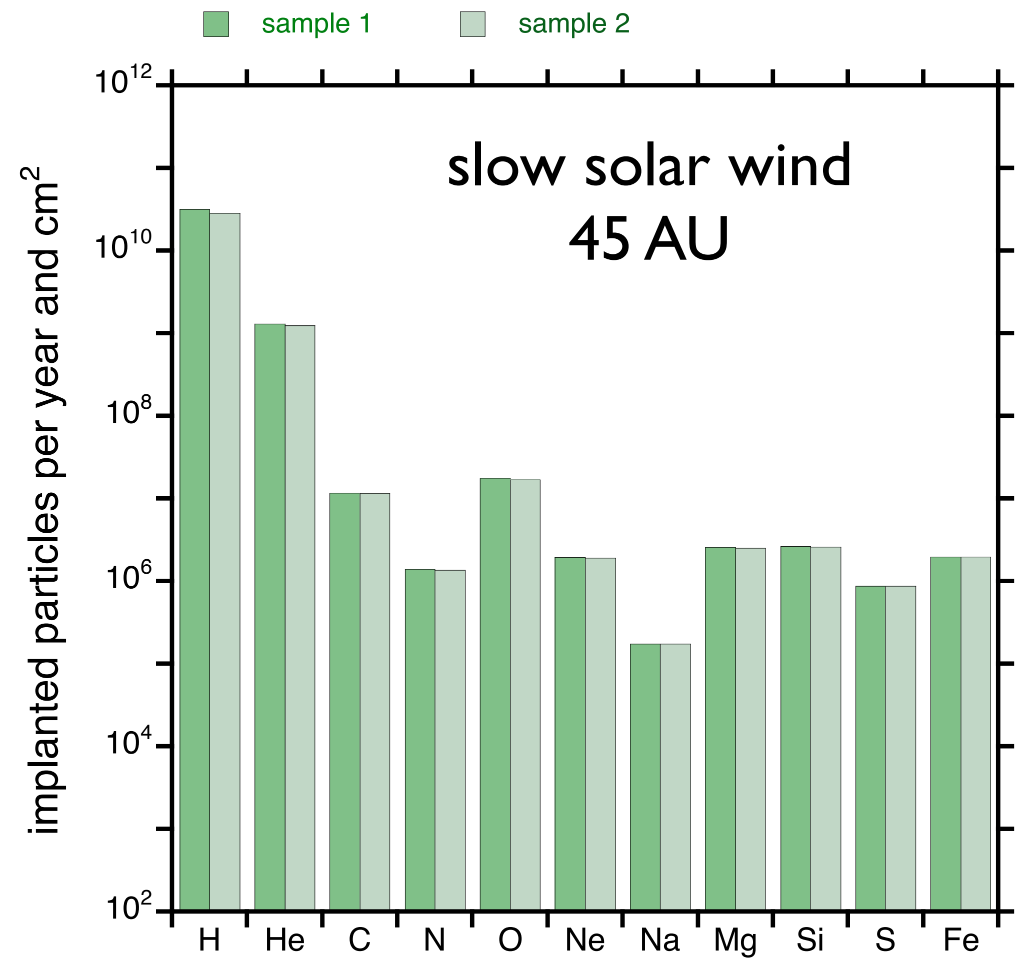


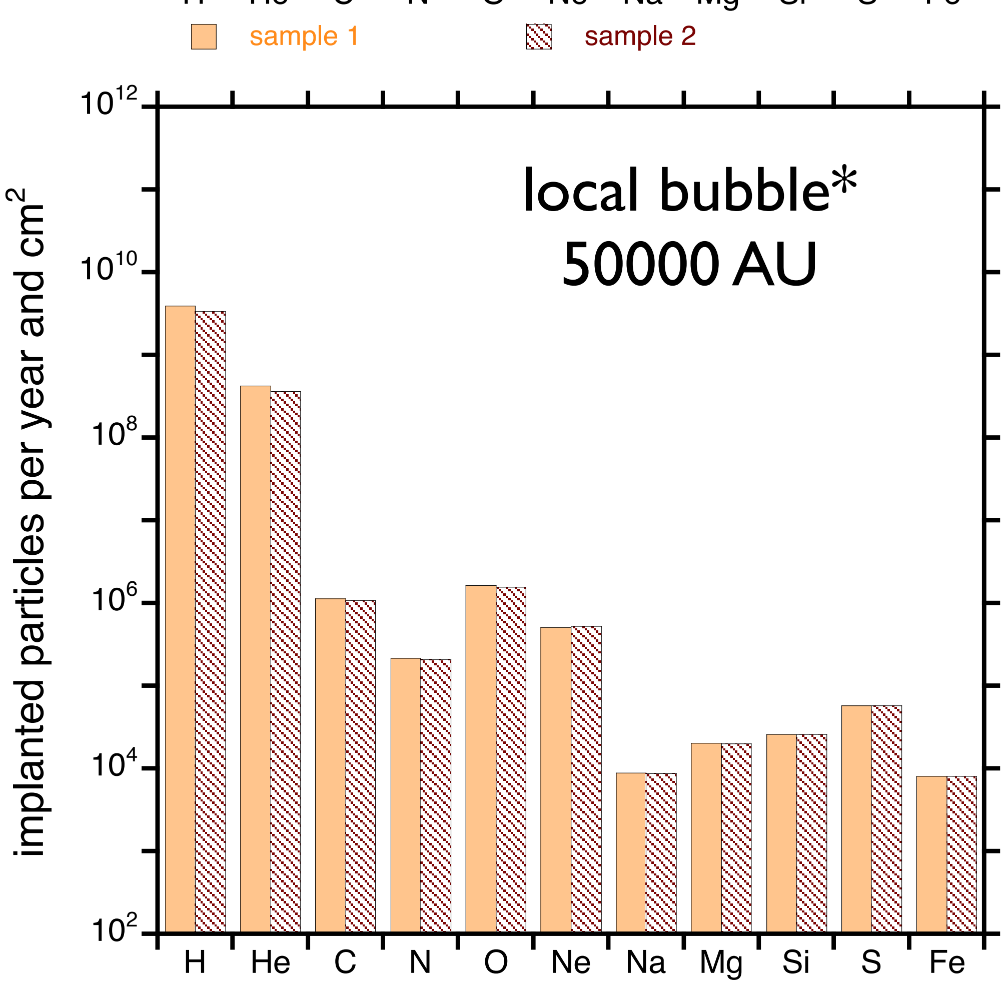
depth of interaction region < visible light wavelength

Implantation and sample composition

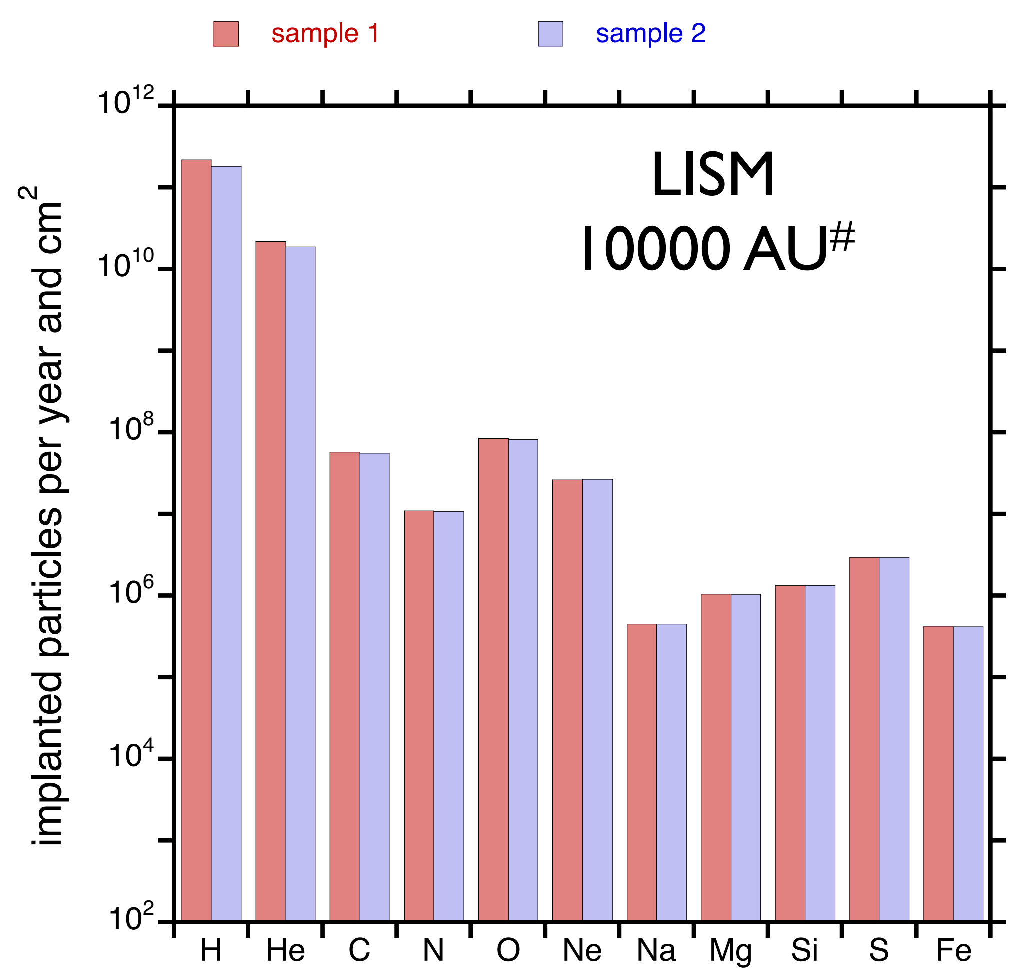


composition:
cometary (1)
and
chondritic (2)



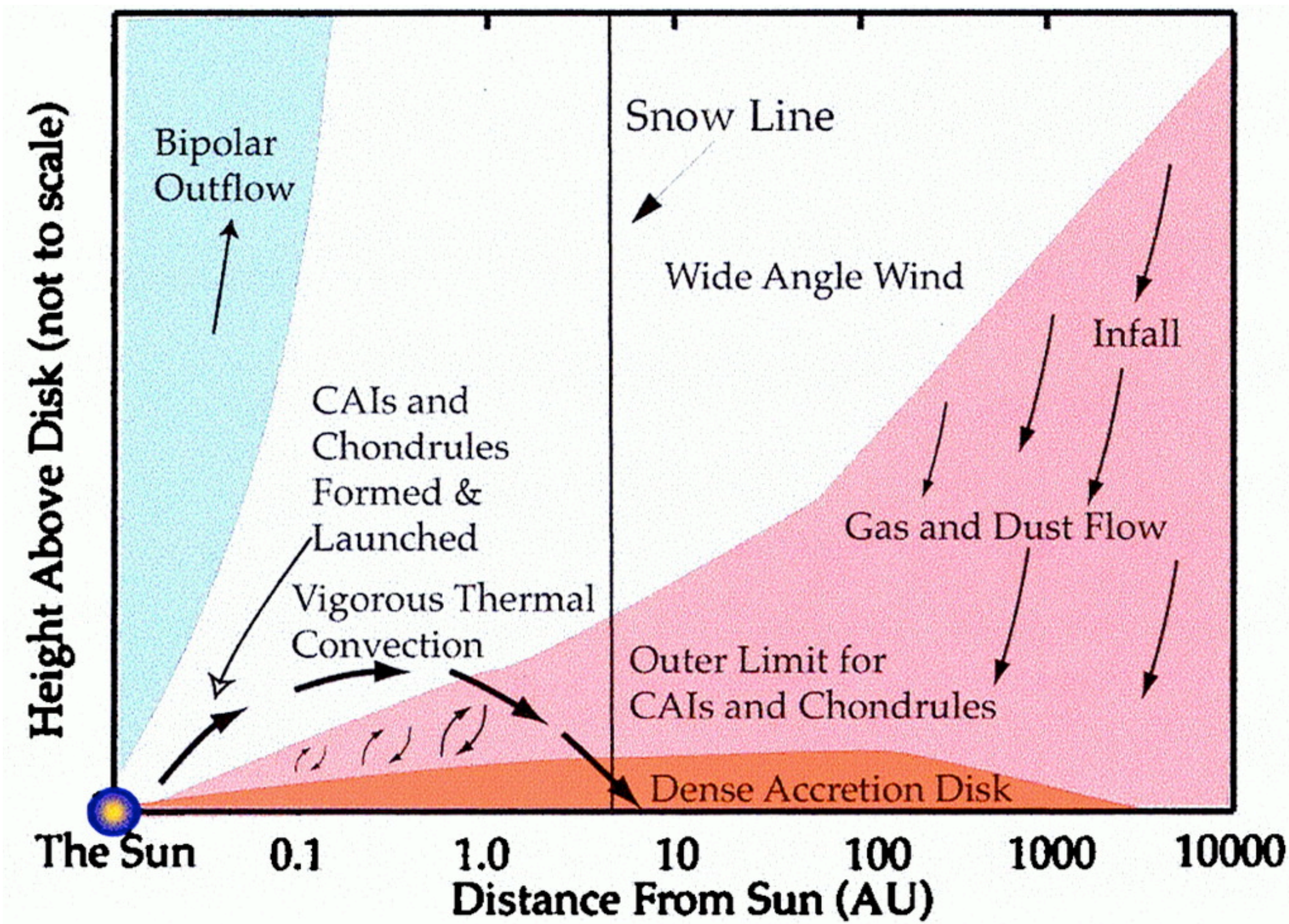


* hot plasma
10^6 K
10^{-3} cm^{-3}



\# surface potential set to 0V

Ancient time of comet assembly.....



Can we explore the "ancient" weathering - before the cometary dust grains were shielded within the nucleus from the solar wind and heliospheric environment with the SIMS Instrument COSIMA onbard Rosetta?

^{115}In projectiles ... cometary grain sputtering from 2014 onward