**Toyama International Symposium on „Physics at the Cosmic Frontier”**

# From the Earth to the Local Interstellar Medium: space physics by IBEX

***Justyna M. Sokół***

Space Research Centre of the Polish Academy of Sciences, (CBK PAN), Warsaw, Poland

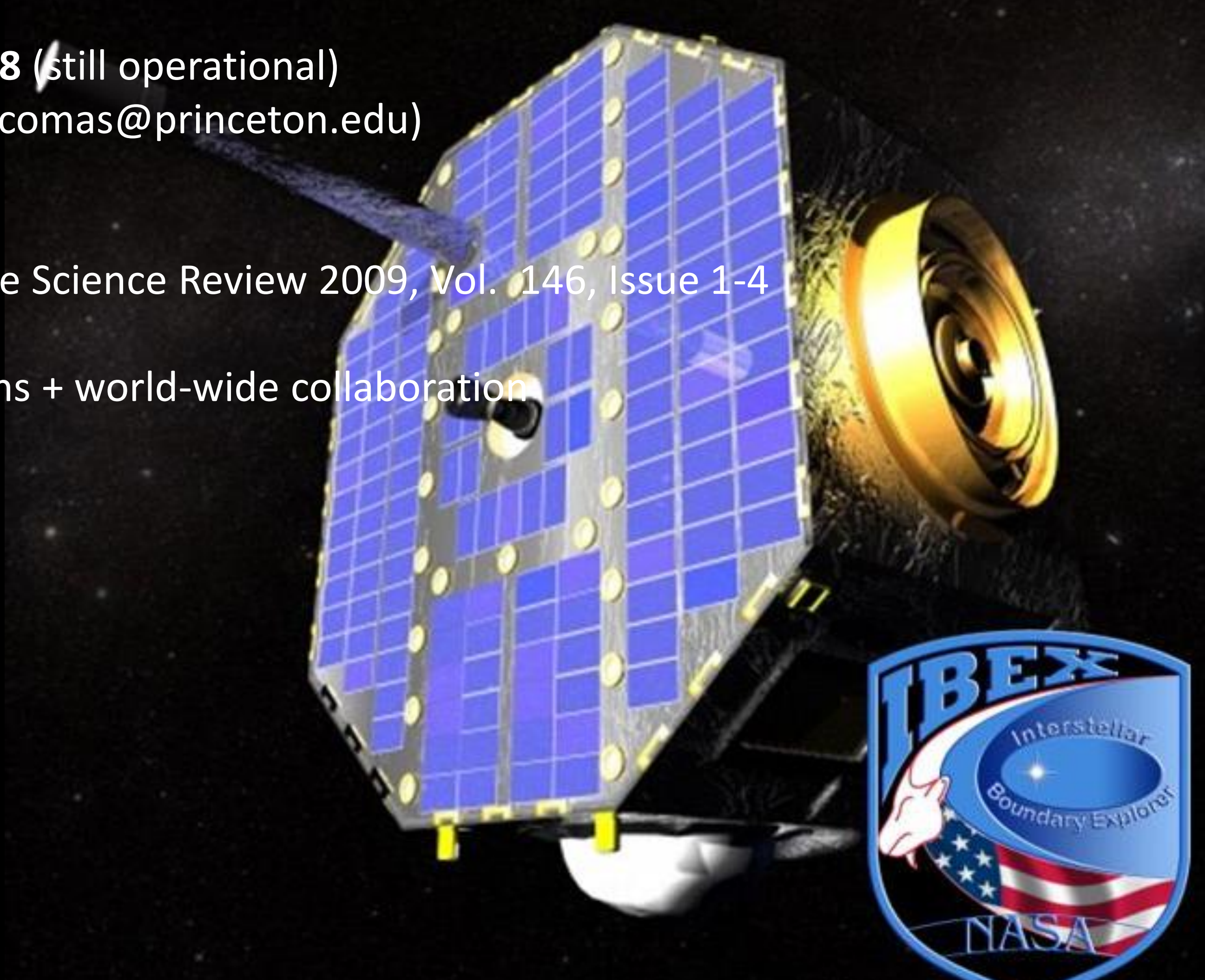
**University of Toyama, Toyama, Japan, March 7-8, 2019**

# INTERSTELLAR BOUNDARY EXPLORER (IBEX)

NASA **SMEX** mission
Launched: **October 19, 2008** (still operational)
PI: **David J. McComas** (dmccomas@princeton.edu)

www: **ibex.swri.edu**
**IBEX book:** 13 papers, Space Science Review 2009, Vol. 146, Issue 1-4

Science Team: 22 institutions + world-wide collaboration




Credits: NASA/GSFC Conceptual Image Lab

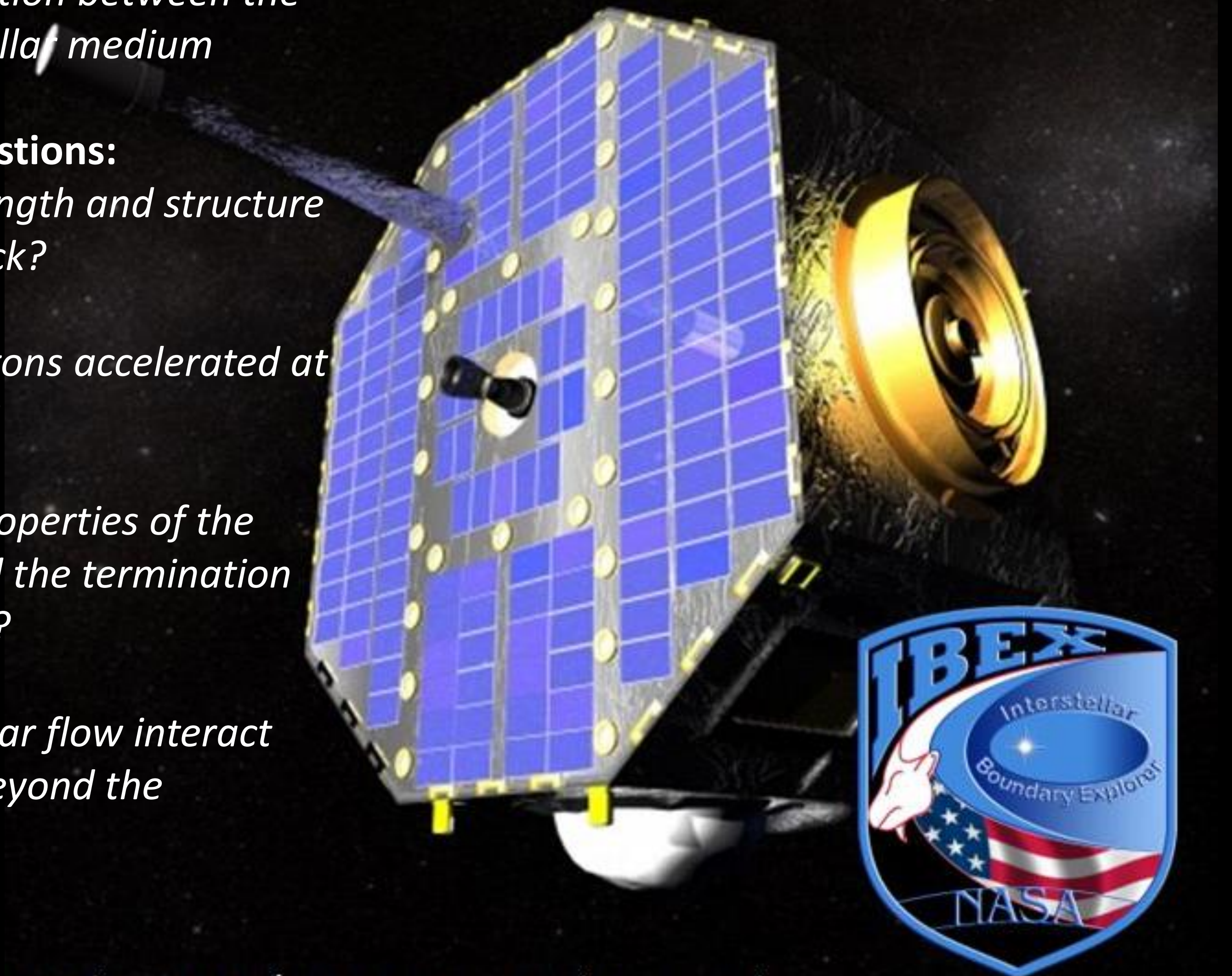
SOUTHWEST RESEARCH INSTITUTE

# INTERSTELLAR BOUNDARY EXPLORER (IBEX)

**Science Objective:**
*Discover the global interaction between the solar wind and the interstellar medium*

**Fundamental Science Questions:**

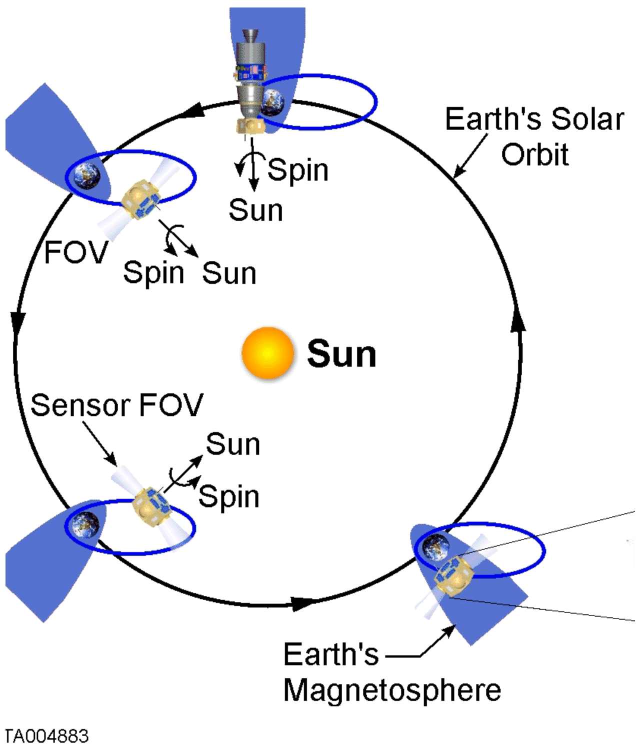
1. *What is the global strength and structure of the termination shock?*
2. *How are energetic protons accelerated at the termination shock?*
3. *What are the global properties of the solar wind flow beyond the termination shock and the heliotail?*
4. *How does the interstellar flow interact with the heliosphere beyond the heliopause?*

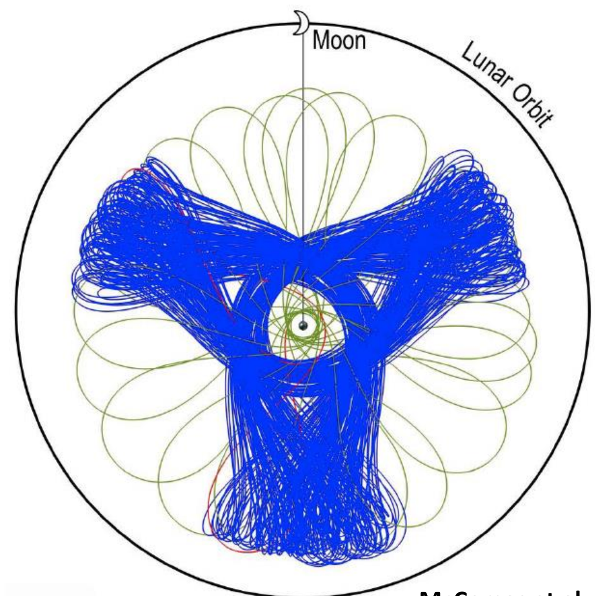



Credits: NASA/GSFC Conceptual Image Lab

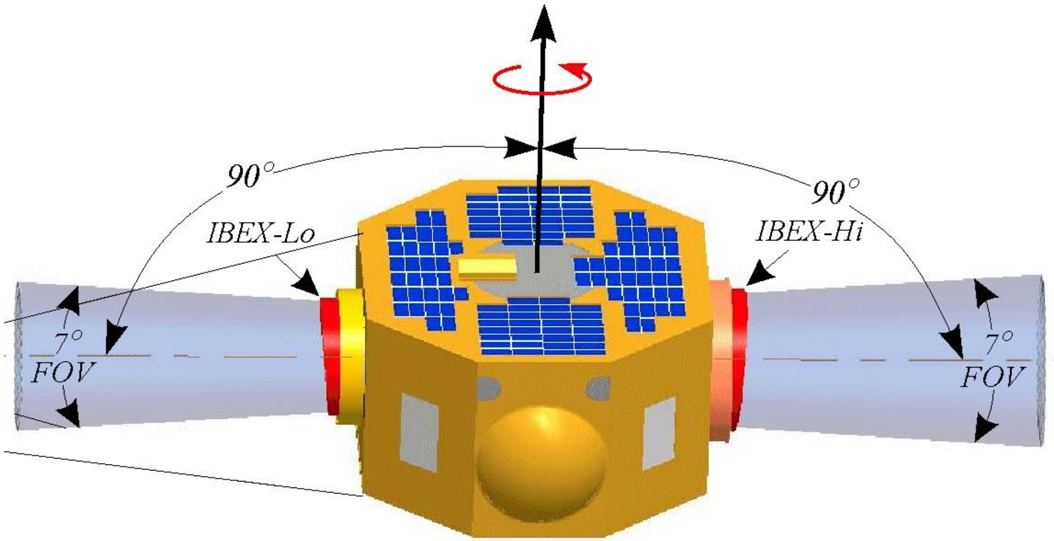
SwRI®
SOUTHWEST RESEARCH INSTITUTE

**Size:** 95 x 89 x 49 cm (124 cm with antennas)
**Mass:** 78.6 kg (dry mass of the spacecraft)
**Rocket:** Pegasus
**Orbit:** Earth synchronized (~7.5 days) change to long-term stable lunar resonance orbit in 2011 (~9.1 days), present perigee radii of ~7 $R_E$ (above radiation bells), apogee ~50 $R_E$
**Spin Rate:** 4 RPM (Sun pointed)

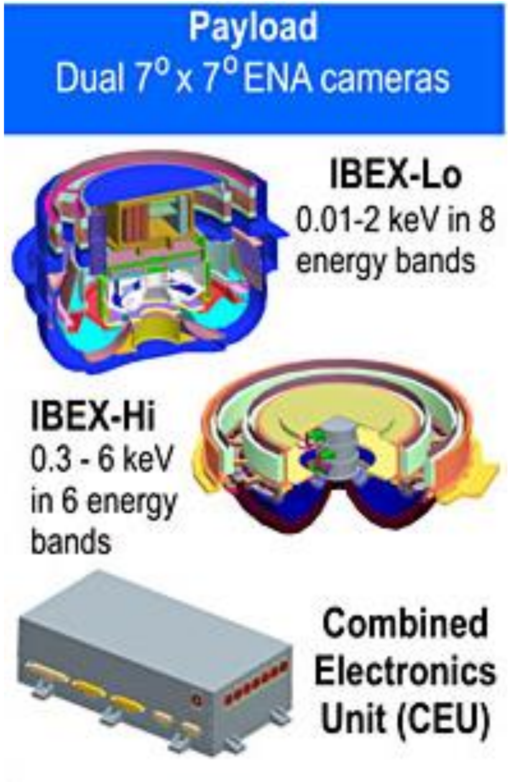



McComas et al. 2011



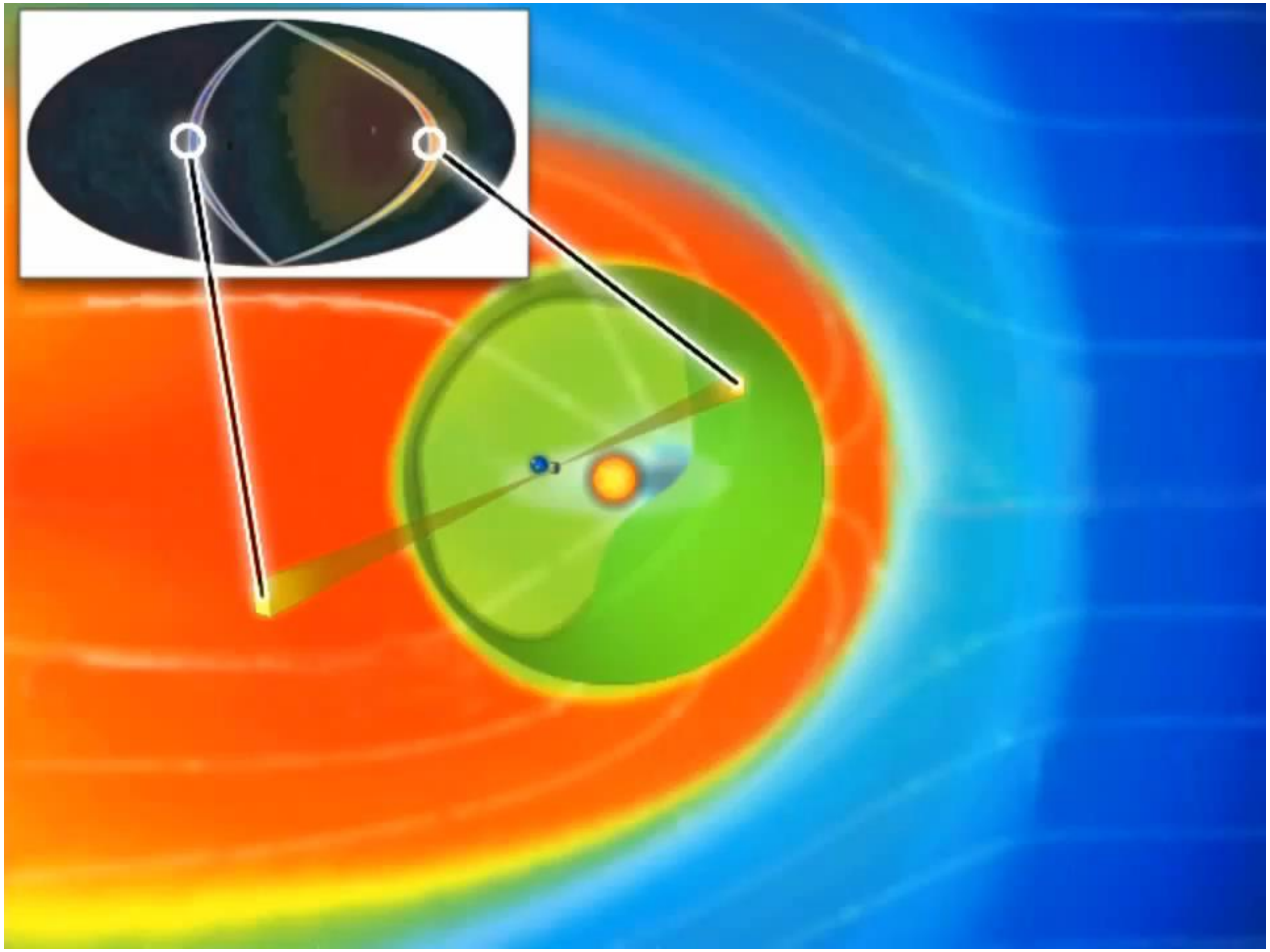

IBEX Spacecraft

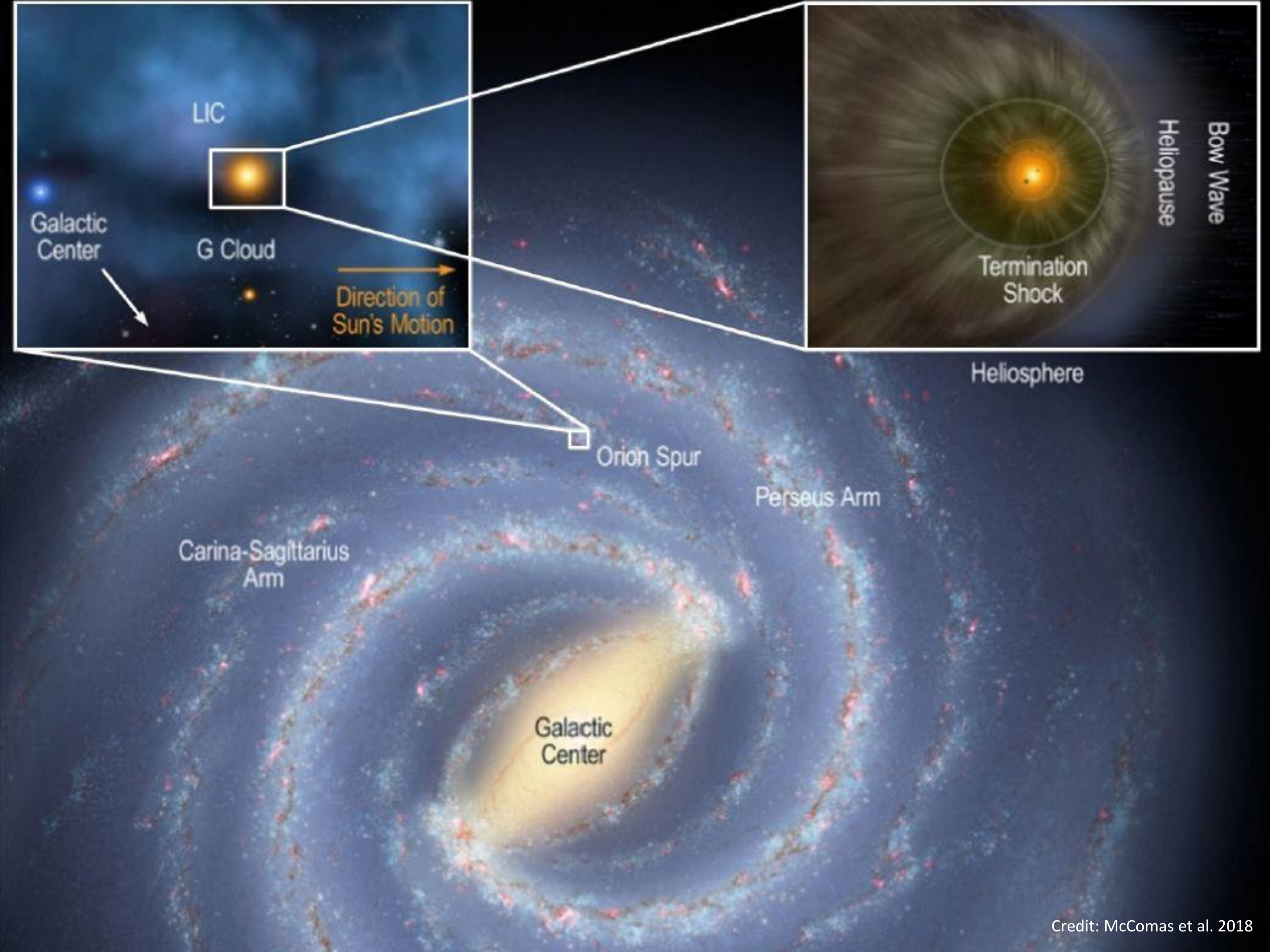



one orbit = one 7° swath across the sky

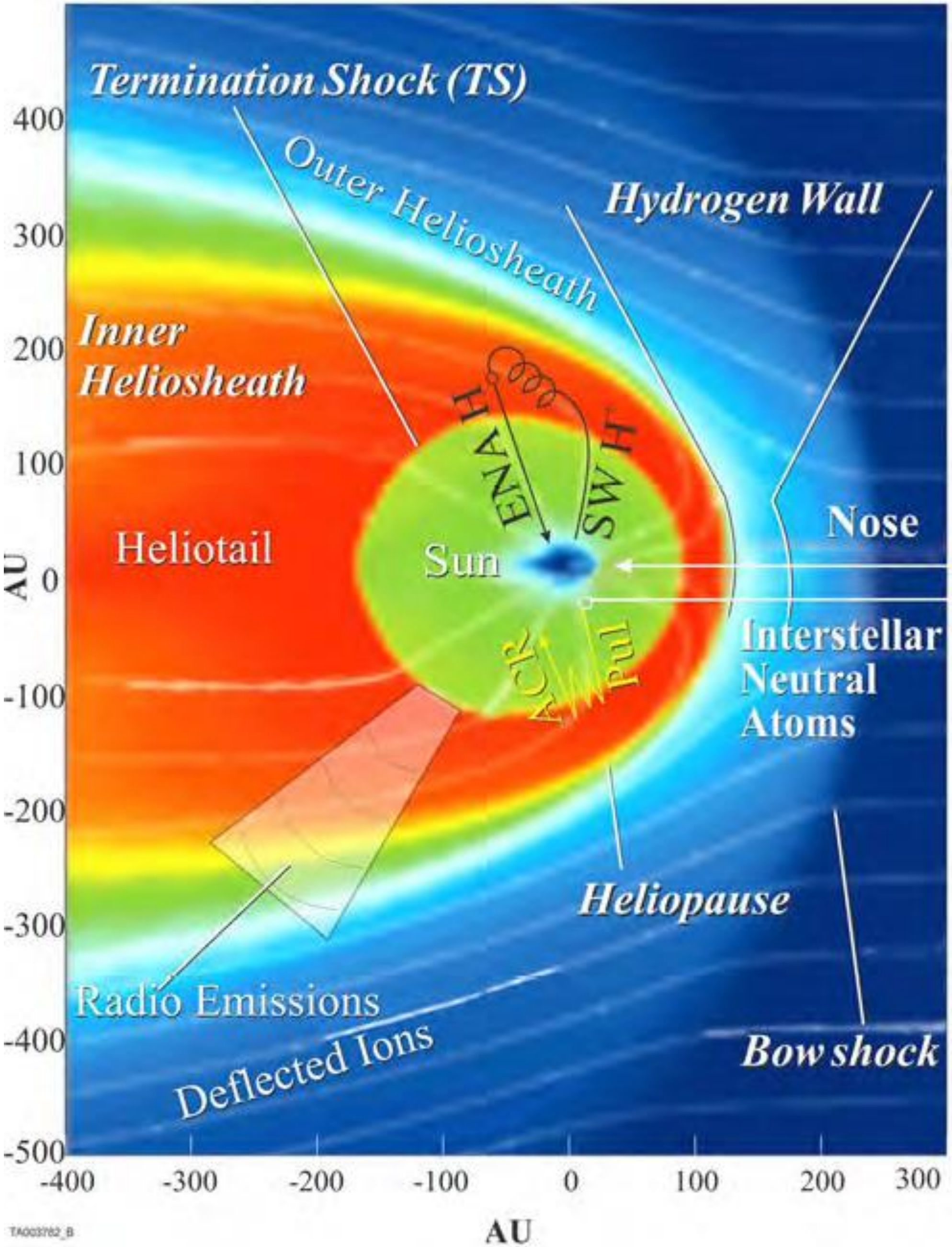
6 months = one full sky map of ENA emission

https://www.nasa.gov/mission_pages/ibex/allsky_visuals.html






Credit: McComas et al. 2018




McComas et al. 2011

**Termination Shock (TS):**
supersonic solar wind slow downs to subsonic speeds

**Heliopause (HP):**
separates the subsonic solar wind flow from the slowed, heated, and diverted interstellar flow

**Bow Shock/Wave:**
separates the undisturbed interstellar flow from the slowed heated and diverted flow

**Inner heliosheath (IHS):** region between TS and HP

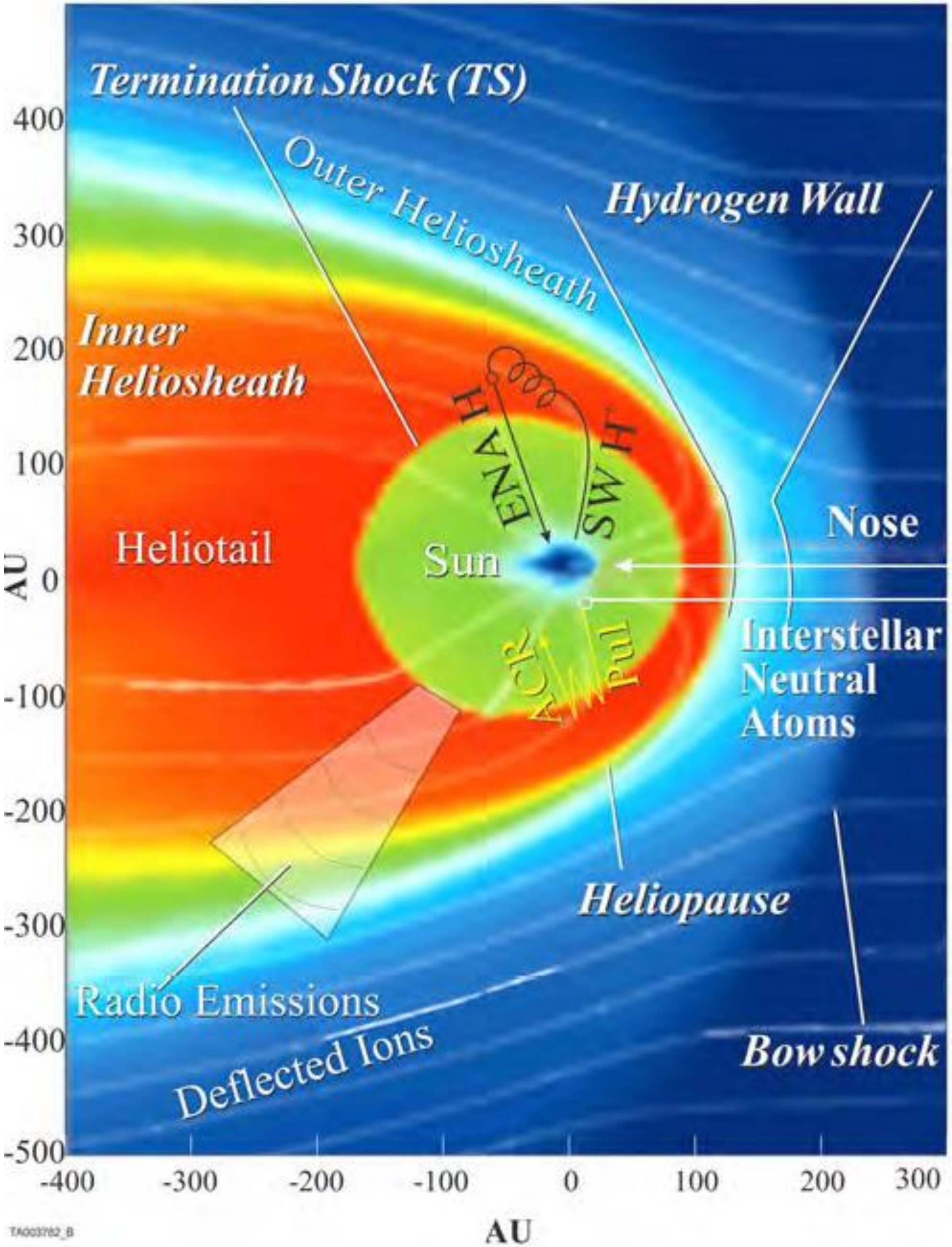
**Outer heliosheath (OHS):** region beyond HP

**Hydrogen Wall:**
a region in OHS where the interstellar H atoms charge exchange with piled-up protons of interstellar flow, causing a similar pile-up of H atoms

**Nose:**
front of the Sun's motions through the Local Interstellar Medium

**Heliotail:** anti-nose, downwind hemisphere

**+ interplanetary & interstellar magnetic fields**




McComas et al. 2011

**Interstellar neutral gas (ISN):** neutral component of the interstellar medium (energies below ~0.8 keV)

**Energetic Neutral Atom (ENA):** product of charge exchange between ions and interstellar atoms

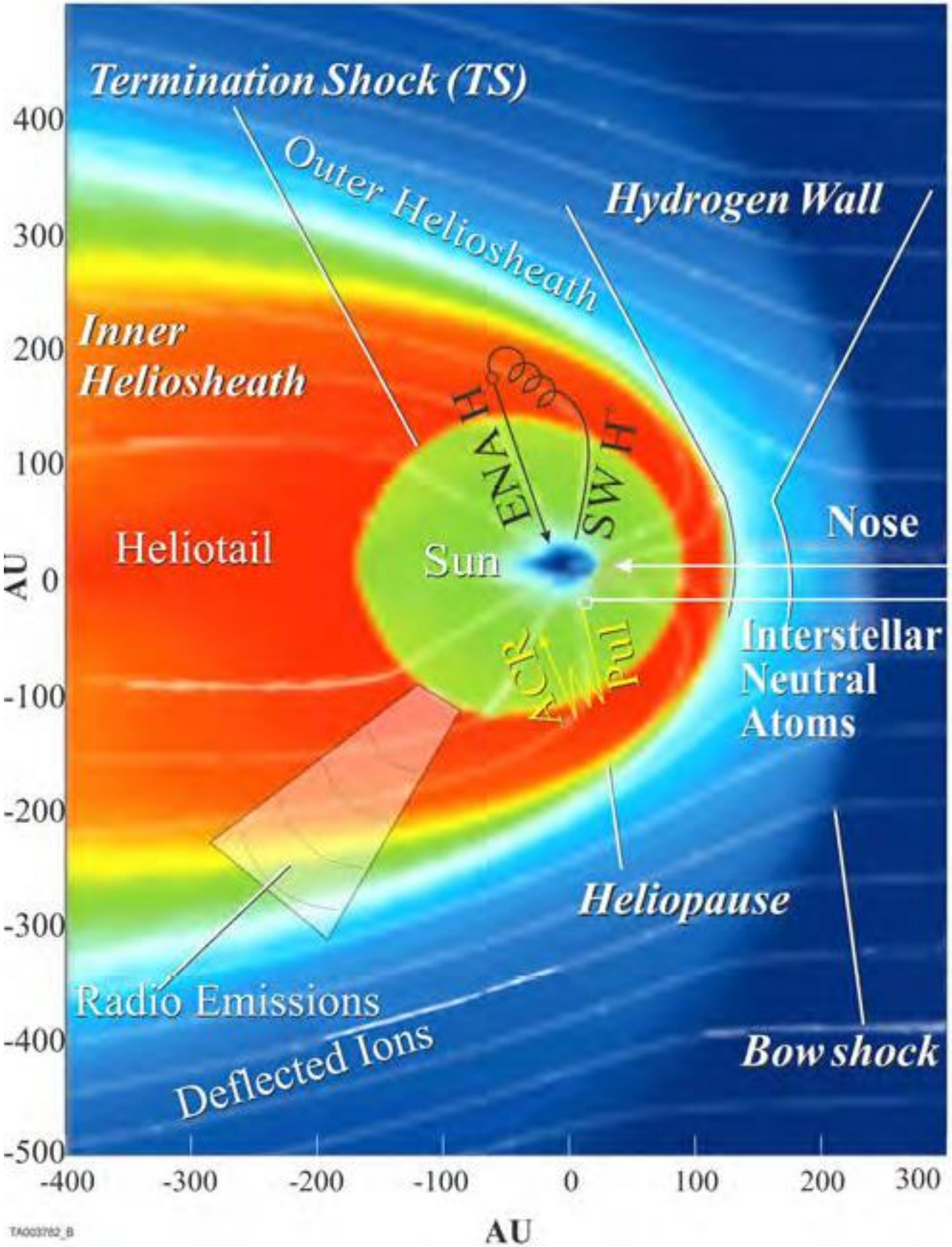
**Pick-up Ion (PUI):** product of ionization of interstellar atom, source population for ACRs and secondary ENAs

**Anomalous Cosmic Rays (ACRs):** PUIs carried out by solar wind to TS and accelerated by diffusive shock acceleration

**Neutralized Solar Wind (NSW):** solar wind that charge exchange ion with interstellar atoms inside the heliosphere

**Helioglow**: resonant backscatter glow of solar EUV flux on interstellar gas around the Sun

*Inside the heliosphere, heliospheric particle flux is modulated by gravitational focusing,* ***solar ionization****, and radiation pressure repulsing force (e.g., H and D).*




McComas et al. 2011

**IBEX measures:**

**I. ISN gas of H, He, Ne, O, D**

- low-energy (0.02 – 0.5 keV)
- enter heliosphere freely, are not affected by the magnetic fields
- good tracer for flow vector
- tool to investigate LISM parameters (e.g., temperature or composition)
- allows for probing interaction processes in the outer heliosheath

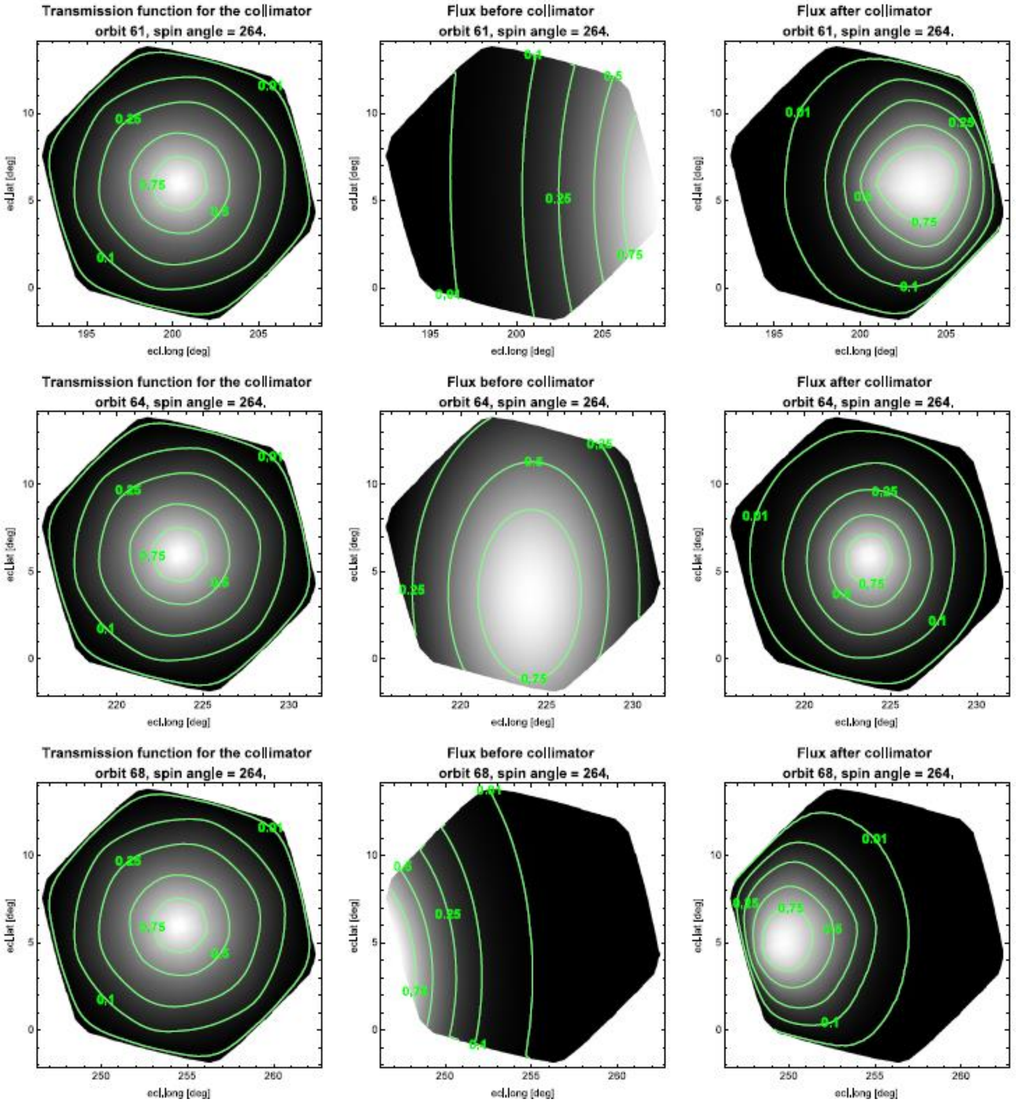
**II. H ENAs**

- high-energy (0.5 – 80 keV)
- various populations depending on region of creation
- tracers for interaction processes between solar medium and interstellar matter
- tool to investigate interstellar magnetic field
- allow for probing plasma flow in heliosheath

# Warsaw Test Particle Model (WTPM)

- software to track atom's trajectories inside the heliosphere based on hot model paradigm (thermal spread of the gas included)
- hot model with ionization rates and radiation pressure variable in time, distance, and heliolatitude
- mostly Maxwell-Boltzmann distribution function assumed in the source region (other functions easily applicable)
- ionization rates estimated based on available measurements
- homogeneous and continues in time model of solar ionizing factors over solar cycles needed (ISN atoms travel time from few months to few years)
- operational for H, He, Ne, O, D
- applications: survival probabilities, ISN gas density and flux distribution, PUI production rates, *distribution of He helioglow
- adjusted to, e.g., IBEX (incl. orbital and instrumental details)

Sokół et al. 2015



# Composite model of ionization rates for heliospheric particles

## Charge exchange:

$$\text{atom}_{\text{ISN}} + \text{ion}_{\text{sw}} \rightarrow \text{PUI} + \text{ENA}$$

$$\beta_{\text{cx}}(t, r, \phi) = n_{\text{sw}}(t, r, \phi) v_{\text{rel}}(t, r, \phi) \sigma_{\text{cx}}(v_{\text{rel}}(t, r, \phi))$$

$$n_{\text{sw}}(r) = n_{\text{sw}}(r_0)\left(\frac{r_0}{r}\right)^2, \quad v_{\text{sw}}(r) = v_{\text{sw}}(r_0)$$

- **solar wind** protons and alpha particles
- speed and density
- time: **solar cycle, long-trends**
- latitude: **in & out of the ecliptic plane**
- heliocentric distance variations, $r^{-2}$ decrease

## Electron impact ionization:

$$X + e \rightarrow X^+ + 2e \qquad \beta_{\text{el}}(r) \neq \beta_0\left(\frac{r_0}{r}\right)^2$$

$$\beta_{\text{el}}(t, r, \phi) = \frac{8\pi}{m_e^2}\int_{E_i}^{\infty} f_{\text{el}}(E, t, r, \phi)\sigma_{\text{el}}(E) E dE$$

$$\beta_{\text{el}}^{\text{slow}}(r, t) = n_{\text{sw}}(r, t)\exp\left[\frac{a + b\ln r + c\ln^2 r}{d + e\ln r + f\ln^2 r + g\ln^3 r}\right]$$

- **solar wind** electrons
- temperature and density
- time: **solar cycle, long-trends**
- latitude: **in & out of the ecliptic plane**
- **heliocentric distance variations**: not $r^{-2}$ decrease

## Photoionization:

$$X + h\nu \rightarrow X^+ + e$$

$$\beta_{\text{ph}}(t) = \int_0^{\lambda_0} F_{\text{EUV}}(\lambda, t)\sigma_{\text{ph}}(\lambda) d\lambda$$

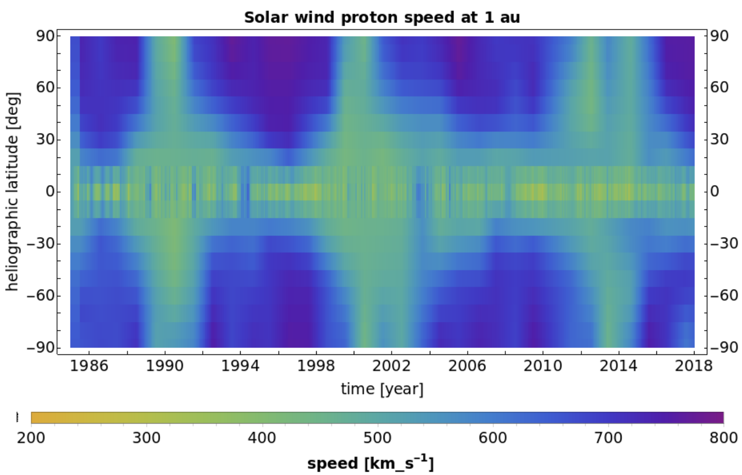
$$\beta_{\text{ph}}(\phi) = \beta_{\text{ph}}(0°)(0.85\sin^2(\phi) + \cos^2(\phi))$$

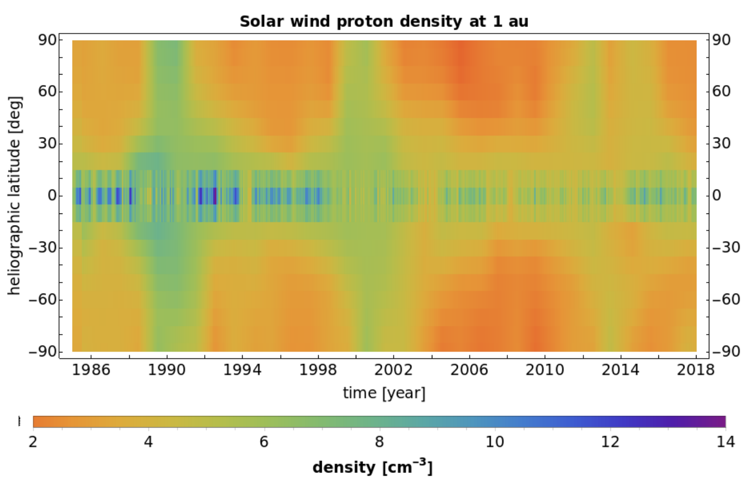
- **solar EUV** flux
- solar EUV proxies
- time: **solar cycle, long-trends**
- latitude: **in & out of the ecliptic plane**
- heliocentric distance variations, $r^{-2}$ decrease
- absolute calibration essential

# Composite model of ionization rates for heliospheric particles

http://users.cbk.waw.pl/~jsokol/

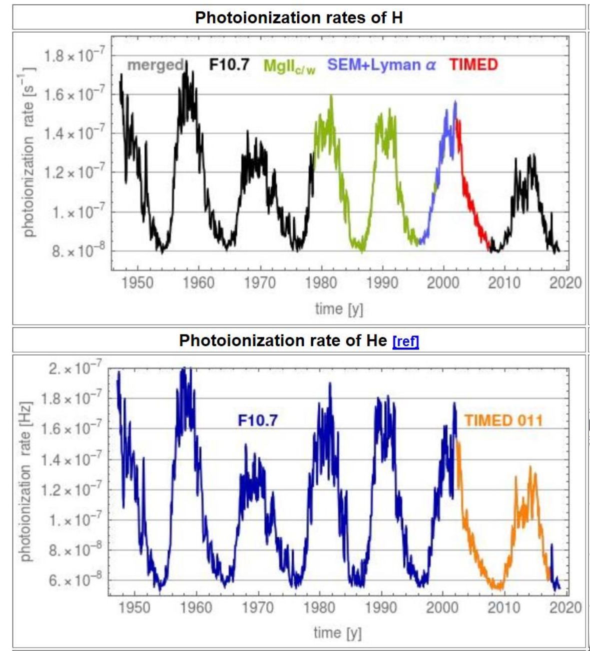
## OMNI data collection of in-ecliptic measurements + ISEE IPS $V_{sw}$ observations



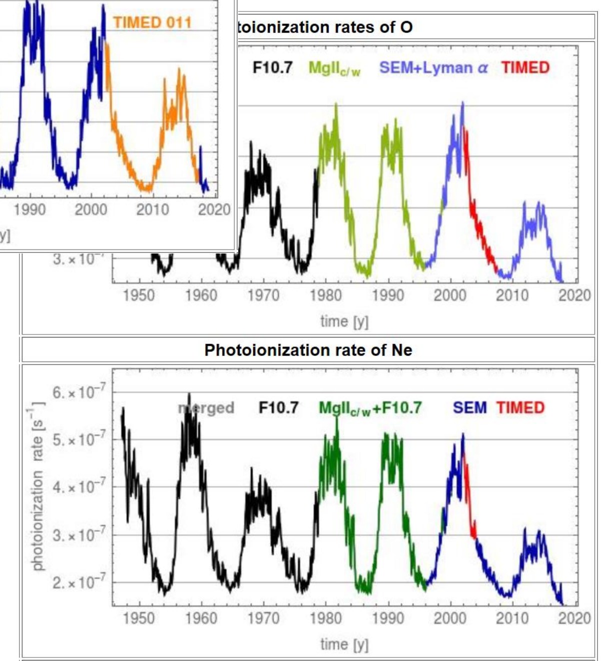




Sokół et al. 2013, 2015

## EUV flux from TIMED/SEE + EUV proxies (F10.7, $MgII_{c/w}$, Lyman-α, SEM/SOHO)

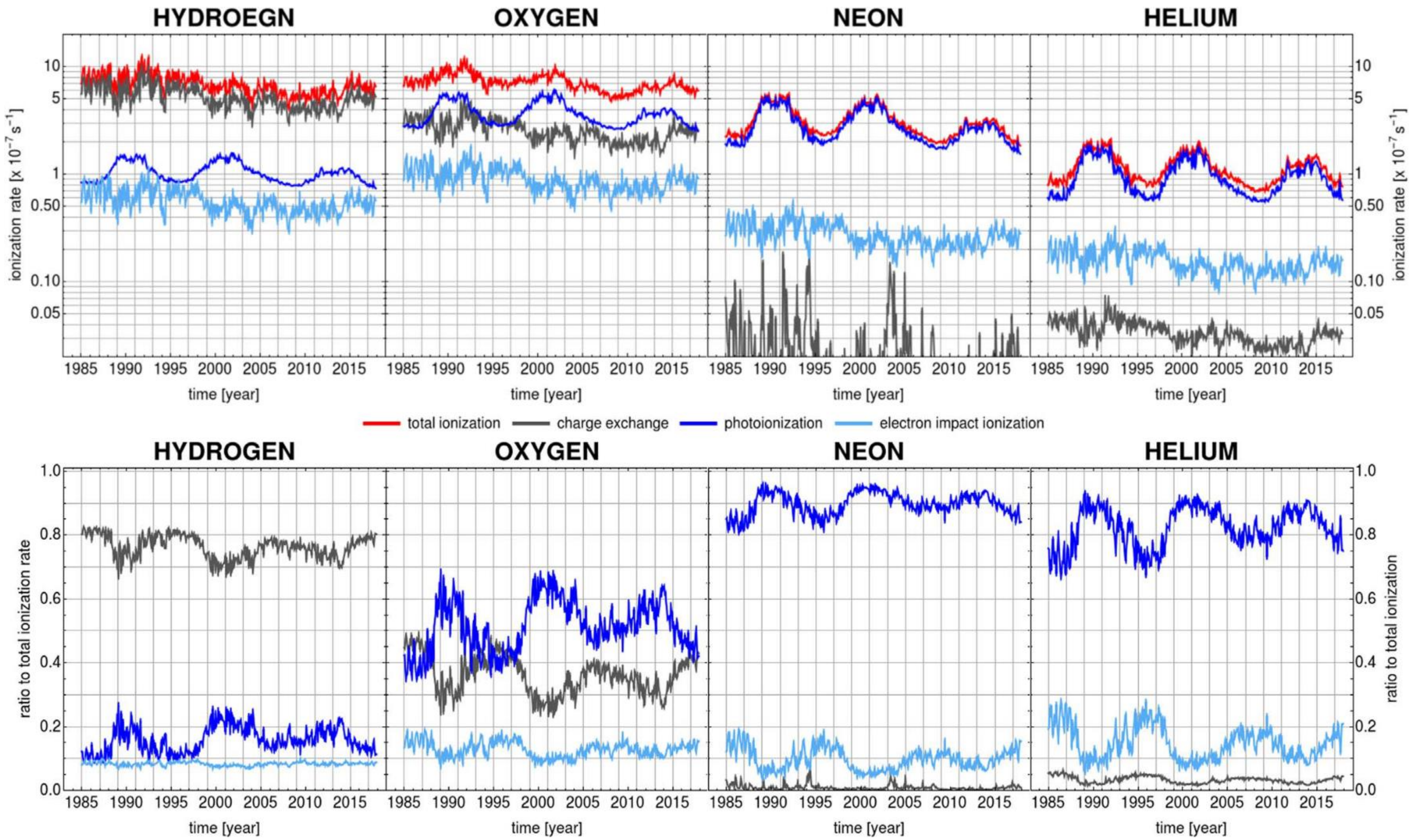


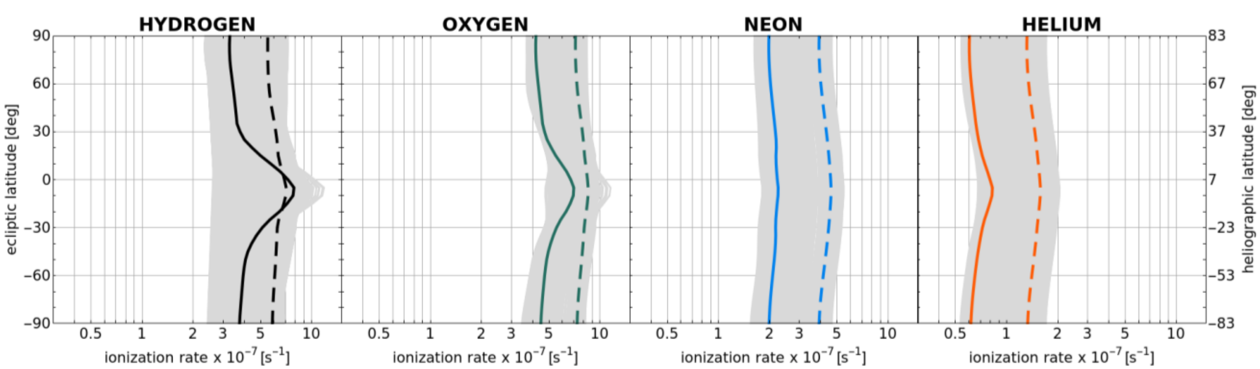

Bzowski et al. 2013 a,b
Sokół & Bzowski 2014

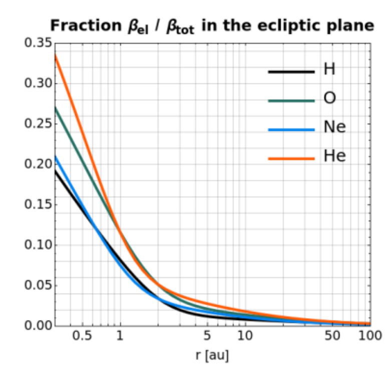


Sokół et al. 2019

# Composite model of ionization rates for heliospheric particles



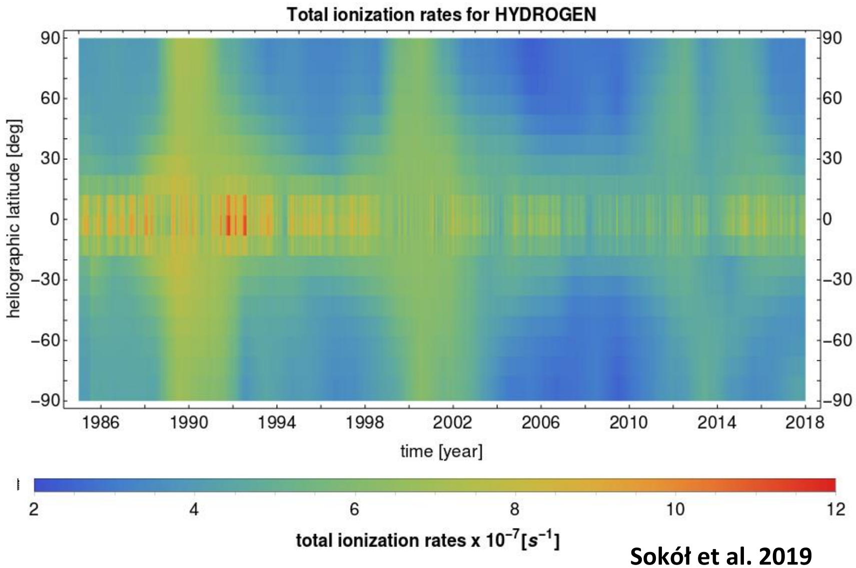



## Survival probabilities:

- correction factor for solar modulation of the ENA flux inside the heliosphere
- ENA flux measured at 1 au is attenuated by the ionizing interaction with the solar wind particles (charge exchange with SW protons and alpha particles, impact ionization with SW electrons) and solar EUV flux (photoionization)
- H ENAs most prone for ionization by charge exchange with solar wind protons (~0.75 $\beta_{tot}$ )
- the attenuation via ionization needs to be taken out to obtain fluxed in the source region
- travel time of H ENAs depends on the energy of the atoms and the distance to the source (from months to years)
- the highest losses due to ionization happen at few au before detection
- orbits of ENAs measured in the ecliptic plane can cross the out of ecliptic latitudes (especially in the downwind hemisphere)
- the highest losses at few au before detection

## Total ionization rates for H ENAs:

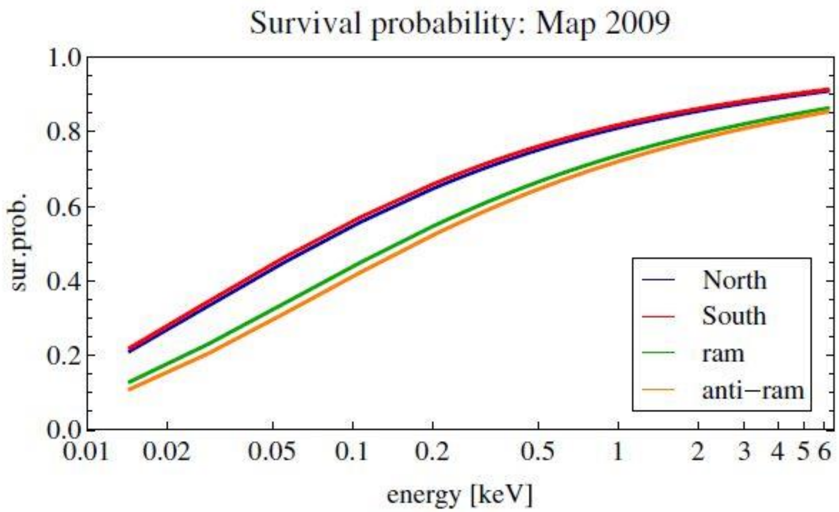
- In-ecliptic SW from OMNI, out-of-ecliptic SW from ISEE IPS observations (Sokół et al. 2013)
- Photoionization rates based on composite multi-data model (TIMED/SEE, SEM/SOHO, Lyman-alpha, $MgII_{c/w}$, F10.7; Bzowski et al. 2013)
- Appendixes B in McComas et al. 2012, 2014, 2017 (IBEX's 3, 5, 7 years papers)

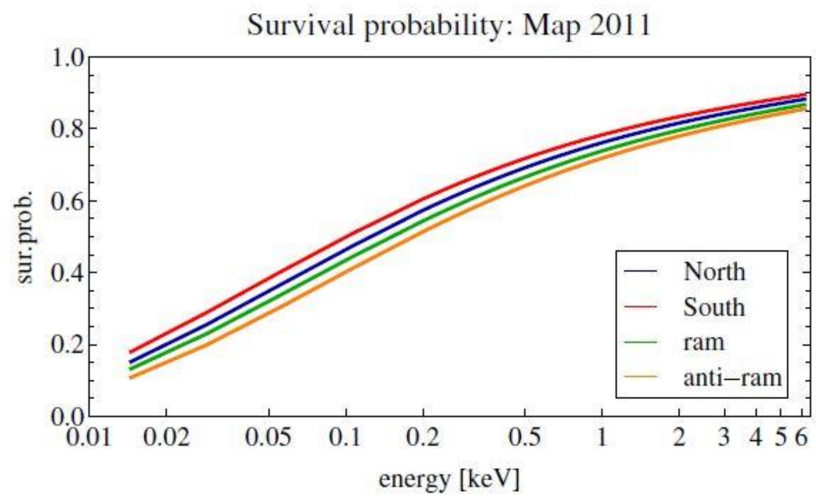


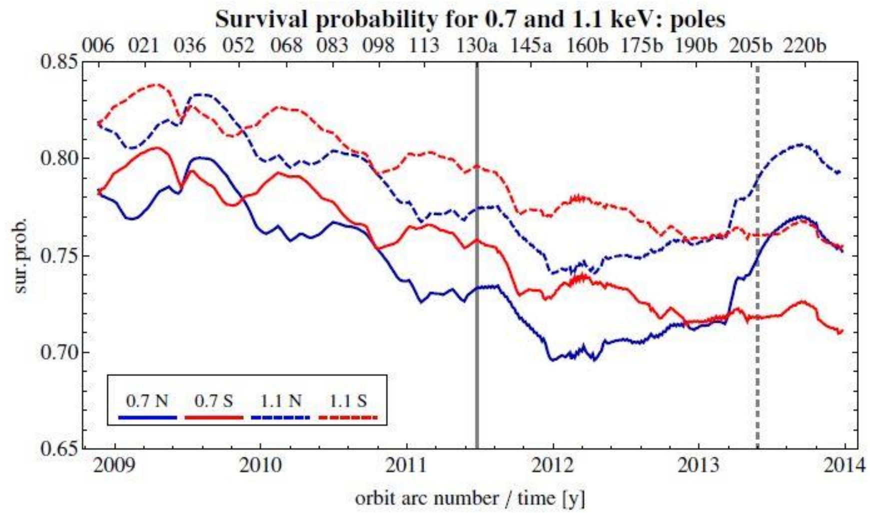

Sokół et al. 2019

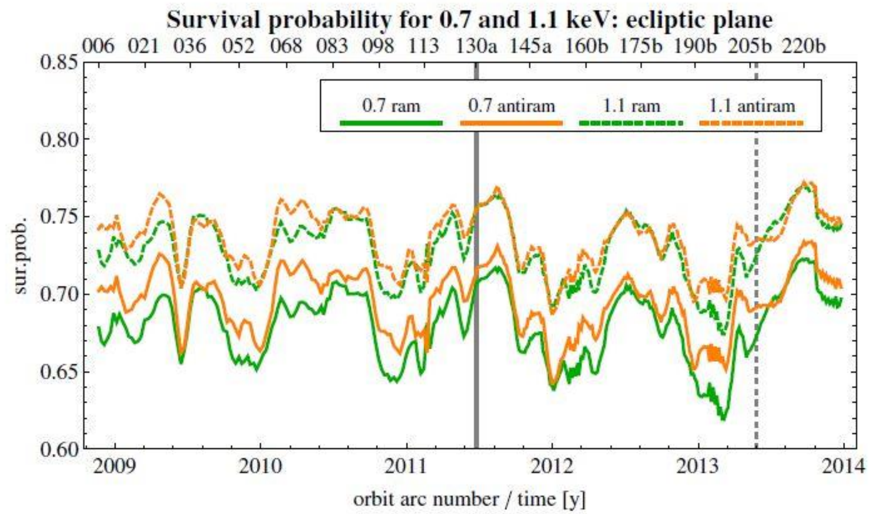
# IBEX H ENA survival probabilities:

$$w_{\rm sur} = \exp\left[-\int_{t_{\rm start}}^{t_{\rm stop}} \beta(t)\, dt\right]$$



IBEX

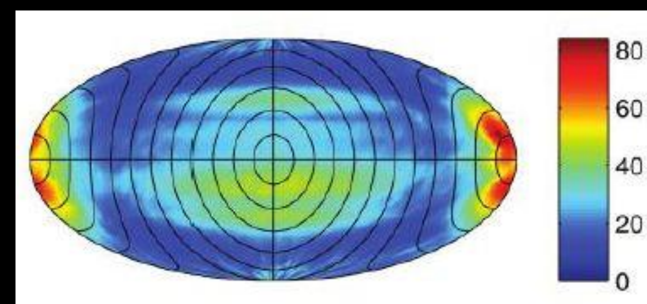
INTERSTELLAR BOUNDARY EXPLORER


**Ribbon?!**

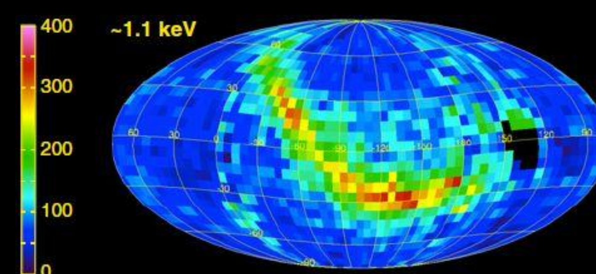
**November 2009: IBEX cover in Science!**

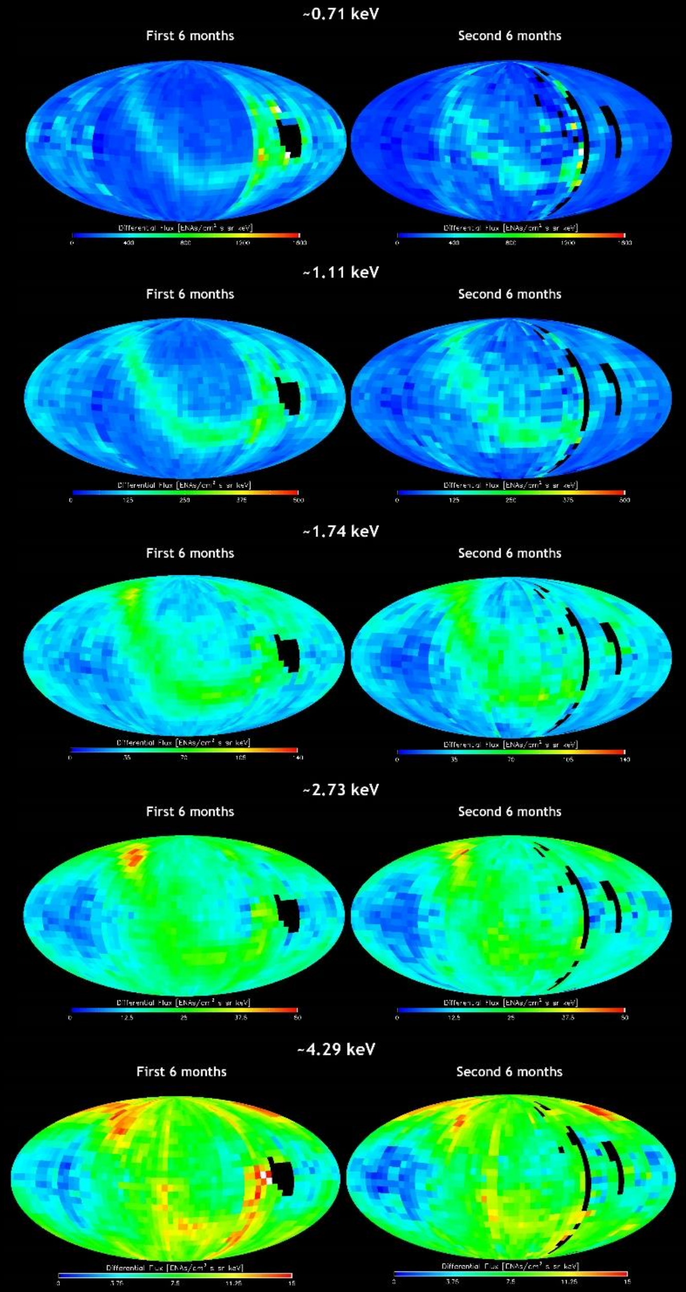
**Five IBEX first-light articles:**
McComas et al., Fuselier et al., Funsten et al., Schwadron et al., Möbius et al.

Model predictions (Heerikhuisen et al. 2008)




IBEX observations:






# IBEX ENA Ribbon

(surprising, mysterious, intriguing)

- present in energies from 0.7 to 4.3 keV
- small variation of structure depending of energy
- stable throughout the years with variations with the solar activity
- IBEX ENA maps: GDF + Ribbon

The second set of the solar system boundary maps released by the IBEX team in September 2010. Each shows a range of energetic neutral atom (ENA) energies, using data collected over the course of six months. In each map, red indicates the highest number of ENAs measured by the spacecraft. Yellow and green indicate lower numbers of ENAs, and blue and purple show the lowest number of ENAs detected by IBEX.

The maps on the left represent the first six months of ENAs that the IBEX spacecraft collected between December 25, 2008 and June 18, 2009. The maps on the right represent the second six months of ENAs that the IBEX spacecraft collected between June 18, 2009 and December 10, 2009.

*Image Credit: SwRI/IBEX Team*

# at 1 au

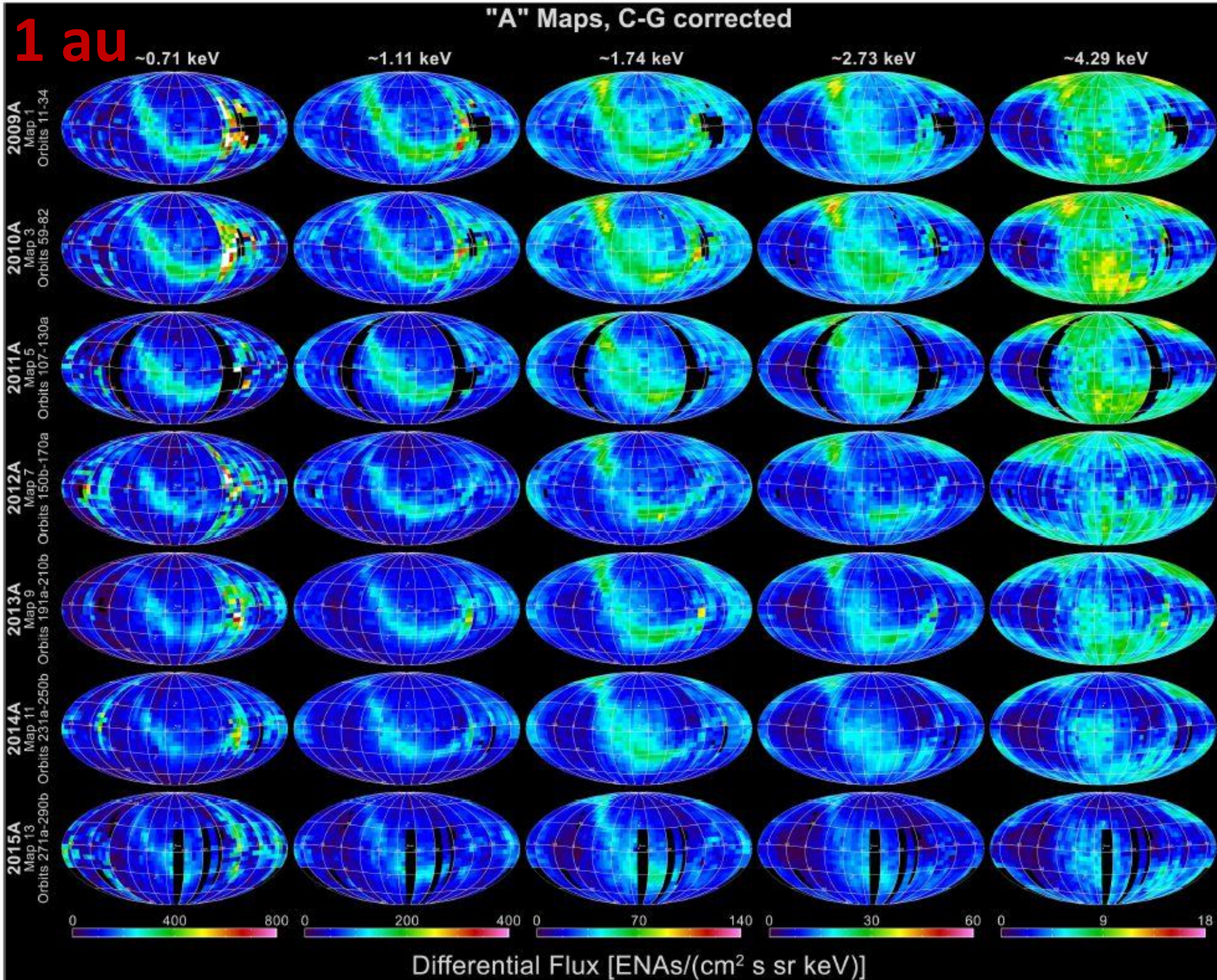



**Figure 3.** *IBEX* ENA first half year (A) maps as in Figure 1, but C–G corrected into the heliospheric reference frame.

McComas et al. 2017

# source region

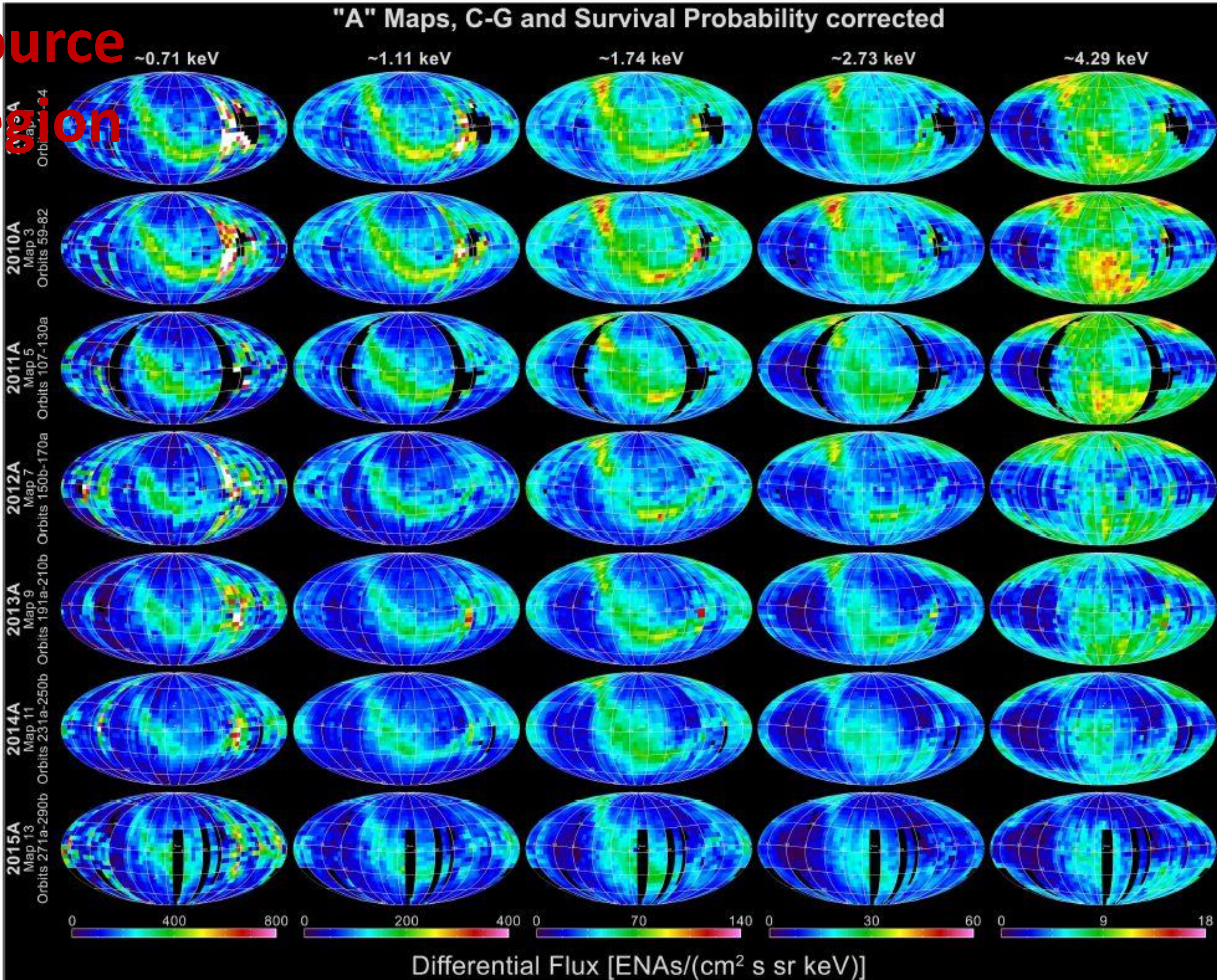



Figure 7. First half year (A) ENA flux maps including survival probability and C–G corrections; these represent the expected inward-directed ENA fluxes around the termination shock.

McComas et al. 2017

**McComas et al. 2012, 2017**

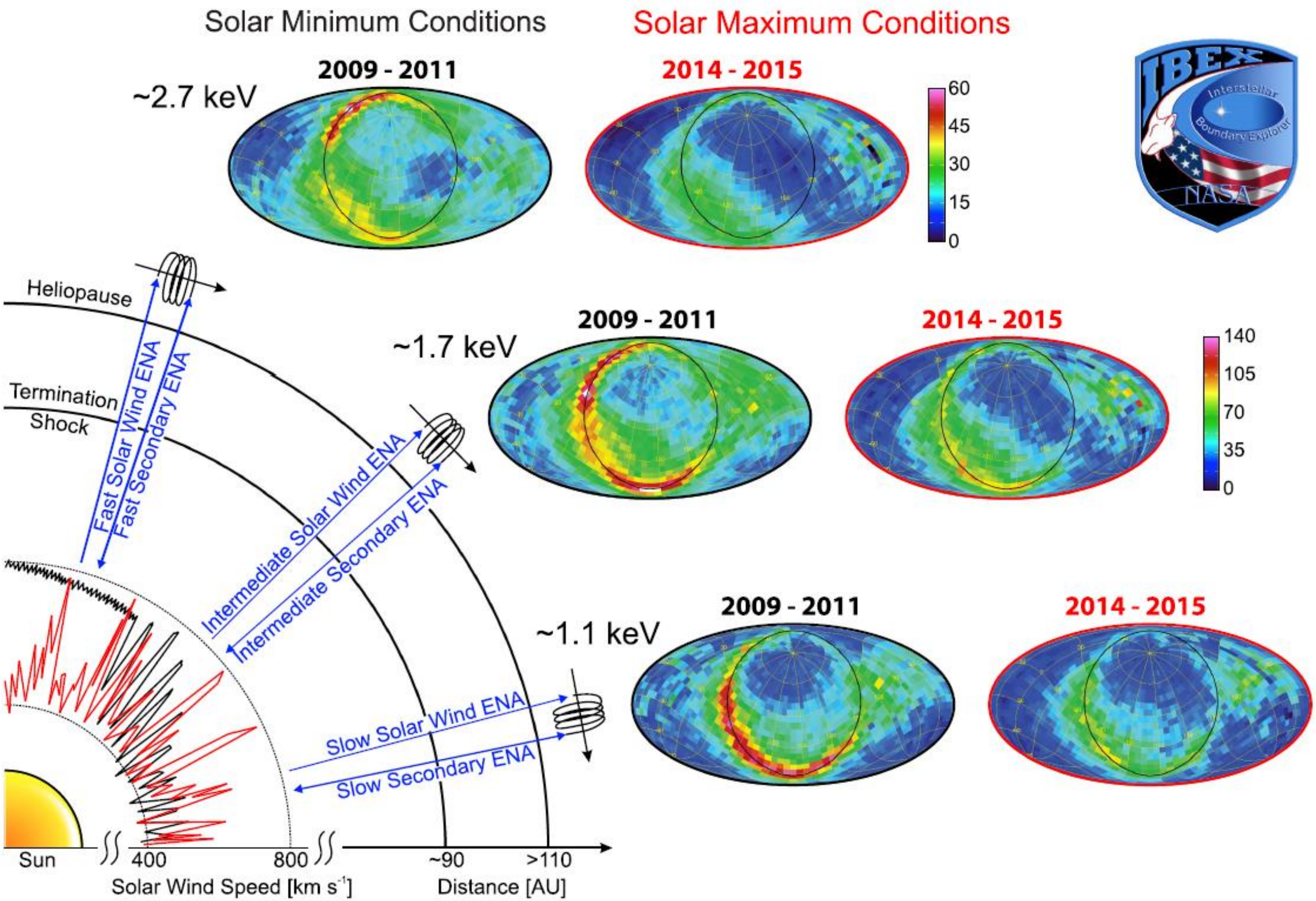
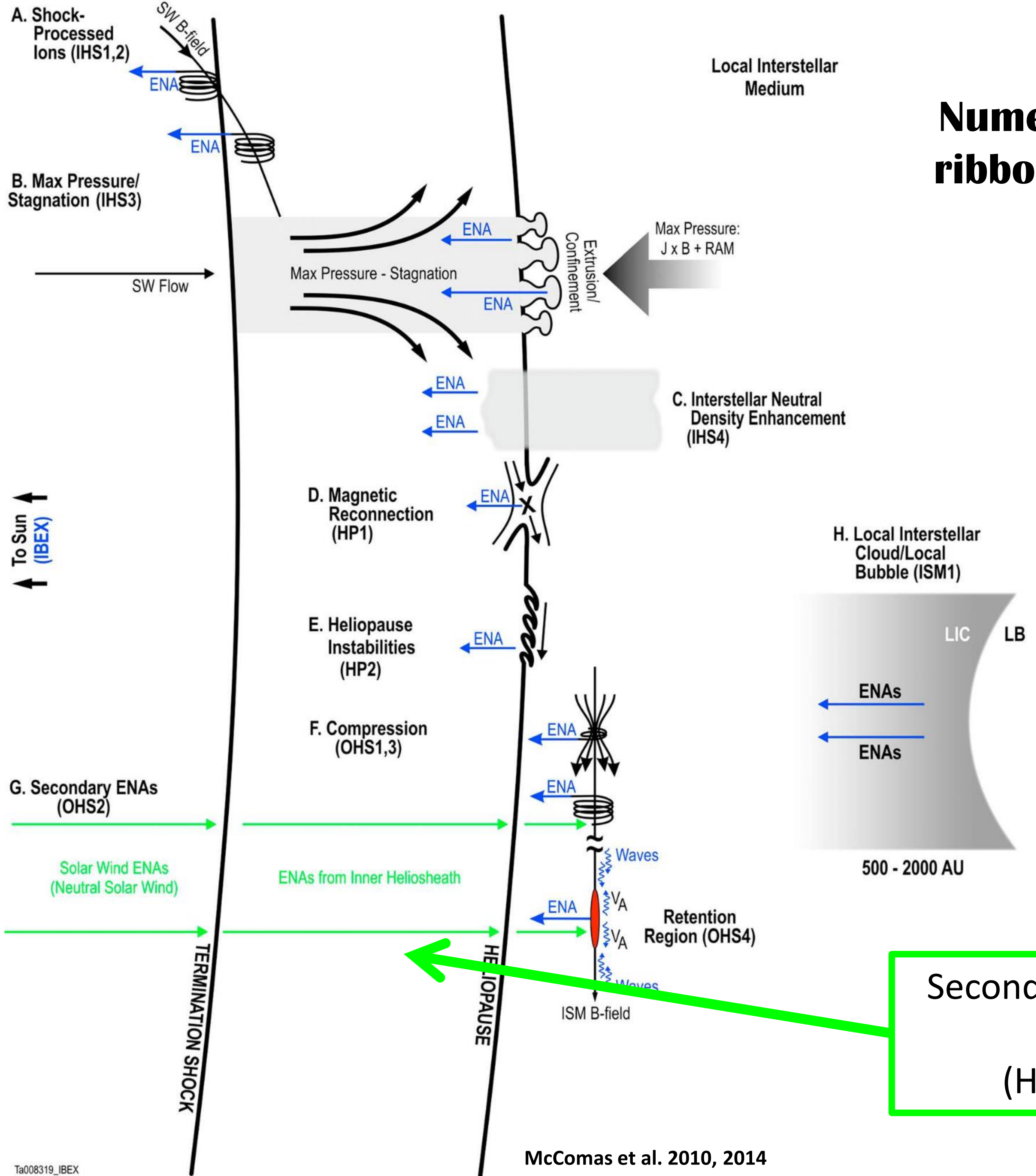



**Figure 30.** Combined *IBEX* ENA data and schematic diagram highlighting the differences between Ribbon emission reflective of solar minimum (left set of Mollweide projection maps, black) and those indicative of the breakdown of solar wind-latitude order in the approach to solar maximum (right set of maps, red). Together, these demonstrate the response of the Ribbon to solar minimum (fast solar wind at high latitudes, slow wind at low latitudes) and solar maximum (slow to intermediate solar wind speeds at all latitudes) conditions, and the recycling time between them.

# Numerous hypothesis about ribbon creation mechanism!




Secondary ENAs the most probable source of the Ribbon (Heerikhuisen et al. 2010)

McComas et al. 2010, 2014

## Determination of ISMF based on B•r~0: strenght: 2.93 μG, direction: (227.28 °, 34.62°) ~8.3° offset from the Ribbon center toward $V_{LISM}$

**Zirnstein et al. 2016b**

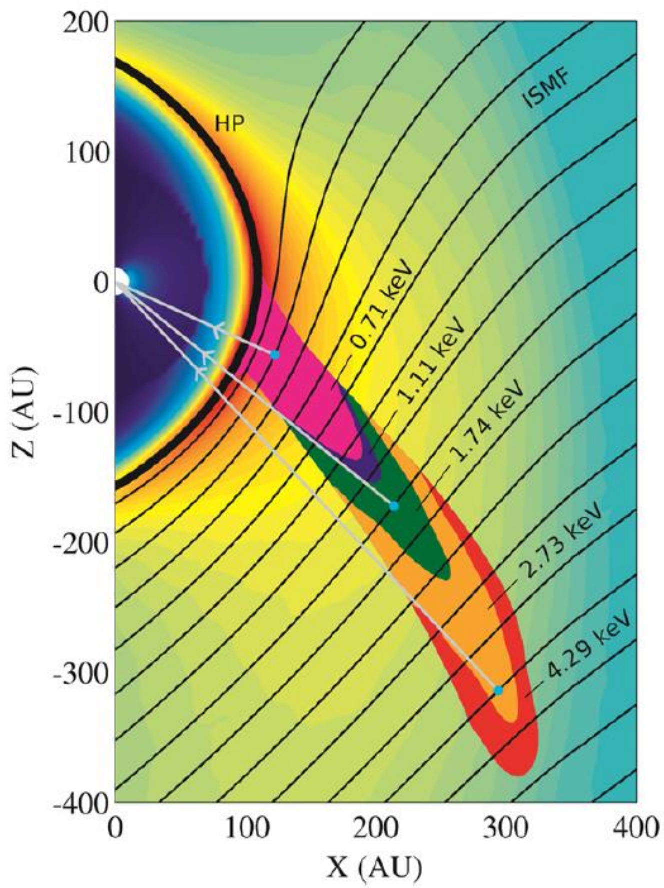
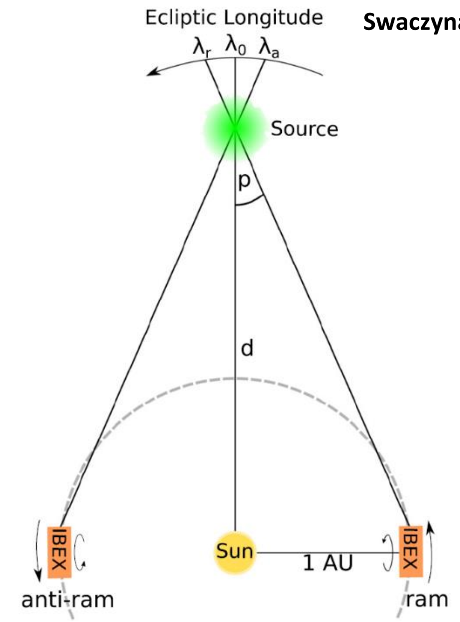



**Figure 1.** Isocontours of the ribbon ENA production rate outside the heliopause (HP) denoted by five colors distinguishing the ENA energies. The background color represents the magnetic field magnitude, with some ISMF lines (black curves). Suprathermal ions outside the HP become neutralized by charge-exchange (blue circles) and form ENAs that may travel back inward toward *IBEX* (gray lines). The majority of ribbon ENAs originate near $\boldsymbol{B}\cdot\boldsymbol{r} \sim 0$ (colored contours, only shown for $\cos^{-1}(\boldsymbol{B}\cdot\boldsymbol{r}) > 85°$). Due to the curvature of the ISMF and the finite temperature of parent ENAs, the ribbon source region is broad; however, the line of sight integrated flux decreases farther from $\boldsymbol{B}\cdot\boldsymbol{r} = 0$ (see Zirnstein et al. 2015).

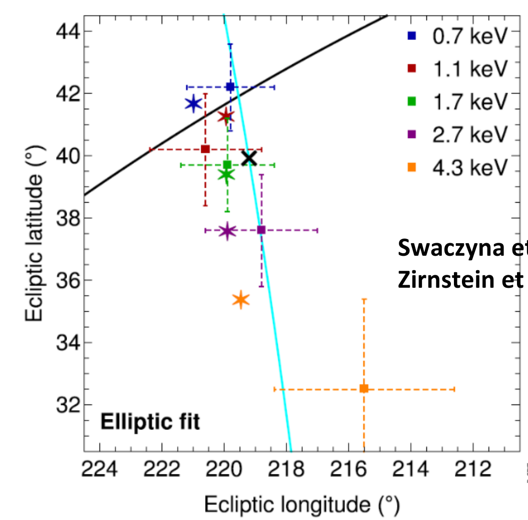
## Distance to the Ribbon from parallax geometry:

## ~ 140 au

**Swaczyna et al. 2016b**




## Energy-dependent position of the IBEX ribbon due to the solar wind structure:

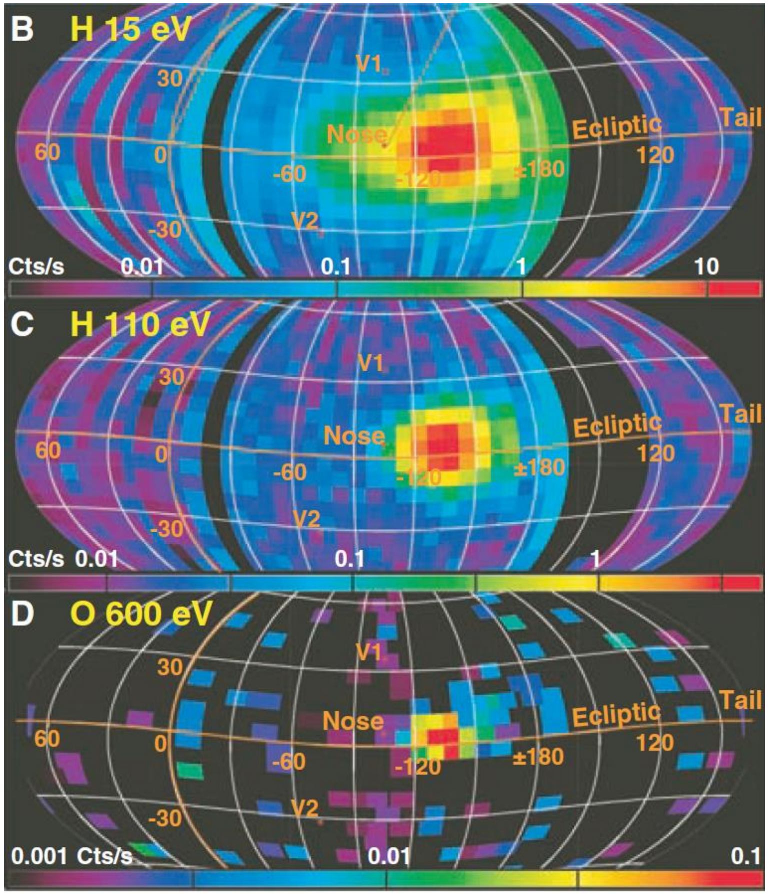



**Swaczyna et al. 2016a**
**Zirnstein et al. 2016a**

# IBEX-Lo measurements of He, H, Ne, O, and D ISN gas

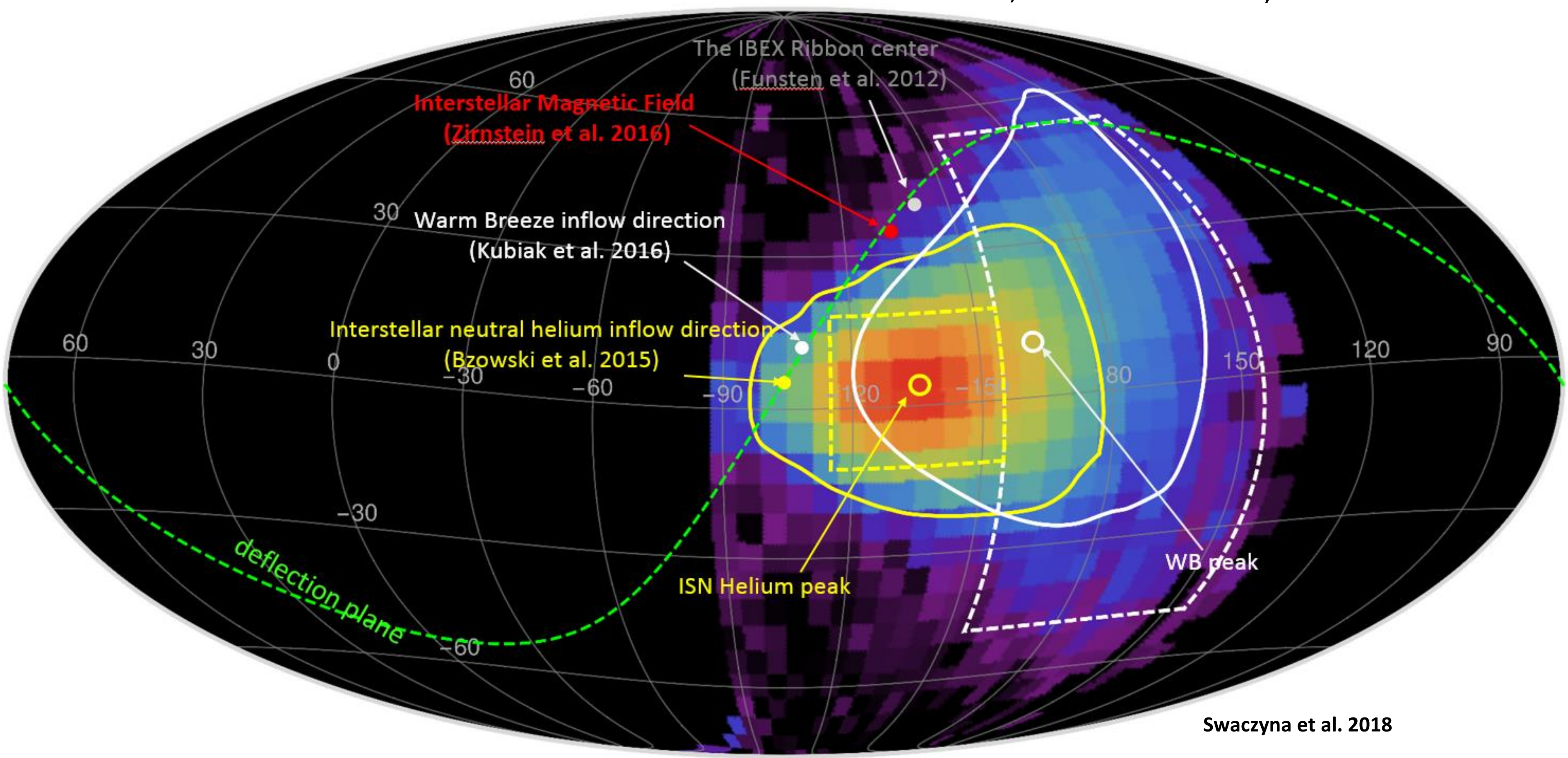
- IBEX-Lo measures directly H and O ISN atoms
- He and Ne are detected by measurements of ions sputtered from the conversion Surface ($H^-$, $C^-$, $O^-$)
- Time-of-flight (TOF) analysis allows for differentiation between species
- First direct measurement of ISN H and O (Möbius et al. 2009)
- Determination of the ISN flow direction and temperature after two years of observations (Bzowski et al. 2012, Möbius et al. 2012): two independent methods, same result – ISN flow different by ~4° than obtained by GAS/Ulysses, but temperature of LISM similar (*IBEX-Ulysses enigma*) supported by LOS observations towards nearby starts
- Parameter tube of ISN flow parameters from IBEX
- Moreover, additional, unknown signal in the data (secondary population?, cross section for charge exchange between He and $He^+$ higher; Bzowski et al. 2012)

**Möbius et al. 2009**



# IBEX-Lo measurements of He, H, Ne, O, and D ISN gas

- Re-analysis of GAS/Ulysses data (three independent groups: Bzowski et al. 2014, Wood et al. 2015, Katushkina et al. 2014): parameters unchanged, temperature higher!
- Warm Breeze discovered in the IBEX-Lo data! (Kubiak et al. 2014)
- Re-analysis of IBEX data (6 years of observations, Warm Breeze included, careful analysis of uncertainties): temperature of LISM is higher (7440 K instead of 6200 K)! Flow vector consistent with Ulysses (25.8 km/s, 255.8°, 5.2°).
- Warm Breeze is the secondary ISN He (Kubiak et al. 2016, Bzowski et al. 2017)

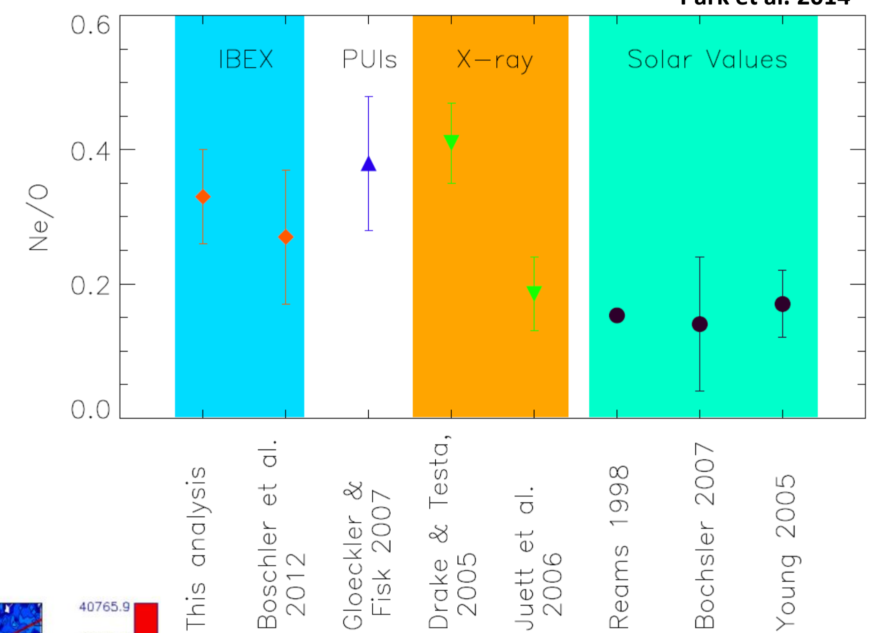


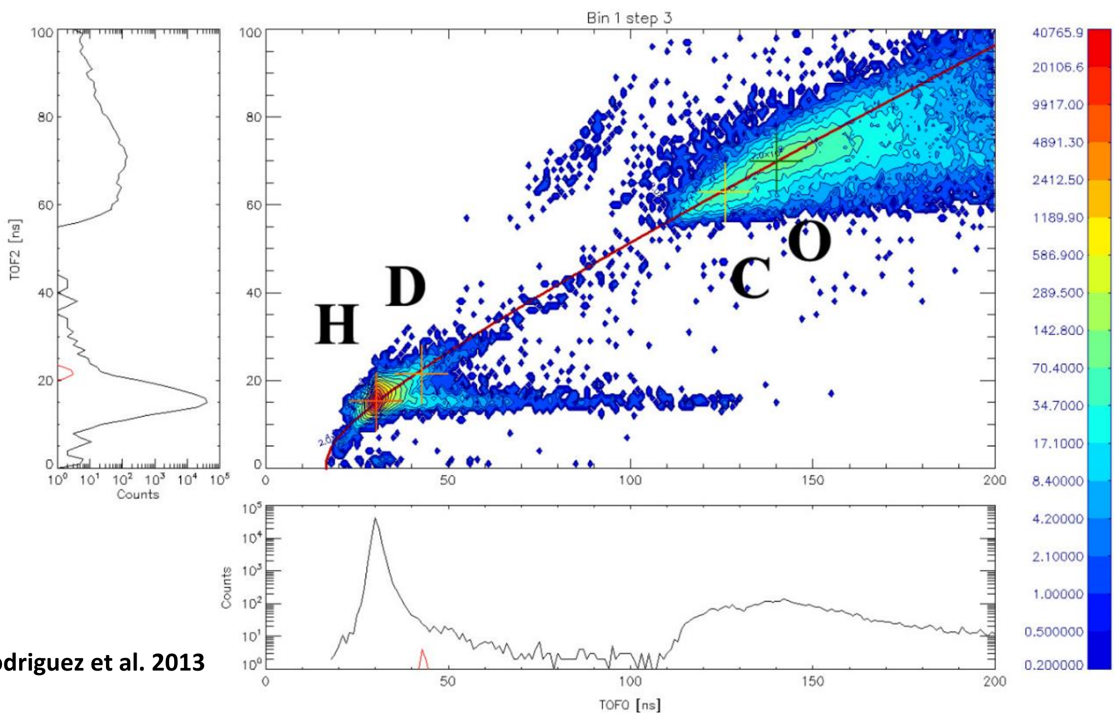

Swaczyna et al. 2018

# IBEX-Lo measurements of He, H, Ne, O, and D ISN gas

- Secondary ISN O detected (Park et al. 2015, 2016)
- Solar cycle variations of ISN H (disappearing of the flux during solar maximum; Galli et al. 2019)
- Determination of the Ne/O ratio in LIC (Ne/O=0.33±0.07; Park et al. 2014)
- Determination of the D/H ratio based on statistical analysis of the measured signal ($D/H_{LISM}=1.6\pm1.0 \times 10^{-5}$; Rodriguez et al. 2013, 2014)

**Park et al. 2014**




**Rodriguez et al. 2013**

# IBEX major steps in understanding the interstellar boundary region

## H ENA discoveries:

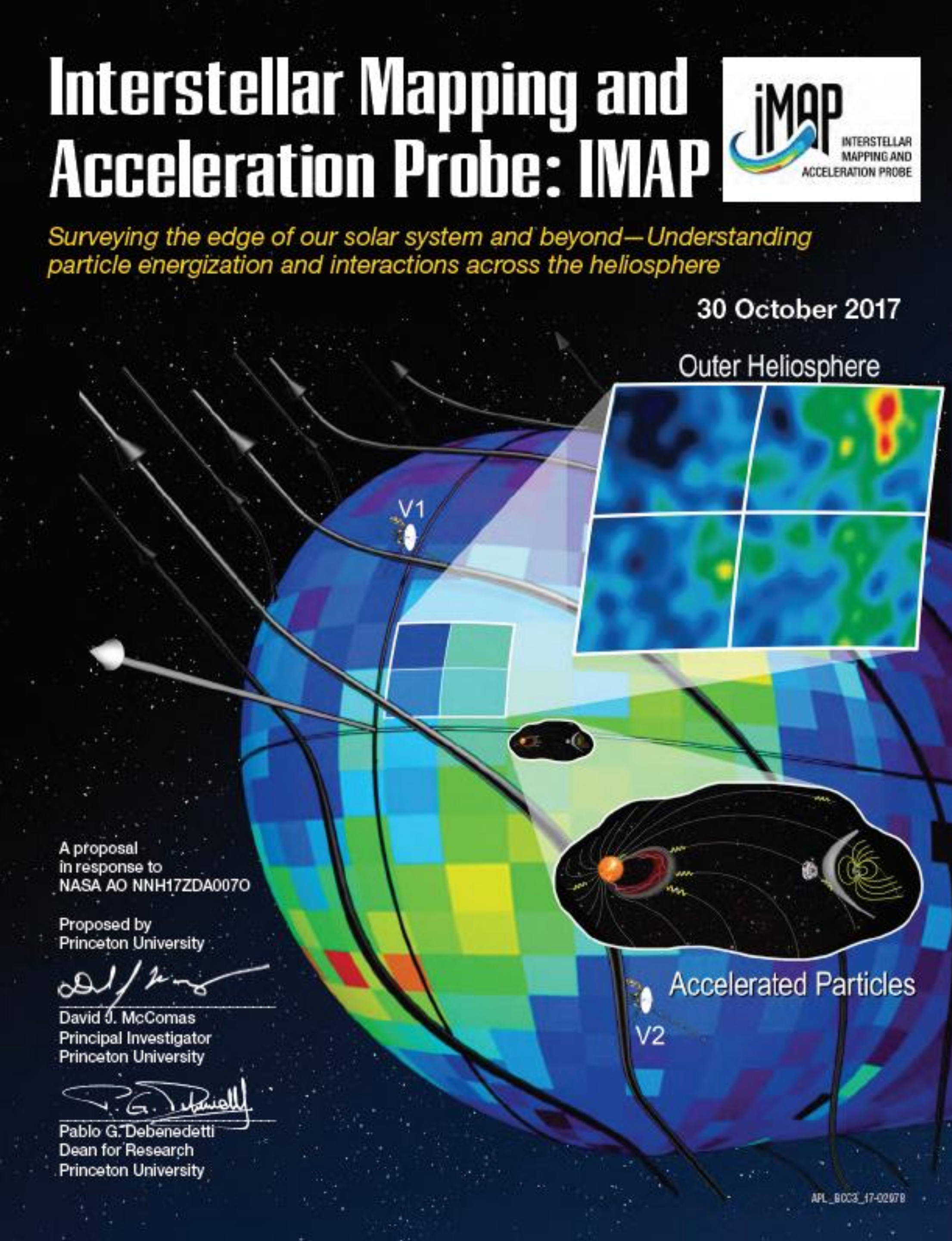
- Ribbon and its connection to IMF
- Solar wind-like latitude/Energy ordering of Ribbon emission
- Secondary ENA Ribbon source
- distance to ribbon ~140 au

- GDF from inner heliosheath
- GDF ordering by latitudinal solar wind structure
- Investigation of the heliotail
- Heliosheath pressure variations with the solar cycle (poles, heliotail)
- ENA response on changes in the SW ram pressure

## Interstellar Medium discoveries:

- Direct observations of ISN H, D, O, Ne
- Discovery of secondary population of He
- Bow wave instead of bow shock
- Precise estimation of IMF strength and direction
- VLISM is warmer
- Co-planarity of ISN He, H, secondary He, Ribbon center, and IFM
- Determination of Ne/O ratio
- Detection of ISN D (on statistical level)

McComas et al. 2017



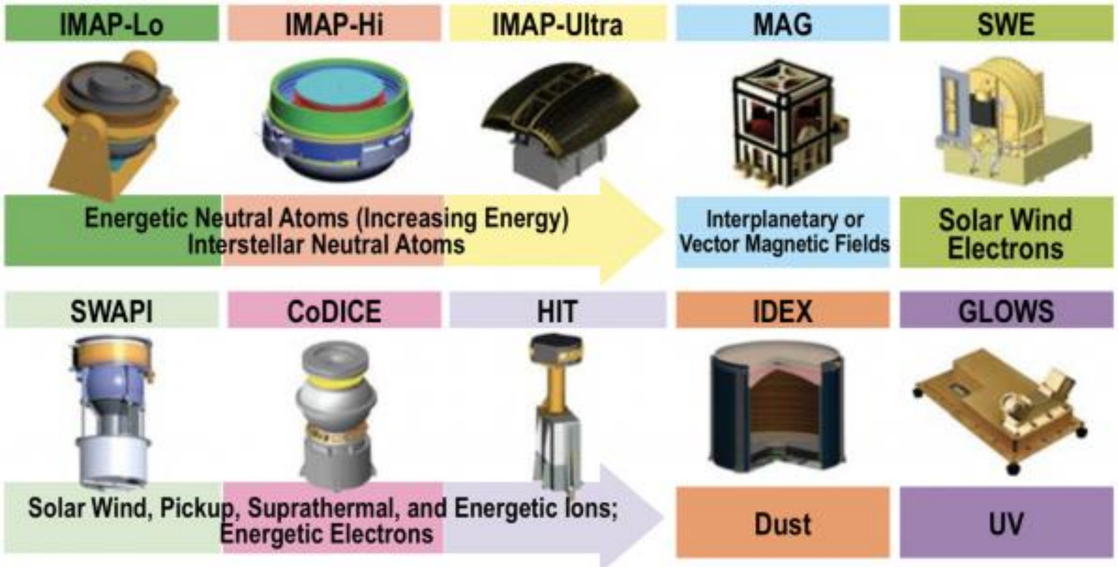

NASA selected IMAP!
June 1, 2018

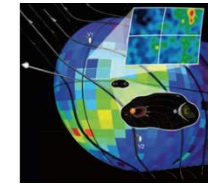
PI: David J. McComas
(Princeton University)

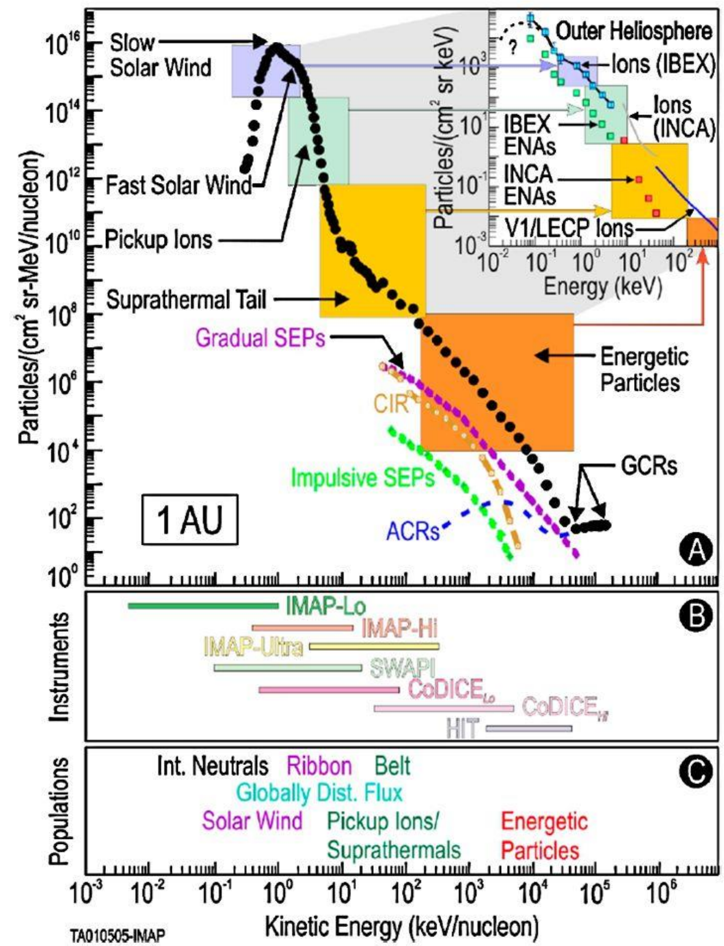
Launch in L1 in 2024

IMAP Team: **24 institutions**
(USA, Germany, Poland, Switzerland, Japan)

IMAP Payload: **10 instruments**






IMAP Paper **(Open Access)**
McComas et al. Space Sci Rev (2018) 2014:116

IMAP website: **imap.princeton.edu**

Contact: **David McComas** (dmccomas@princeton.edu)

Collaboration possibilities:
Guest Investigators, Student Collaboration, Heliophysics Future Leaders