Towards an understanding of collapsar gamma-ray burst environments through circumstellar medium population synthesis

Ashley Chrimes[1,2], Ben Gompertz et al.

ESA Research Fellow | email: ashley.chrimes@esa.int

1 - European Space Research & Technology Centre (ESTEC), European Space Agency (ESA), Noordwijk, the Netherlands

2 - Department of Astrophysics/IMAPP, Radboud University, Nijmegen, the Netherlands

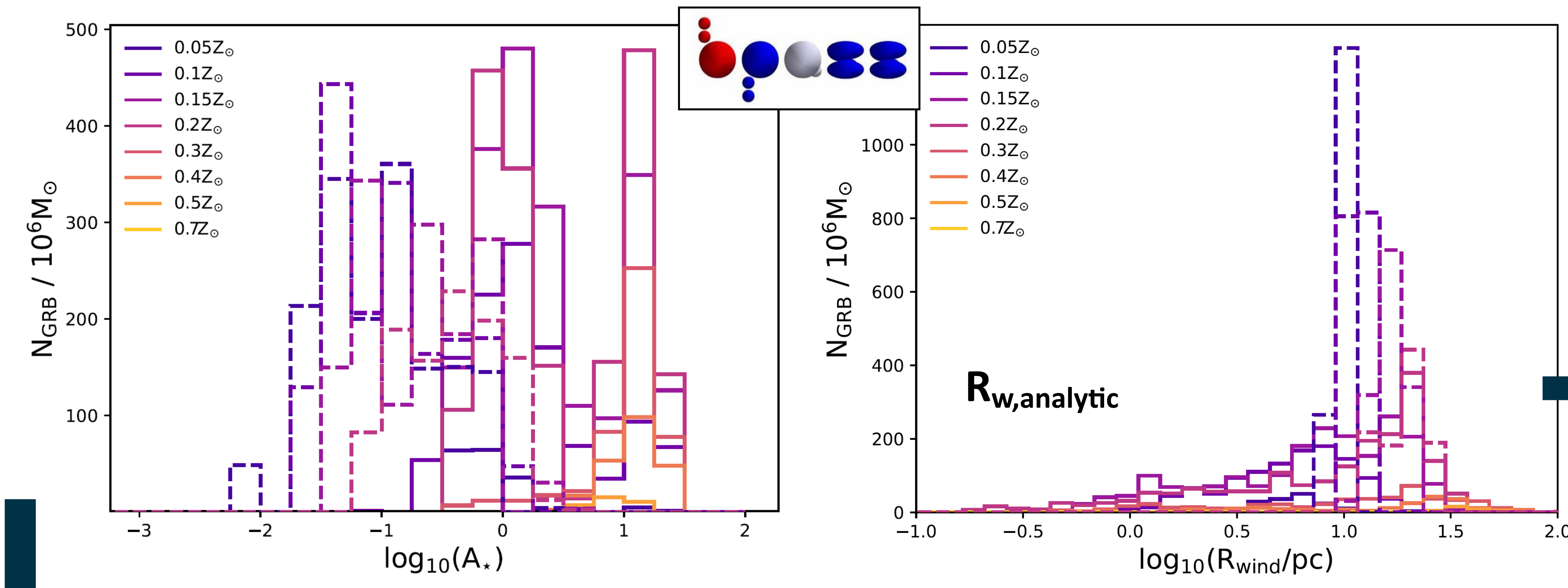
MNRAS, 515, 2591

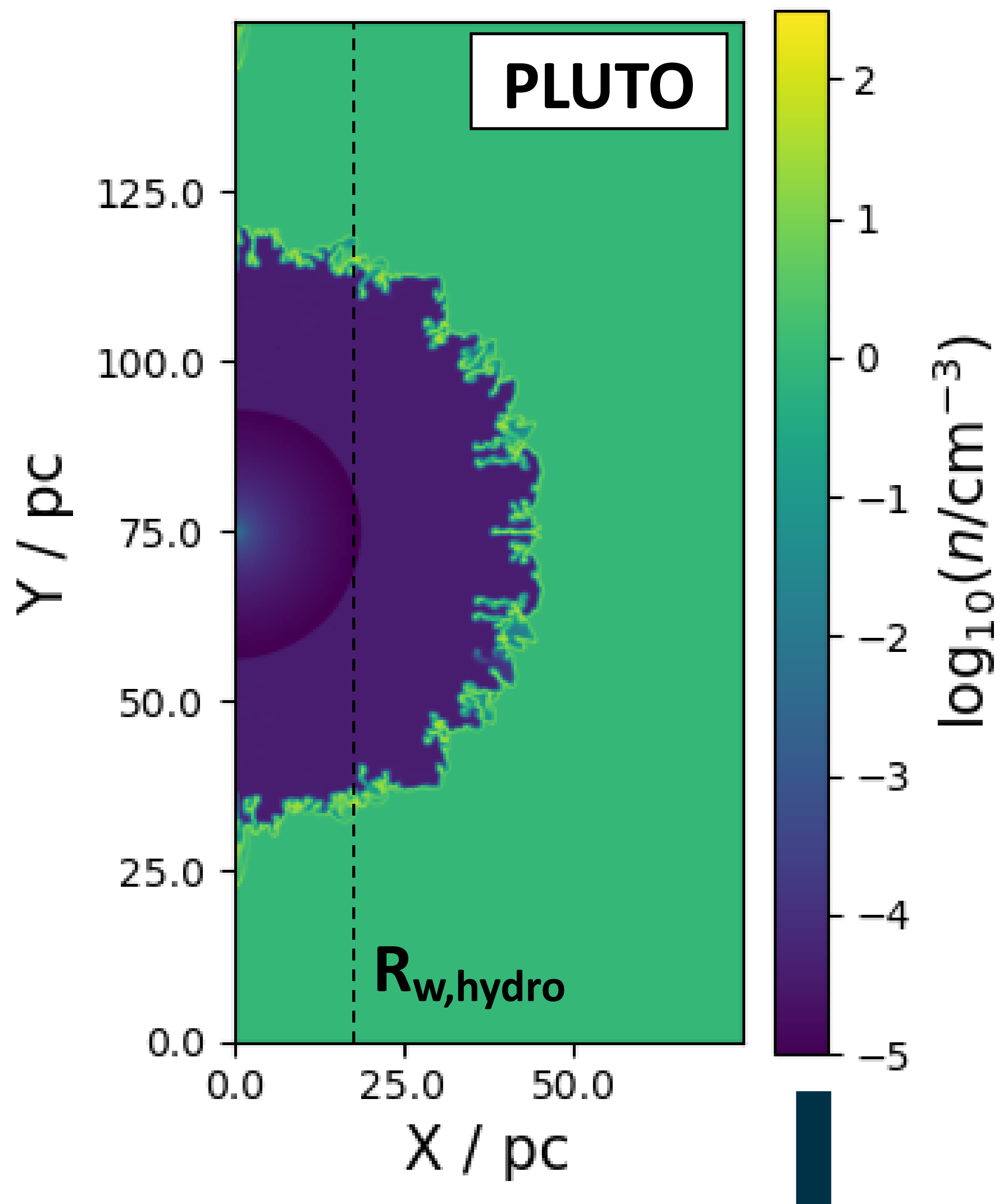
1.THE PROBLEM

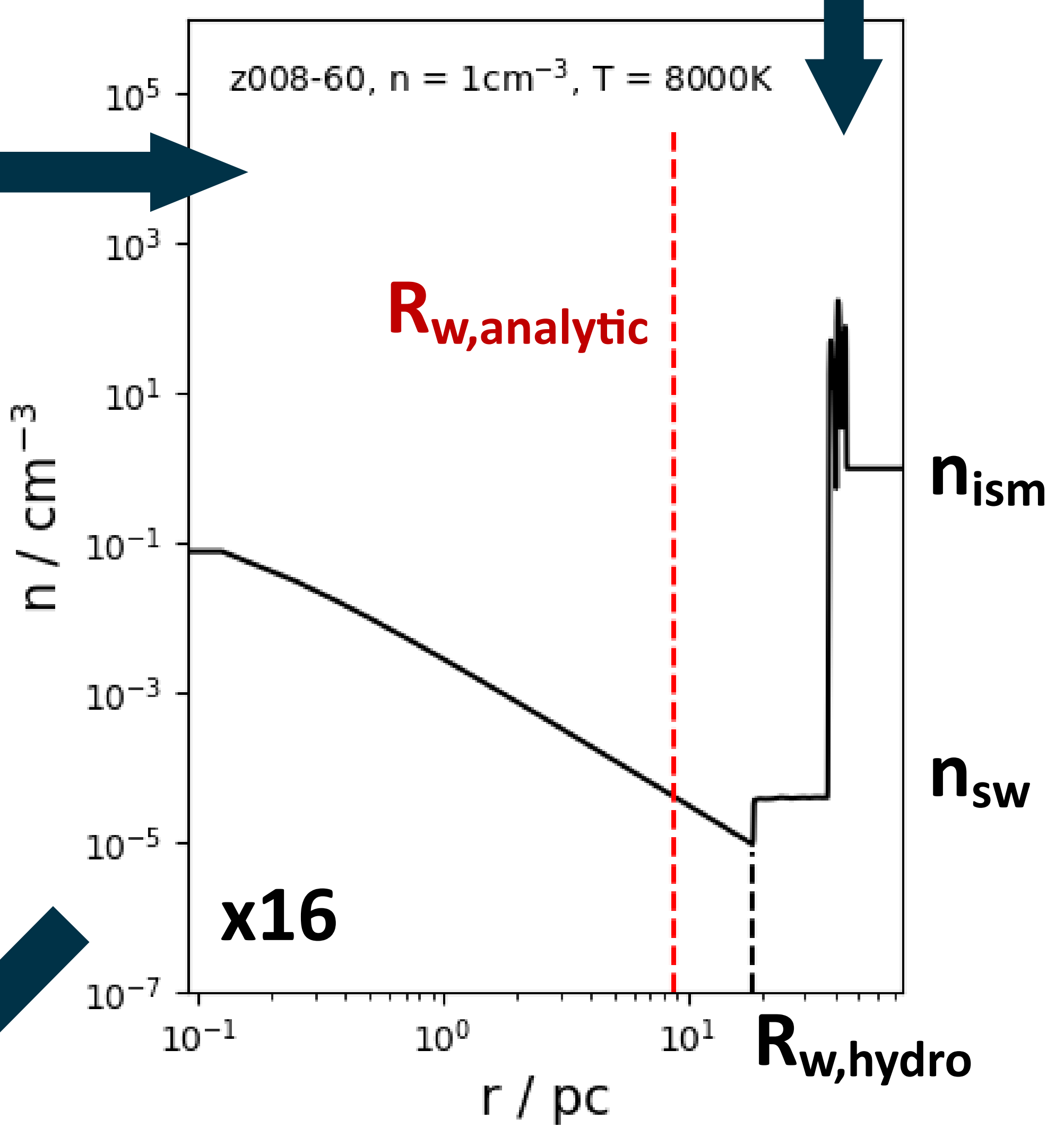
Core-collapse gamma-ray burst (GRB) progenitors are thought to be massive, stripped envelope stars, which launch a jet through accretion onto a nascent compact object [1]. These stars are expected to drive strong winds, producing bubbles in the circumstellar medium (CSM). The jet collides with the CSM and produces an afterglow [2], but this often exhibits evolution consistent with a flat density profile close to the star [3,4], in tension with the expected wind profile around a massive progenitor.

2. CSM POP SYNTH

Stellar evolution models can be used to predict the termination shock radius R_{wind} and wind density parameter *A* for a given ISM density *n*, through analytic prescriptions for $R_{wind}(t)$ and jet propagation in r^{-2} and flat density profile environments. We make use of long GRB progenitor models identified with the population synthesis code BPASS [5,6]. Using the semi-analytic wind bubble model of [7], the results for our suite of GRB progenitor models are shown in the two figures below.

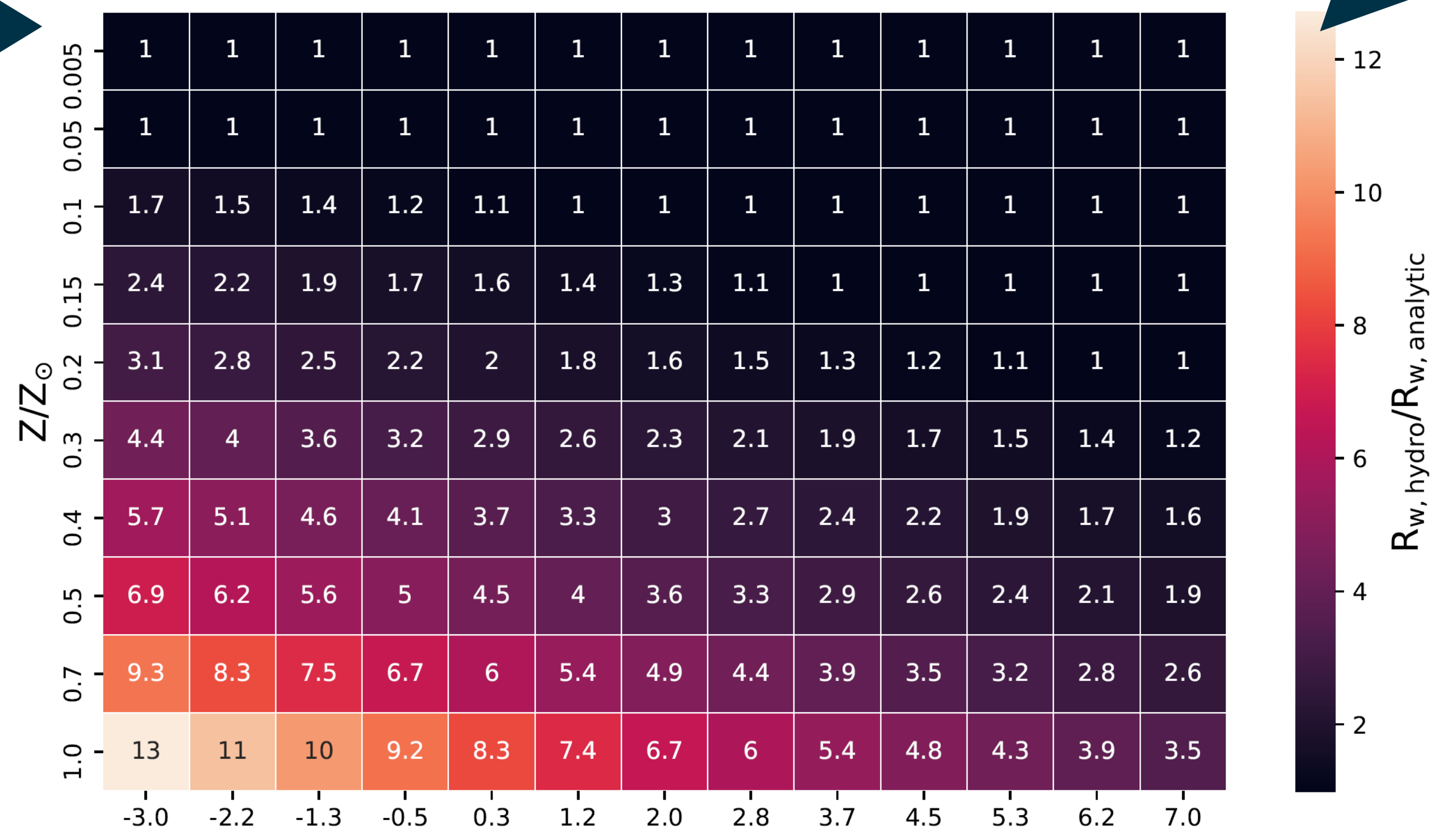






3. HYDROSIM CORRECTIONS

The model of [7] assumes no thermal pressure in the interstellar medium (ISM) and that the shocked shell is infinitely thin (i.e. the ISM is cold and dense). We perform 16 hydrodynamical simulations with PLUTO [8] (e.g. top right) in various ISM environments, comparing to analytic results for the same stars (see right). We fit a trend, over ISM density and metallicity, to $R_{w,analytic}$ / $R_{w,hydro}$ (below, center). We also fit a relationship between the stalled wind (SW, the flat region between the wind and ISM) and ISM density. We use these relations to add the stalled wind region and improve R_{wind} accuracy for every set of BPASS analytic results at minimal computational cost.



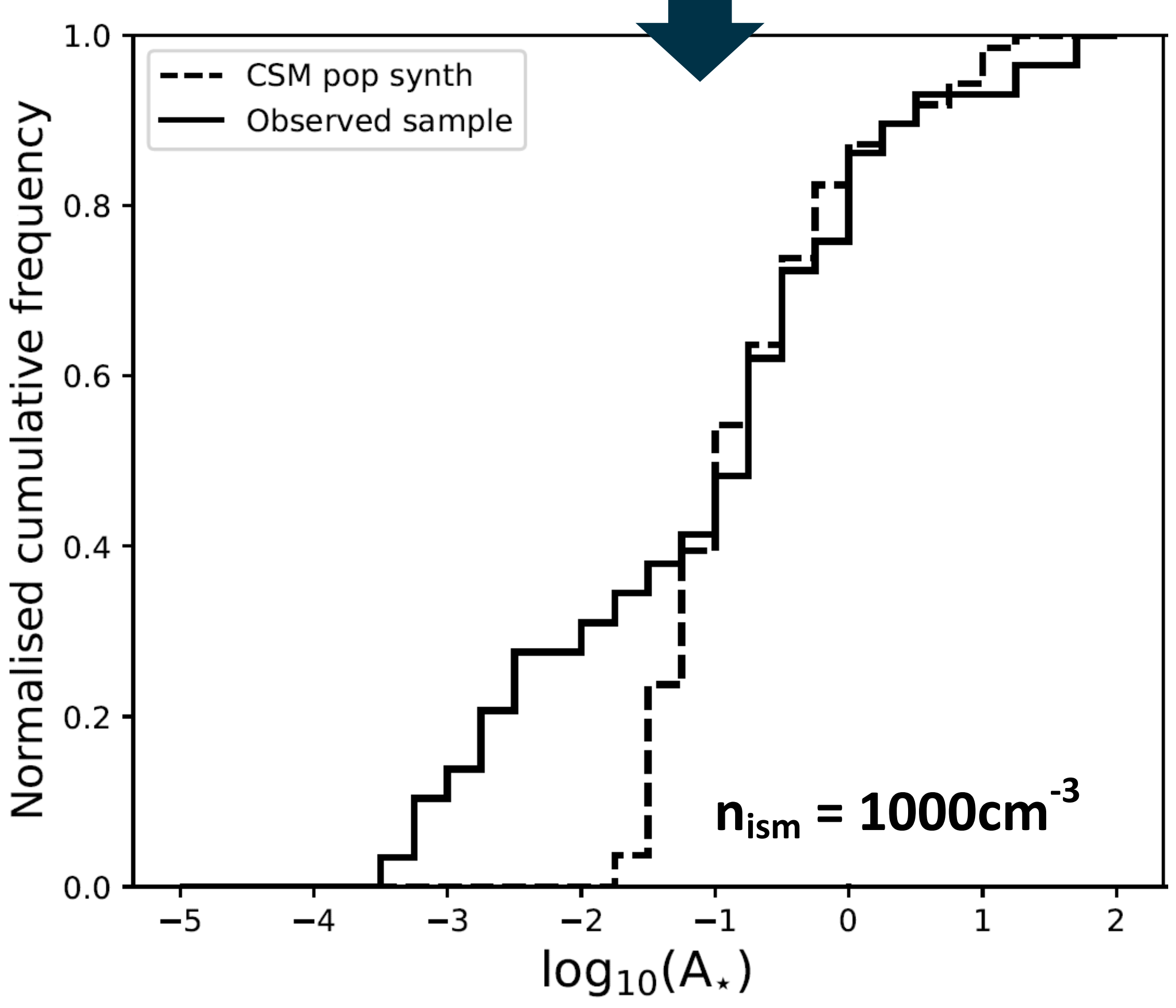
Z/Z⊙	-3.0	-2.2	-1.3	-0.5	0.3	1.2	2.0	2.8	3.7	4.5	5.3	6.2	7.0
0.005	1	1	1	1	1	1	1	1	1	1	1	1	1
0.05	1	1	1	1	1	1	1	1	1	1	1	1	1
0.1	1.7	1.5	1.4	1.2	1.1	1	1	1	1	1	1	1	1
0.15	2.4	2.2	1.9	1.7	1.6	1.4	1.3	1.1	1	1	1	1	1
0.2	3.1	2.8	2.5	2.2	2	1.8	1.6	1.5	1.3	1.2	1.1	1	1
0.3	4.4	4	3.6	3.2	2.9	2.6	2.3	2.1	1.9	1.7	1.5	1.4	1.2
0.4	5.7	5.1	4.6	4.1	3.7	3.3	3	2.7	2.4	2.2	1.9	1.7	1.6
0.5	6.9	6.2	5.6	5	4.5	4	3.6	3.3	2.9	2.6	2.4	2.1	1.9
0.7	9.3	8.3	7.5	6.7	6	5.4	4.9	4.4	3.9	3.5	3.2	2.8	2.6
1.0	13	11	10	9.2	8.3	7.4	6.7	6	5.4	4.8	4.3	3.9	3.5

4. AFTERGLOW SAMPLE

To compare with observations, we compile a dataset based on [9], adding radio data, and performing MCMC afterglow fits [10]. Each dataset is fit with wind-like and flat density profiles, and the better fit of the two is chosen. The observed ratio of ISM/wind-like bursts is 45/29 = 1.55±0.37 (Poisson uncertainties). Wind-like environments have more energetic bursts (at 2σ significance). The fits yield *A* for wind-like environments, *n* for constant density and the emission radius at 11 rest-frame hours, R_{emit}, in each case.

5. RESULTS

We produce synthetic distributions of *A*, *n* and R_{emit} for $10^{-3} < n < 10^7$ in order of magnitude steps. KS-tests between the synthetic and observed distributions are made at each density. For each of *A*, *n*, and R_{emit}, we determine the $\log_{10}(n/cm^3)$ which best reproduces observations. We find that $\log_{10}(n/cm^3)$=-1 best reproduces the observed *A* distribution, 5 best reproduces *n*, 7 is best for R_{emit} and 3 for the ratio of wind/ISM. Overall, high ISM densities of n=1000cm^{-3} best reproduce the observed distributions (e.g. right). High densities are required with our fiducial models in order to push R_{wind} to lower radii.



References: [1] Levan et al. (2016) – [2] Frail et al. (2001) – [3] Chevalier et al. (2004) – [4] Gompertz et al. (2018) – [5] Chrimes et al. (2020) – [6] Eldridge et al. (2017) – [7] - Garcia-Segura et al. (1995) – [8] Mignone et al. (2014) – [9] Kann et al. (2006) – [10] Dyer et al. (2020) – [11] van Marle et al. (2006)

6. CONCLUSIONS

We have shown that the gap between CSM theory and observation persists at a population level. Contributing factors may include wind strength overestimation, magnetic confinement, or actual occurrence in dense environments. It is unlikely that just one of these is responsible, but rather a combination of several effects [11].

A final thought: LFBOTs

Chrimes et al. (2024a,b) - Luminous Fast Blue Optical Transients (AT2018cow-like events) also show very dense Wolf-Rayet-like circumstellar media: do they have similar progenitors to collapsar GRBs?