NAOC 中国科学院国家天文台 NATIONAL ASTRONOMICAL OBSERVATORIES, CAS

SWCX Contribution to the Soft X-Ray Background Using X-LEAP Data

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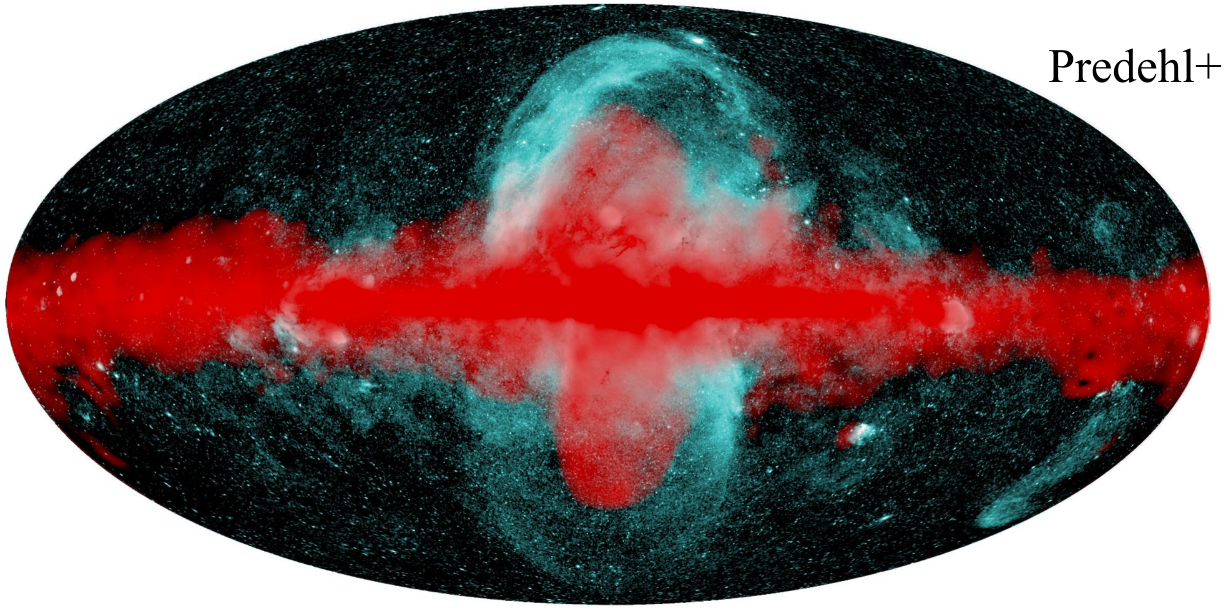
1. **MW Hot Gas and SWCX in Soft X-Ray Background**
2. **Complex Nature of SWCX Emission**
3. **The *XMM-Newton* Line Emission Analysis Program (X-LEAP)**
4. **SWCX Variations in Dataset and Correlations to SW Ion Data Measured by ACE**
5. **An Empirical Model Estimating SWCX Emissions (Before 2012)**

1. MW Hot Gas and SWCX in Soft X-ray Background

MW Hot Gas (T > 10^6 K) Emission:

- **Thermal Emission**: continuum (Bremsstrahlung)
- **Line Emissions**: O VII, O VIII, and Fe-L lines (0.56, 0.65, 0.7-1.0 keV; collisional ionization)
- **Coverage**: whole sky; faint

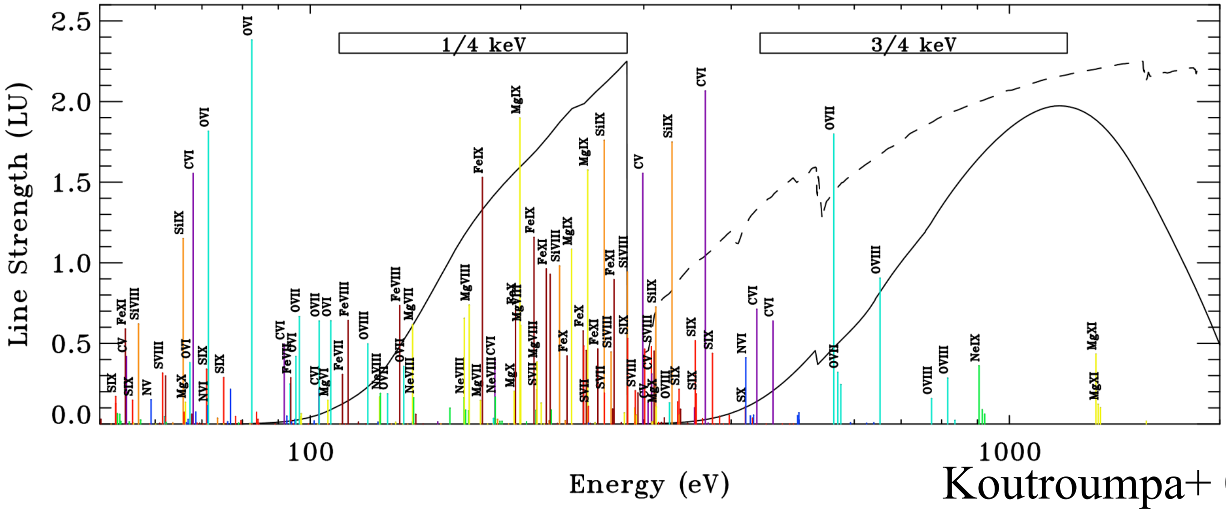
eROSITA All-Sky Survey (0.6 – 1.0 keV)



Predehl+ 20

SWCX Emission:

- **Highly-Charged Ions**: O7+, O8+, and Fe+;
- **Line Emissions**: O VII, O VIII, and Fe-L lines (SWCX)
- **Coverage**: Whole sky
- **Nature**: Complicated



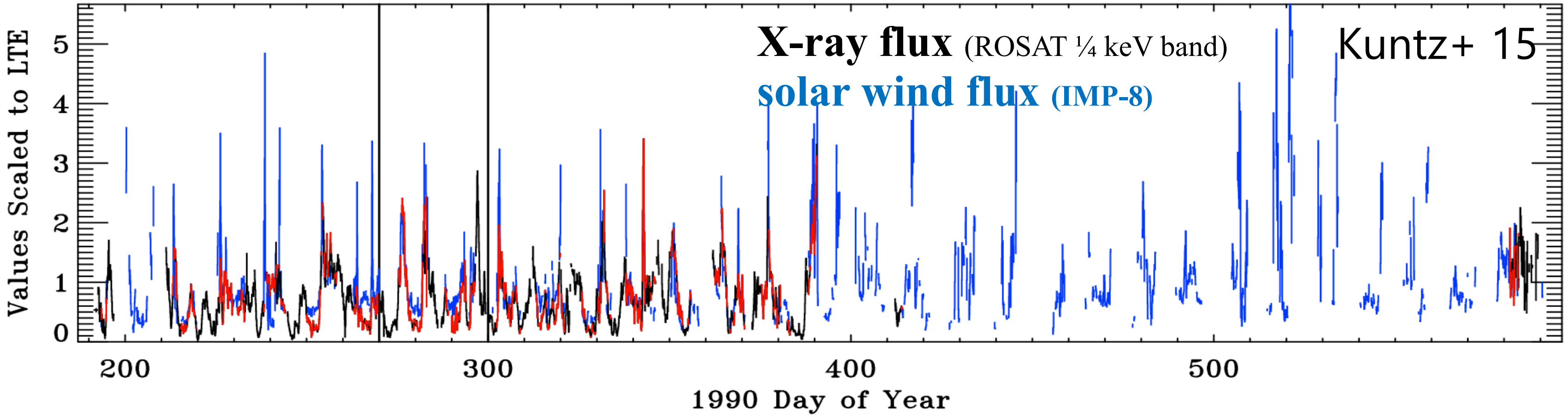
Koutroumpa+ 09b

2. Complex nature in SWCX emission — Regions & Variations

Magnetospheric SWCX

Region: Earth's Exosphere (H & He)

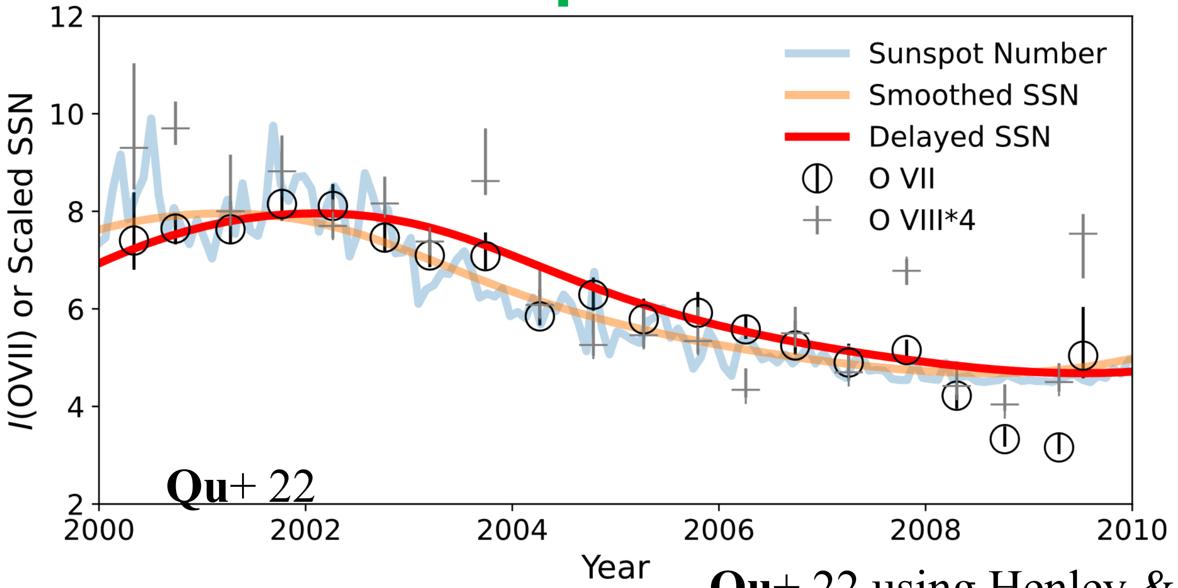
- **Variability**: Varies over days; sensitive to SW flux (e.g., Cravens 97; Freyberg 98)



Heliospheric SWCX

Region: Within the Heliopause (Neutral ISM)

- **Variability**: Varies over years with lower amplitude; latitude-dependence expected;



Qu+ 22 using Henley & Shelton 12 data

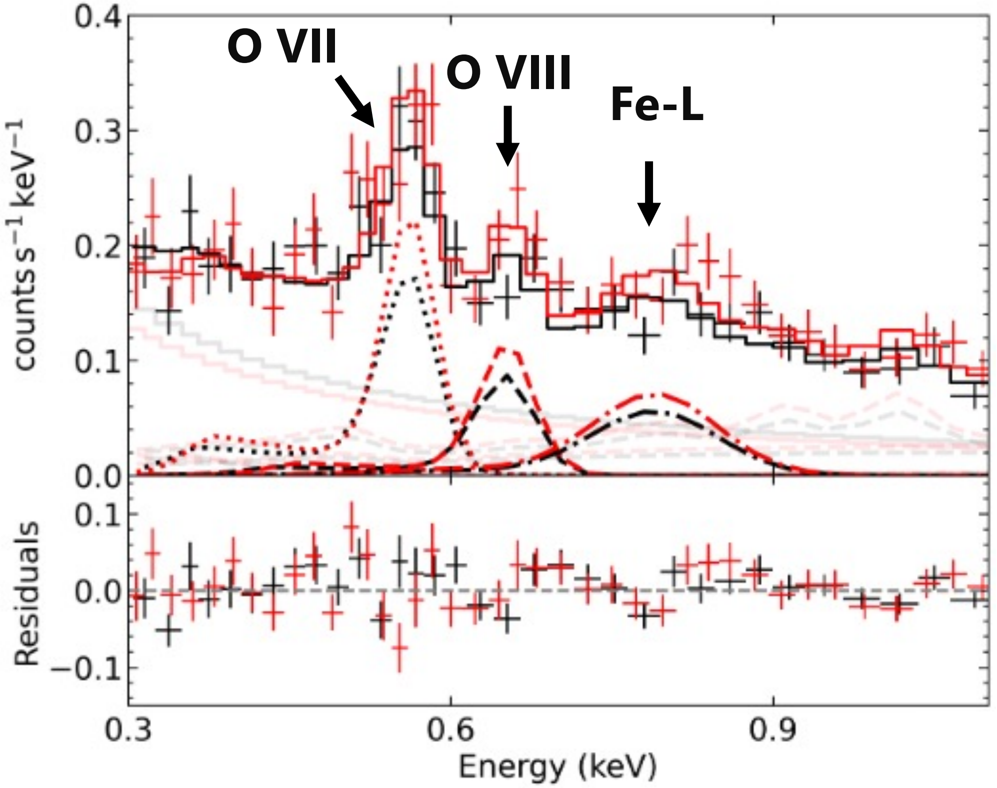
3. The XMM-Newton Line Emission Analysis Program (X-LEAP)

Need: Requires extensive, long-term line emission data in soft X-rays

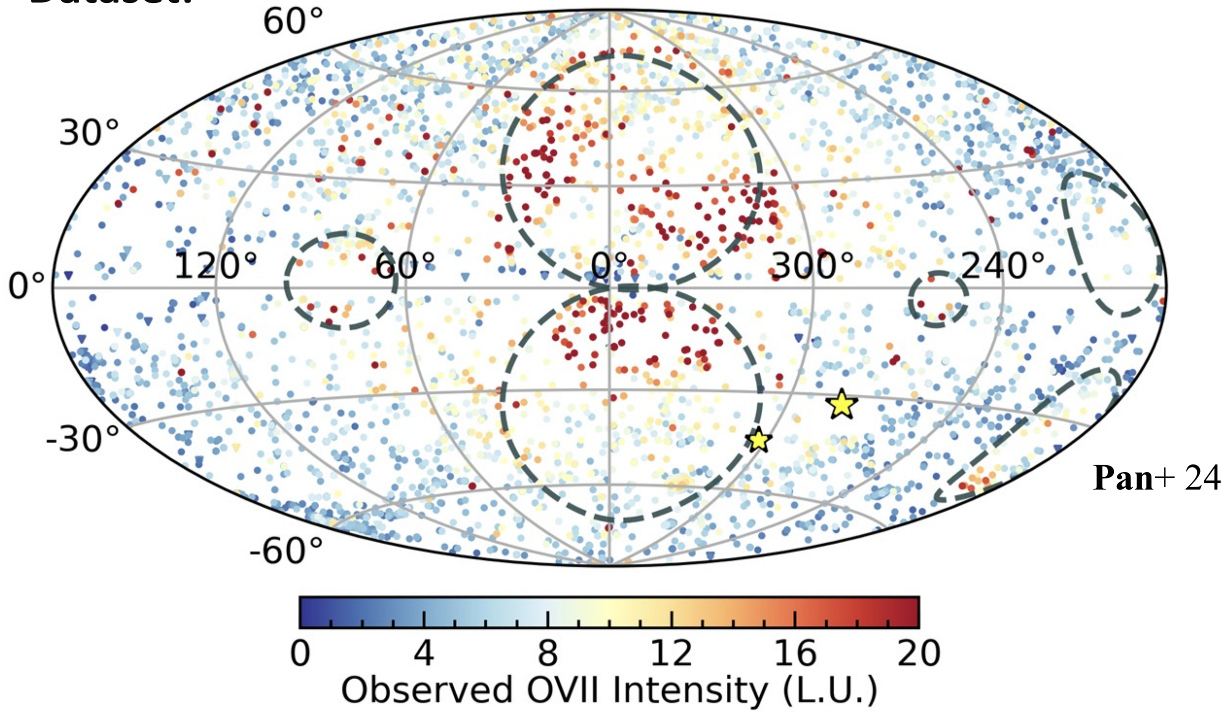
Opportunity – MOS/XMM-NEWTON: 1. > 22 years; 2. deep observations with large FOV.

Goal: To study variations in SWCX & the MW hot gas emission, using all usable MOS/XMM images

Method:

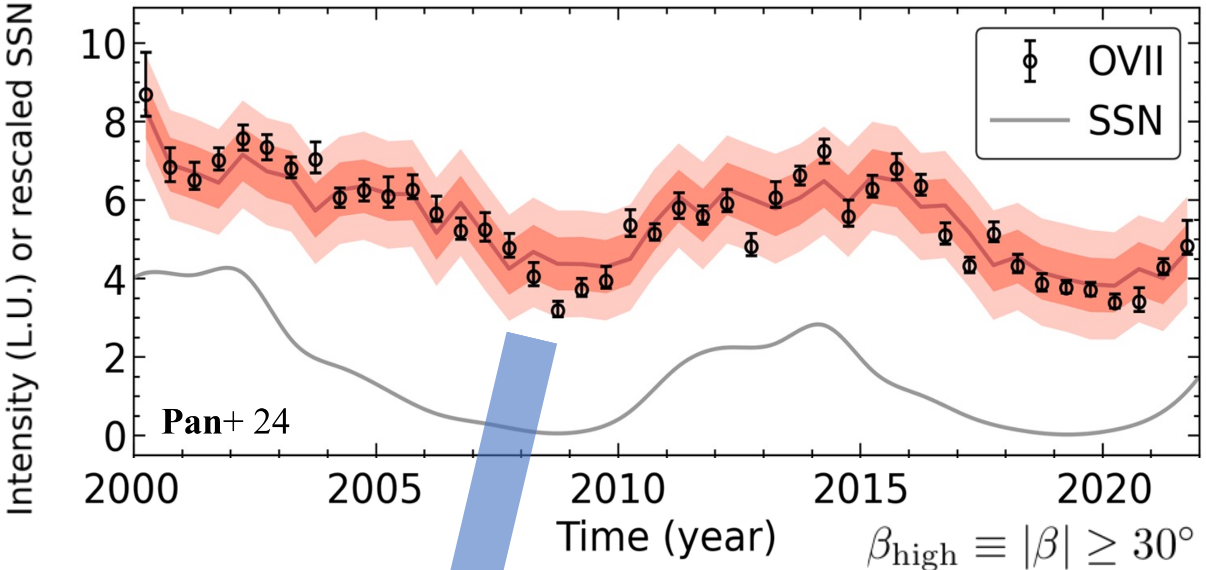


Dataset:

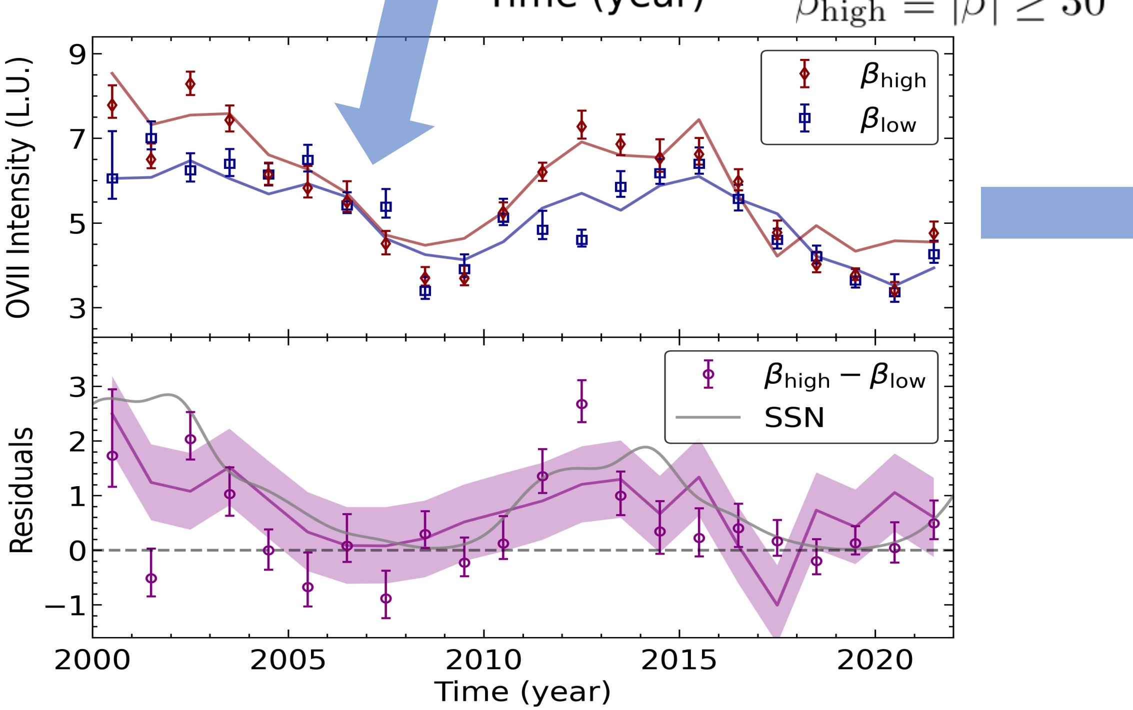


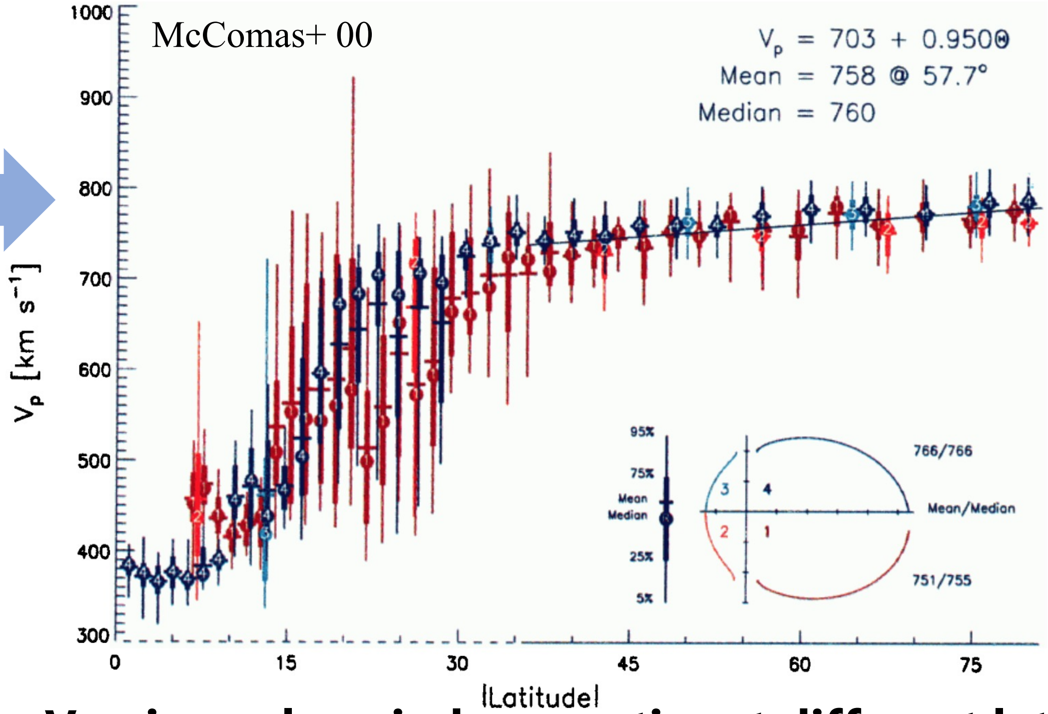
- **5470 measurements (~3% sky)**
- **Largest & machine-readable (X-LEAP I)**
- **Long exposure (~ 20 ks) & Low contaminations**

4.1. Long-Term & Spatial Variations Seen in X-LEAP data



- **Highly correlates with solar activity**
- **Contributes ~30% to the observed intensity in average**
- **Includes both $I_{helio, SWCX}$ and $I_{mag, SWCX}$**





- **O VII intensities are higher at high latitudes**
- **Varying solar wind properties at different latitudes**

4.2.0. SWCX Emission Intensity

The X-ray flux in a given spectral line:

$$I_{\mathrm{SWCX}} = \frac{1}{4\pi}\int_0^s n_M(s)\, n_{X^{q+}}(s)\, V(s)\, \sigma_{M,X^{q+}}(V)\, Y_{X^{q+},j}(V)\, ds$$ (Cravens+ 97)

$$I_{\mathrm{SWCX}} \propto \int_0^s n_M(s)\, n_{X^{q+}}(s)\, V(s)\, ds$$

Assume constant neutral gas density:

$I_{\mathrm{O\,VII,\,SWCX}} \propto n_{O^{7+}} v_{O^{7+}}$ **(O7+ flux) at where the CX happens**

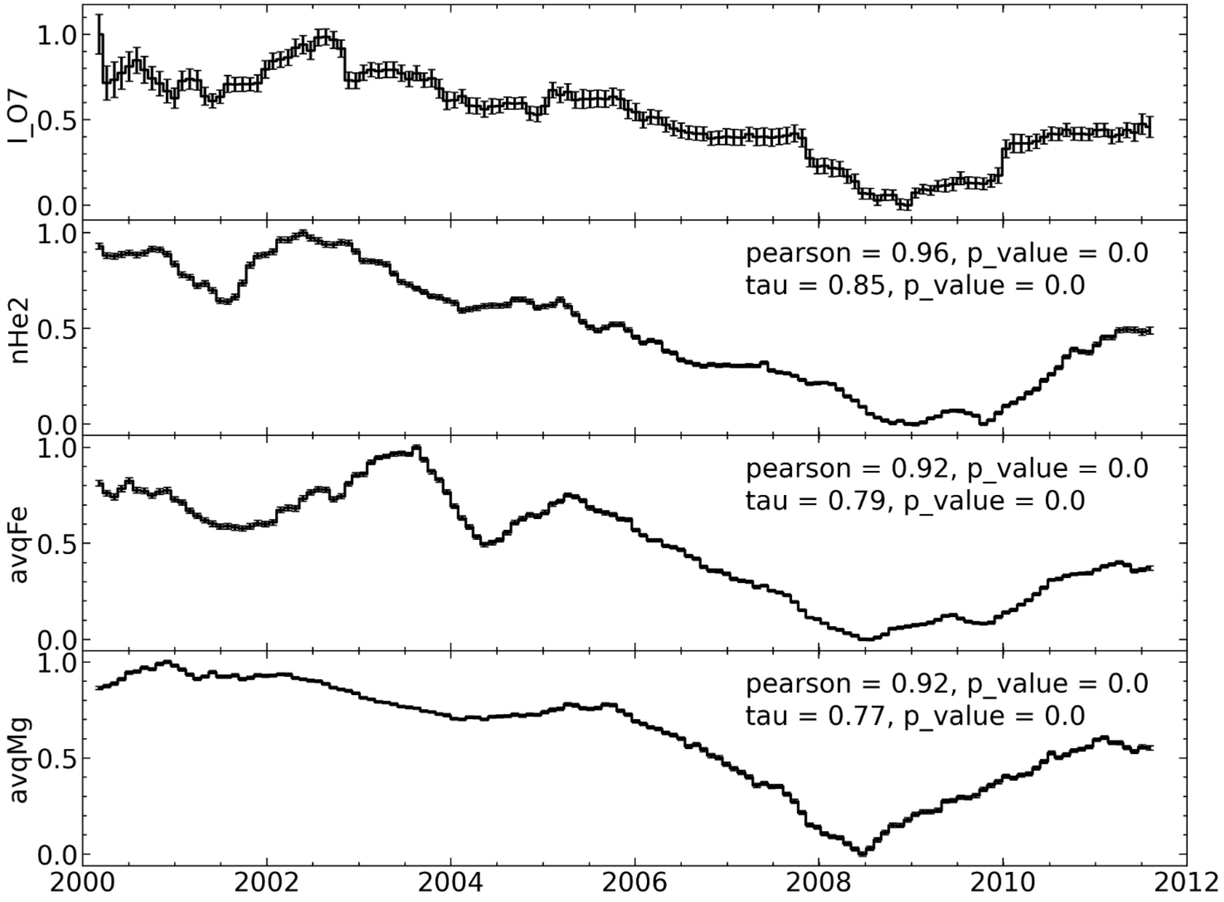
- **mag: exosphere**
- **helio: within heliopause**

SWICS/ACE:

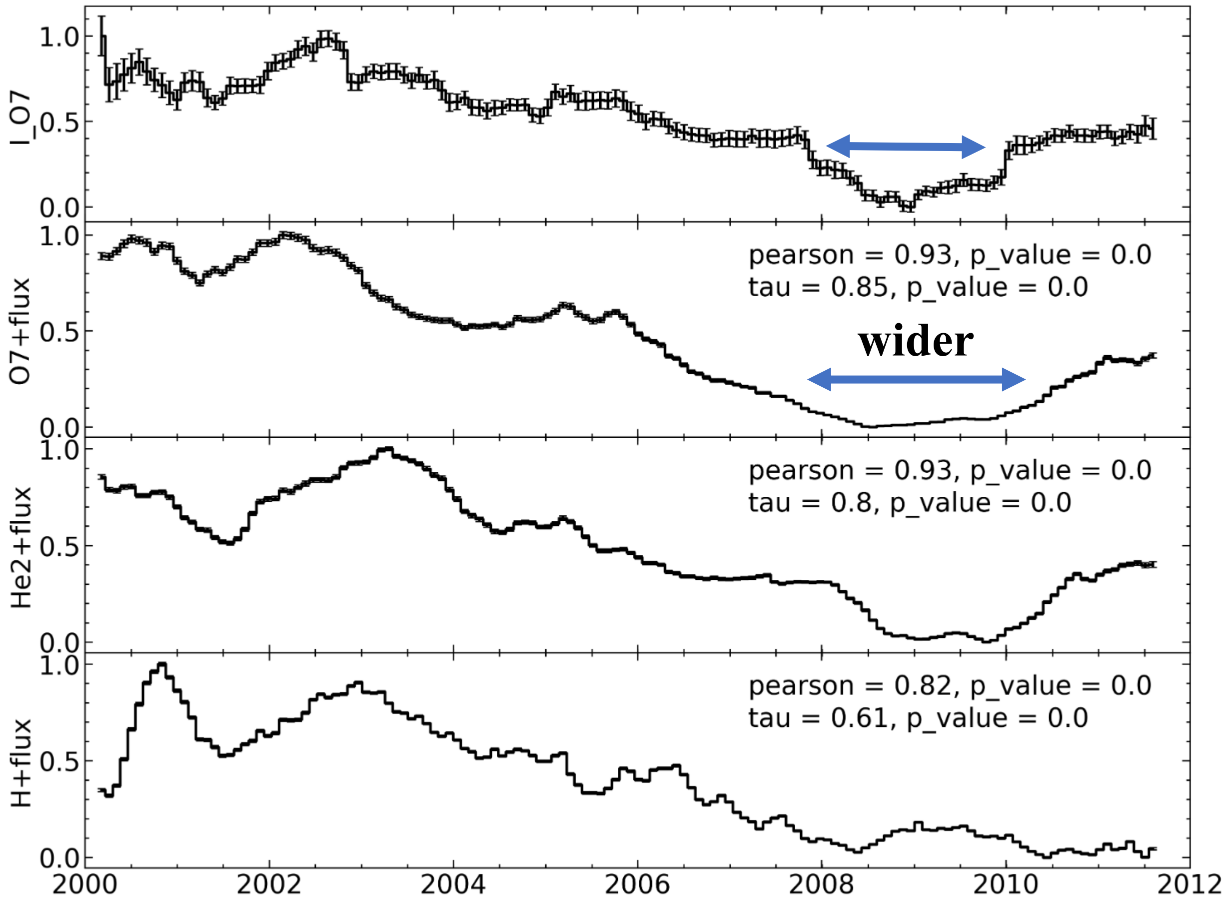
- **Measures SW ion properties at L1 (e.g. vH+, nH+, HetoO, vC5+, etc.)**
- **delay time (τ): ~ 1 h to exosphere; >1 year to heliopause**
- **Less reliable ion data after 2012, except H+ measurements**

4.2. Correlations between Long-term SWCX and SW ion data

smoothed $I_{\mathrm{O\,VII}}$ & ACE parameters



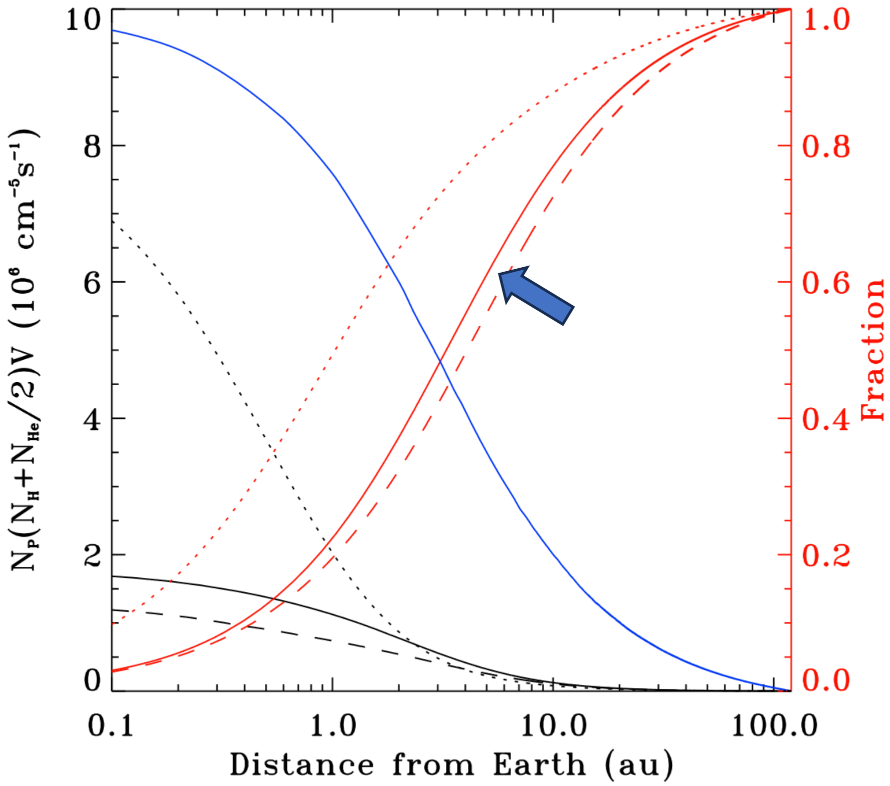
smoothed $I_{\mathrm{O\,VII}}$ & ACE ion flux

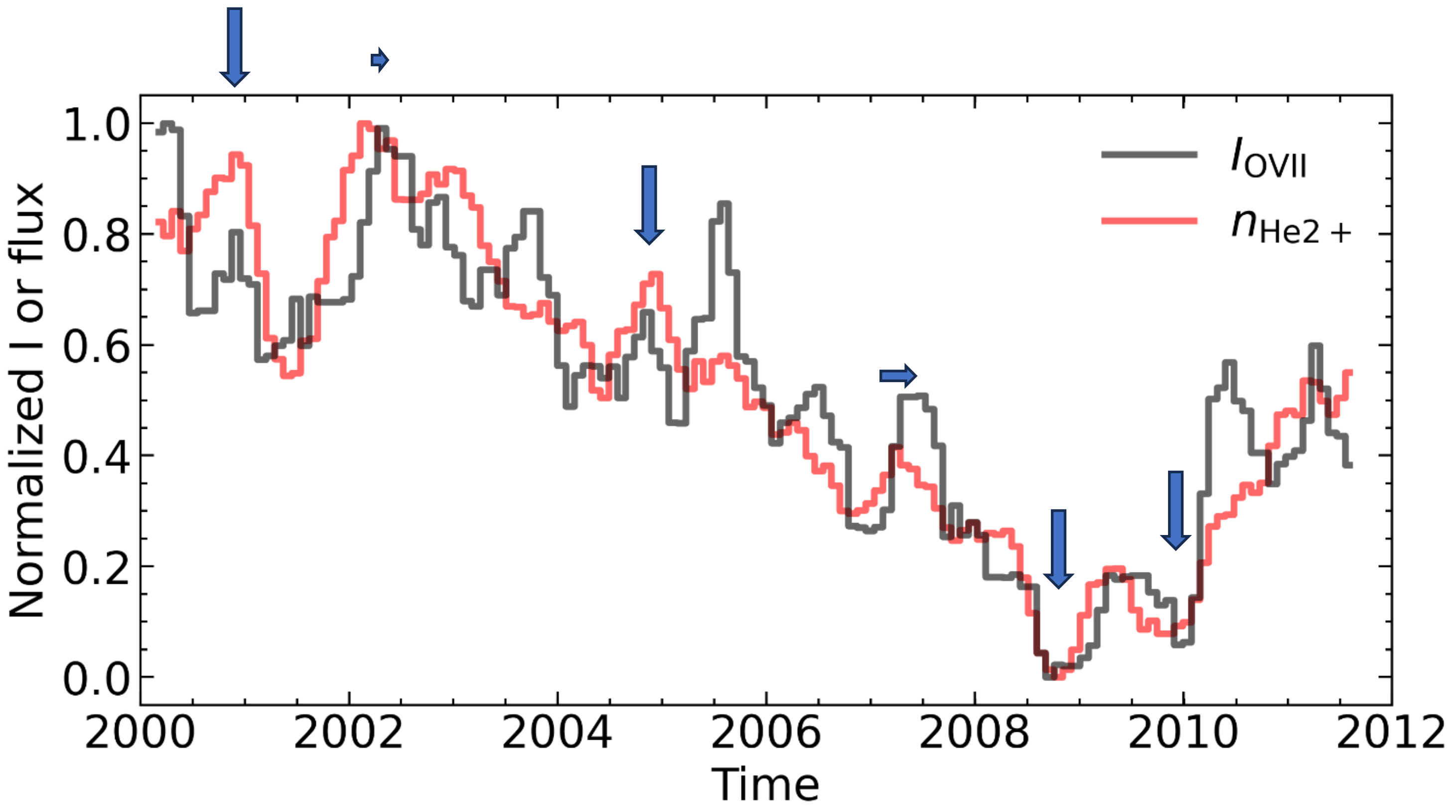


- **Most linearly correlated to He2+ number density**
- **nHe2+ shows stronger correlation than O7+ flux**

4.2. Correlations between Long-term SWCX and SW ion data

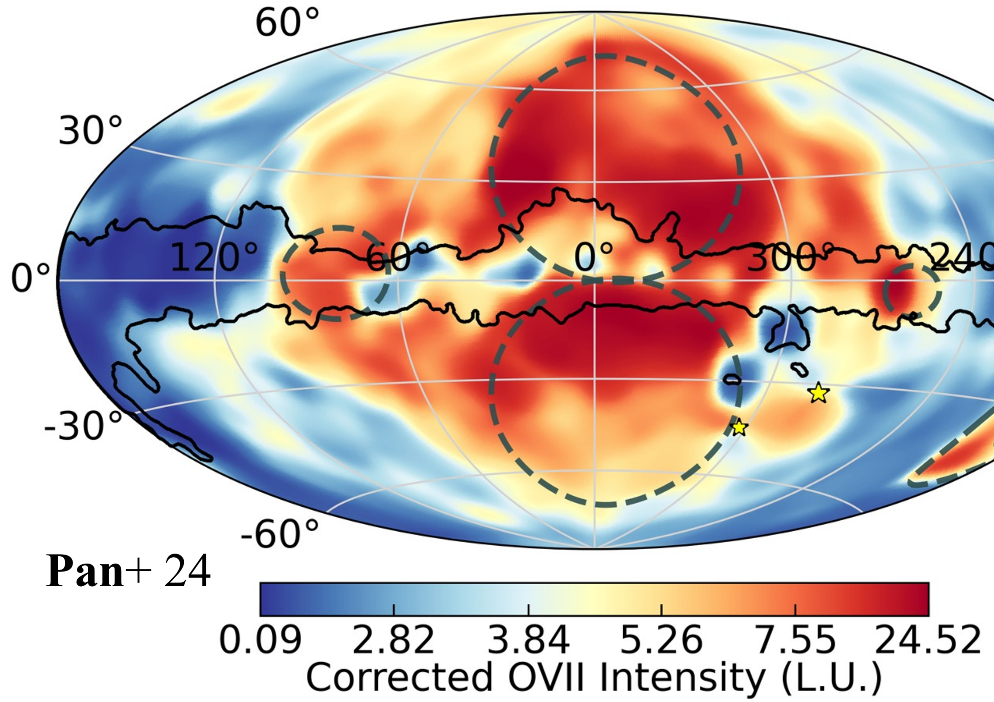
Kuntz 19 (D. Koutroumpa model)



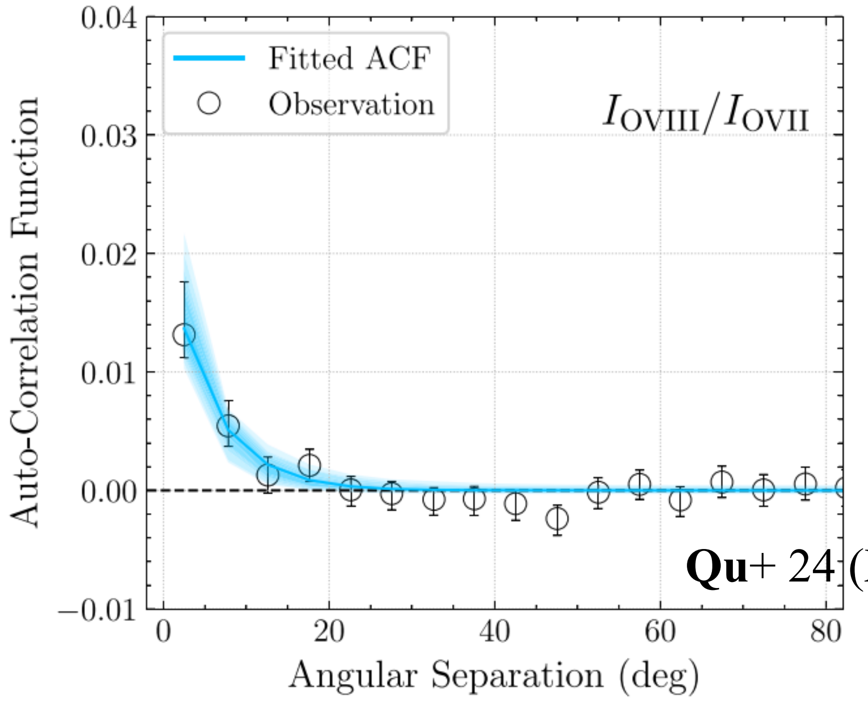


- **Cumulative fraction of SWCX emission (red)**
- **~80% SWCX <20 au; delay time < 3 months**
- **No obvious time-delay between X-ray and ACE data**

4.3.0. Seeing Short-Term Variations after Minimizing MW Contribution



Pan+ 24



Qu+ 24 (X-LEAP II)

- ➢ **MW hot gas emission**
- ➢ $I_{\rm obs.\,O\,VII}$ **vs. O7+flux ($t - 1$ h) ?**

- ➢ **MW emission < 2°** **are considered negligible**
  (Kaaret+ 20; Qu+ 24)

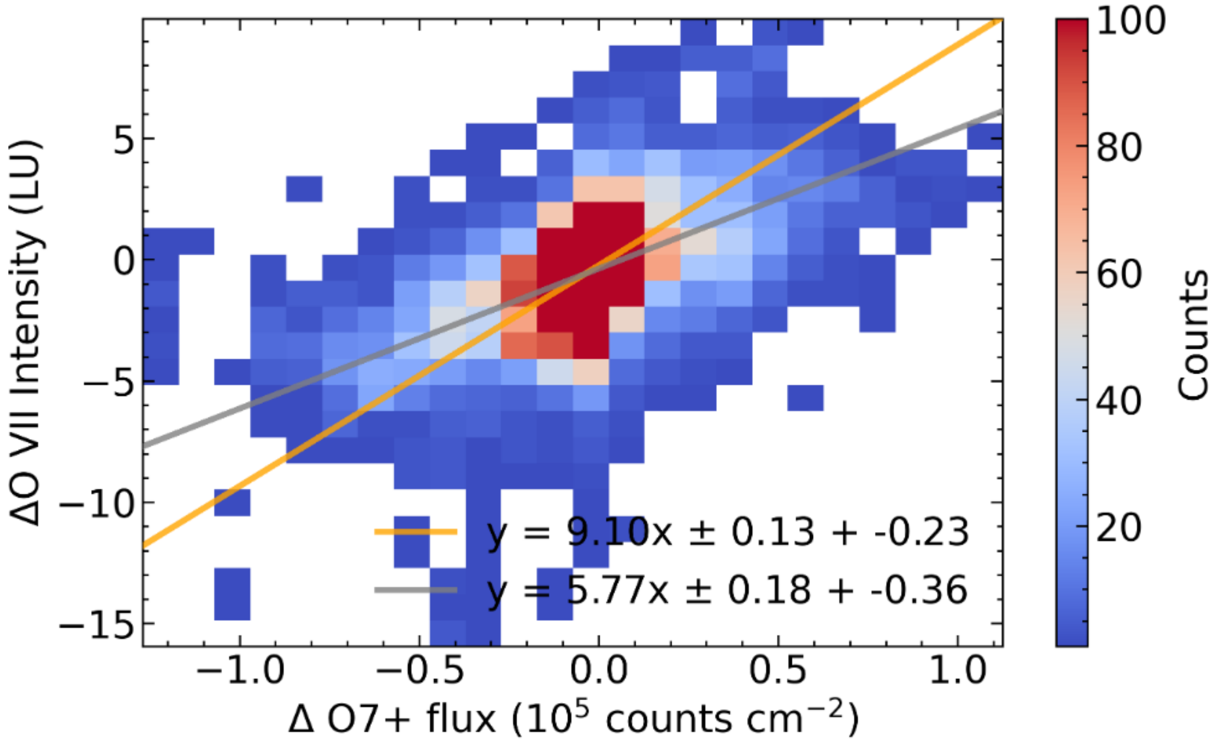
Remove MW emission:

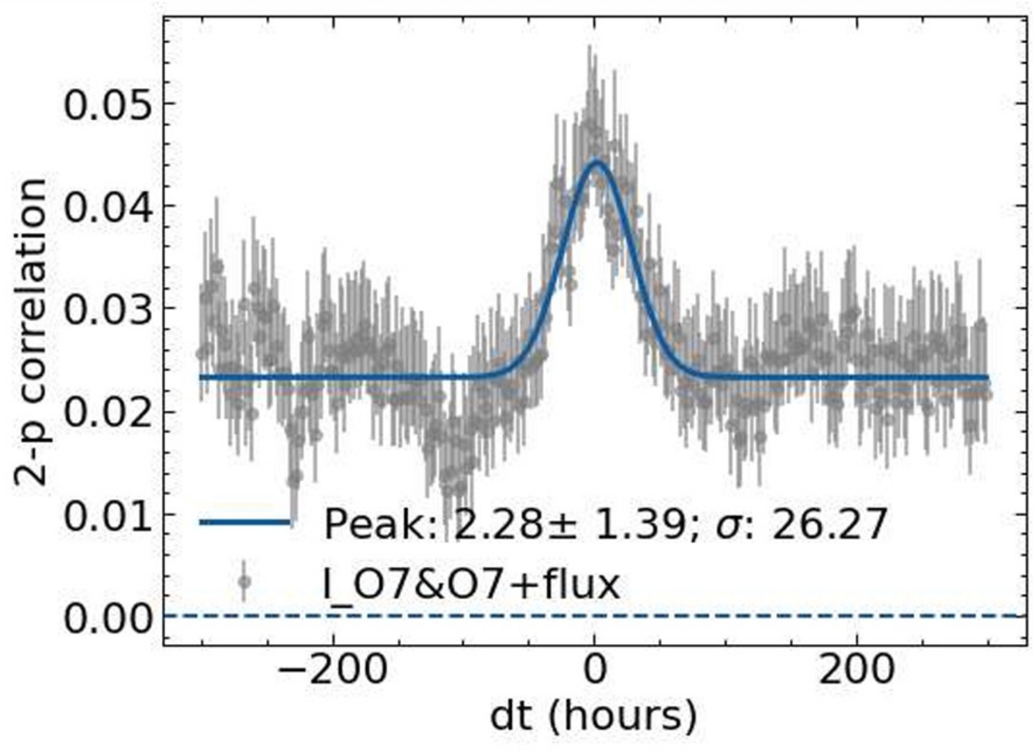
➢ **Intensity differences in observational pairs < 2°**

$$\Delta I_{\rm obs,\,O\,VII}(t1, t2) \begin{cases} A * \Delta\, \text{Flux}\,(t1 - \tau_{mag};\, t2 - \tau_{mag}) & \text{differences in mag SWCX} \\ B * \Delta\, \text{smoothed Flux}\,(t1 - \tau_{helio};\, t2 - \tau_{helio}) & \text{differences in helio SWCX} \end{cases}$$

4.3. Short-Term Variation Seen in X-LEAP data

$$\Delta I_{\text{obs, O VII}}(t1, t2) \begin{cases} A * \Delta \text{Flux } (t1 - 1\text{ h}; t2 - 1\text{h}) & \text{differences in mag SWCX} \\ B * \Delta \text{ smoothed Flux } (t1 - \tau_{\text{helio}}; t2 - \tau_{\text{helio}}) & \text{differences in helio SWCX} \end{cases}$$



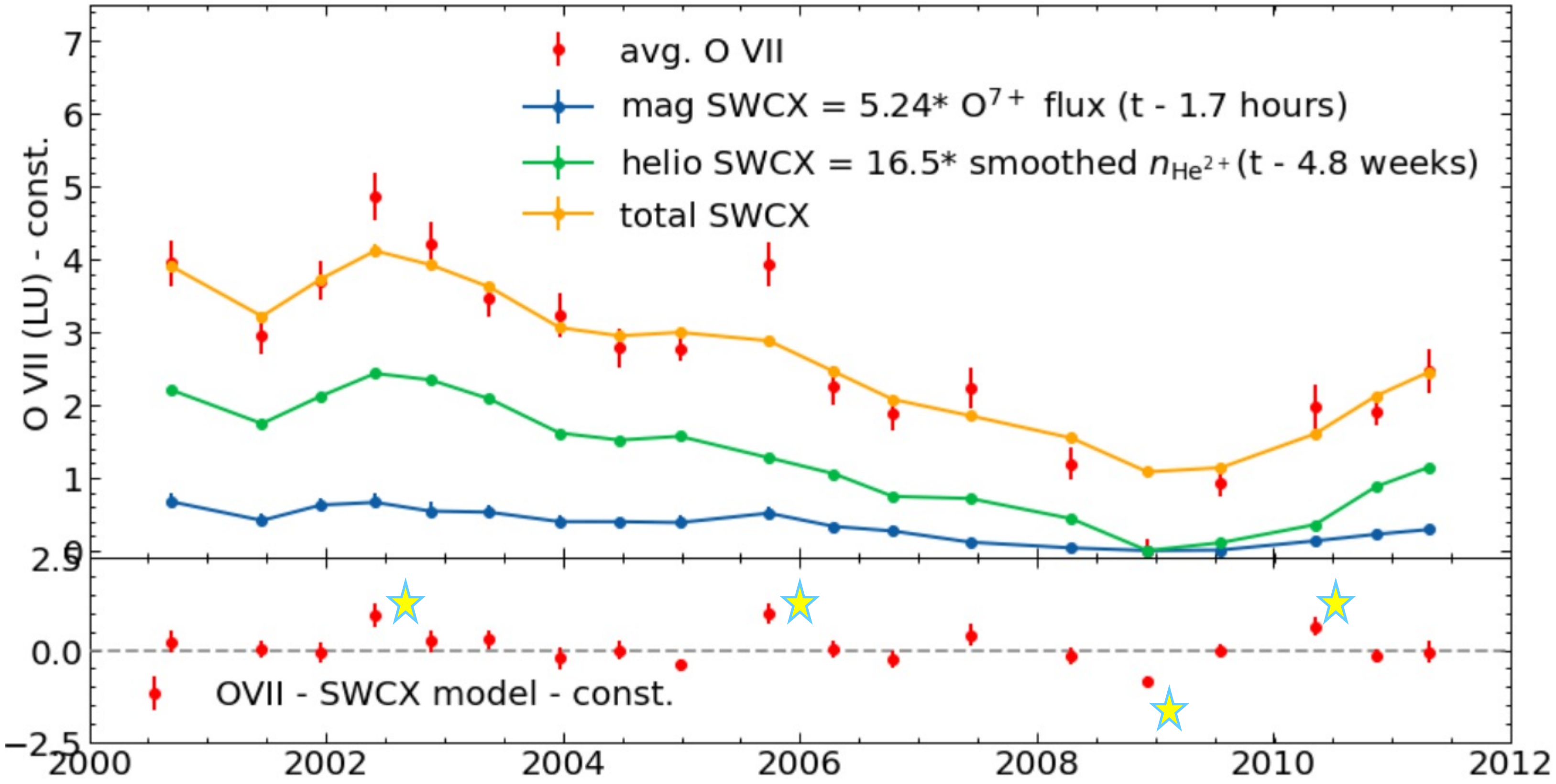


- ➢ **Linear correlation between X-ray and O7+ flux differences**
- ➢ **Residuals**
- ➢ **delay time ~ 2 hours from CCF; expected > 1h**
- ➢ **2h interval?**

5. An Empirical Model to Estimate SWCX Emissions (Before 2012)

Mag SWCX **Helio SWCX** **MW**

$$I_{\text{obs, O VII}}(t) = A * O^{7+}(t - \tau_{\text{mag}}) + B * n_{He^{2+}}(t - \tau_{\text{helio}}; \sigma = 6\text{ m}) + \text{Const.}$$



- **An estimation of the SWCX strength at certain *t***

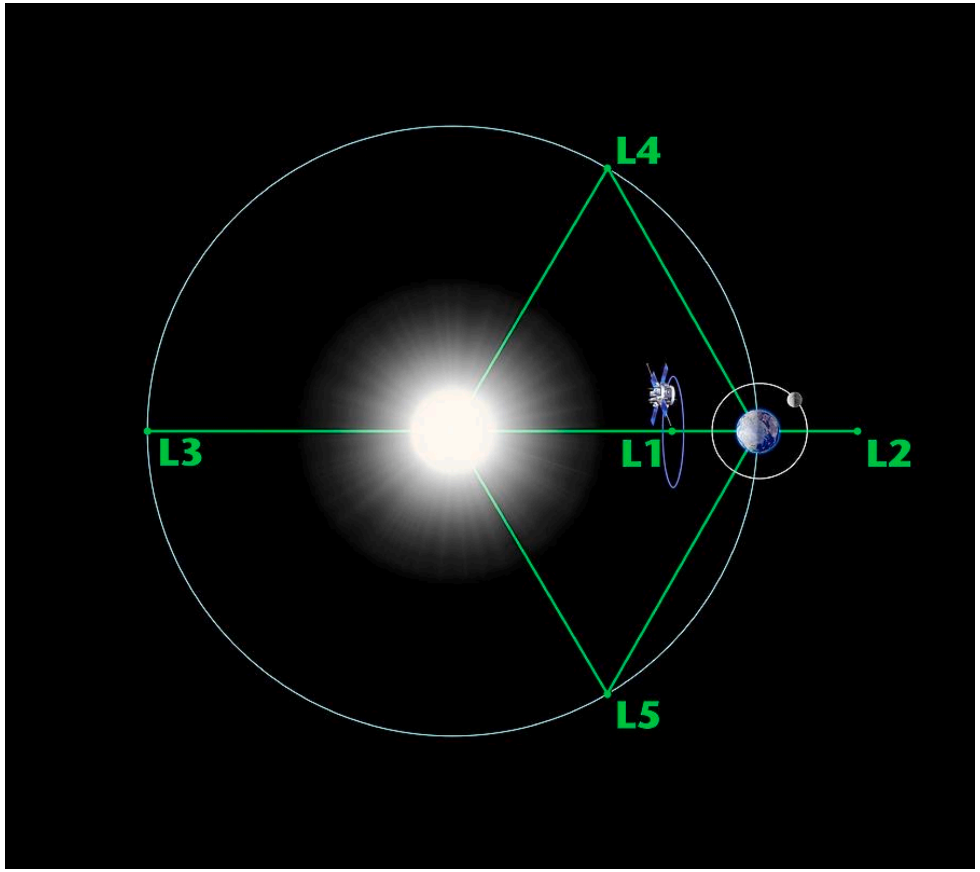
Future Improvements:

- **Spatial variations (SW ion and neutral gas distributions across latitudes)**
- $\sigma_{H,\, O^{7+}}(V)$

Thank you ☺

Supplementary Materials

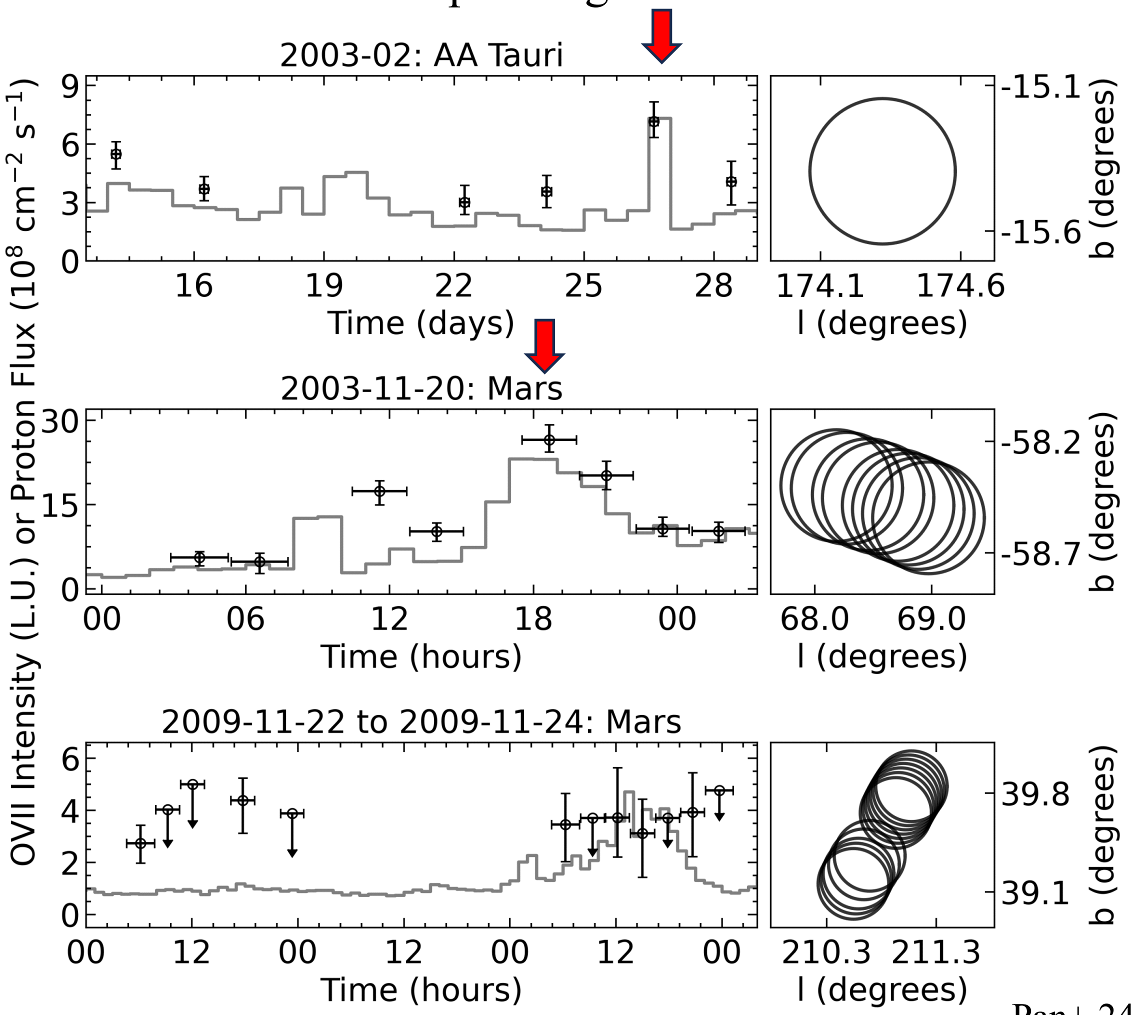
SWICS/ACE



SWICS:

- **Installed on ACE satellite**
- **Measures SW ion properties at L1 (e.g. H+ flux)**

Observation sets pointing at same directions



Pan+ 24

- **O VII line intensity increases with proton flux**
- **Evidence of short-term variations due to $I_{\mathrm{mag,\,SWCX}}$**

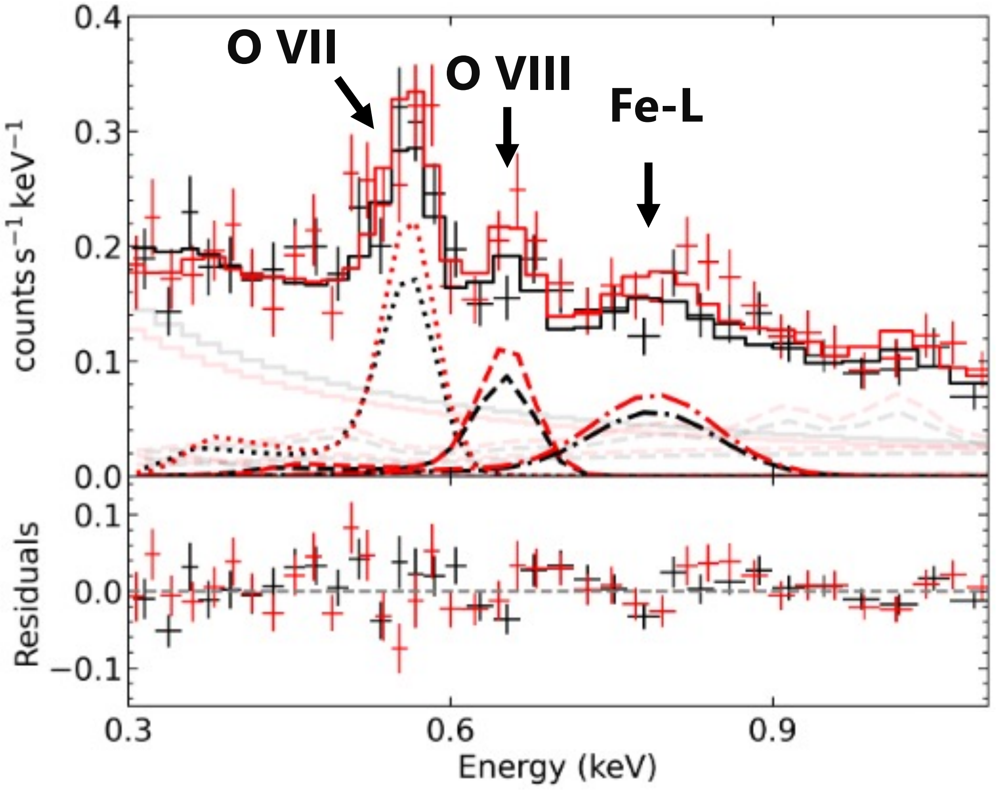
三. The XMM-Newton Line Emission Analysis Program (X-LEAP)

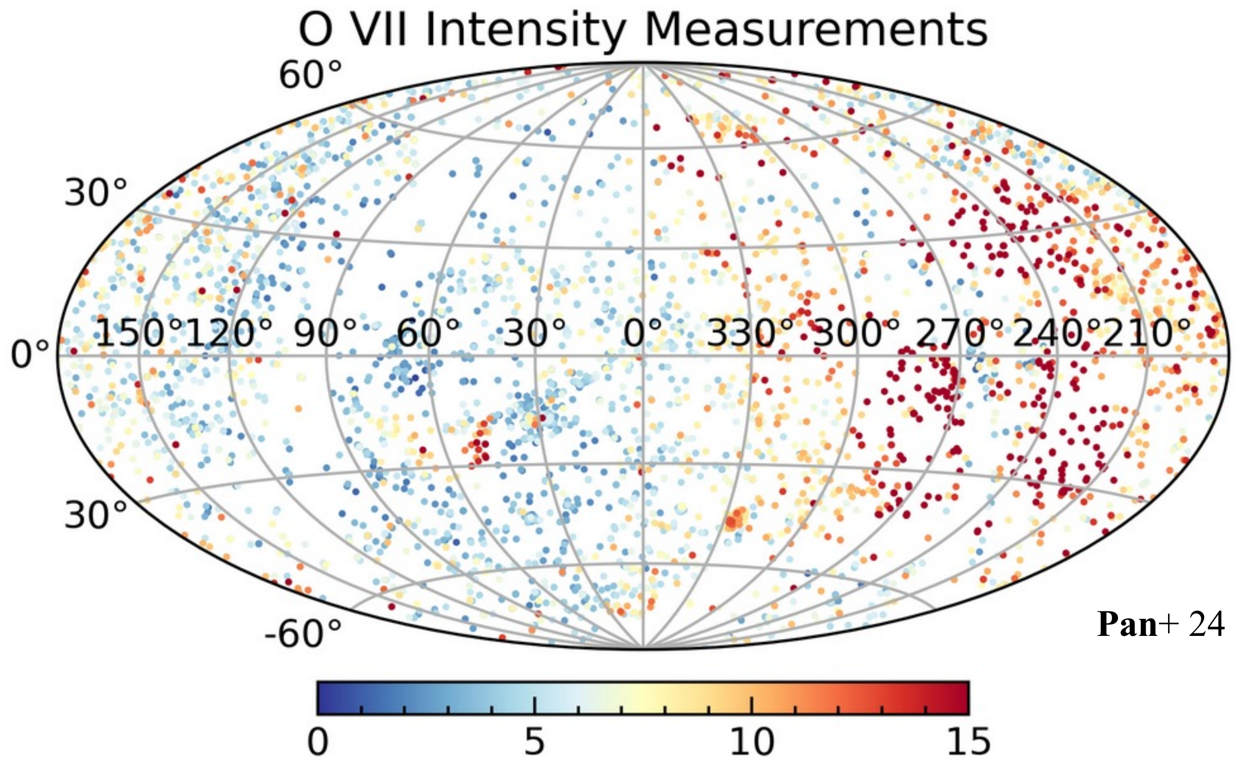
Need: requires extensive, long-term soft X-ray line emission data

XMM-NEWTON X-ray Telescope: 1. deep observations with large FOV; 2. > 22 years

Goal: To study the short/long-term & spatial variations in SWCX using all usable MOS images

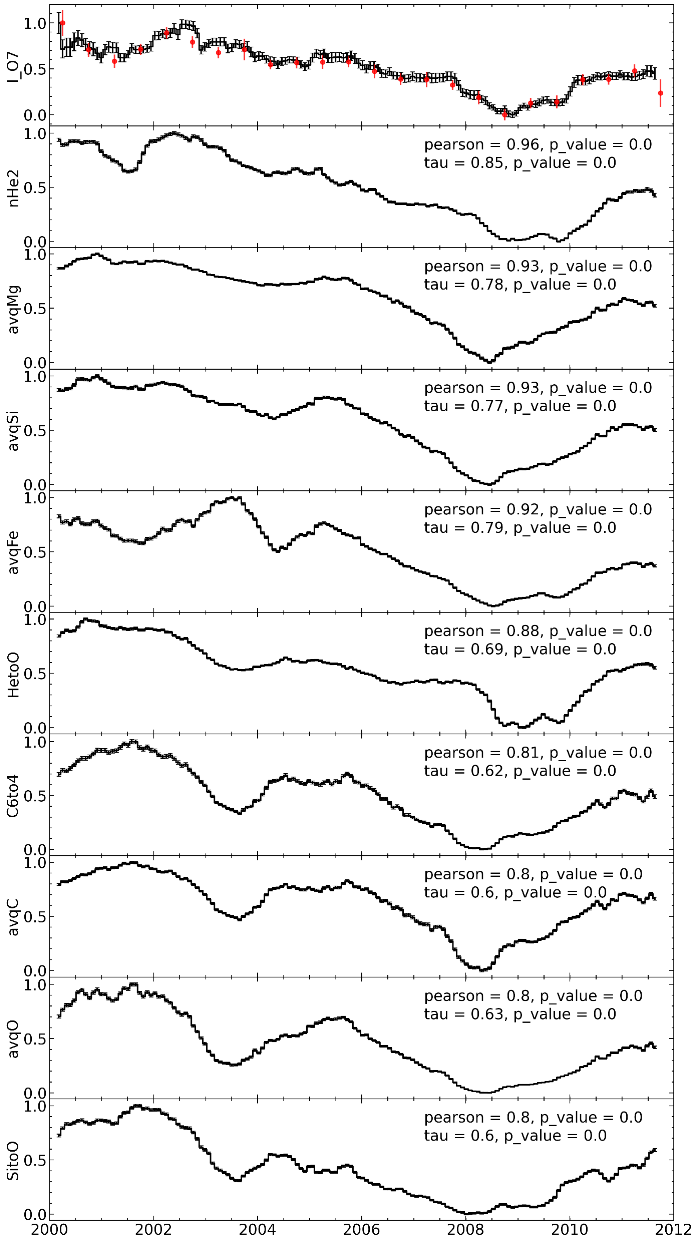
Method:





- **5418 measurements (~3% sky)**
- **Long exposure (~ 20 ks) & Low contaminations**
- **Machine-readable**

Supplementary Materials

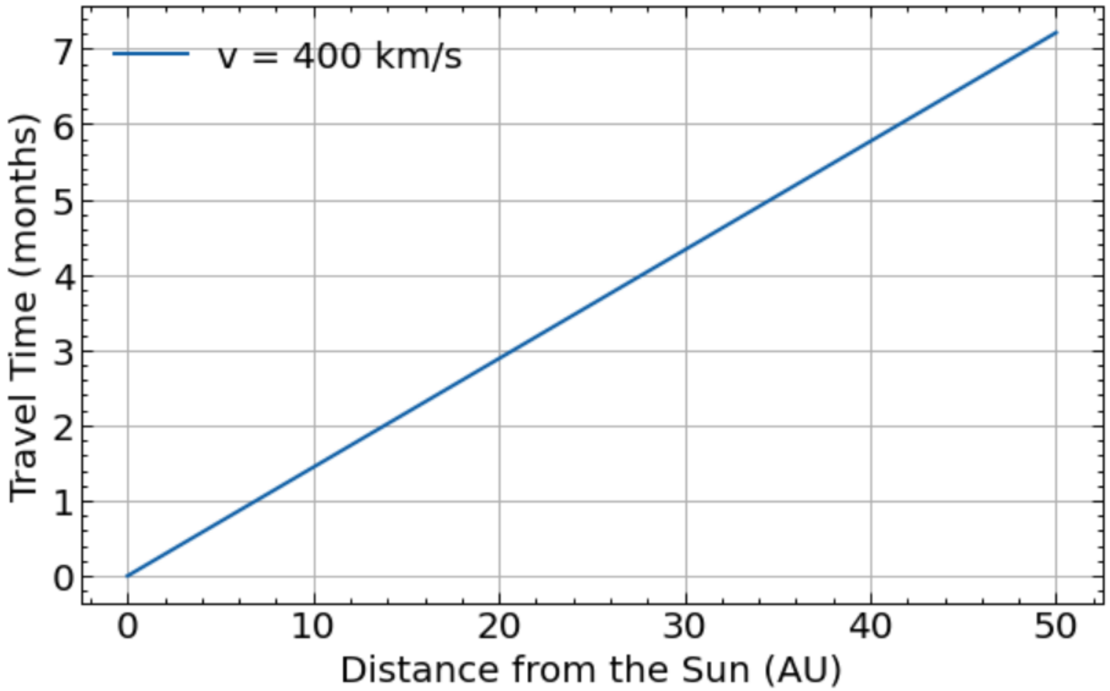


Supplementary Materials

ACE SWICS 1.1 Data			
12 min	**1-hour**	**2-hour**	**1-day**
vH+ (aux)	Year	Year	Year
nH+ (aux)	DOY fraction	DOY fraction	DOY fraction
vthH+ (aux)	nHe2+	nHe2+	nHe2+
He+ dist func (G.G. - main channel)	vHe2+	vHe2+	vHe2+
	vthHe2+	vthHe2+	vthHe2+
	vC5+	vC5+	vC5+
	vthC5+	vthC5+	vthC5+
	vO6+	vO6+	vO6+
	vthO6+	vthO6+	vthO6+
	vFe10+	vFe10+	vFe10+
	vthFe10+	vthFe10+	vthFe10+
	C6/C4	C6/C4	C6/C4
	C6/C5	C6/C5	C6/C5
	O7/O6	O7/O6	O7/O6
		He(2)/O(5-8)	He(2)/O(5-8)
		C(4-6)/O(5-8)	C(4-6)/O(5-8)
			N(5-6)/O(5-8)
		Ne(8-9)/O(5-8)	Ne(8-9)/O(5-8)
		Mg(6-12)/O(5-8)	Mg(6-12)/O(5-8)
		Si(6-12)/O(5-8)	Si(6-12)/O(5-8)
			S(6-14)/O(5-8)
	Fe(6-20)/O(5-8)	Fe(6-20)/O(5-8)	Fe(6-20)/O(5-8)
	<Q>C(4-6)	<Q>C(4-6)	<Q>C(4-6)
	<Q>O(5-8)	<Q>O(5-8)	<Q>O(5-8)
	<Q>Mg(6-12)	<Q>Mg(6-12)	<Q>Mg(6-12)
	<Q>Si(6-12)	<Q>Si(6-12)	<Q>Si(6-12)

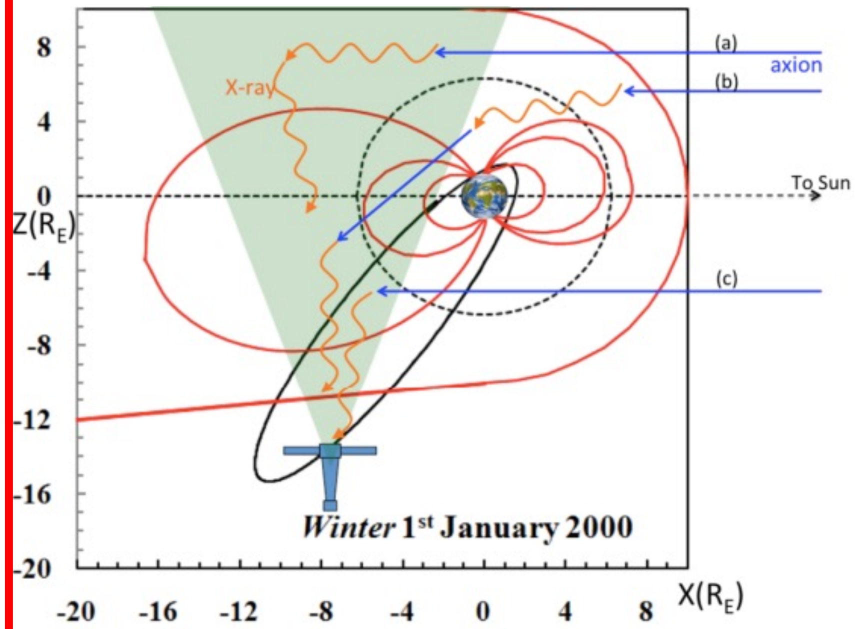
$$F_{O^{7+}} = n_{He} v_{He} \frac{n_O}{n_{He}} \frac{n_{O^{7+}}}{n_O}$$

$$\text{smoothed } f(t, \sigma = 6\text{ m}) = \text{np.median}\,(f[t - \sigma, t + \sigma])$$

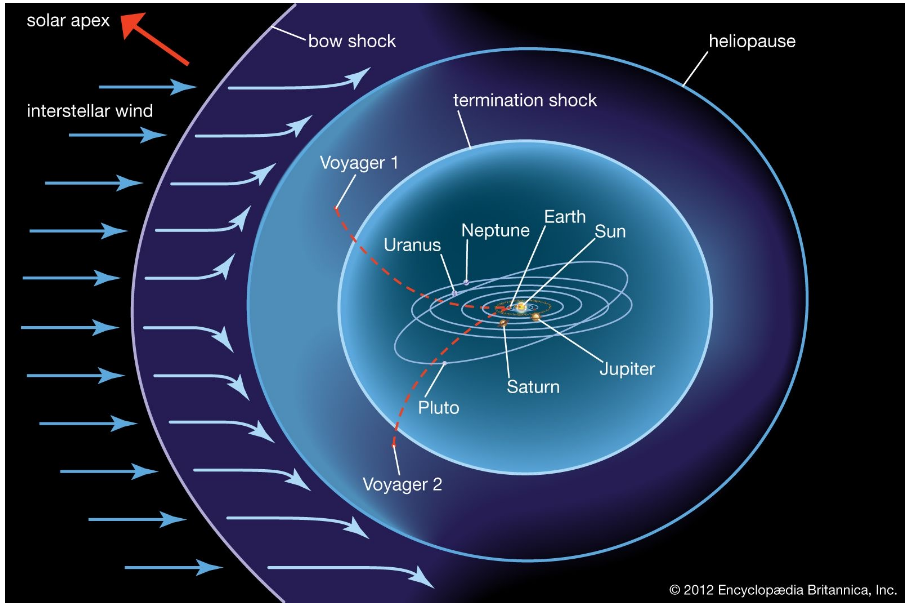


Supplementary Materials

Earth's Outer Atmosphere (I_{mag})



Heliosphere (I_{helio})

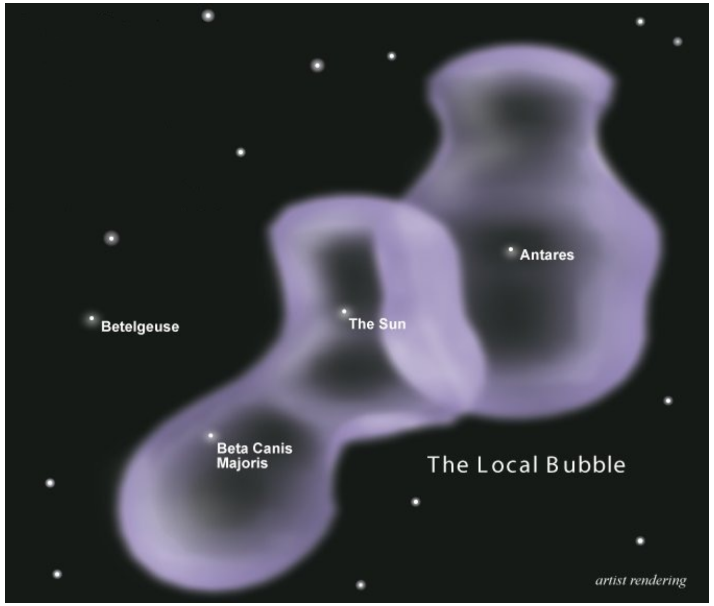


Solar wind ions can capture electrons from neutral atoms, producing X-ray photons (**SWCX**).

e.g.

$$O^{+7} + H \rightarrow O^{+6*} + H^{+}$$
$$\rightarrow O^{+6} + H^{+} + h\nu$$

Local Hot Bubble (I_{LHB})



$T \sim 10^{6}$ K

$n_e = 4 \times 10^{-3}$ cm^{-3}

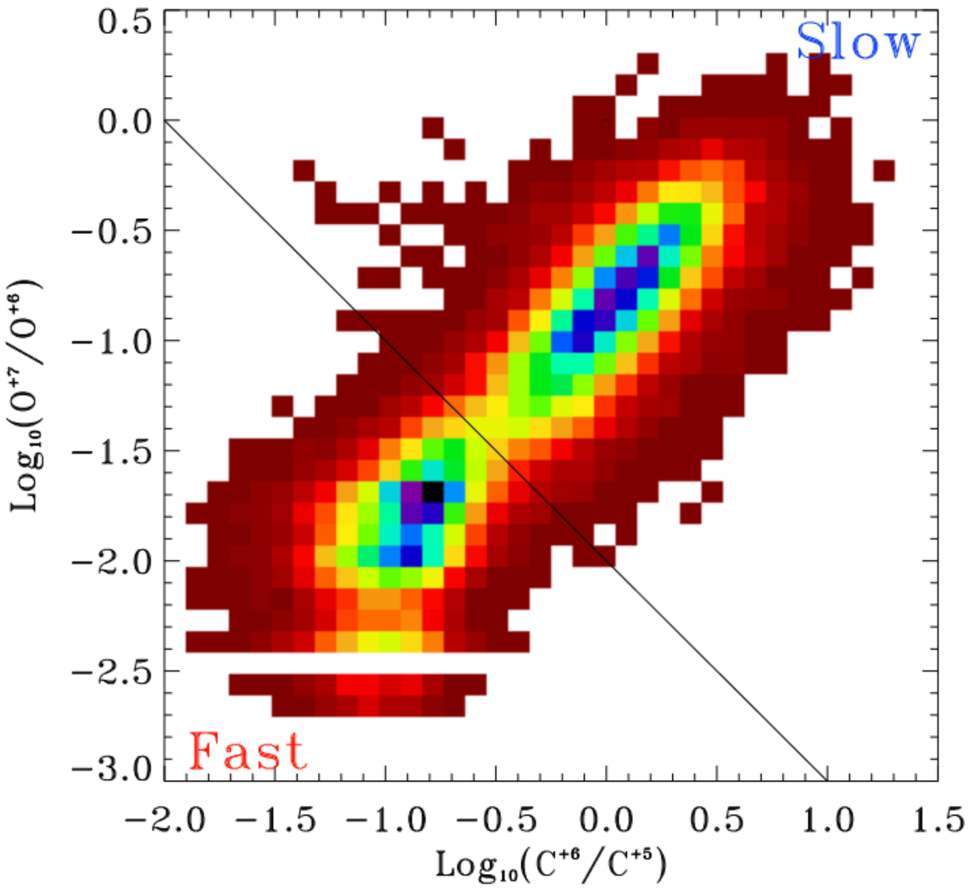
(e.g., Liu+ 16; Yeung+ 23)

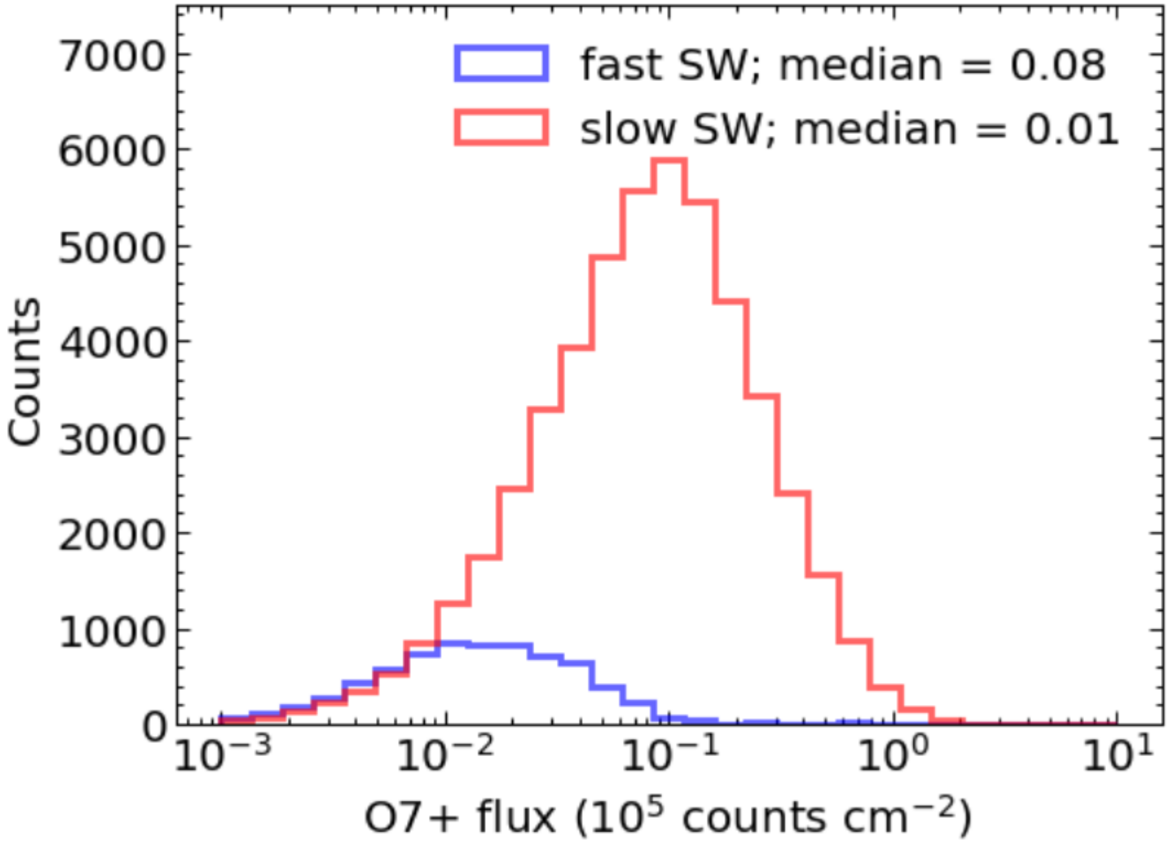
Collisional excitation

→ Recombination

Supplementary Materials

Ulysses Spacecraft (1990-2009)
SWICS/Ulysses





Kuntz 2019