PRINCETON UNIVERSITY

Space Physics at Princeton

Suprathermal H^+ Pickup Ion Tails in the Outer Heliosphere

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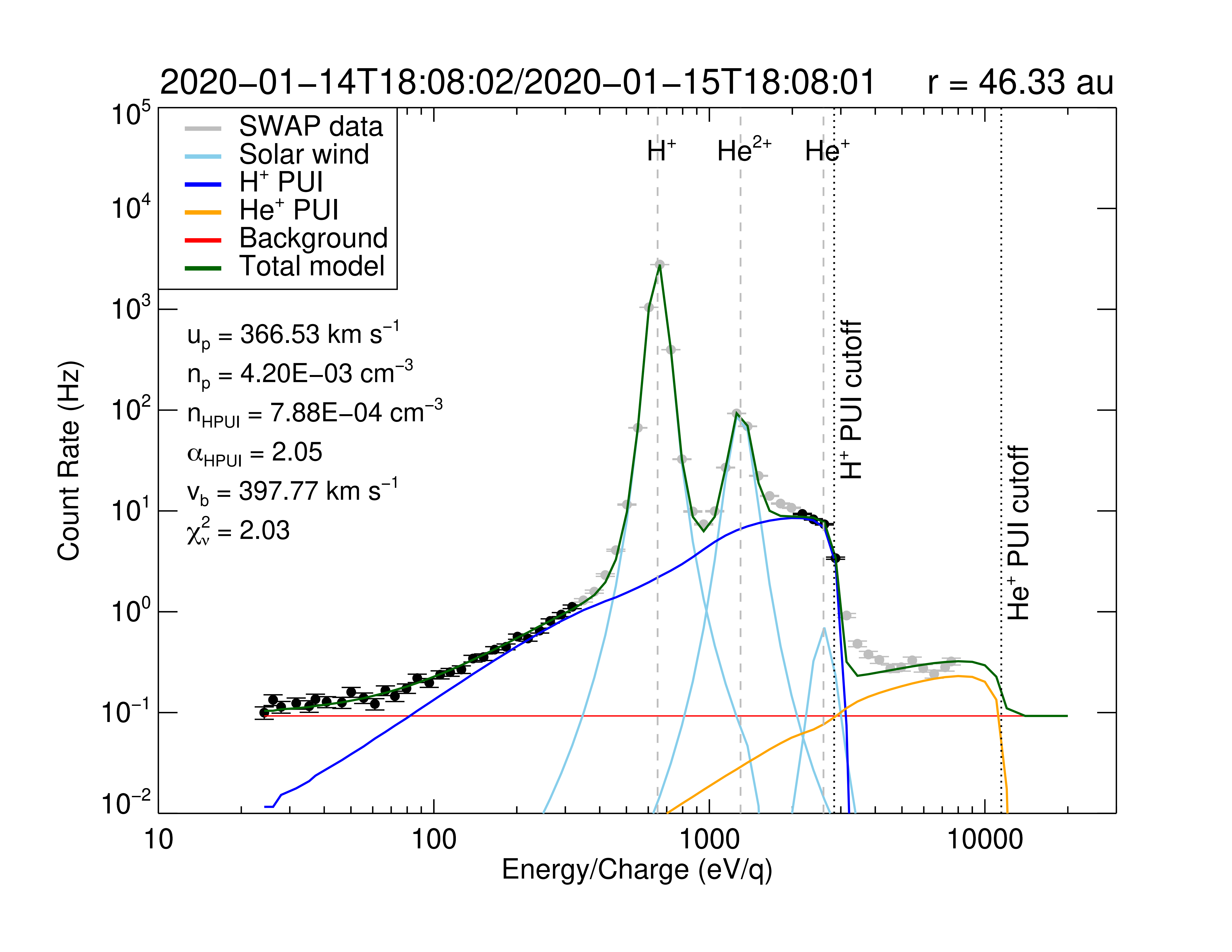
H⁺ PUI Observation from SWAP

Chen et al. (2014) model (Generalized V&S Model):

$$f(\boldsymbol{r},w) = \frac{\alpha_{PUI}\, S(\boldsymbol{r},w)}{4\,\pi} \frac{\beta_0\, r_0^2}{r\, u_{SW}\, v_{inj}^3} w^{\alpha_{PUI}-3}$$

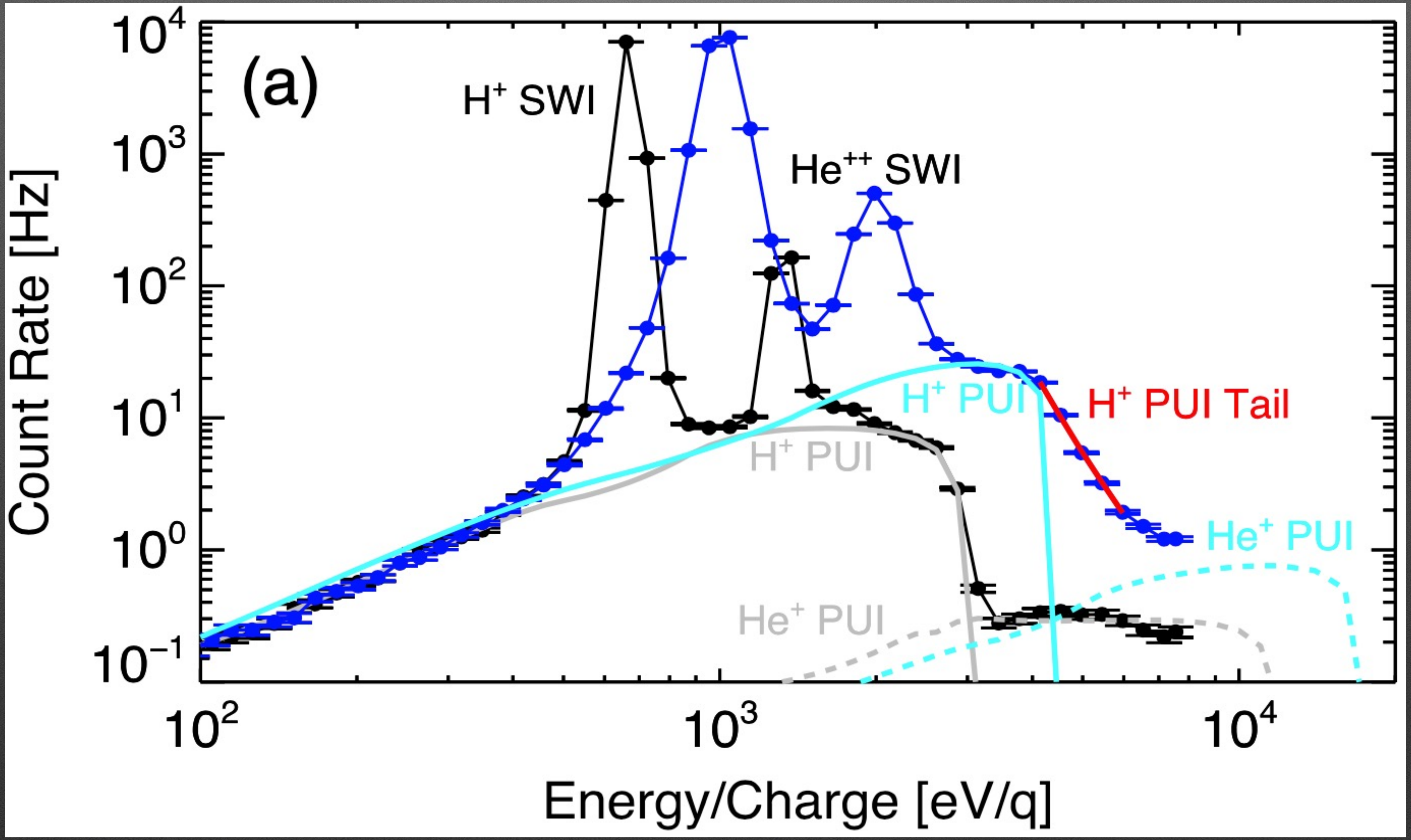
$$n_{H,HTS} \exp\left(-\frac{\lambda}{r}\, \frac{\theta}{\sin\theta} w^{-\alpha_{PUI}}\right) \Theta(1-w),$$

$$\text{where } \left(\frac{\boldsymbol{v}}{\boldsymbol{v}_{inj}}\right)^{\alpha_{PUI}} = \left(\frac{\boldsymbol{r}_{pickup}}{\boldsymbol{r}}\right)$$



Daily averaged SWAP data (McComas et al. 2021)

Observation of H^+ PUI Tail



Zirnstein et al. (2018)

Shrestha et al. (2023)

- Five distant interplanetary shocks with suprathermal H^+ PUI tail downstream of shocks (including Zirnstein et al. 2018)

➢ Chen et al. (2014) model for the PUI filled-shell distribution

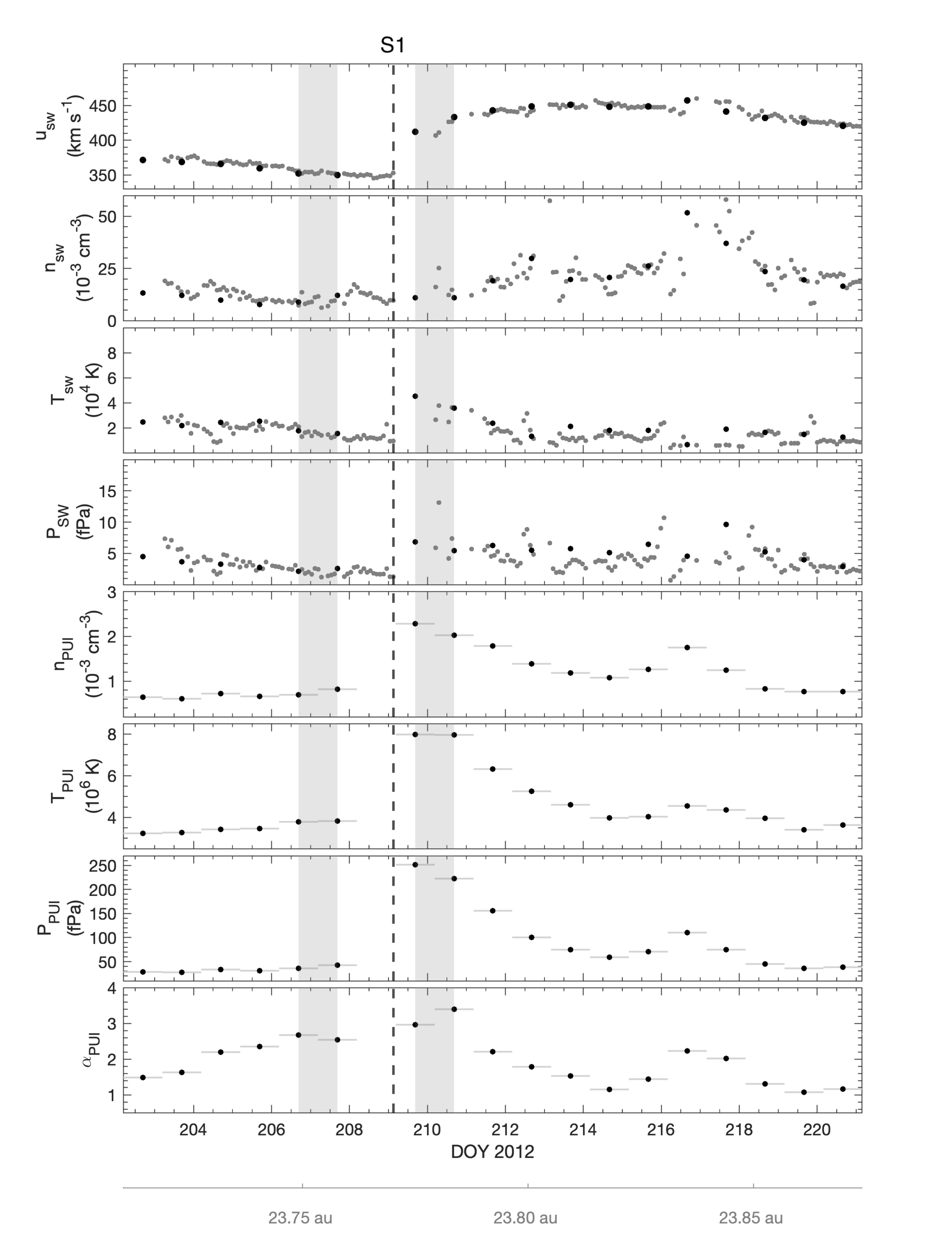
➢ v_{inj} free parameter for fitting

➢ Different Energy bins are used for fitting

➢ Correct conversion formula from distribution function to count rates

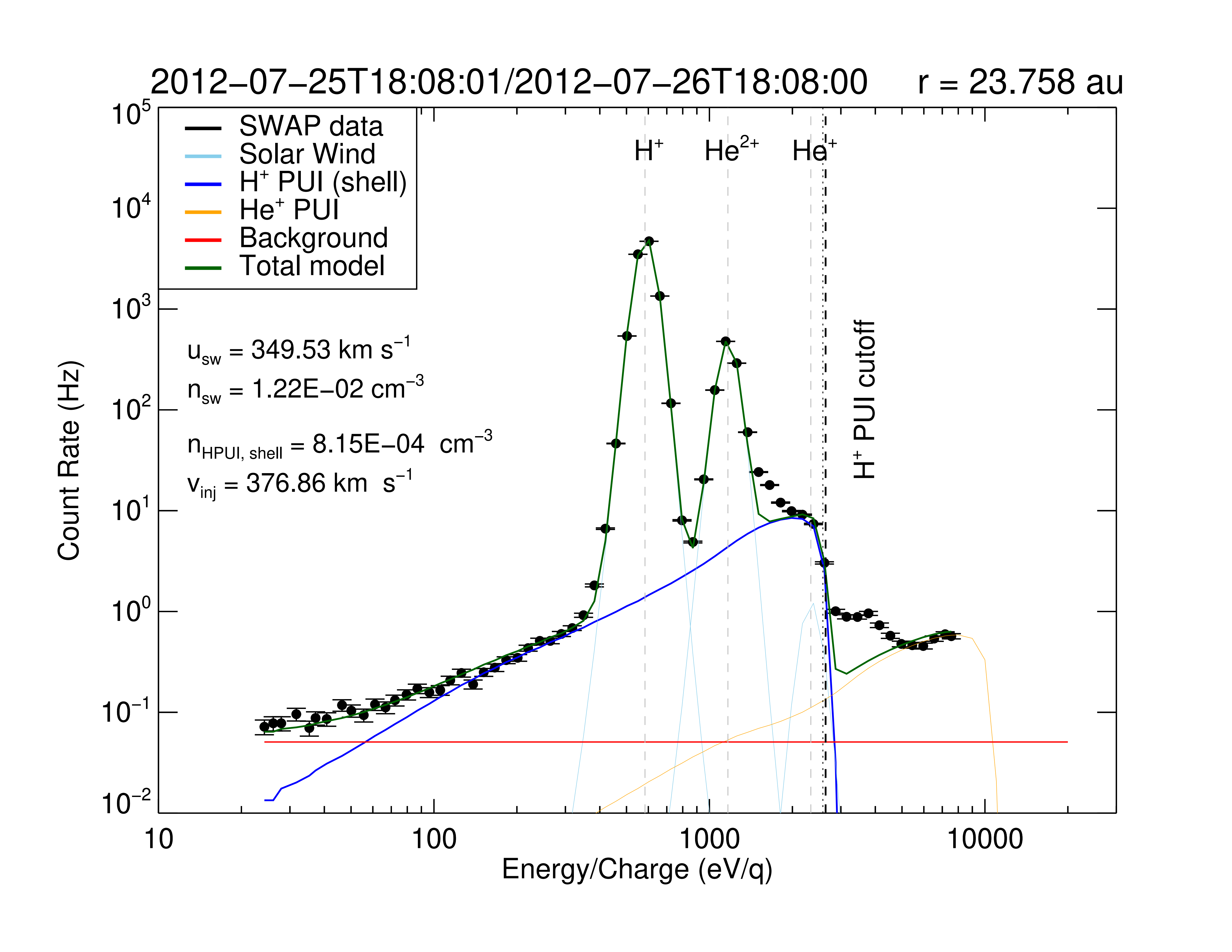
Shock S1

- Compression ratio, $r_c = 3.2$
- Shock speed, $V_{sh} = 495.1$ km s^{-1}
- Upstream bulk flow speed in the shock frame, $u_{1,sh} = 107.6$ km s^{-1}
- Downstream bulk flow speed in the shock frame, $u_{2,sh} = 33.8$ km s^{-1}

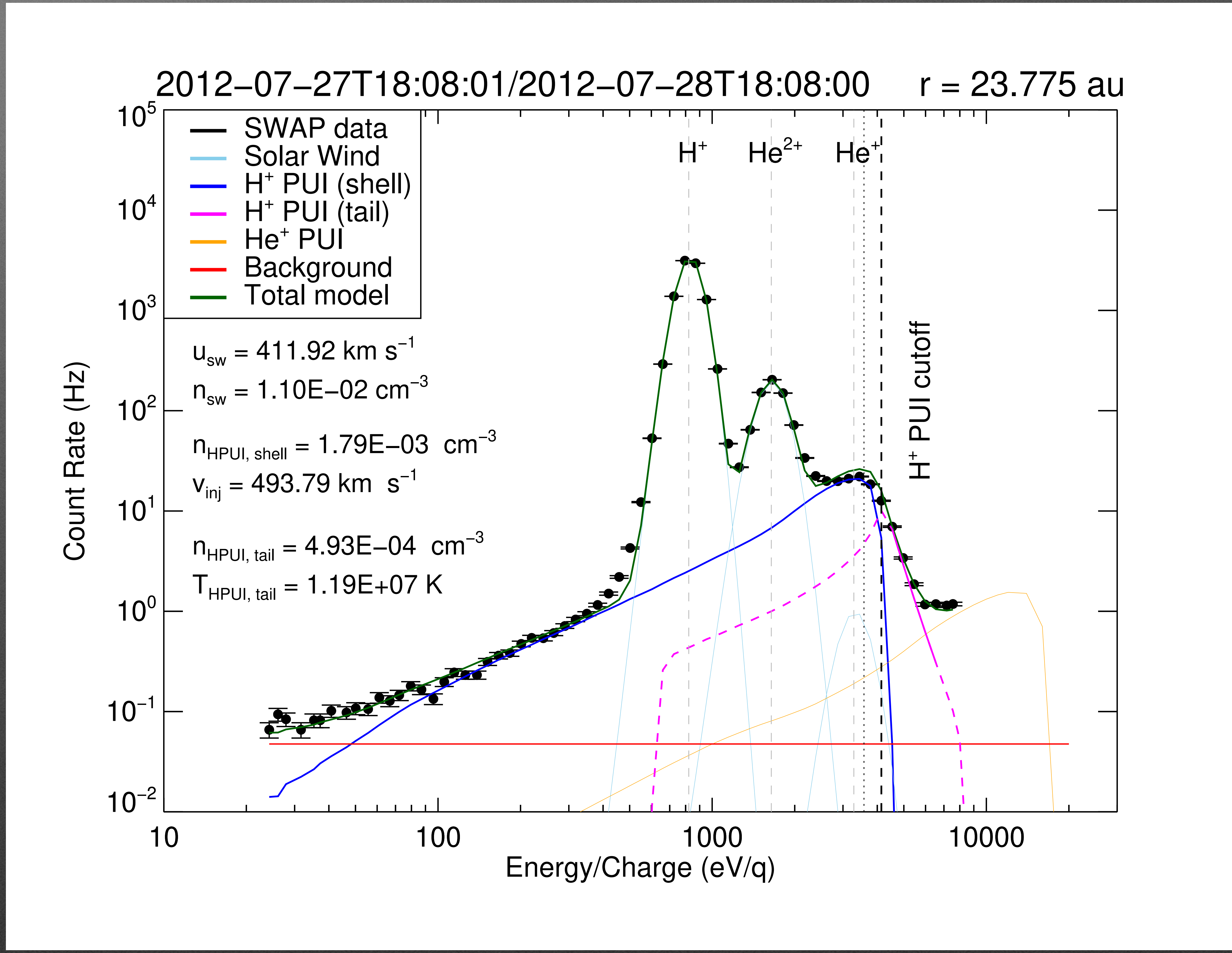


Shock S1

Upstream PUI distribution



Downstream PUI distribution

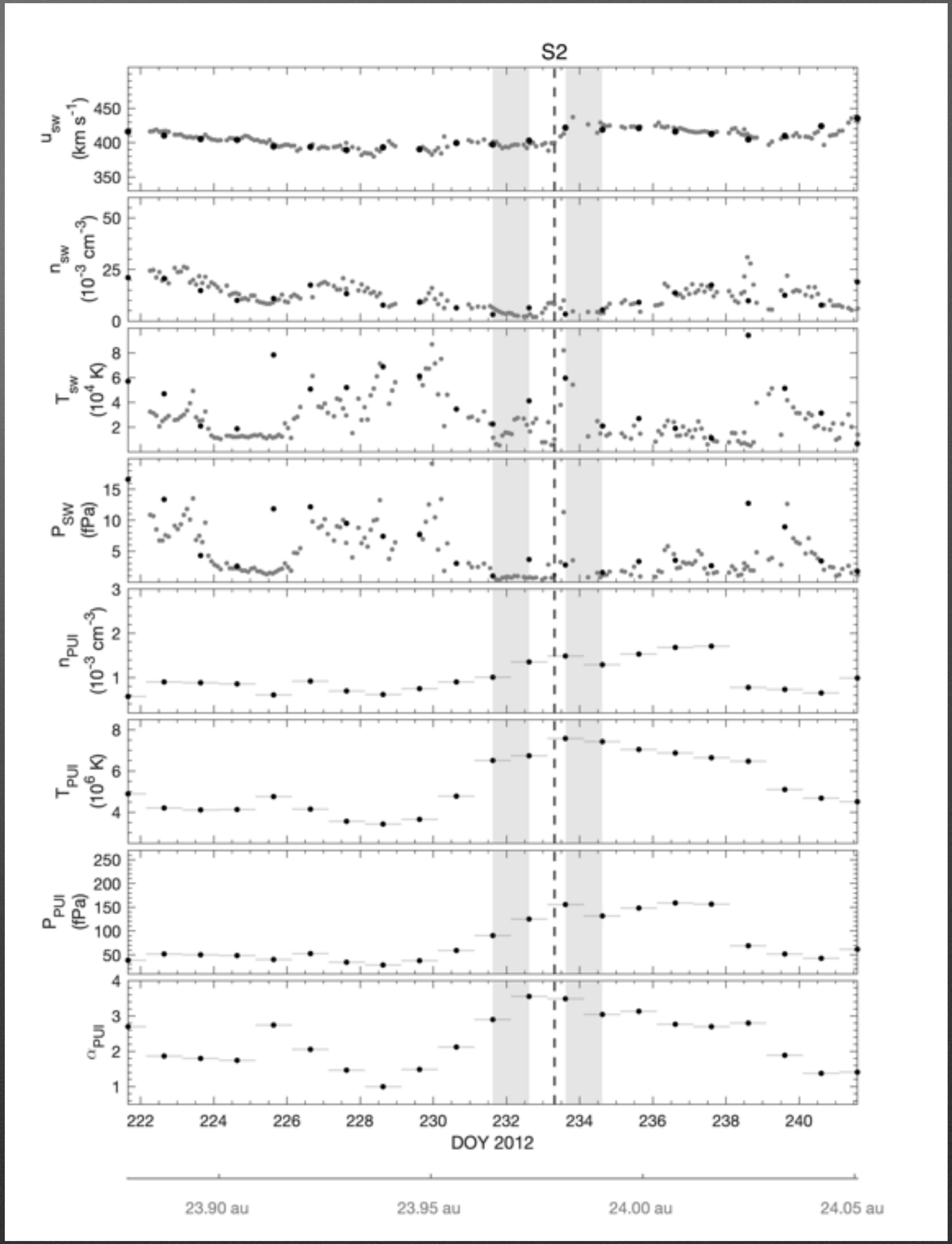


- H^+ PUI tail density fraction, $\frac{n_{tail}}{n_{pui}} = 0.18$
- H^+ PUI Tail temperature: 1.20×10^7 K

- $f(v) = 3407.9 \left(\frac{v}{v_{inj}}\right)^{-13.2}$ [s^3 km^{-6}]

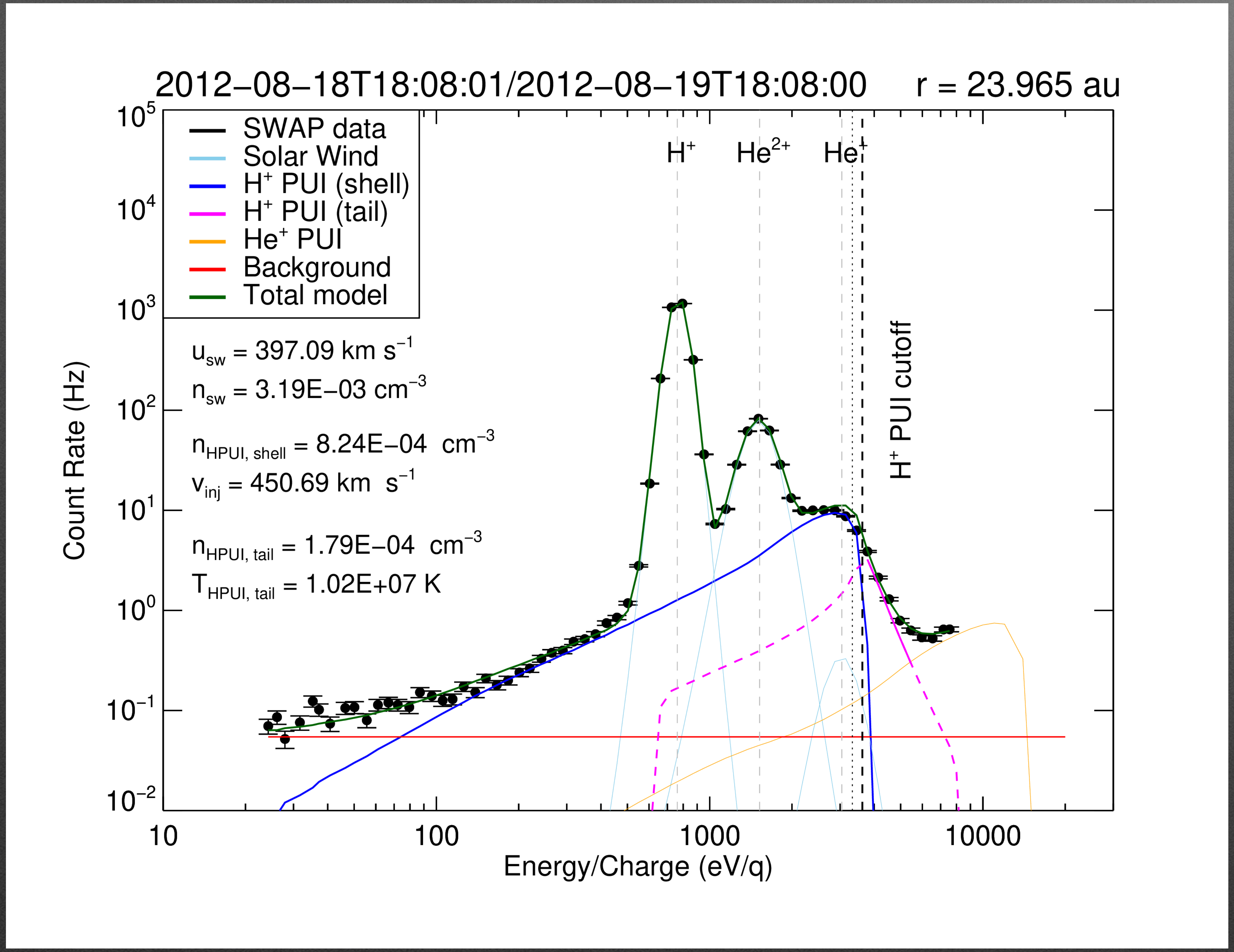
Shock S2

- Compression ratio, $r_c = 1.4$
- Shock speed, $V_{sh} = 485.5$ km s^{-1}
- Upstream bulk flow speed in shock frame, $u_{1,sh} = 89.2$ km s^{-1}
- Downstream bulk flow speed in shock frame, $u_{2,sh} = 61.9$ km s^{-1}

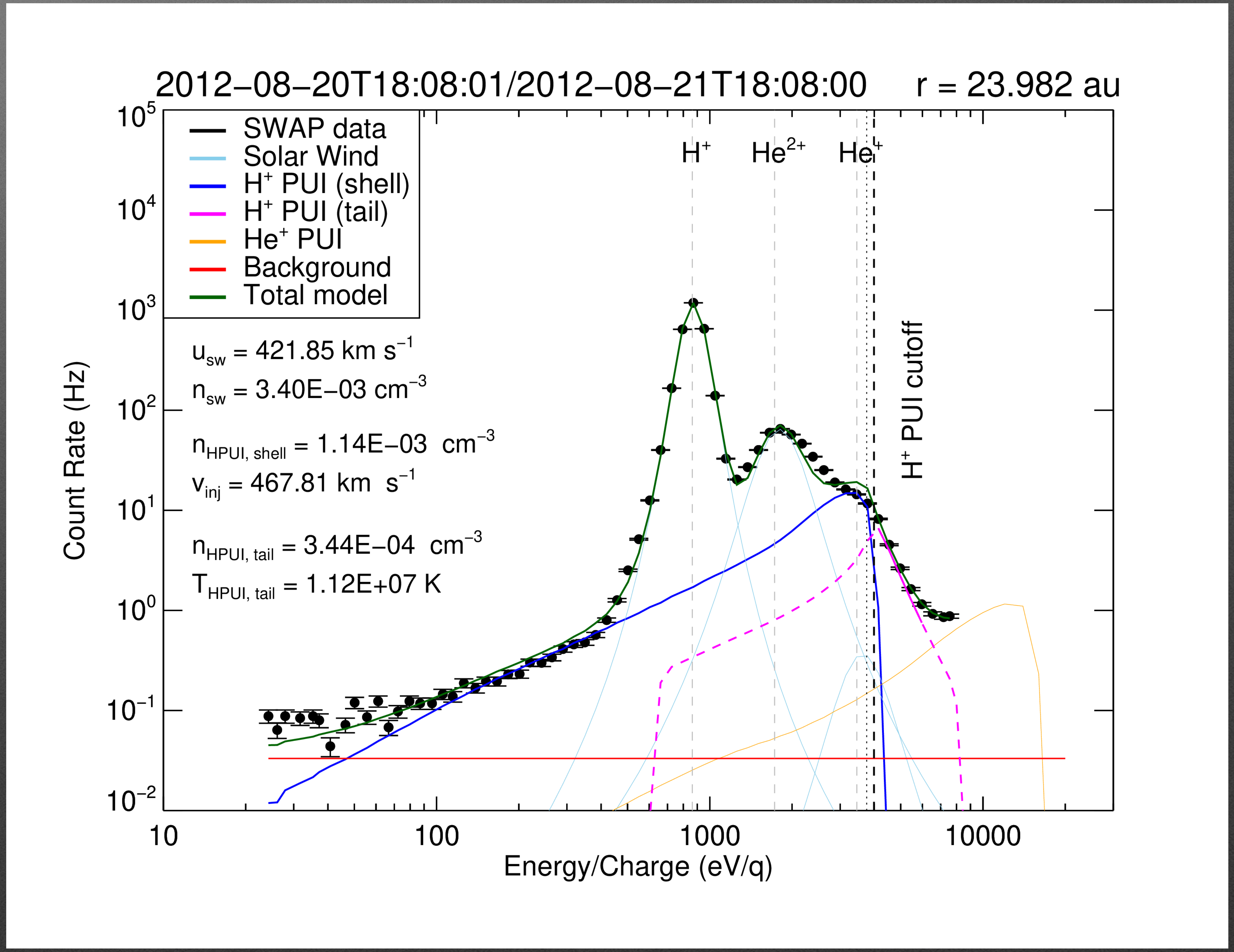


Shock S2

Upstream PUI distribution



Downstream PUI distribution

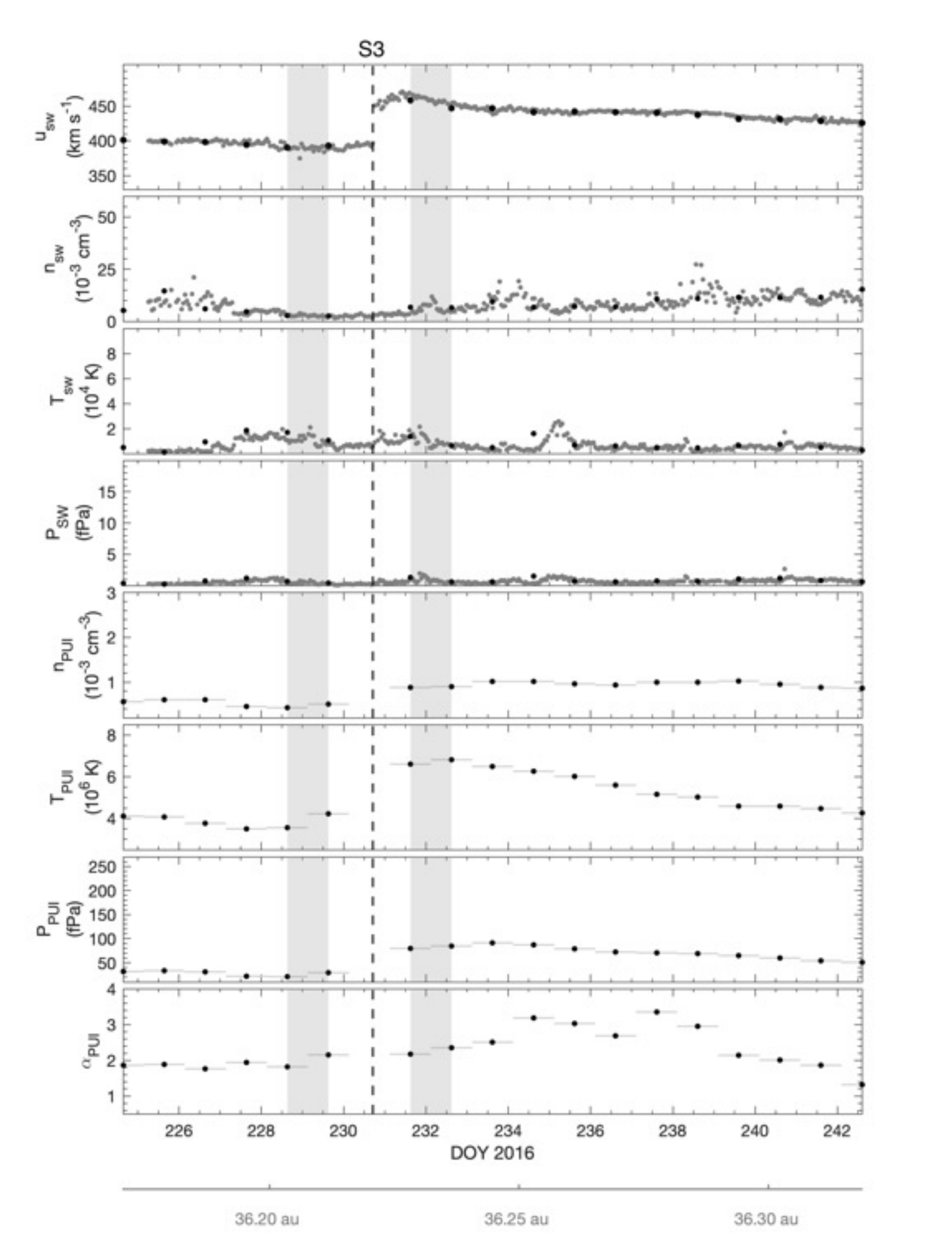


- H^+ PUI tail density fraction, $\frac{n_{tail}}{n_{pui}} = 0.20$
- H^+ PUI Tail temperature: 1.02×10^7 K

- $f(v) = 2082.0 \left(\frac{v}{v_{inj}}\right)^{-10.1}$ [s^3 km^{-6}]

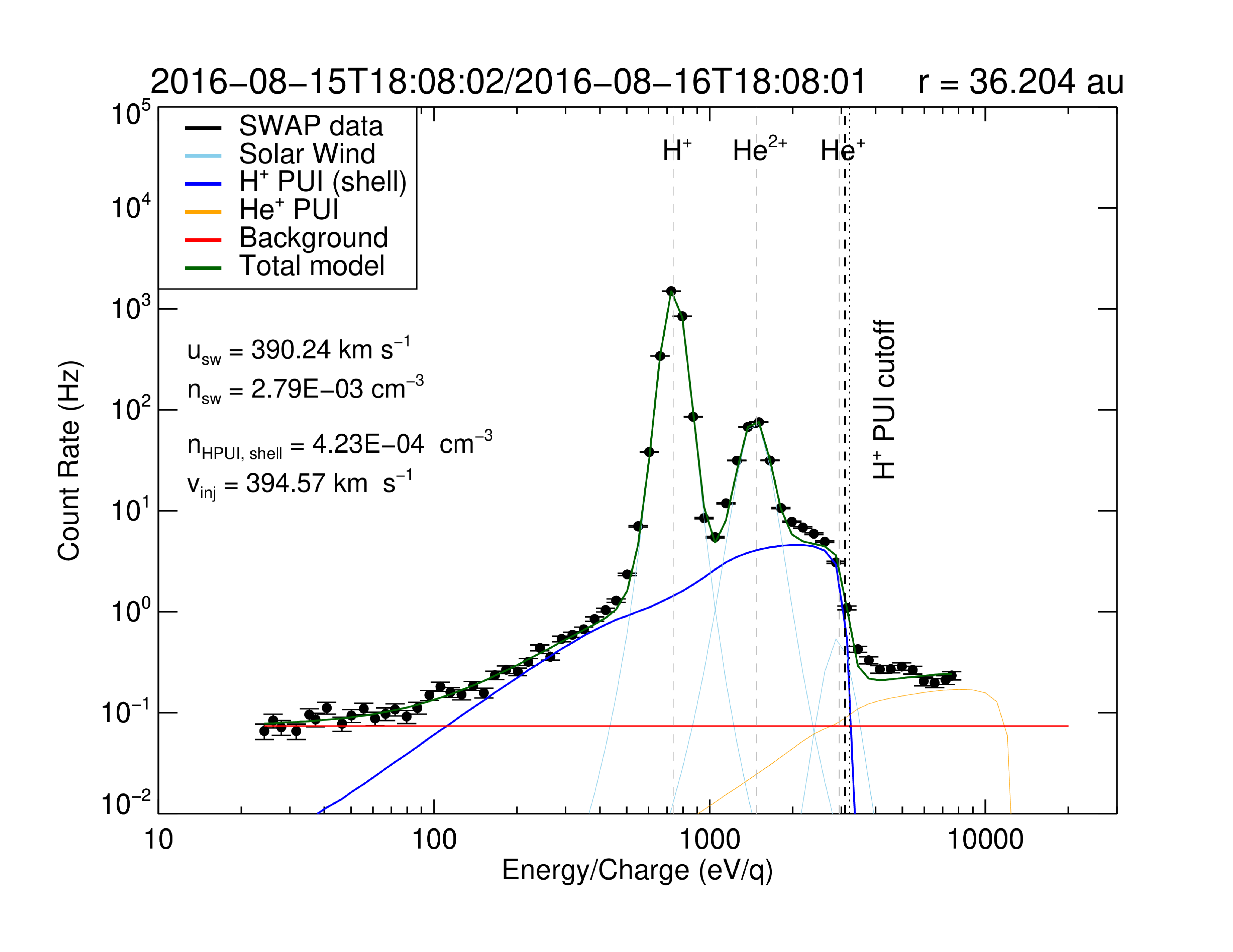
Shock S3

- Compression ratio, $r_c = 1.9$
- Shock speed, $V_{sh} = 519.5$ km s^{-1}
- Upstream bulk flow speed in shock frame, $u_{1,sh} = 130.1$ km s^{-1}
- Downstream bulk flow speed in shock frame, $u_{2,sh} = 67.8$ km s^{-1}

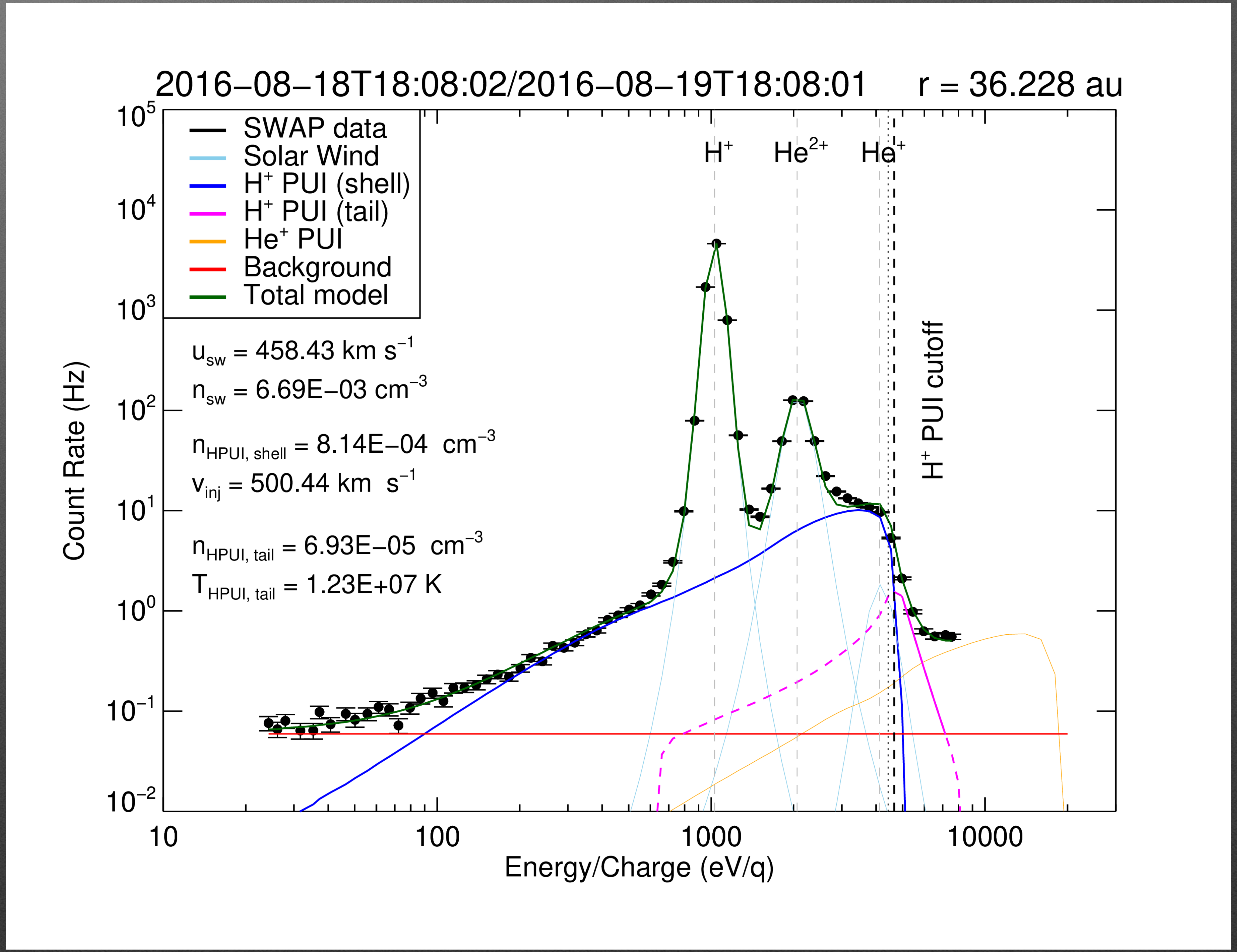


Shock S3

Upstream PUI distribution



Downstream PUI distribution

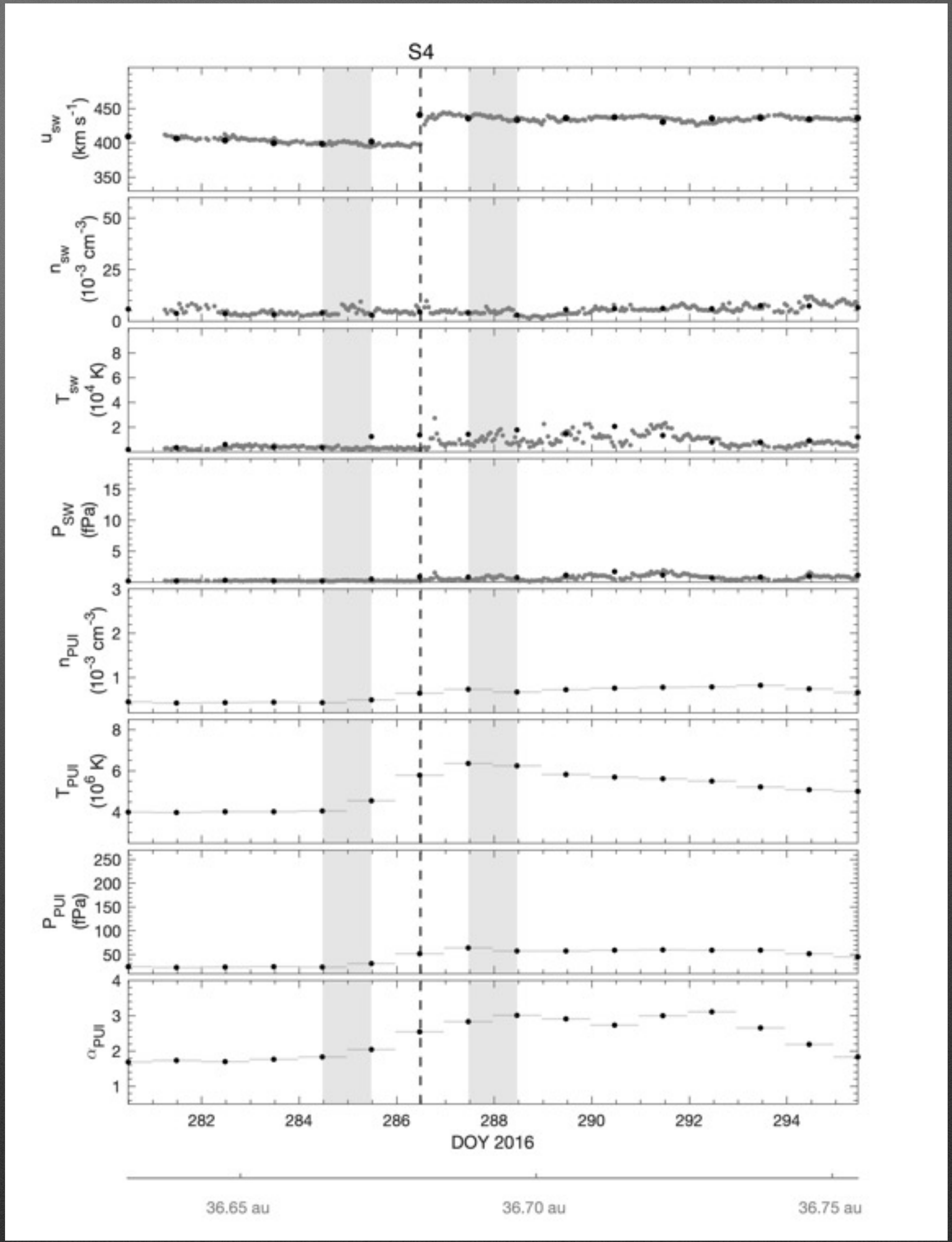


- H^+ PUI tail density fraction, $\frac{n_{tail}}{n_{pui}} = 0.08$
- H^+ PUI Tail temperature: 1.22×10^7 K

- $f(v) = 457.8\left(\frac{v}{v_{inj}}\right)^{-13.2}$ [s^3 km^{-6}]

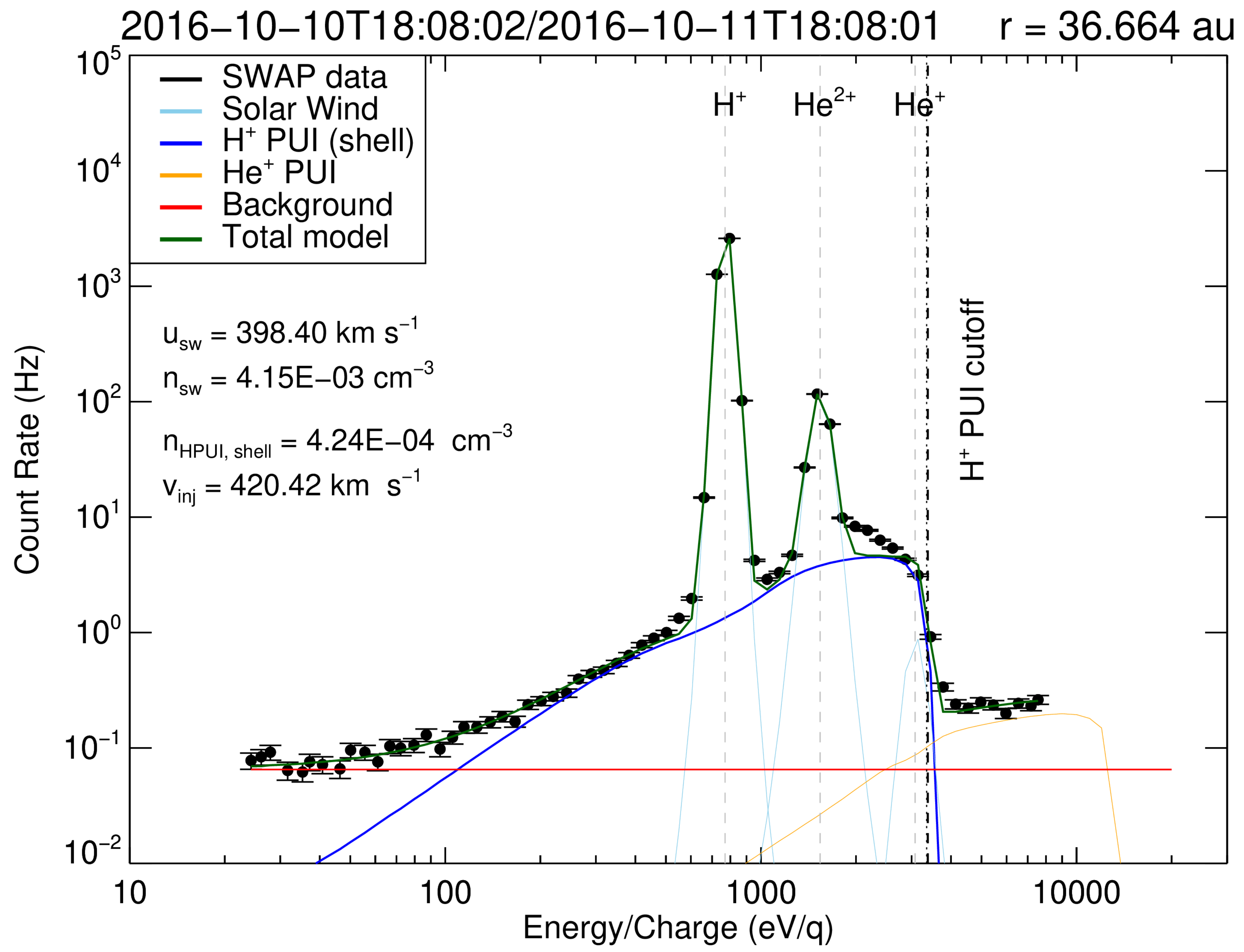
Shock S4

- Compression ratio, $r_c = 1.49$
- Shock speed, $V_{sh} = 524.3$ km s^{-1}
- Upstream bulk flow speed in shock frame, $u_{1,sh} = 107.5$ km s^{-1}
- Downstream bulk flow speed in shock frame, $u_{2,sh} = 72.3$ km s^{-1}

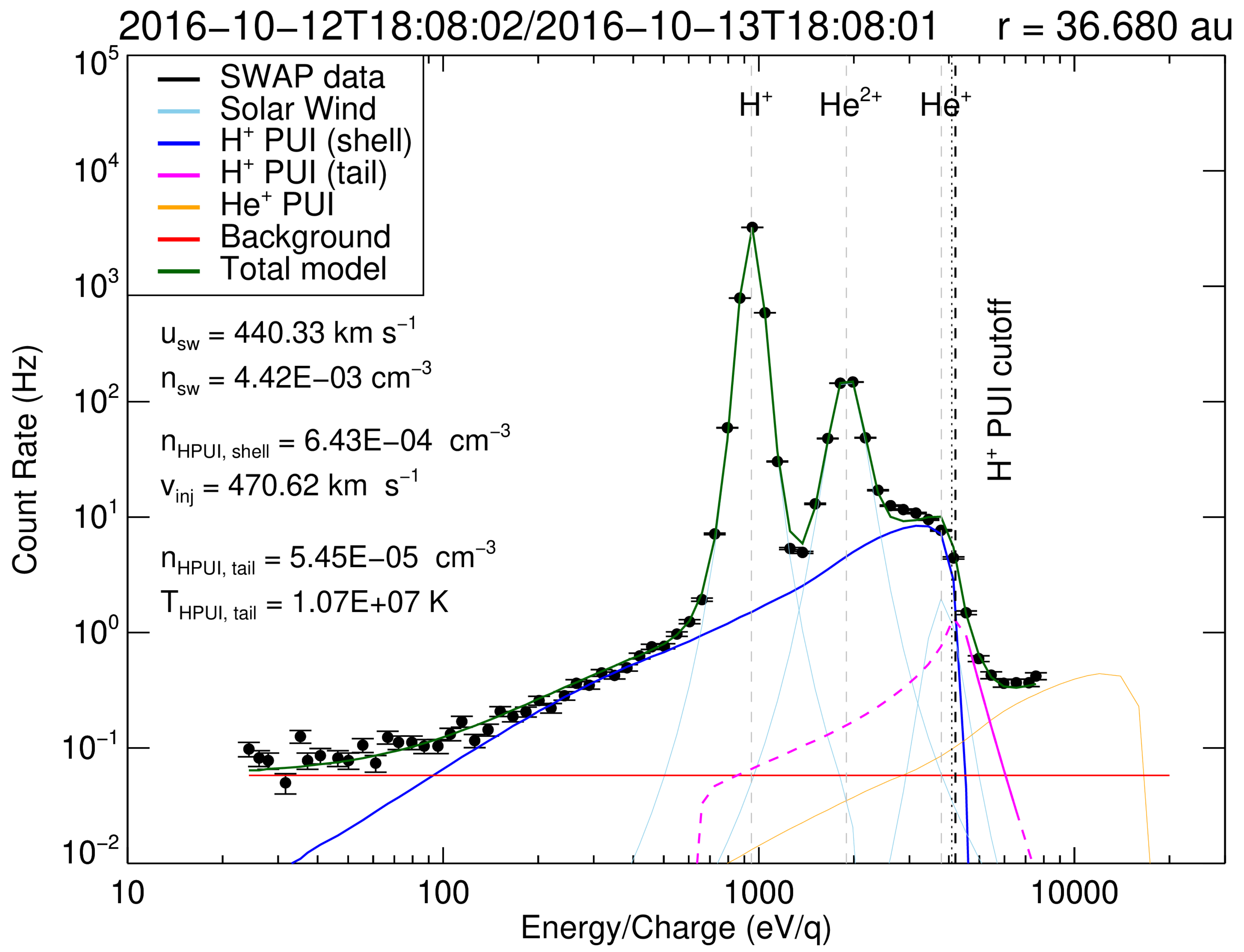


Shock S4

Upstream PUI distribution



Downstream PUI distribution

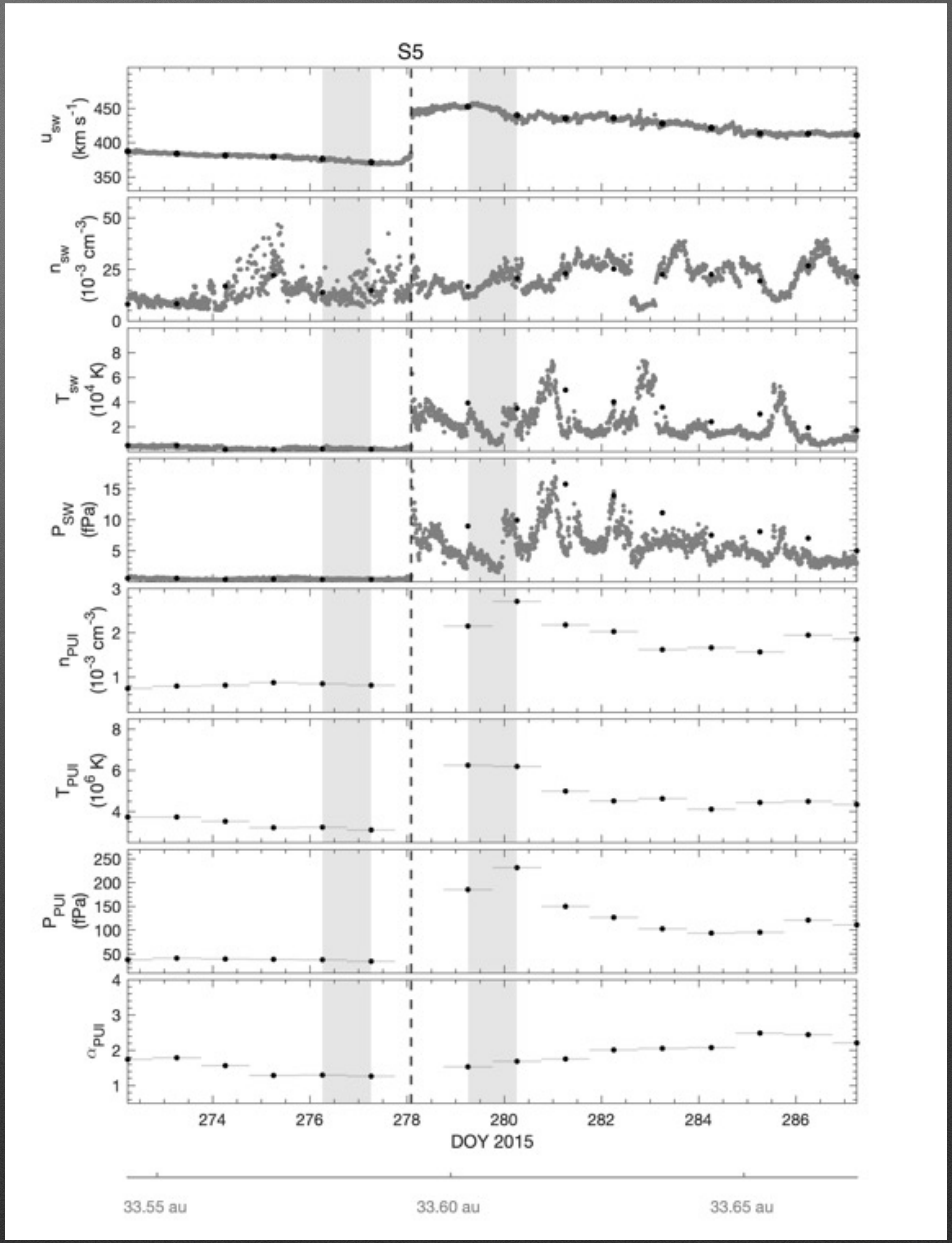


- H^+ PUI tail density fraction, $\frac{n_{tail}}{n_{pui}} = 0.05$
- H^+ PUI Tail temperature: 1.10 x 10^7 K

- $f(v) = 467.6\left(\frac{v}{v_{inj}}\right)^{-14.1}$ [s^3 km^{-6}]

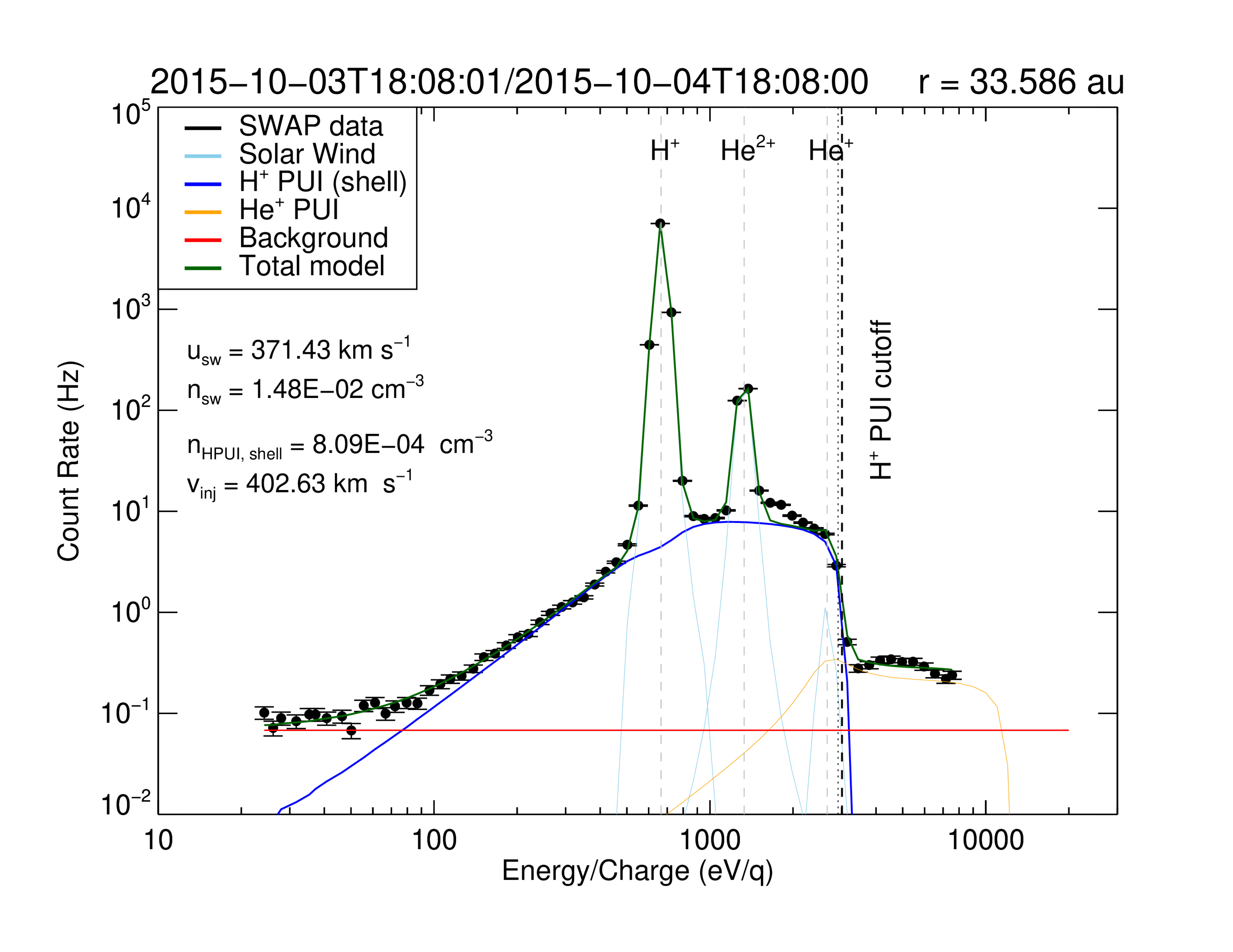
Shock S5

- Compression ratio, $r_c = 2.9$
- Shock speed, $V_{sh} = 486.2$ km s^{-1}
- Upstream bulk flow speed in shock frame, $u_{1,sh} = 112.8$ km s^{-1}
- Downstream bulk flow speed in shock frame, $u_{2,sh} = 38.4$ km s^{-1}

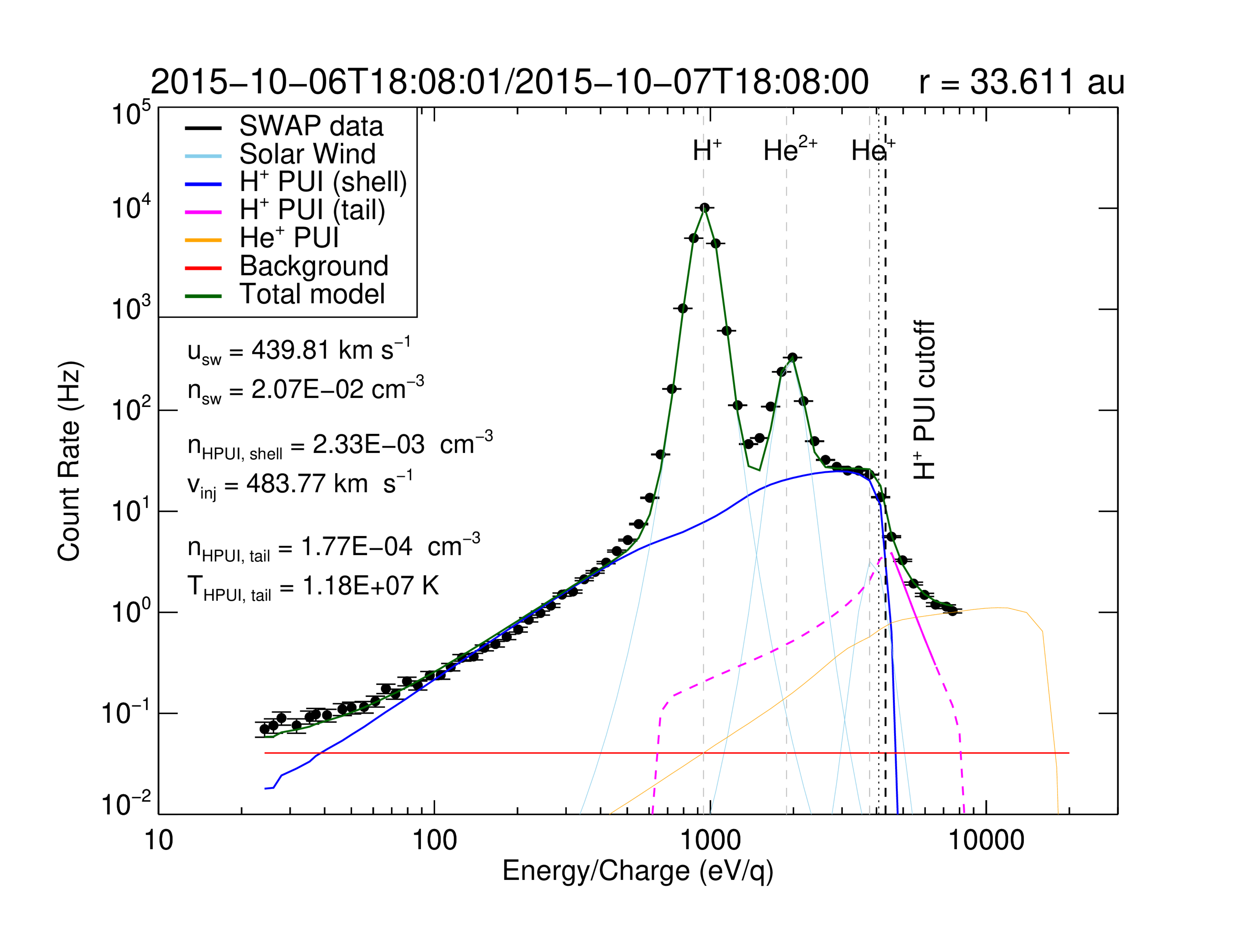


Shock S5

Upstream PUI distribution



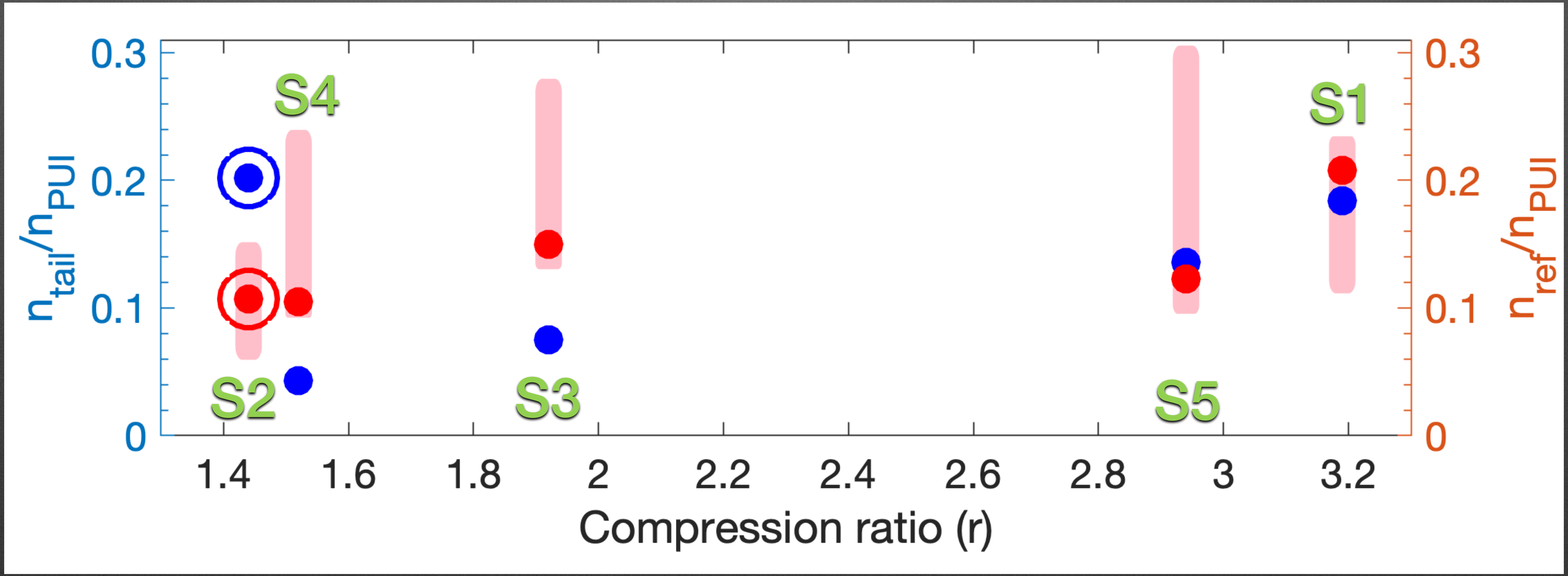
Downstream PUI distribution



- H^+ PUI tail density fraction, $\frac{n_{tail}}{n_{pui}} = 0.14$
- H^+ PUI Tail temperature: 1.16×10^7 K

- $f(v) = 1077.8\left(\frac{v}{v_{inj}}\right)^{-11.2}$ [$s^3\ km^{-6}$]

Variation of H^+ PUI Tail Density with Compression Ratio



- Blue – SWAP data
- Red – Theoretical Estimate (Electrostatic cross-shock potential)

Summary and Conclusions

- We have presented a detailed analysis of five fast-forward interplanetary shocks that exhibit the signature of a suprathermal tail in the H^+ PUI distribution downstream of the shock.
- The estimated shock compression ratios range from ~1.4 to 3.2, with shock S1 being the strongest interplanetary shock observed by SWAP so far in the outer heliosphere, and shock S2 being the weakest shock still showing the signature of H^+ PUI tail.
- In general, the H^+ SW density displayed erratic behavior across the shock without showing a clear compression downstream.
- Conversely, the H^+ PUI density and temperature exhibited a gradual increase across the shock, allowing us to compute the shock compression ratio.
- The variation of H^+ PUI cooling index across the shock shows no consistent pattern among the five shocks.
- The H^+ PUI tail density is found to be very close to the theoretical estimate based on the theory of PUI reflection from the electrostatic CSP for stronger shocks ($r_c \geq 2.9$).
- However, for weaker shocks, the theoretical estimates are larger than the observed values, except for the shock S2.
- Additionally, this study suggests that observed suprathermal H^+ PUI tail density in the SWAP energy range is proportional to the strength of the shock.

Thanks!