How can circumstellar interaction explain the special light curve features of Type Ib/c supernovae?

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Introduction

As far as we know, stripped-envelope supernova (SESN) progenitors go through significant mass-loss during the pre-supernova evolution that supposedly leads to circumstellar matter around the progenitor star. The structure of this CSM mainly depends on the mass-loss history of the evolving star. If the mass loss is episodic, the surroundings of these progenitors could be complex and may significantly modify the overall observable light curve features of the supernova explosions.

Recent studies only find a possible connection between CSM interaction and the re-brightening of late-time SESNe light curves (e.g., Kuncarayakti et al. 2023), which suggests a far-away CSM. However, theoretical considerations (e.g., Maeda et al. 2021) suggest the CSM radius around a stripped-envelope supernova progenitor should be much smaller ($10^{14} - 10^{15}$ cm), which presumes that this matter is just ejected a few months before the SN explosion. But we may resolve this controversy if we assume an extreme episodic mass-loss (0.1 - $1 M_\odot$) event at the end of stellar evolution. This theory may also explain the earlier (at around 60-100 days after the explosion) light curve bumps of SESNe if an eruption occurs some days or weeks before the supernova explosion.

Basic modeling features

To test how different progenitor scenarios and CSM configurations affect the observable parameters of Type Ib/c supernovae, we computed the bolometric light curve of both interacting single- and binary progenitor models via hydrodynamic simulations. Then, we add a simple CSM structure using analytic approximations to create the unique physical configuration of a close circumstellar matter caused by an extreme mass-loss event just a few days or weeks before the cataclysm.

We calculate all the progenitor models using the Modules for Experiments in Stellar Astrophysics (MESA version r-12778), which is a 1-dimensional, numerical hydrodynamic stellar evolution code (Paxton et al. 2011).

Then, we use an analytic code to generate different thin ($R_{CSM} \leq 10\, R_p$) and low-mass ($M_{CSM} \leq 2\, M_\odot$) CSM configurations with a power-law density profile and add them to the MESA models. As a final step, we calculate the bolometric light curves of our progenitor models with and without the attached circumstellar matter using the 1D spherical Lagrangian SuperNova Explosion Code (SNEC, Morozova et al. 2015).

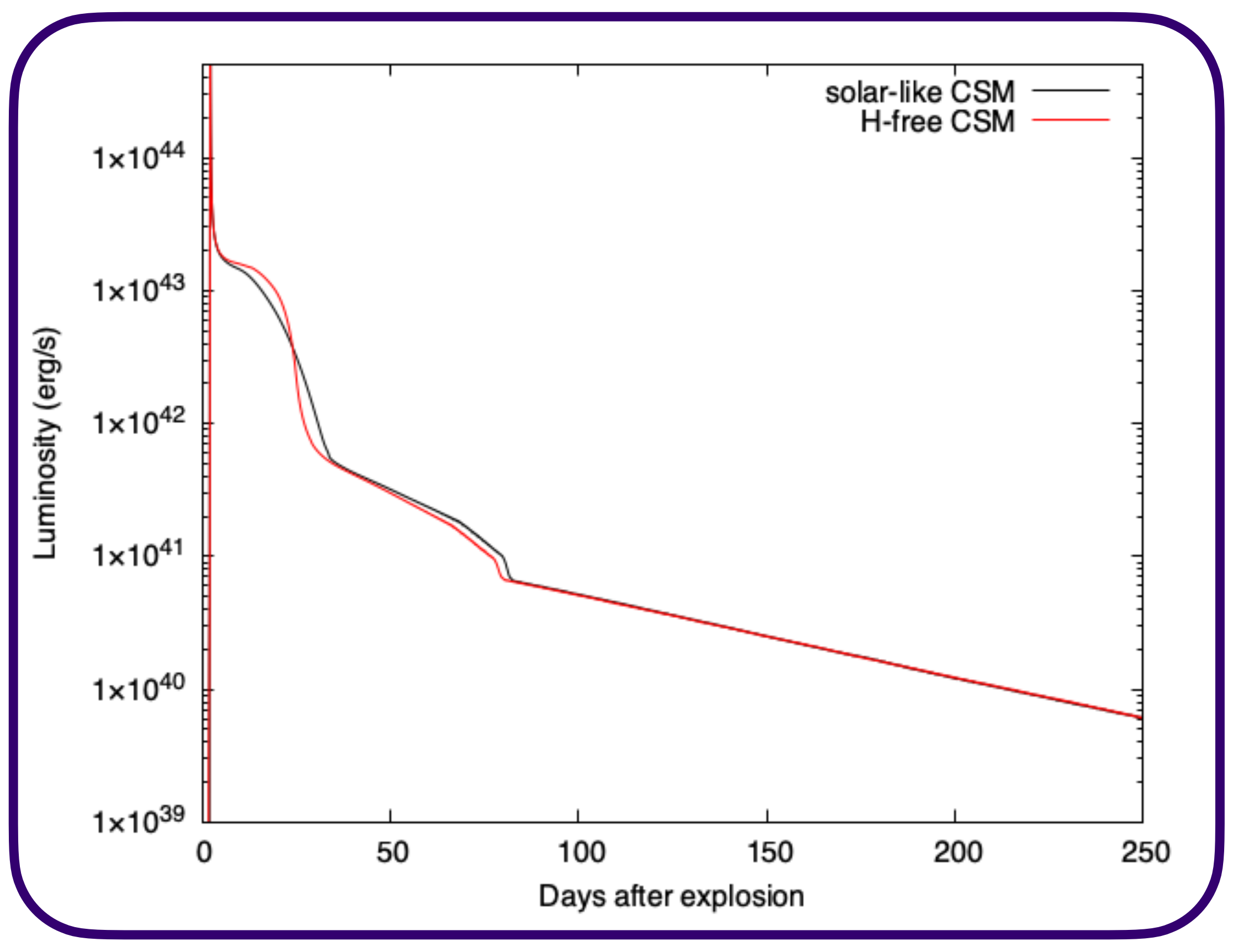

Fig. 1. Comparing the bolometric light curve features of a He-free (red line) and a solar-like (black line) CSM.

CONCLUSIONS

> a close, dense CSM may be responsible for the unique light curve features (re-brightening, double peak) of some stripped-envelope supernovae

> the light curve shape of stripped-envelope supernovae could indicate that the cataclysmic death of the massive star happened in a binary system or was related to the explosion of a single star

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CSM configuration

Here, we assume that the circumstellar matter is attached to the progenitor. Thus, its inner radius is equal to the radius of the progenitor.

We adopt a power-law density profile, where the initial density of the CSM (ρ_0) is estimated to be identical to the density at the progenitor surface and its value proportionate to the quadratic of the radius element of the CSM (r) as

$$\rho(r) = \rho_0 \left(\frac{R_p}{r}\right)^2 .$$

Here, we also assume that the chemical composition of the circumstellar matter is solar-like, mainly containing hydrogen and helium. A pure He-composition would be more realistic as an expected blown-off layer of a massive, convective star in such a late evolution phase. However, for an H-free CSM, SNEC calculations become time-consuming and, in many cases, numerically unstable. Moreover, no significant differences can detected for the overall light curve features or maximal luminosities, except the first peak shows a steeper luminosity cut (Fig. 1).

Bolometric light curves

We examined how the mass and the radius of the CSM affect the bolometric light curve of Type Ib/c supernovae. Here, Fig. 2. and 3. demonstrate the mass dependence, while Fig. 4. and 5. shows the effect of different CSM radii of interacting single- and binary stars, respectively.

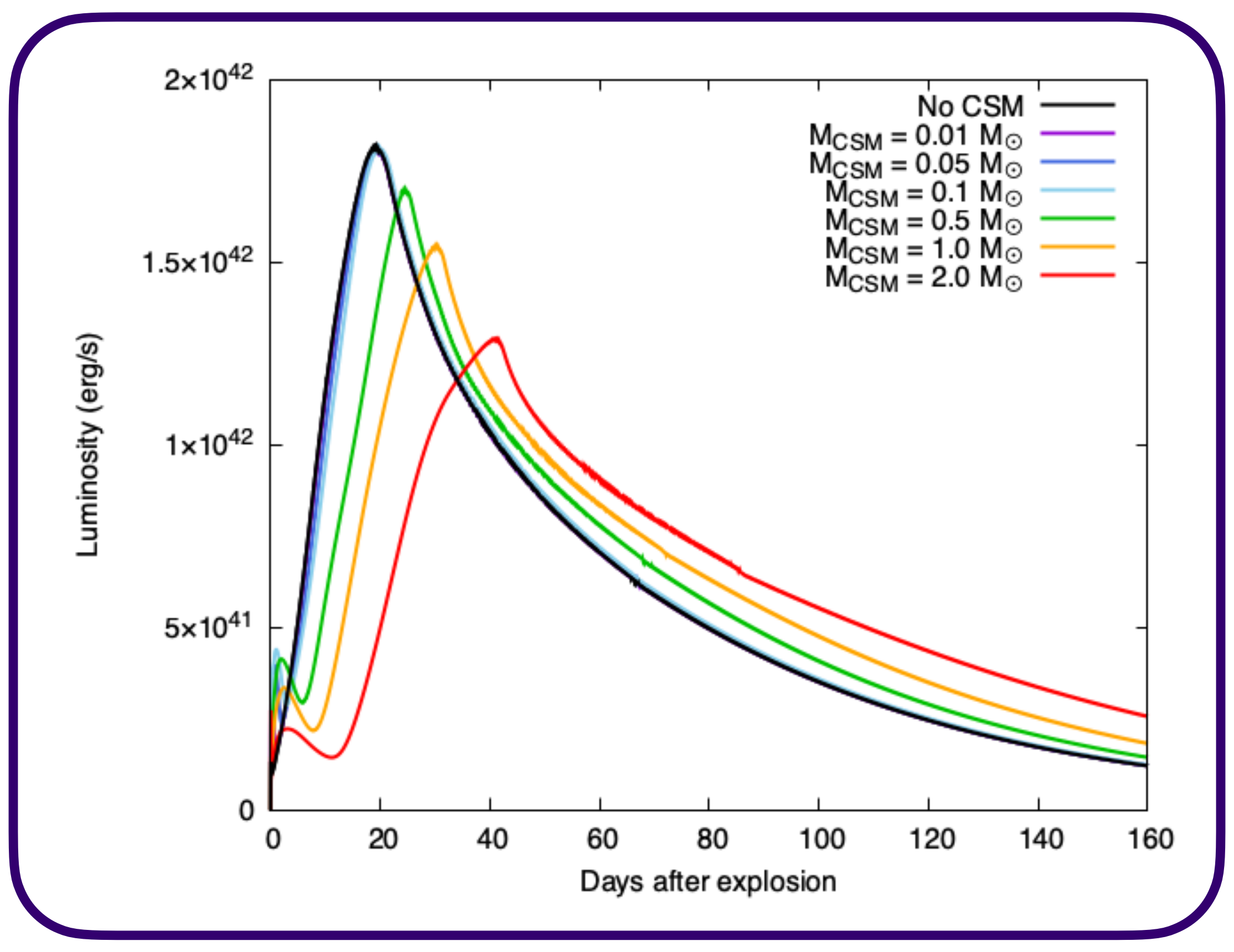

Fig. 2. The effect of different CSM mass on the bolometric light curves of single-star models.

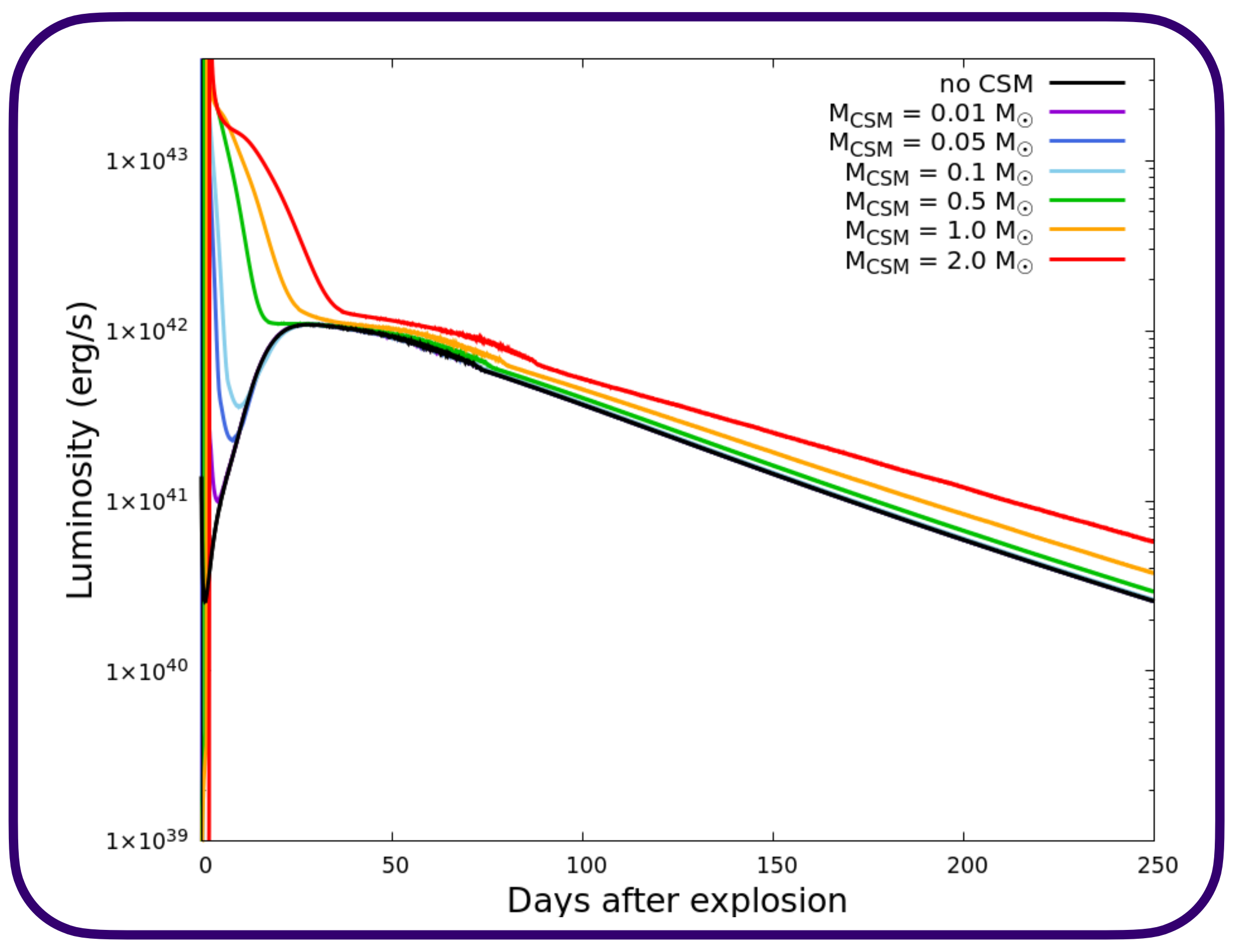

Fig. 3. The effect of different CSM mass on the bolometric light curves of binary models.

For both progenitor scenarios, a fast-declining early peak appears. With increasing CSM mass, this early LC characteristic turns less luminous and broader, while the second light curve peak also changes significantly by this early bump. Moreover, with higher CSM mass, the late-time light curves more and more depart from the nickel-cobalt tail, and its slope becomes less steep.

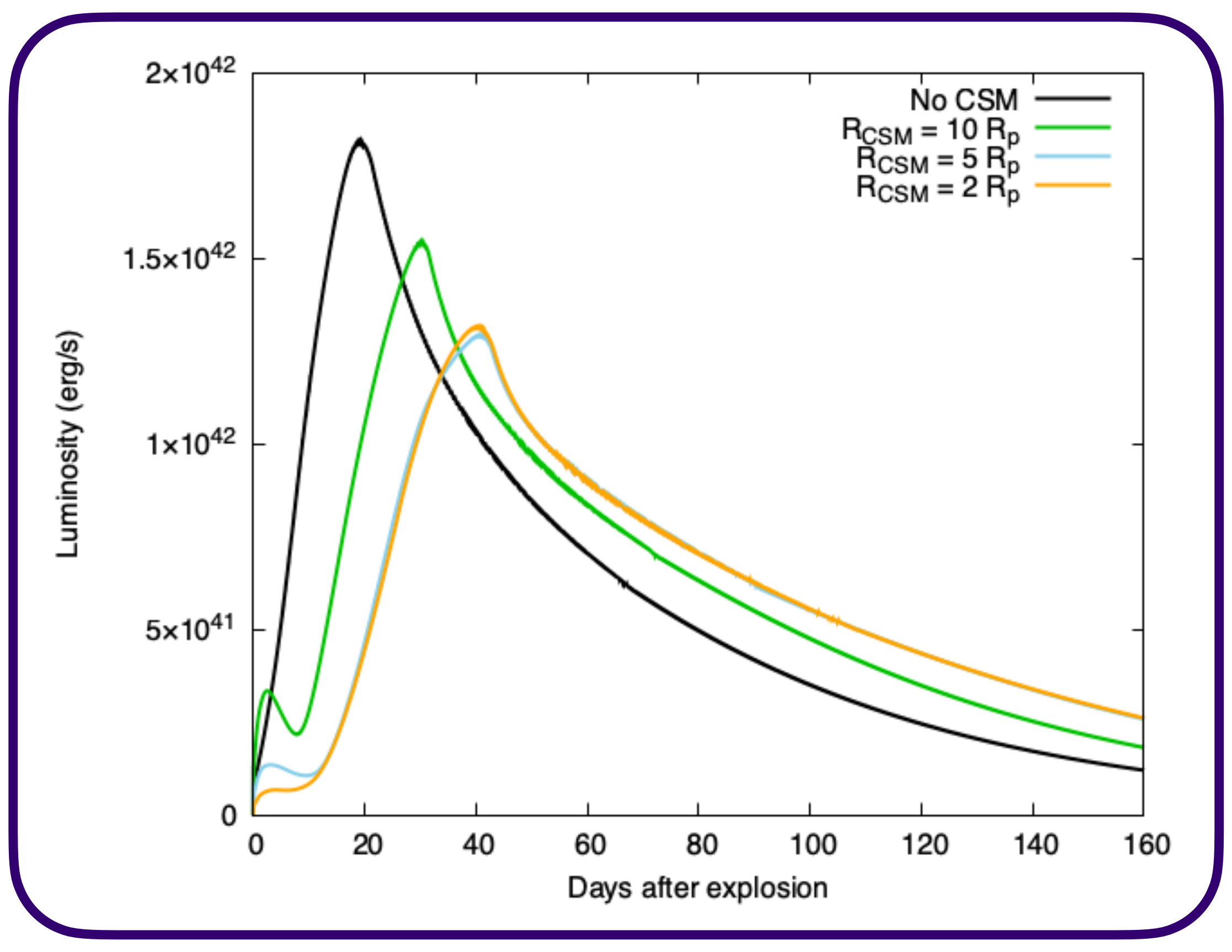

Fig. 4. The effect of different CSM radii on the bolometric light curves of single-star models.

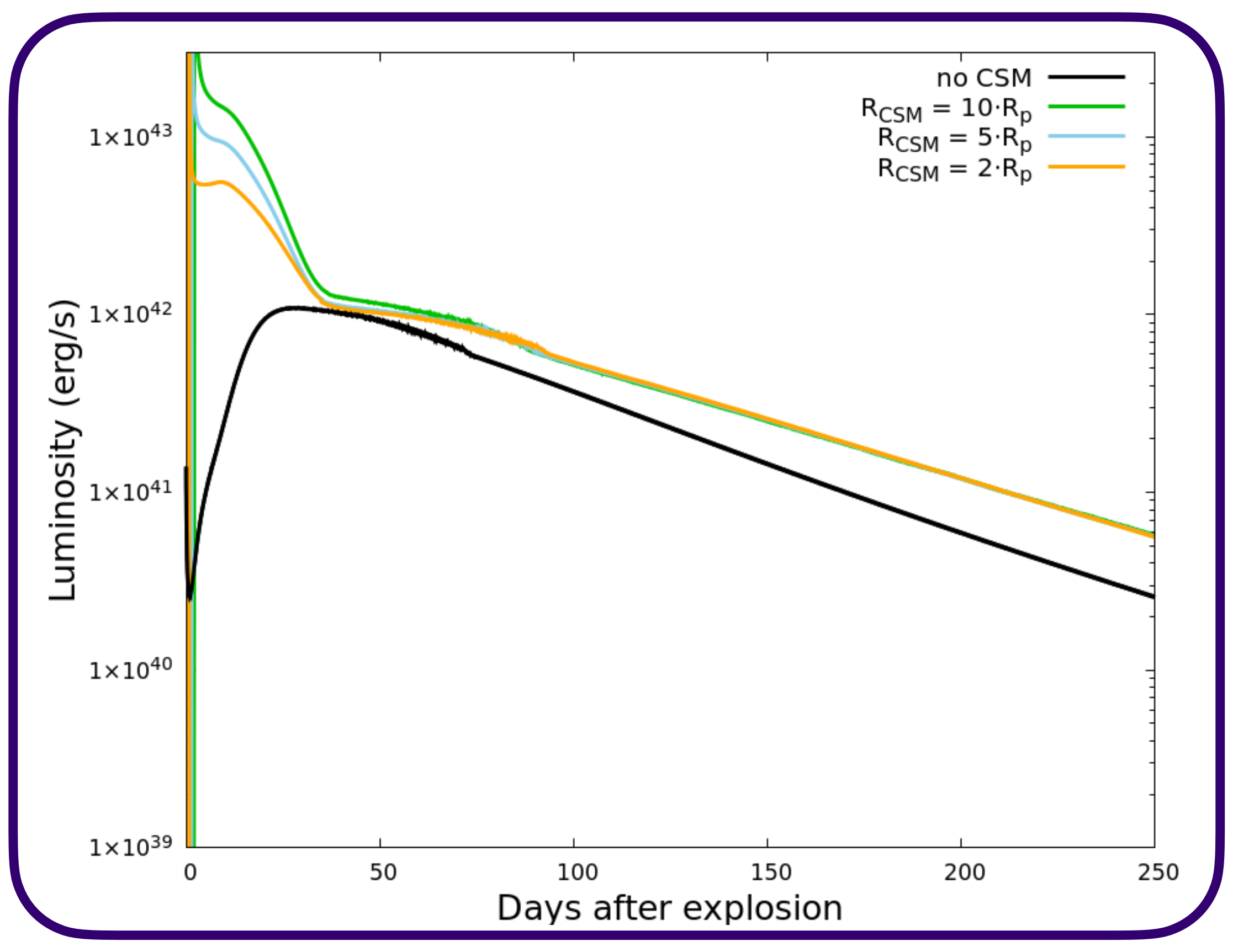

Fig. 5. The effect of different CSM radii on the bolometric light curves of binary models.

Acknowlegements

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