A hot subdwarf–white dwarf super-Chandrasekhar candidate supernova Ia progenitor

Ingrid Pelisoli, P. Neunteufel, S. Geier, T. Kupfer, U. Heber, A. Irgang, D. Schneider, A. Bastian, J. van Roestel, V. Schaffenroth and B. N. Barlow

Supernovae Ia are bright explosive events that can be used to estimate cosmological distances, allowing us to study the expansion of the Universe. They are understood to result from a thermonuclear detonation in a white dwarf that formed from the exhausted core of a star more massive than the Sun. However, the possible progenitor channels leading to an explosion are a long-standing debate, limiting the precision and accuracy of supernovae Ia as distance indicators. Here we present HD 265435, a binary system with an orbital period of less than a hundred minutes that consists of a white dwarf and a hot subdwarf, which is a stripped core–helium-burning star. The total mass of the system is $1.65 \pm 0.25$ solar masses, exceeding the Chandrasekhar limit (the maximum mass of a stable white dwarf). The system will merge owing to gravitational wave emission in 70 million years, likely triggering a supernova Ia event. We use this detection to place constraints on the contribution of hot subdwarf–white dwarf binaries to supernova Ia progenitors.

Type Ia supernovae (SNe Ia) represent one of the crucial rungs on the cosmic distance ladder. As bright standard candles, they contribute to obtaining measurements of the Hubble constant $H_0$, which describes how fast the Universe is expanding at different distances. An accurate determination of the systematic uncertainties involved in these cosmological measurements requires a reliable identification of the progenitor channels that contribute to the observed SN Ia population. Current measurements of $H_0$ in the local Universe that rely on SNe Ia are inconsistent with estimates using the cosmic microwave background radiation observed by the Planck experiment. To establish whether this $H_0$ tension is evidence for new physics or rather a consequence of poor determination of systematic uncertainties, it is imperative to understand possible SN Ia channels and their relative contributions.

Although the origin of SNe Ia has long been understood as a thermonuclear detonation in a white dwarf, triggered when a critical mass near the Chandrasekhar limit of $1.4M_\odot$ is reached, the mechanism for the explosion itself remains under debate. Possible channels for achieving critical mass can be generally grouped as either double-degenerate or single-degenerate. In the double-degenerate channel, the white dwarf has another compact star as a companion, and the detonation is triggered by the merger of the two objects. In the single-degenerate channel, the white dwarf accretes mass from a companion to a point at which thermonuclear explosion is triggered. Confirmed progenitors are extremely scarce for both channels, making it challenging to explain observed rates. The once promising Henize 2-428 system has recently been shown to have a total mass significantly lower than previously derived, and can no longer be considered as an SN Ia progenitor. Even in the dedicated European Southern Observatory (ESO) Supernovae Type Ia Progenitor Survey (SPY), only two systems (WD2020-425 and HE2209-1444) have been identified as possible progenitors, both with sub-Chandrasekhar total masses. The only known super-Chandrasekhar candidate progenitor is KPD1930+2752 (refs. 18, 19), a hot subdwarf with a close white dwarf companion. Another similar albeit less massive binary, CD-30°11223 (refs. 19, 20), also qualifies as SN Ia progenitor. These merging massive systems can also be of interest as gravitational wave sources, in particular as verification sources for the upcoming Laser Interferometer Space Antenna (LISA).

Here we report the discovery that HD 265435 is a candidate supernova progenitor and LISA verification binary composed of a hot subdwarf with a massive white dwarf companion. This binary system, with an apparent visual magnitude $V = 11.78$, is at a distance of less than 500 pc from the Sun, making it the closest super-Chandrasekhar candidate supernova progenitor. We analysed the light curve obtained by the Transiting Exoplanet Survey Satellite (TESS) together with time-series spectroscopy to characterize the system and determine the component masses. The properties of this binary make it a candidate for both the single-degenerate and double-degenerate SN Ia channels.

Results

HD 265435 (TIC 68495594) was observed by TESS in Sector 20. The data revealed strong ellipsoidal variation, suggesting that the visible component of the system is tidally deformed by a compact object. The light curve also reveals pulsation frequencies showing rotational splitting. Following this discovery, we obtained time-series spectroscopy at the Palomar 200-inch telescope with the Double-Beam Spectrograph (DBSP) covering one orbital cycle, with the aim of obtaining the radial velocity curve of the visible star. We also obtained high-resolution spectra with the Echelle Spectrograph and Imager (ESI) at the Keck II telescope to determine the line-of-sight rotational velocity, $v\sin i$. Combining the
Periodogram of the TESS light curve. 

In the full periodogram, a dominant peak can be seen at 49.54959(15) min, corresponding to half of the orbital period. Multiple low-period peaks can also be identified in the range of 4–6 min, as detailed in the inset.

period determination. A Lomb–Scargle periodogram of the TESS light curve showed a dominant peak at 49.54959(15) min (Fig. 1). Phase-folding of the light curve to twice this dominant peak revealed the occurrence of Doppler boosting\(^1\), which caused a height difference of \(\sim 0.3\%\) between consecutive maxima, indicating that the real orbital period is \(P = 99.09918(29)\) min. A smaller amplitude peak can be seen at this period, as well as harmonics at \(P/3\) and \(P/4\). The periodogram also shows a wealth of short-period peaks, which are in the correct range for \(p\)-mode pulsations of the hot subdwarf\(^2\). We identified a total of 33 frequencies above a detection level of five times the average amplitude of the Fourier transform (Supplementary Table 1). Many of these frequencies are part of rotational multiplets, which result from the spherical symmetry being broken by rotation\(^2\). The separation is expected to be proportional to the rotation period and close to equal to it for \(p\)-mode oscillations\(^2\). We find the separation between peaks to be equal to the orbital period (Supplementary Fig. 1), suggesting that the hot subdwarf of spectral type OB (sdOB). The orbital inclination \(i\) of the system was obtained from the estimated \(v\sin i\), given the evidence that the hot subdwarf is tidally locked, and that in turn allowed us to constrain the mass of the unseen companion, which is likely a white dwarf with a carbon–oxygen (CO) core. We also fitted the TESS light curve without relying on any stellar parameters derived from the spectroscopy, obtaining a consistent solution (within 2\(\sigma\)) that confirms the nature of the companion. The obtained stellar and binary parameters for HD 265435 are provided in Table 1.

### Table 1: Astrometric, stellar and orbital parameters for HD 265435

| Parameter | Spectroscopic solution | Light curve solution | Adopted value |
|-----------|------------------------|----------------------|---------------|
| RA (J2000) | -                      | -                    | 06:53:24.30   |
| dec. (J2000) | -                      | -                    | +33:03:34.2   |
| \(\pi\) (mas) | -                      | -                    | 2.216 ± 0.055 |
| \(\mu_\alpha\) (mas yr\(^{-1}\)) | -                      | -                    | -4.83 ± 0.06  |
| \(\mu_\delta\) (mas yr\(^{-1}\)) | -                      | -                    | -4.583 ± 0.0492 |
| \(T_{\text{eff}}\) (K) | 34,300 ± 400           | Fixed                | 34,300 ± 400  |
| \(\log g\) | 5.62 ± 0.10            | 5.52 ± 0.04          | 5.55 ± 0.04   |

Astrometric parameters are from Gaia EDR3\(^3\), with a zero-point correction applied to the parallax\(^1\). For stellar and orbital parameters, we show the values obtained from both spectroscopic analyses and the light curve fit, if derived independently, as well as the adopted values that result from combining the two solutions by concatenating the distributions obtained for each parameter. Quoted values are the median, and uncertainties give the 68% confidence interval. Where a \(2\) fit was employed, the systematic uncertainty was quadratically added to the statistical fit uncertainty. Quantities shown are the right ascension RA; declination dec.; proper motions in the right ascension, \(\mu_\alpha\) and declination, \(\mu_\delta\); directions; hot subdwarf effective temperature \(T_{\text{eff}}\); luminosity \(L\); white dwarf mass \(M\); zero point of the ephemeris \(T_0\); orbital period \(P\); radial velocity semi-amplitude of the hot subdwarf \(K_{\text{eff}}\); systemic velocity of the binary \(V_0\); mass ratio \(q\); orbital inclination \(i\); orbital distance \(a\); merging time owing to gravitational waves \(\tau\); and gravitational wave amplitude \(A\).
Characterizing the system and the nature of the companion. The obtained spectra revealed the visible component to be an sdOB, as already suggested based on its Gaia DR2 parameters. We performed spectral fits of the Doppler-corrected DBSP spectra (Methods), obtaining an effective temperature of $T_{\text{eff}} = 34,300 \pm 400$ K and surface gravity with $\log g = 5.62 \pm 0.10$. With $T_{\text{eff}}$ and log $g$ fixed, we obtained $v \sin i$ and helium-to-hydrogen ratio (by number) $\log y$ by fitting each of the high-resolution ESI spectra separately, to avoid additional broadening introduced by co-adding the spectra. This resulted in $\log y = -1.46 \pm 0.04$ and $v \sin i = 152 \pm 6$ km s$^{-1}$.

Radial velocity curve of the hot subdwarf. We determined the radial velocities by cross-correlating each spectrum obtained with DBSP with a best-fit spectral template (see Methods for a full description of the procedure). We analysed spectra from the blue and red arms separately, as they are not obtained simultaneously, and obtained consistent radial velocities. We fitted the radial velocities assuming a circular orbit with the period fixed to the photometric period, as the time span of our radial velocity curve would not allow a precise independent determination of the period. We allowed the zero point of the ephemeris to vary by $P/2$ to account for possible phase shifts between the photometric and spectroscopic data, obtaining a value consistent with the photometry within four decimal places. The best-fit model is shown in Fig. 2b. The obtained radial velocities revealed a large radial semi-amplitude of $K_{\text{sd}} = 343.1 \pm 1.2$ km s$^{-1}$, implying a mass function for the unseen companion of

$$f_{\text{comp}} = \frac{M_{\text{comp}}^3 \sin^3(i)}{(M_{\text{sd}} + M_{\text{comp}})^2} = \frac{P K_{\text{sd}}^3}{2\pi G} = 0.288 \pm 0.003 M_{\odot}. \quad (1)$$

By combining the obtained systemic velocity with the Gaia astrometric information, we found the system to show dynamics consistent with the thin disk of the Galaxy (Methods).

Fig. 2 | Phased data for HD 265435. a, b. Light curve data (a) and radial velocity data (b), all phase-folded to the obtained ephemeris. In a, the original TESS data are shown as grey dots. The phased data were binned every 50 points for the light curve fit, as shown by the black crosses. The median 1σ uncertainty for the binned data is shown as a bar at the top left. In b, the individual radial velocity estimates are shown in black with their 1σ uncertainties.

The TESS two-minute cadence is not adequate for correctly sampling such short periods, and therefore we attempted no asteroseismological analysis. These periods were identified so that their effect could be subtracted from the light curve before modelling the effect of the binary companion; otherwise, they would have led to systematic errors on the final fit parameters. This was done recursively: we first calculated a preliminary model for the variability due to binarity (Methods), which we then subtracted from the original light curve to determine the short periods. Next, we performed a global fit using all 33 identified peaks and subtracted the obtained model from the original light curve. The preliminary model was also used to fit the full light curve to refine the period and determine the zero point of the ephemeris (adopted here as the superior conjunction of the unseen companion). We obtained a period of $P = 0.0688184888(32)$ days and a zero point with Barycentric Julian Date of BJD$_0$ = 24571909.6899552(26) days. The light curve and radial velocity data folded using this ephemeris is shown in Fig. 2.
By performing a fit to the SED (Methods), we found the photometry to be consistent with a single hot subdwarf, finding no contribution from the unseen companion. Using the Gaia EDR3 parallax, our SED fit provided a radius estimate of $R_{\text{sd}} = 0.203 \pm 0.006 R_\odot$ implying a hot subdwarf mass of $0.62^{+0.17}_{-0.12} M_\odot$ from the obtained log g. Based on the indication that the rotational period of the hot subdwarf is synchronized with the orbital period, the orbital inclination can also be obtained from the radius and from $v \sin i$, which give $76 \pm 6^\circ$. Finally, equation (1) can be solved to obtain the mass of the unseen companion, which is found to be $0.91^{+0.11}_{-0.09} M_\odot$; this corroborates its nature as a compact object, as no contribution from an early-type companion is observed.

Alternatively, the multiple effects observed in the light curve of HD 265435 can be used to constrain some stellar parameters of the system independently from the spectroscopy. The ellipsoidal variation, gravity darkening and Doppler boosting effects depend mainly on the radius of the hot subdwarf and on the masses of both components. The temperature and radius of the unseen companion, by contrast, can still not be constrained, as its contribution to the light curve is negligible and no eclipses are observed.

We fitted the light curve using LCURVE (v.1.3)31, a code that uses an inhomogeneous grid of points, which was optimized to reproduce the stellar surface area, to model the brightness of two orbiting stars with shapes set by a Roche potential. We left as free parameters the mass ratio $q$, the inclination angle $i$, the scaled equatorial radius of the hot subdwarf $r_{\text{sd}} = R_{\text{sd}}/a$, where $a$ is the orbital distance, and the velocity scale $V_{\text{scale}} = (K_{\text{sd}} + K_{\text{comp}})/\sin i$, where $K_{\text{comp}}$ is the semi-amplitude of the companion. The value of $K_{\text{sd}}$ was required to be consistent with the determination from the radial velocity observations, but no other priors were applied (see Methods for details on the procedure).

We obtained $q = 1.70^{+0.11}_{-0.09}$, $i = 60 \pm 2^\circ$, $r_{\text{sd}} = 0.289 \pm 0.009$ and $V_{\text{scale}} = 625 \pm 25$ km s$^{-1}$. These parameters imply masses of $M_{\text{sd}} = 0.64^{+0.10}_{-0.09} M_\odot$ and $M_{\text{comp}} = 1.10^{+0.11}_{-0.09} M_\odot$ and a hot subdwarf radius of $R_{\text{sd}} = 0.232^{+0.012}_{-0.012} R_\odot$, which are consistent with the parameters derived from spectroscopic fitting within their 95% confidence intervals, as illustrated in Fig. 3.

By combining the two consistent solutions by concatenating the distributions obtained for each parameter, we found the stellar and orbital parameters given in the third column of Table 1. The mass of the companion is found to be $M_{\text{comp}} = 1.01 \pm 0.15 M_\odot$. This implies that the companion is likely a white dwarf with a CO core, although an O–Ne(−Mg) composition is possible if the mass is above $1.088 M_\odot$ (ref. 22). The total mass of the system is found to be $1.65 \pm 0.25 M_\odot$.

**Future evolution of HD 265435.** The evolution of a binary is primarily determined by the total mass of the system, the initial orbital separation and the evolutionary status of the hot subdwarf at the time of Roche-lobe overflow (RLOF). The obtained radius hints at a hydrogen envelope with a current mass around $1.5 \times 10^{-4} M_\odot$, which is typical for hot subdwarf stars32.

We carried out numerical simulations of the evolution of the system to determine its possible outcomes. Assuming solar metallicity, a helium star with a total mass of $0.63 M_\odot$ and a remaining H-envelope of $10^{-3} M_\odot$ about halfway through its expected core–helium-burning lifetime yields physical parameters consistent with the observed values (Fig. 4a). The model was placed in a binary with a carbon–oxygen-core white dwarf approximated by a point mass. We included the effects of rotation, assuming tidal locking and angular momentum loss through gravitational radiation. Our benchmark model assumes no wind mass loss, which is the standard assumption in modelling of hot subdwarfs. However, as our results are partially sensitive to the occurrence of winds, which are, in the case of hot subdwarf stars, still a matter of debate, we also included a weak wind34 in an alternative model. We note that inclusion of wind suggests an initial mass of the hydrogen envelope of $3 \times 10^{-3} M_\odot$, half of which has been ejected by the time of observation. Further details of the simulation are given in the Methods section.

We found that RLOF is precipitated by the end of the hot subdwarf’s core–helium-burning phase after $\sim 29.6$ million years (Fig. 4b,c). In our benchmark model, subsequent expansion then leads to RLOF. The transferred material will be hydrogen-enriched for the first $\sim 3.0$ million years of RLOF, and will subsequently become helium-enriched as the remaining hydrogen envelope is stripped. The He-enriched phase is expected to last for $\sim 1$ million years, resulting in $\sim 0.015 M_\odot$ of He-rich material being transferred. Mass transfer rates are expected to lie in the range of $10^{-11} - 10^{-9} M_\odot$ yr$^{-1}$, enough to induce a phase of classical nova eruptions35,36, and will not exceed $2.5 \times 10^{-8} M_\odot$ yr$^{-1}$ during the He-rich phase, which indicates that helium will be accumulated quiescently, without igniting37,38, on the white dwarf.

The introduction of a weak wind has the effect of delaying the RLOF phase, which then happens after $\sim 37$ million years (Fig. 4b,d).
This discrepancy in the onset of RLOF is explained first by the benchmark model requiring ~5 million years longer to acquire the observed properties and, second, by the presence of a H-enriched envelope, which is removed by winds in the alternative scenario. This envelope expands faster than the H-depleted parts of the envelope as the star moves into He-shell burning. The expansion of the helium envelope preceding the end of core-helium burning in the alternative model is a result of the removal of the H-rich envelope by the weak wind, to which the helium envelope, in preserving the star’s boundary conditions and smooth pressure gradient, reacts by expanding. We note that our qualitative and quantitative predictions for the future evolution of this system are otherwise unaffected by the presence of a wind.

This mass transfer rate is sufficient to stabilize the binary against further inspiral due to gravitational wave radiation for the duration of the mass transfer phase, leading to an increase of the merger time (71.8 Myr according to our simulation)\textsuperscript{39,40}. Quiescent accumulation is a prerequisite for ignition of a thermonuclear SN according to the double-detonation mechanism (Methods); however, the amount of transferred material is too small. The end of this mass transfer phase is precipitated by the remaining helium envelope of the hot subdwarf losing sufficient mass, owing to both nuclear burning and mass transfer to the companion, for further helium burning to become unsustainable. At this point the hot subdwarf will contract thermally to become a CO white dwarf with a remnant He envelope of ~0.03\,$M_\odot$, that is, a hybrid He–CO white dwarf.

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**Fig. 4 | Model and prediction of the future evolution of HD 265435.**

- **a.** Predicted evolutionary tracks in $T_{\text{eff}}$–log\,$g$ for hot subdwarfs of mass 0.63\,$M_\odot$ and H envelopes between $10^{-4}$\,$M_\odot$ and $10^{-3}$\,$M_\odot$. The solid purple line represents the favoured models with $1.5\times10^{-4}$\,$M_\odot$ (no wind) starting from the beginning of the binary run. The weak wind model with an initial hydrogen envelope of $1.5\times10^{-4}$\,$M_\odot$ is represented by the dashed orange line. The observed position of the hot subdwarf in the diagram is as indicated, with error bars representing the systematic uncertainty of the obtained spectral parameters.

- **b.** Evolution of the system’s mass transfer rate under the assumption of either no wind (solid lines) or a weak wind (dashed). Colour indicates whether the transferred mass is H-enriched or He-enriched. Shaded areas indicate where H-accretion-induced novae or He-accretion-induced flashes are expected.

- **c.** Orbital evolution of the benchmark model system without wind. $R_{\text{sdB}}$ is the total radius of the hot subdwarf, including hydrogen envelope; $R_{\text{He}}$ is the radius of the He-rich shell; $R_{\text{CO}}$ is the radius of the inert CO core; and $R_{\text{RL}}$ is the radius of the Roche lobe of the hot subdwarf. The shaded areas indicate expected mass transfer (MT) phases and dominant composition of the transferred material. Dyn. RLOF marks the occurrence of dynamically unstable Roche Lobe Overflow.

- **d.** Graph equivalent to **c** but for the weak wind model.
Following this mass transfer phase, the system will continue to lose angular momentum because of gravitational wave radiation. The former hot subdwarf will then fill its Roche lobe once again. With a mass ratio of $q > 1.64$, this episode will likely lead to dynamically unstable RLOF, in the course of which the former hot subdwarf is disrupted and merges with the heavier companion. This would result in one of three possible channels for the thermonuclear detonation: a prompt detonation of the more massive white dwarf, a violent merger of the two white dwarfs, or unstable ignition of helium on the more massive white dwarf travelling along the accretion stream and leading to the double detonation of the white dwarf donating mass. However, we emphasize the presence of a non-negligible amount of unburnt helium on the accretor. The derived masses allow us to constrain the merger time because of gravitational wave emission, which is found to be $70^{+26}_{-16}$ Myr, consistent with our numerical simulation. The characteristic strain of the system places it above the detection limit of LISA (Fig. 5).

We note that, given our obtained mass intervals, there is a $\sim 16\%$ probability that the total mass of the system is below the Chandrasekhar mass. In this case, the system would not lead to a supernova through any standard double-degenerate or single-degenerate channel. The likely scenario is recurrent novae starting some $20\,\text{Myr}$ from the time of observation, followed by a double-degenerate dynamical merger. There remains a possibility for prompt detonation, which depends on the presence of helium on the former hot subdwarf.

Discussion

The newly discovered system HD 265435 brings the number of hot subdwarf with white dwarf companions that qualify as supernova progenitors to three, making this the class of binaries with the most observed progenitor candidates. These supernovae may ultimately not show typical SN Ia spectra, but may appear subluminous and/or peculiar depending on their mass ratio. HD 265435 has very similar properties to KPD 1930+2752: both harbour a relatively hot subdwarf star ($T_{\text{eff}} > 30,000\,\text{K}$) and a massive white dwarf with a CO core as companion, bringing the total mass of the system above the Chandrasekhar limit. In addition, the hot subdwarfs in both HD 265435 and KPD 1930+2752 have been observed to show peaks in the range of $p$-mode pulsations.

has lower-mass components and total mass slightly below the Chandrasekhar limit. However, KPD 1930+2752 will likely evolve through the core-helium-burning phase without filling its Roche lobe and transferring mass to the companion, whereas mass transfer is predicted to happen to both HD 265435 and CD-30°11223. Therefore, in terms of its evolutionary fate, HD 265435 is more similar to CD-30°11223. A class of Roche-lobe-filling hot subdwarf binaries has recently been discovered, providing observational evidence for the existence of systems undergoing mass transfer before the hot subdwarf evolves into a white dwarf.

Perhaps the most remarkable common property of these candidate supernova progenitors is the fact that they are all found within $1\,\text{kpc}$ of the Sun and seem to be members of the thin disk, showing relatively low Galactic latitudes. Given their Gaia EDR3 zero-point-corrected parallaxes, CD-30°11223 is at $349^{+6}_{-3}\,\text{pc}$ and $b = 28.9^\circ$, HD 265435 is at $451^{+11}_{-11}\,\text{pc}$ and $b = 14.8^\circ$ and KPD 1930+2752 is at $825^{+7}_{-7}\,\text{pc}$ and $b = 4.3^\circ$. With the assumption that these three objects constitute the entire sample of hot subdwarf–white dwarf binaries that qualify as supernova progenitors within $1\,\text{kpc}$ and taking into account a Poissonic uncertainty, that would imply a space density of $0.22^{+0.13}_{-0.13}\,\text{kpc}^{-3}$ for this type of system, considering the effective volume given by the thin-disk density. We can also roughly estimate the rate of SNe Ia that can be attributed to such systems. There are $\sim 3,000$ hot subdwarf candidates within $1\,\text{kpc}$ (ref. 40). Accounting for an estimated contamination level of $10\%$ (ref. 40), this would suggest that $3$ of the $2,700$ hot subdwarfs within $1\,\text{kpc}$ are possible SN Ia progenitors. Given the birth rate of such stars of $0.014$–$0.063\,\text{yr}^{-1}$ (ref. 40), this implies that the SN Ia rate that can be attributed to hot subdwarf–white dwarf binaries is $1.5$–$7\times 10^{-4}\,\text{yr}^{-1}$. Population synthesis simulations suggest a larger value of $3\times 10^{-4}\,\text{yr}^{-1}$ for the contribution of helium star–white dwarf binaries to the SN Ia rate, but this estimate includes also helium stars more massive than hot subdwarfs. Our estimate is comparable to the estimated contribution from double-degenerate white dwarf binaries, which is $2.1^{+1.0}_{-0.3}\times 10^{-4}\,\text{yr}^{-1}$ (ref. 40). The Galactic SN Ia rate is in turn estimated to be $7.2^{+2.3}_{-1.0}\times 10^{-4}\,\text{yr}^{-1}$ (ref. 40). Therefore, our estimate suggests that hot subdwarf–white dwarf binaries cannot bring the Galactic SN Ia rate into agreement with observed progenitor rates, despite being the most numerous observed class of progenitors. Our estimate should, however, be regarded as a lower limit, as we have assumed that there are no other SN Ia progenitors consisting of hot subdwarf–white dwarf binaries within $1\,\text{kpc}$. The TESS extended mission, as well as future missions such as the Legacy Survey of Space and Time, will put this assumption to test.

Methods

Observations and data reduction. HD 265435 (TIC 68495594) was observed by TESS in Sector 20, yielding two-minute cadence data over a baseline of $26.3$ days, with a three-day gap after $12.3$ days during which the data were being downloaded to Earth. We retrieved the light curve derived by the TESS Science Processing Operations Center (SPOC) and used the PDCSAP flux, which corrects for instrumental trends and contributions to the aperture that are expected from neighbouring stars identified in a pre-search data conditioning (PDC). The pipeline also provides an estimate of the contribution of helium star–white dwarf binaries to the double-degenerate channel. The TESS light curve allows us to constrain the merger time because of gravitational wave emission, which is found to be $70^{+26}_{-16}$ Myr, consistent with our numerical simulation. The characteristic strain of the system places it above the detection limit of LISA (Fig. 5).

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performs standard image processing and spectral reduction procedures, including bias subtraction, flat-field correction, wavelength calibration, optimal spectral extraction and flux calibration. The trailed spectra (Supplementary Fig. 2) clearly show periodical changes of the line centres. Finally, we obtained ten 60-s exposures with ESI at the Keck II telescope on 10 September 2020, which were combined into an \( R \approx 6,000 \), high signal-to-noise ratio (\( S/N \approx 170 \)) spectrum. ThAr arc exposures were taken at the end of the night. The spectra were reduced using the M AKEE pipeline following the standard procedure, which consists of bias subtraction, flat fielding, sky subtraction, order extraction and wavelength calibration.

**Spectral fit of the hot subdwarf.** The observed spectra were matched to a model grid by \( x^2 \) minimization. The quantitative spectral analysis is based on a new grid of model atmospheres and synthetic hydrogen and helium spectra that account for deviations from local thermodynamic equilibrium (LTE). We start from an LTE temperature and surface-brightness consistent model calculation. Non-LTE population numbers of hydrogen and helium levels are then calculated with the DETAIL code\(^ {58,59} \) and handed back to ATLAS12 to correct the atmospheric structure for non-LTE effects in an iterative process\(^ {60} \). After convergence, DETAIL is used again to numerically solve the coupled equations of radiative transfer and statistical mechanics\(^ {60} \), which have better normalization and cover the Balmer jump, to determine \( T_\text{eff} \) and \( log \, g \) \( \upnu \) \( \sin i \) was also left as a free parameter. We found \( T_\text{eff} = 34,300 \pm 400 \) K and \( \log g = 5.62 \pm 0.10 \). Our \( V \) magnitude differs from previous literature results\(^ {61} \) because of orbital smearing of their spectra, which were exposed for \( \approx 1/3 \) of the orbital period.

Next, we fitted each of the higher-resolution ESI spectra to determine the hot subdwarf. We then performed a new fit, applying a factor of two. We performed a fit to the radial velocity curve using the Markov chain Monte Carlo (MCMC) method implemented with the emcee package\(^ {62} \). We assumed a circular orbit and thus fitted the radial velocities by using

\[
RV(t) = V_t + K_a \sin(2\pi(t - t_0))/P, \tag{2}
\]

where \( V_t \) is the systemic velocity, \( K_a \) is the radial velocity semi-amplitude of the hot subdwarf, \( t_0 \) is the zero point of the ephemeris and \( P \) is the orbital period. The period was fixed to the photometric period, whereas \( t_0 \) was allowed to vary by \( \pm 0.2 \). The velocities \( V_t \) and \( K_a \) were kept to vary freely within physical limits, but we used values from \( x^2 \) minimization as the initial guess. We note that, given

that the spectral lines of hot subdwarfs are inherently broad, the effect of orbital smearing for our integration time of 2% of the orbital period is of the same order of magnitude as the radial velocity uncertainties, which were taken into account in our MCMC fit. We obtained \( V_t = 8.2 \pm 0.8 \) km s\(^{-1} \) and \( K_a = 343.1 \pm 1.2 \) km s\(^{-1} \).

**Galactic orbit of HD 265435.** We calculated the Galactic orbit of HD 265435 using the galpy package (v. 1.4.0)\(^ {71} \). The Galactic potential was modelled with three components (bulge, disk and halo) plus a central black hole of mass 4 \( \times 10^9 \) M\(_\odot\)\(^ {72} \). The Sun was placed at a distance of \( R = 8.27 \pm 0.29 \) kpc from the Galactic centre with peculiar motion in the Local Standard of Rest of \( U_\odot = (11.1, 12.2, 7.25) \) km s\(^{-1} \) and the Milky Way rotation speed at the Solar circle was set to \( V_\odot = 238 \pm 9 \) km s\(^{-1} \) (refs. \(^ {73,74} \)). The system shows dynamics consistent with the thin disk of the Galaxy (Supplementary Fig. 5). Other indicators, namely the Galactic velocity components \( (U, V, W) = (11 \pm 2, 2, 7.5) \) km s\(^{-1} \), and angular momentum and eccentricity \( (j = 2130 \pm 3 \) km s\(^{-1} \) kpc\(^{-1} \) and \( e = 0.277 \pm 0.001) \) also point to thin-disk membership\(^ {75} \).

**Light-curve fitting method.** We used lcurveV\(^ {76} \) to carry out the light curve analyses. This code uses a grid of points to model the two original light curves set by a Roche potential. The flux emitted by each grid point is calculated from a blackbody with a given estimated temperature at the bandpass wavelength, taking into account corrections for the effects of limb darkening, gravity darkening, Doppler boosting and reflection.

The temperature of the hot subdwarf was fixed at the value determined from the spectroscopy. The lack of blue excess in the \( V \) flux leads to a maximum temperature of the component \( T_\text{rad} = 90,000 \) K. Assuming the minimum mass \( M_\text{min} \) of the binary system is \( \approx 0.5 M_\odot \), we obtain the total mass \( M \) of the system to be \( (30 \mp 3) M_\odot \). Assuming \( M = (3-1) M_\odot \), we obtain the total mass of the binary system to be \( (30 \mp 3) M_\odot \). The mass of the hot subdwarf is then determined from the integrated \( V \) flux and the total mass. We find that the mass of the hot subdwarf is \( (30 \mp 3) M_\odot \). We then performed a new fit, applying a factor of two. We performed a fit to the radial velocity curve using the Markov chain Monte Carlo (MCMC) method implemented with the emcee package\(^ {62} \). We assumed a circular orbit and thus fitted the radial velocities by using

\[
RV(t) = V_t + K_a \sin(2\pi(t - t_0))/P, \tag{2}
\]

where \( V_t \) is the systemic velocity, \( K_a \) is the radial velocity semi-amplitude of the hot subdwarf, \( t_0 \) is the zero point of the ephemeris and \( P \) is the orbital period. The period was fixed to the photometric period, whereas \( t_0 \) was allowed to vary by \( \pm 0.2 \). The velocities \( V_t \) and \( K_a \) were kept to vary freely within physical limits, but we used values from \( x^2 \) minimization as the initial guess. We note that, given

that the spectral lines of hot subdwarfs are inherently broad, the effect of orbital smearing for our integration time of 2% of the orbital period is of the same order of magnitude as the radial velocity uncertainties, which were taken into account in our MCMC fit. We obtained \( V_t = 8.2 \pm 0.8 \) km s\(^{-1} \) and \( K_a = 343.1 \pm 1.2 \) km s\(^{-1} \).
burning disabled, to hydrostatic equilibrium. A H-rich envelope of appropriate mass and metallicity was then accreted onto this model and the model again relaxed to hydrostatic equilibrium. Following this, the model was evolved until it matched the observational properties of the observed hot subdwarf. To preserve consistency, this was repeated for an alternative model with the inclusion of a weak wind (see below). We found that, with a wind, an initial hydrogen envelope of $3.0 \times 10^{-3} M_\odot$ was required. At the point at which the alternative model matched the observations, about half of this envelope had been removed by winds. However, to evolve from its initial position in the Hertzsprung-Russell diagram, the benchmark model took ~31.2 Myr, whereas the alternative model required only ~26.2 Myr. The initial model was then placed in a binary system with an orbital period of $P_{\text{orb}} = 101$ min and with a $1.02 M_\odot$ white dwarf, which was approximated as a point mass.

To model the evolution of the hot subdwarf star, we used the predictive mixing scheme included in MESA with the same parameter setting as Ostrowski et al.50,103 but instead an SN Iax or an otherwise subluminous or material will be accumulated at rates not exceeding $2.5 M_\odot$ yr$^{-1}$ for the hot subdwarf to evolve to its currently observed physical properties. In broad agreement system requires an additional ~31.2 Myr (benchmark) or ~26.2 Myr (alternative) of their analysis. Discrepancies are due to the overshooting prescription used. The radial velocity determination curve RVSÅO is available from http://tdc-www.harvard.edu/iraf/rvsao/. The package can be installed following https://docs.galpy.org/en/v1.6.0/. The SED and spectral fitting routines are publicly documented as described above, but not publicly available. The Period04 software employed for pre-whitening the light curve can be obtained from https://www.univie.ac.at/tops/Period04/. LCURVE is available at https://github.com/trmrsh/cpp-lcurve. The stellar evolution code MESA can be downloaded from http://mesa.sourceforge.net/.

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References

1. Schmidt, B. P. et al. The high-Z supernova search: measuring cosmic deceleration and global curvature of the universe using Type Ia supernovae. Astrophys. J. 507, 46–63 (1998).
2. Riess, A. G. et al. Observational evidence from supernovae for an accelerating universe and a cosmological constant. Astron. J. 116, 1009–1038 (1998).
3. Perlmutter, S. et al. Measurements of $\Omega$ and $\Lambda$ from 42 high-redshift supernovae. Astrophys. J. 517, 565–586 (1999).
4. Riess, A. G., Casertano, S., Yuan, W., Macri, L. M. & Scolnic, D. Large Magellanic Cloud Cepheid standards provide a 1% foundation for the determination of the Hubble constant and stronger evidence for physics beyond ΛCDM. Astrophys. J. 876, 85 (2019).
5. Aghanim, N. et al. Planck 2018 results. VI. Cosmological parameters. Astron. Astrophys. 641, A6 (2020).
6. Bernal, J. L., Verde, L. & Riess, A. G. The trouble with $H_0$. J. Cosmol. Astropart. Phys. 2016, 019 (2016).
7. Hoyle, F. & Fowler, W. A. Nucleosynthesis in supernovae. Astrophys. J. 132, 565–590 (1960).
8. Hillebrandt, W., Kromer, M., Röpke, F. K. & Ruiter, A. J. Towards an understanding of Type Ia supernovae from a synthesis of theory and observations. Front. Phys. 8, 116–143 (2013).
9. Whelan, J. & Iben, I. Jr. Binaries and supernovae of Type I. Astrophys. J. 186, 1007–1014 (1973).
10. Iben, I. Jr. & Tutukov, A. V. Supernovae of Type I as end products of the evolution of binaries with components of moderate initial mass. Astrophys. J. Suppl. Ser. 54, 335–377 (1984).
11. Liu, D., Wang, B. & Han, Z. The double-degenerate model for the progenitors of Type Ia supernovae. Mon. Not. R. Astron. Soc. 473, 5352–5361 (2018).
12. Han, Z. & Podsiadlowski, Ph. The single-degenerate channel for the progenitors of Type Ia supernovae. Mon. Not. R. Astron. Soc. 350, 1301–1309 (2004).
13. Rebassa-Mansergas, A., Toonen, S., Korol, V. & Torres, S. Where are the double-degenerate progenitors of Type Ia supernovae? Mon. Not. R. Astron. Soc. 482, 3656–3668 (2019).
14. Maoz, D. & Mannucci, F. Type-Ia supernova rates and the progenitor problem: a review. Publ. Astron. Soc. Austral. 29, 447–465 (2012).
15. Santander-García, M. et al. The double-degenerate, super-Chandrasekhar mass white dwarf plus white dwarf binary CD-30 11223 (GALEX J1411-3053). Mon. Not. R. Astron. Soc. 390, 1301–1309 (2008).
16. Reindl, N. et al. An in-depth reanalysis of the alleged type Ia supernova progenitor Henize 2-428. Mon. Not. R. Astron. Soc. 390, 1301–1309 (2008).
17. Napiwotzki, R. et al. The ESO supernovae type Ia progenitor survey (SPY). The radial velocities of 643 DA white dwarfs. Astron. Astrophys. 638, A131 (2020).
18. Maxted, P. F. L., Marsh, T. R. & North, R. C. KPD 1930+2752: a candidate Type Ia supernova progenitor. Mon. Not. R. Astron. Soc. 317, L41–L44 (2000).
19. Vennes, S., Kawka, A., O’Toole, S. J., Németh, P. & Burton, D. The shortest period sdB plus white dwarf binary CD-30 11223 (GALEX J1411-3053). Astrophys. J. Lett. 759, L25 (2012).
20. Geier, S. et al. A progenitor binary and an ejected mass donor remnant of faint type Ia supernovae. Astron. Astrophys. 554, A54 (2013).
21. Ricker, G. R. et al. Transiting Exoplanet Survey Satellite (TESS). J. Telesc. Instum. Sys. 1, 014003 (2015).
22. Oke, J. B. & Gunn, J. E. An efficient low- and moderate-resolution spectrograph for the Hale telescope. Publ. Astron. Soc. Pac. 94, 586–594 (1982).

Data availability

The TESS data used in this work are publicly available and can be accessed via the Barbara A. Mikulski Archive for Space Telescopes (https://mstastsci.edu/). Obtained follow-up spectra, evolutionary models and MESA inlists are available on Zenodo (https://doi.org/10.5281/zenodo.4792304).
23. Brown, A. G. A. et al. Gaia Early Data Release 3. Summary of the contents and survey properties. Astron. Astrophys. 649, A1 (2021).
24. Shukura, N. I. & Postnov, K. A. Doppler-effect modulation of the observed radiation flux from ultracompact binary stars. Astron. Astrophys. 183, L21–L22 (1987).
25. Chapiro, S., Fontaine, G., Brassard, P. & Dorman, B. The potential of asteroseismology for hot, subdwarf B stars: a new class of pulsating stars? Astrophys. J. 471, L103 (1996).
26. Ninkin, D., Konig, J., O’Donoghue, D. & Stobie, R. S. A new class of rapidly pulsating star — I. EC 14026-2647, the class prototype. Mon. Not. R. Astron. Soc. 285, 640–644 (1997).
27. Kawaler, S. D. & Hosler, S. R. Internal rotation of subdwarf B stars: limiting cases and asteroseismological consequences. Astrophys. J. 621, 43 (2005).
28. Reed, M. D. et al. Analysis of the rich frequency spectrum of KIC 10670103 revealing the most slowly rotating subdwarf B star in the Kepler field. Mon. Not. R. Astron. Soc. 440, 3809–3824 (2014).
29. Geier, S., Karl, C., Edelmann, H., Heber, U. & Napiwotzki, R. in Hot Subdwarf Stars and Related Objects Vol. 392 (eds Heber, U., Jeffery, C. S. et al.) 207–214 (ASP Conference Series, 2008).
30. Geier, S., Raddi, R., Gentile Fusillo, N. P. & Marsh, T. R. The population of hot subdwarf stars studied with Gaia. II. The Gaia DR2 catalogue of hot subluminous stars. Astron. Astrophys. 621, A38 (2019).
31. Copperwheat, C. M. et al. Physical properties of IP Pegasi: an eclipsing hot subdwarf nova with He-star and white dwarf components towards Type Ia supernovae. Astron. Astrophys. J. 621, 432 (2010).
32. Lauffer, G. R., Romero, A. D. & Kepler, S. O. New evolutionary sequences of H- and He-atmosphere massive white dwarf stars using MESA. Mon. Not. R. Astron. Soc. 480, 1547–1562 (2018).
33. Heber, U. Hot subluminous stars. Publ. Astron. Soc. Pac. 128, 082001 (2016).
34. Unglaub, K. Mass-loss and diffusion in subdwarf B stars and hot white dwarfs: do weak winds exist? Astron. Astrophys. 486, 923–940 (2008).
35. Ibek, I., Fujimoto, M. Y. & MacDonald, J. On mass-transfer rates in classical nova precursors. Astrophys. J. 384, 580–586 (1992).
36. Shara, M. M., Prialnik, D., Hillman, Y. & Kovetz, A. The masses and accretion rates of white dwarfs in classical and recurrent novae. Astrophys. J. 860, 110 (2018).
37. Woosley, S. E. & Kasen, D. Sub-Chandrasekhar mass models for supernovae. Astrophys. J. 734, 38 (2011).
38. Neunteufel, P., Tonne, S.-C. & Langer, N. Models for the evolution of close binaries with He-star and white dwarf components towards Type Ia supernova explosions. Astron. Astrophys. 589, A43 (2016).
39. Tutukov, A. V. & Yungelson, L. R. On the influence of emission of gravitational waves on the evolution of low-mass close binary stars. Acta Astron. 29, 665–680 (1979).
40. Neunteufel, P. Exploring velocity limits in the thermonuclear supernova ejection scenario for hypervelocity stars and the origin of US 708. Astron. Astrophys. 641, A52 (2020).
41. Kromer, M. et al. Double-detonation sub-Chandrasekhar supernovae: synthetic observables for minimum helium shell mass models. Astrophys. J. 734, 1067–1082 (2011).
42. Palmor, R. et al. Sub-luminous type Ia supernovae from the mergers of equal-mass white dwarfs with mass ~0.9M⊙. Nature 463, 61–64 (2010).
43. Palmor, R., Zenati, Y., Perets, H. B. & Tonne, S. Thermonuclear explosion of a massive hybrid HeCO white dwarf triggered by a He detonation on a companion. Mon. Not. R. Astron. Soc. 503, 4734–4747 (2021).
44. Kraft, R. P., Mathews, J. & Greenstein, J. L. Binary stars among cataclysmic variables. II. Nova WZ Sagittae: a possible radiator of gravitational waves. Astrophys. J. 136, 312–315 (1965).
45. Shah, S., van der Sluys, M. & Nelemans, G. Using electromagnetic observations to aid gravitational-wave parameter estimation of compact binaries observed with the LISA. Astron. Astrophys. 544, A153 (2012).
46. Moore, C. J., Cole, R. H. & Berry, C. P. L. Gravitational-wave sensitivity curves. Class. Quantum Gravity 32, 015014 (2015).
47. Gronon, S. et al. SNe Ia from double detonations: impact of core-shell mixing on the carbon ignition mechanism. Astron. Astrophys. 635, A16 (2020).
48. Kapfer, T. et al. A new class of Roche lobe-filling hot subdwarf binaries. Astrophys. J. Lett. 898, L25 (2020).
49. Jurić, M. et al. The Milky Way tomography with SDSS. I. Stellar number density distribution. Astrophys. J. 673, 864–914 (2008).
50. Han, Z., Podsiadlowski, P., Maxted, P. F. L. & Marsh, T. R. The origin of subdwarf B stars. Mon. Not. R. Astron. Soc. 341, 669–691 (2003).
51. Wang, R. et al. Birthrates and delay times of Type Ia supernovae. Sci. China Phys. Mech. Astron. 53, 586–590 (2010).
52. Li, W. et al. Nearby supernova rates from the Lick Observatory Supernova Search – III. The rate-size relation, and the rates as a function of galaxy Hubble type and colour. Mon. Not. R. Astron. Soc. 412, 1473–1507 (2011).
84. Paxton, B. et al. Modules for Experiments in Stellar Astrophysics (MESA). Astrophys. J. Suppl. Ser. 192, 3 (2011).
85. Paxton, B. et al. Modules for Experiments in Stellar Astrophysics (MESA): planets, oscillations, rotation, and massive stars. Astrophys. J. Suppl. Ser. 208, 4 (2013).
86. Paxton, B. et al. Modules for Experiments in Stellar Astrophysics (MESA): binaries, pulsations, and explosions. Astrophys. J. Suppl. Ser. 220, 15 (2015).
87. Paxton, B. et al. Modules for Experiments in Stellar Astrophysics (MESA): convective boundaries, element diffusion, and massive star explosions. Astrophys. J. Suppl. Ser. 234, 34 (2018).
88. Paxton, B. et al. Modules for Experiments in Stellar Astrophysics (MESA): pulsating variable stars, rotation, convective boundaries, and energy conservation. Astrophys. J. Suppl. Ser. 243, 10 (2019).
89. Ostrowski, J., Baran, A. S., Sanjayan, S. & Sahoo, S. K. Evolutionary modelling of subdwarf B stars using MESA with the predictive mixing and convective pre-mixing schemes. Mon. Not. R. Astron. Soc. 503, 4646–4661 (2021).
90. de Jager, C., Nieuwenhuijzen, H. & van der Hucht, K. A. Mass loss rates in the Hertzsprung-Russell diagram. Astron. Astrophys. Suppl. Ser. 72, 259–289 (1988).
91. Krüüka, J. et al. Hot subdwarf wind models with accurate abundances. I. Hydrogen dominated stars HD 49798 and BD+18° 2647. Astron. Astrophys. 631, A75 (2019).
92. Zenati, Y., Toonen, S. & Perets, H. B. Formation and evolution of hybrid He–CO white dwarfs and their properties. Mon. Not. R. Astron. Soc. 482, 1135–1142 (2019).
93. Nomoto, K. Supernova explosions in accreting white dwarfs and Type I supernovae. In Proc. Texas Workshop on Type I Supernovae (ed. Wheeler, J. C.) 164–181 (Univ. Texas at Austin, 1980).
94. Livne, E. Successive detonations in accreting white dwarfs as an alternative mechanism for type I supernovae. Astrophys. J. Lett. 354, L53 (1990).
95. Shen, K. J. & Bildsten, L. The ignition of carbon detonations via converging shock waves in white dwarfs. Astrophys. J. 785, 61 (2014).
96. Pakmor, R., Hachinger, S., Röpke, F. K. & Hillebrandt, W. Violent mergers of nearly equal-mass white dwarf as progenitors of subluminous Type Ia supernovae. Astron. Astrophys. 528, A117 (2011).
97. Pakmor, R. et al. Normal Type Ia supernovae from violent mergers of white dwarf binaries. Astrophys. J. Lett. 747, L10 (2012).
98. Röpke, F. K. et al. Constraining Type Ia supernova models: SN 2011fe as a test case. Astrophys. J. Lett. 750, L19 (2012).
99. Sato, Y. et al. The critical mass ratio of double white dwarf binaries for violent merger-induced type Ia supernova explosions. Astrophys. J. 821, 67 (2016).
100. Li, W. et al. SN 2002cx: the most peculiar known Type Ia supernova. Publ. Astron. Soc. Pac. 115, 453–473 (2003).
101. Foley, R. J. et al. Type Iax supernovae: a new class of stellar explosion. Mon. Not. R. Astron. Soc. 423, 1891–1907 (2012).
102. Wang, B., Justham, S. & Han, Z. Producing Type Iax supernovae from a specific class of helium-ignited WD explosions. Astrophys. J. 599, A94 (2003).
103. Han, Z., Podsiadlowski, P., Maxted, P. F. L., Marsh, T. R. & Ivanova, N. The origin of subdwarf B stars – I. The formation channels. Mon. Not. R. Astron. Soc. 336, 449–466 (2002).
104. Weidemann, V. Revision of the initial-to-final mass relation. Astron. Astrophys. 363, 647–656 (2000).
105. Robitaille, T. P. et al. Astropy: a community Python package for astronomy. Astron. Astrophys. 558, A33 (2013).
106. Price-Whelan, A. M. et al. The Astropy Project: building an open-science project and status of the v2.0 core package. Astron. J. 156, 123 (2018).
107. Robson, T., Cornish, N. J. & Liu, C. The construction and use of LISA sensitivity curves. Class. Quantum Gravity 36, 105011 (2019).
108. Kupfer, T. et al. LISA verification binaries with updated distances from Gaia Data Release 2. Mon. Not. R. Astron. Soc. 480, 302–309 (2018).

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Author contributions
I.P. carried out the radial velocity estimates and fitting and the light curve fitting, and led the writing of the manuscript. P.N. calculated the evolution of the system. S.G. and U.H. performed the spectral fitting. T.K. did the spectroscopic reduction and cross-checked the light curve fitting. D.S. and U.H. performed the SED fitting. A.B. wrote the SED fitting tool and calculated the spectral models used for SED and spectral fitting. A.B. calculated the Galactic orbit of the system. J.v.R. performed the radial velocity estimates and fitting. All authors reviewed the manuscript.

Competing interests
The authors declare no competing interests.

Additional information
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