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Imprints of dark stars in the 21-cm signal

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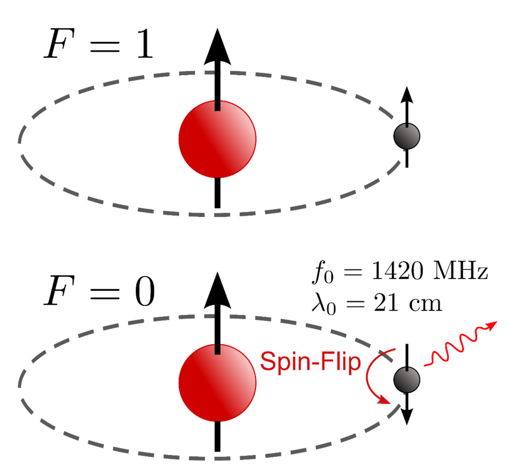
1. The 21-cm line



The hyperfine spin-flip transition of neutral hydrogen emits photons with wavelength of 21 cm. The line is commonly observed in astrophysics due to the high density of hydrogen in the intergalactic medium (IGM).

The relative abundance of the hydrogen states defines the **spin temperature** T_s .

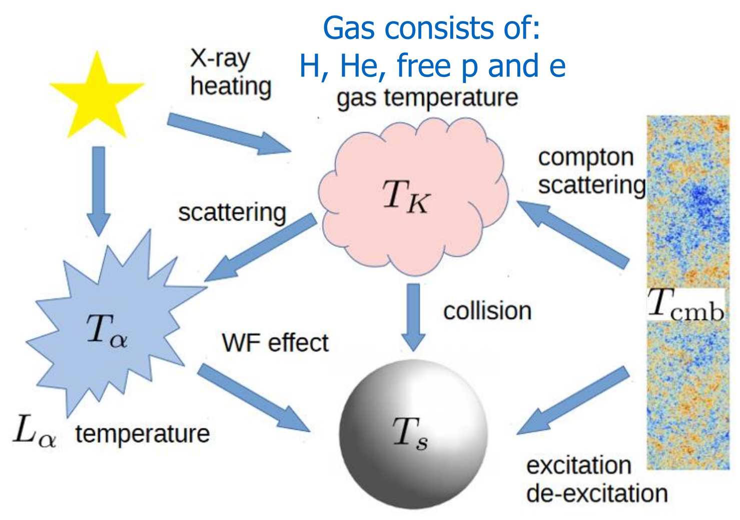
$$\frac{n_1}{n_0} = \frac{g_1}{g_0} e^{-\frac{E_{21}}{k_B T_s}} \sim 3\left(1 - \frac{E_{21}}{k_B T_s}\right)$$

This is a good quantity to track in order to measure the amount of hydrogen in the Universe.

What determines the spin temperature?

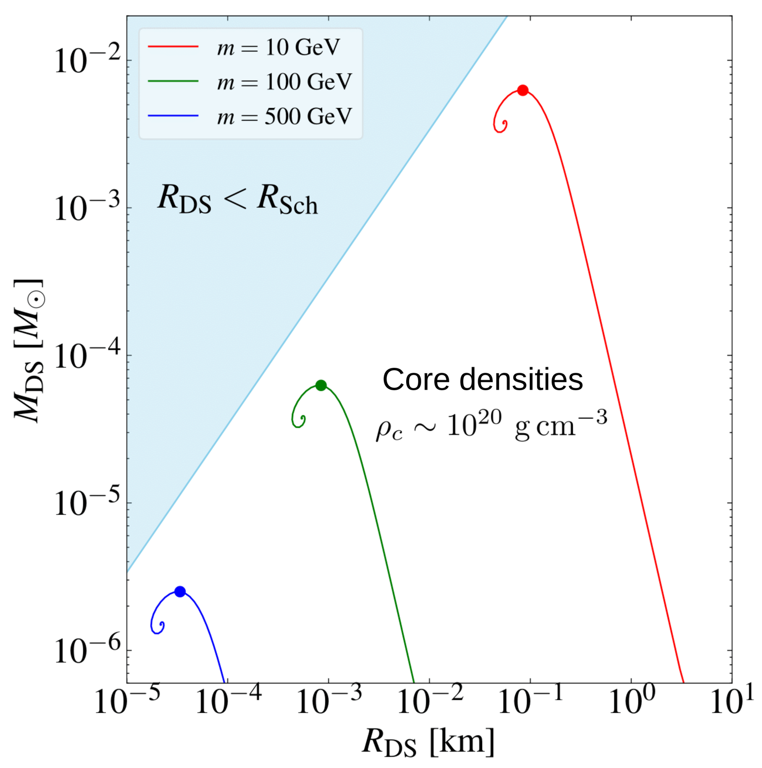
Three main effects:

1. H-H, H-e and H-e collisions induce the transition. The collision rate is related to the gas temperature T_k .
2. Absorbtion and emission of CMB flux.
3. Interaction with UV (Lyman-alpha) photons from the first stars. Wouthuysen-Field effect (ionization, excitation) related to radiation temperature T_α .



Our idea: could dark stars modify the spin temperature and consequently the amount of H? ★ ???

2. What are dark stars?

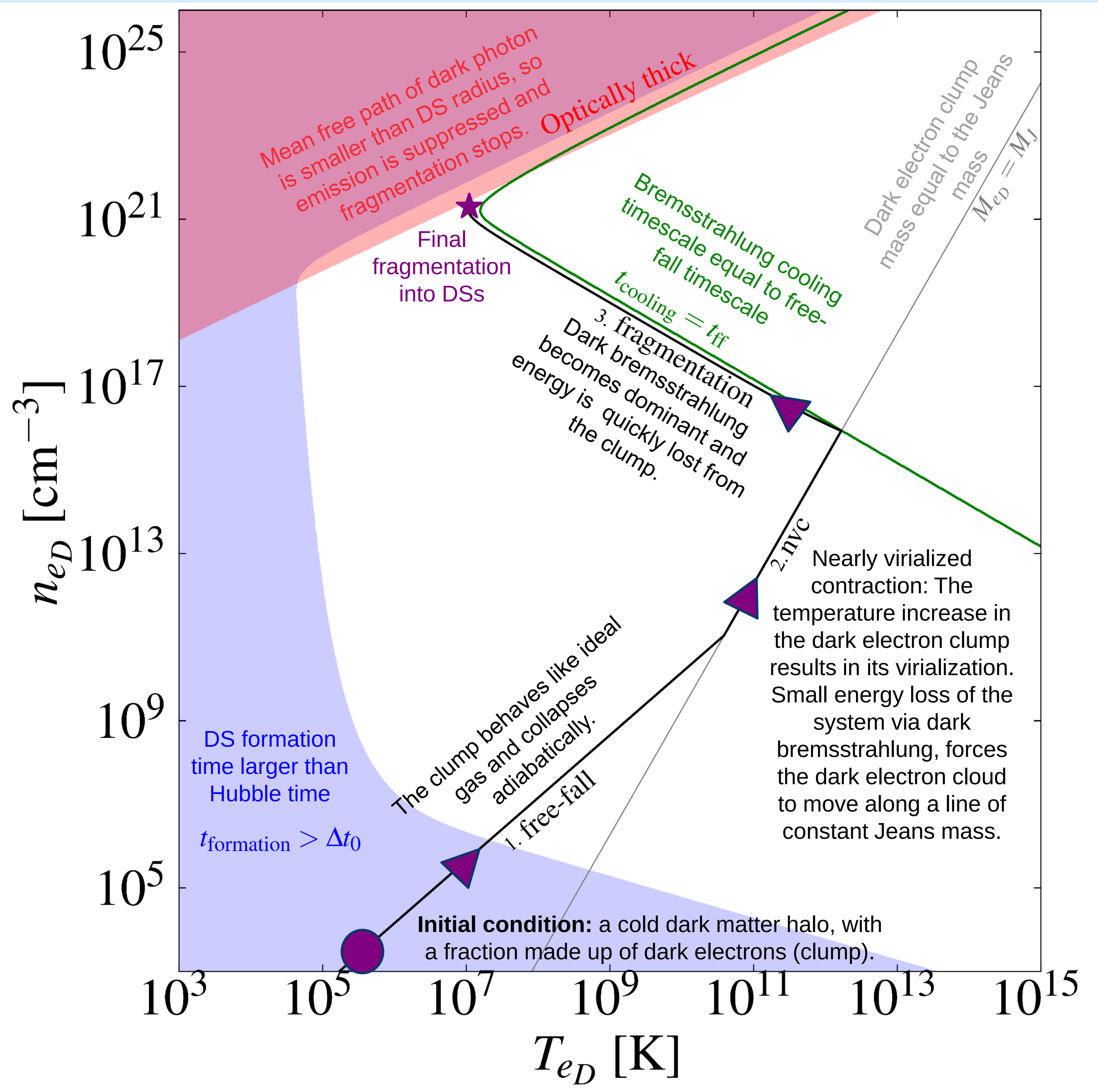


Self-interacting particle dark matter (DM) can lead to the formation of compact objects, the so-called "dark stars" (DS).

- We consider a dark "electron", as a subdominant component of DM (<1%).
- The structure of the DS will depend on the mass of the dark electron and the strength of the self-interaction.
- The figure shows the branches of possible solutions. Each curve is built by variation of the central density of the DS. The blue area denotes the region where the radius of the DS would be smaller than the Schwarzschild radius.

3. How do dark stars form?

Within a DM halo, the free dark electron component can proceed to further collapse only if there is an efficient mechanism that can evacuate energy from the system. In our case, we consider emission of bremsstrahlung dark "photons". This will result in a contraction of the dark electron population and fragmentation of the dark electron halo into DSs. In the figure, we show the trajectory in phase space of the initial dark electron halo until its fragmentation into DSs.

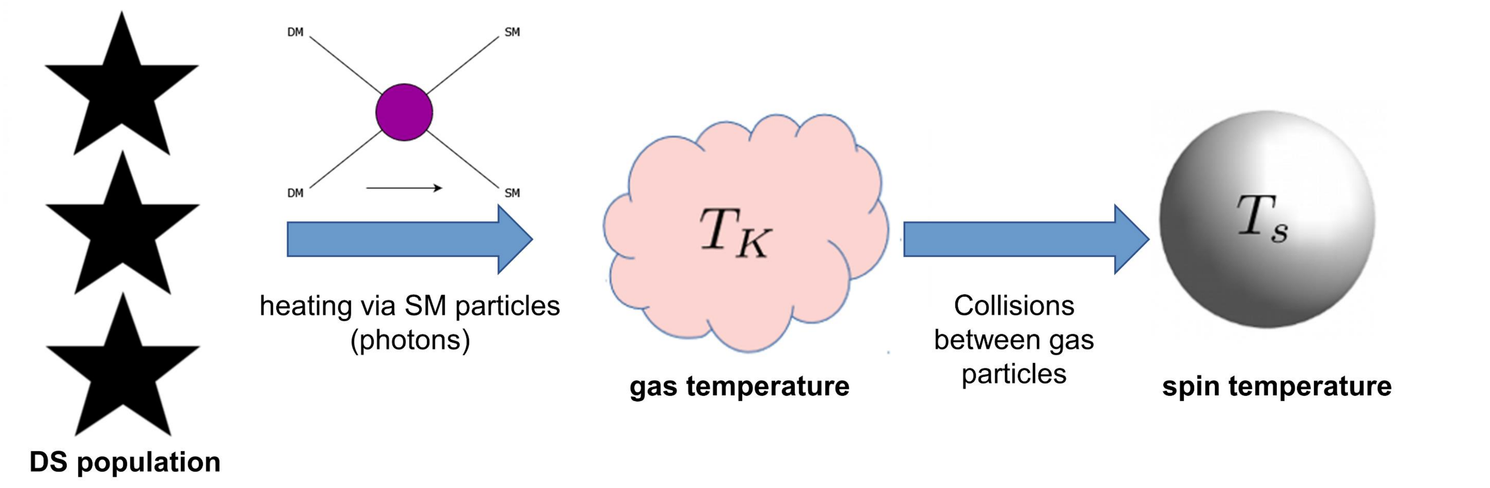


4. How do dark stars inject energy?

The high DM density of DSs offers a unique environment to probe DM number changing processes. Even with very weak interactions, DM particles inside a DS could be annihilating into Standard Model particles, with a cross section $(\sigma v)_{\rm ann}$. This would lead to a **luminosity**

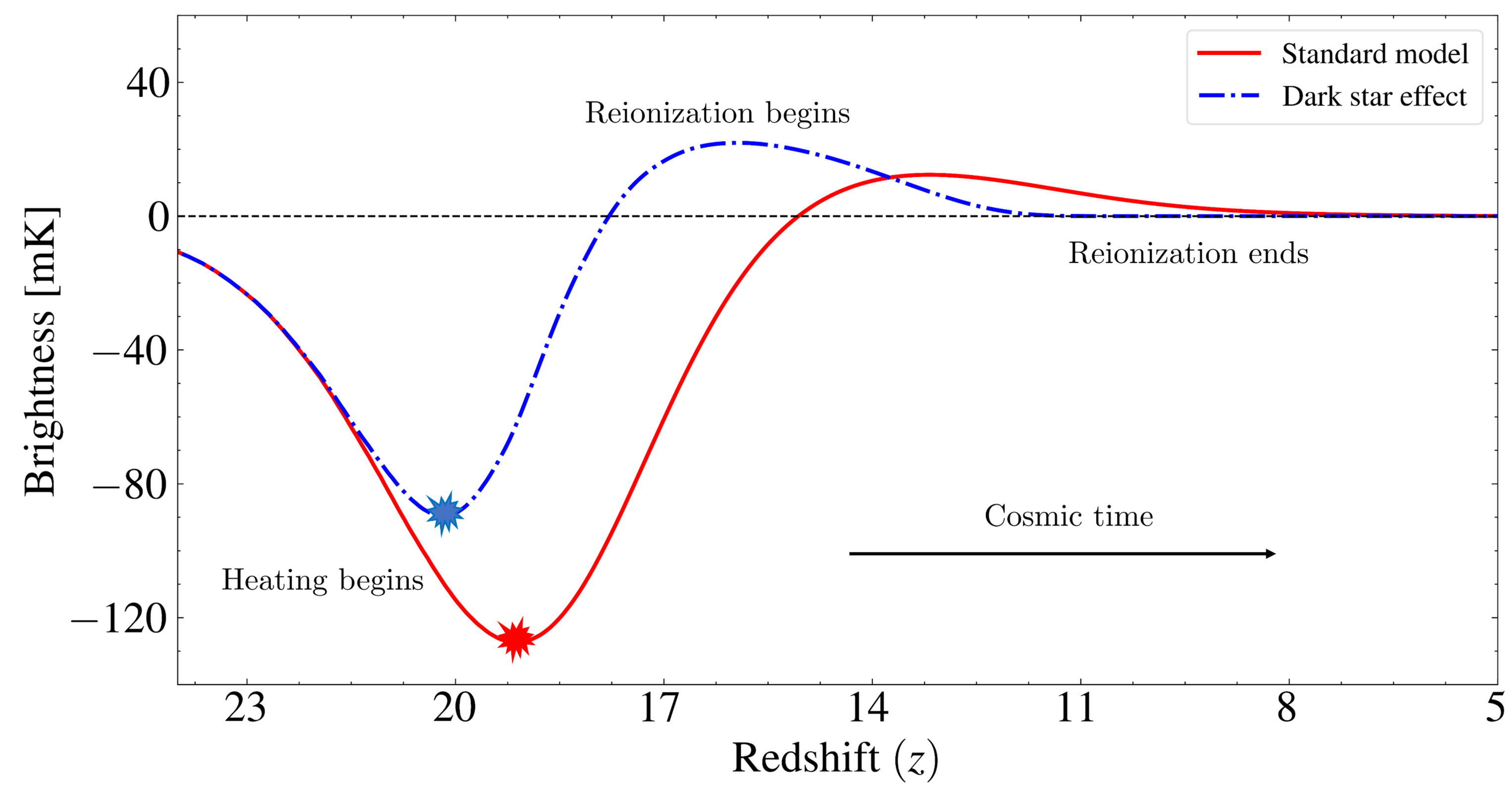
$$L = 8.3 L_\odot \left(\frac{(\sigma v)_{\rm ann}}{10^{-60}\,{\rm cm^3\,s^{-1}}}\right)\left(\frac{R_{\rm DS}}{100\,{\rm m}}\right)^3\left(\frac{\rho_c}{10^{20}\,{\rm g\,cm^{-3}}}\right)^2\left(\frac{m}{10\,{\rm GeV}}\right)^{-1}$$

The energetic Standard Model particles, which we particularize to photons, will then interact with the IGM and heat up the gas, which will influence the spin temperature.

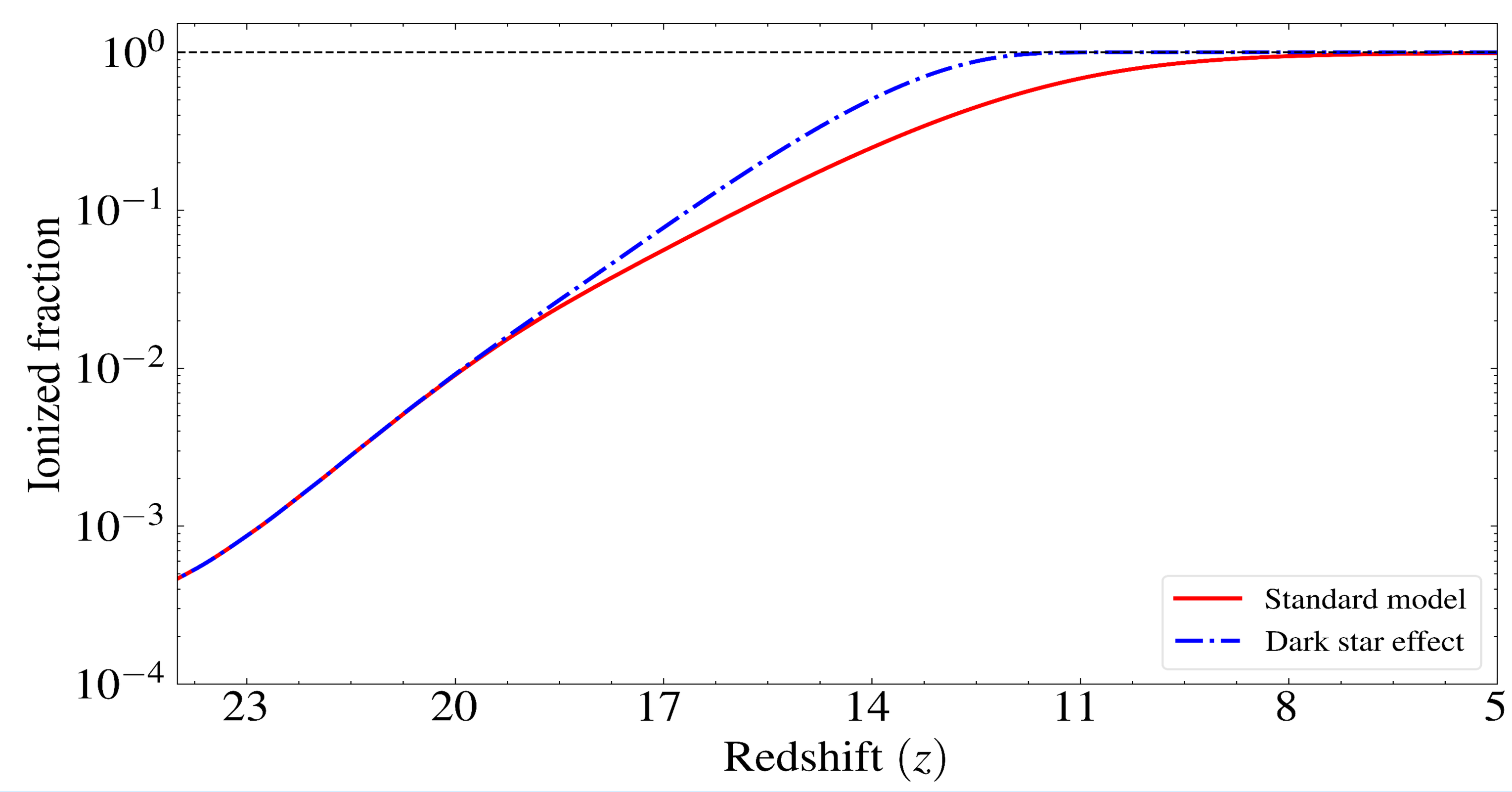


5. Imprints in the 21-cm signal

The crucial observable to determine the effect of DSs is the **21-cm brightness temperature** $T_{21} \propto (T_s - T_{\rm CMB})$. The figure below shows its evolution for the standard model (without DSs) and for a model with DSs to showcase their differences.



The brightness temperature also depends on the optical depth of the IGM $T_{21} \propto (1 - e^{-\tau})$. This is a measure of the amount of neutral hydrogen compared to the amount of free electrons in the Universe, encapsulated by the **ionized fraction** $x_e = \frac{n_e}{n_H}$, shown below.



From both plots we notice that:

- DSs **form earlier** than other stars, so they affect the signal at larger redshifts.
- As an ensemble, they **inject more energy**, which leads to a higher maximum of the brightness temperature.
- Both effects lead to an **earlier reionization** $x_e \sim 1$.

6. Conclusions

- If a small component of DM is self-interacting, it may collapse and form **compact objects called dark stars** inside DM halos.
- If this component possesses **DM annihilations** to photons, the high compactness and core densities of these dark stars may produce luminosities significantly larger than those of population II and III stars.
- Dark stars can then **heat up the IGM** and induce dramatic changes in the shape and amplitude of the 21 cm signal as well as in the overall ionized fraction of hydrogen.