Hybrid-Vlasov simulation of soft X-ray emissions at the Earth's dayside magnetospheric boundaries

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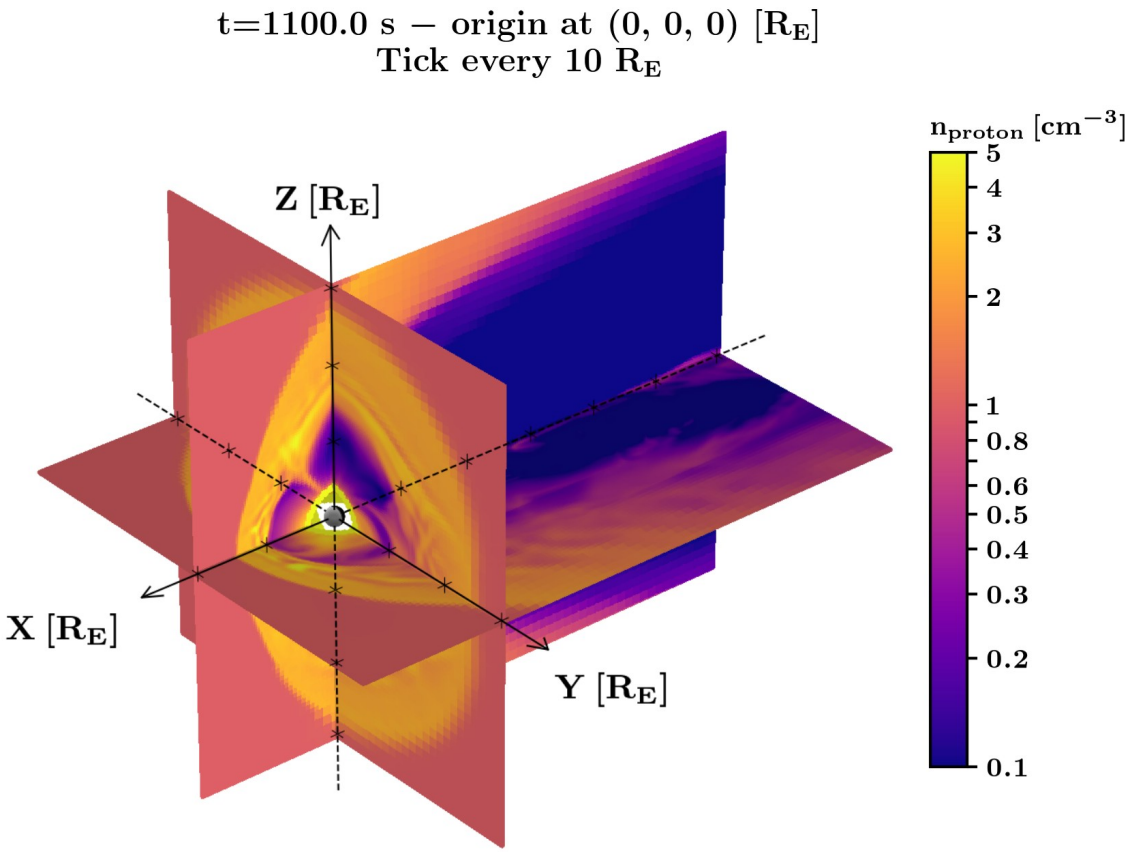
Motivation

Two upcoming satellite missions will observe the Earth's plasma environment with soft X-ray imagers:

- SMILE (ESA–CAS)
- LEXI (NASA/Boston University)

Since no global images of near-Earth space exist yet, **numerical simulations** are needed to predict the expected science enabled by those missions

Vlasiator 6D run



- **Vlasiator:** Global hybrid-Vlasov model of near-Earth space
  - Some kinetic processes (e.g. waves) can be studied
- Driving conditions (uniform & constant):
  - Southward IMF, 5 nT
  - $V_{SW} = 750$ km/s, $n_{SW} = 1$ cm^{-3}, $T_{SW} = 500$ kK
- Spatial resolution: 8000 to 1000 km
- Key papers:
  - Palmroth et al. (2018)
  - Ganse et al. (2023)

Soft X-ray emissivity calculation

At a given time in the simulation, the local soft X-ray emissivity due to solar wind charge exchange is calculated [in eV cm^{-3} s^{-1} sr^{-1}] by

$$Q_{\mathrm{loc}}(\mathbf{r}) = \frac{\alpha_X}{4\pi} n_{\mathrm{p}}(\mathbf{r}) n_{\mathrm{H}}(\mathbf{r}) V_{\mathrm{eff}}(\mathbf{r})$$

- α_X: Interaction efficiency factor [10^{-15} eV cm^{-2}]
- $n_{\mathrm{p}}(\mathbf{r})$: Proton density [cm^{-3}]
- $n_{\mathrm{H}}(\mathbf{r})$: Neutral density [cm^{-3}]
- $V_{\mathrm{eff}}(\mathbf{r})$: Effective velocity [cm/s]

$$n_{\mathrm{H}}(\mathbf{r}) = 25 \left(\frac{10\, R_{\mathrm{E}}}{r} \right)^3$$

- r: Distance to Earth centre [R_{E}]

$$V_{\mathrm{eff}}(\mathbf{r}) = \sqrt{V_{\mathrm{p}}(\mathbf{r})^2 + \frac{5}{3} \frac{k_B T(\mathbf{r})}{m_{\mathrm{p}}}}$$

- $V_{\mathrm{p}}(\mathbf{r})$: Proton bulk velocity [m/s]
- $T(\mathbf{r})$: Proton temperature [K]

Soft X-ray image generation

- We use two virtual imaging spacecraft providing two different views on the dayside magnetosheath and cusps
  - dawnside view (analogous to LEXI): (0, −30 R_E, 0)
  - polar view (analogous to SMILE): (0, 0, 30 R_E)
- For each local azimuth–elevation pair (image pixel) every 0.33°, we integrate the line-of-sight soft X-ray emissions from the spacecraft until the backwall of the simulation domain

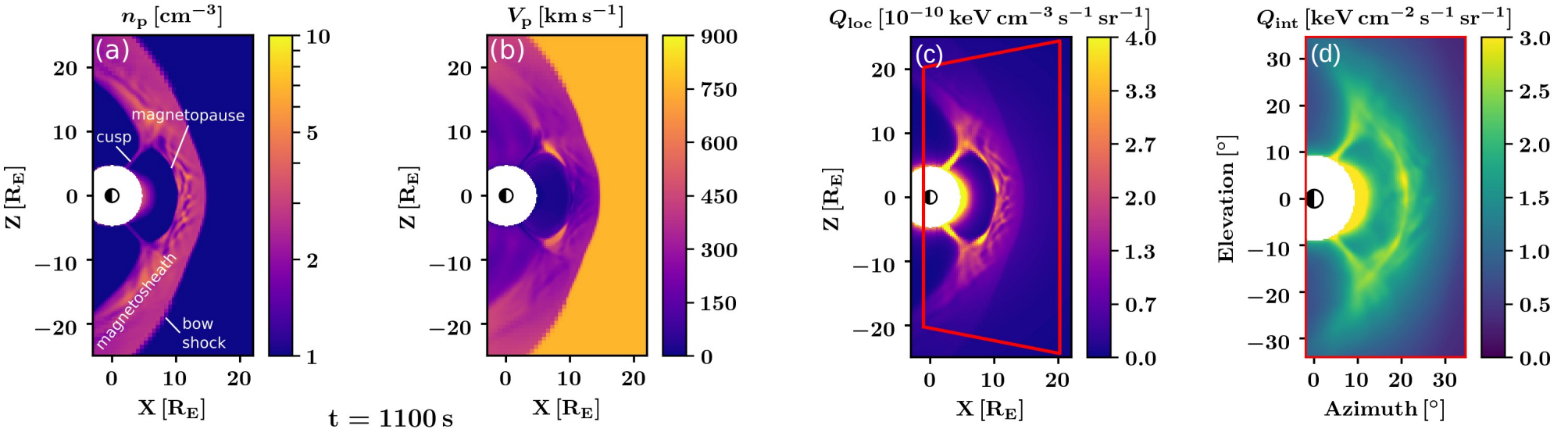
$$Q_{\mathrm{int}}(\varphi, \lambda) = \int Q_{\mathrm{loc}}(l_{\varphi,\lambda})\, \mathrm{d}l_{\varphi,\lambda}$$

- We express Q_{loc} in keV cm^{-3} s^{-1} sr^{-1} and Q_{int} in keV cm^{-2} s^{-1} sr^{-1}

“Instantaneous” soft X-ray images: from dawn

In-plane variables ($Y = 0$)

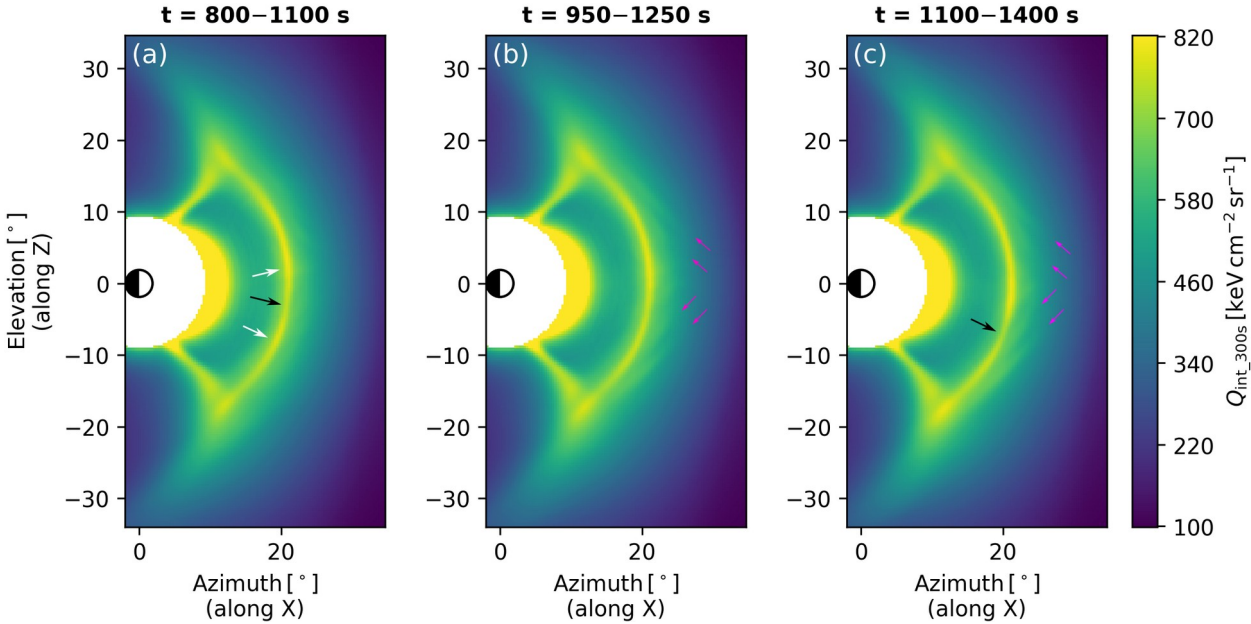
Line-of-sight integrated



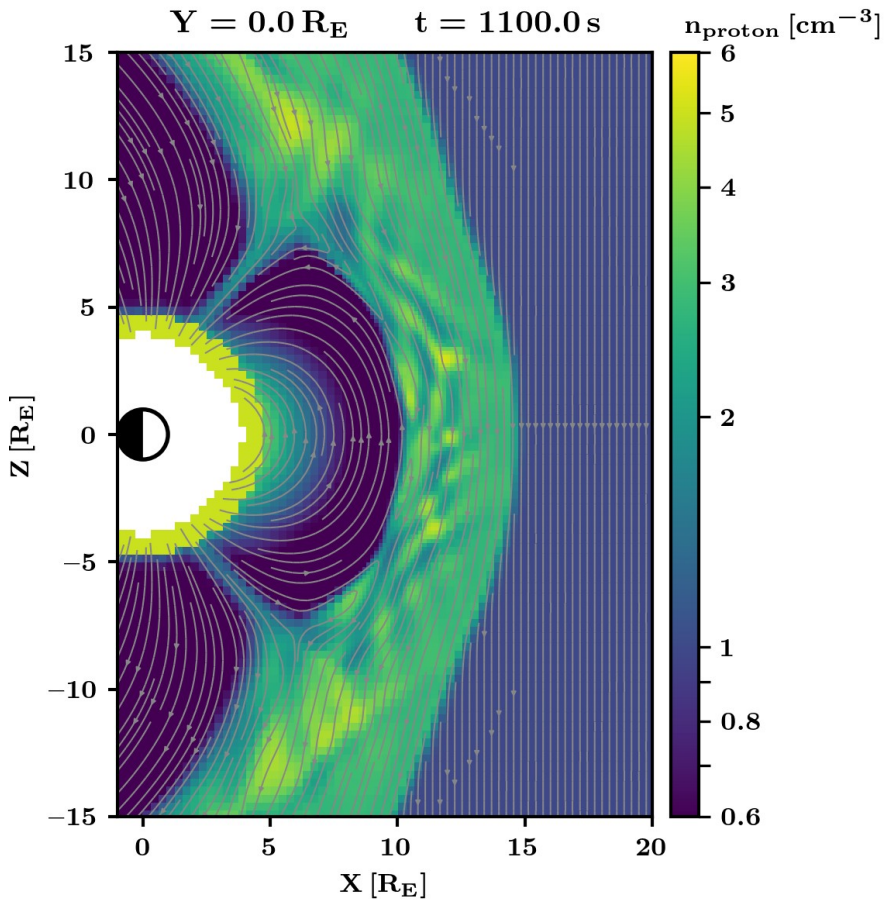
$$Q_{\mathrm{loc}}(\mathbf{r}) = \frac{\alpha_X}{4\pi} n_{\mathrm{p}}(\mathbf{r}) n_{\mathrm{H}}(\mathbf{r}) V_{\mathrm{eff}}(\mathbf{r}) \qquad Q_{\mathrm{int}}(\varphi, \lambda) = \int Q_{\mathrm{loc}}(l_{\varphi,\lambda})\, \mathrm{d}l_{\varphi,\lambda}$$

Time-integrated images: from dawn

- 300 s integration to reflect expected instrument capability
- Three time intervals considered in the simulation
- Brightness differences at the magnetopause, and faint oblique structures in the magnetosheath

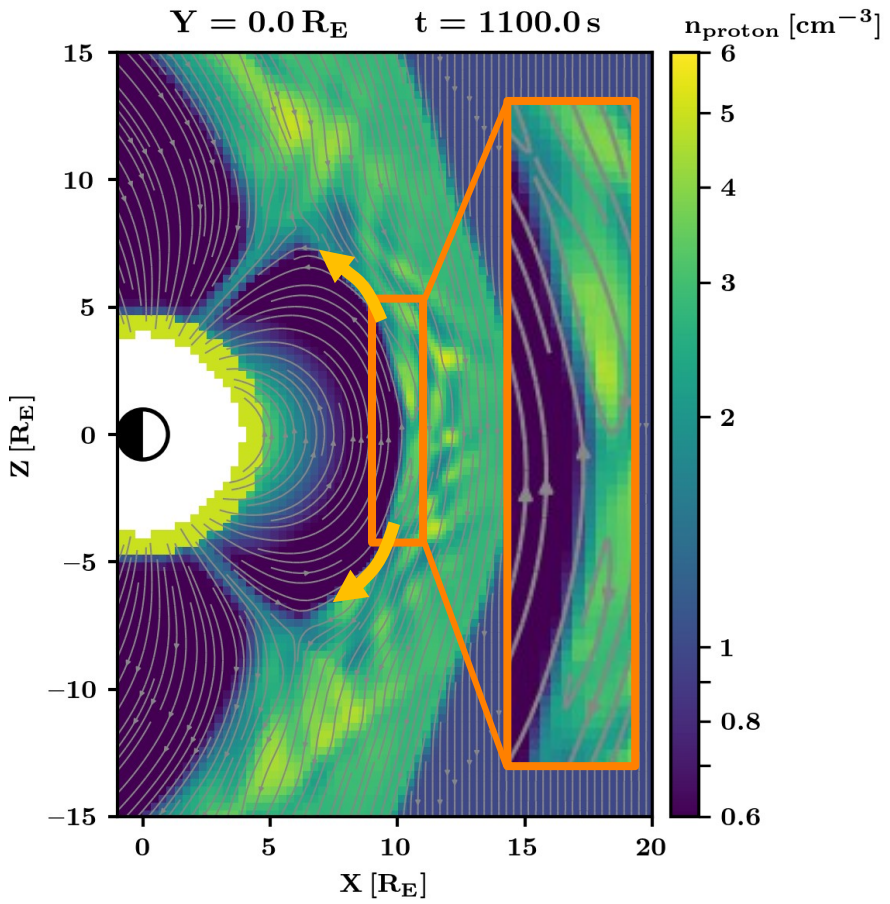


Signatures of transient processes?



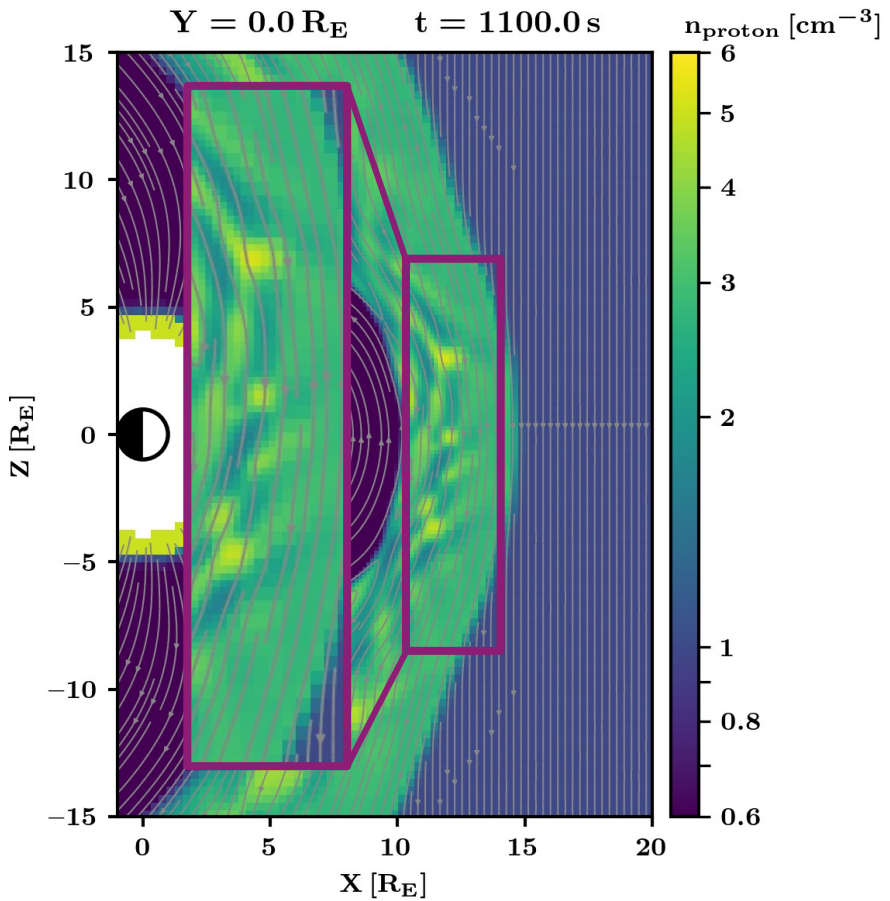
Signatures of transient processes?

- **FTEs** forming at the magnetopause near the subsolar point, propagating towards the cusps



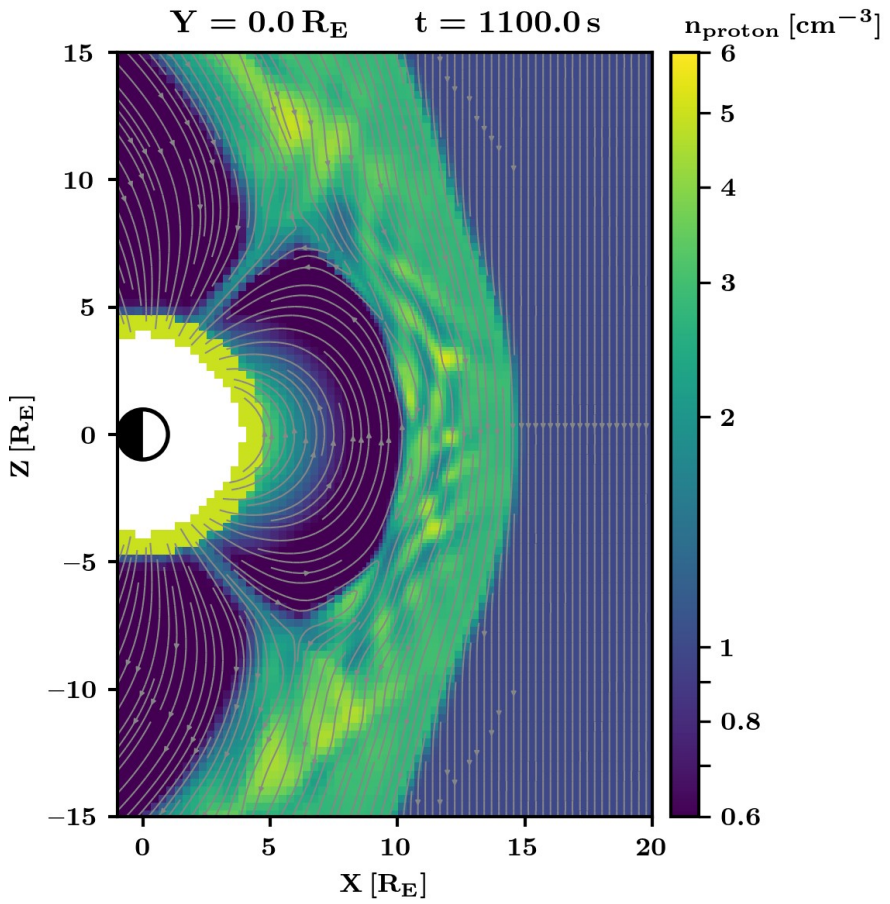
Signatures of transient processes?

- **FTEs** forming at the magnetopause near the subsolar point, propagating towards the cusps
- **Mirror-mode waves** in the magnetosheath

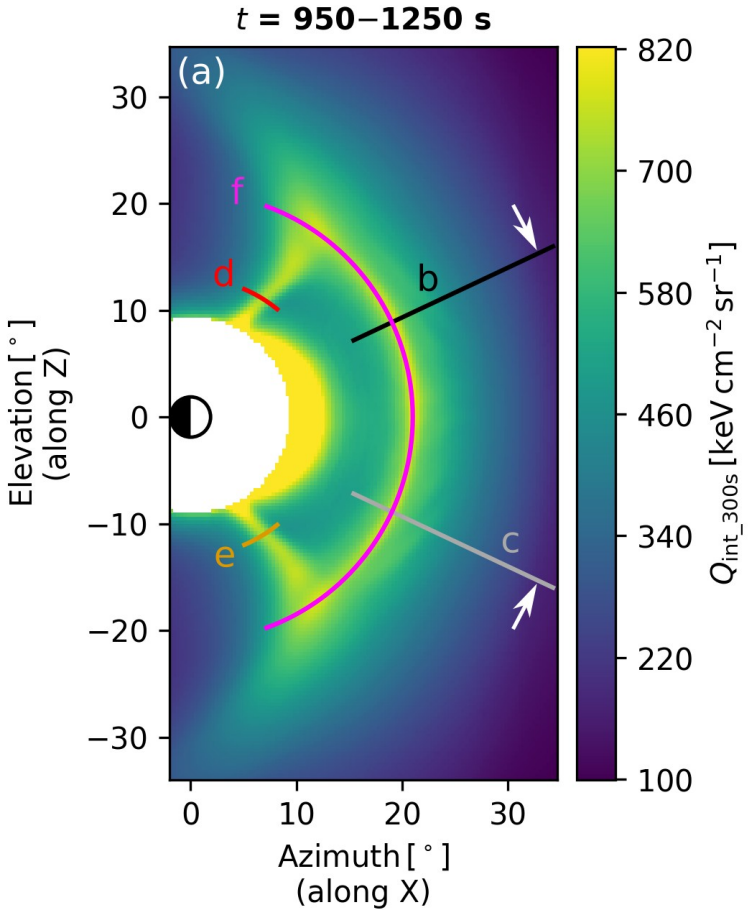


Signatures of transient processes?

- **FTEs** forming at the magnetopause near the subsolar point, propagating towards the cusps
- **Mirror-mode waves** in the magnetosheath
- *Can these have signatures in time-integrated soft X-ray images?*

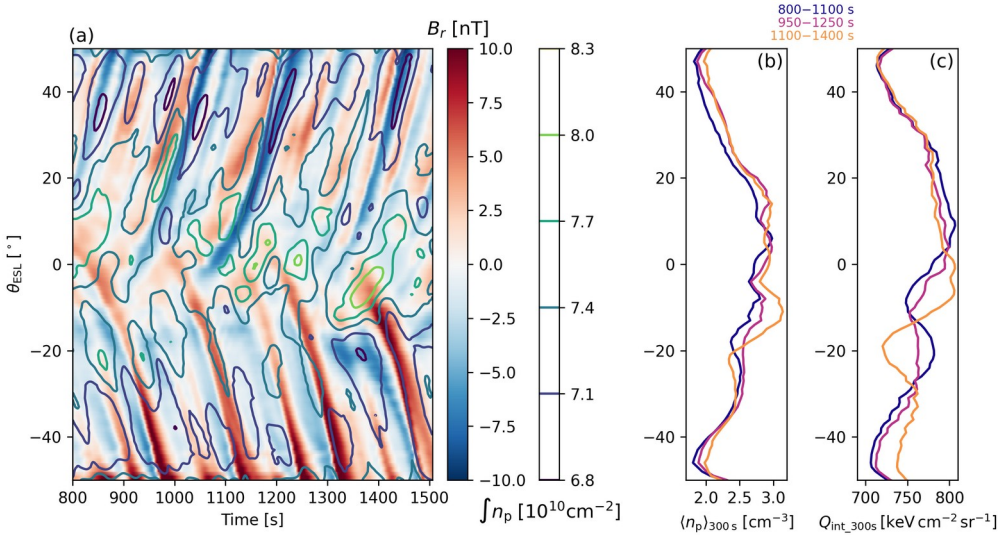


Transient signature detection: method

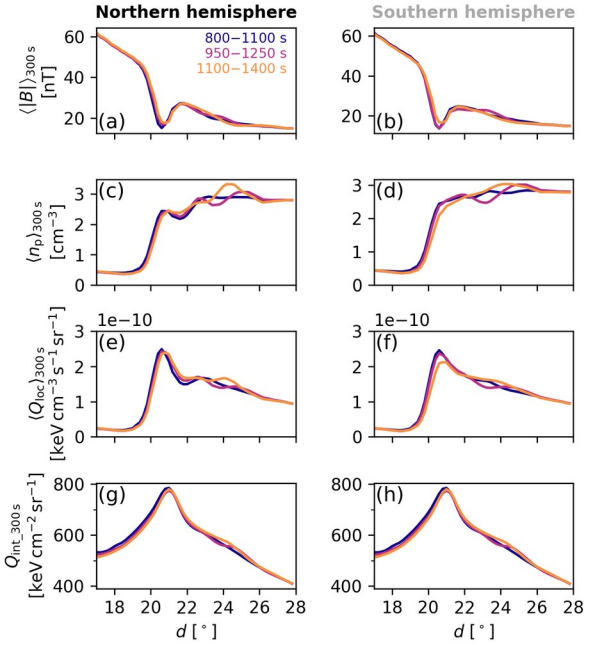


- We take cuts in images and look at the soft X-ray signal along with plasma parameters and the magnetic field
- For FTEs: **B**, n_p , Q_{int} along the magenta cut
  - We search for bipolar signatures in the **B** field component normal to the magnetopause
- For mirror-mode waves: B, n_p, Q_{loc}, Q_{int} along the **black** and grey cuts
  - We search for anticorrelated signatures in B and n_p

Results (teaser)



- *Can mirror-mode waves have signatures?*
  - Maybe yes, as a collective effect
  - Lower relative signal than for FTEs



- *Can FTEs have signatures in time-integrated soft X-ray images?*
  - Maybe yes, if there is no strong guide field and plasma density peaks in their core
  - Collective effect, not individual FTE over 300 s

Discussion & conclusions

- Large-scale features (cusp, magnetosheath, magnetopause) are clearly visible in soft X-rays
- Q_{int} values obtained with Vlasiator are consistent with earlier MHD studies (e.g., Sun et al., 2019; Connor et al., 2021)
- Transient phenomena could lead to soft X-ray signatures:
  - **FTEs:** if cumulative n_p enhancements locally amount up to ~30%, Q_{int_300s} is increased by ~12% ("crater FTEs"; Zhang et al., 2010)
  - **Mirror-mode waves:** if cumulative n_p enhancements locally amount up to ~14%, Q_{int_300s} is increased by ~4%
- Note that driving conditions in this run are more representative of high-speed streams (fast, tenuous solar wind) than of typical conditions

Preprint

- Paper accepted for publication as part of the SMILE special section of *Earth and Planetary Physics*
- Preprint available on arXiv: https://arxiv.org/abs/2301.13325