Binary evolution and formation of compact objects

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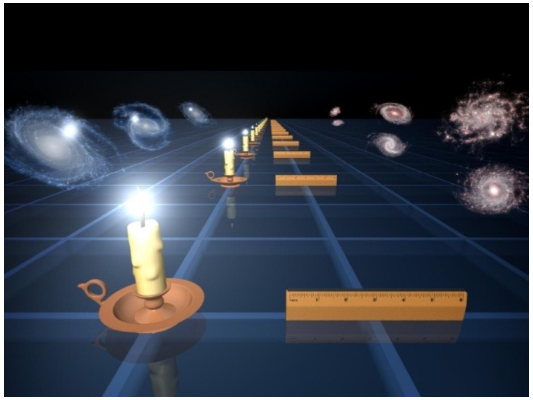
TianQin Astrophysics Workshop

Outline

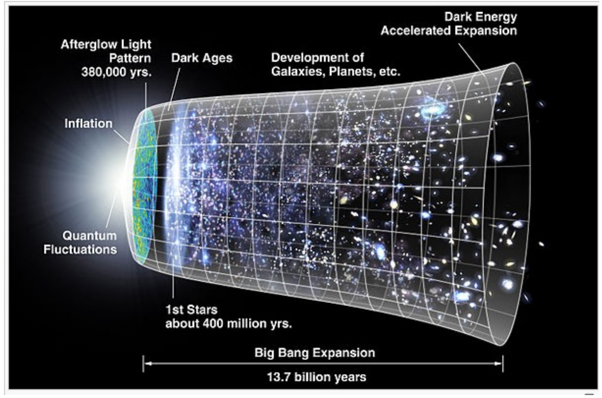
- The progenitors of type Ia supernovae
- The formation of ultra-compact X-ray binaries
- Double WDs & Gravitational wave radiation

Type Ia supernovae

1、



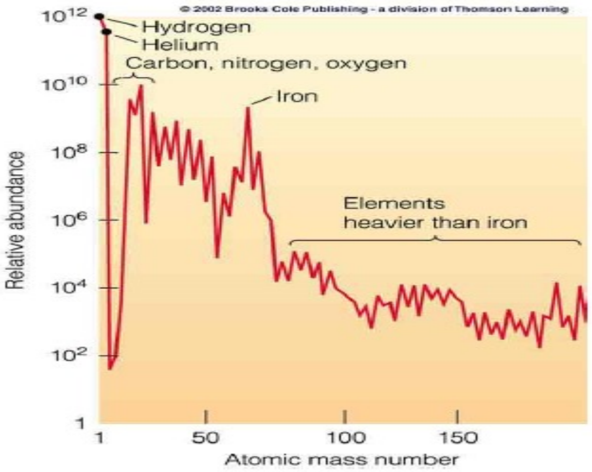
Standard Candle



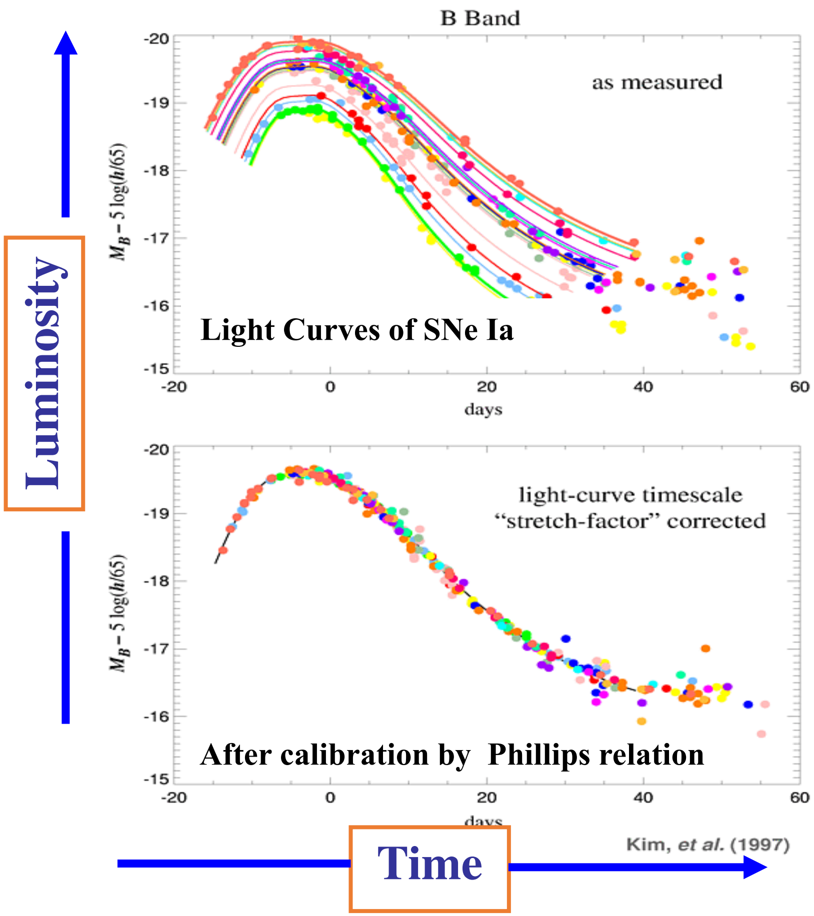
Accelerating Expansion of the Universe

2、 **galactic chemical evolution：**

Half Iron in their host galaxy are produced by SNe Ia



Phillips relation



Phillips relation

(Luminosity－width)

The wider the light curve

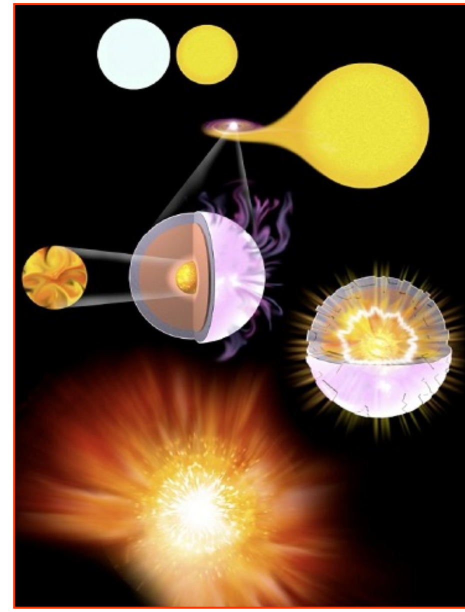
The brighter the peak luminosity

However, several key issues for the nature of the progenitors of SNe Ia are still not well understood (e.g., Howell et al. 2011; Podsiadlowski et al. 2008).

Progenitor models of SNe Ia

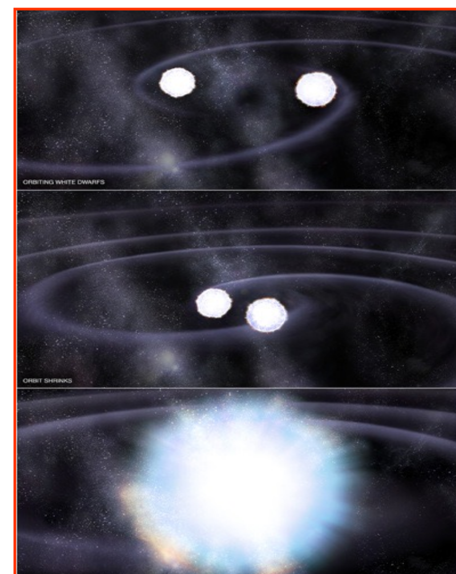
Single-degenerate model
- **WD + MS**
- **WD + RG**
- **WD + He star**

(Hachisu et al. 1996; Han & Podsiadlowski 2004, 2006; Chen & Li 2007; Han 2008; Wang et al. 2009a,b; Meng & Yang 2010; Chen et al. 2011)



Double-degenerate model: WD + WD

(Iben & Tutukov 1984; Webbink 1984; Han 1998; Chen et al. 2012; Schwab et al. 2016)



WD+He star channel & SNe Ia

SD model

↓

WD+He star

(HD 49798)

↓

Chandrasekhar mass limit

↓

Young SNe Ia

Wang et al. 2009a, b

Double detonation model

↓

WD+He star

(CD 30° 11223)

↓

~0.15 Msun

↓

Sub-luminous SNe Ia

Nomoto 1982
Wang et al. 2013

DD model

↓

WD+He subgiant

(KPD 1930+2752)

↓

WD+WD

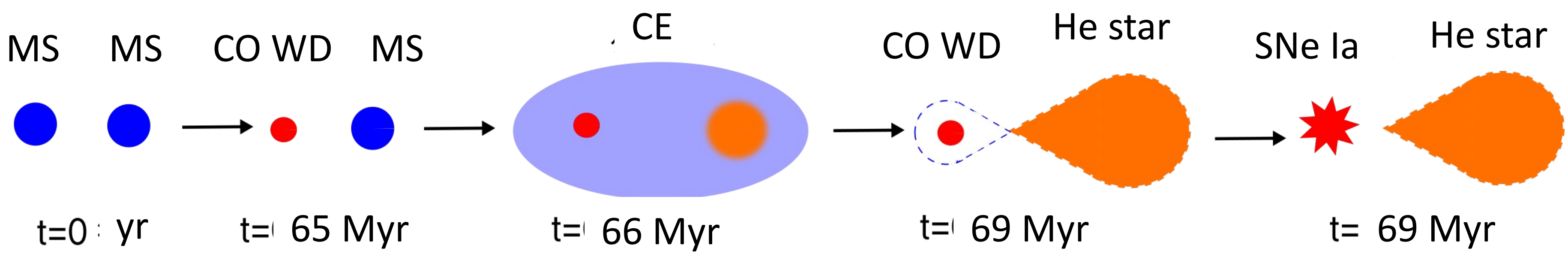
(GW sources)

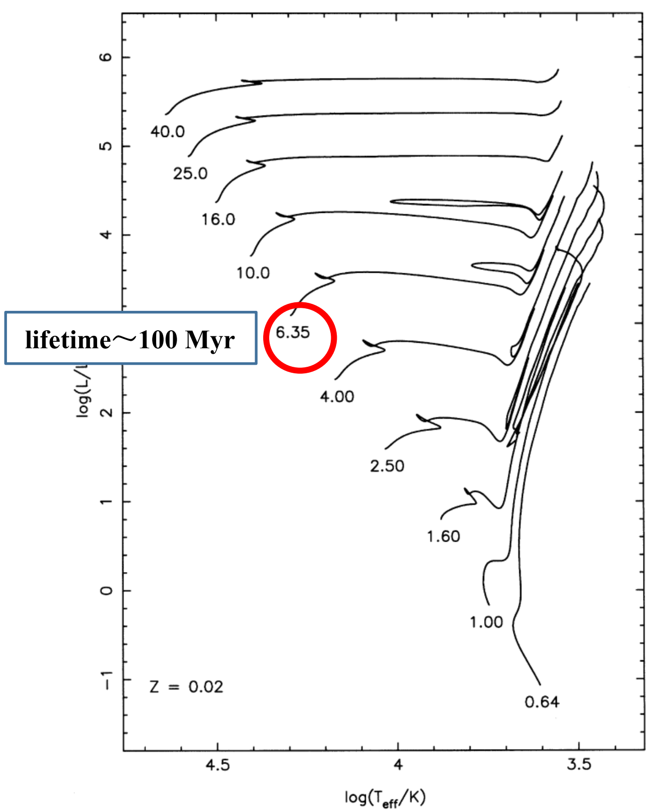
↓

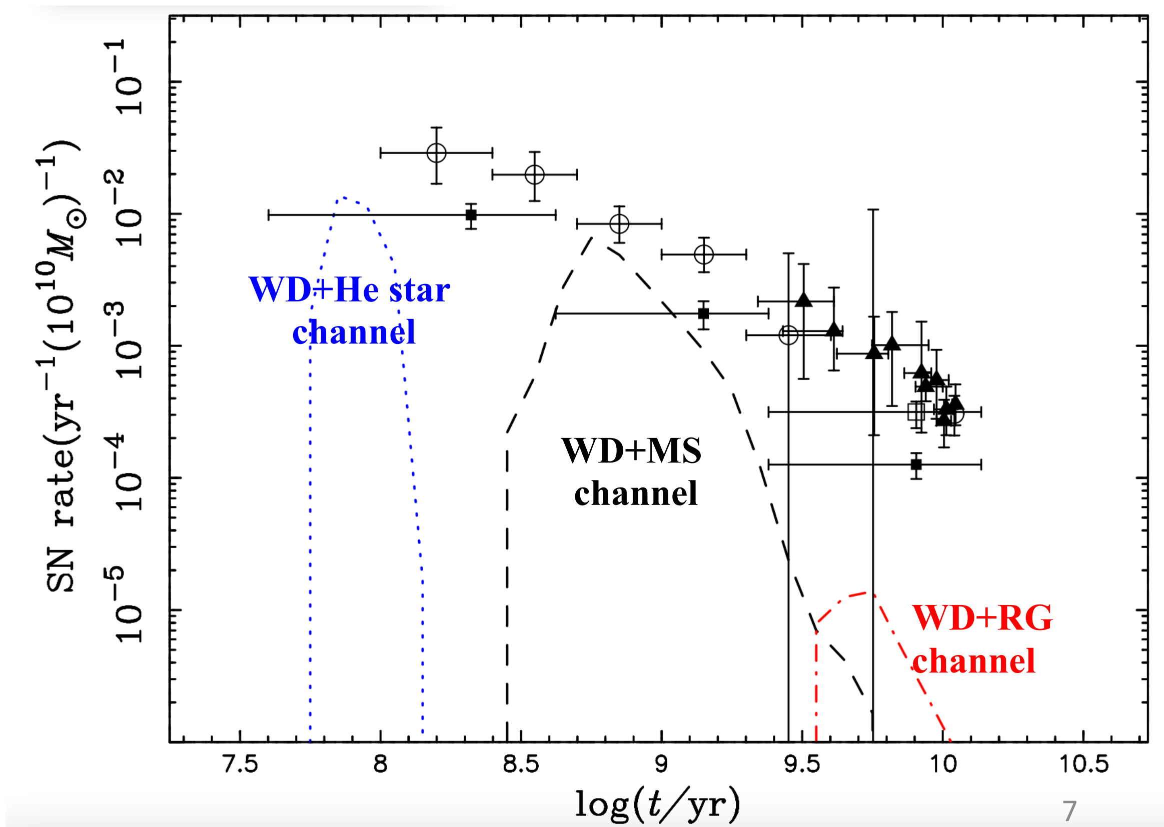
SNe Ia

Ruiter et al. 2013
Liu et al. 2016,2018

The WD+He star channel in the SD model

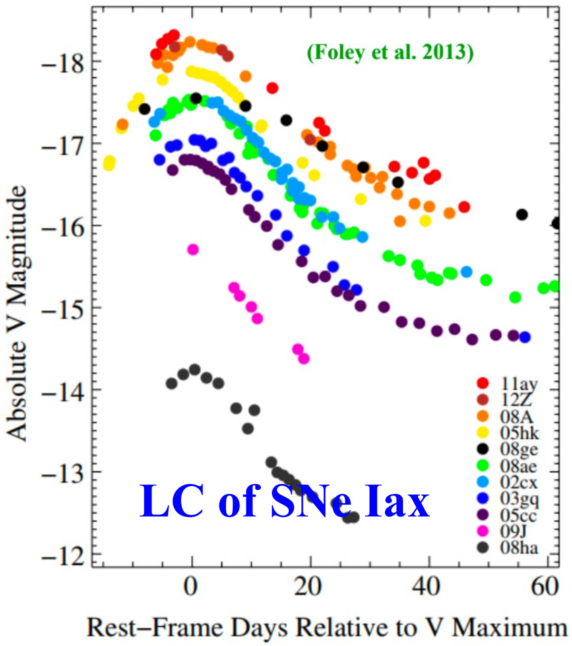




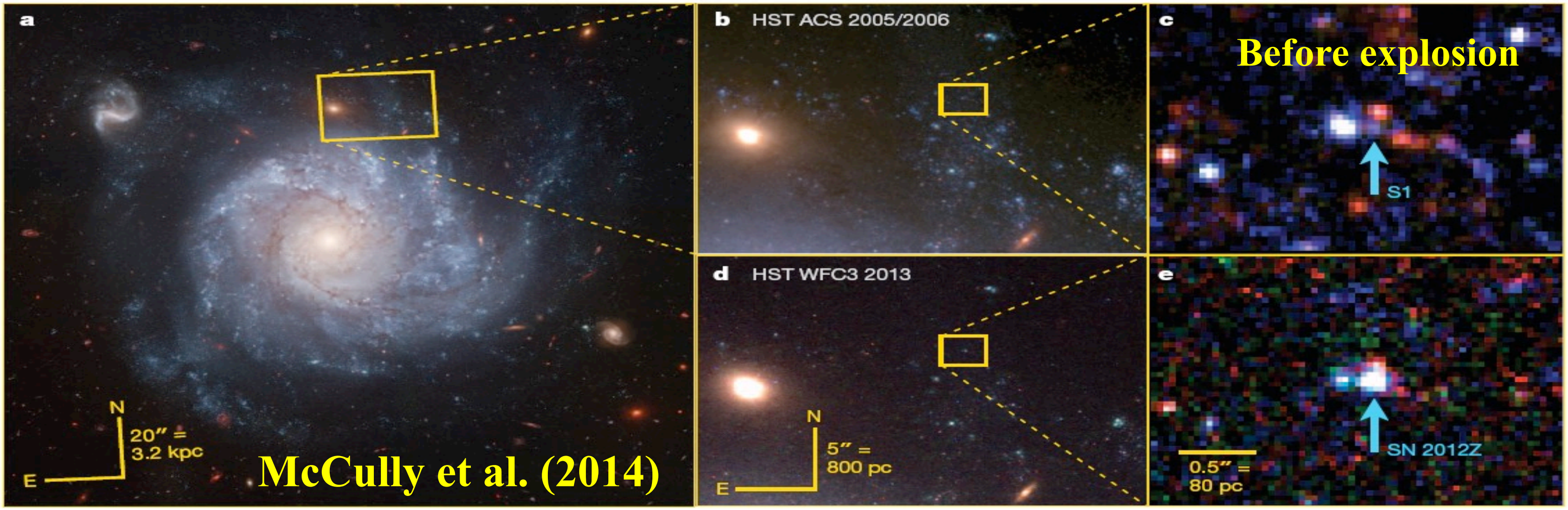


Type Iax supernovae:

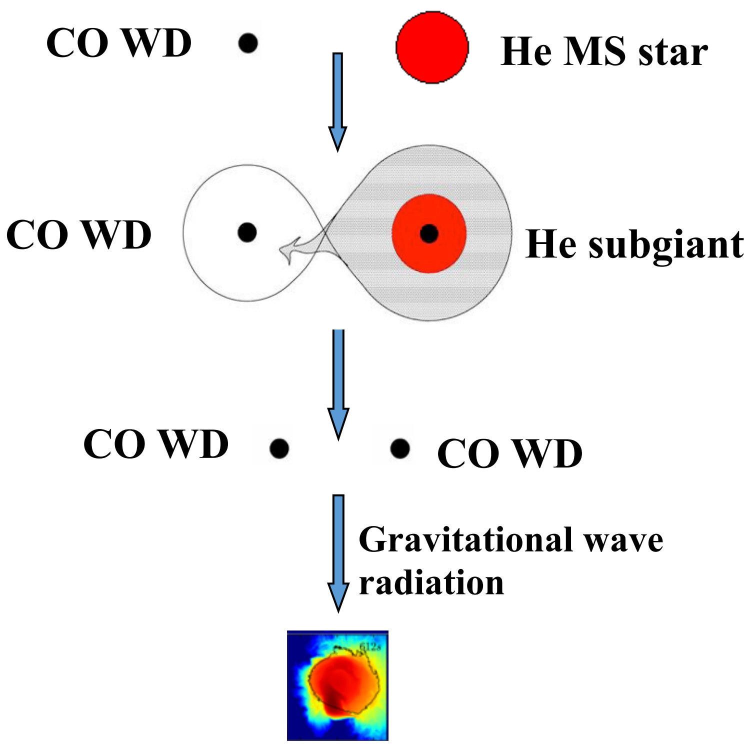
- Spectroscopically similar to normal SNe Ia;
- Lower maximum_x0002_light velocities;
- Lower peak magnitudes;



A He star was found at the position of SN 2012Z before the explosion occurs.

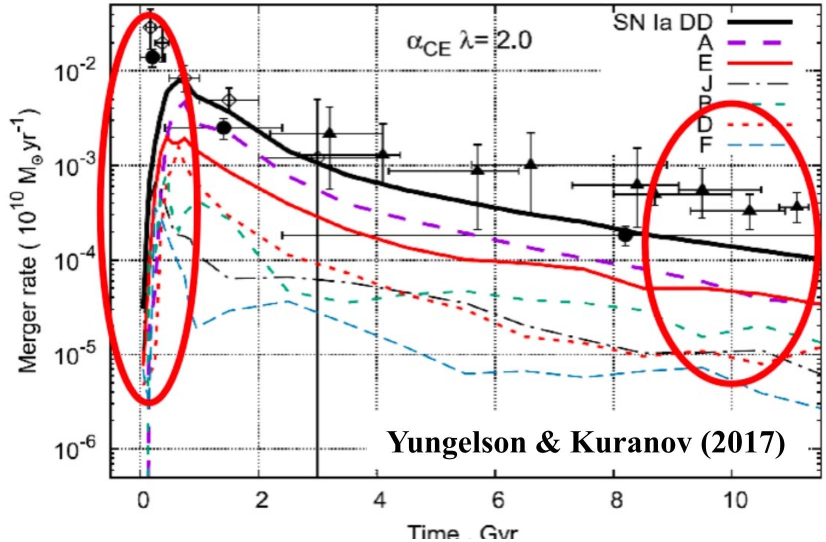


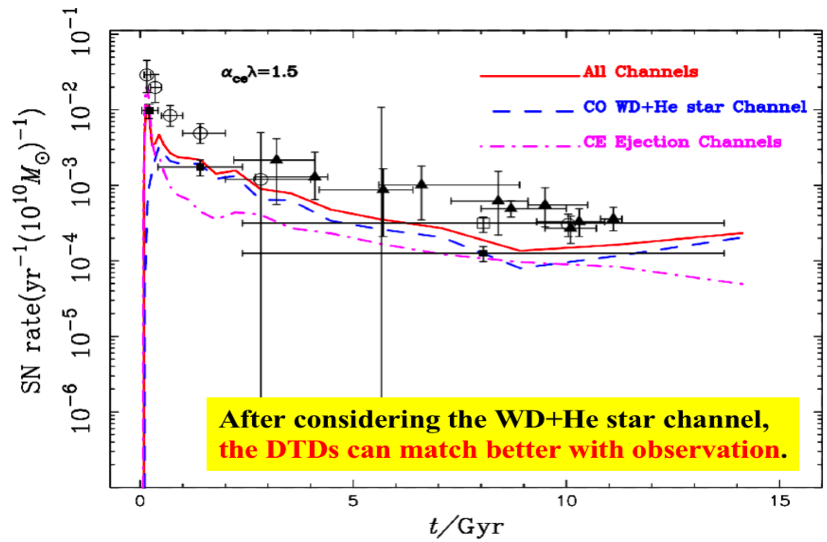
The WD+He subgiant channel:
an important for the formation of double WDs



Ruiter et al. (2013)

Liu et al. (2016, 2018)





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A Photometric and Spectroscopic Investigation of the DB White Dwarf Population Usi SDSS and *Gaia* Data

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Abstract

We present a comprehensive analysis of DB white dwarfs drawn from the Sloan Digital Sky Survey, based on model fits to *ugriz* photometry and medium-resolution spectroscopy from the Sloan Digital Sky Survey. We also take advantage of the exquisite trigonometric parallax measurements recently obtained by the *Gaia* mission. Using the so-called photometric and spectroscopic techniques, we measure the atmospheric and physical parameters of each object in our sample ($T_{\rm eff}$, $\log g$, H/He, Ca/He, R, M), and compare the values obtained from both techniques in order to assess the precision and accuracy of each method. We then explore in great detail the surface gravity, stellar mass, and hydrogen abundance distributions of DB white dwarfs as a function of effective temperature. We present some clear evidence for a large population of unresolved double-degenerate binaries composed of DB+DB and even DB+DA white dwarfs. In the light of our results, we finally discuss the spectral evolution of DB white

Table 3. List of DB+DB double degenerate candidates

	Photometry		Spectroscopy				Photometry		Spectroscopy		
SDSS name	$T_{\rm eff}$ (K)	M ($M_\odot$)	$T_{\rm eff}$ (K)	M ($M_\odot$)	log H/He	SDSS name	$T_{\rm eff}$ (K)	M ($M_\odot$)	$T_{\rm eff}$ (K)	M ($M_\odot$)	log H/He
000730.75+275111.90	13,932	0.41	16,305	0.63	−5.880	120203.13+285647.07	16,043	0.38	17,179	0.69	−5.231
002153.33+083141.82	27,313	0.49	17,789	0.81	−5.733	120735.19+225905.70	25,020	0.46	20,592	0.68	−5.201
004900.48-094203.00	18,466	0.46	19,419	0.78	−4.434	122444.73+174145.85[a]	15,967	0.40	14,527	0.61	−5.613
010532.40+064234.18[a]	13,368	0.36	13,404	0.41	−5.694	123230.41+035036.70[a]	19,349	0.38	18,295	0.57	−5.801
011023.82+223716.25[a]	12,275	0.42	12,771	0.59	−5.714	123735.52+602833.00[a]	12,195	0.22	15,863	0.48	−5.649
011409.86+272739.42	15,833	0.34	17,540	0.68	−4.887	124058.65+532623.60	16,327	0.57	17,591	0.89	−5.271
020409.84+212948.58	15,071	0.59	20,605	0.83	−3.186	125030.21+594932.90[a]	14,844	0.42	15,831	0.59	−5.963
024232.63-050954.75[a]	12,181	0.40	14,438	0.56	−5.871	130106.26+023455.30	17,660	0.45	17,706	0.77	−5.570
034741.96+010823.80	26,320	0.55	17,809	0.78	−4.844	130830.53+470017.90[a]	14,705	0.42	17,109	0.54	−5.737
052941.58+603806.80[a]	13,612	0.39	16,823	0.50	−5.665	131658.16+305148.00	18,987	0.52	19,635	0.76	−4.448

could not have formed within the lifetime of the Galaxy. After removing the previously identified DA+DB systems, we were left with 55 DB+DB unresolved double degenerate candidates. These

systems, as well as the best photometric and spectros

DA+DB systems, we were able to separate the contr

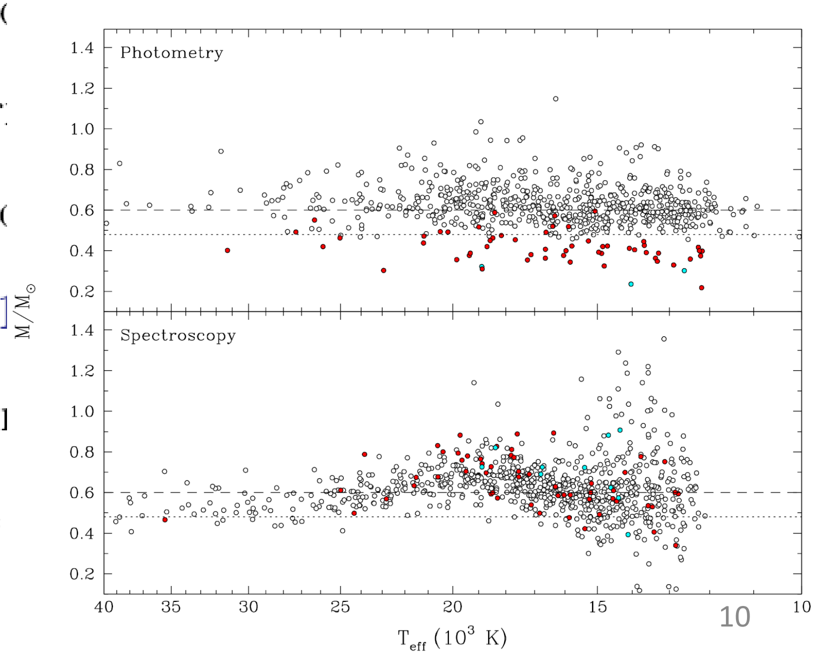
DB+DB binaries, it is possible, in principle, to deconv

photometry and parallax information (Bédard et al. 201

paper. We would like to note that, since we applied a

paral e

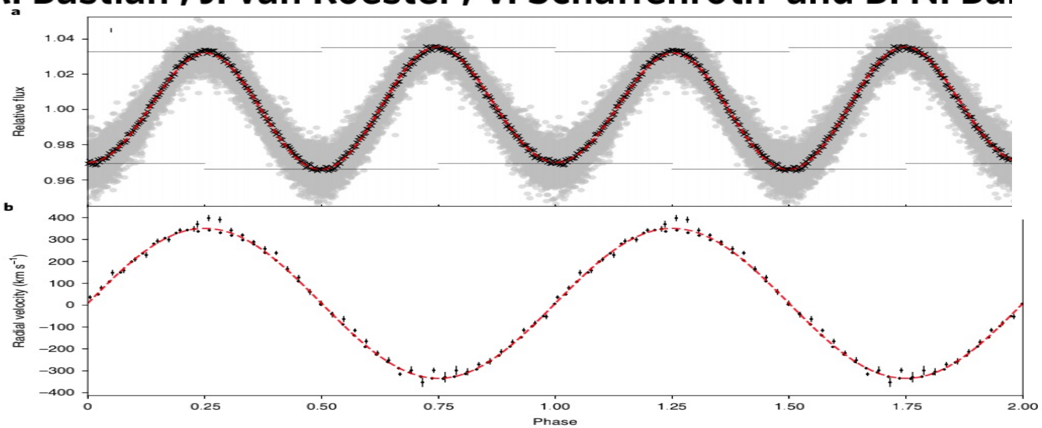
means complete.



nature astronomy
ARTICLES
https://doi.org/10.1038/s41550-021-01413-0

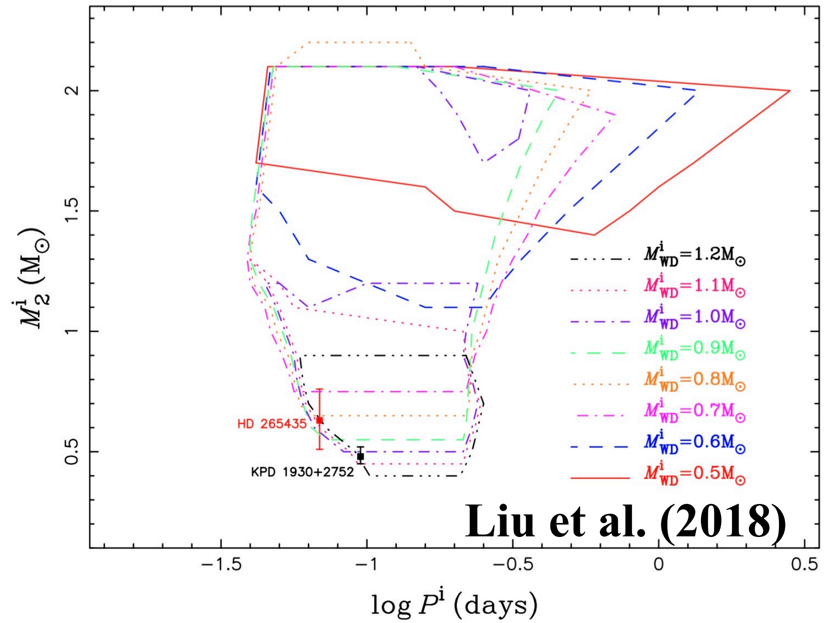
A hot subdwarf–white dwarf
candidate supernova Ia prog

Ingrid Pelisoli[1,2], P. Neunteufel[3], S. Geier[1], T. Kupfer
A. Bastian[1], J. van Roestel[7], V. Schaffenroth[1] and B. N. Ba



nels 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[9–11].

11. Liu, D., Wang, B. & Han, Z. The double-degenerate model fo progenitors of Type Ia supernovae. *Mon. Not. R. Astron. Soc.* 5352–5361 (2018).



Recently, a WD+hot subdwarf system, HD 265435, was detected. It will evolve to a double CO WD (or CO WD+ HeCO hybrid WD) system, and may produce an SN Ia explosion when the merges.

As gravitational wave sources

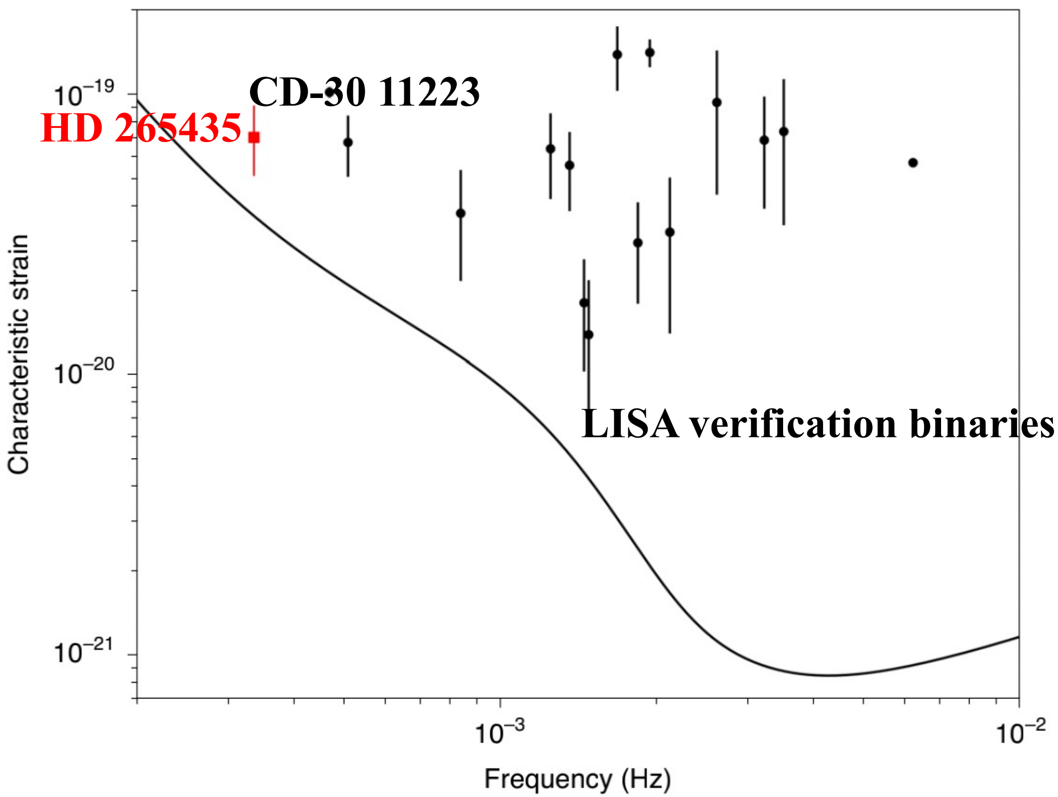


Fig. 5 | Gravitational wave frequency and strain of HD 265435. The black line shows the LISA sensitivity curve for a four-year mission[107]. The red square shows the median strain and frequency of HD 265435, with the error bar representing the 68% confidence interval. Black data points are previously known verification binaries[108].

Pelisoli et al. (2021)

LISA verification binaries

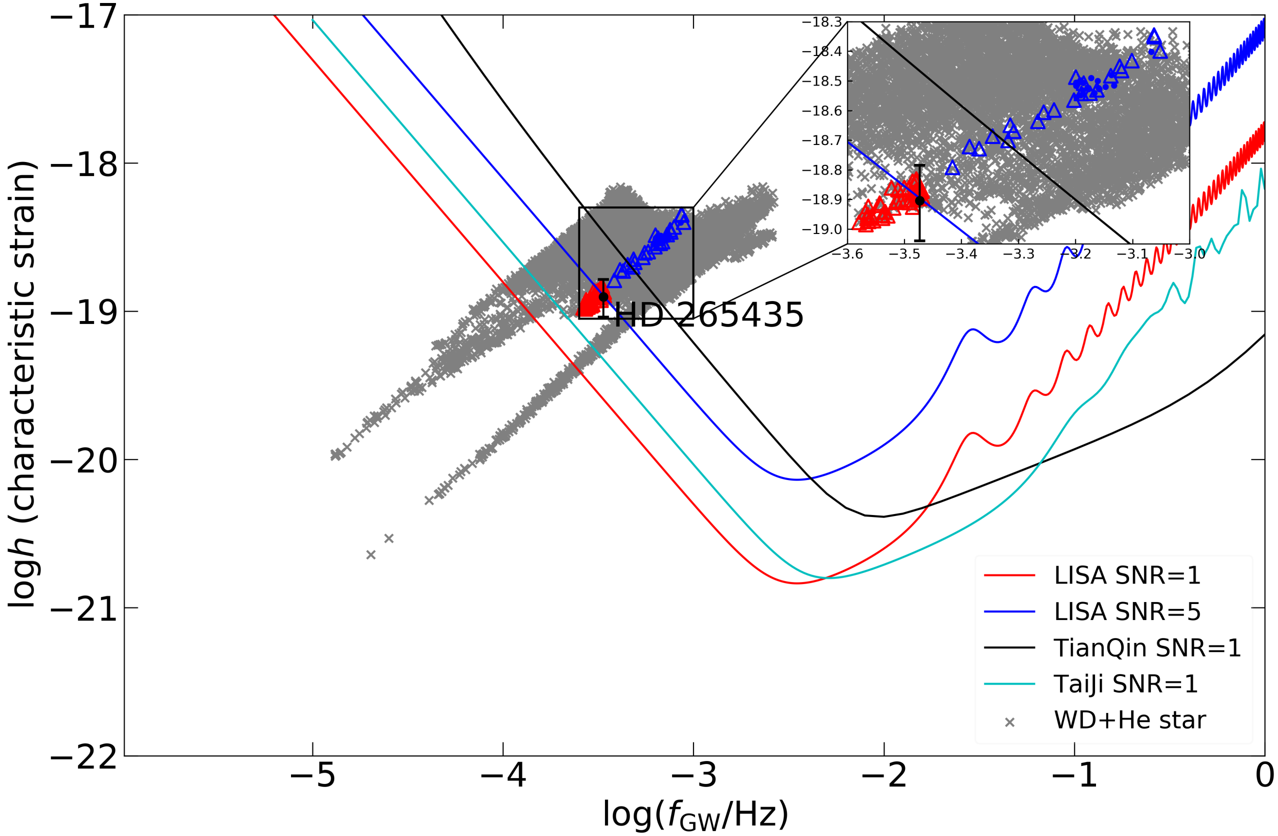
Table 1. Physical properties of the known verification binaries. Masses and inclination angles in brackets are assumed and based on evolutionary stage and mass ratio estimations.

Source	l_{Gal} (deg)	b_{Gal} (deg)	Orbital period (sec)	m_1 ($M_\odot$)	m_2 ($M_\odot$)	ι (deg)	Refs.
AM CVn type							
HM Cnc	206.9246	23.3952	321.529	0.55	0.27	≈38	1, 2
V407 Vul	57.7281	6.4006	569.395	[0.8 ± 0.1]	[0.177 ± 0.071]	[60]	3
ES Cet	168.9684	− 65.8632	620.21	[0.8 ± 0.1]	[0.161 ± 0.064]	[60]	4
SDSS J135154.46–064309.0	328.5021	53.1240	943.84	[0.8 ± 0.1]	[0.100 ± 0.040]	[60]	5
AM CVn	140.2343	78.9382	1028.73	0.68 ± 0.06	0.125 ± 0.012	43 ± 2	6, 7
SDSS J190817.07+394036.4	70.6664	13.9349	1085.7	[0.8 ± 0.1]	[0.085 ± 0.034]	10 - 20	8, 9
HP Lib	352.0561	32.5467	1102.70	0.49-0.80	0.048-0.088	26-34	10, 11
PTF1 J191905.19+481506.2	79.5945	15.5977	1347.35	[0.8 ± 0.1]	[0.066 ± 0.026]	[60]	12
CXOGBS J175107.6–294037	359.9849	− 1.4108	1375.0	[0.8 ± 0.1]	[0.064 ± 0.026]	[60]	13
CR Boo	340.9671	66.4884	1471.3	0.67-1.10	0.044-0.088	30	11, 14
V803 Cen	309.3671	20.7262	1596.4	0.78-1.17	0.059-0.109	12 - 15	11,15
Detached white dwarfs							
SDSS J065133.34+284423.4	186.9277	12.6886	765.5	0.247 ± 0.015	0.49 ± 0.02	$86.9^{+1.6}_{-1.0}$	16, 17
SDSS J093506.92+441107.0	176.0796	47.3776	1188.0	0.312 ± 0.019	0.75 ± 0.24	[60]	18, 19
SDSS J163030.58+423305.7	67.0760	43.3604	2389.8	0.298 ± 0.019	0.76 ± 0.24	[60]	18, 20
SDSS J092345.59+302805.0	195.8199	44.7754	3883.7	0.275 ± 0.015	0.76 ± 0.23	[60]	18, 21
Hot subdwarf binaries							
CD–30°11223	322.4875	28.9379	4231.8	0.54 ± 0.02	0.79 ± 0.01	82.9 ± 0.4	22

[1]Strohmayer (2005), [2]Roelofs et al. (2010), [3]Ramsay et al. (2002), [4]Espaillat et al. (2005), [5]Green et al. (2018a), [6]Skillman et al. (1999), [7]Roelofs et al. (2006), [8]Fontaine et al. (2011), [9]Kupfer et al. (2015), [10]Patterson et al. (2002), [11]Roelofs et al. (2007c), [12]Levitan et al. (2014),[13]Wevers et al. (2016), [14]Provencal et al. (1997), [15]Roelofs et al. (2007a), [16]Brown et al. (2011), [17]Hermes et al. (2012), [18]Brown et al. (2016b), [19]Kilic et al. (2014), [20]Kilic et al. (2011), [21](Brown et al. 2010), [22]Geier et al. (2013).

Kupfer et al. (2018)

The GW signal from WD+He star systems



Qi, Liu & Wang (2022)

Outline

- The progenitors of type Ia supernovae
- The formation of UCXBs
- Double WDs & Gravitational wave radiation

UCXBs: defined as the accretion-powered X-ray sources with orbital period < 60-80 min

UCXBs play an important role in broad aspects of astrophysics

1) Strong continuous gravitational wave (GW) sources in the low-frequency region ($\sim 10^{-4}$–10^{-3} Hz)

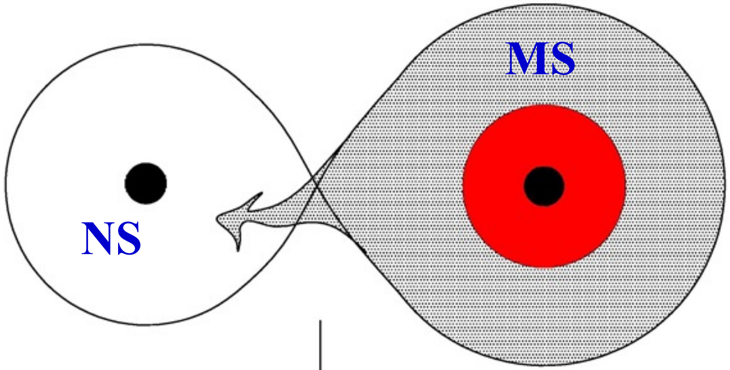
2) Can provide important constraints on the binary evolution, (e.g. Zhu, Lu & Wang ¨ 2012)

3) Excellent astrophysical laboratories (Nelemans & Jonker 2010; Lin & Yu 2018).

4) Progenitor candidates of millisecond radio pulsars (Alpar et al. 1982).

The formation of Ultracompact X-ray binaries (UCXBs)

Channel 1



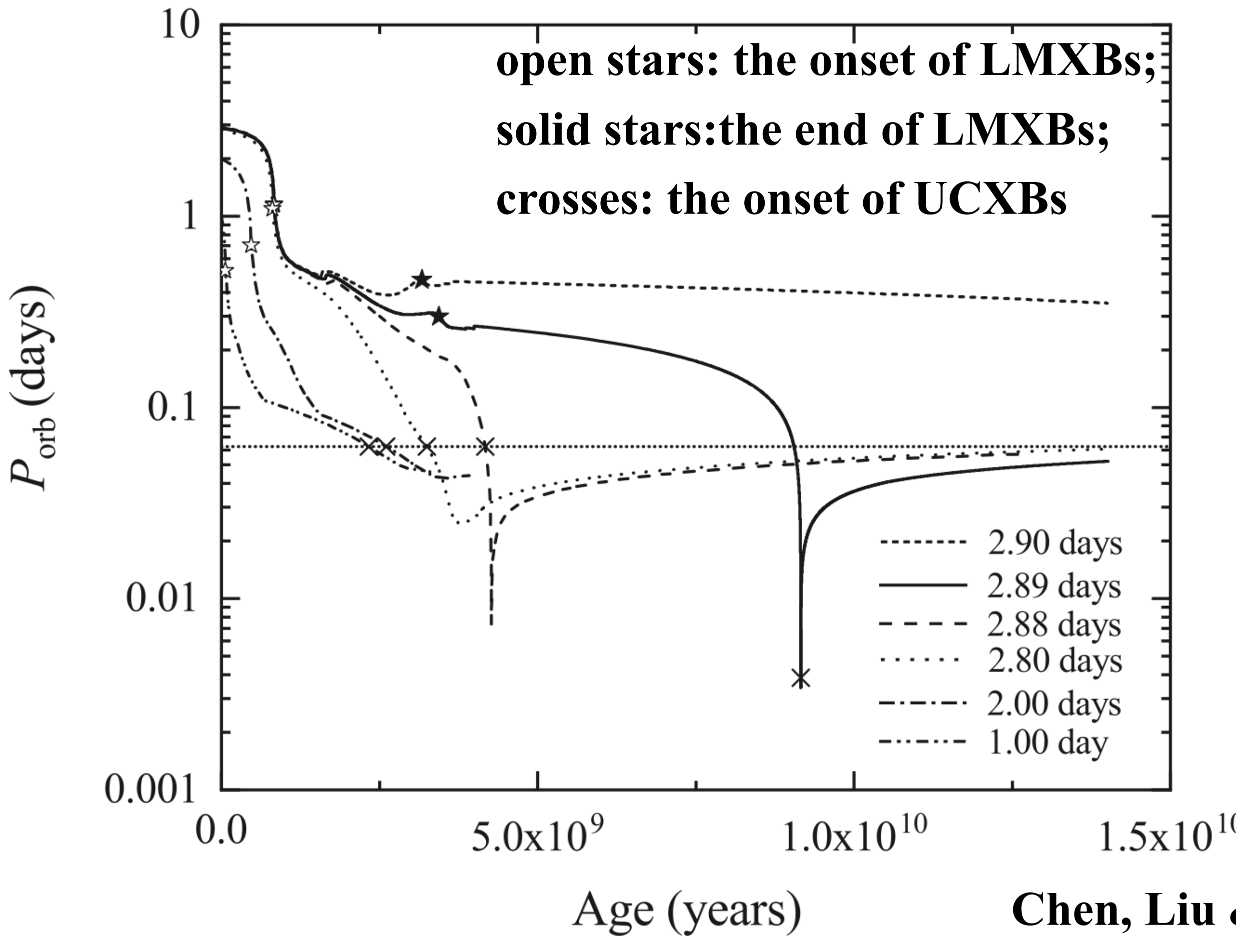
Magnetic braking

Detached system with 2-3 hours

Gravitational radiation

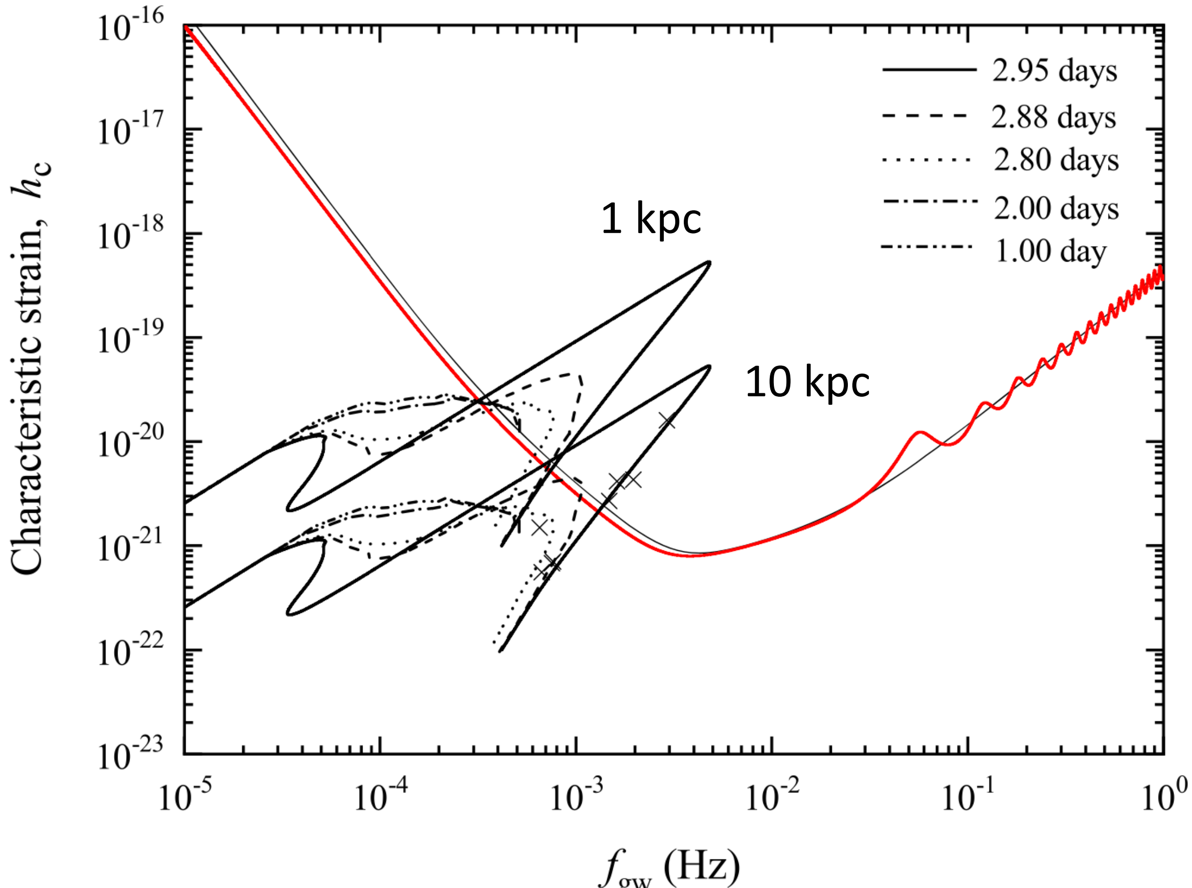
UCXB

Binary evolution track



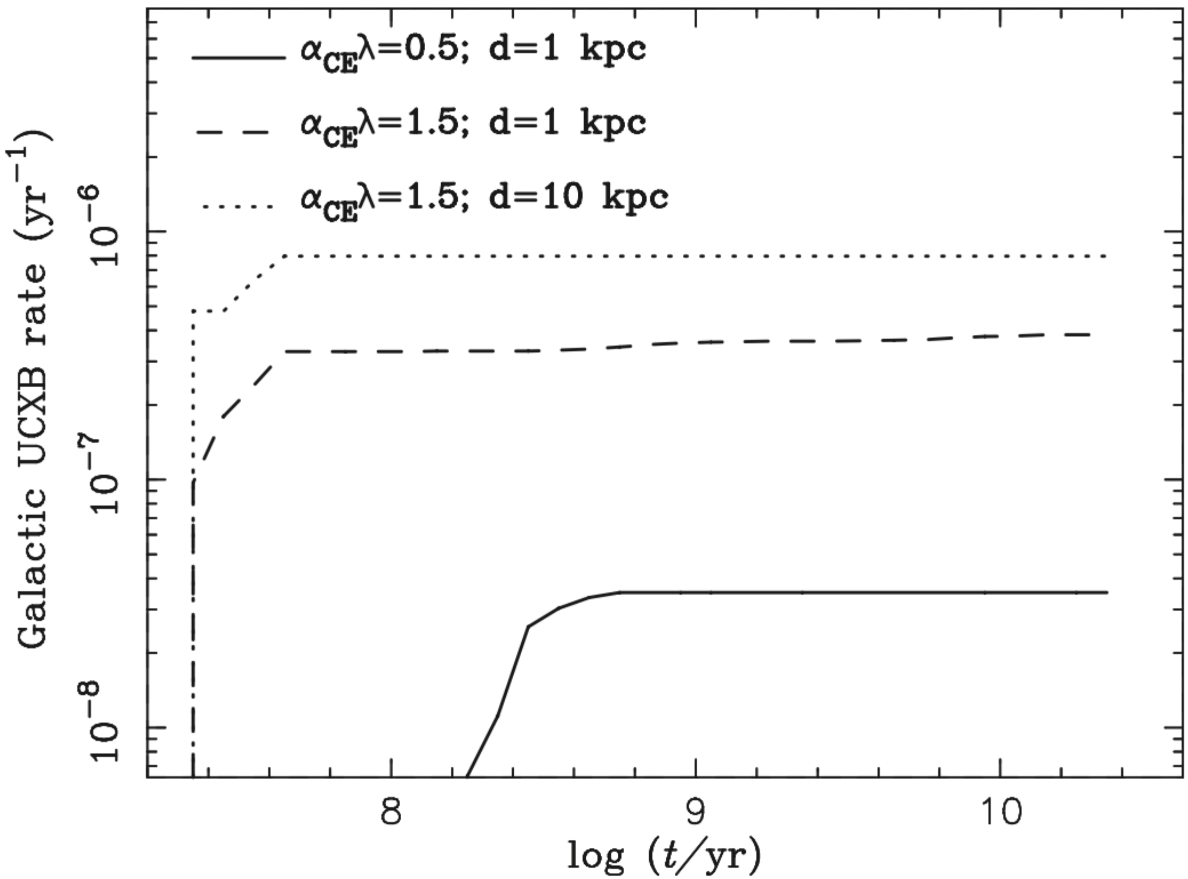
Chen, Liu & Wang (2020)

As Gravitational wave sources



Chen, Liu & Wang (2020)

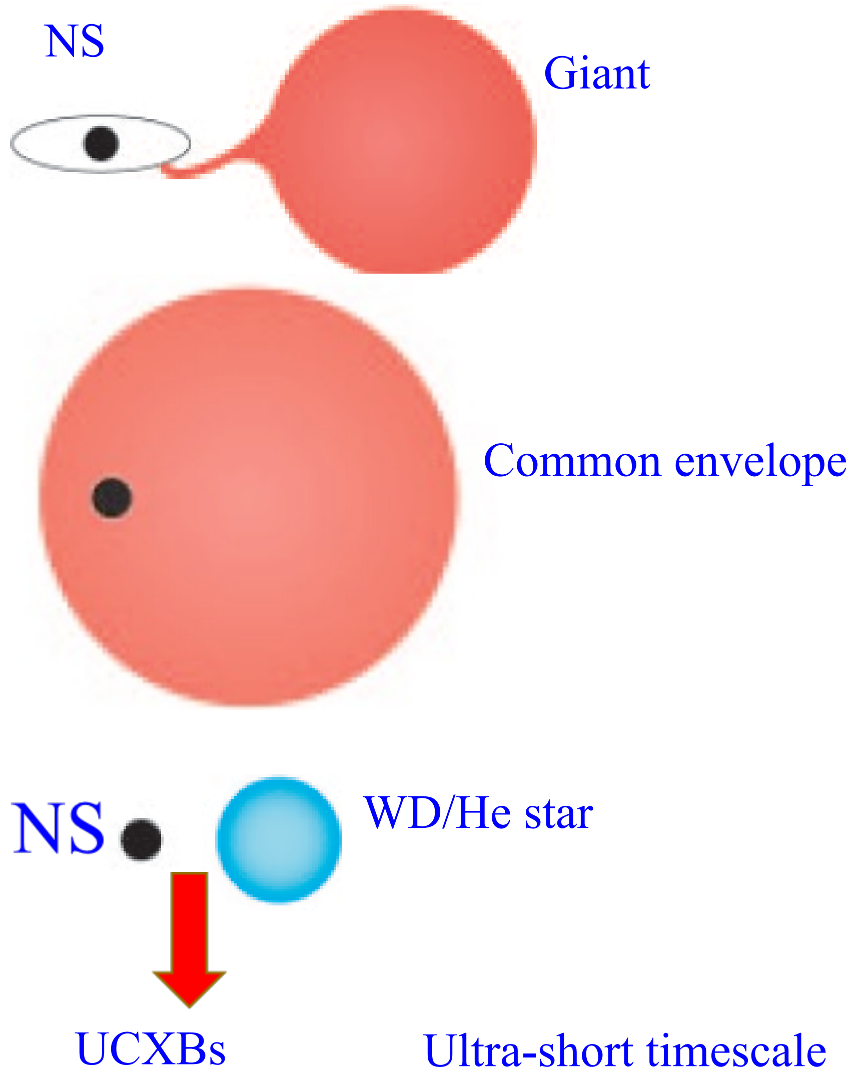
Galactic rates of UCXBs appearing as GW sources (NS+MS channel)



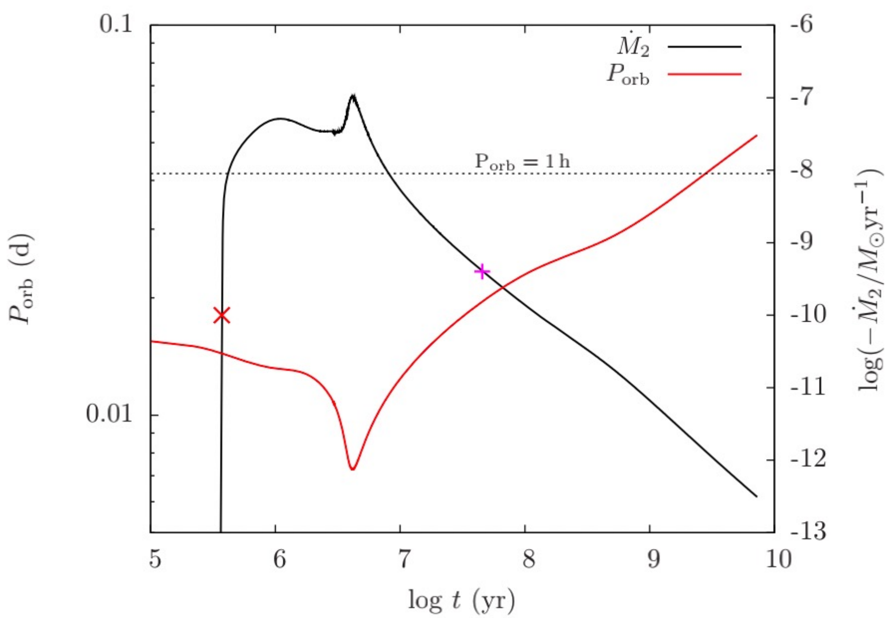
Considering the contribution of UCXBs in globular clusters, the number of UCXB-LISA sources can reach 240–320.

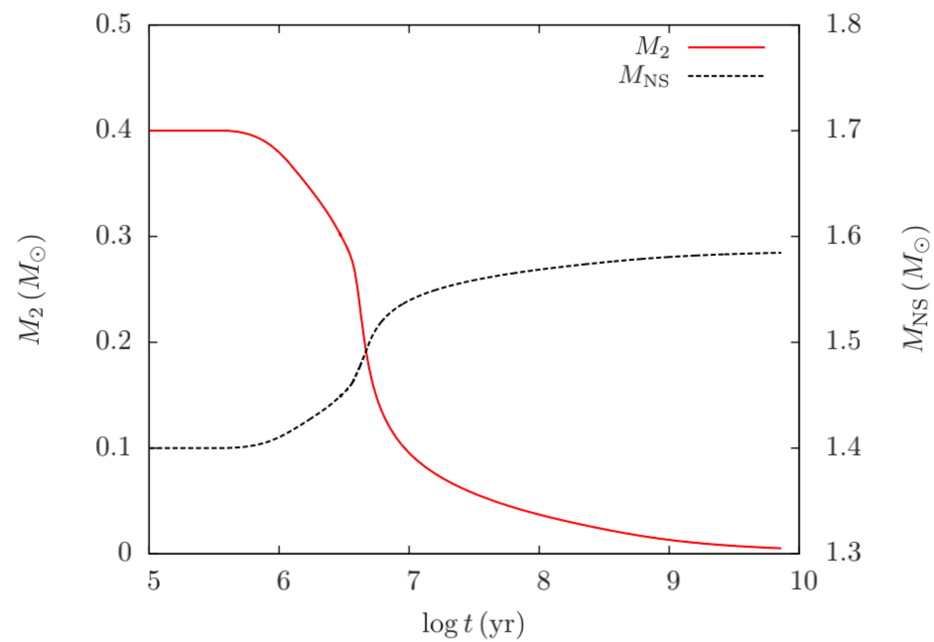
Chen, Liu & Wang (2020)

Channel 2


NS
Giant
Common envelope
NS
WD/He star
UCXBs
Ultra-short timescale

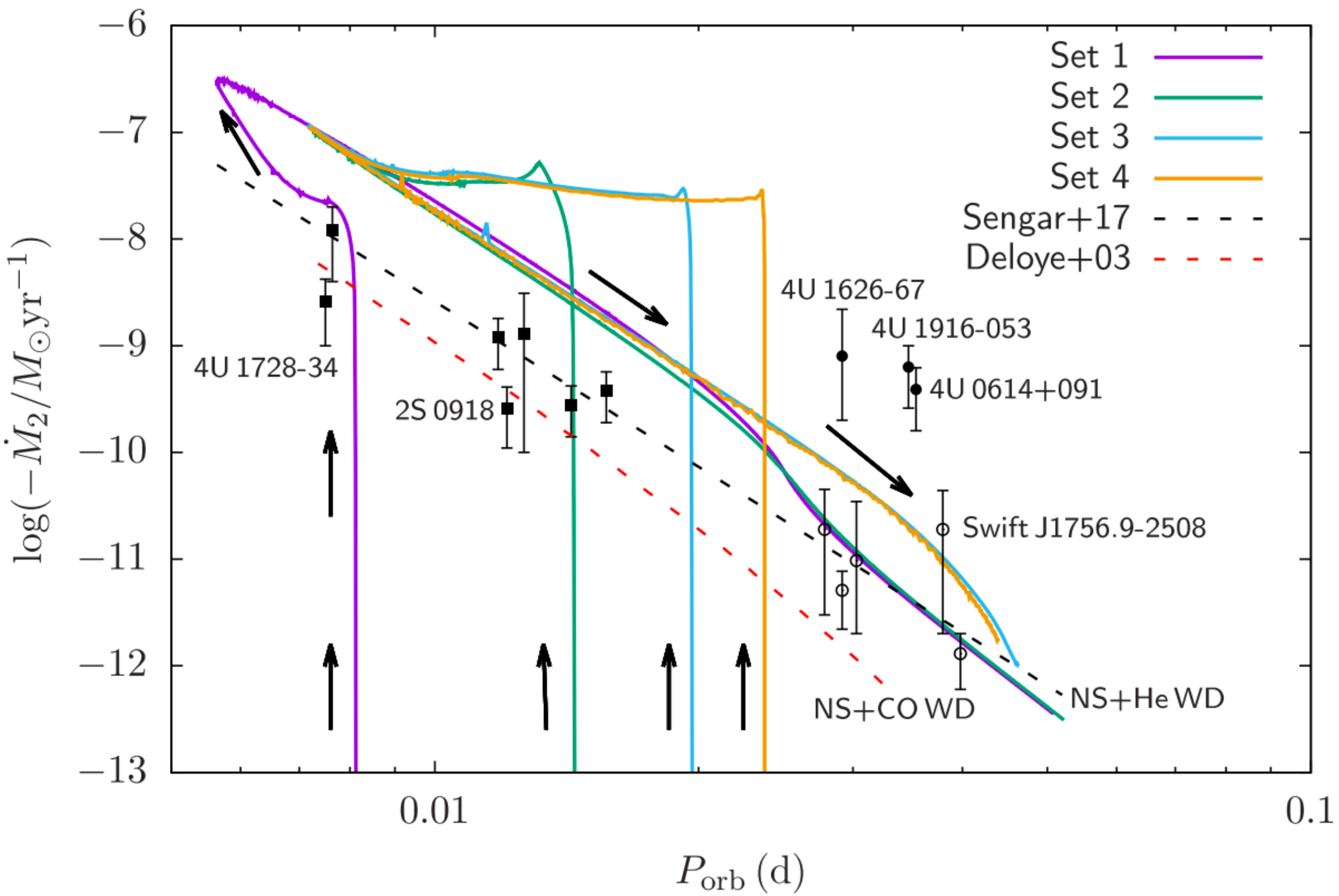
An example of NS+He star system





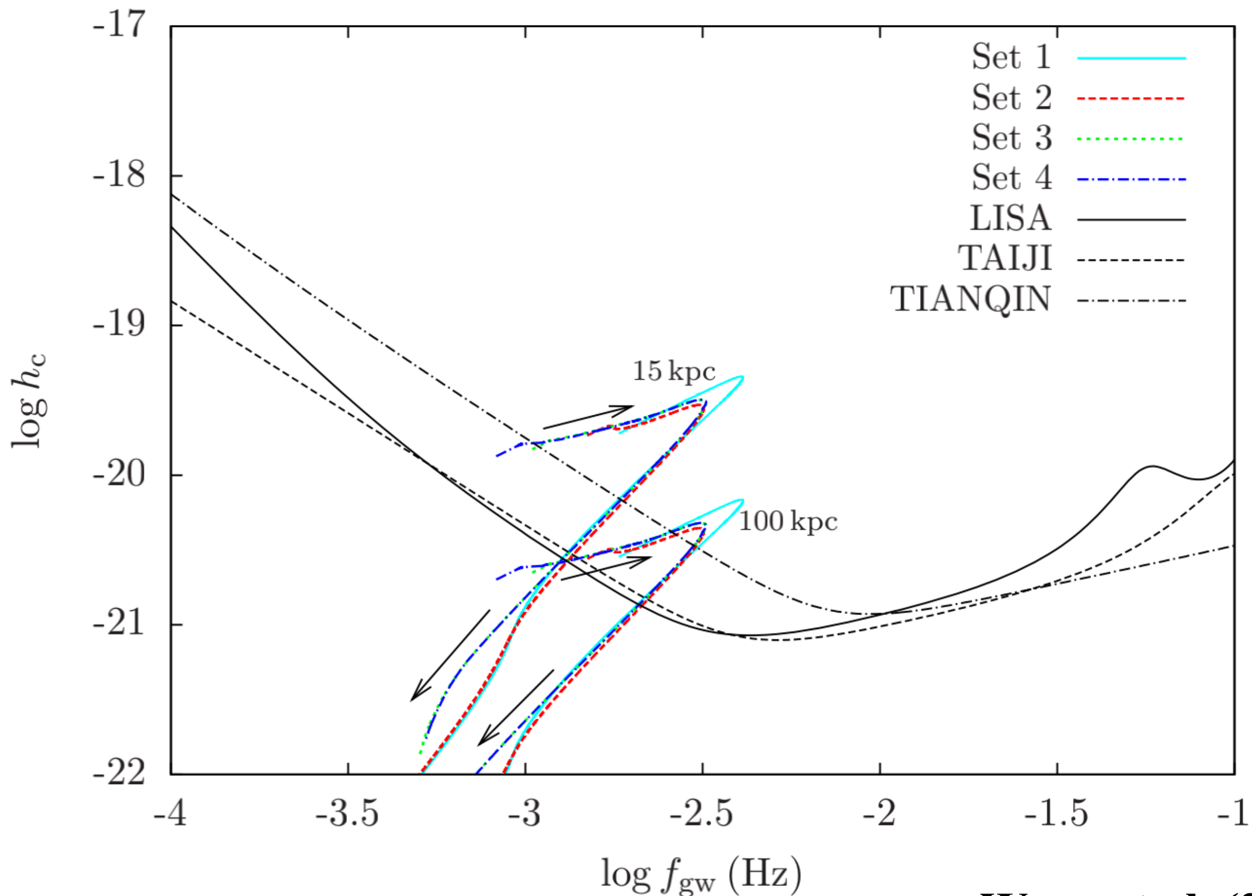
Wang et al. (2021)

Comparied with observations



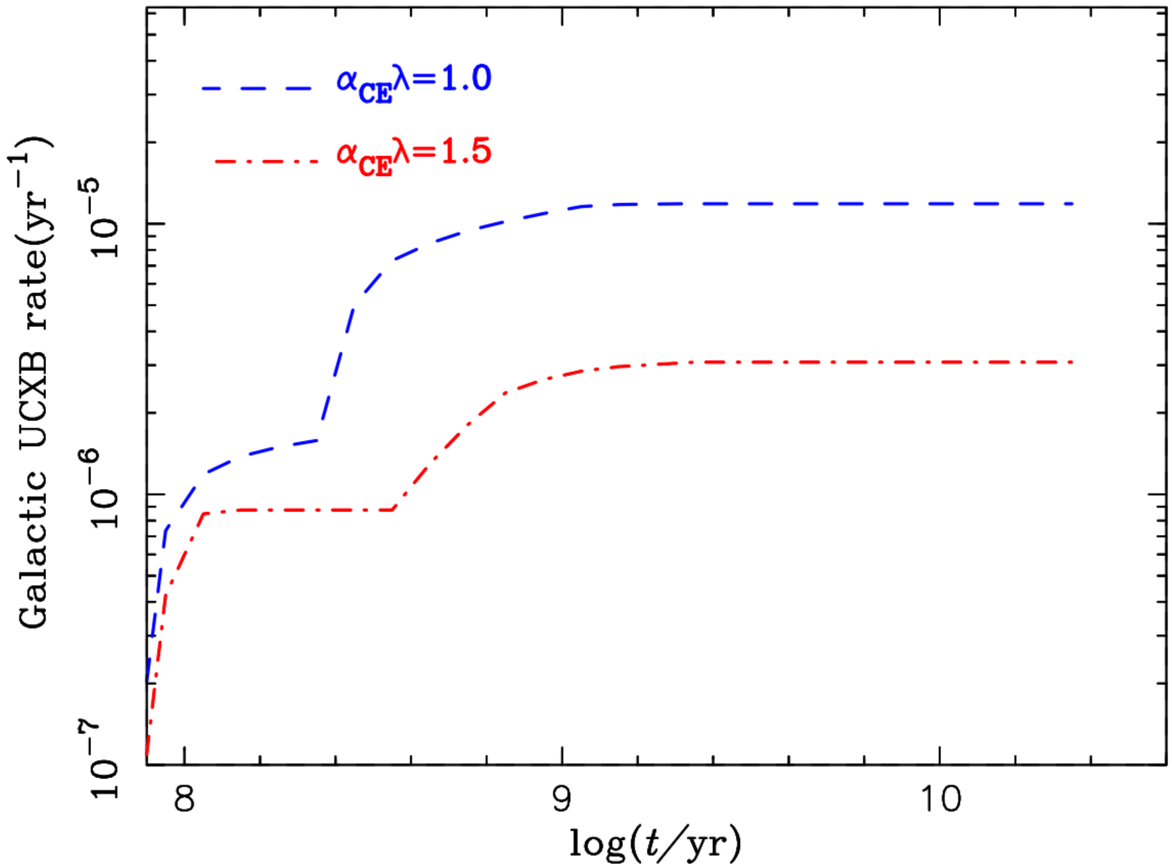
Wang et al. (2021)

As Gravitational wave sources



Wang et al. (2021)

Galactic rates of UCXBs appearing as GW sources (NS+He star channel)

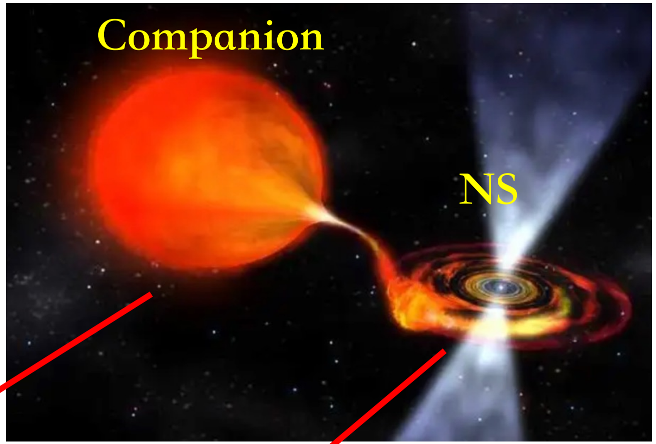


The number of UCXB-LISA sources can reach about 1–26 in the Galaxy.

Wang et al. (2021)

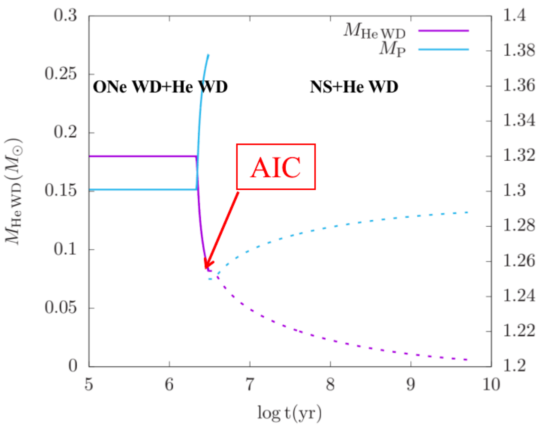
An AIC channel for the formation of UCXBs

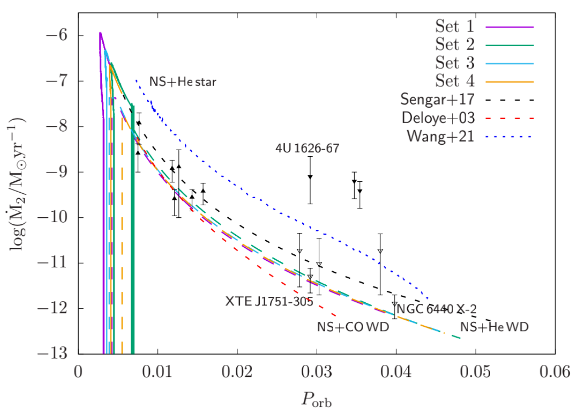
Name	P (ms)	B (G)	Porb (days)	Mc($M_\odot$)	Ref.
GRO J1744-28	467	$1.0*10^{13}$	11.8	~0.08	Van Paradijs+(1997)
PSR J1744-3922	172	$5.0*10^{9}$	0.191	~0.1	Breton+ (2007)
PSR B1831-00	521	$2.0*10^{10}$	1.81	~0.08	Sutantyo & Li (2000)
4U 1626-67	7680	$3.0*10^{12}$	0.028	~0.02	Yungelson+ (2002)

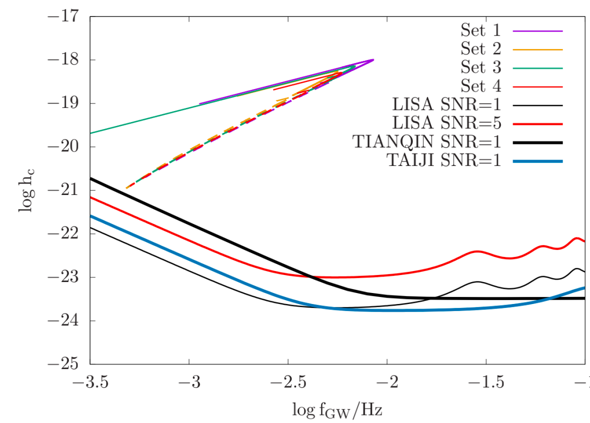


ultra-low M, short Porb：
Have transfer much material

high B, low spin： Have not accrete material







Liu & Wang (2022)

Outline

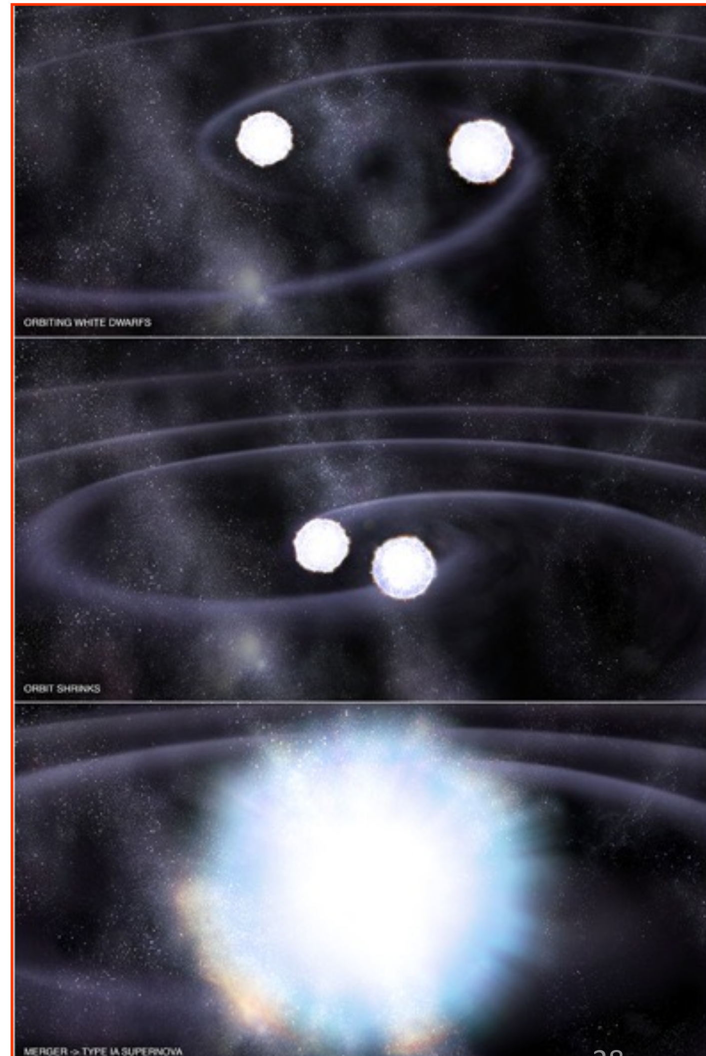
- The progenitors of type Ia supernovae
- The formation of UCXBs
- Double WDs & Gravitational wave radiation

Double WD systems

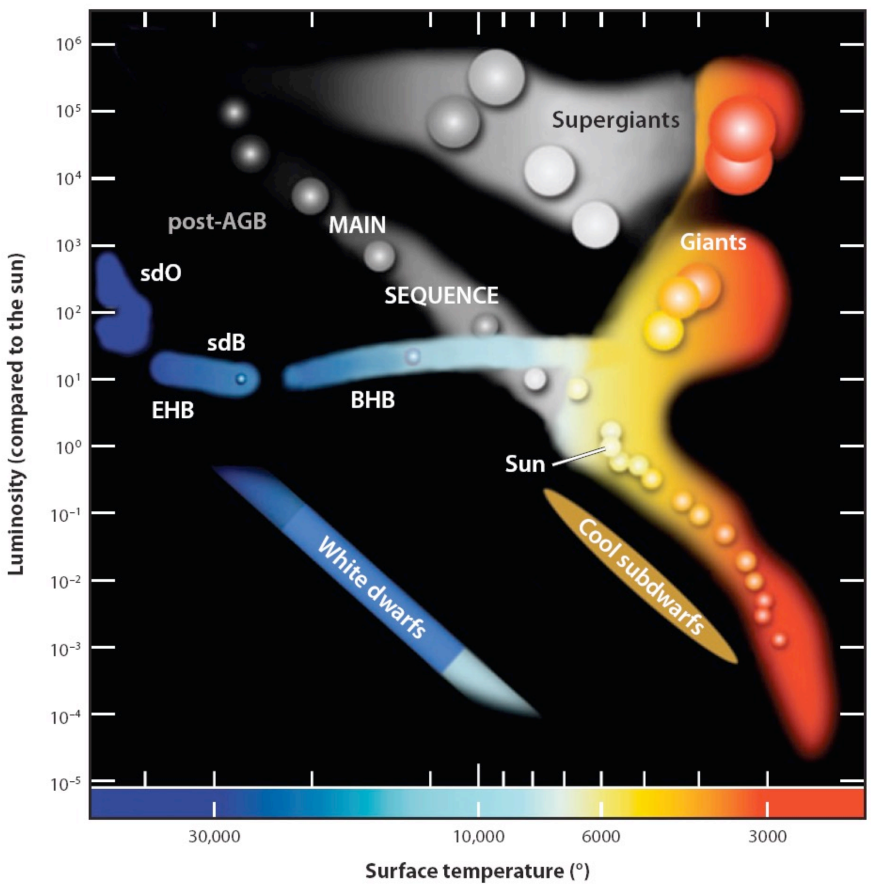
- Originate from intermediate- and low-mass binaries.

- Rotate each other, and may eventually merge due to the gravitational wave radiation.

- Mergers are relevant to many interesting peculiar events. like……



Hot subdwarfs
from CO/He WD+He WD mergers



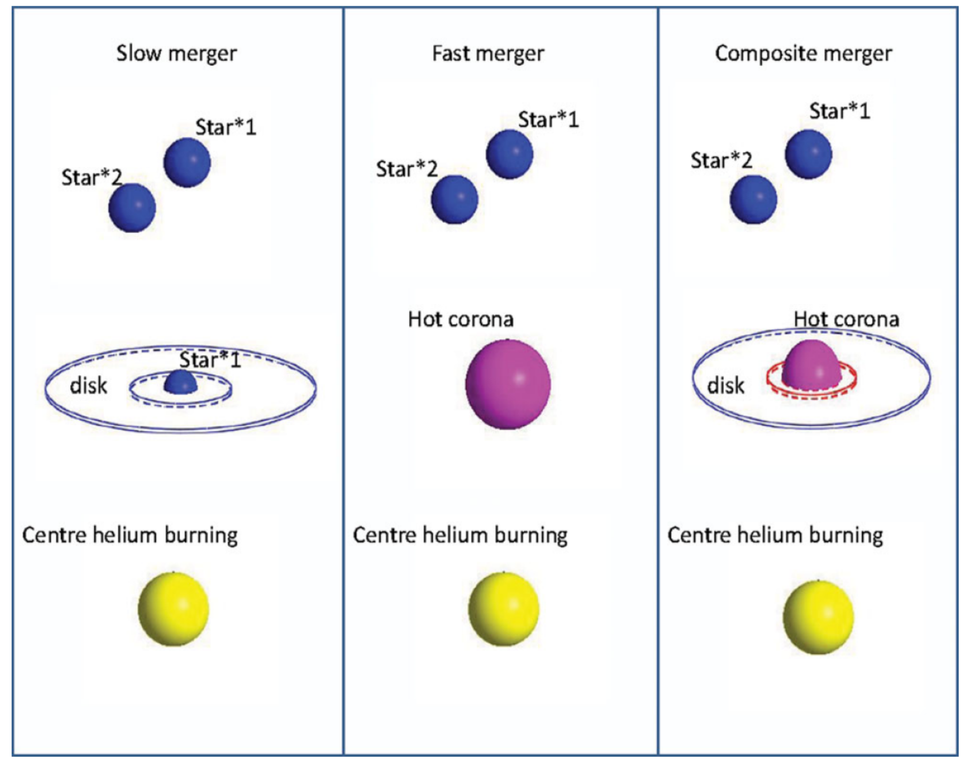
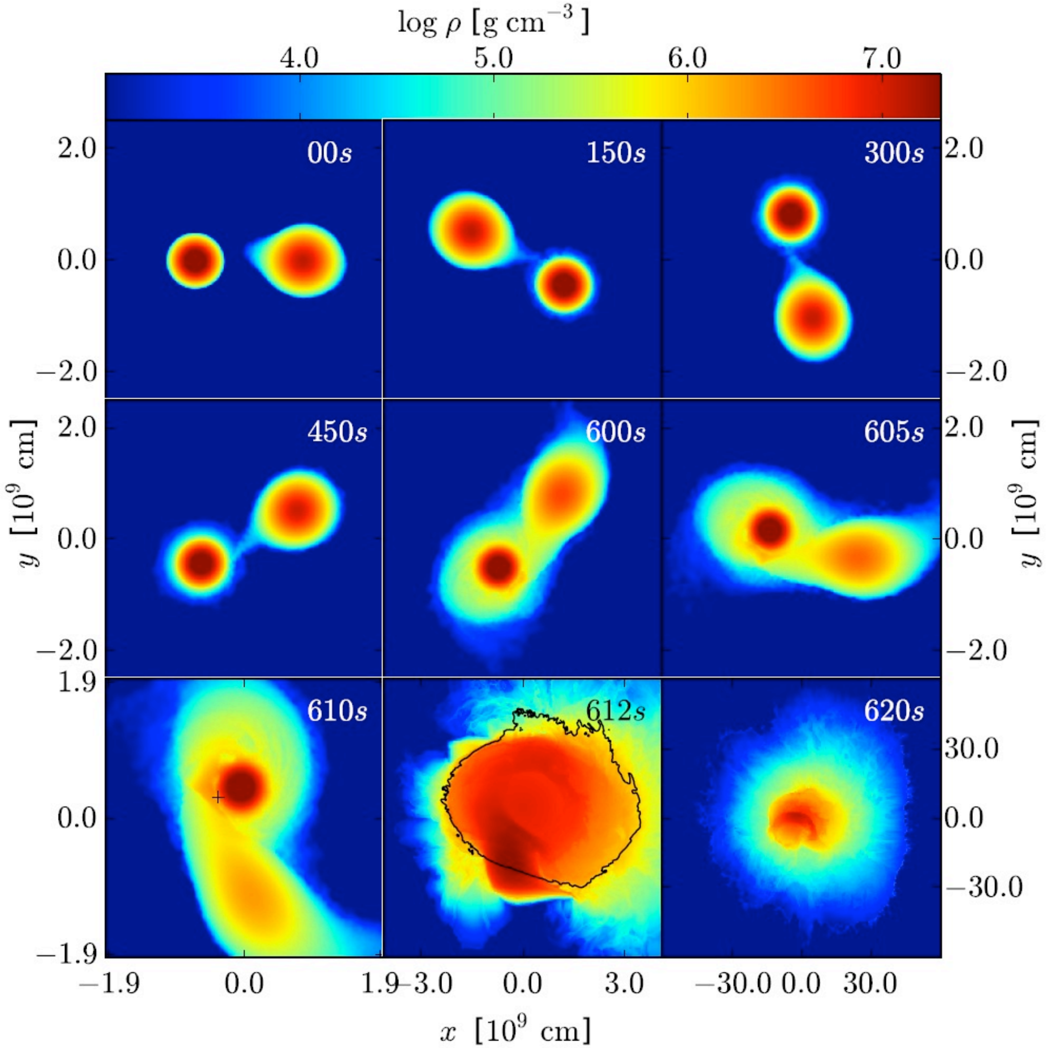


Figure 1. Schematic of three possible ways in which two helium white dwarfs might merge.

Heber (2009)

Zhang & Jeffery (2012)

Type Ia supernove from double CO WD mergers



Pakmor et al. (2012)

R CrB stars
from of CO WD+He WD mergers

- ✓ **R Coronae Borealis (R CrB or RCB) stars are C-rich, H-poor supergiants (Clayton 1996).**
- ✓ **Teff: 4000 to 8000 K**
- ✓ **log g: 0.5 to 1.5**

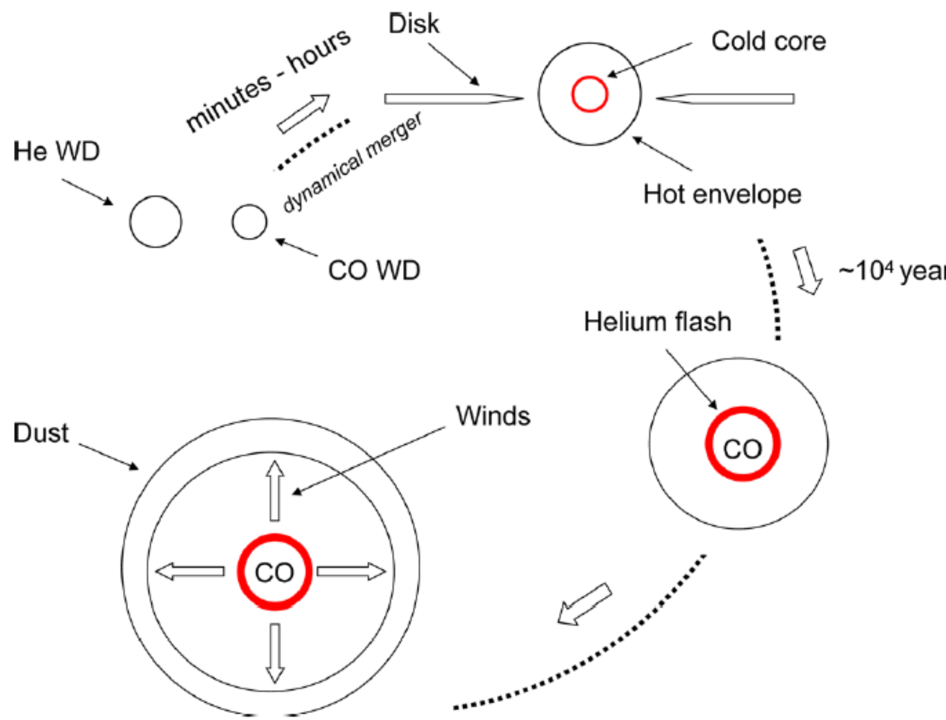
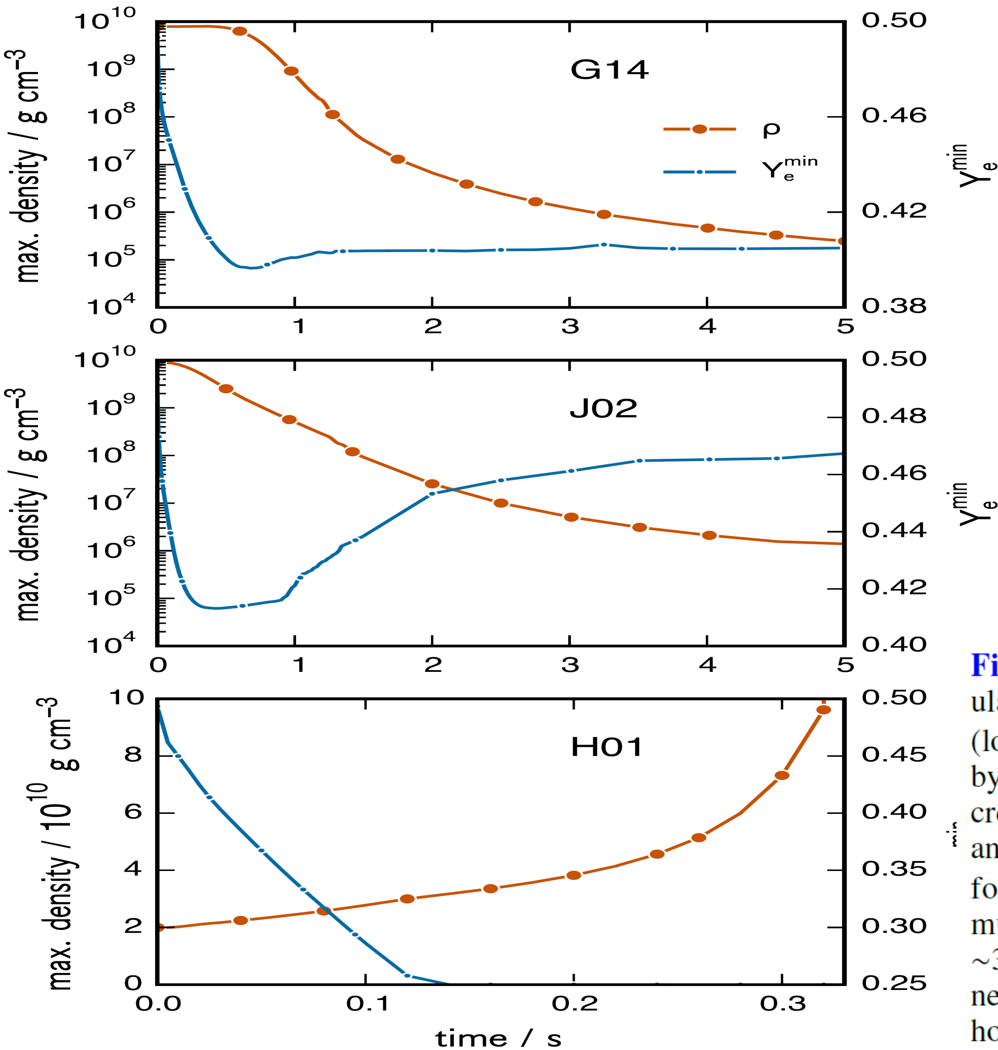


Figure 2. Schematic of possible steps in a CO+He WD merger leading to the formation of an RCB star.

Zhang et al. (2014)

AIC events
from ONe WD+ONe/CO WD mergers



Jones et al. (2016)

First multidimensional hydrodynamic simulations of the oxygen deflagration

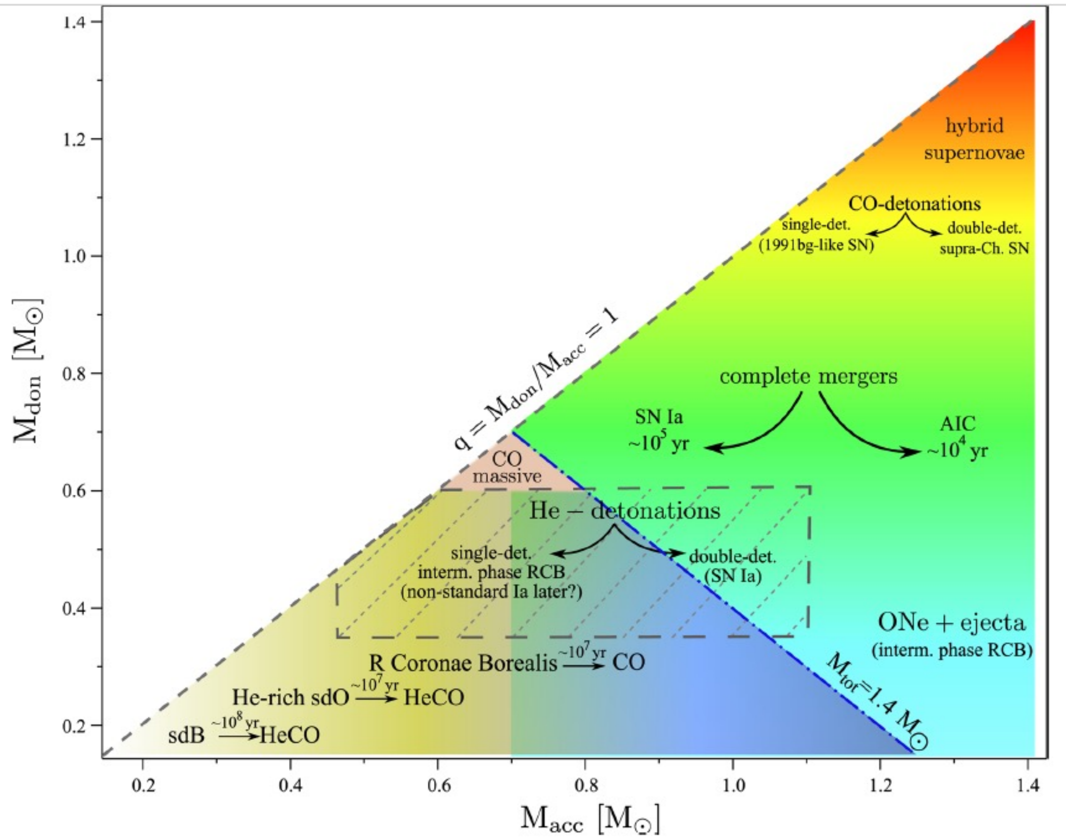
Fig. 2. Maximum density and minimum electron fraction Y_e in the simulations G14, J02 and H01 (see Table 1). In the G and J simulations ($\log_{10}\rho_c^{ign}$ = 9.9 and 9.95), respectively, the maximum density drops by several orders of magnitude in the first 5 s despite the marked decrease in the minimum Y_e, leading to the partial disruption of the core and the formation of an ONeFe white dwarf that does not collapse to form a neutron star. In the H01 simulation ($\log_{10}\rho_c^{ign} = 10.3$), the maximum density only increases with time, reaching 10^{11} g cm^{-3} in the first ~330 ms. The simulation was not continued beyond this point because neutrino interactions with matter were not included in the microphysics, however the most likely outcome is collapse into a neutron star.

Double WD mergers

- Hot subdwarfs
- Type Ia supernovae
- R CrB stars
- Accretion-induced collapse
- ……

✓High-energy phenomena, like Gamma-ray burst, etc (Lyutikov & Tonoon 2017)

✓Gravitational wave sources



Dan et al. (2014)

Double WD mergers

- Hot subdwarfs
- Type Ia supernovae
- R CrB stars
- **Accretion-induced collapse**
- ……

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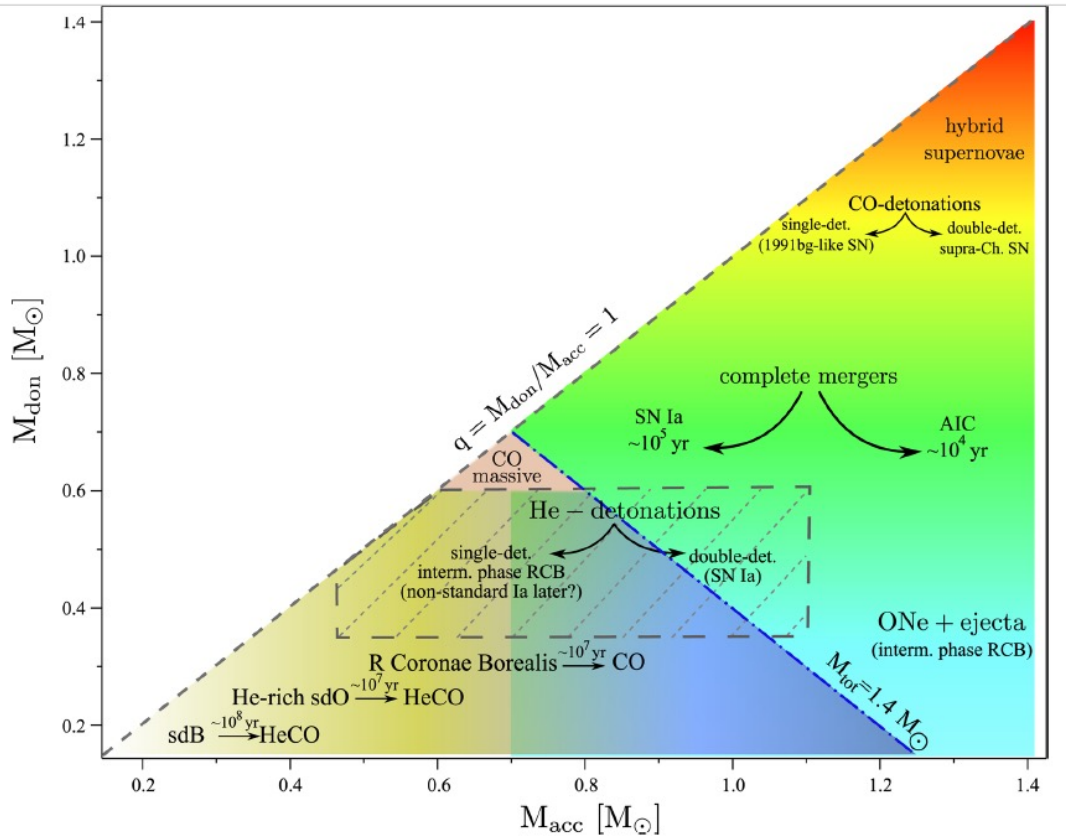
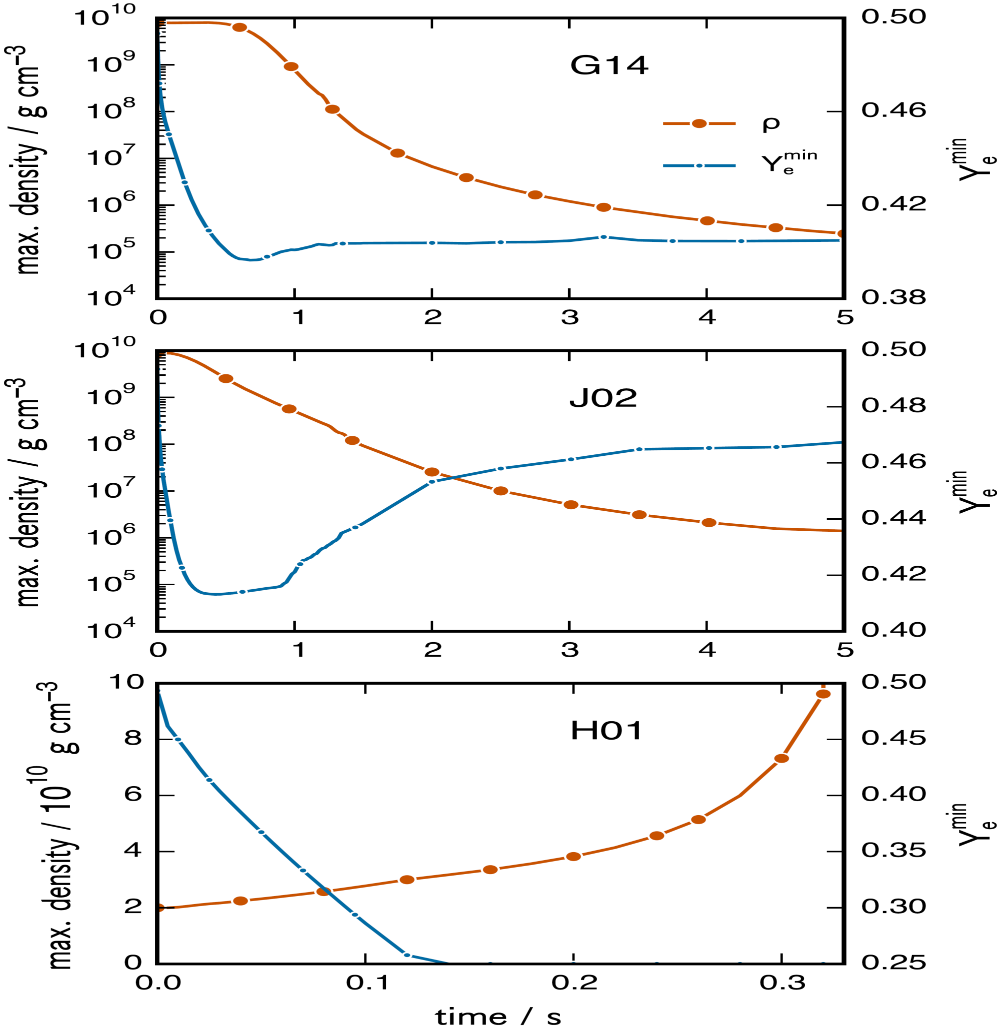


Dan et al. (2014)

Double WD mergers and AIC events

- ONe WD+ONe WD
- ONe WD+CO WD

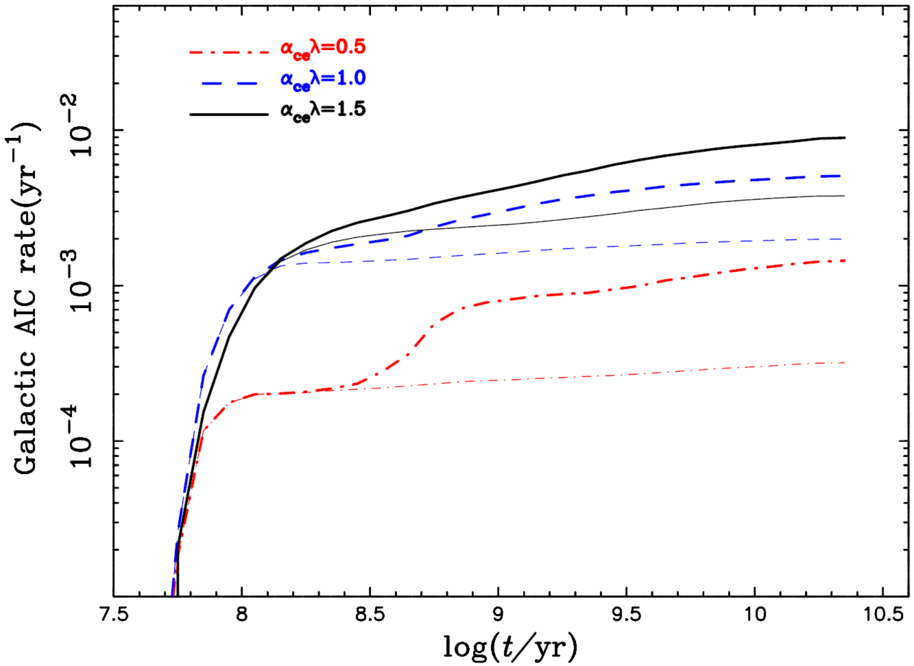


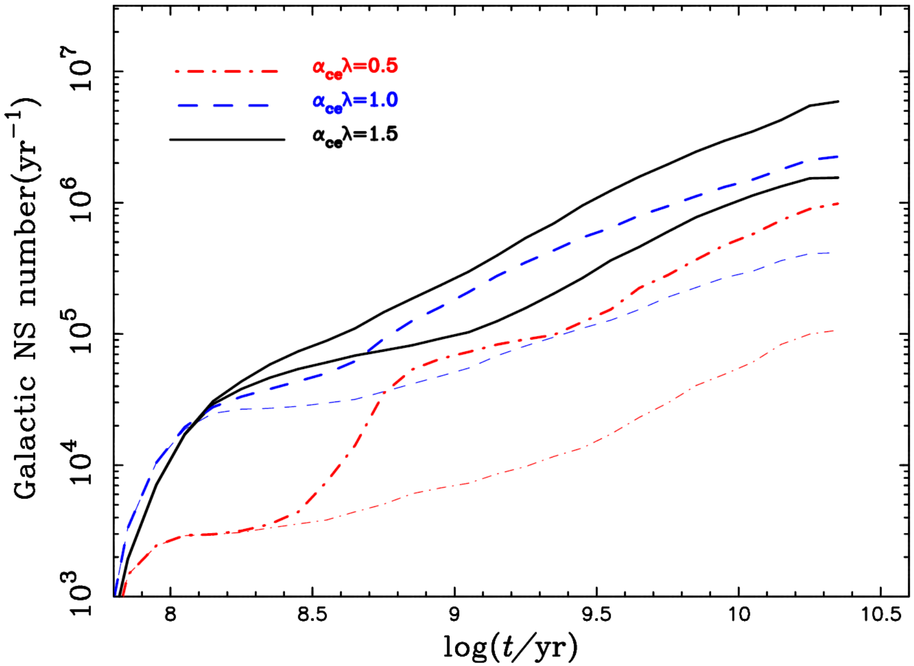
Jones et al. (2016)

Double WD mergers and AIC events

- ONe WD+ONe WD
- ONe WD+CO WD
- CO WD+CO WD？
  AIC or SNe Ia?

AIC Birthrate and Single NS Number in the Glaxy





Consider double CO WD mergers:
$1.4-8.9 \times 10^{-3}\mathrm{yr}^{-1}$
Do not Consider DCOWD mergers:
0.3 to $3.8\times10^{-3}\mathrm{yr}^{-1}$

Consider double CO WD mergers:
$1-5.9\times10^{6}$
Do not Consider DCOWD mergers:
$0.1-1.5 \times 10^{6}$

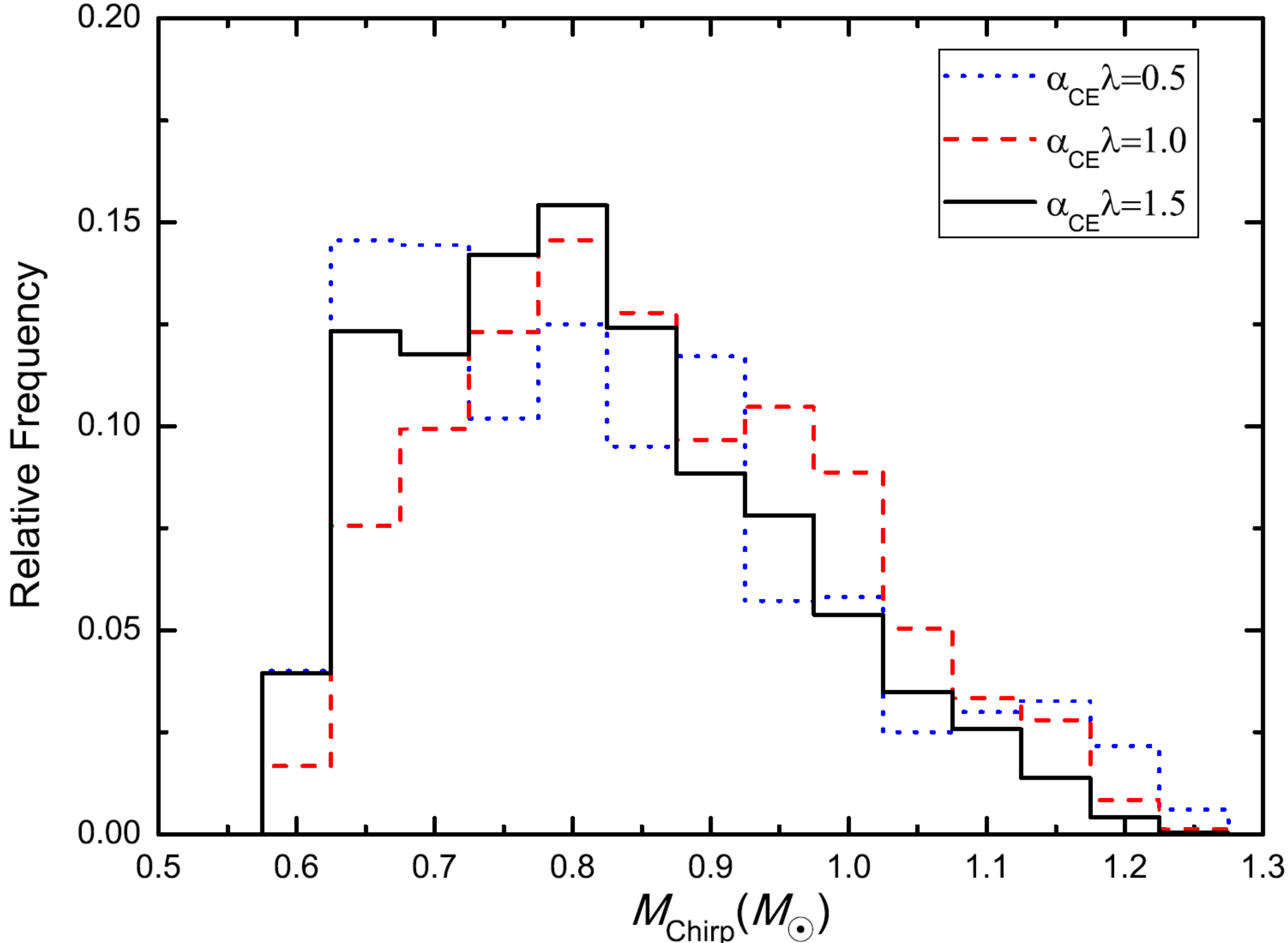
Liu et al. (2020)

Double CO WD merger channel

Set	*Criteria*	Birthrates ($10^{-3}\mathrm{yr}^{-1}$)	NS Number (10^6)
1	$q < 0.8$	3.080	1.825
2	$q < 0.7$	2.125	1.153
3	$q < 2/3$	1.586	0.908
4	$q < 0.6$	0.554	0.320
5	$q < 0.5$	0.082	0.122
6	$q < 0.4$	0.007	0.027
7	$q < 0.3$	0	0

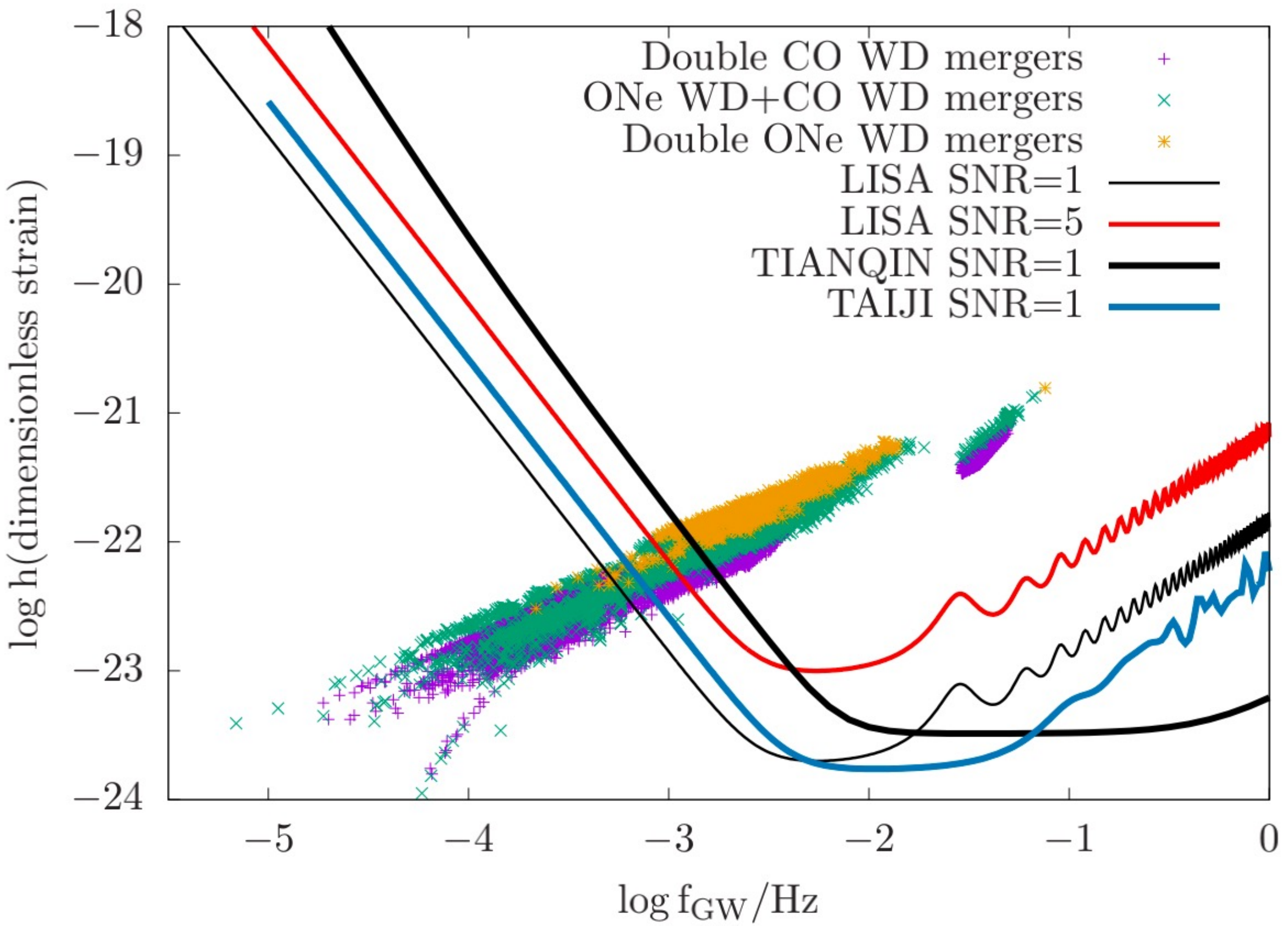
Liu et al. (2020)

Chirp Mass Distribution



Liu et al. (2020)

Gravitational Wave Signals



Liu et al. (2020)

Possible reasons of no direct detections

- **Reason 1:**

  Ejected mass < 0.1 $M_\odot$

  ^{56}Ni production < 0.01 $M_\odot$

  5 magnitude fainter than a typical SN Ia

  Last for only a few days

- **Reason 2:**

  Mixed in some other transients, like faint CCSNe, kilonovae, Gamma-ray burst, etc.

➢ **How to distinguish them?**

Detections of AIC events I: **VTC J095517.5+690813**

The SD model

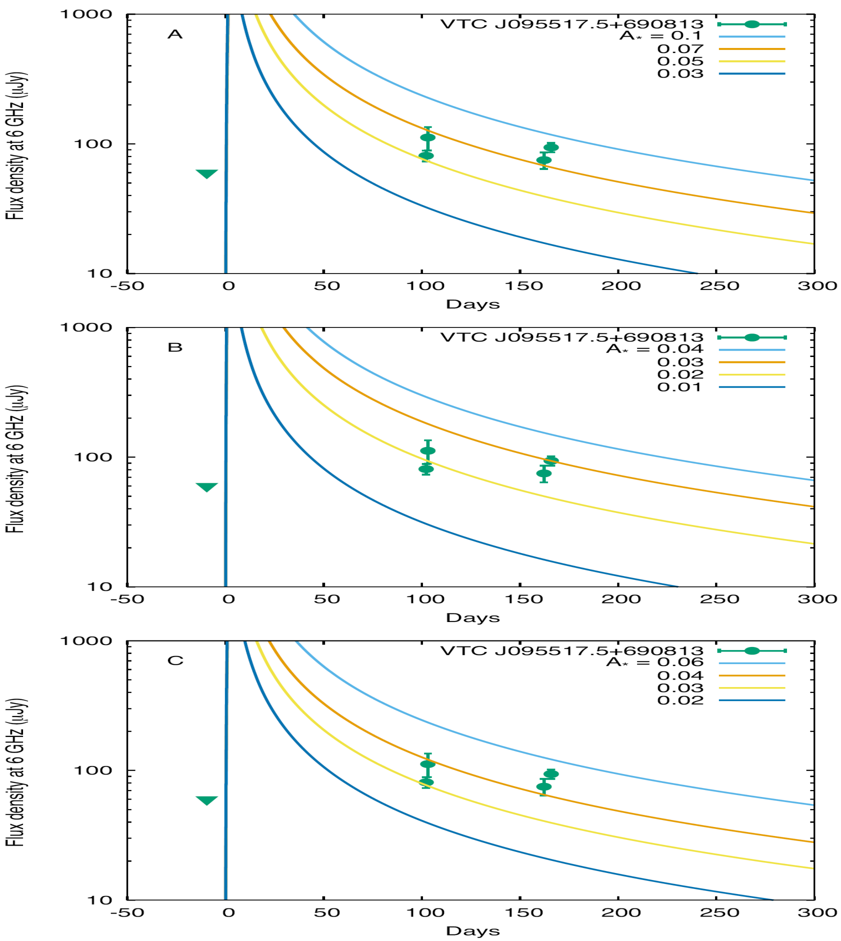


Figure 1. Radio (6 GHz) LC of AIC from the SD channel having the CSM density profile of $\rho_{\rm CSM}(r) = 5 \times 10^{11} A_\star r^{-2}$ (cgs units) at the distance of VTC J095517.5 + 690813 (3.6 Mpc). The different panels have different ejecta properties (Table 1). The radio LC of VTC J095517.5 + 690813 at 6 GHz (Anderson et al. 2019) is presented for comparison. The triangle shows the upper flux limit. The explosion date of the synthetic LCs is 0 d, and the observed LC is shifted to compare with the synthetic LCs.

The DD model

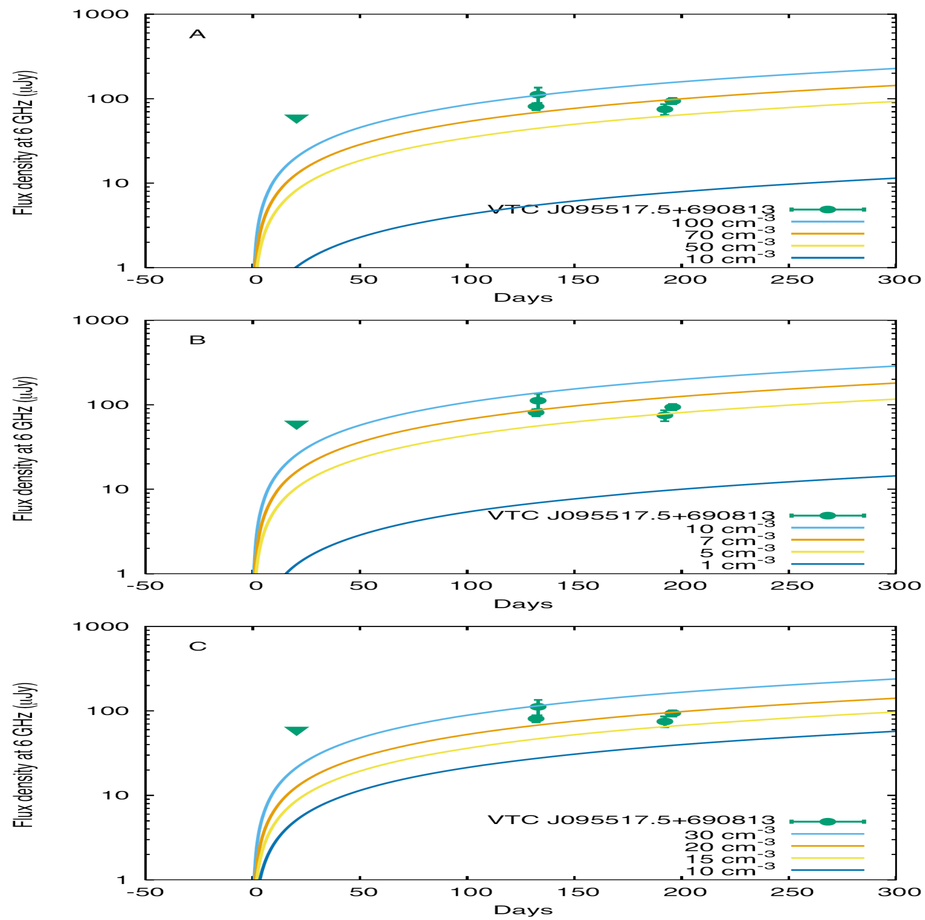


Figure 2. Radio (6 GHz) LC of AIC from the DD channel with a constant CSM density at the distance of VTC J095517.5 + 690813 (3.6 Mpc). The different panels have different ejecta properties (Table 1). The radio LC of VTC J095517.5 + 690813 at 6 GHz (Anderson et al. 2019) is presented for comparison. The triangle shows the upper flux limit. The explosion date of the synthetic LCs is 0 d, and the observed LC is shifted to compare with the synthetic LCs.

Moriya (2019)

Detections of AIC events II: **SN 2018kzr**

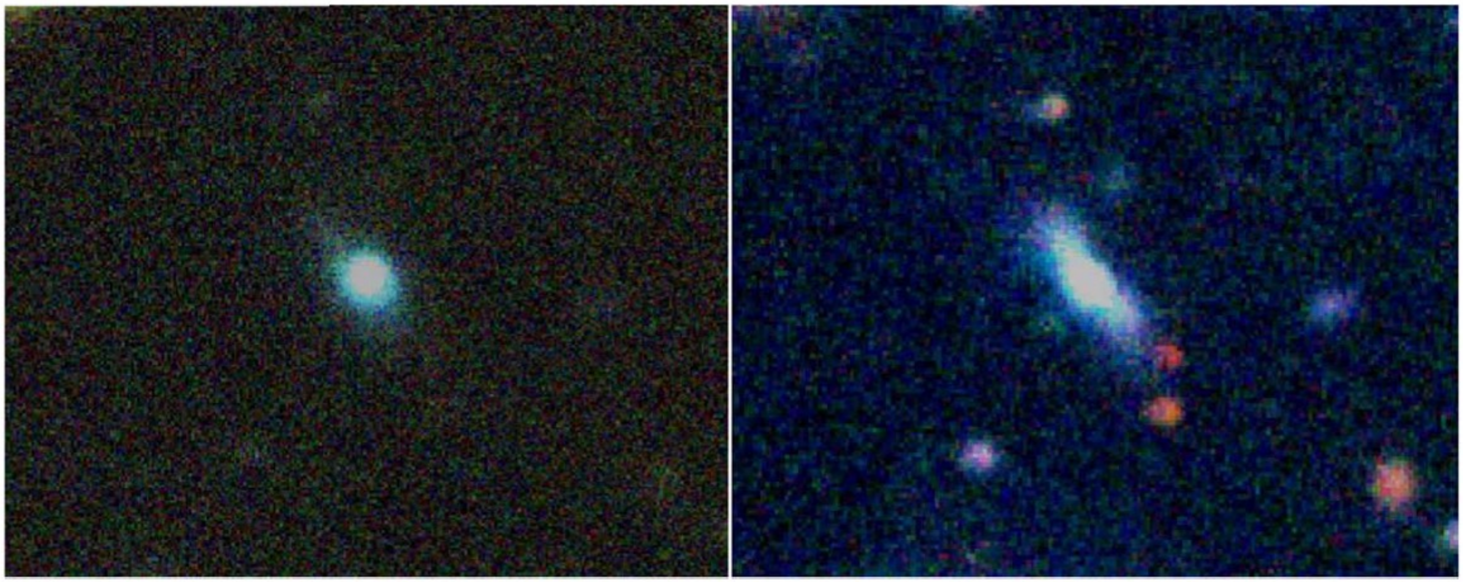


Figure 1. RGB composite images of the host of SN2018kzr, SDSS J082853.50+010638.6. Left: the GROND *gri* exposures from +3.731 days. Right: the NTT: EFOSC2 *gri* exposures taken at +68.676 days (Table 1). The host is a blue star-forming galaxy with a bright core.

The Second fastest declining supernova-like transient.

- ✓ **Peak magnitude: M_r=−17.98 (~1.4×10^{43} erg/s);**
- ✓ **Decline rate: 0.48±0.03 mag/day;**
- ✓ **Ejecta mass: M_{ej}=0.10±0.05Msun**

Mcbrien et al. (2019)

Single NSs from AIC events

- Supermassive NSs: ~2.2 Msun (Metzger et al. 2015) ?
- Rotation?
- If they are strongly magnetized: Fast radio bursts (Moriya 2016)

- Corresponding to a specific type of NSs?

Summary

- ✓The WD+He star channel is an important path for the formation of SNe Ia, and the WD+He star systems are also important GW sources.

- ✓UCXBs play an important role in broad aspects of astrophysics, and are Strong continuous gravitational wave (GW) sources in the low-frequency region.

- ✓Double WD systems related to many interesting objects, and are detectable for space-based GW telescopes.