Session: *Observations of the Local Interstellar Medium and Motivations for IMAP*

Poster: **SH41E-2412**

Modeling of the solar cycle modulated interstellar He, Ne, and O pick-up ions along the Earth's orbit

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Introduction

- **Interstellar neutral** (ISN) atoms are **ionized** by solar wind and solar EUV radiation inside the **heliosphere** and create the so-called interstellar **pick-up ions (PUIs)**.

- The joint action of **solar gravity** and **ionization** results in the creation of a **focusing cone** at the downwind side and, for some species, an **upwind crescent** in the density distribution of the ISN gas in the inner heliosphere

- The **locations of the peaks** of the downwind focusing cone and the upwind crescent as observed in the **PUI count rate** have been used as **signatures** for the **flow longitude** of ISN gas into the heliosphere.

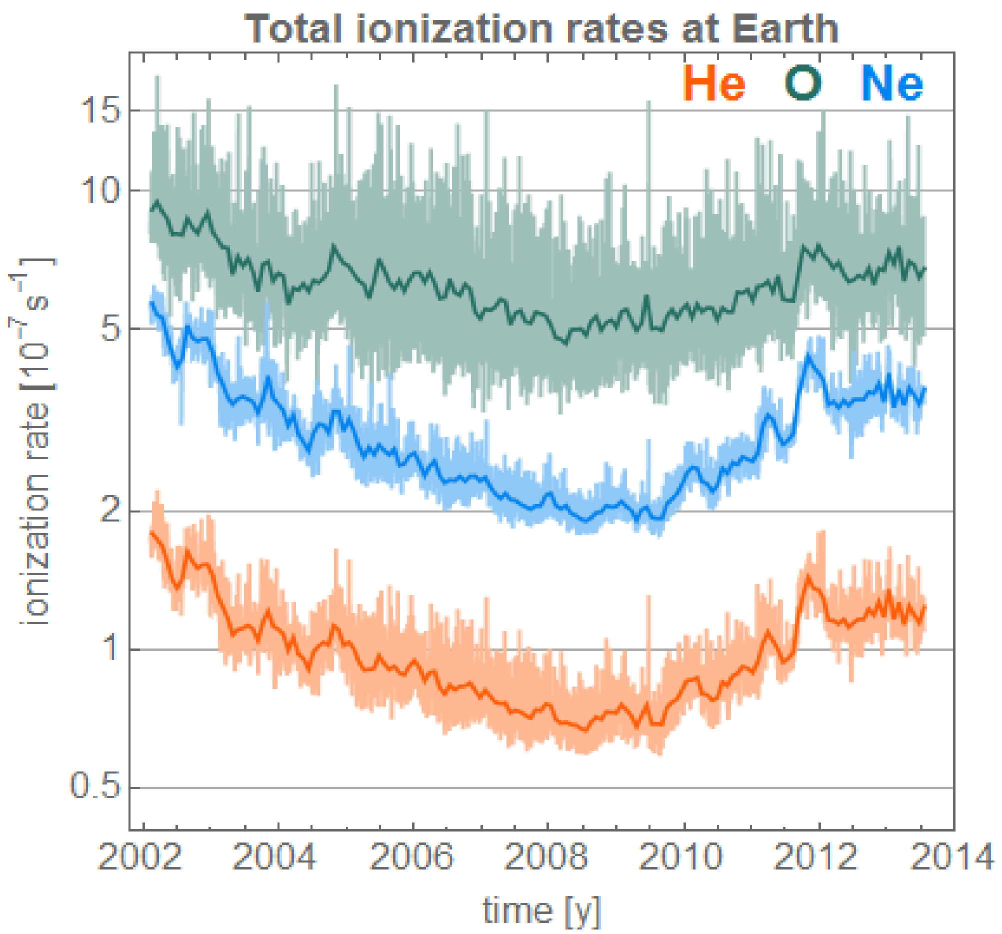
- We study the modulation of ISN **He, Ne, and O density and PUIs** along the **Earth's orbit** from **2002** to **2013** (almost the entire **solar activity cycle**).

- We derive the **longitudes** of the cone and crescent peaks by fitting a **Gaussian** function and study how they change due to solar-cycle variations of the ionization rate.

Presented results are a content of:

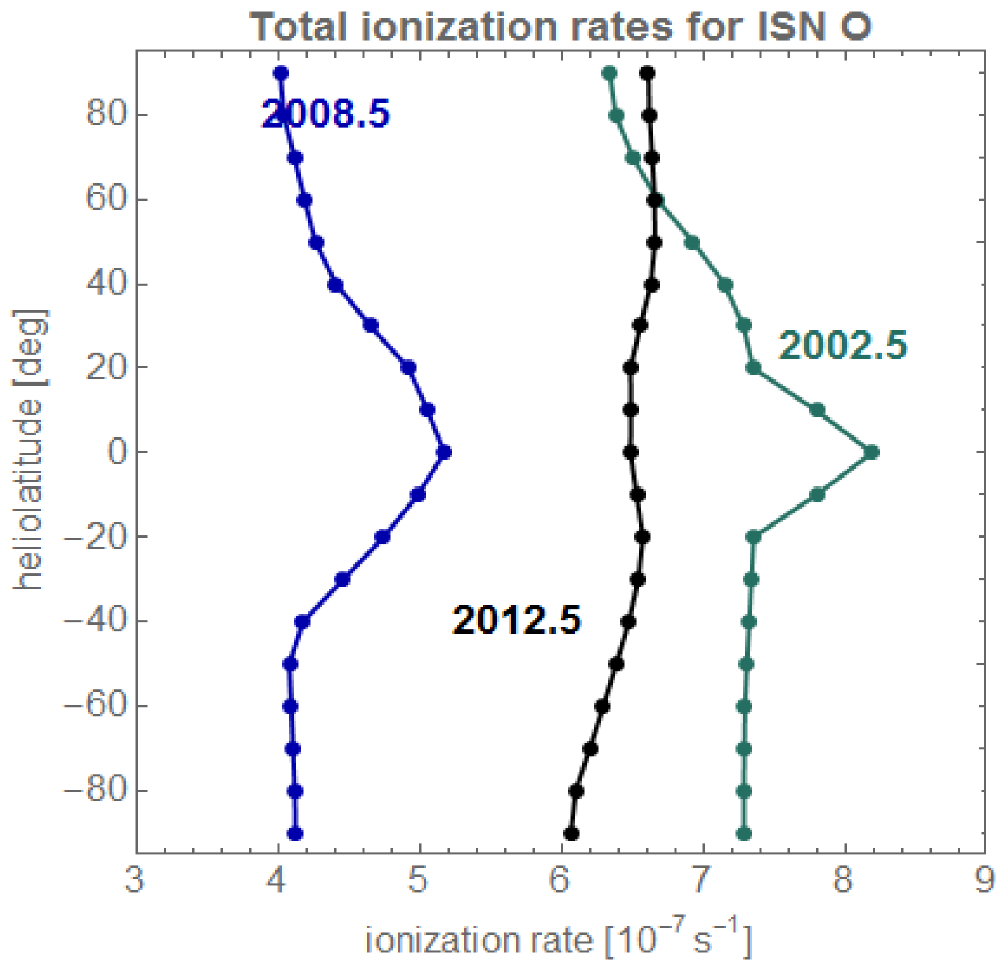
Sokół et al., ***Solar cycle variation of interstellar neutral He, Ne, O density and pick-up ions along the Earth's orbit***, submitted to MNRAS

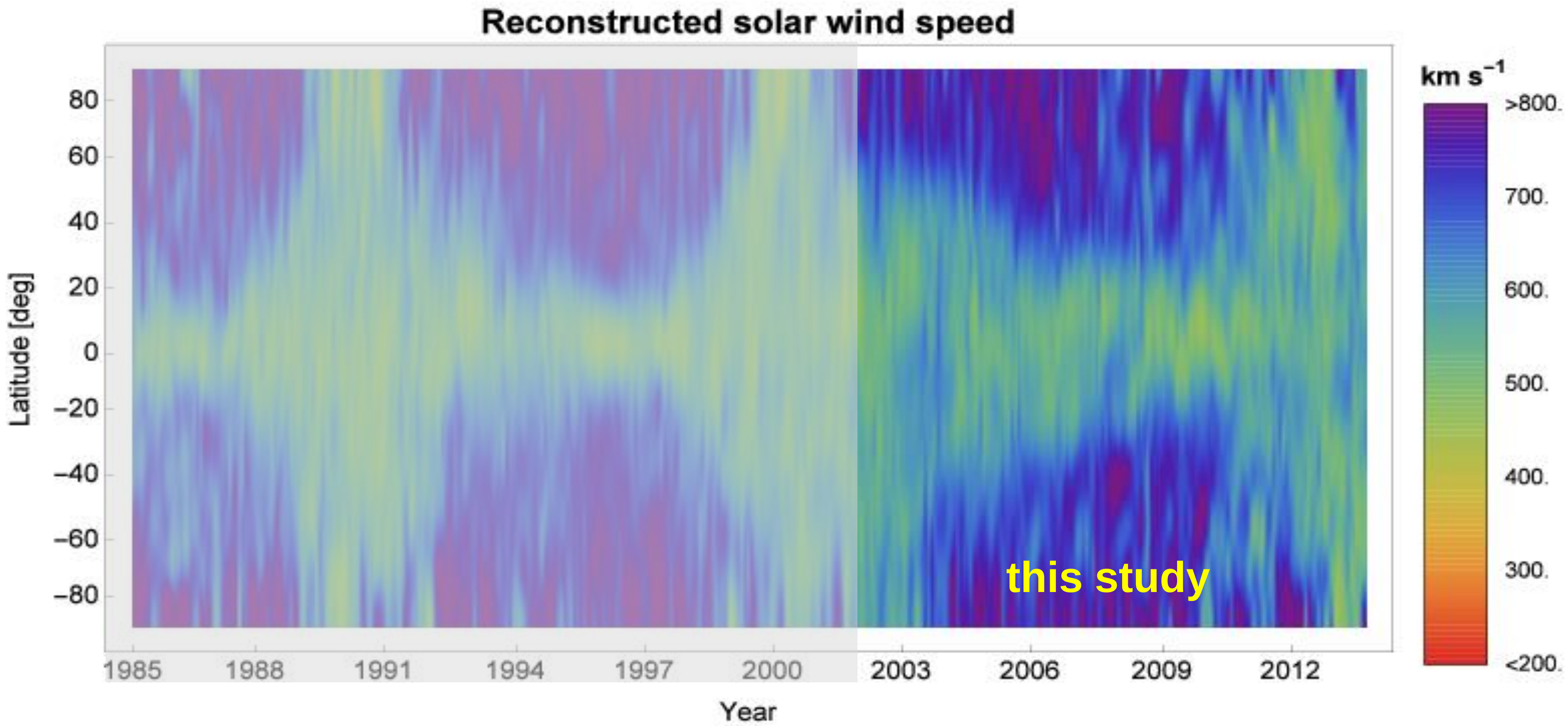
ISN He, Ne, and O ionization rates



Total ionization rates calculated as a sum of:

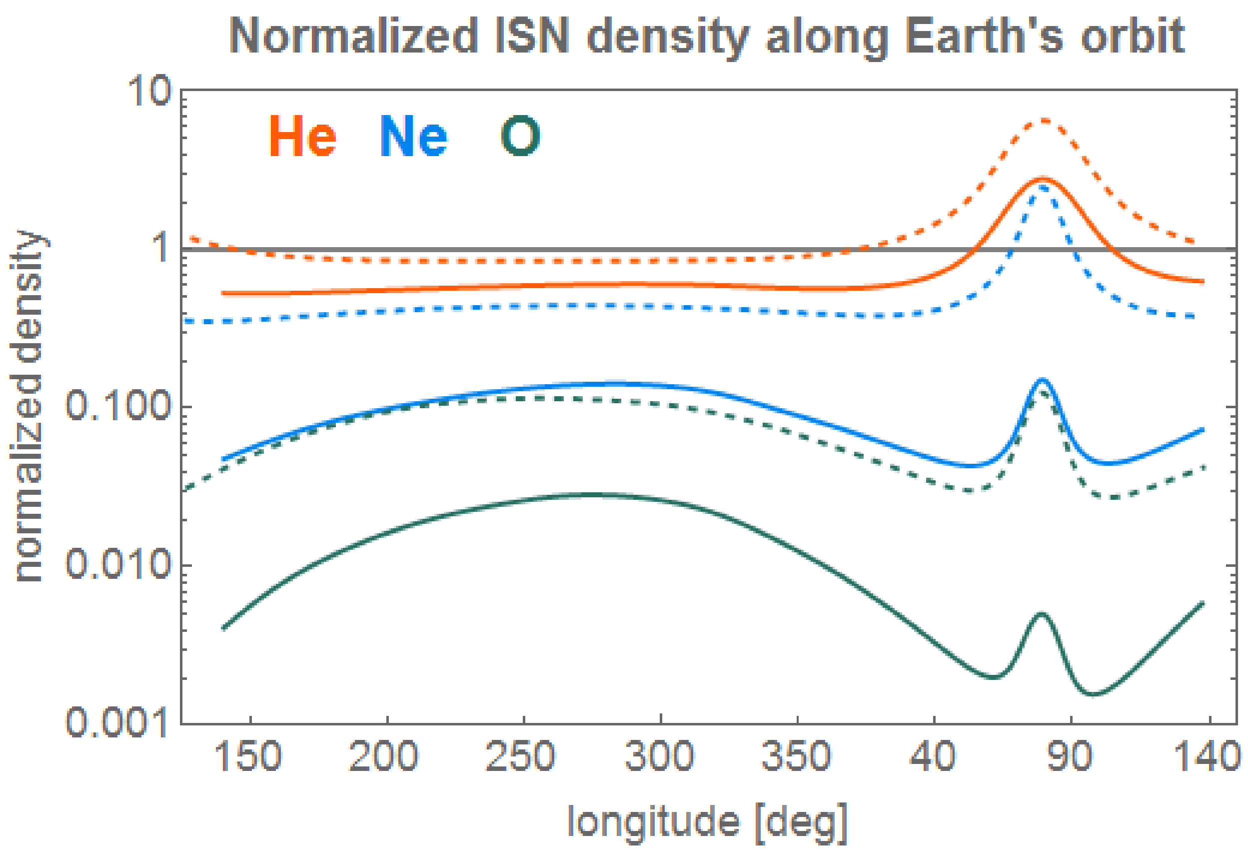
- **photoionization** (Sokół & Bzowski 2014)
- **charge exchange** with solar wind particles (Bzowski et al. 2013), with the heliolatitudinal structure of the solar wind proton speed and density (Sokół et al. 2013, 2015) taken into account
- **electron impact ionization** (Bzowski et al. 2013)



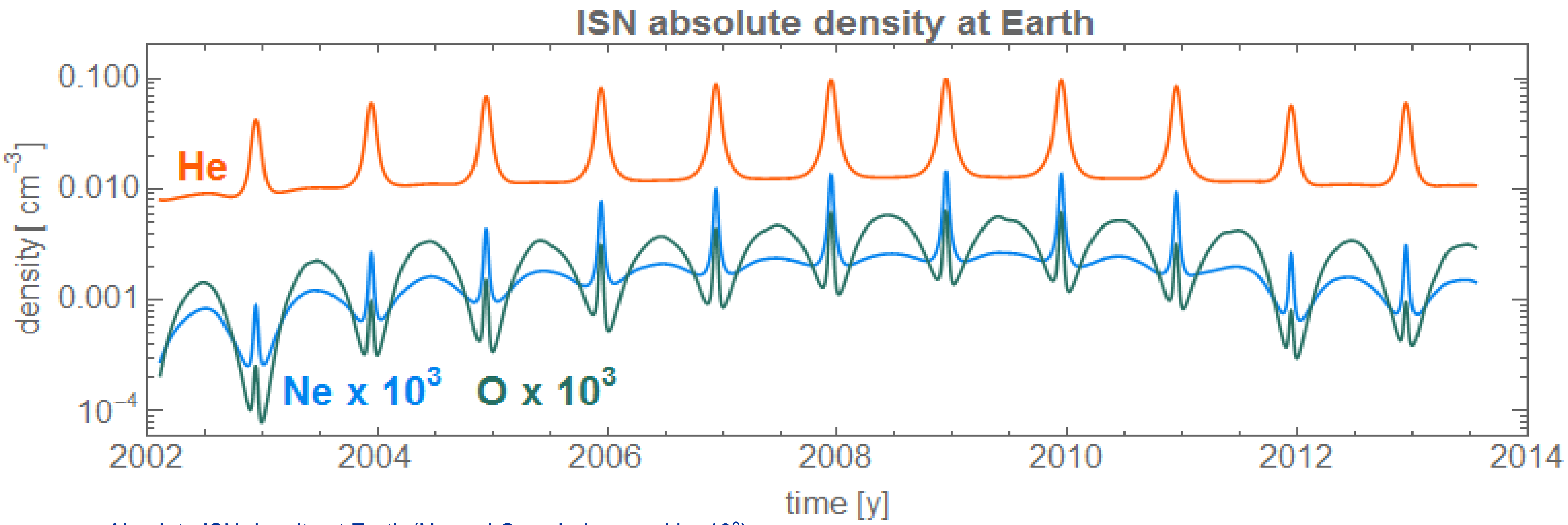


ISN He, Ne, and O density in Earth orbit

- **ISN density** calculated with the use of the **Warsaw Test Particle Model** (recent review Sokół et al. 2015)
- ISN flow parameters in front of the heliosphere adopted after Bzowski et al. 2012
- Ne and O strongly **highly attenuated** in the heliosphere, strongly **modulated** during the **solar cycle**
- densities of **Ne and O comparable** to each other **at Earth**
- He **density in the cone larger** than in front of the heliosphere



Densities normalized to the respective densities in the LIC (He_{LIC} = 0.015 cm^{-3}, Ne_{LIC}=0.582 x 10^{-5} cm^{-3}, O_{LIC}=0.5 x 10^{-4} cm^{-3}) for solar maximum (2002, solid lines) and solar minimum (2008, dashed lines).



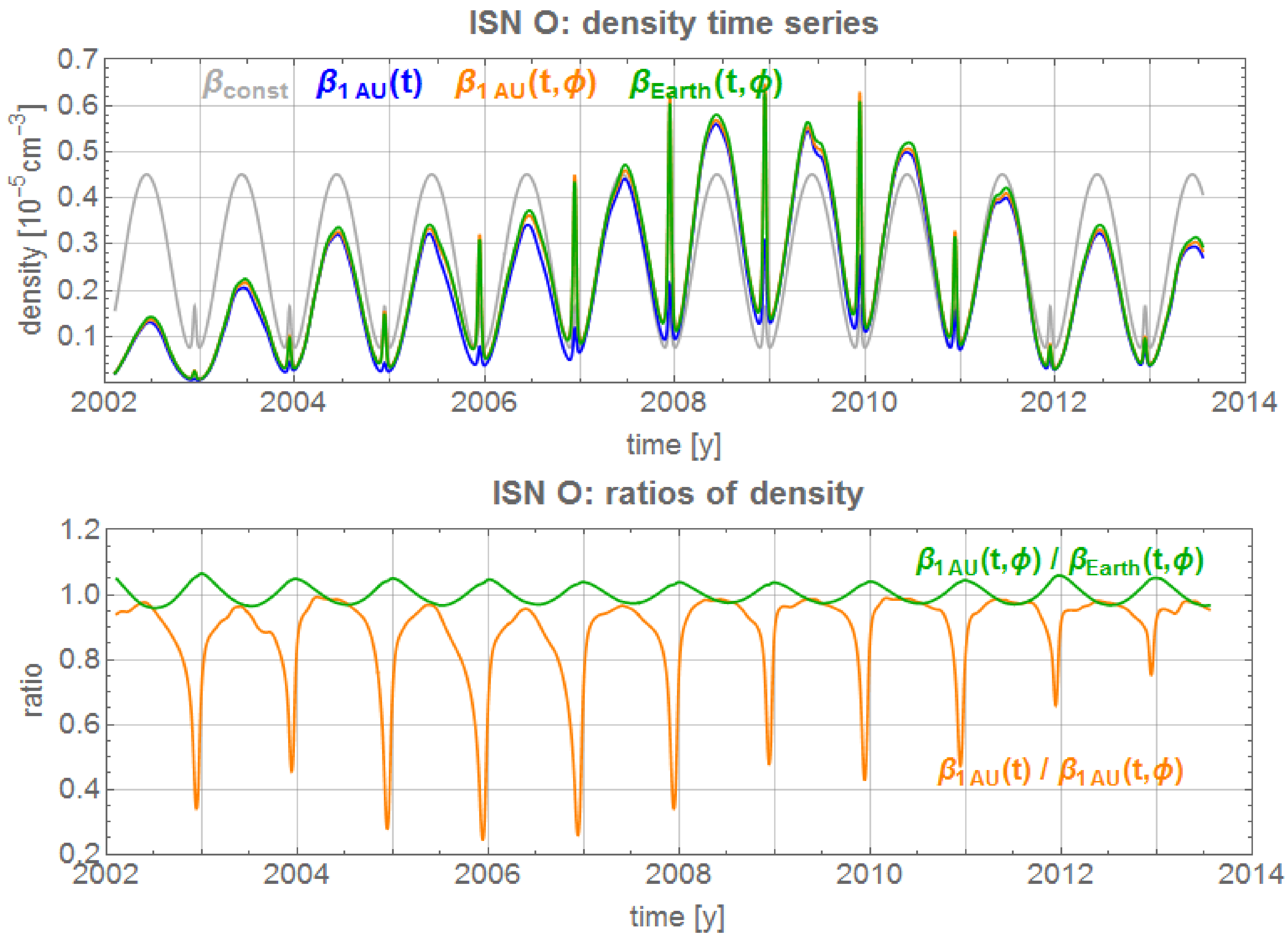
Absolute ISN density at Earth (Ne and O scaled upward by 10^3).

Modulation of ISN density

ISN density along the Earth's orbit is **modulated** due to time and heliolatitudinal **variations** of the **ionization losses**.

Three effects were analyzed:

- **time variations** with solar cycle $\boldsymbol{\beta_{1AU}(t)}$
- **heliolatitudinal variations** of solar wind flux $\boldsymbol{\beta_{1AU}(t,\phi)}$
- **ellipticity** of the Earth's orbit $\boldsymbol{\beta_{Earth}(t,\phi)}$



Top panel: modification of the ISN O density calculated using different assumptions and simplifications in the modeling.
Bottom panel: ratios of the results for the spherically symmetric versus latitudinally dependent ionization rates (orange line) and for a circular 1~AU orbit versus the realistic Earth's orbit (green line).

- The effects related with the heliolatitudinal structure of the solar wind can strongly affect the density close to the cone region.
- The ellipticity of the Earth's orbit introduces a periodical ~7% annual variation.
- The crescent peak can be corrugated (see e.g., 2009) due to the time and latitudinal variations of the ionization rate.

ISN PUIs: modeling

Pick-up ions modeling assumptions:

- observations day-by-day along the Earth's orbit using a virtual detector with a **radial**, **pencil-beam FoV** (geometric factors neglected), at rest in the Sun frame

- flux after Ruciński et al. 2003

$$F(R) = \frac{1}{R^2}\int_{r_0}^{R} S(r) r^2 dr = \frac{1}{R^2}\int_{r_0}^{R} n(r)\beta(r) r^2 dr$$

- **instantaneous pitch angle scattering** (spherically symmetric PUI distribution in the solar wind frame)

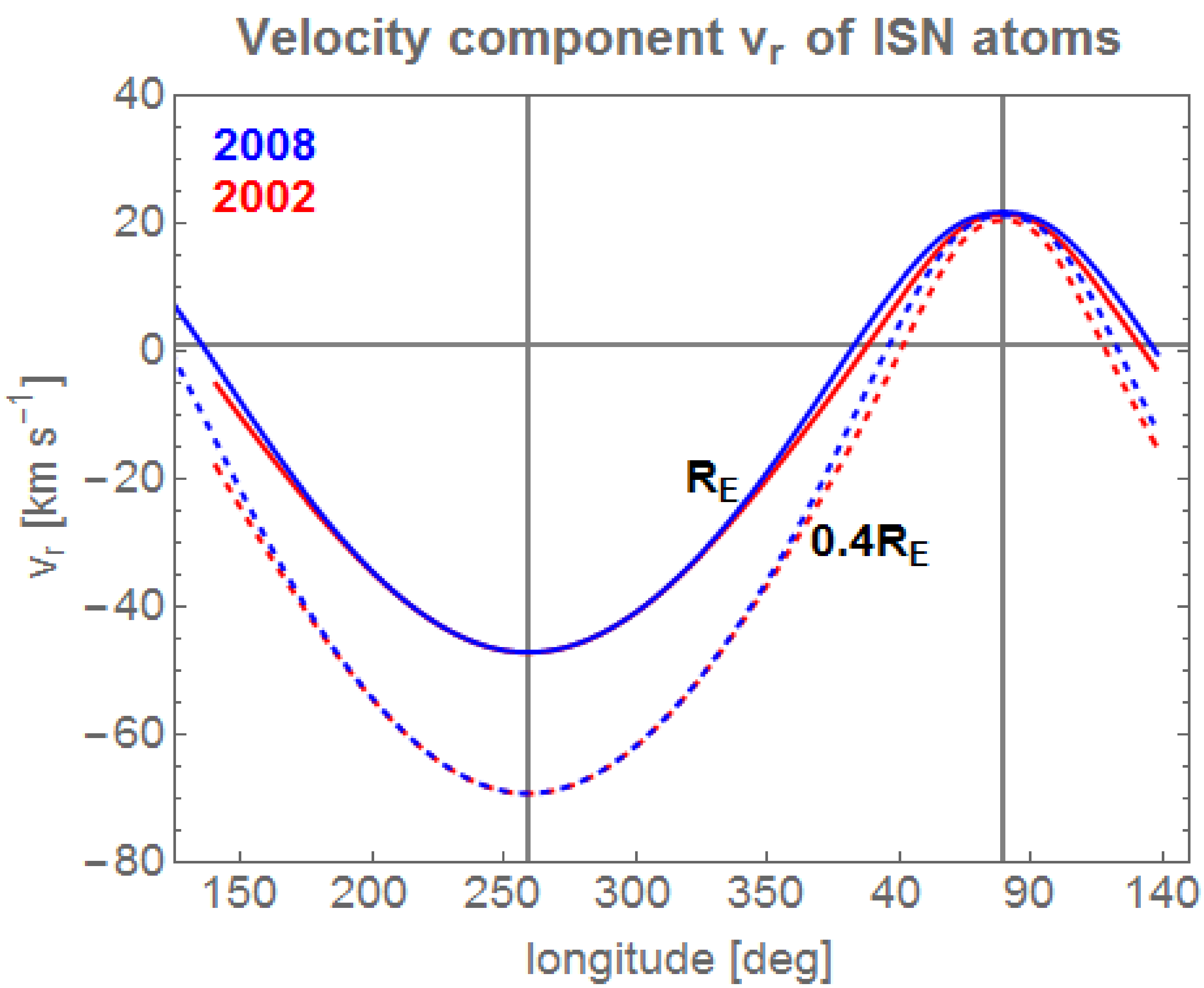
- due to finite **radial component of the velocity** of the parent-population ISN gas **PUIs are not at rest at** the moment of **pickup**

- **adiabatic cooling** following Möbius et al. 1995

$$\mathrm{v}_{\mathrm{PUI}}^{\mathrm{sc}} = \mathrm{v}_{\mathrm{PUI}}^{\mathrm{sw}}(r)\left(\frac{R}{r}\right)^{-\gamma} + \mathrm{v}_{\mathrm{sw}}(R); \quad \mathrm{v}_{\mathrm{PUI}}^{\mathrm{sw}}(r) = \mathrm{v}_{\mathrm{sw}}(R) - \mathrm{v}_{\mathrm{r}}(r)$$

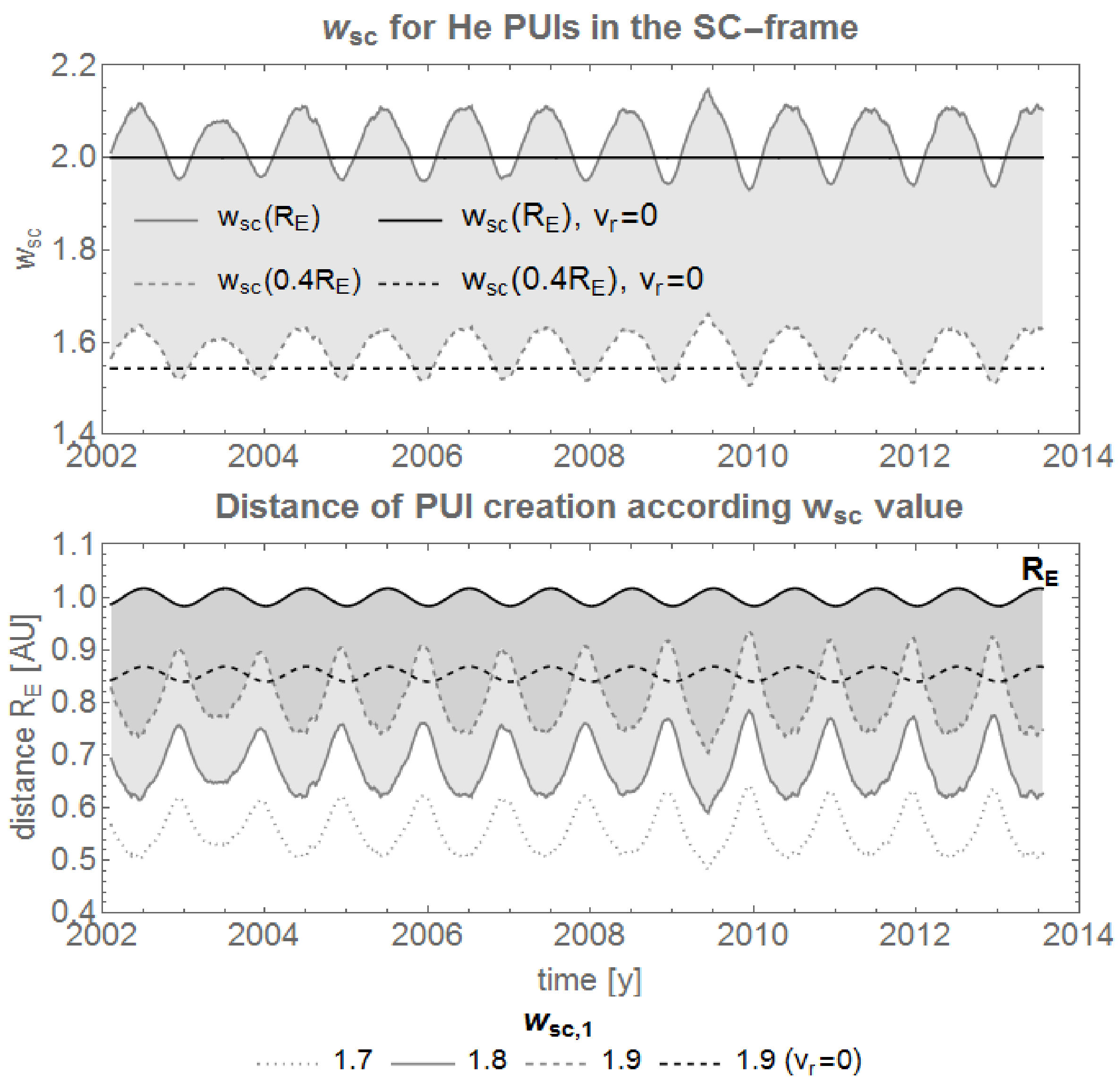
- magnetic field and transport effects neglected

- two quantities of PUIs studied**: local production rate** at Earth and **count rate** (integrated in the w_{sc}-domain)



The radial component of the velocity vector of the ISN He bulk flow, shown along the Earth's orbit for 2002 (red lines) and 2008 (blue lines) for distances to the Sun equal to R_E (solid lines) and 0.4 R_E (dashed lines). The vertical bars indicate the longitudes of the upwind and downwind directions adopted in calculations. R_E – is the real Earth's distance from the Sun, changing with time. The yearly patterns of the sample average are not exactly repeatable from year to year because of modifications due to the varying ionization rate

ISN PUIs: count rates

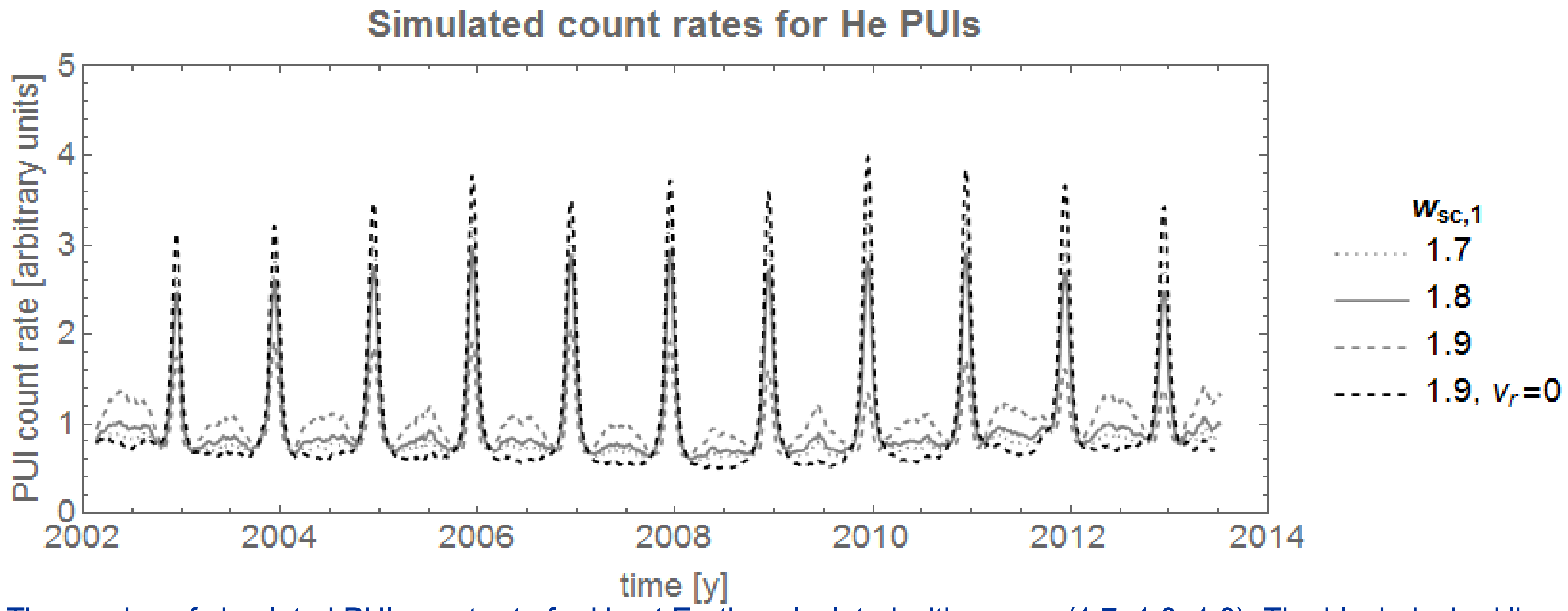


Top: Time series of the normalized PUI speed w_{sc} for PUIs created between $0.4R_E$ and R_E assuming adiabatic cooling. Presented are series for He, but they are identical for Ne and O. The horizontal lines illustrate the case where the radial speed of ISN atoms at the moment of ionization is neglected.
Bottom: The interval of solar distances over which the PUIs contributing to the measured signal are created, calculated for different values of the lower boundary $w_{sc,1}$ (cf. the upper panel), shown as a function of the Earth's longitude on its orbit. The black solid line R_E represents the varying distance of the Earth from the Sun.

PUI count rate:
α = 1/γ; γ=2/3 – adiabatic cooling index
R – detection distance, A – instrumental geometric constant
w_{sc} – PUI normalized speed in the **spacecraft frame**
v_{sw} – solar wind speed, v_r – radial speed of the parent ISN atom

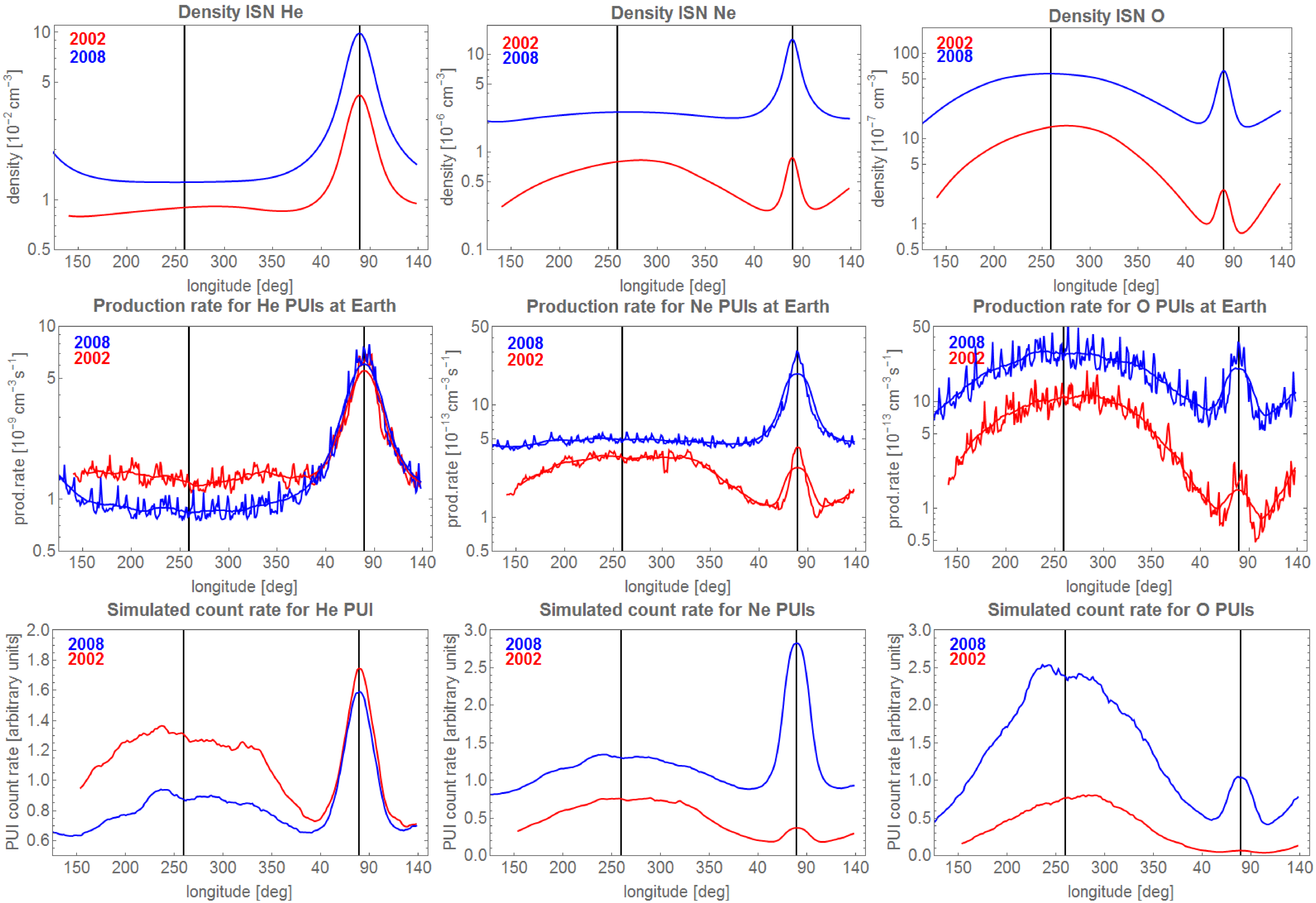
$$w_{sc} = \frac{v_{PUI}^{sc}}{v_{sw}}; \quad w_{sw} = 1 - \frac{v_r}{v_{sw}}$$

$$C_p = \frac{1}{2}\alpha R A \int_{w_{sc,1}}^{w_{sc,2}} n\beta \left(1 - \frac{v_r}{v_{sw}}\right)^{-3\alpha} (w_{sc}-1)^{3\alpha-1} w_{sc} dw_{sc}$$



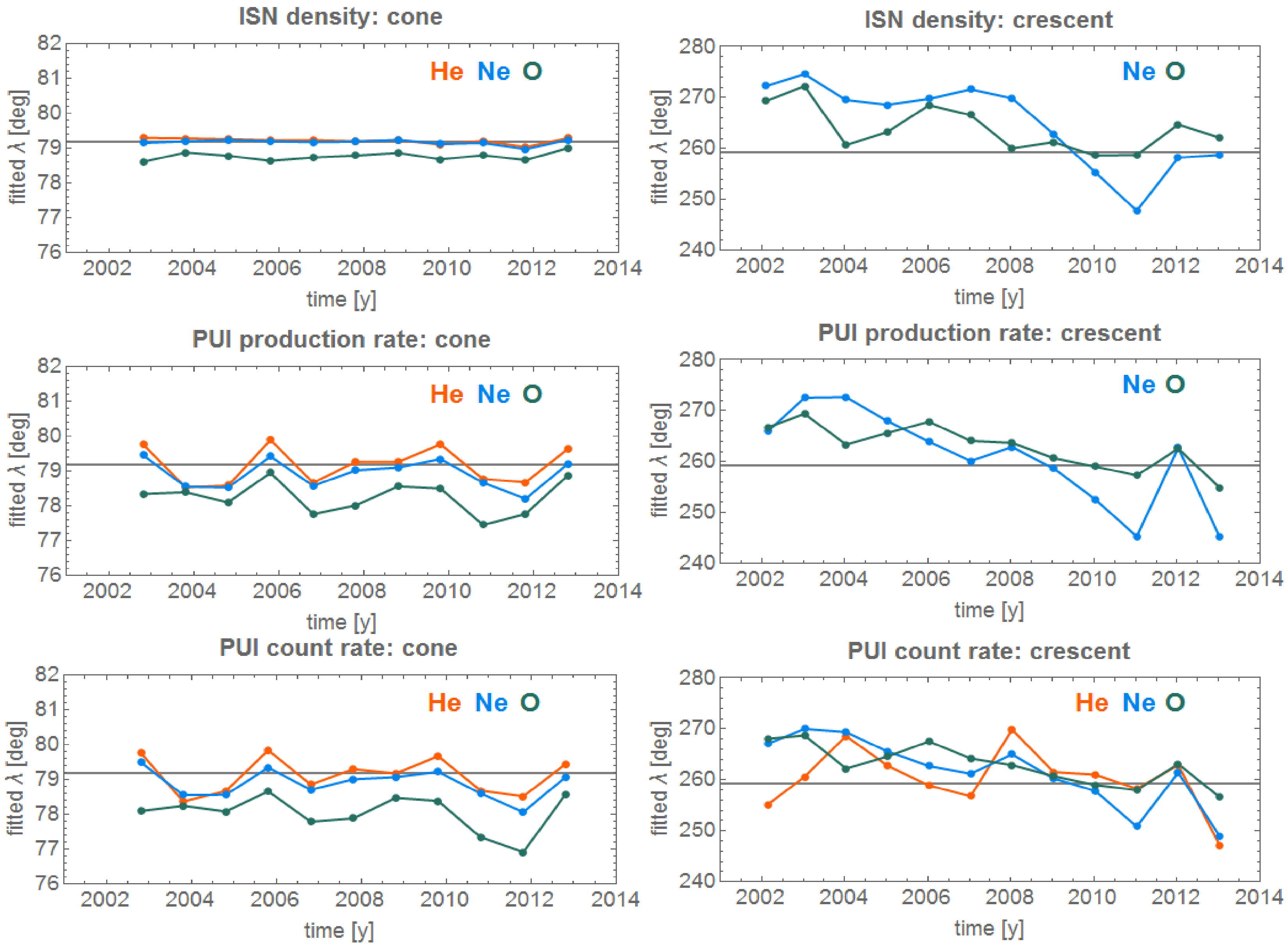
Time series of simulated PUI count rate for He at Earth, calculated with $w_{sc,1}$ =(1.7, 1.8, 1.9). The black dashed line represents the case with the radial speed v_r ignored in the calculation of the PUI count rates.

ISN density and PUIs series

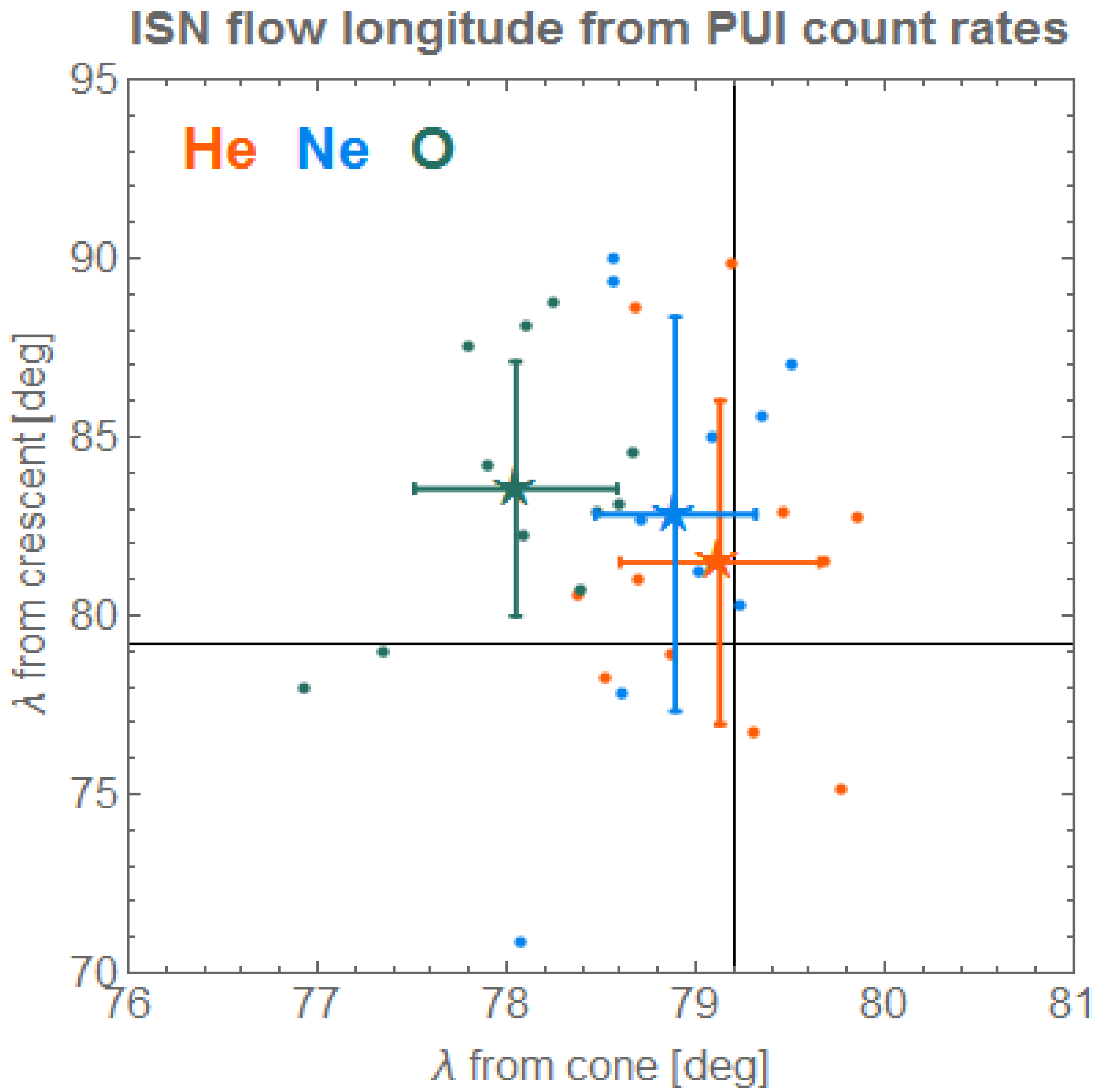


Top row: ISN He, Ne, and O density. **Middle row:** instantaneous local PUI production rates in the Earth's orbit (the oscillating daily values and the 27-day moving average). **Bottom row:** simulated count rates integrated over a fixed range in the w_{sc} space and normalized by an average value over the whole time interval studied for each species separately, given in arbitrary units. All lines are shown for 2002 (**red, solar maximum**) and 2008 (**blue, solar minimum**). The vertical bars indicate the ecliptic longitudes of the upwind (259.2°) and downwind (79.2°) directions of the flow of the ISN gas in front of the heliosphere assumed in the calculation of ISN density.

Gaussian fit to cone and crescent peaks



Positions of the peaks of the cone and crescent from the Gaussian fits to the density and to 27-day moving averages of the PUI production rates and count rates for the detector moving with Earth. The horizontal solid lines mark the ISN inflow longitude at the upwind and downwind sides.



Longitudes of the ISN flow derived from Gaussian fits to the He, Ne, and O PUI count rate in the cone and crescent for each of the analyzed years. The star-points with error bars are the averages with standard deviations. Cross-hair marks the longitude expected to reproduce.

- **Gaussian fit** used to retrieve the ISN flow longitudes from the ISN density and PUI production rate and count rate (both smoothed by 27-day moving average)
- ISN **He and Ne density cones** are almost **perfect** indicators of the ISN gas inflow longitude
- He and Ne PUIs **cones** show **about 1° year-to-year variation** around the expected value
- ISN O density and PUIs have a systematic shift (towards smaller longitudes)
- fits to **crescent** deviate **up to 10°** upward and downward, solar cycle dependent (?)

Summary and conclusions

- The analysis was carried out to mimic observations by an observer traveling with the Earth around the Sun (calculating exact position for each day of year).

- Considering the important role of the **finite injection speed** of ISN atoms and of adiabatic PUI cooling, we show that Ne and O always form an upwind crescent in the PUI flux, but that the crescent formation for He PUIs strongly depends on the integration boundaries for the PUI distribution ($w_{sc} \geq 1.9$).

- For the PUI local production rate and count rates the retrieved longitudes **vary from year to year around the expected value**.

- We also find that ecliptic longitude of the PUI peak in the **focusing cone** is a **good proxy** for the inflow direction of ISN He and Ne during solar minimum, but less accurate for ISN O, which exhibits a systematic shift in the model.

- The ISN flow longitude derived from the peak location for the **crescent may not be a good proxy** because it is far from the Gaussian shape (it is neither symmetrical nor smooth in the peak). It is due to short-time (few months) **variations** in the **ionization losses**. These lead to a **corrugated crescent structure** and may **shift the fitted position** of the crescent peak used to determine the inflow direction by up to 10°, with the strongest effects for the species that are heavily affected by ionization, i.e., O and Ne.

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