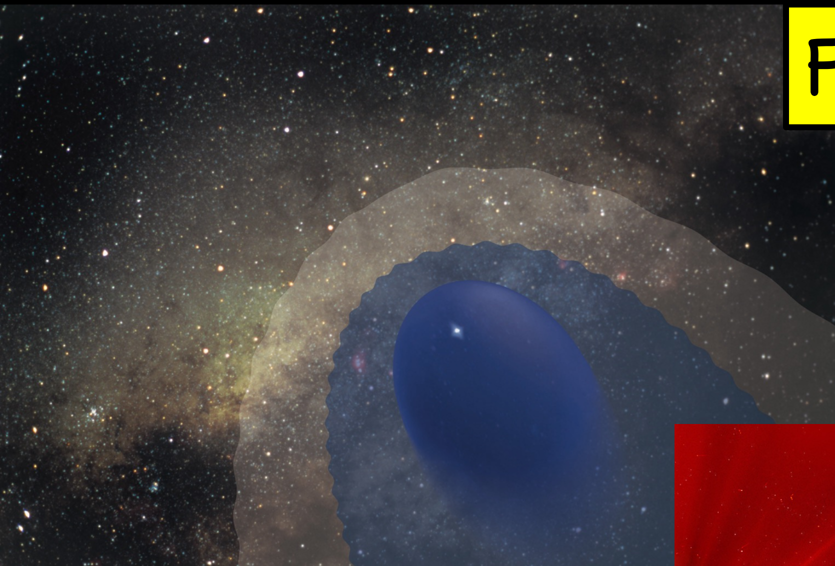
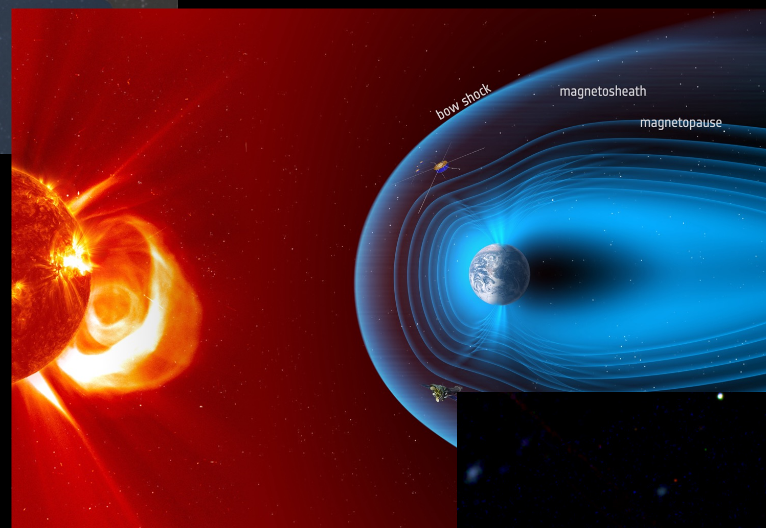
# From CX to SWCX to CXU

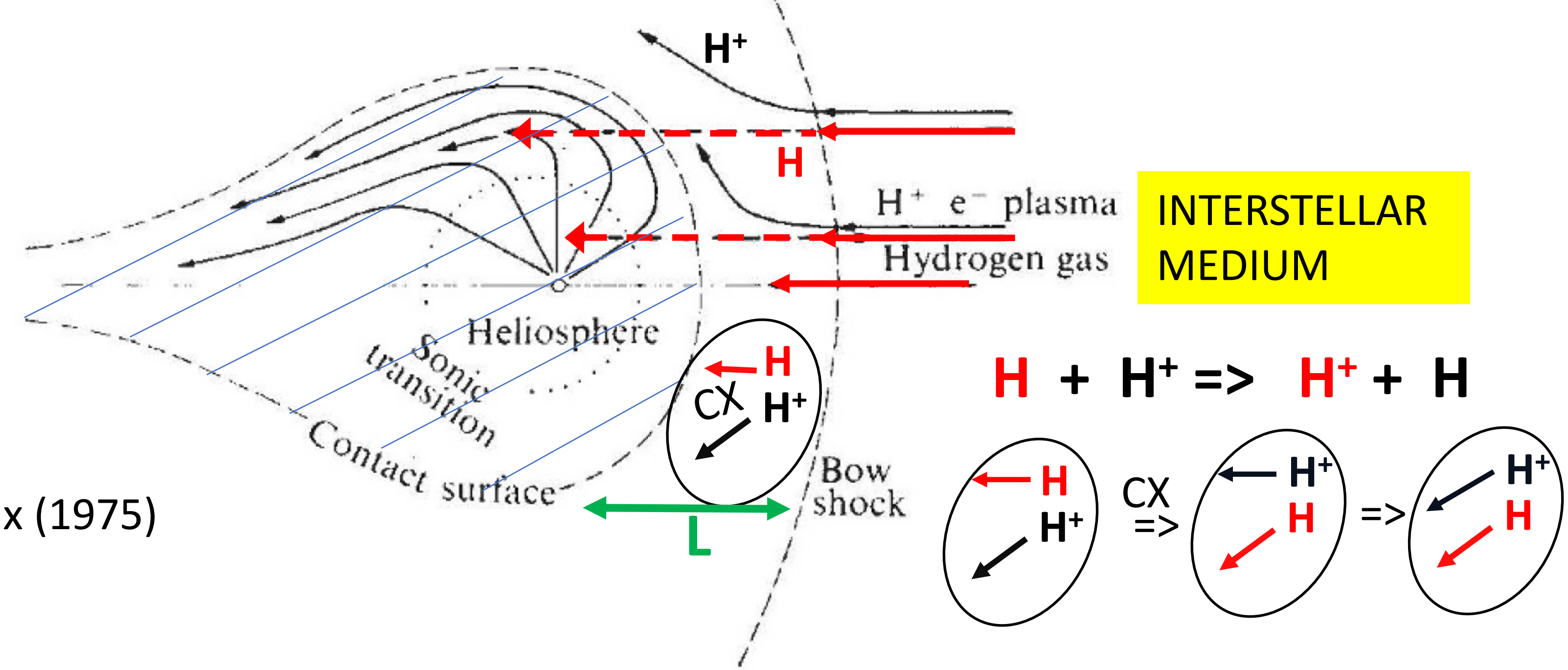
R. Lallement / GEPI, Obs. Paris, PSL*






# H – H+ CX
# SHAPES THE HELIOSPHERE

Sun in partly ionized cloud; $H^+$, $e^-$ start to be deflected and surround the heliosphere ;
Neutrals do NOT feel the interface and flow directly



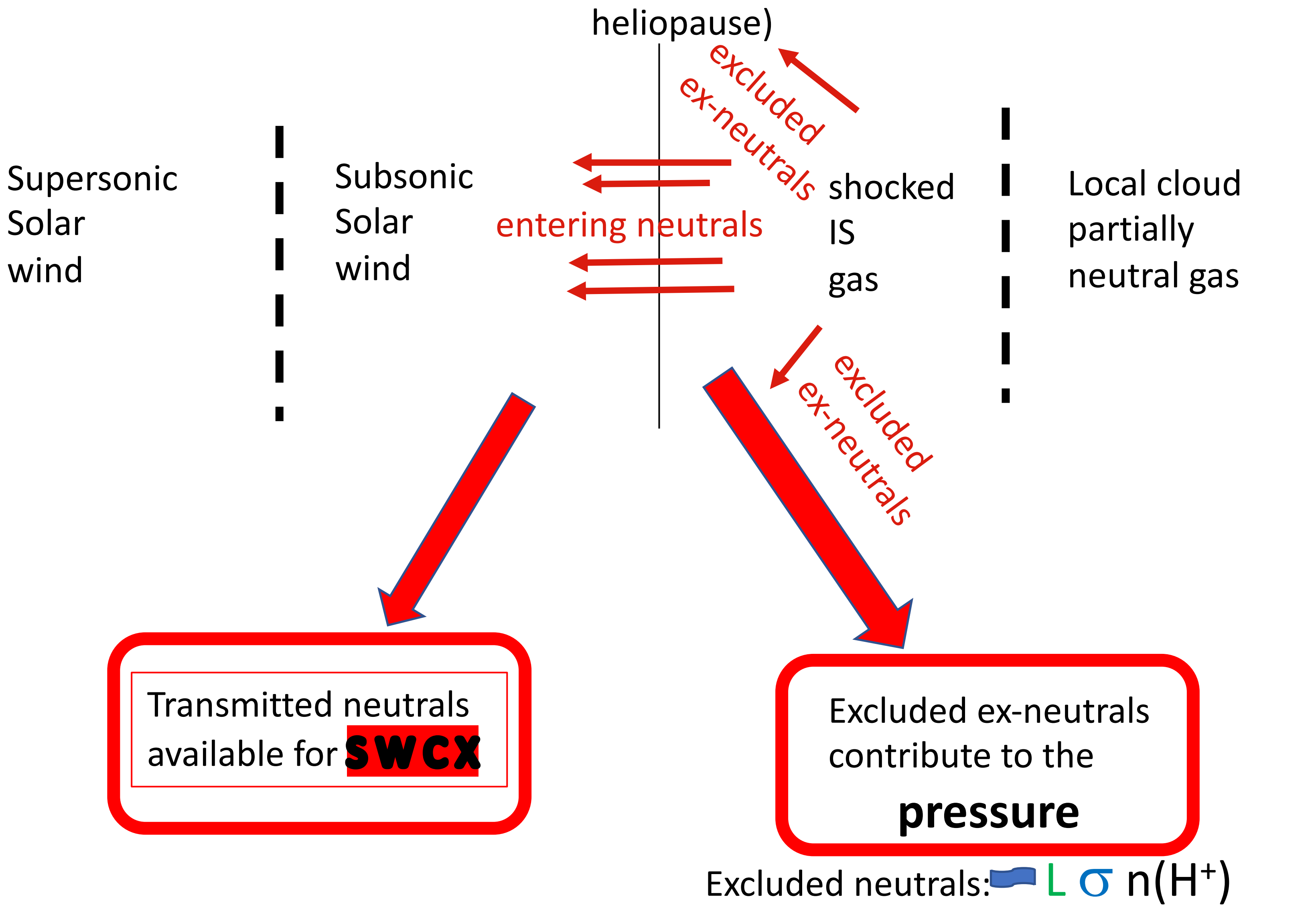

Wallis, Max (1975)

H-H+ charge-exchange=> H and H+ exchange their momentum

=> the « new » H+ is advected in the plasma flow, the « new » H gets the deviation of the proton

Affected neutrals: $L\,\sigma\, n(H^+)$ => a fraction of neutrals are not entering the heliosphere

Note: Chevalier and Raymond (1978) also started to model H-H+ CX to explain H$\alpha$ lines in SNRs




If L or $n(H^+)$ are large enough for $L\,\sigma\,n(H^+) > 1$ all neutrals are coupled to the plasma and do not enter the fully ionized gas= > a mono-fluid model is appropriate

If $L\,\sigma\,n(H^+) < 1$ a fraction of neutrals enters the fully ionized gas, two-fluid models are needed

# Influence of CX on size and shape of the heliosphere

Baranov, Malama, 1993

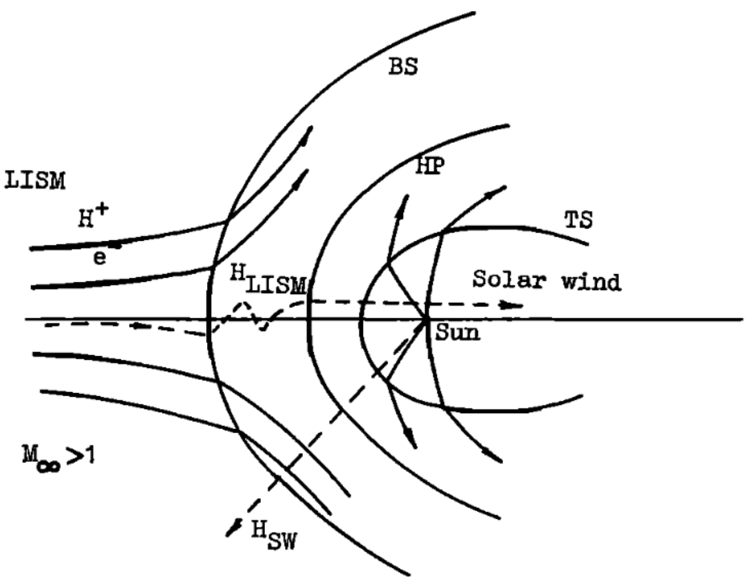



**Fig. 1. Qualitative picture of the solar wind interaction with the LISM: BS is the bow shock, HP is the heliopause, TS is the termination (inner) shock; $H_{LISM}$ are H atoms of the LISM's origin, $H_{SW}$ are energetic H atoms of the solar wind origin (neutral solar wind).**

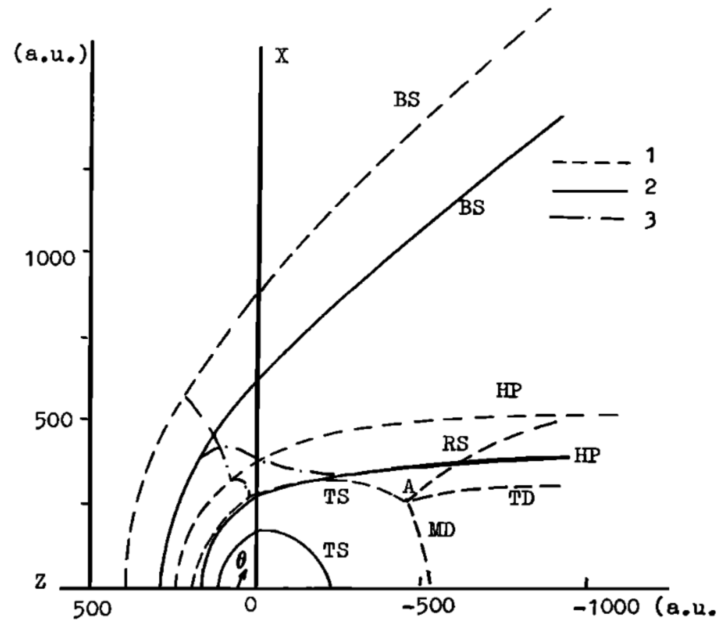
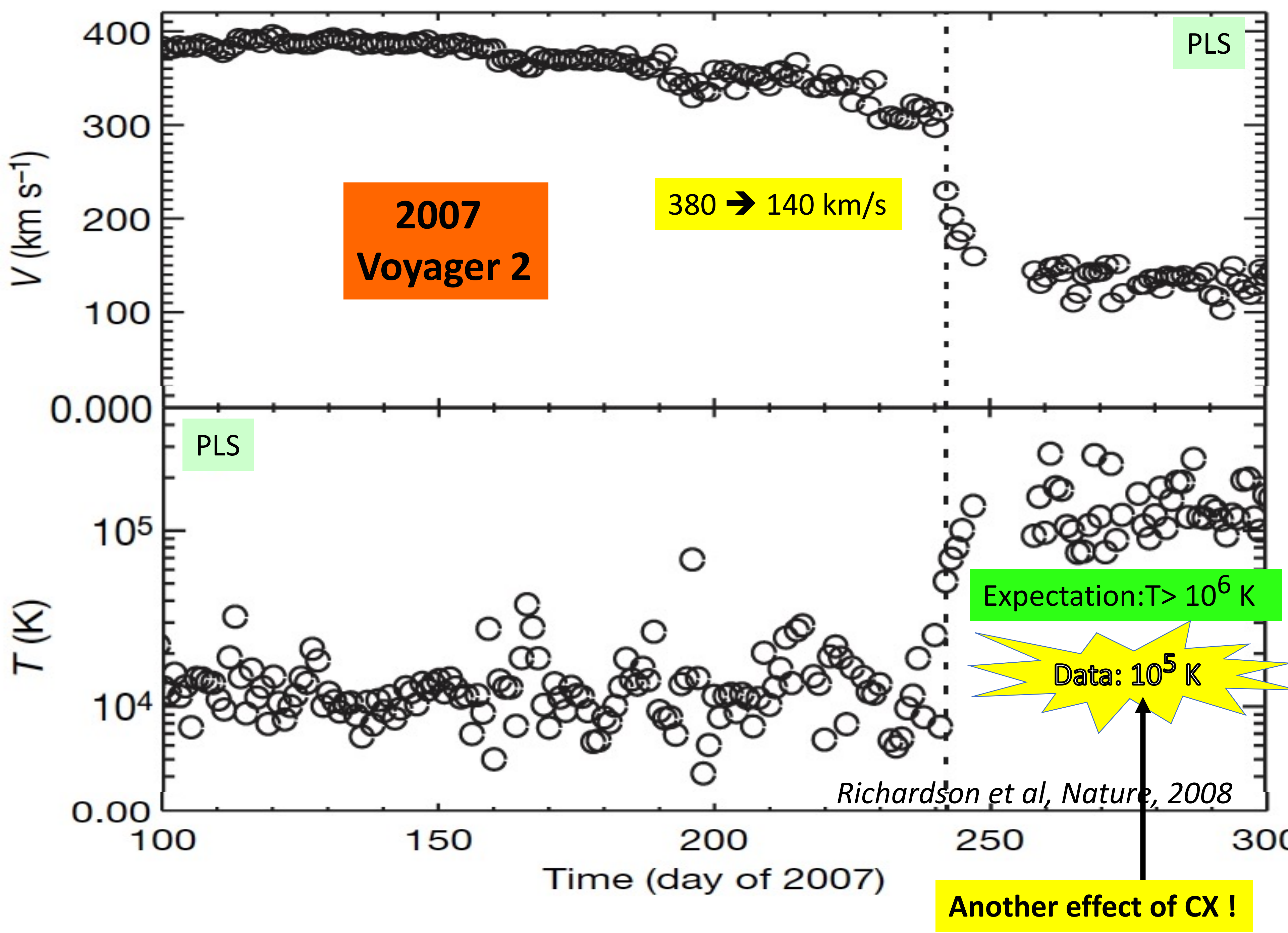



**Fig. 2. Geometrical pattern of the interface. Results of the numerical calculations for $n_{H\infty} = 0$ (1) and $n_{H\infty} = 0.14\ cm^{-3}$ (2); curves (3) are the sonic lines. Positions of bow shock (BS), termination shock (TS), heliopause (HP), reflected shock (RS), tangential discontinuity (TD), and Mach disc (MD) are shown.**

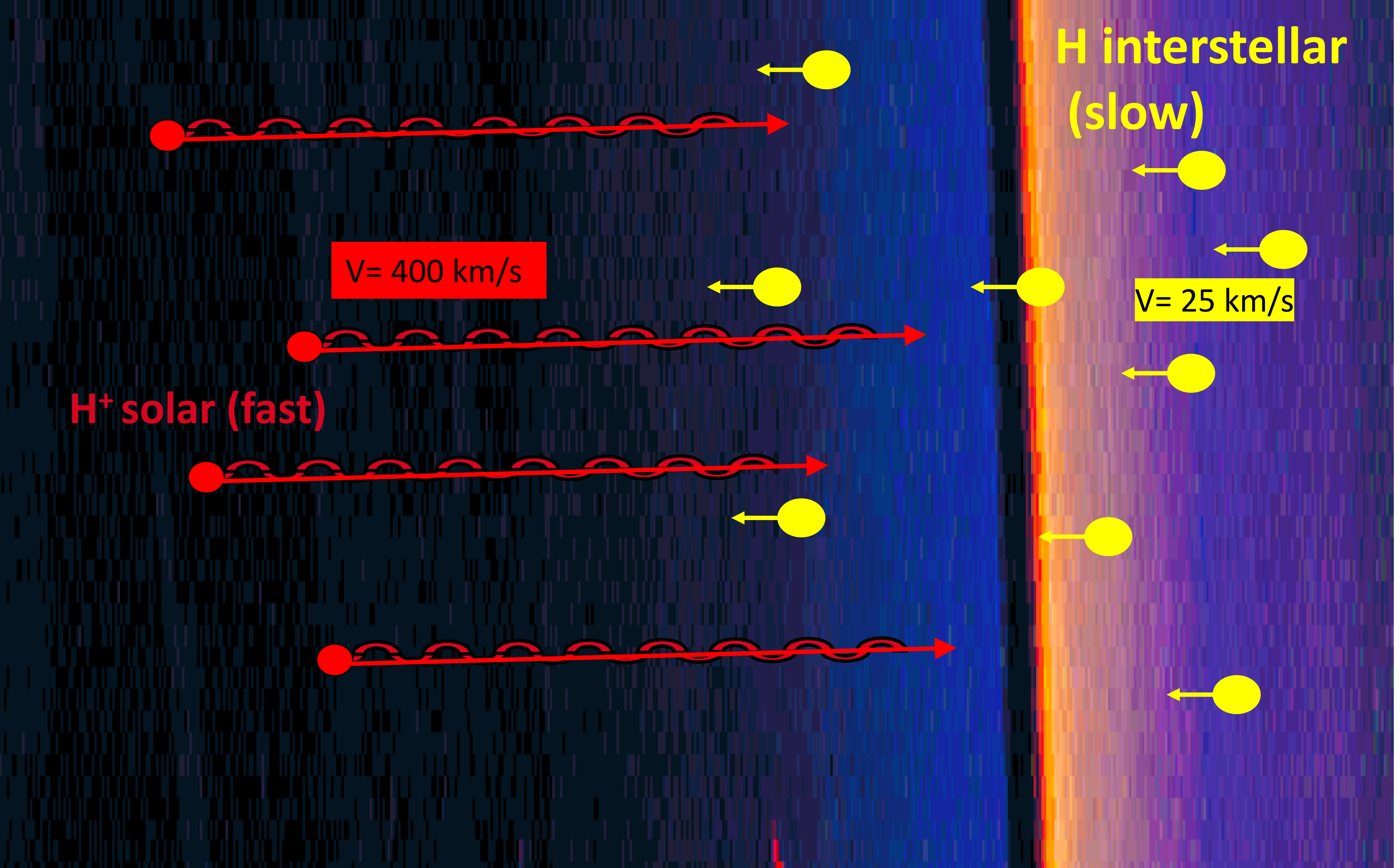
Self-consistent
-HD model for the plasma
-Kinetic mode for the nutrals

The helioause and the solar wind termination shock get closer to the Sun !

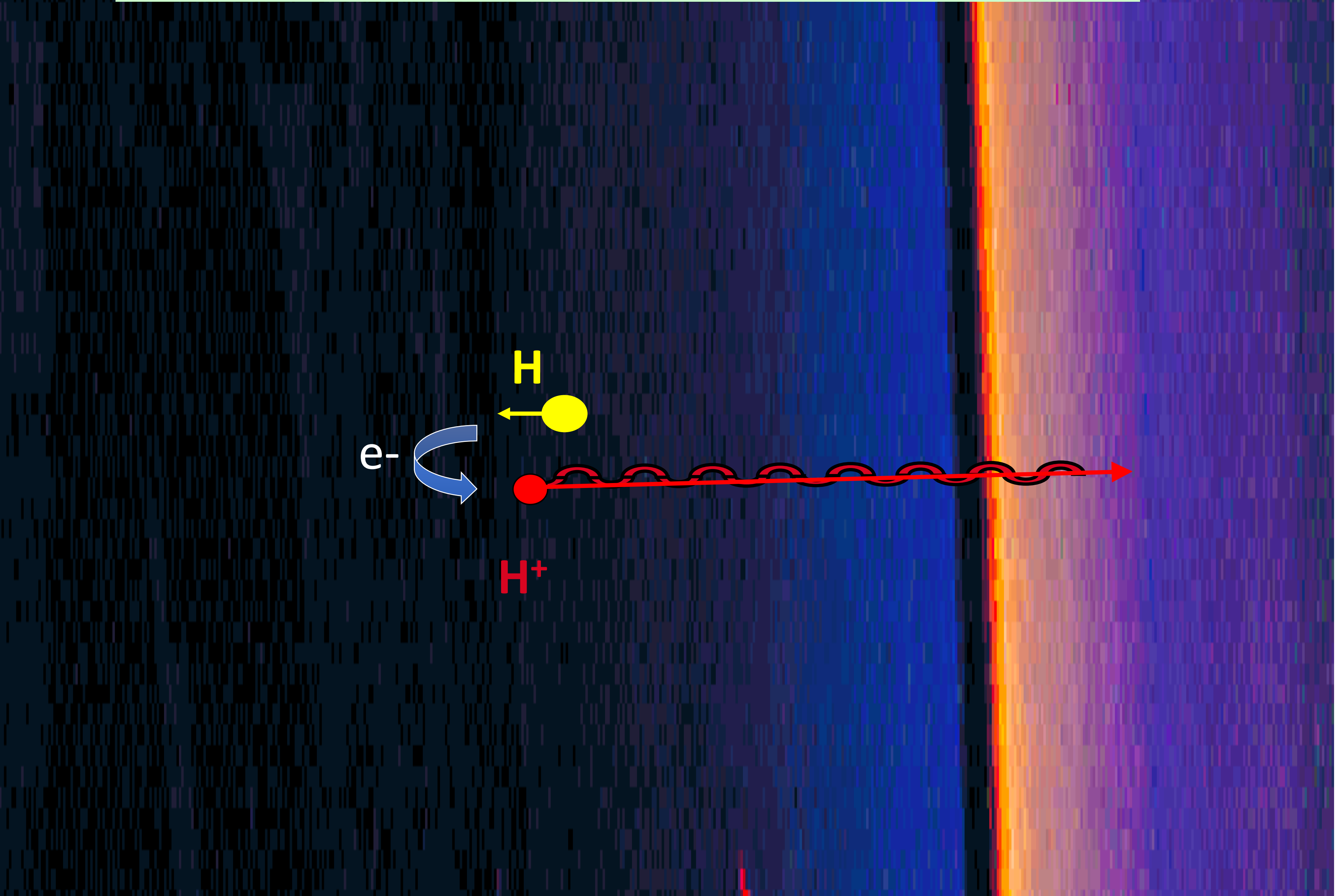


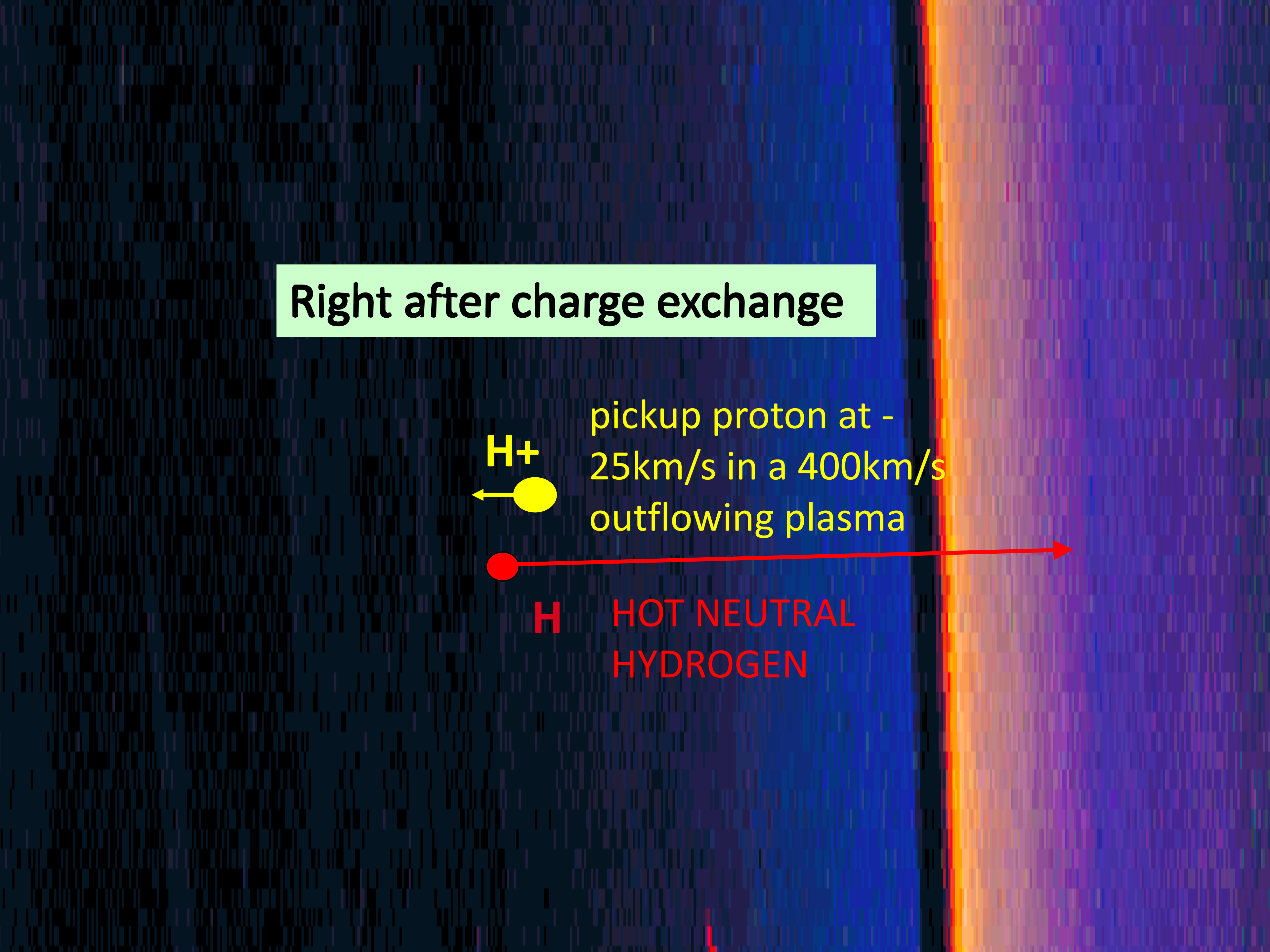
400
300
200
100
0.000
V (km s⁻¹)
PLS
2007
Voyager 2
380 → 140 km/s
PLS
10⁵
10⁴
0.00
T (K)
Expectation:T> 10⁶ K
Data: 10⁵ K
Richardson et al, Nature, 2008
100
150
200
250
300
Time (day of 2007)
Another effect of CX !

# Charge exchange in the supersonic SW
# (mainly H + H+ ➔ H+ + H)

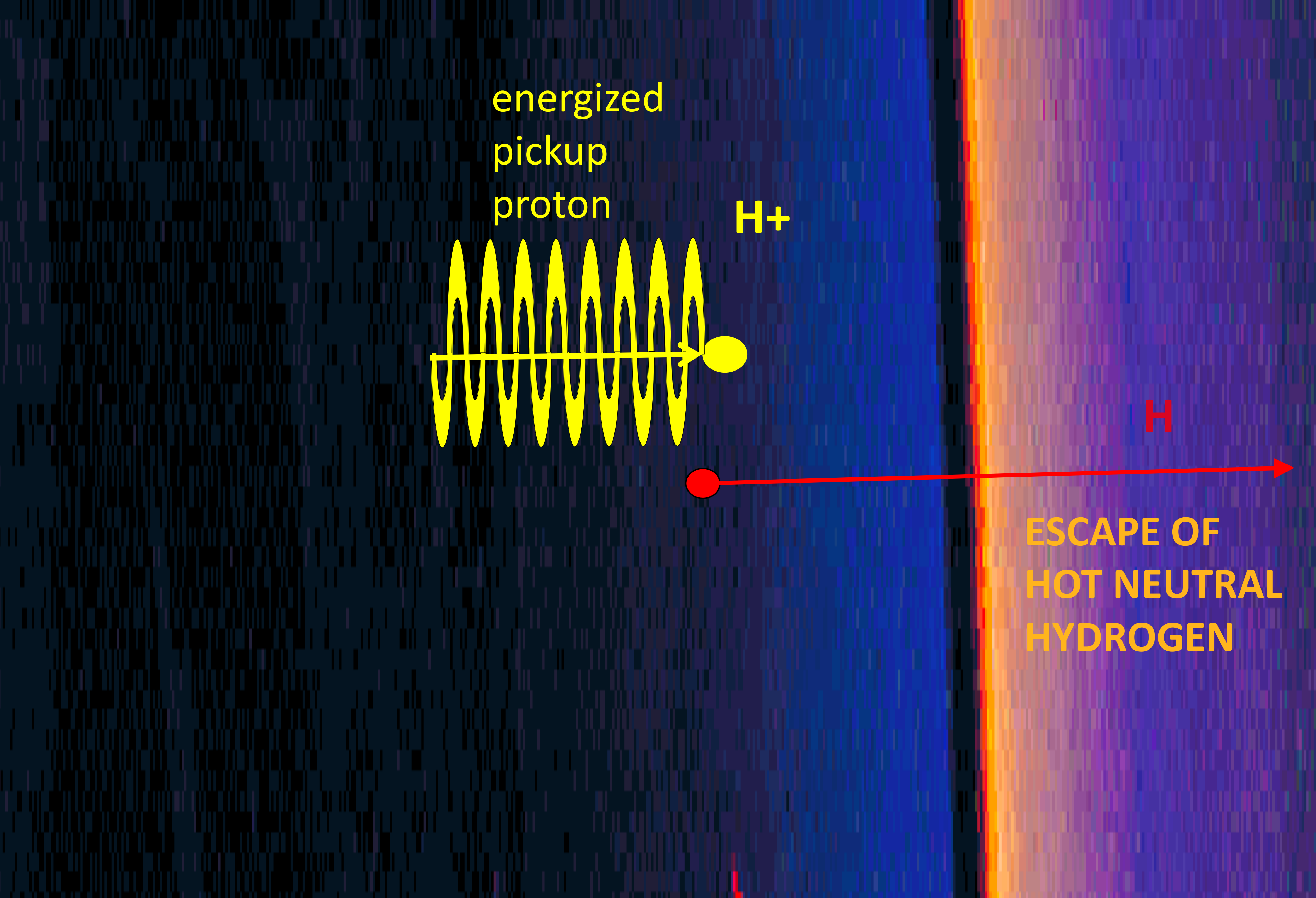


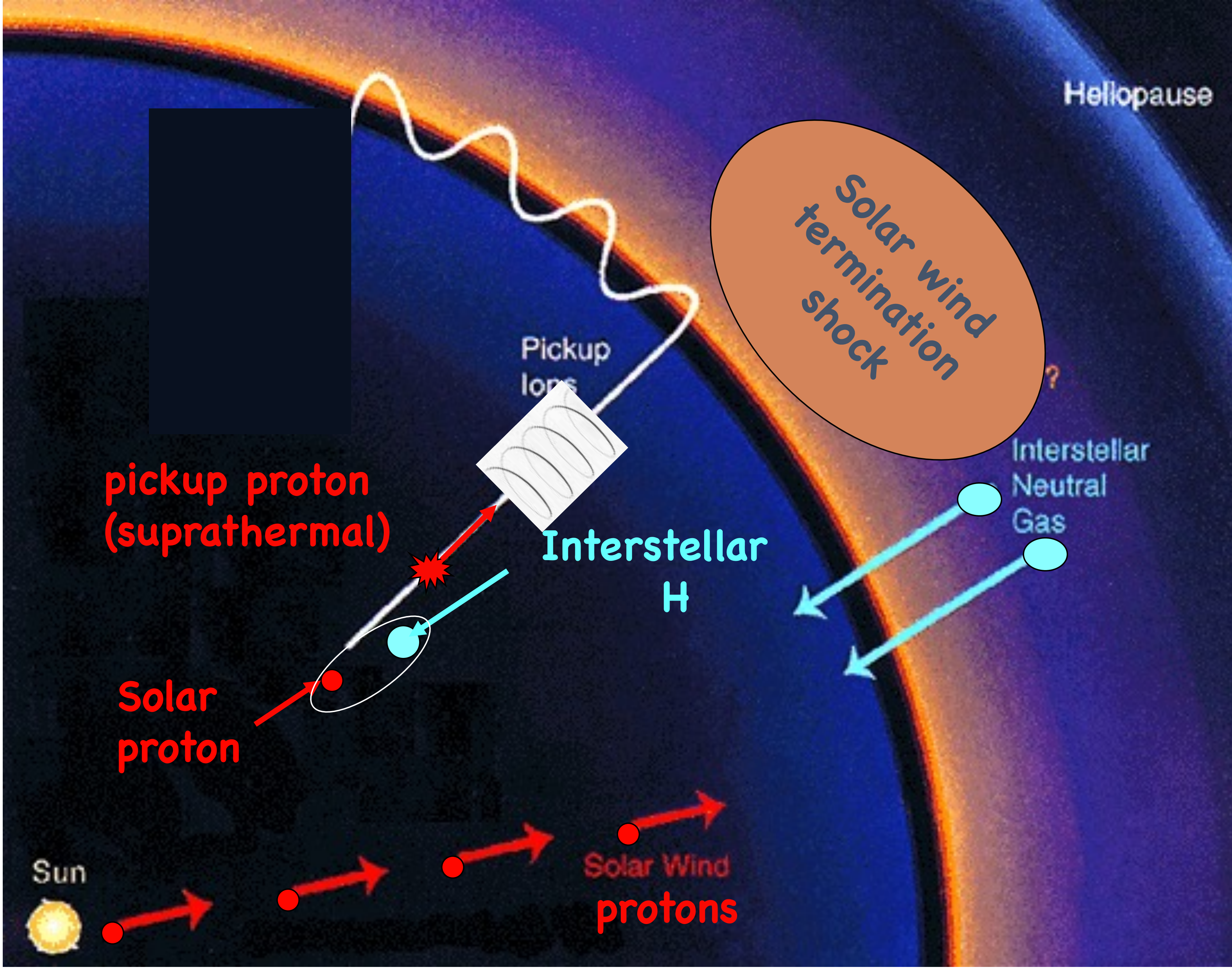
# Charge exchange: mainly H + H+ → H+ + H




Right after charge exchange
H+
pickup proton at -25km/s in a 400km/s outflowing plasma
H
HOT NEUTRAL HYDROGEN

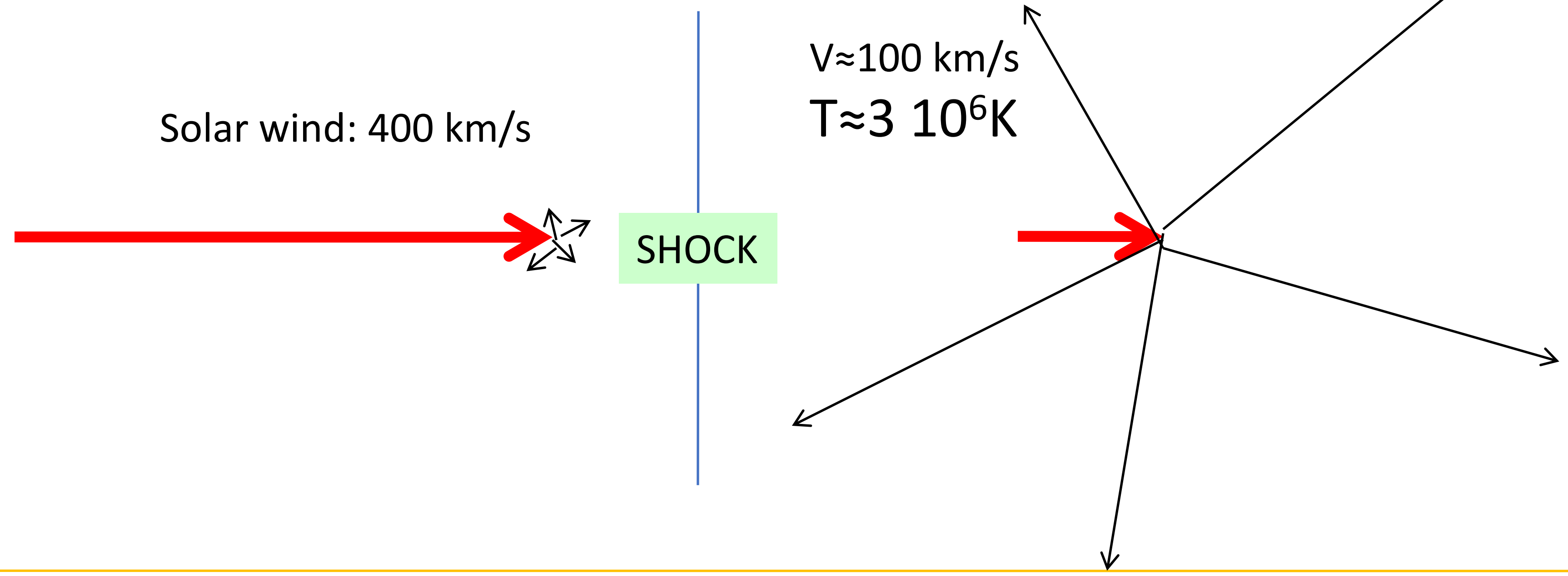
# Charge exchange consequences

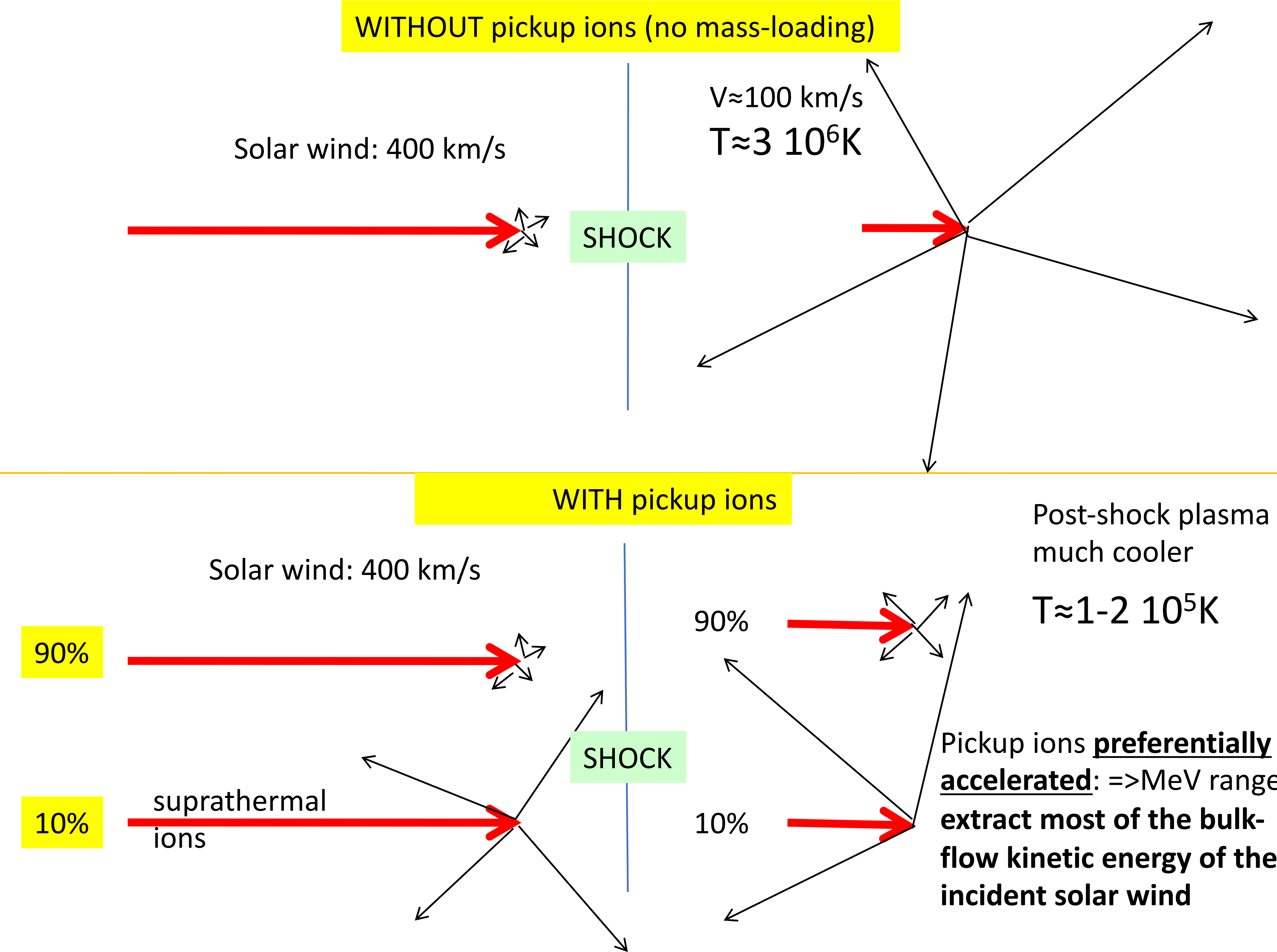




Hellopause
Solar wind termination shock
Pickup
pickup proton (suprathermal)
Interstellar H
Interstellar Neutral Gas
Solar proton
Sun
Solar Wind
protons

WITHOUT pickup ions (no mass-loading)




WITHOUT pickup ions (no mass-loading)
V≈100 km/s
T≈3 10⁶K
Solar wind: 400 km/s
SHOCK
WITH pickup ions
Post-shock plasma
much cooler
Solar wind: 400 km/s
90%
T≈1-2 10⁵K
90%
SHOCK
Pickup ions preferentially
accelerated: =>MeV range
10%
suprathermal
ions
10%
extract most of the bulk-
flow kinetic energy of the
incident solar wind

Conclusions:

The influences of the H-H+ (or He-H+, He, He+) CX reactions are very different
-depending on **densities**, relative velocities (through fluxes and cross-section values),
-depending on sizes of interfaces relative to the volumes of interacting media
=> complex, multi-fluid models are sometime needed

- **Pickup ions** may also have a significant role on the structure of the interface

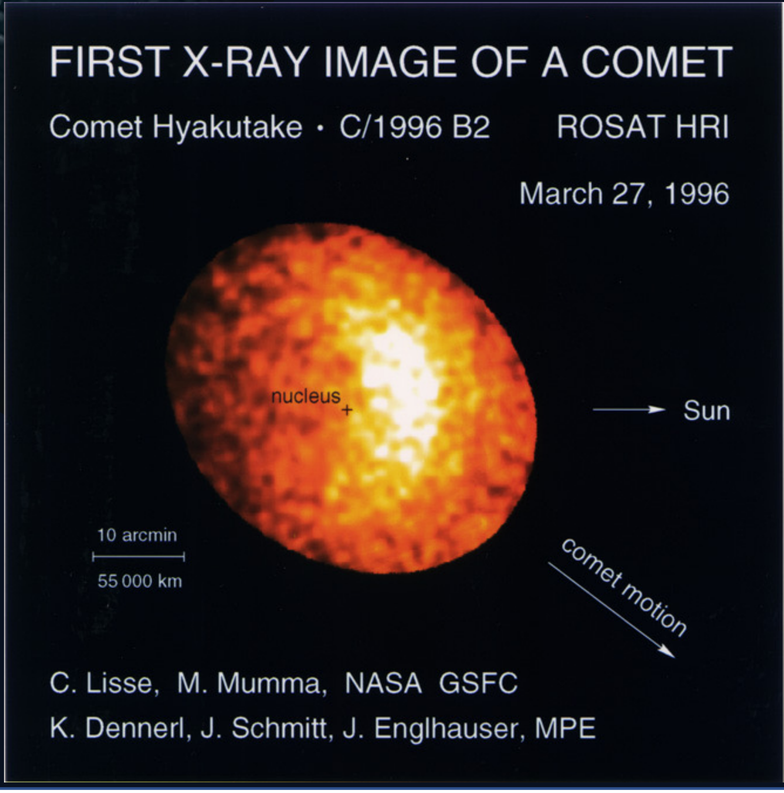
**Until 1996, no mentions of charge-exchange between interstellar neutrals and solar wind high ions !!**

Yuji Hyakutake en compagnie de ses jumelles Fujinon 25x150

And along came Hyakutake, blazing away …

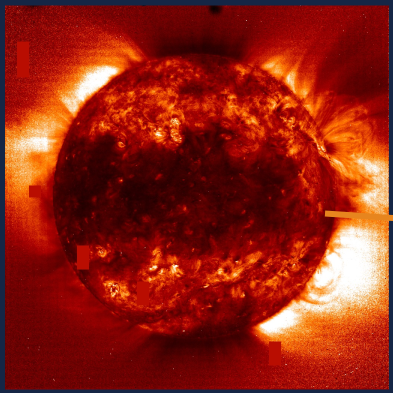
Cox, D, 1998

**50 years** after the discovery of the solar wind due to **comets (Biermann 1951)**, a **comet** again is at the origin of a new discovery: solar wind charge-exchange X-ray (SWCX)



**SOLAR WIND HIGHLY CHARGED IONS,**
FROM THE 1-2 MK CORONA

## CHARGE STATE « FROZEN » in INTERPLANETARY SPACE



$X^{+n}$

$e^-$

$X^{+n-1\,*}$ → $X^{+n-1}$

Radiative cascade

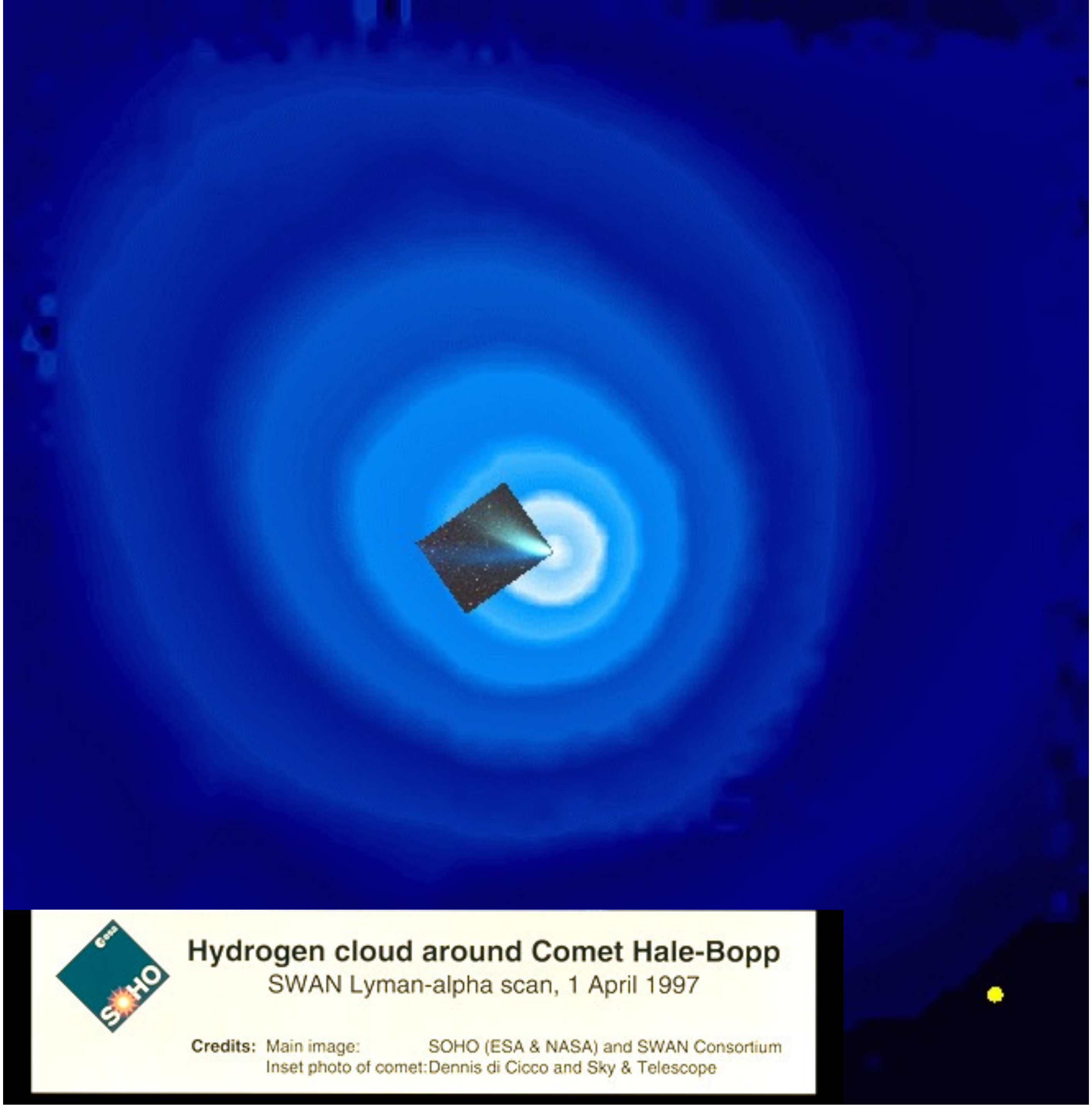
**Atoms or Molecules**
Outgassed by the comet

M

Electronic capture

$M^+$

Mechanism devised by Cravens, 1997 (Geophys. Res. Let.)




H2O outgassed by the comet is rapidly dissociated into H and OH

H is scattering the solar Ly-a radiation

# Main High Ions in the Solar Wind

$C^{4+,5+,6+}$ N $^{5+,6+,7+}$ $O^{5+,6+,7+,8+}$ Ne $^{8+,9+,10+}$

$Mg^{7+,8+,9+,10+}$ Si $^{8+,9+,10+,11+}$ S $^{10+,11+,12+,13+,14+}$ **Fe** $^{9+,10+,11+,12+,13+,14+}$

Higher charge states during episodic energetic events (solar flares) ==> e.g. **$Fe^{12+,13+,14+}$, S $^{12+,13+,14+}$**

## Neutral populations to participate in CX

**-origin: comets, planetary exospheres, IS gas**
**-H, He, H2O, O**

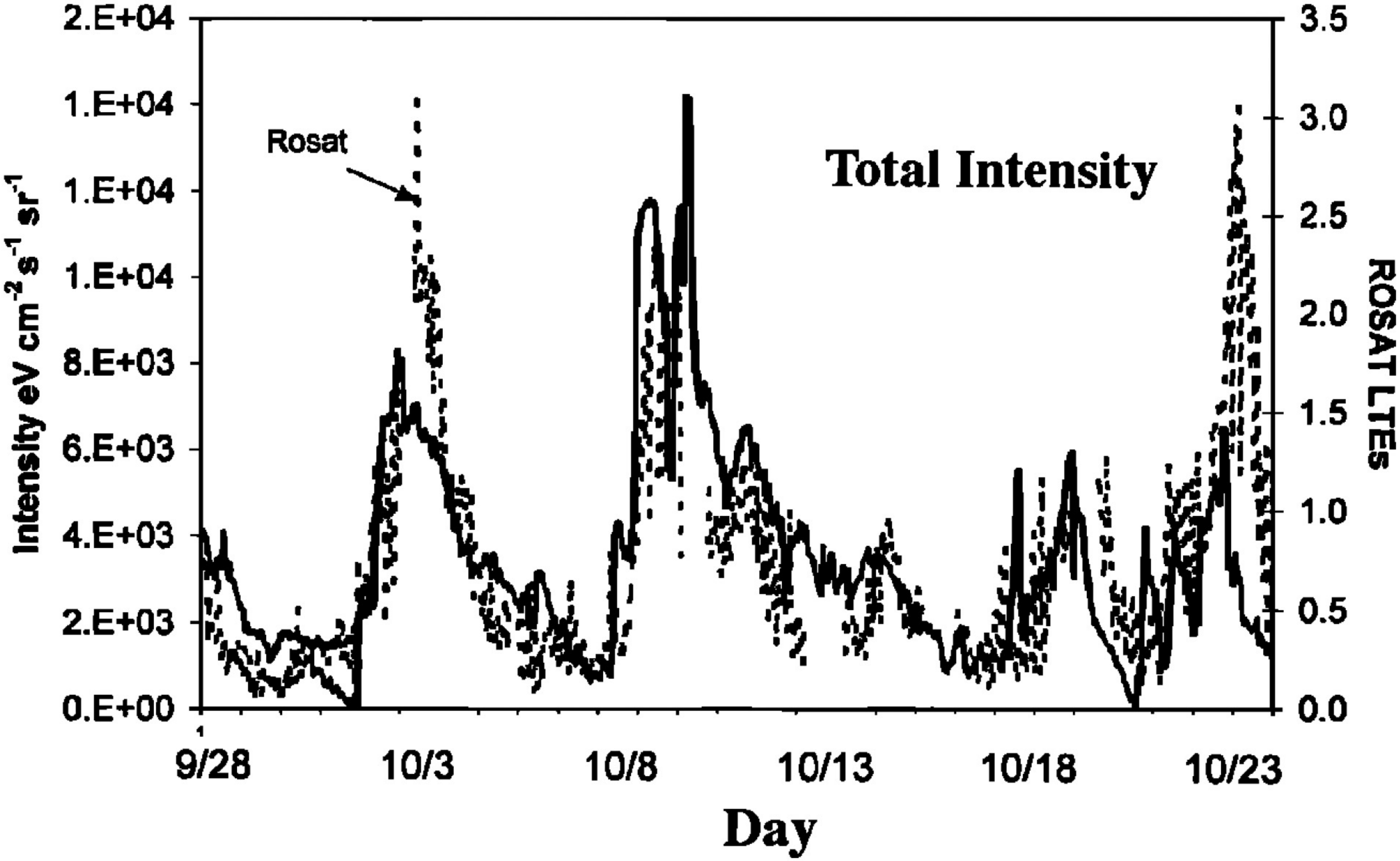
## **Parameters controling the emission:**

**-Ion properties (solar activity, wind source region):**
**influence SW velocity, composition, charge state**
**-neutral density distributions**
**-Ion charge state-neutral cross sections (type, velocity)**
**-Radiative cascade probabilities**

SWCX
A tool but also a foreground difficult to predict

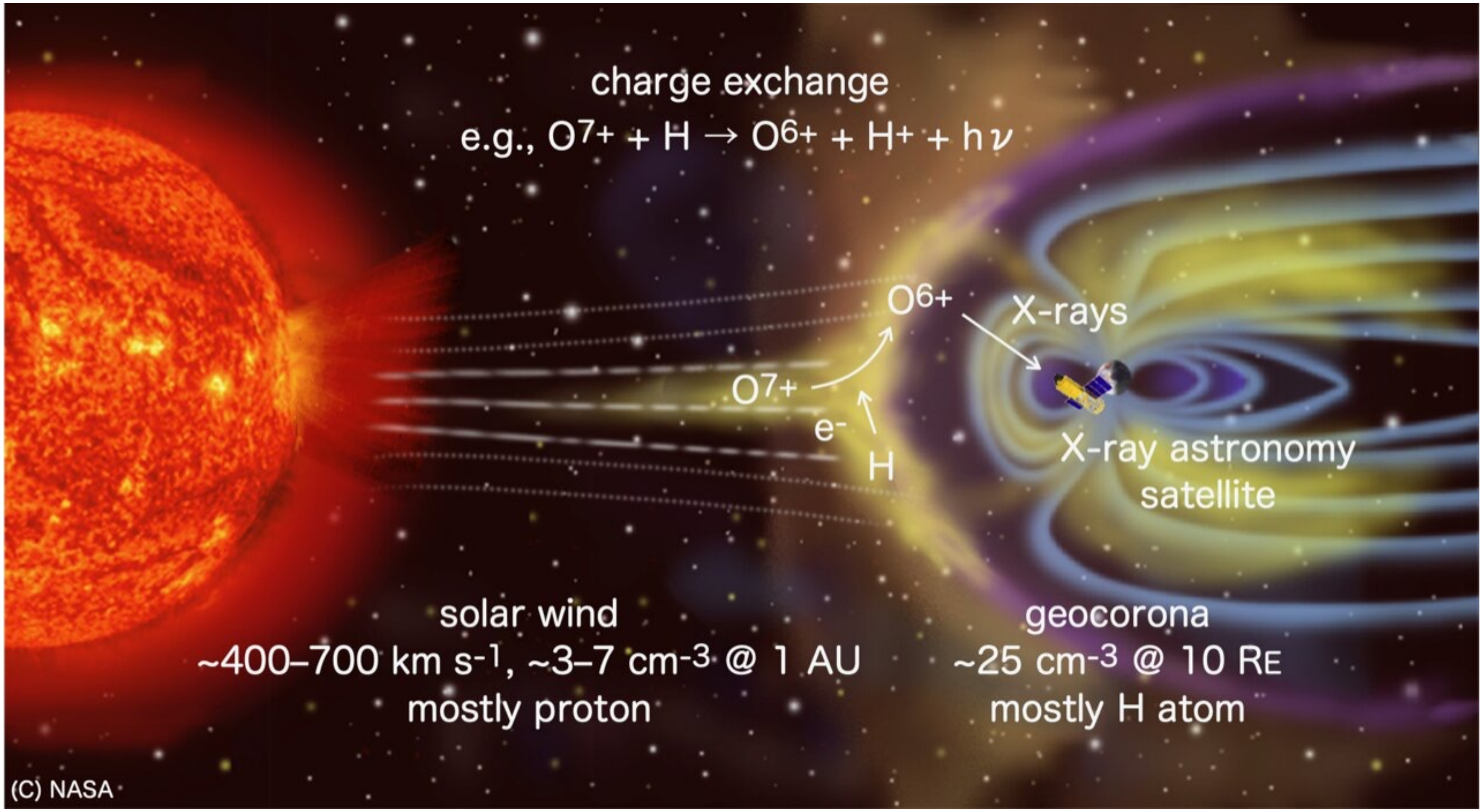
The « Long Term Enhancements » (LTEs) of the ROSAT data

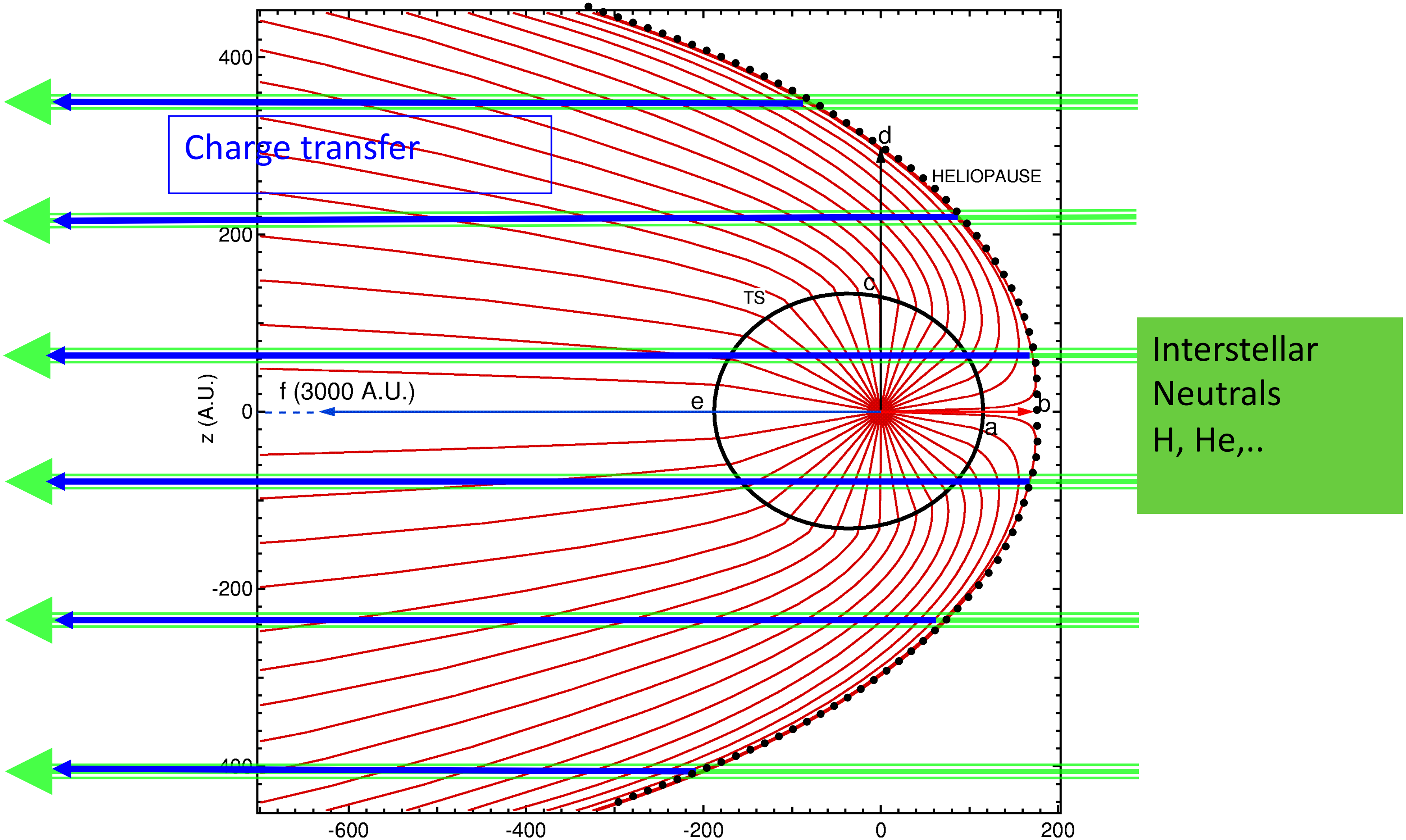
The diffuse background intensity in a fixed direction varies with time




Timescales from minute to several days

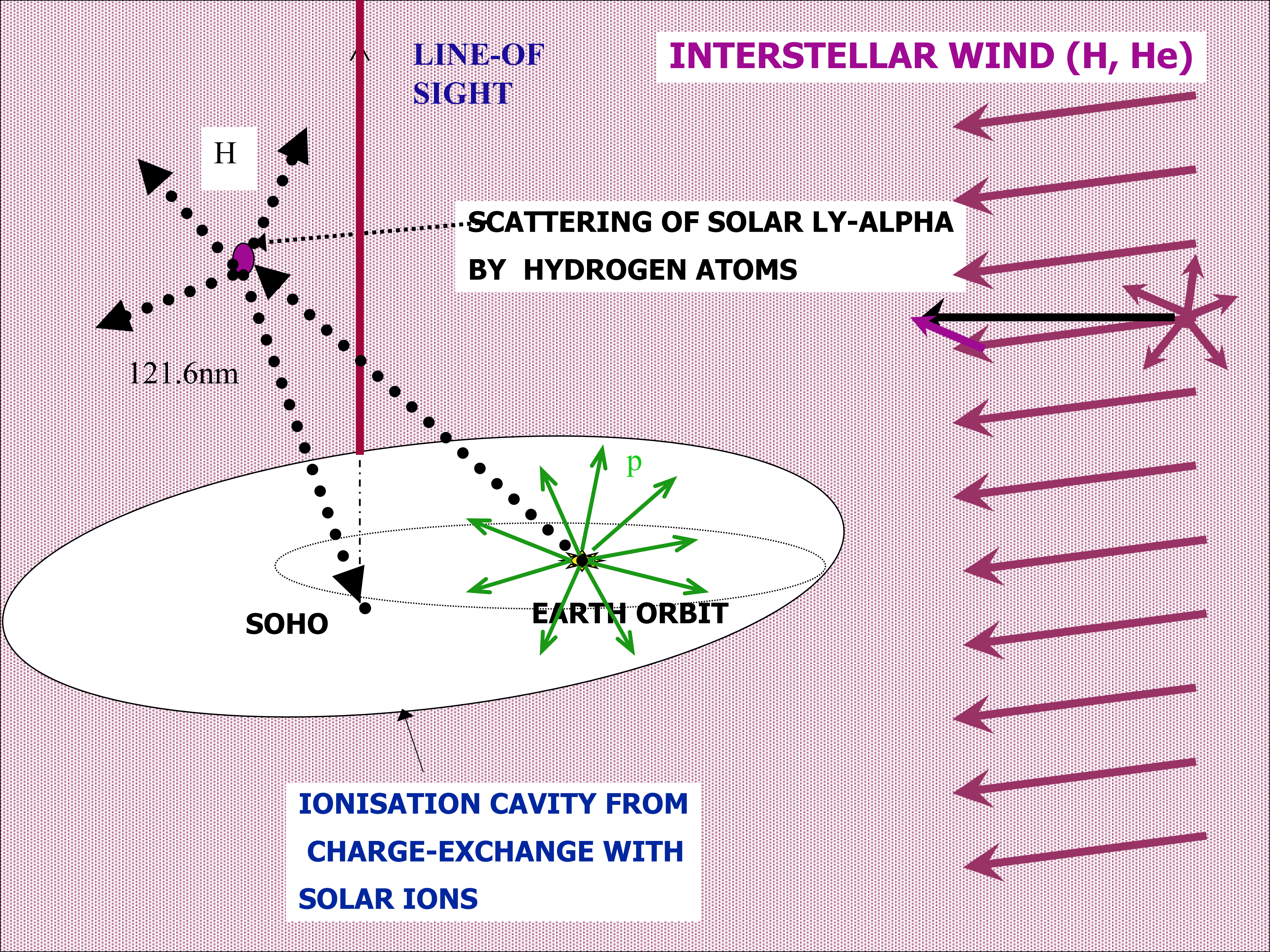
*Cravens, Robertson, Snowden, 2001*


charge exchange
e.g., O7+ + H → O6+ + H+ + hν
O6+
X-rays
O7+
e-
H
X-ray astronomy
satellite
solar wind
~400–700 km s-1, ~3–7 cm-3 @ 1 AU
mostly proton
geocorona
~25 cm-3 @ 10 RE
mostly H atom
(C) NASA




Along a given line-of-sight the contribution to the emission ends:

- either at the heliopause
- in the downwind direction where the particular solar ion has been entirely consumed

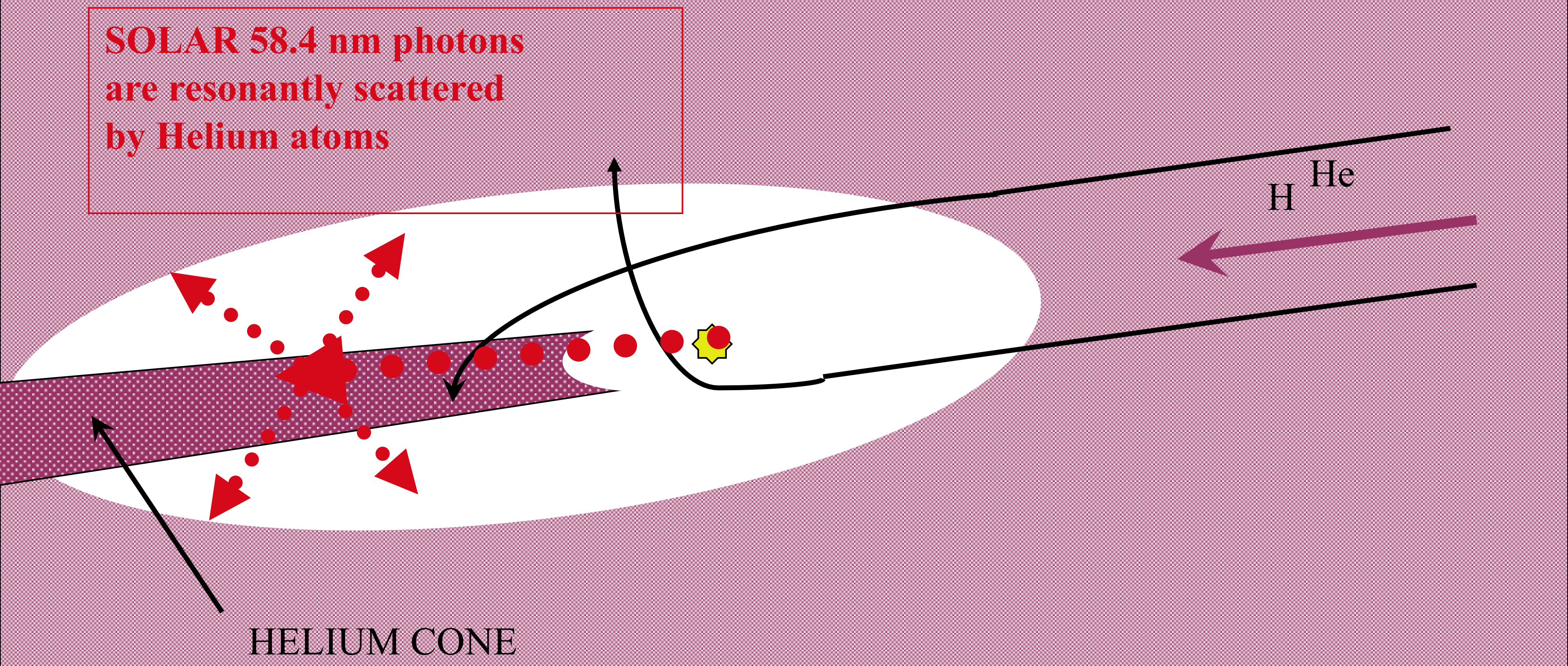


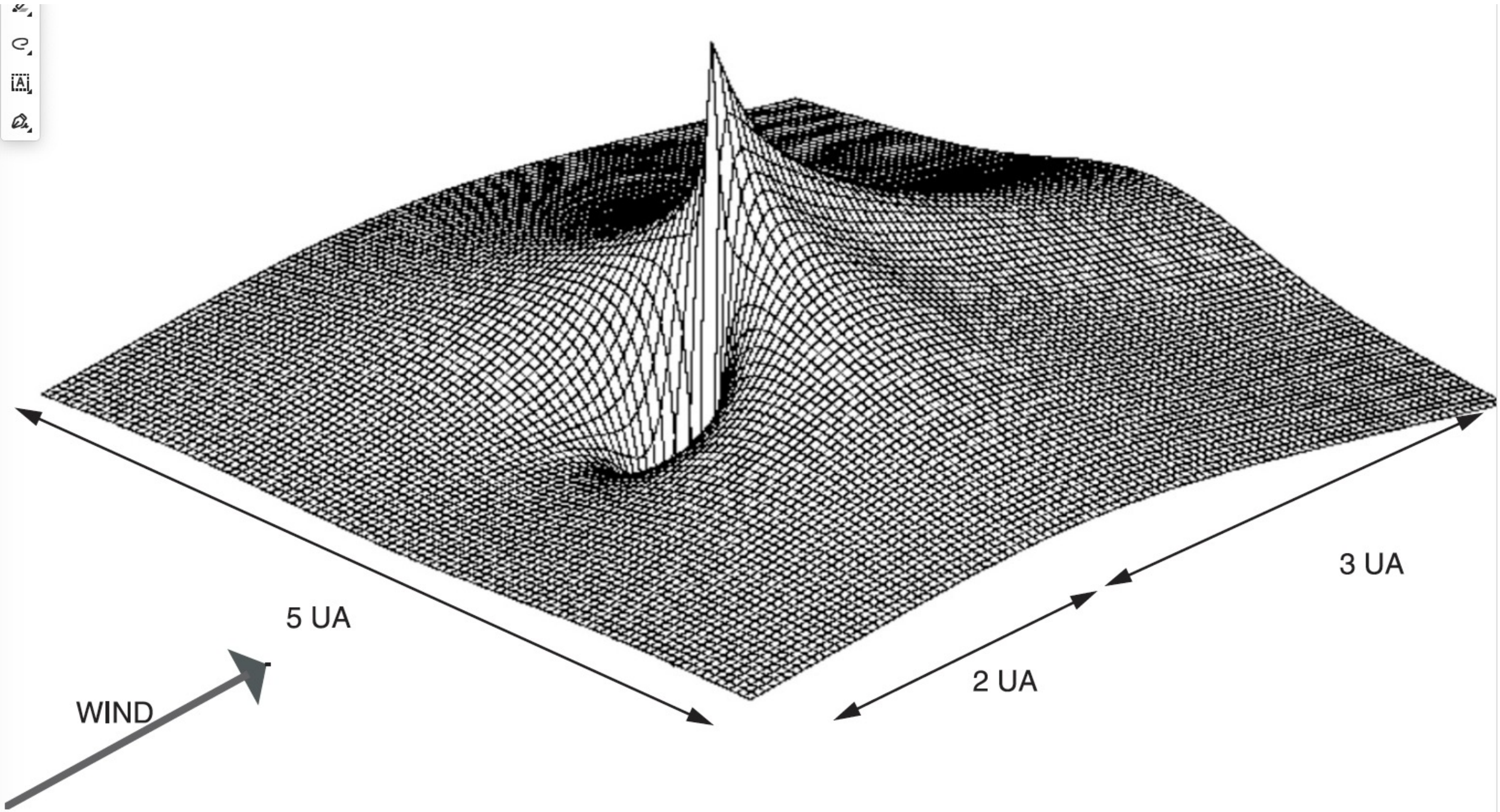
LINE-OF SIGHT
INTERSTELLAR WIND (H, He)
H
SCATTERING OF SOLAR LY-ALPHA
BY HYDROGEN ATOMS
121.6nm
p
SOHO
EARTH ORBIT
IONISATION CAVITY FROM
CHARGE-EXCHANGE WITH
SOLAR IONS

**HELIUM**

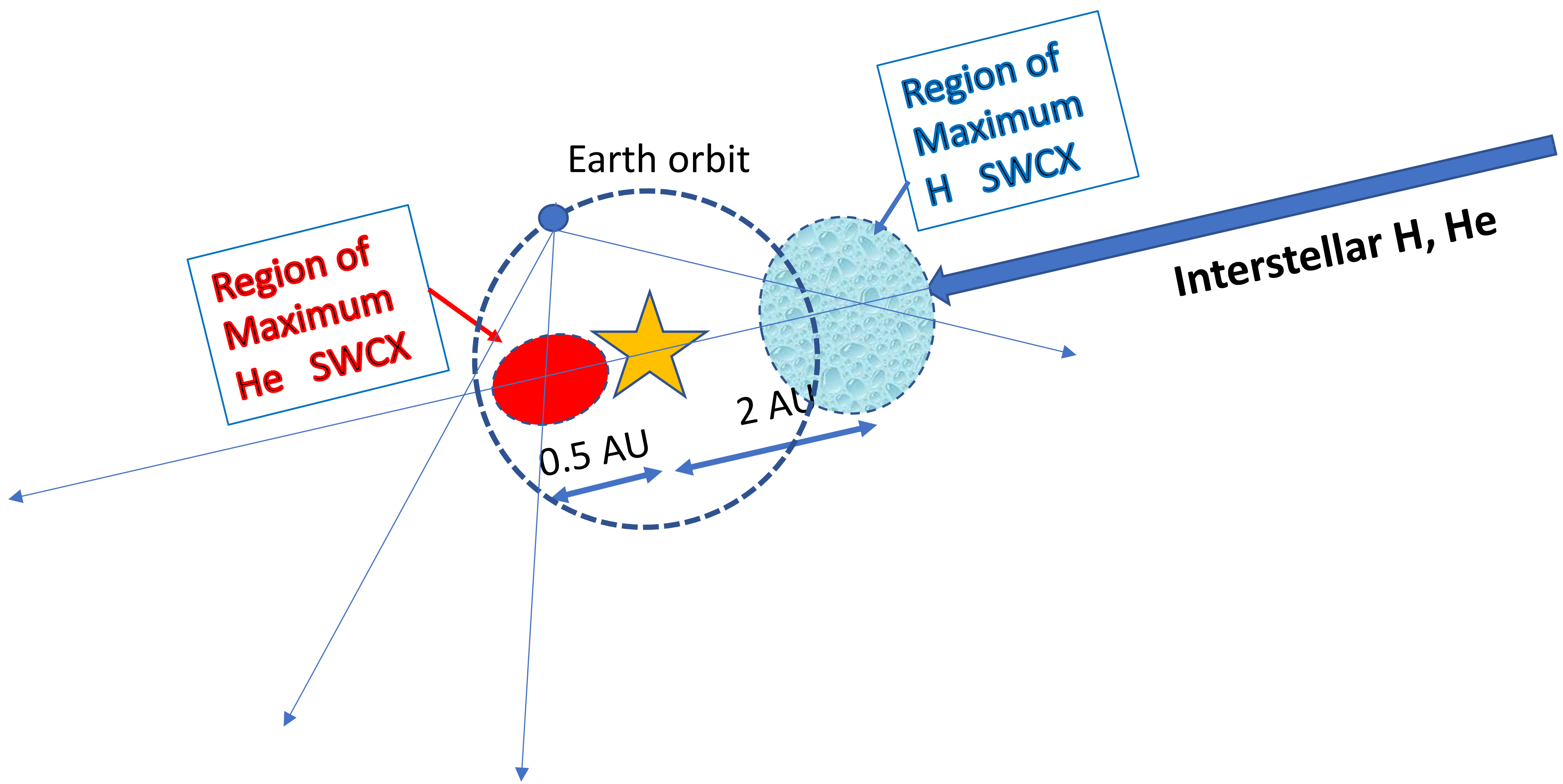
SMALLER IONIZATION

STRONG GRAVITATIONAL FOCUSING






*Lallement, Raymond, Vallerga et al 2004*


Earth orbit
Region of Maximum He SWCX
Region of Maximum H SWCX
Interstellar H, He
0.5 AU
2 AU

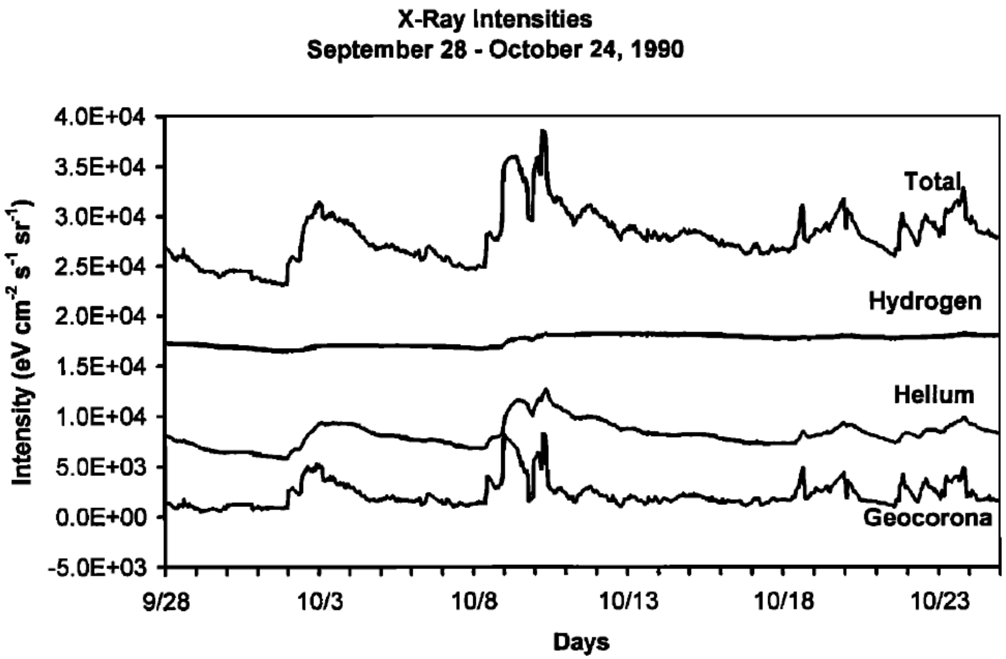
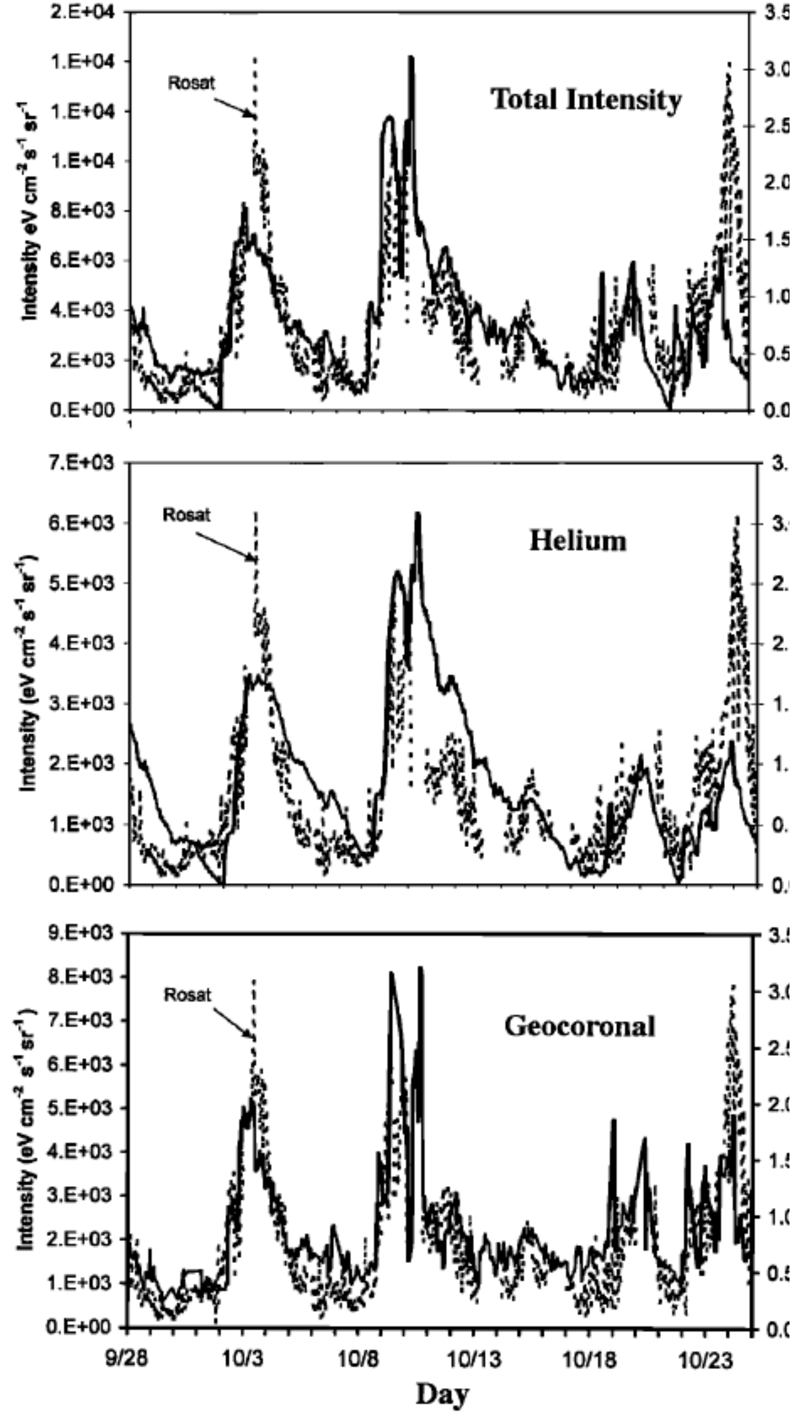



**Figure 4.** Model X-ray intensity versus time for the same time period as in Figure 3. Individual contributions from heliospheric H and He and from the geocorona are shown. The solar wind data used in the model included "interpolations" from other time periods (see text).




*Cravens, Robertson, Snowden, 2001*

# LATITUDINAL EFFECT


Solar maximum solar wind as measured by Ulysses/SWOOPS

# Model description (1)

- density distribution of IS H and He atoms in response to the solar wind and solar EUV conditions for solar minimum and maximum activity.
- densities of heavy solar wind ions ($X^{Q+}$), modulated by collisions with the neutral heliospheric gas (a)

Along a SW streamline

$$\frac{dN_{X^{Q+}}}{dx} = -N_{X^{Q+}}(\sigma_{(H,X^{Q+})}\, n_H(x) + \sigma_{(He,X^{Q+})}\, n_{He}(x)) + N_{X^{(Q+1)+}}(\sigma_{(H,X^{(Q+1)+})}\, n_H(x) + \sigma_{(He,X^{(Q+1)+})}\, n_{He}(x)) \quad \text{(a)}$$

**Loss term**

**Source term**

**Bare ion density & simplified case, loss term only:**

$$N_{X^{Q+}}(r) = \frac{N_{X^{Q+}o}}{r^2} \exp\left(-\int_{r_o}^{r} (\sigma_{(H,X^{Q+})}\, n_H(x) + \sigma_{(He,X^{Q+})}\, n_{He}(x))dx\right) \quad \text{(b)}$$

*Koutroumpa et al, 2006*

# Model description (2)

- **self consistent** density grids of H and He neutral atoms and solar wind ions used to calculate the X-ray emissivity (d) due to the CX collisions

Volume collision Frequency ($cm^{-3}$ $s^{-1}$)

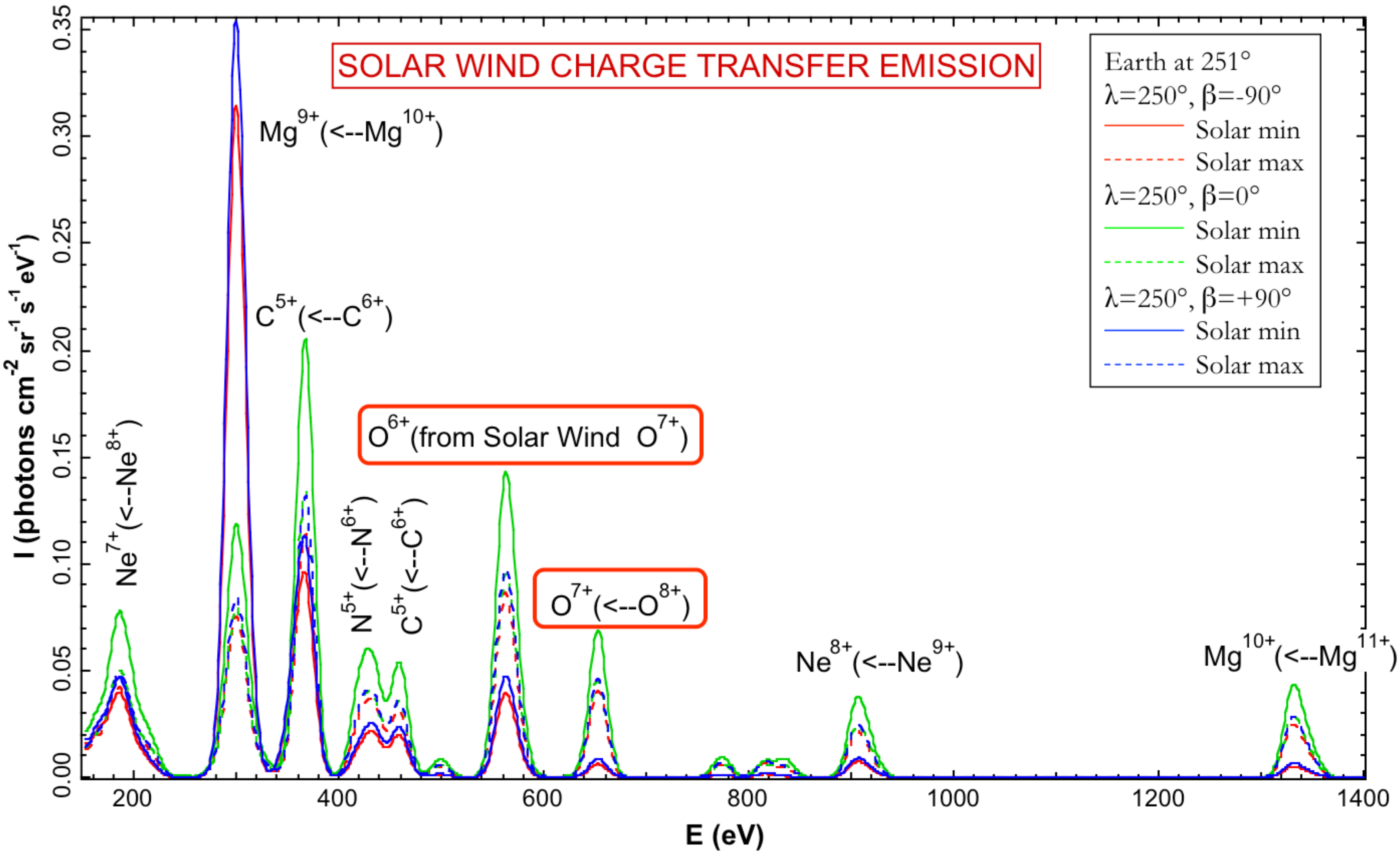
$$R_{X^{Q+}}(r) = N_{X^{Q+}{}_o}(r)\, v_{rel} \left( \sigma_{(H,X^{Q+})}\, n_H(r) + \sigma_{(He,X^{Q+})}\, n_{He}(r) \right) = R_{(X^{Q+},H)}(r) + R_{(X^{Q+},He)}(r). \quad \text{(c)}$$

Emissivity (ph $cm^{-3}$ $s^{-1}$)

$$\varepsilon_{h\nu}(r) = R_{(X^{Q+},H)}(r)\, Y_{(h\nu,H)} + R_{(X^{Q+},He)}(r)\, Y_{(Eh\nu,He)}. \quad \text{(d)}$$

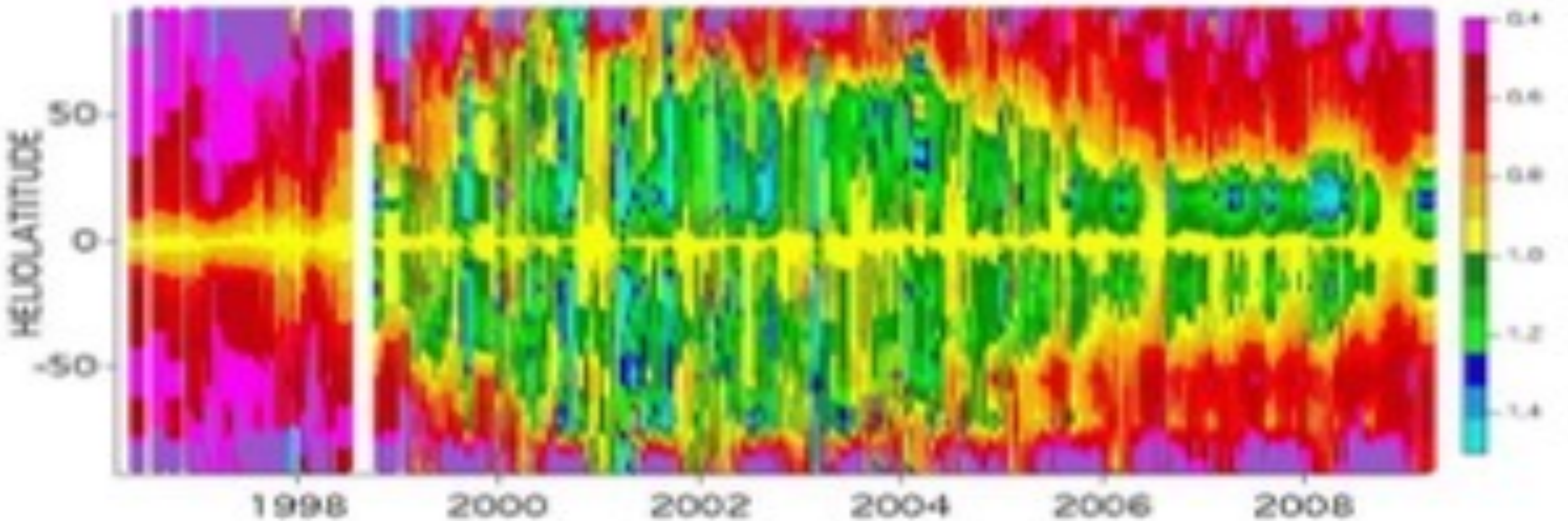
- total intensity along all lines of sight (e)

$$I_{h\nu}(O, \mathrm{LOS}) = \frac{1}{4\pi} \int_0^{\mathbf{heliopause}} \varepsilon_{h\nu}(r)\, \mathrm{d}s. \quad \text{(e)}$$

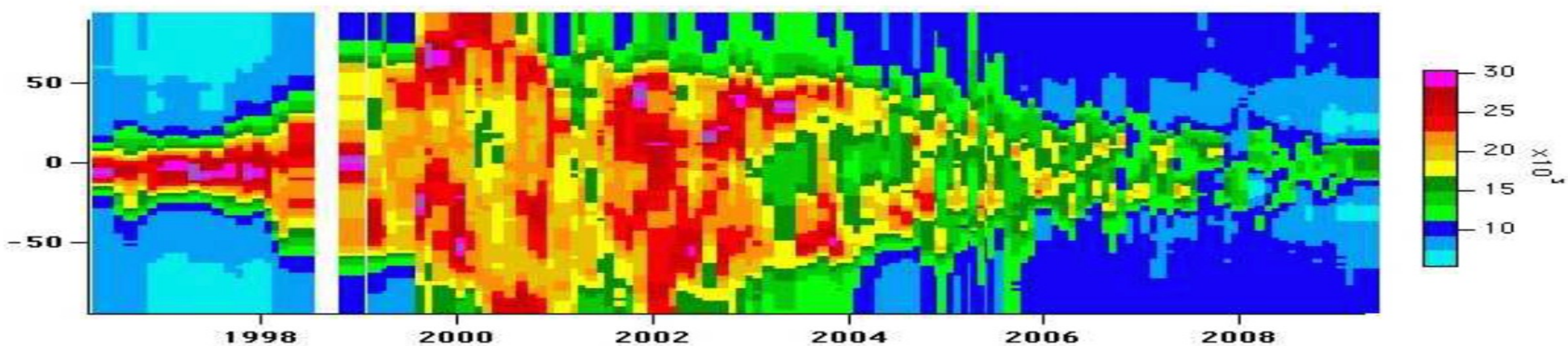



**Koutroumpa et al., A&A, 2006**

# COMPLEX TIME DELAYS AND INTENSITY VARIATIONS DUE TO LATITUDINAL EFFECTS

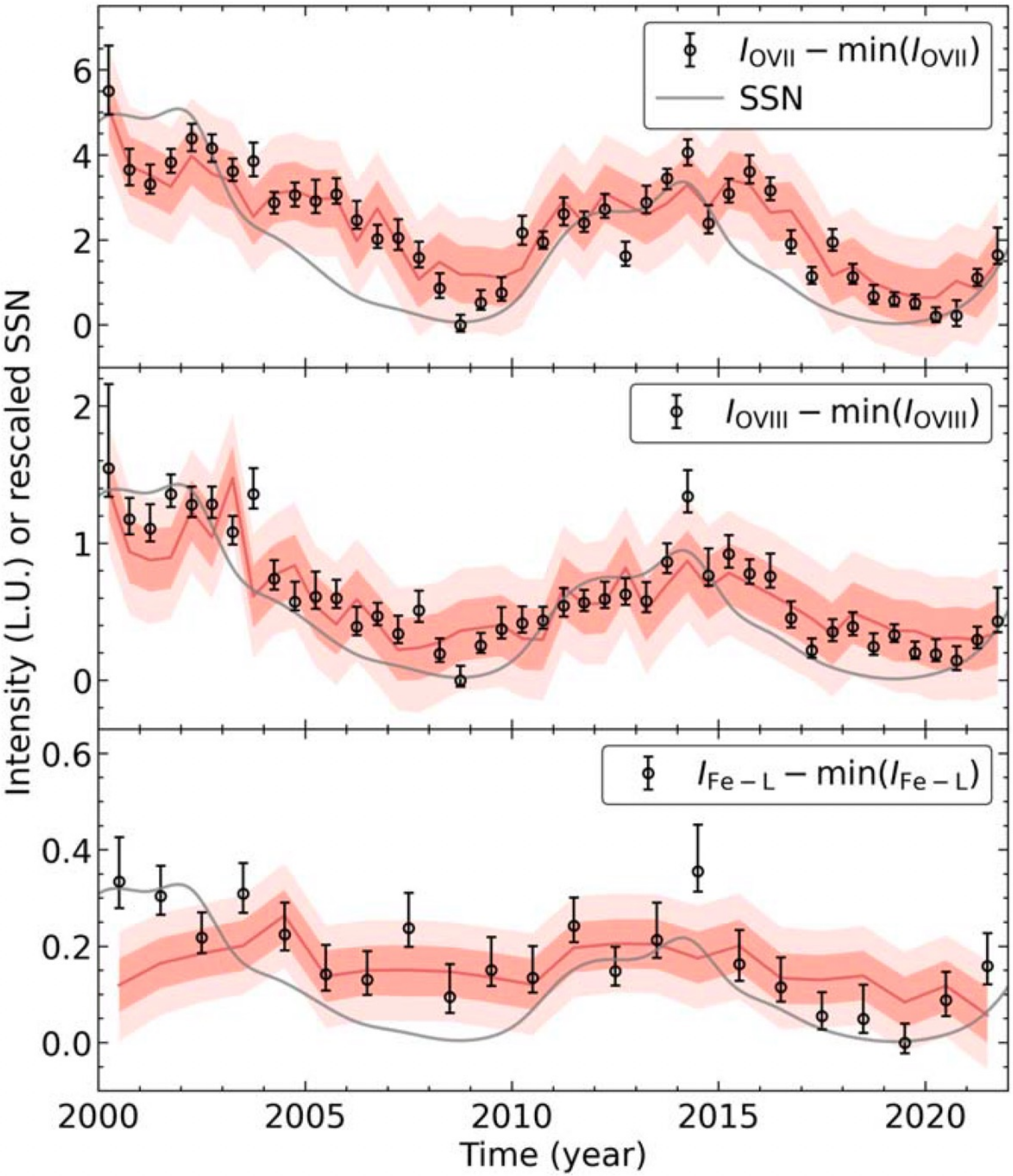



Interstellar H ionization rate at 1 AU as a function of time and heliolatitude (SOHO/SWAN)



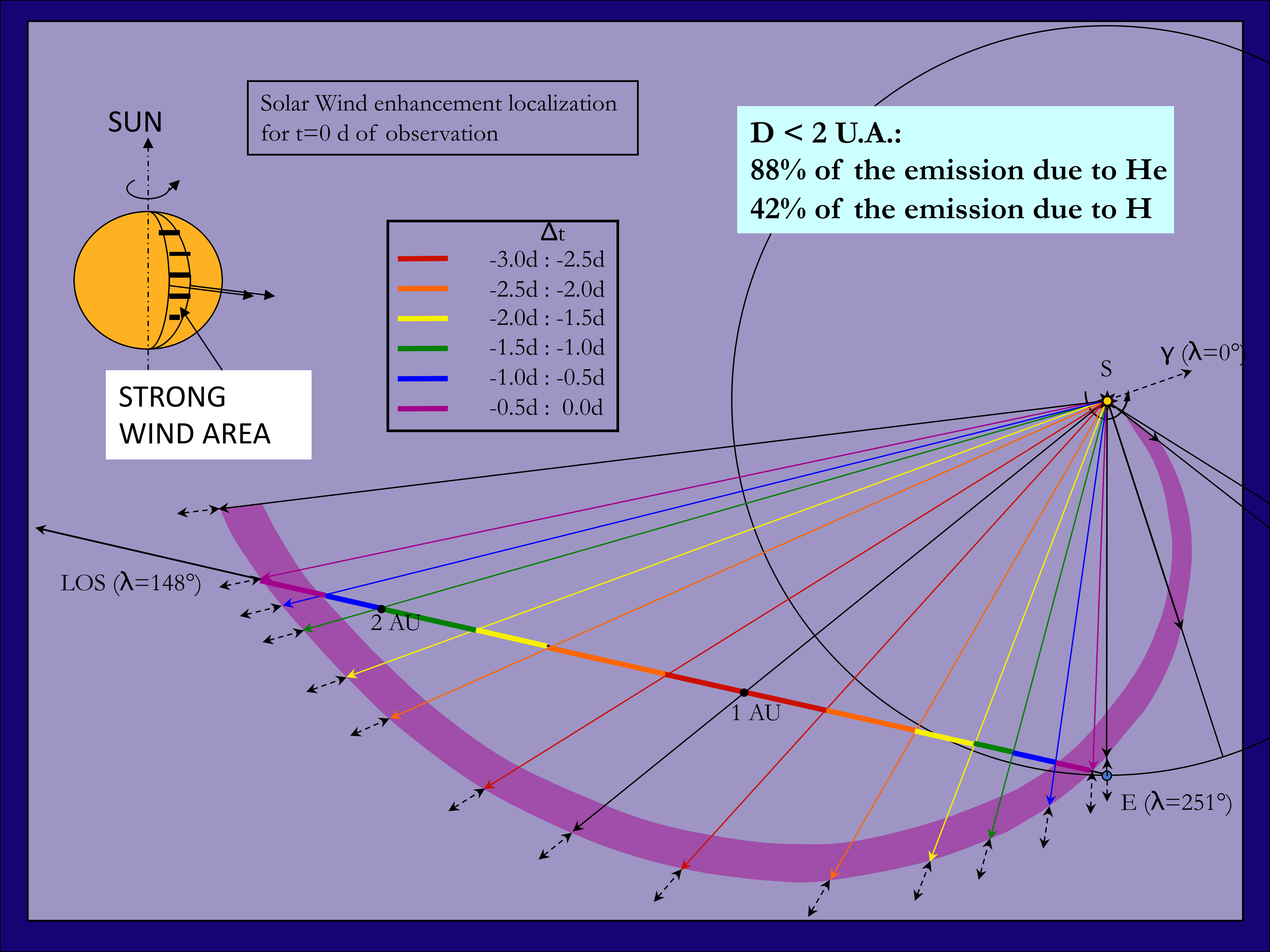

CORONAL ELECTRON DENSITY (SOHO/LASCO/C2)

Signals out of phase in a complex way



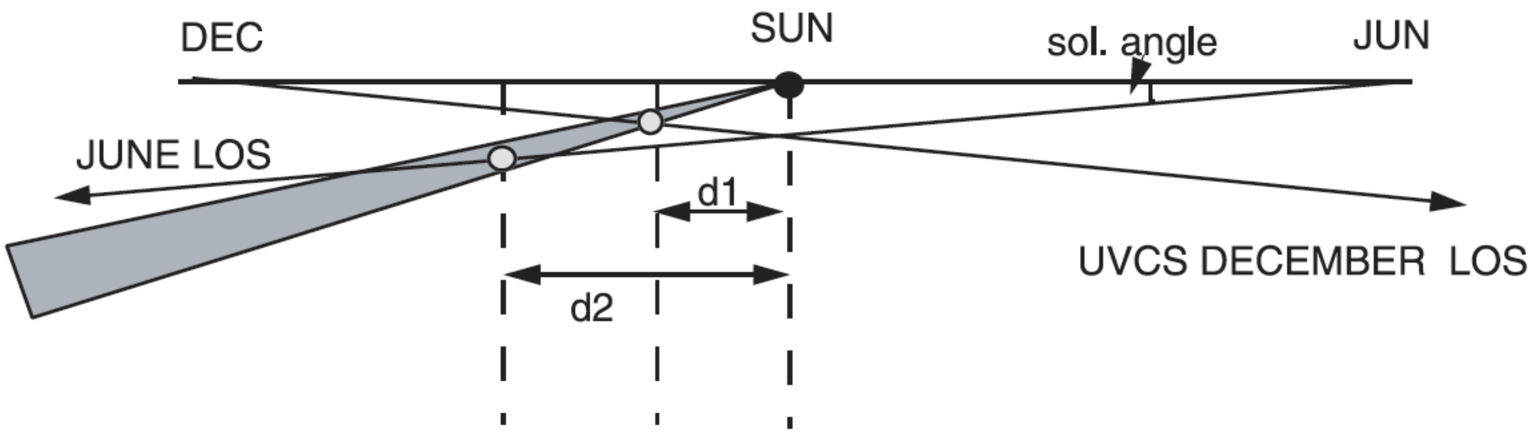

XMM-Newton archival data

Pan et al, 2024

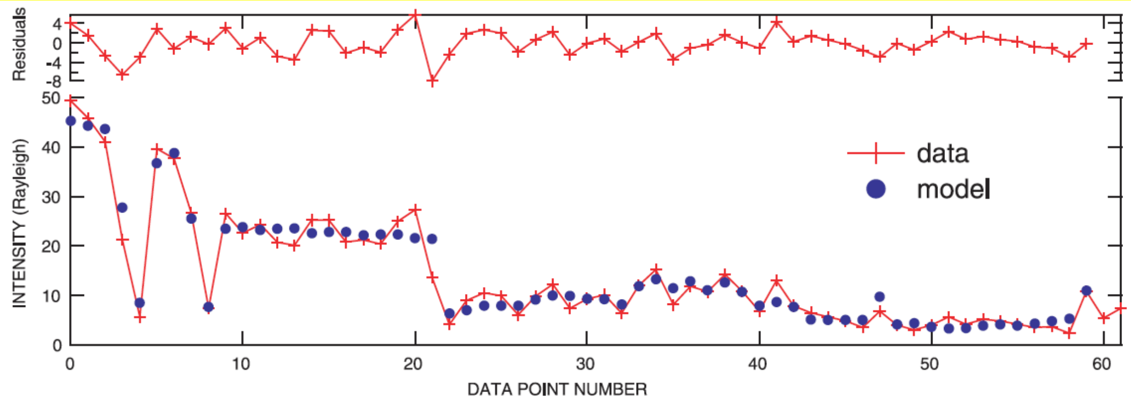


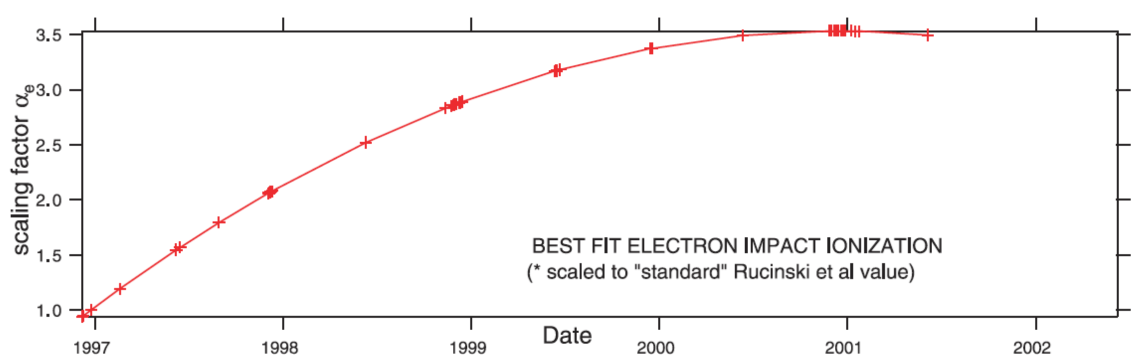
Solar Wind enhancement localization
for t=0 d of observation
SUN
STRONG
WIND AREA
Δt
-3.0d : -2.5d
-2.5d : -2.0d
-2.0d : -1.5d
-1.5d : -1.0d
-1.0d : -0.5d
-0.5d : 0.0d
D < 2 U.A.:
88% of the emission due to He
42% of the emission due to H
S
γ (λ=0°)
LOS (λ=148°)
2 AU
1 AU
E (λ=251°)

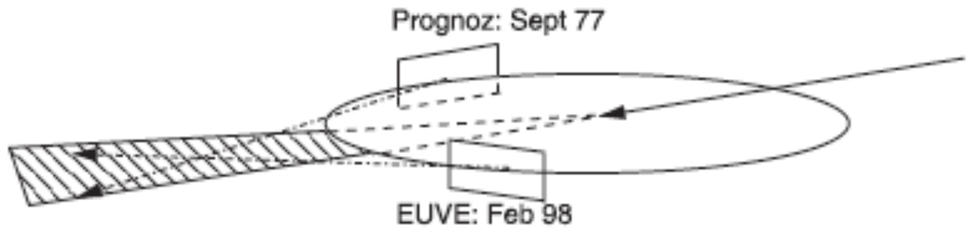
# The very strong variability of the helium cone: electron impact ionization close to the Sun

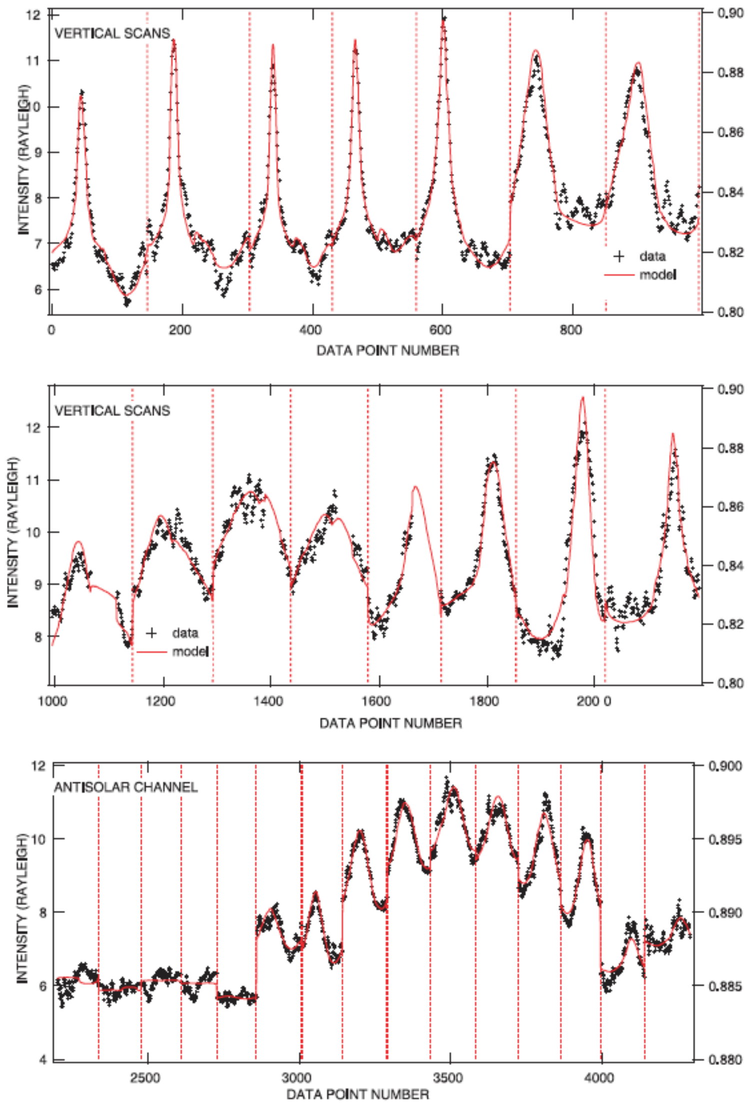



# Observations of the 58.4 nm diffuse emission (the helium glow) with SOHO/UVCS




Prognoz: Sept 77
EUVE: Feb 98


VERTICAL SCANS
INTENSITY (RAYLEIGH)
DATA POINT NUMBER
data
model
VERTICAL SCANS
INTENSITY (RAYLEIGH)
DATA POINT NUMBER
data
model
ANTISOLAR CHANNEL
INTENSITY (RAYLEIGH)
DATA POINT NUMBER

## SWCX simulations for astronomical observations: all difficulties

-Different sources of neutrals
magnetosphere + heliospheric H, + heliospheric He

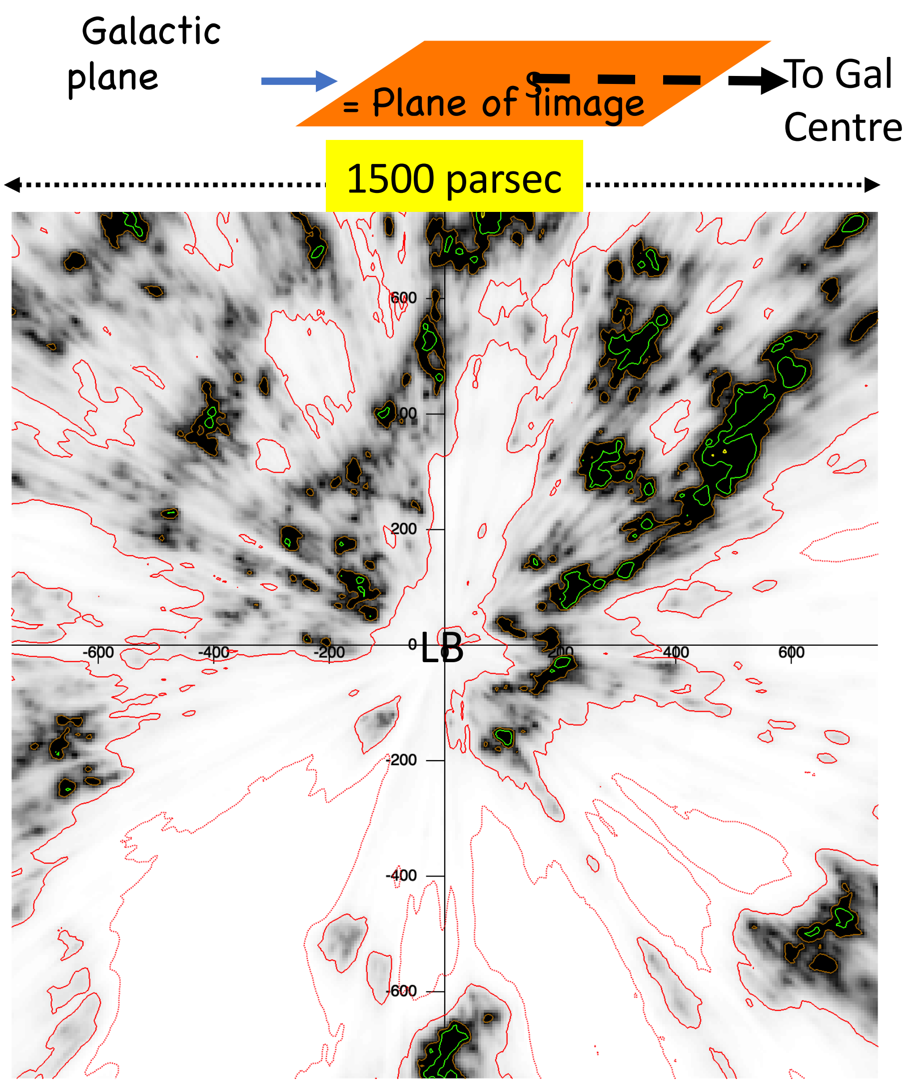
-and corresponding different solar wind propagation time

-Temporal evolution of the sources

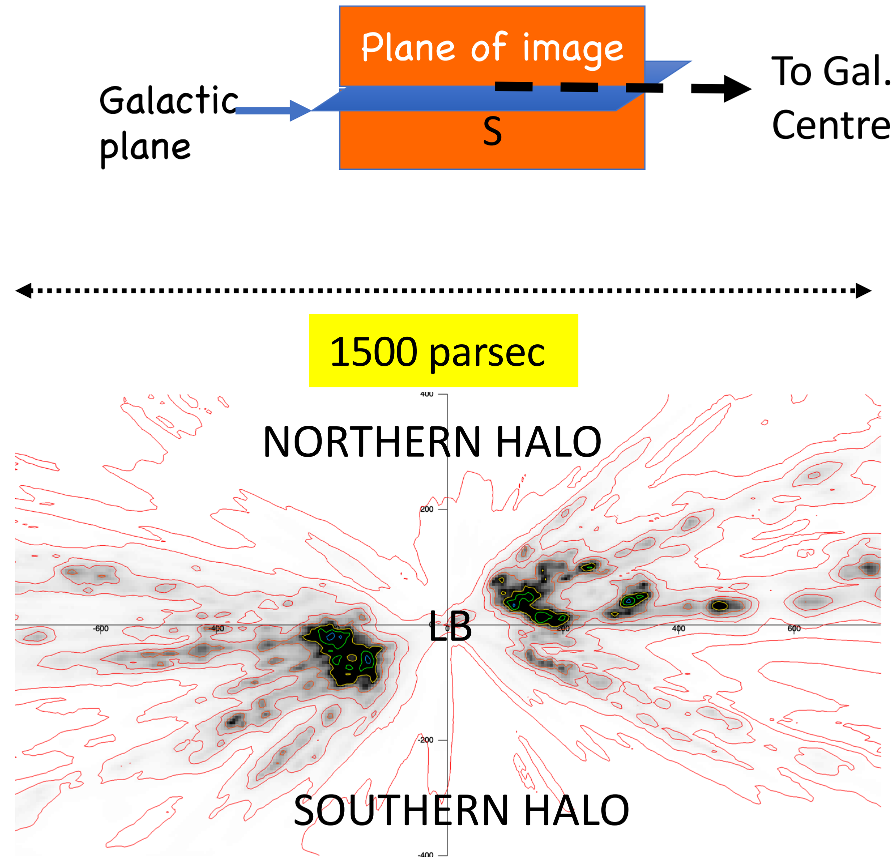
-Need for Parker spiral for very strong SW events

-Strong variability of the Helium cone

# The trouble with the Local Bubble (LB)

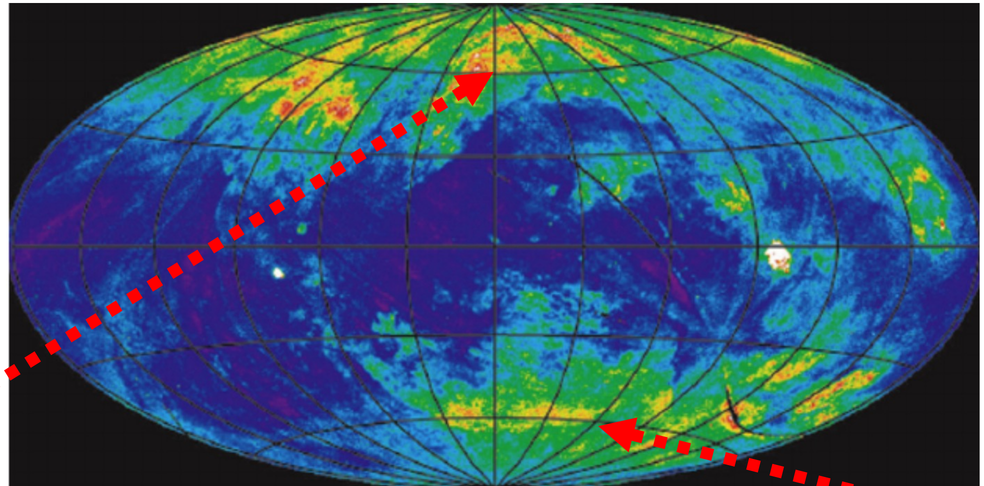



Map with
5 pc covariance length



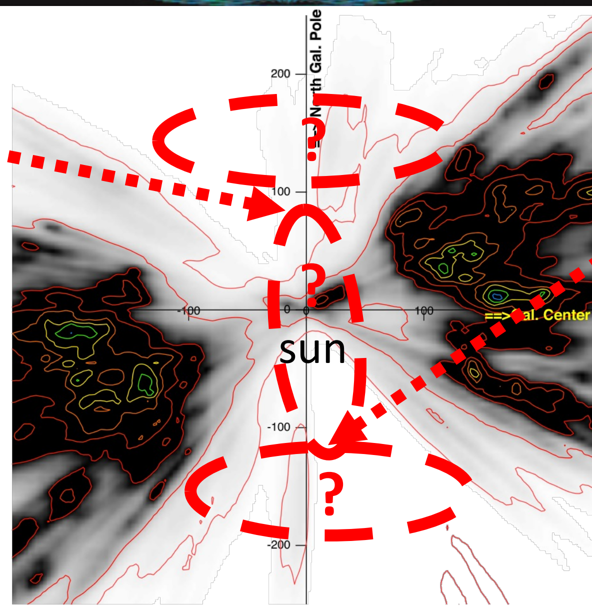

*Vergely et al, 2022*
maps and tools available
at explore-platform.eu

ROSAT ¼ keV map



Northern chimney

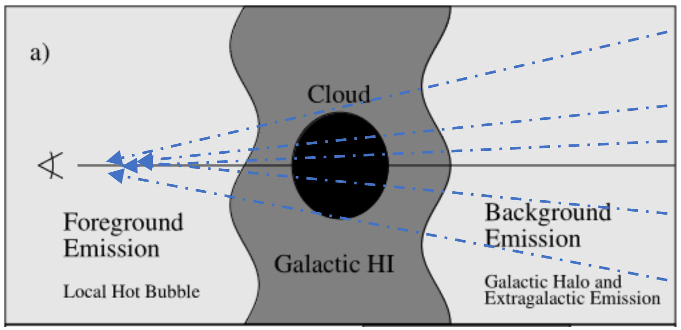
Southern chimney

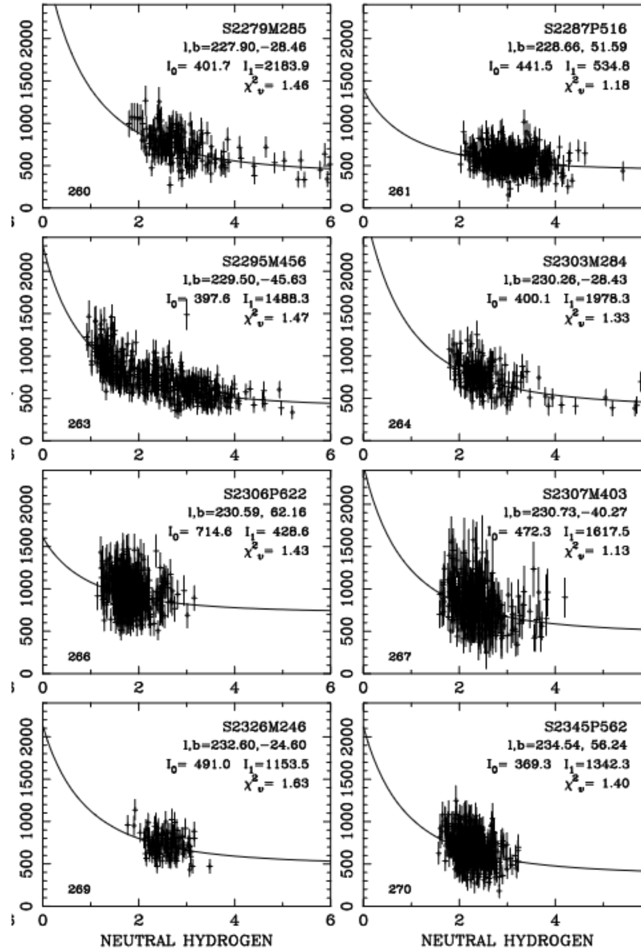



dust map in vertical plane

Is there hot gas X-ray emission only from the halo, or is there a contribution from the local bubble

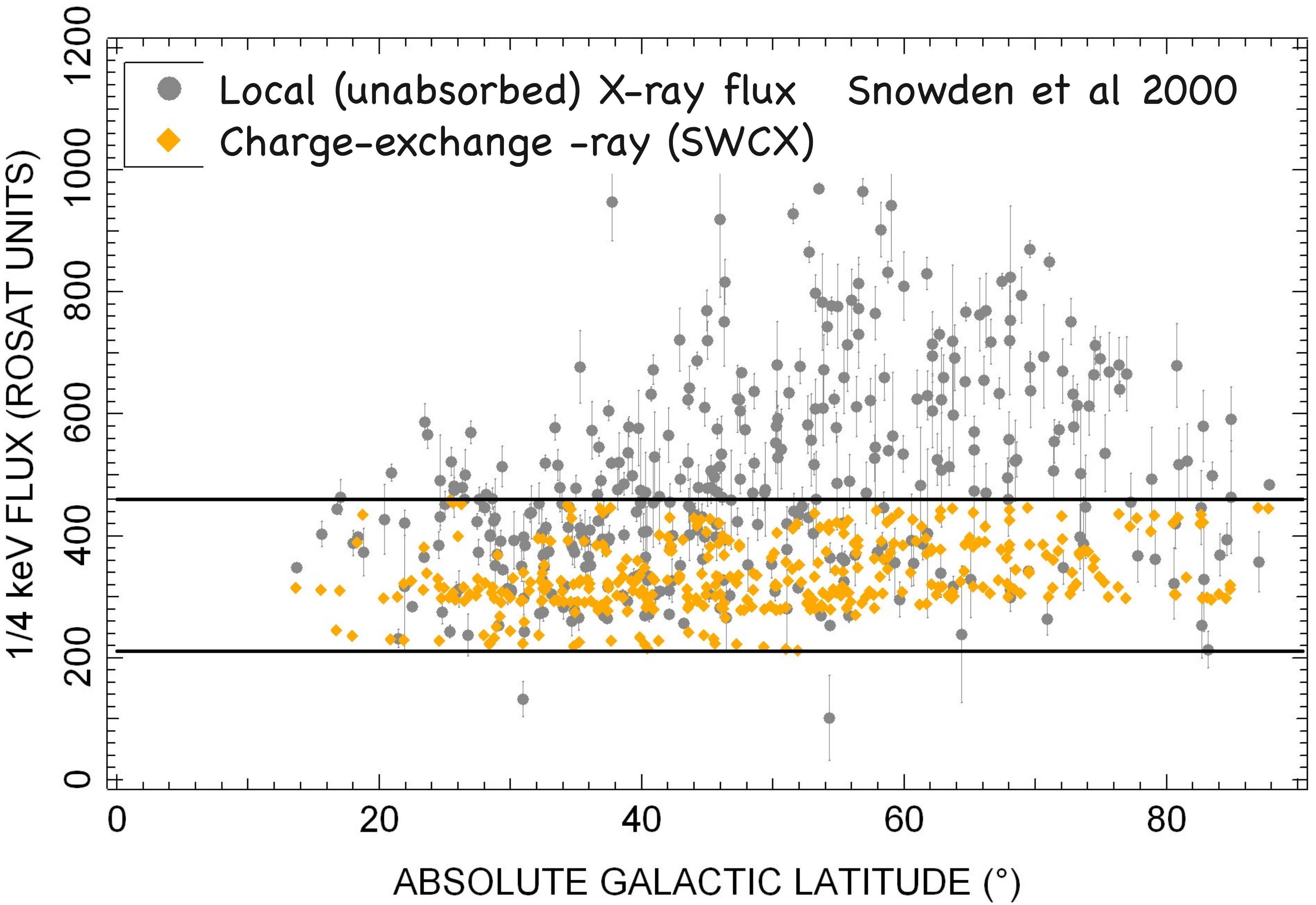
Using shadowing clouds to infer background and foreground emission (Snowden et al, 2000)



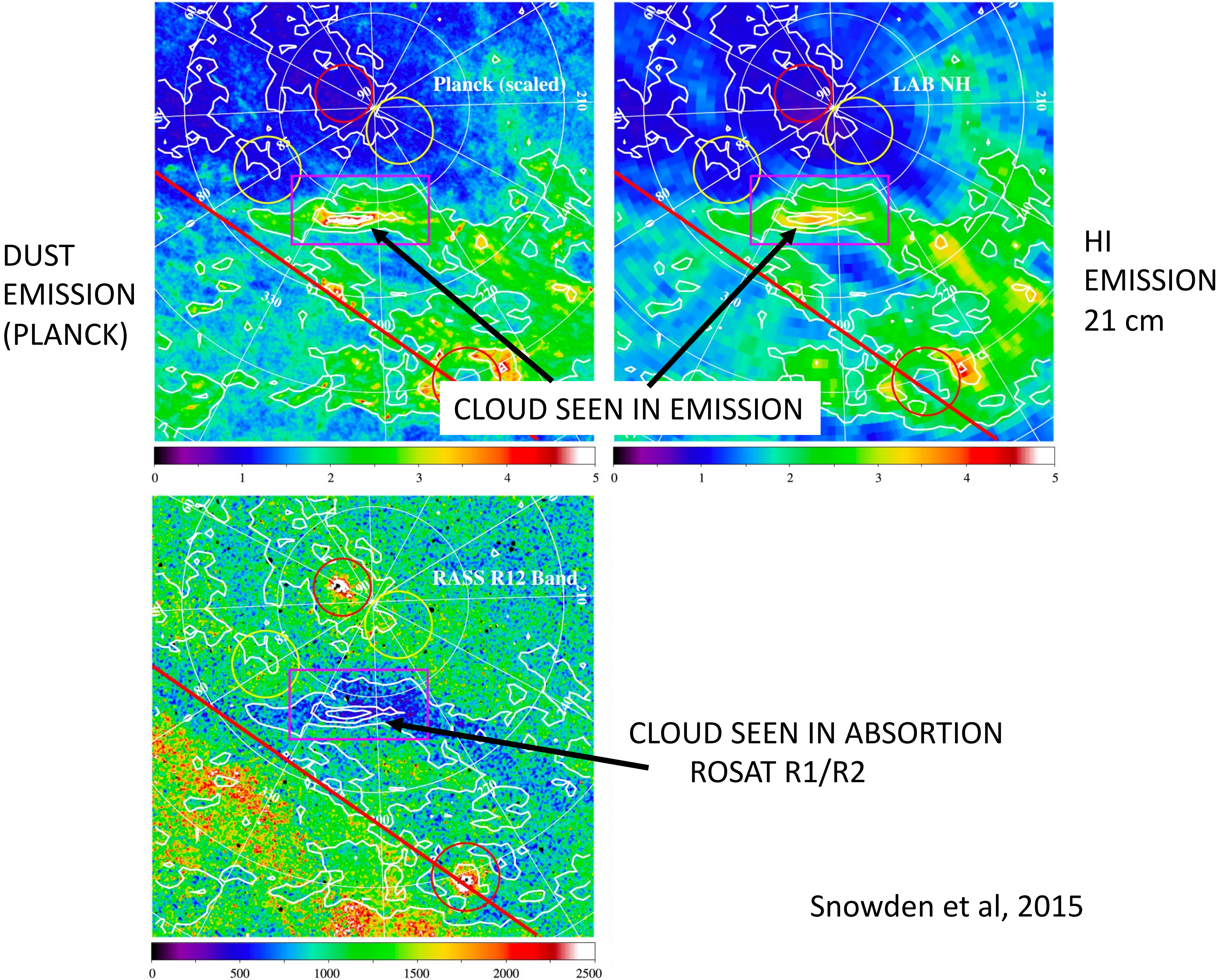

Authors used ROSAT ¼ keV (R12) and ¾ keV (R45) and DIRBE/IRAS 100 mm maps as a proxy for HI.

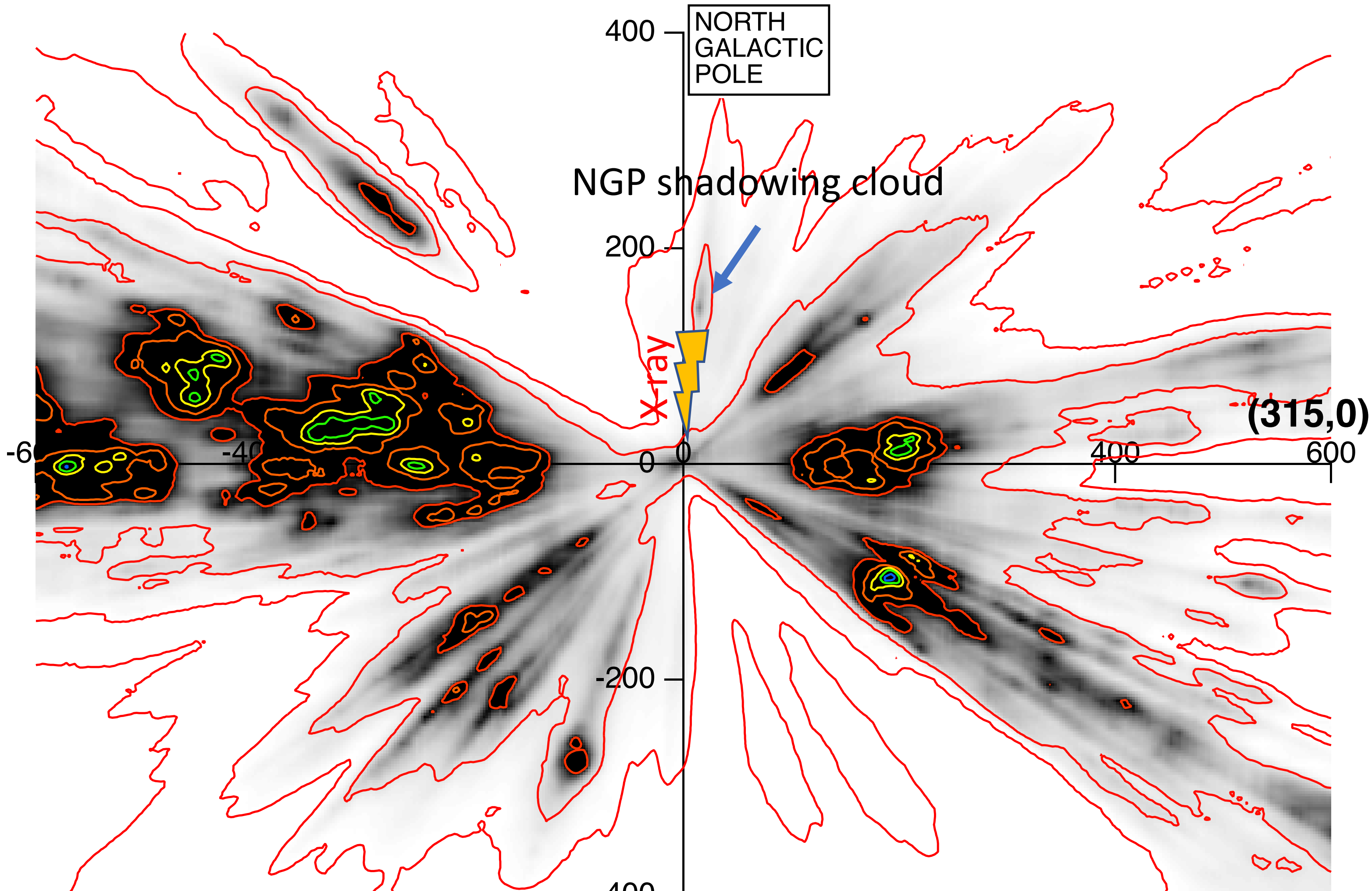
The foreground emission is due to the Local Bubble hot gas and to SWCX




**R12 EMISSION FROM LOW LATITUDES == CLOSED TO SWCX**

*Koutroumpa et al, 2009*


DUST
EMISSION
(PLANCK)
Planck (scaled)
LAB NH
HI
EMISSION
21 cm
CLOUD SEEN IN EMISSION
0 1 2 3 4 5
0 1 2 3 4 5
RASS R12 Band
CLOUD SEEN IN ABSORPTION
ROSAT R1/R2
0 500 1000 1500 2000 2500
Snowden et al, 2015




= CX (magnetosphere) + CX (heliosphere) + Local Bubble hot gas

50 131 217 Rosat Units

Series of shadowing experiments= > there is hot X-ray emitting gas in the local bubble!

# CXU

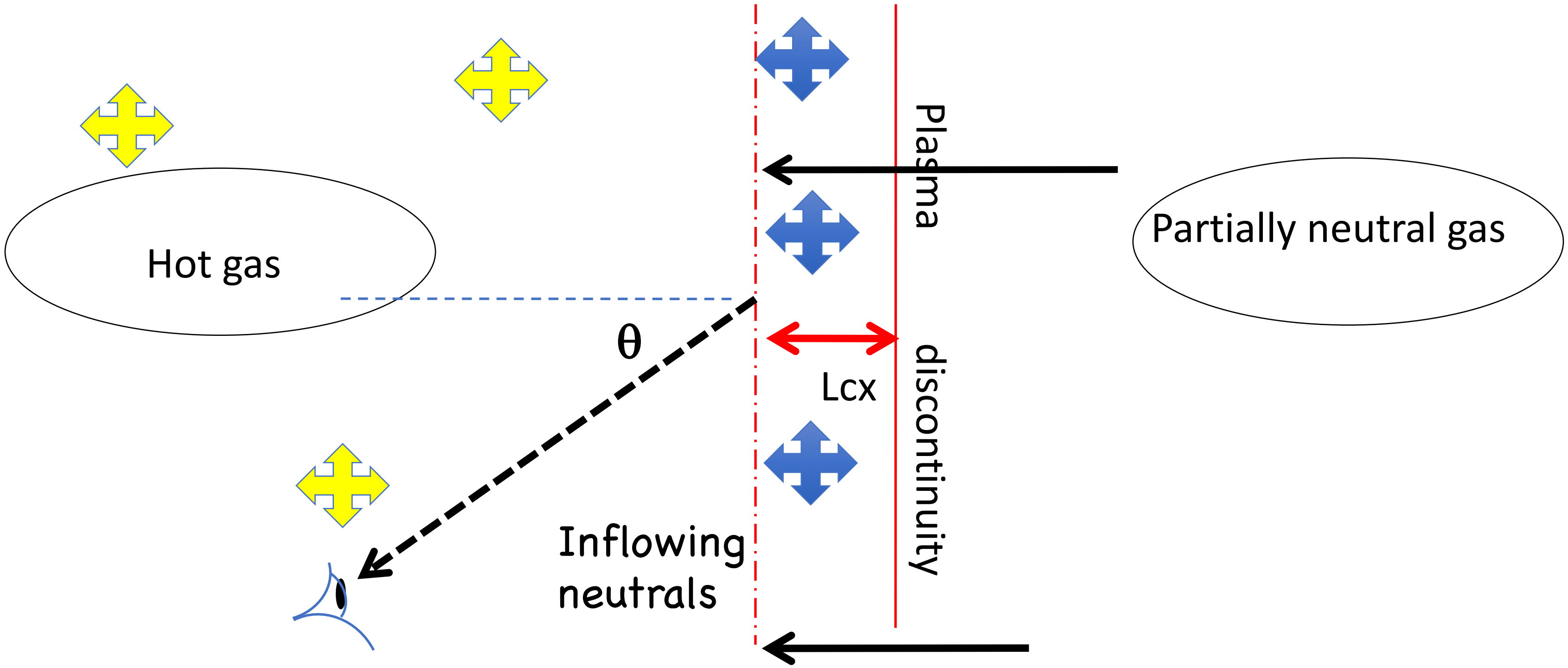
-for a broad view see the very exhaustive review of Gu and Shan (2023) !!!

Question: The solar wind is the CX favourable case of a **cool plasma with « frozen » charge-state** of the ions => neutrals entering the solar wind **do not suffer from collisional ionization with electrons** and **there is no hot gas thermal X-ray**.

It may be the case of astrospheres , or expansion of hot gas in quasi-vacuum.

This is not the case for interfaces between **hot gases and cool partially neutral gas. What happens then?**

CTX emission arises in **narrow layers** that correspond to the **mfp of neutrals against ionization**

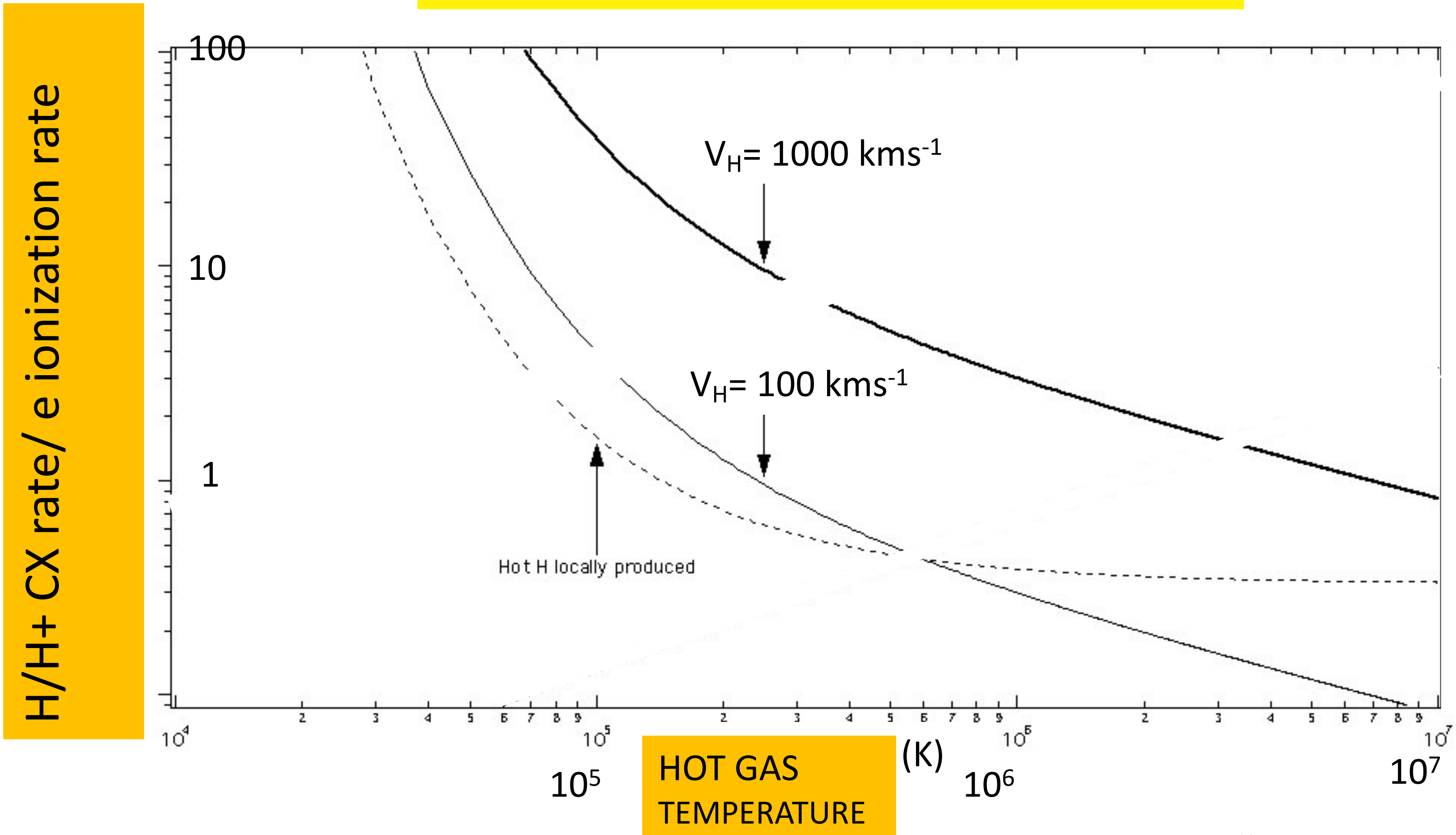



Lcx =mfp of neutrals through the hot gas

**Absolute** emission **unimportant:** what **matters** is the **relative** intensity of the CTX ( ) **w.r.t.** the **hot gas emission** ( )

Neutral H atoms « launched » in hot gas

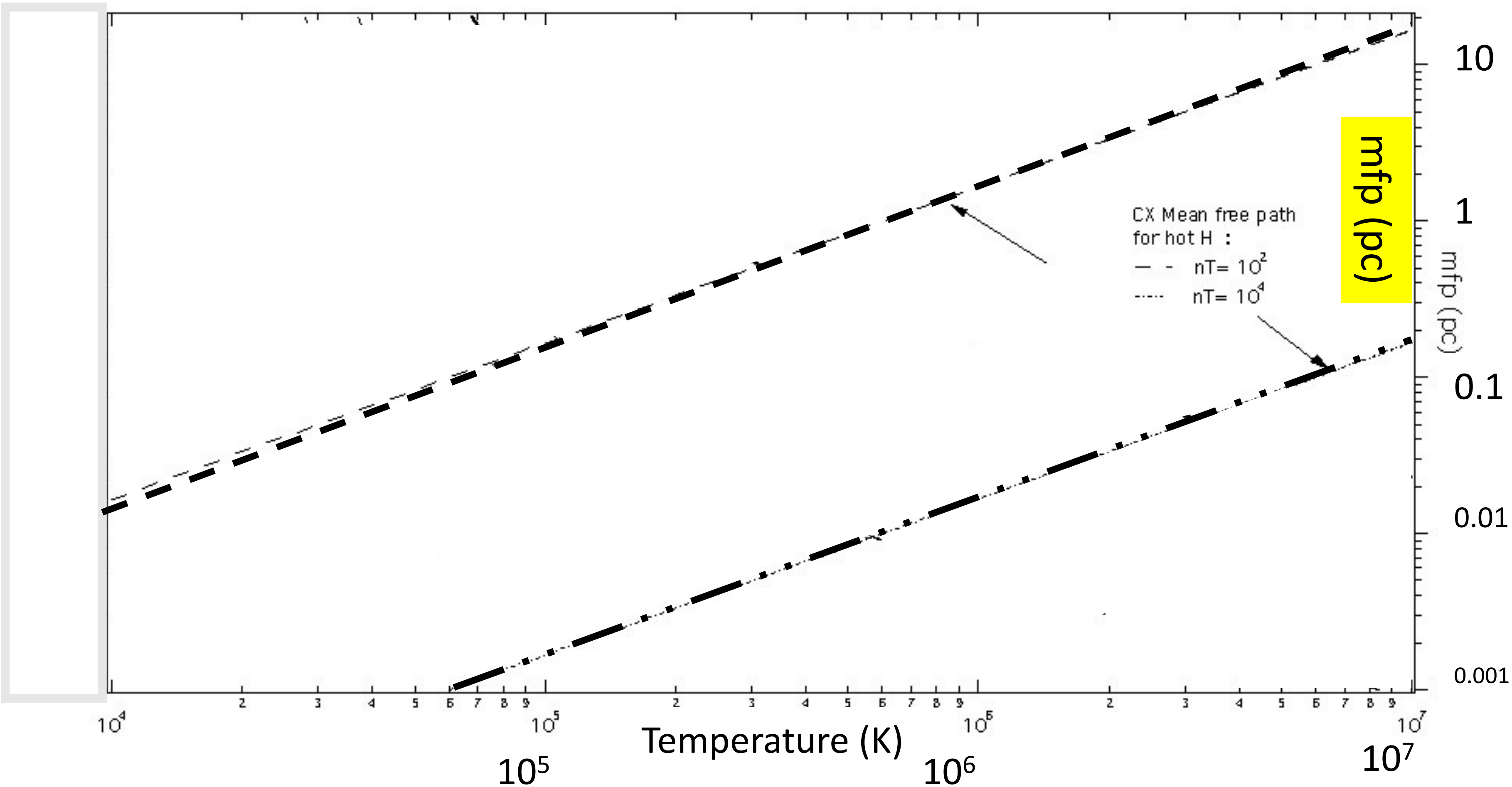
CHARGE-TRANSFER vs COLLISIONAL IONIZATION




*Lallement, 2004*

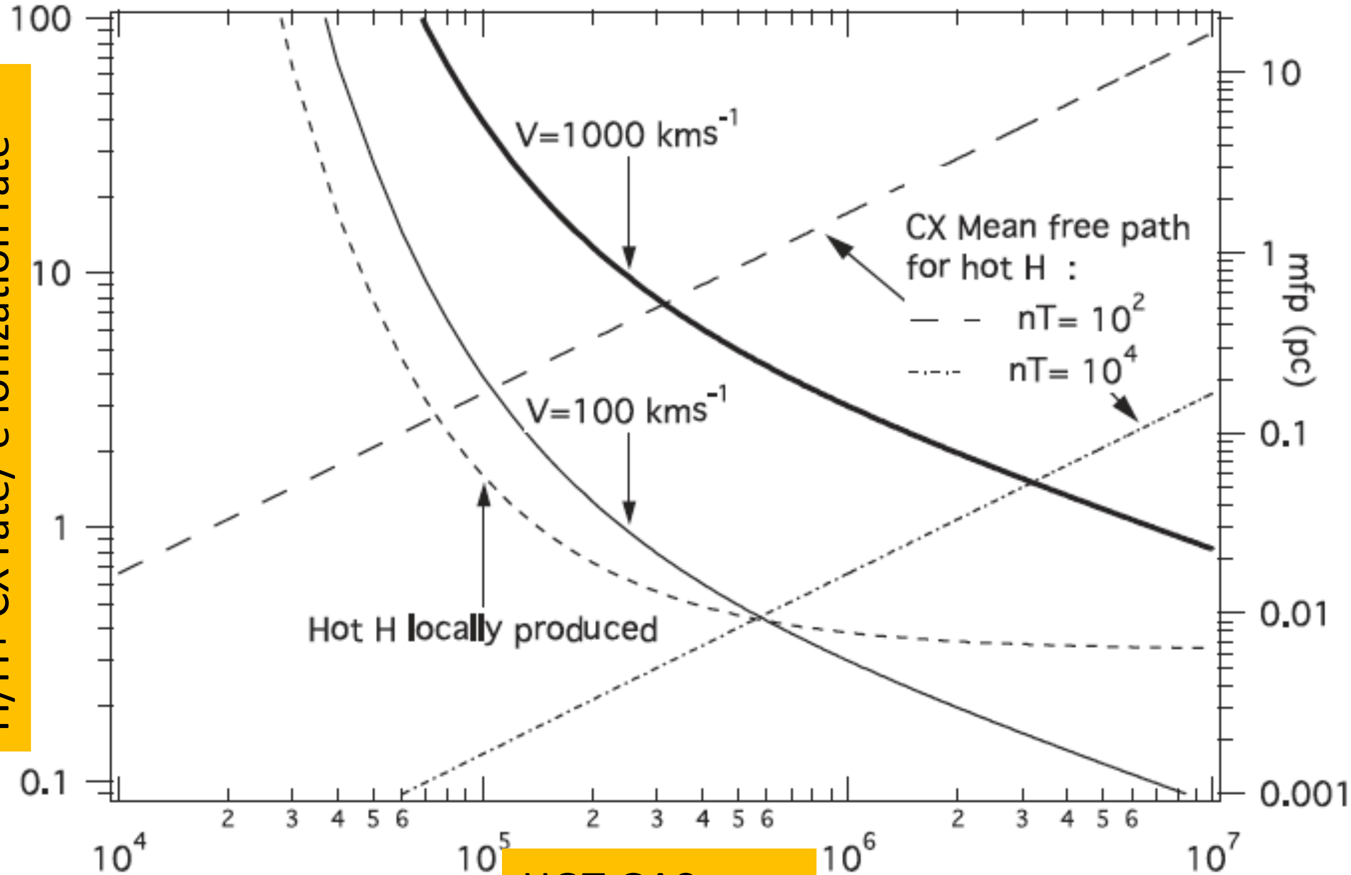
Neutral H atoms « launched » in hot

Mean free path against ionization



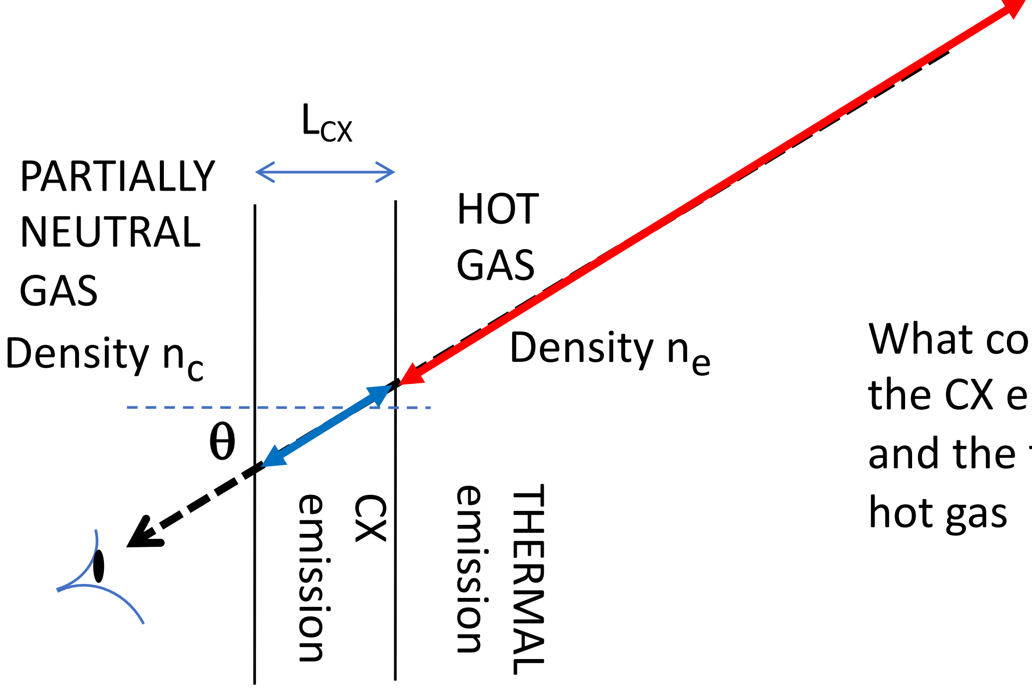
# Ionization of an H atom launched in hot gas

CX ionization vs electron impact ionization




H/H+ CX rate/ e ionization rate

HOT GAS TEMPERATURE




What counts is the ratio between the CX emission (from the narrow layer) and the thermal emission from the hot gas

One way to estimate the potential importance of the CX layer is to convert it into an equivalent path of hot gas thermal emission, and compare with the size of the path through the hot gas

$$_{pc}L = 3 \times 10^{-2} \left(\epsilon \alpha \chi_{T,a}^{-1}\right)\left(n_c V_{100} n_e^{-2}\right)$$

L varies as $n_e^{-2}$

$V_{100}$ : hot/cold gas relative velocity in units of 100kms$^{-1}$

$\varepsilon$ = fraction of neutrals experiencing charge transfer before being collisionally ionized

$\alpha$ = hot gas metallicity/ solar ( $\alpha$ =1 for solar)

$\chi$ = hot gas emissivity/ (T=$10^6$ K, $\alpha$ =1 ) gas emissivity

E.g. L on the order of 100 kpc if $n_c$=0.1 cm$^{-3}$ , $n_e$= $10^{-4}$ cm$^{-3}$
T hot= $10^7$ K, T cold=$10^4$ K (filament in galaxy cluster gas)

Approach used by Katsuda et al, 2011 for the Cygnus loop

Another view:

Estimates of CX in cluster filaments (Fabian et al, 2011)
-1) assumes that **hot gas penetrates the cooler filamentary gas through reconnection dif-fusion** reconne
-2) ions and H+ neutralized by H,He in proportions similar to their abundances
Fabian et al, 2011 conclude in negligible CX intensity, while Walker, Kosec, Fabian et al, find the spectra compatible with CX significant contribution

Diagnostics for CXU

SPECTRAL

Helium-like ions triplet: forbidden line relative increase

$G=(f+i)/r > 2$

$Ly\beta/Ly\alpha$ and in general High-n shells enhancements

anomalous abundances

CX = lines only => ≠ continuum to line ratios (at high T)

SPATIAL

emission from filamentary, sheet-like structures

tight correlation with H-alpha

unexpected emission, overcomes shadowing due to clouds

correlation of spectral properties with presence of clouds

The CXE brightness varies as $n_e \cdot n_h \cdot Vrel$

The hot gas thermal emission brightness varies as $n_e^2$

The relative importance of the increases when the hot gas density decreases

Crucial need for high-resolution spectroscopy !!!

XRISM: please open the door !