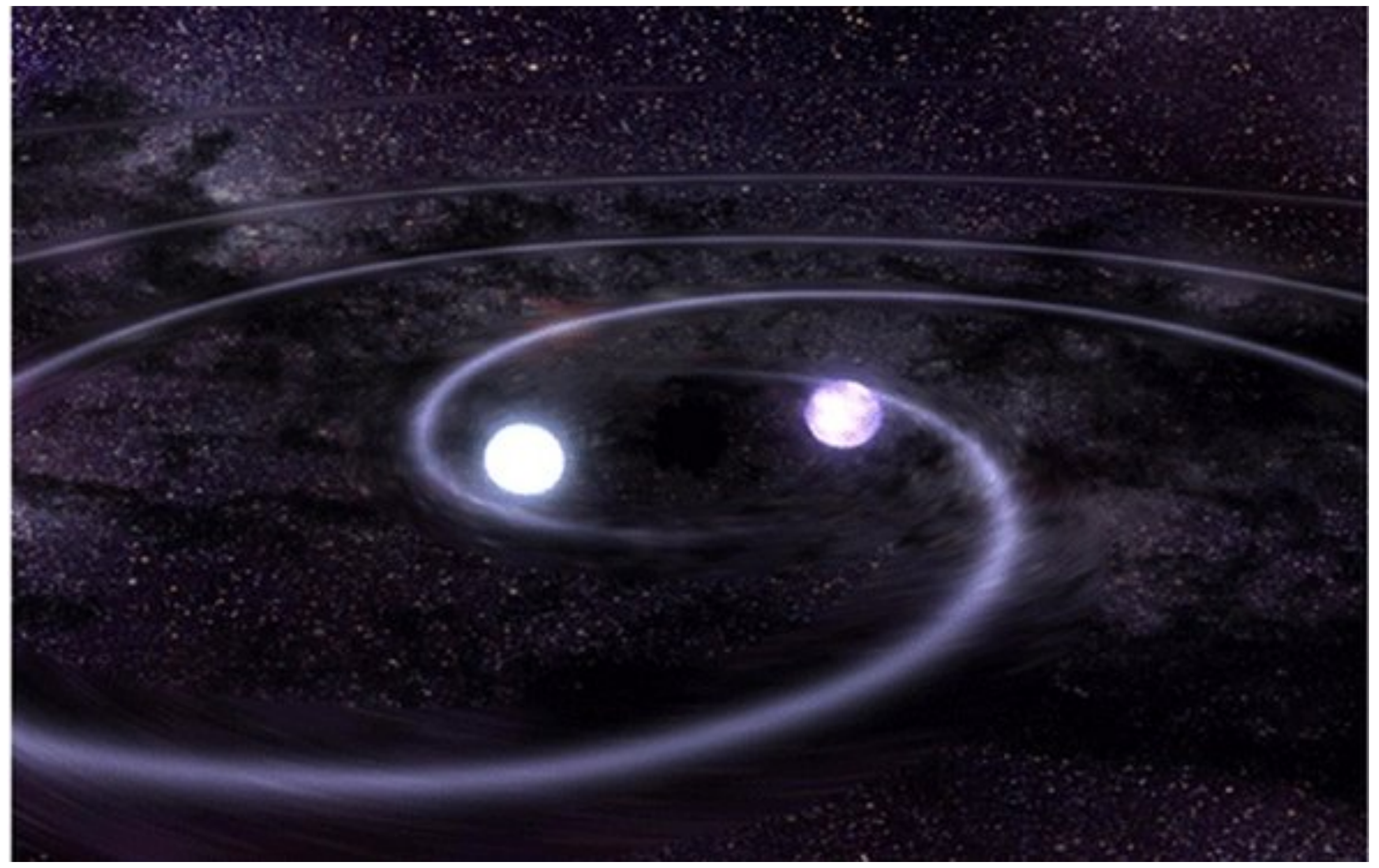
Radio emission from ultra-stripped supernovae as diagnostics for the binary separation of the remnant double neutron star



(NASA)

Tomoki Matsuoka
(D2 @ Dept. of Astronomy, Kyoto Univ.)

Collaborators : Keiichi Maeda (Kyoto Univ.)

For details, see Matsuoka & Maeda, 2020, ApJ, 898, 158

Double neutron star (DNS) binary

Orbital decay

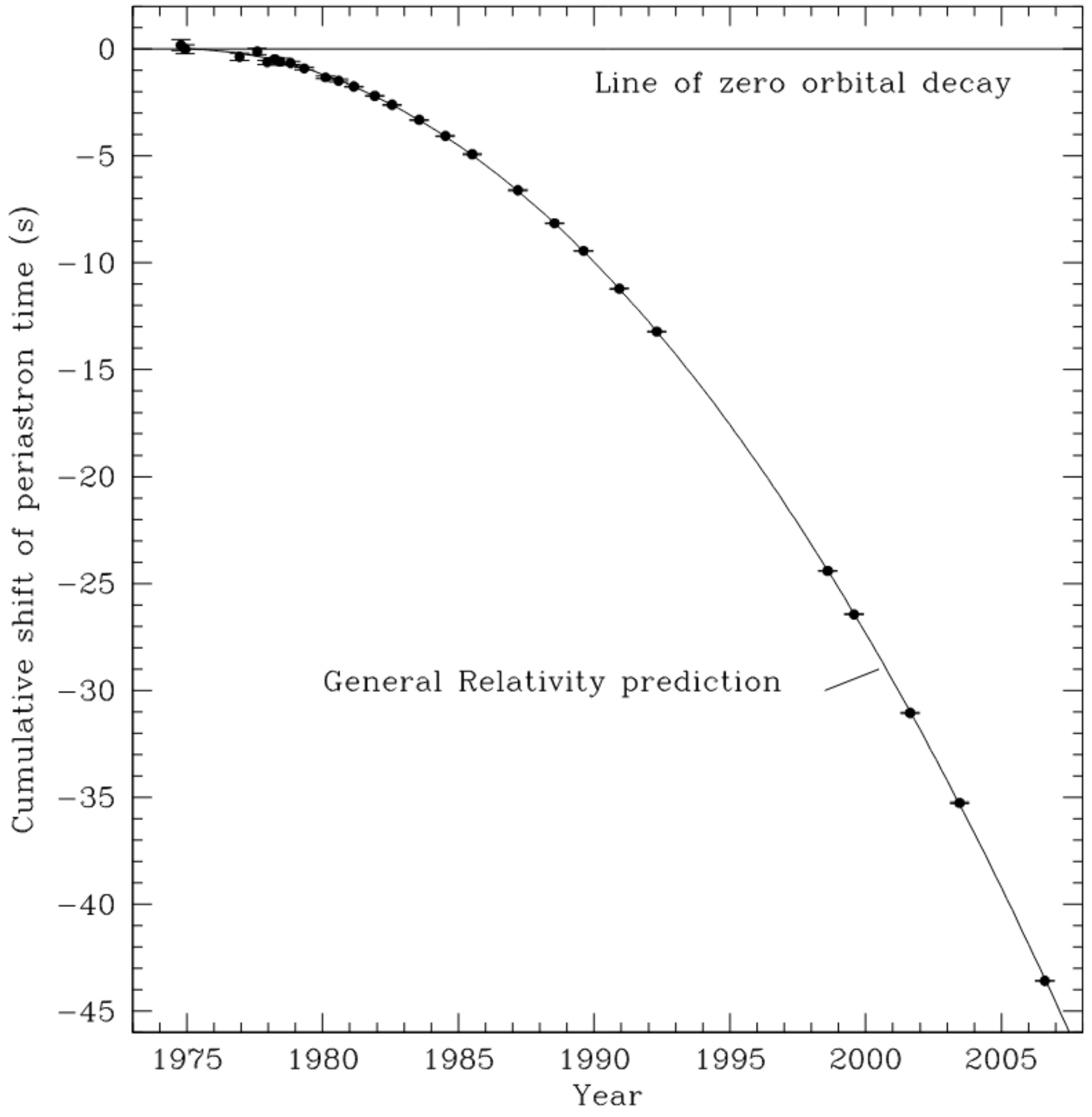
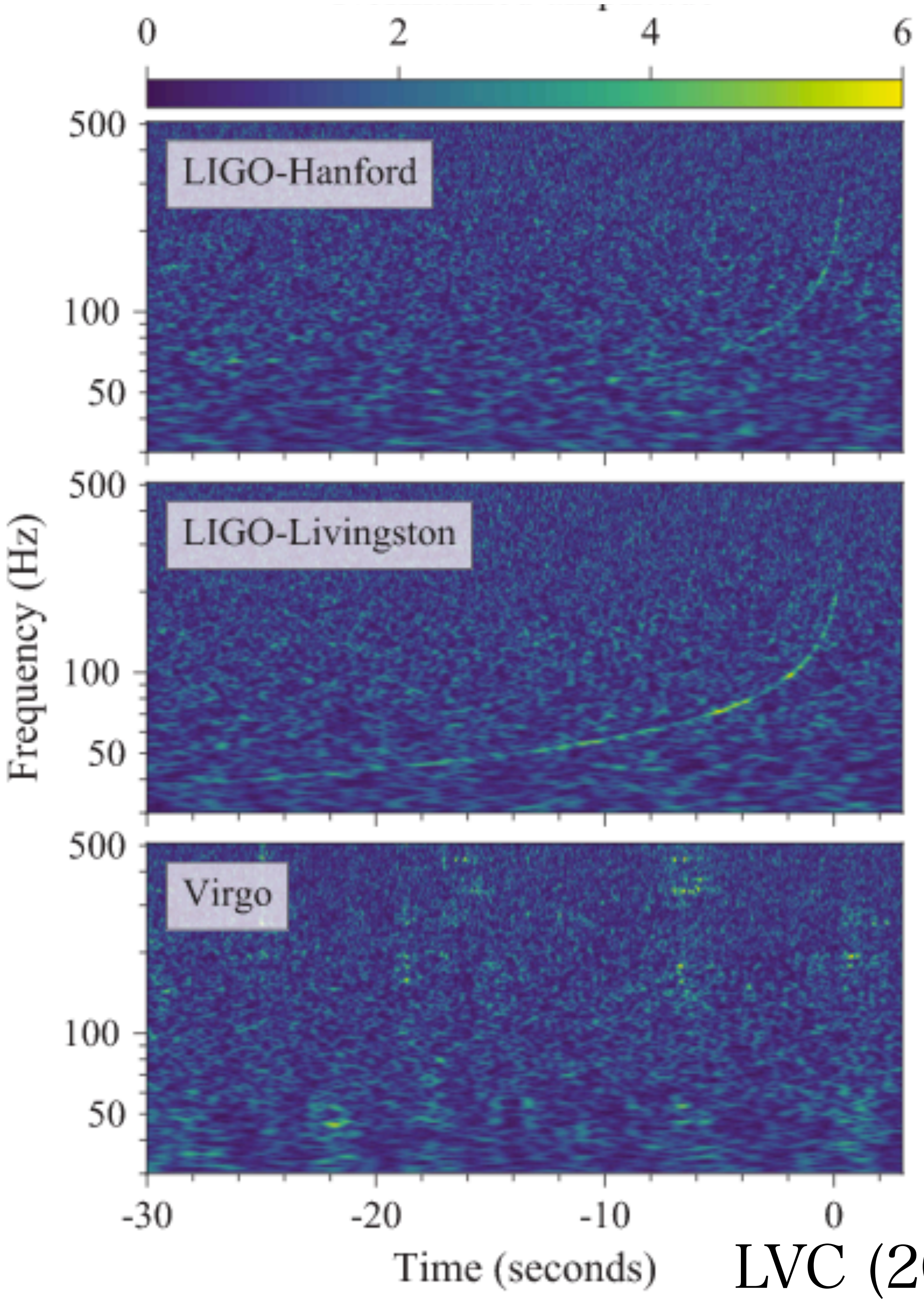


Figure 2. Orbital decay caused by the loss of energy by gravitational radiation. The parabola depicts the expected shift of periastron time relative to an unchanging orbit, according to general relativity. Data points represent our measurements, with error bars mostly too small to see.

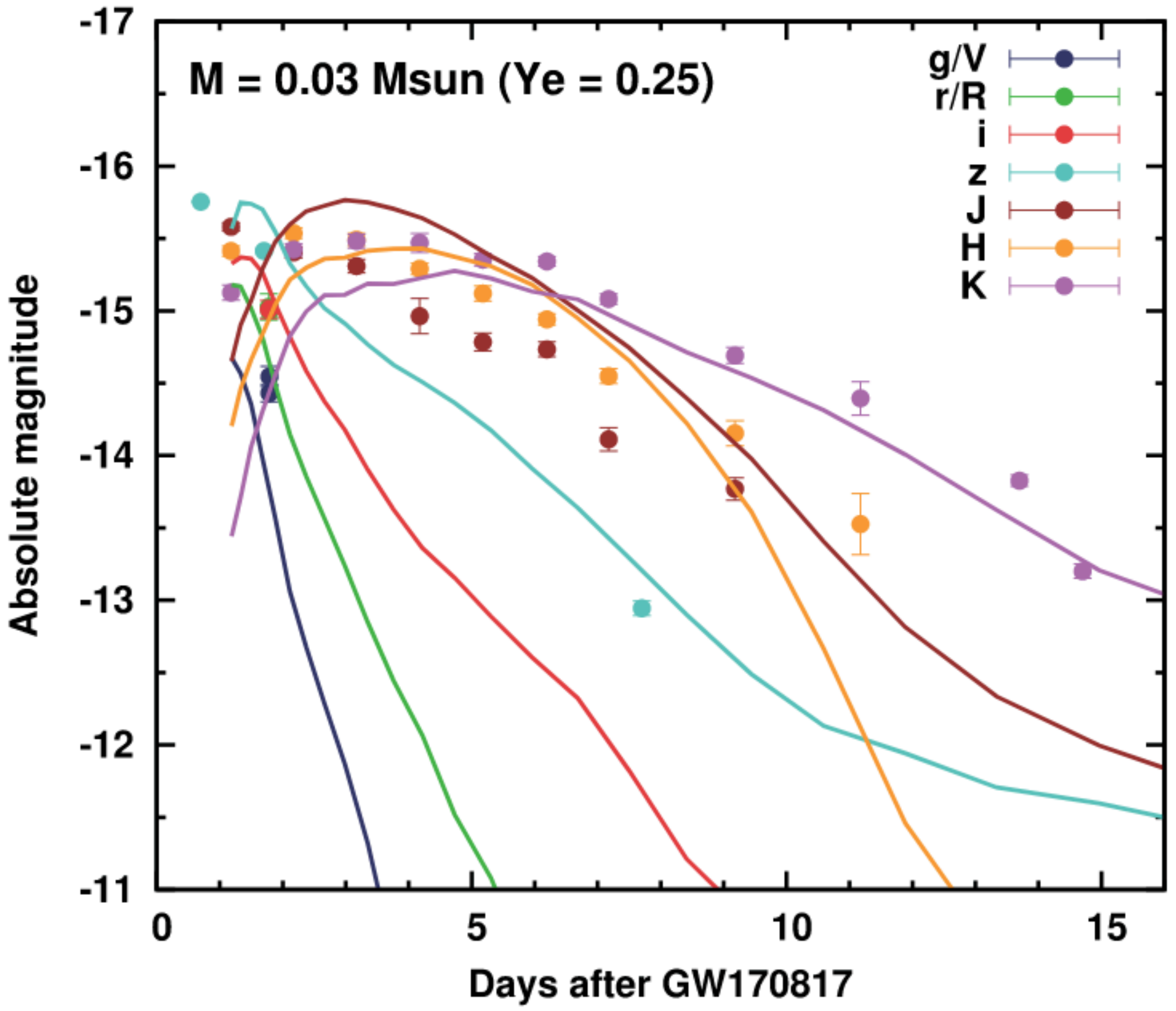
Weisberg+ (2010)

Gravitational wave



LVC (2017)

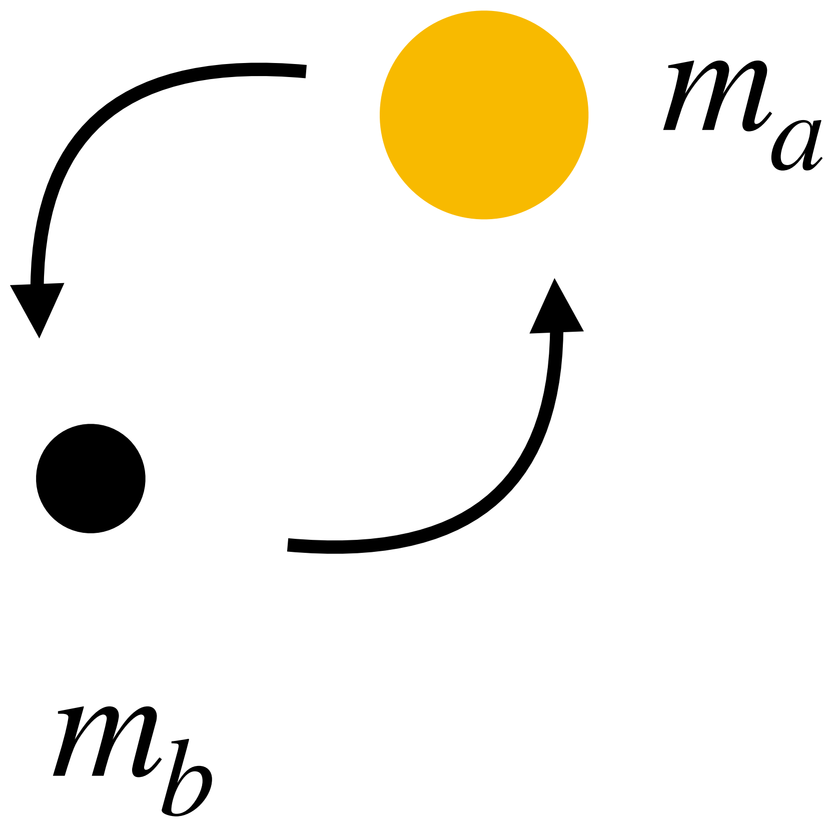
Kilonova



Tanaka+ (2017)

Q. How are DNS binaries formed? ***A. Core collapse supernova twice.***

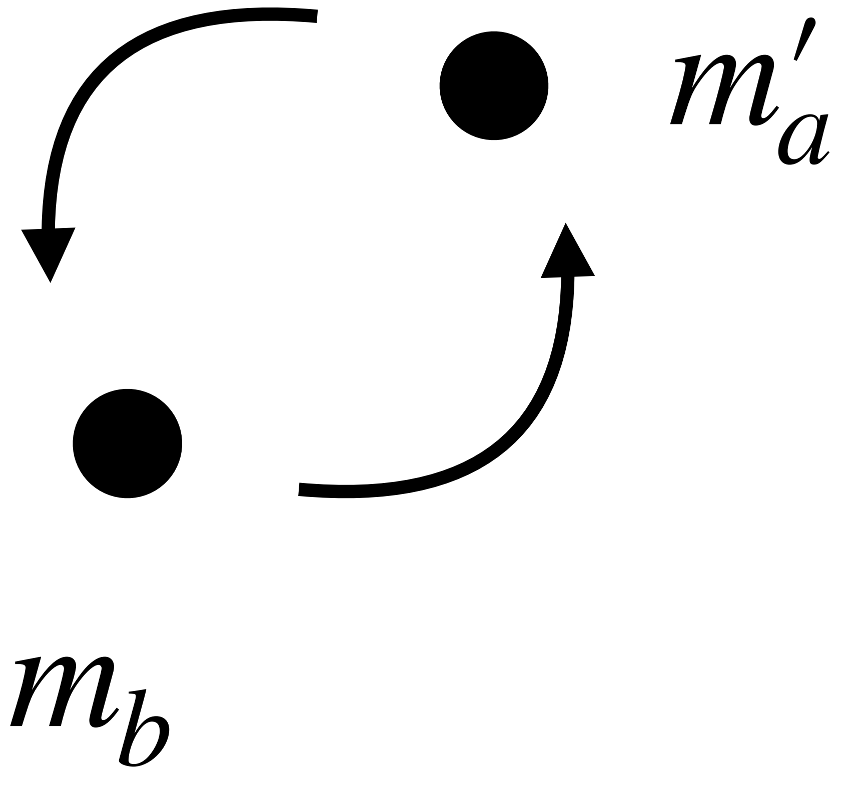
Stability of the binary system



$$E_1 = \frac{m_a m_b}{2(m_a + m_b)} v^2 - \frac{G m_a m_b}{r} < 0$$

$$M_1 = m_a + m_b$$

supernova →



$$E_2 = \frac{m'_a m_b}{2(m'_a + m_b)} v^2 - \frac{G m'_a m_b}{r} = \frac{G m'_a m_b}{2r} \left(\frac{m_a + m_b}{m'_a + m_b} - 2 \right)$$

$$M_2 = m'_a + m_b$$

For the binary system to be stable : $E_2 < 0$ => $M_{\rm ej} < M_2 \sim 3M_\odot$

Supernovae with small ejecta mass ($M_{\rm ej} \lesssim 1M_\odot$) are favorable for the formation of DNS binaries

Ultra-stripped supernova scenario

Hydrogen envelope ($M \sim 10M_\odot$) ejection through common envelope (CE) interaction

Helium layer ($M \sim 1M_\odot$) stripping by Roche lobe overflow (RLO)

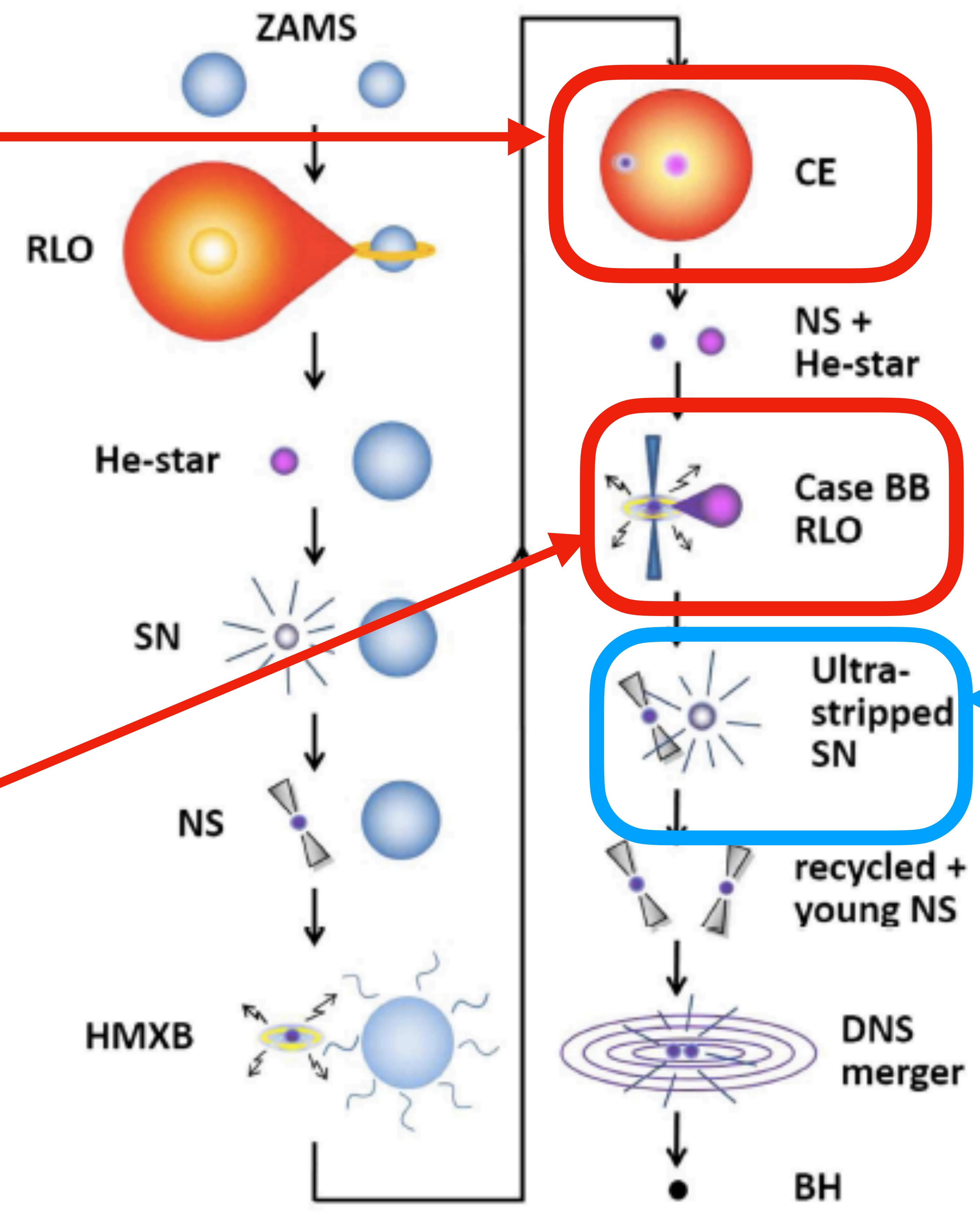


Figure 1. Illustration of the formation of a DNS system that merges within a Hubble time and produces a single BH, following a powerful burst of GWs and a short GRB. Acronyms used in this figure—ZAMS: zero-age main sequence; RLO: Roche-lobe overflow (mass transfer); He-star: helium star; SN:

Tauris+ (2017)

Ultra-stripped supernova (USSN), interacting with

- H-rich gas (CE)
- He-rich gas (RLO)

$M_{\rm ej} \sim 0.1M_\odot$

The USSN can realize the small ejecta mass not to disrupt the binary system

Progenitor models

Tauris+ (2015) systematically presented a series of the progenitor models for the USSN

Table 1. Stellar and binary parameters of 68 helium star–NS systems, and 8 single helium stars, evolved to the pre-SN (or WD) stage – see Section 3.

Wind	$M_{He,i}$ ($M_\odot$)	$P_{orb,i}$ (d)	RLO Case	$M_{core,f}$ ($M_\odot$)	$M^{env}_{He,f}$ ($M_\odot$)	M_{*f} ($M_\odot$)	$P_{orb,f}$ (d)	ΔM_{NS} ($M_\odot$)	Δt_x (yr)	$\lvert\dot{M}^{max}_{He}\rvert$ ($M_\odot$ yr^{-1})	$\lvert\dot{M}_f\rvert$ ($M_\odot$ yr^{-1})	Final fate	τ_{grw} (Myr)	Comment
Yes	2.5	–	–	1.29	1.099	2.41	–	–	–	–	–	ONeMg	–	Single star
Yes	2.6	–	–	1.37	0.961	2.37	–	–	–	–	–	EC-SN	–	Single star
Yes	2.7	–	–	1.41	1.010	2.46	–	–	–	–	–	EC-SN	–	Single star
Yes	2.8	–	–	1.46	0.984	2.49	–	–	–	–	–	FeCCSN	–	Single star
Yes	2.9	–	–	1.50	0.982	2.54	–	–	–	–	–	FeCCSN	–	Single star
Yes	3.0	–	–	1.58	0.970	2.60	–	–	–	–	–	FeCCSN	–	Single star
Yes	3.2	–	–	1.70	0.973	2.72	–	–	–	–	–	FeCCSN	–	Single star
Yes	3.5	–	–	1.83	1.003	2.91	–	–	–	–	–	FeCCSN	–	Single star
Yes	3.0	120	–	1.58	0.968	2.59	145.5	–	–	–	–	FeCCSN	1.e11	No RLO at all
Yes	3.0	100	BC	1.57	0.750	2.38	109.7	4.8e-5	1.2e3	2.7e-4	2.7e-4	FeCCSN	5.e10	–
Yes	3.0	80	BC	1.57	0.736	2.37	87.1	5.2e-5	1.3e3	2.6e-4	1.4e-4	FeCCSN	3.e10	–
Yes	3.0	50	BC	1.58	0.689	2.32	53.2	6.3e-5	1.5e3	2.7e-4	1.1e-3	FeCCSN	6.6e9	–
Yes	2.5	20	BC	1.29	0.137	1.45	20.3	6.1e-4	1.4e4	2.2e-4	6.7e-5	ONeMg	1.1e8	–
Yes	2.6	20	BC	1.37	0.189	1.56	19.3	6.3e-4	1.5e4	8.8e-5	8.1e-5	EC-SN	1.9e8	–
Yes	2.7	20	BC	1.42	0.150	1.59	19.7	4.5e-4	1.1e4	2.2e-4	7.7e-5	EC-SN	1.9e8	–
Yes	2.8	20	BC	1.47	0.217	1.72	19.4	3.2e-4	7.8e3	3.0e-4	detached	FeCCSN	2.1e8	–
Yes	2.9	20	BC	1.52	0.342	1.91	19.3	2.2e-4	5.4e3	3.2e-4	3.9e-8	FeCCSN	2.6e8	–
Yes	3.0	20	BC	1.58	0.548	2.17	20.0	1.4e-4	3.5e3	3.0e-4	8.1e-5	FeCCSN	3.8e8	–
Yes	3.2	20	BC	1.70	0.919	2.67	23.8	2.8e-5	7.0e2	1.6e-4	1.6e-4	FeCCSN	1.0e9	–
Yes	3.5	20	–	1.83	1.007	2.91	25.7	–	–	–	–	FeCCSN	1.4e9	No RLO at all
Yes	3.0	10	BC	1.57	0.375	2.00	9.51	2.3e-4	5.6e3	2.9e-4	4.e-10	FeCCSN	4.1e7	–
Yes	3.0	5.0	BC	1.57	0.246	1.86	4.61	4.1e-4	1.0e4	2.0e-4	detached	FeCCSN	4.7e6	–
No	2.5	2.0	BC	1.29	0.093	1.40	1.94	6.8e-4	2.2e4	2.5e-4	1.5e-5	ONeMg	2.2e5	–
No	2.6	2.0	BC	1.37	0.079	1.46	1.78	8.3e-4	2.2e4	2.9e-4	3.8e-5	EC-SN	2.8e5	–
No	2.7	2.0	BC	1.42	0.092	1.53	1.62	6.9e-4	1.8e4	2.5e-4	3.7e-6	EC-SN	2.2e5	–
No	2.8	2.0	BC	1.47	0.121	1.62	1.47	6.2e-4	1.6e4	2.0e-4	4.2e-5	FeCCSN	1.8e5	–

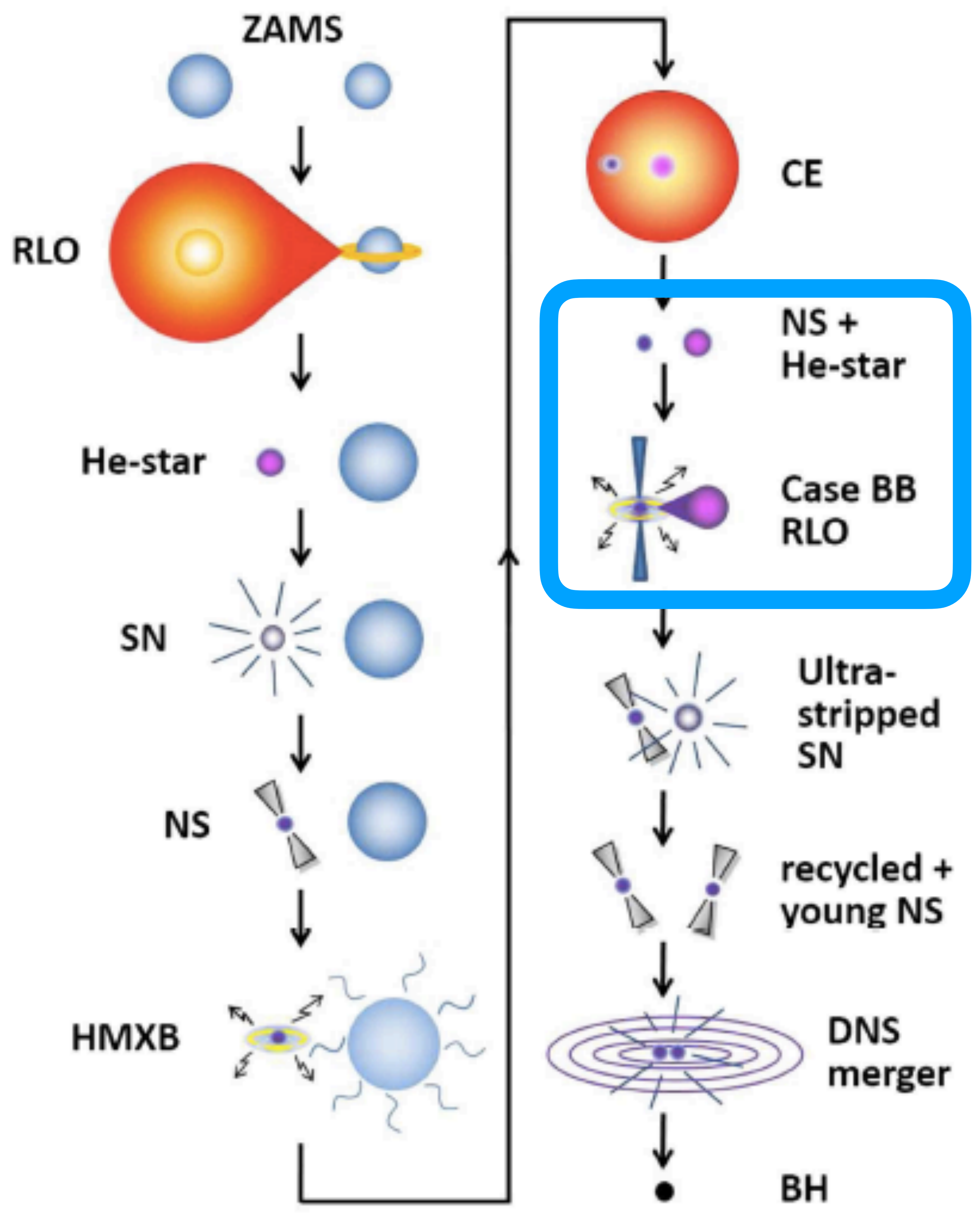
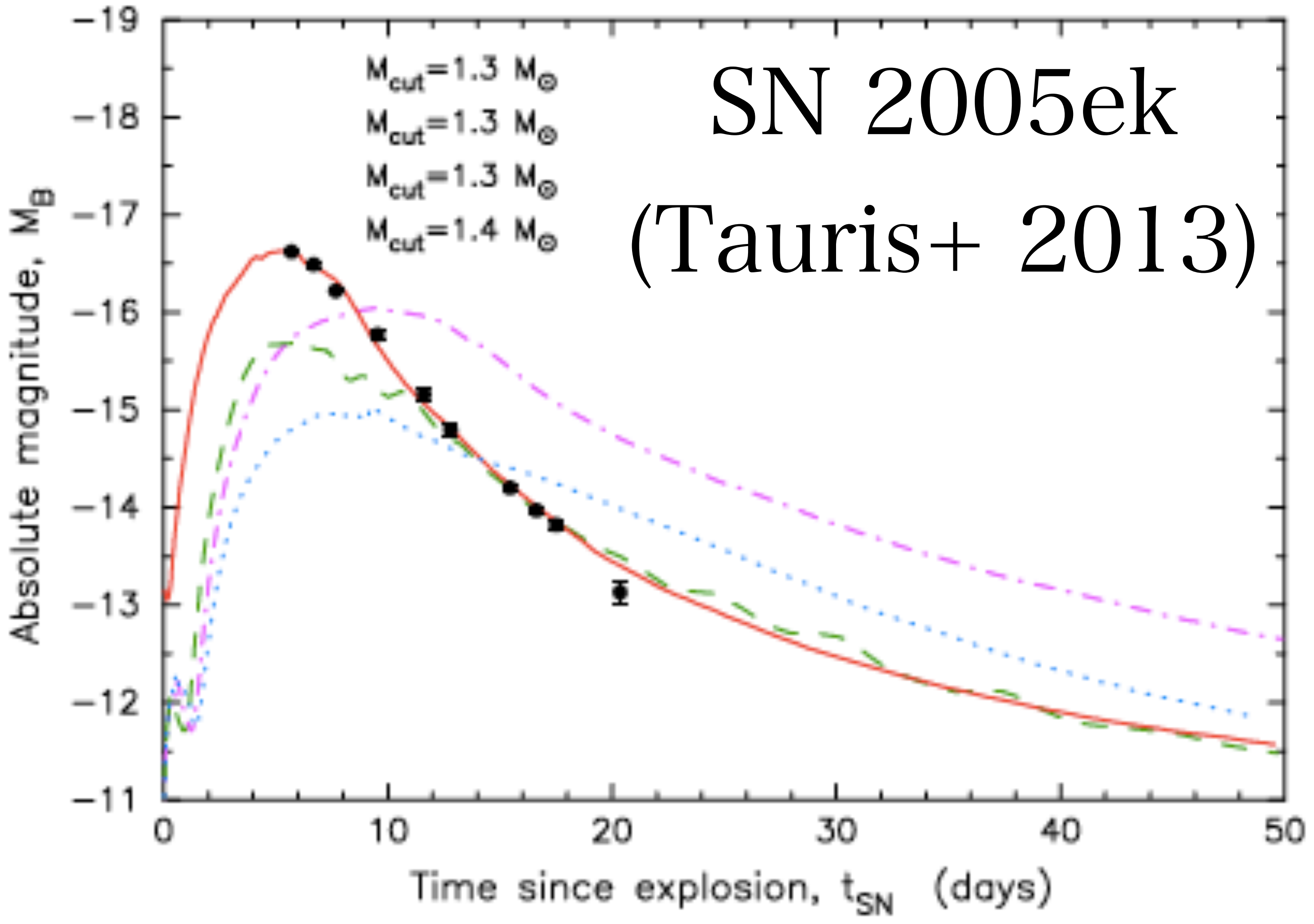


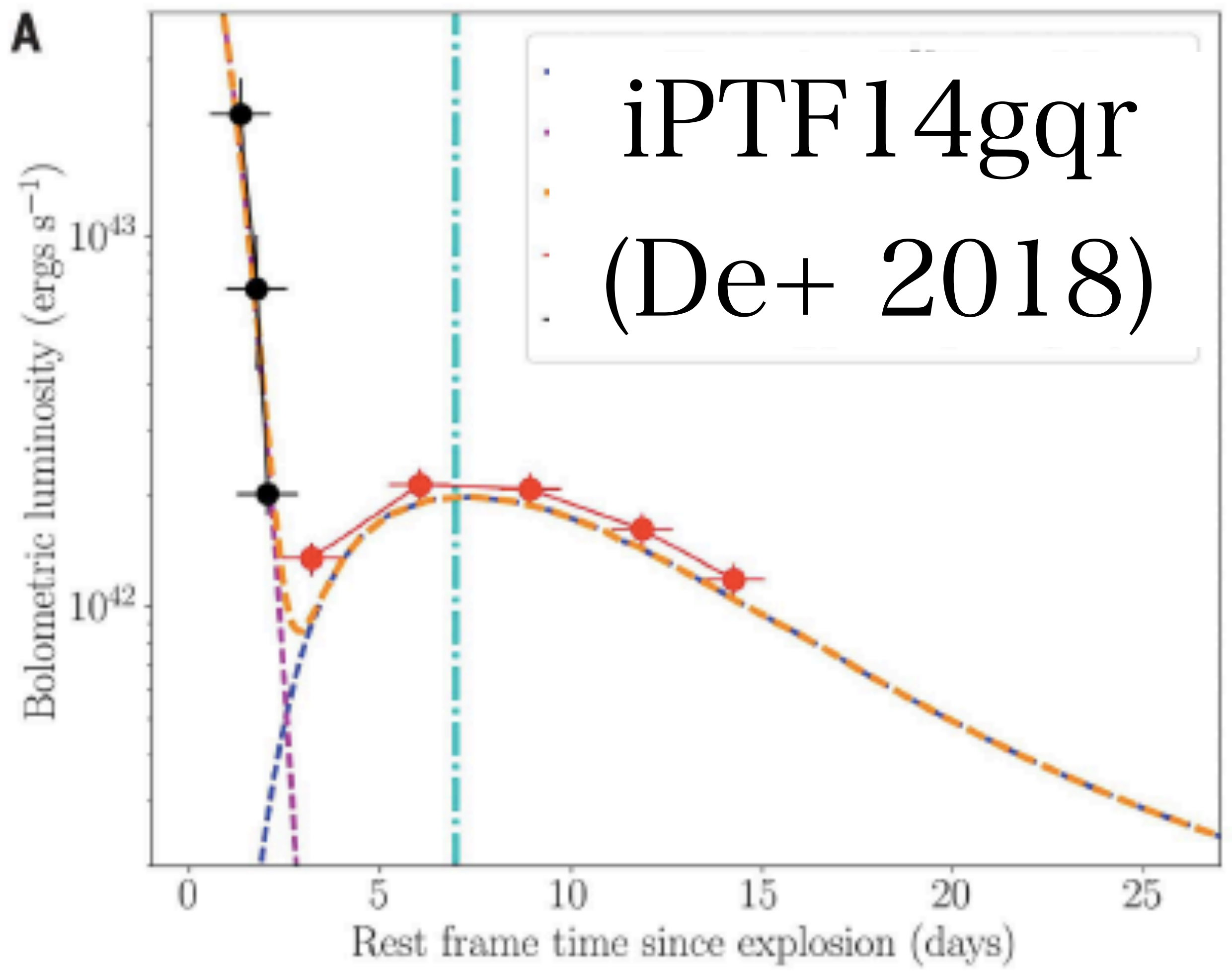
Figure 1. Illustration of the formation of a DNS system that merges within a Hubble time and produces a single BH, following a powerful burst of GWs and a short GRB. Acronyms used in this figure—ZAMS: zero-age main sequence; RLO: Roche-lobe overflow (mass transfer); He-star: helium star; SN: supernova; NS: neutron star; HMXB: high-mass X-ray binary; CE: common envelope; BH: black hole.

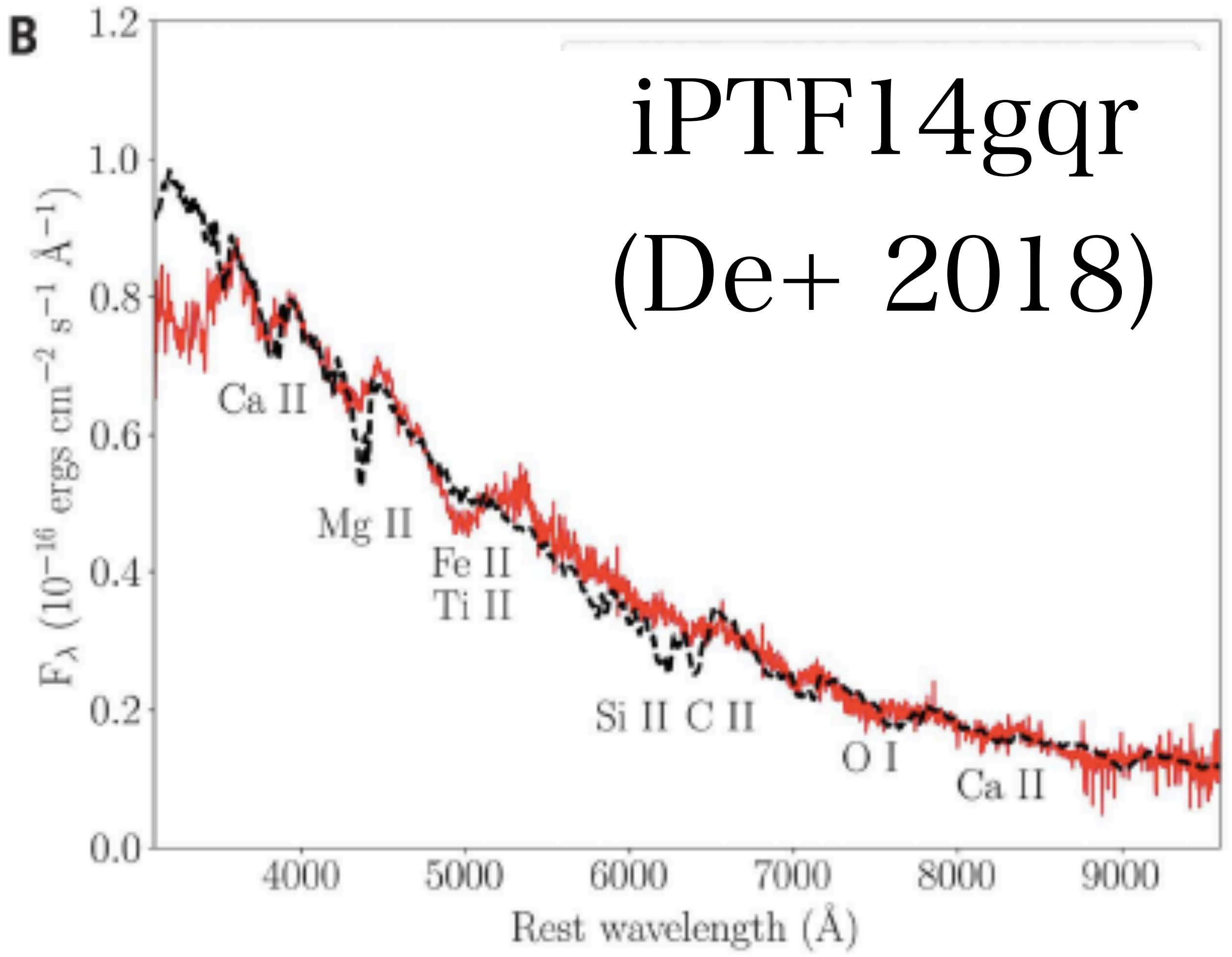
Candidates have been discovered

<u>Observational clue</u> (Moriya+ 2017)

- Short timescale ($t \lesssim 10$days)
- Spectra reminiscent of Type Ic SNe







$t \sim 10\text{days} \Rightarrow M_{\rm ej} \sim 0.1 M_\odot$

lines of C, O => Type Ic-like

Other cases: SN 2010X (Kasliwal+ 2010), SN 2019ehk (Nakaoka+ 2021)

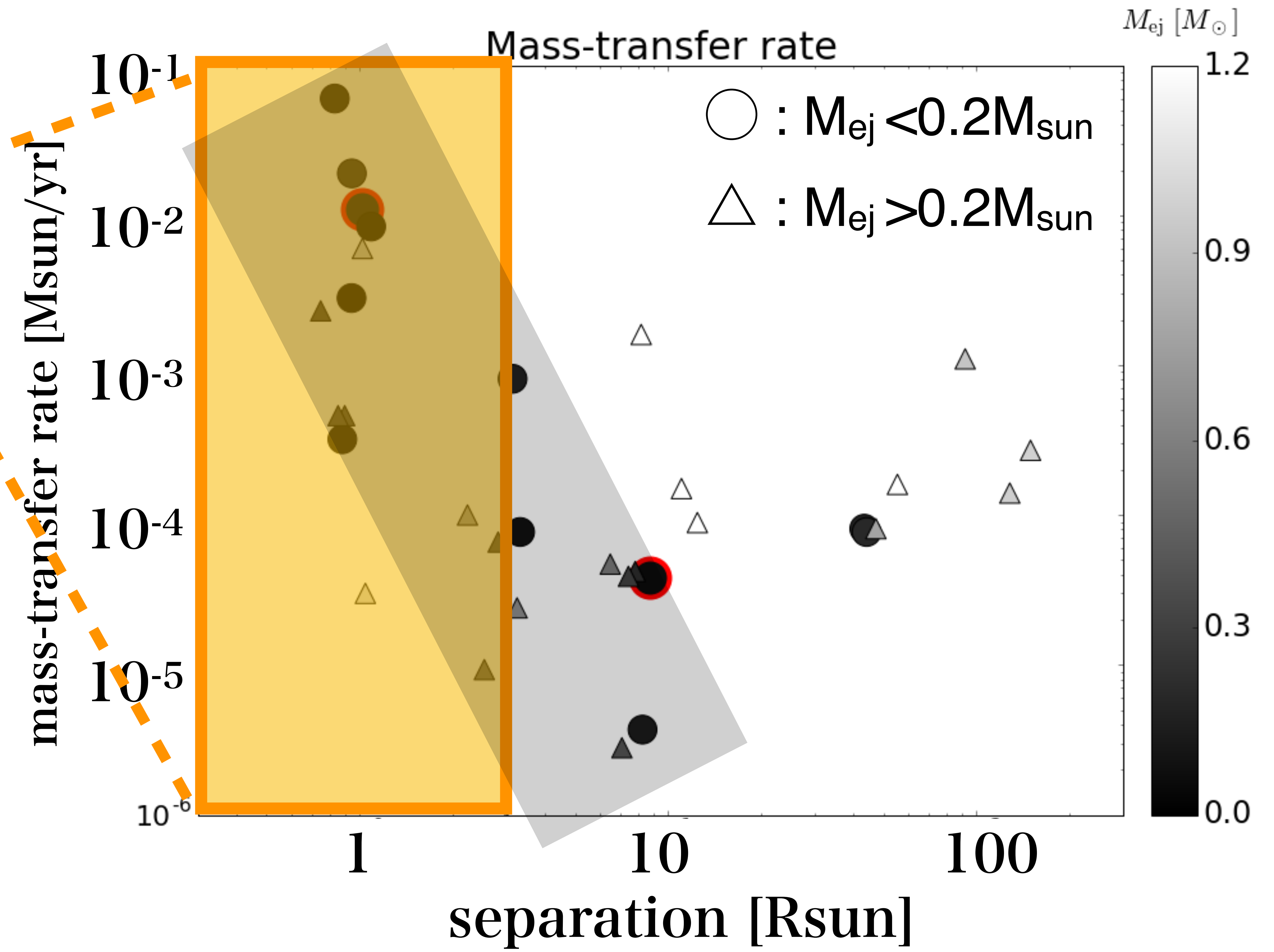
Questions

- Is it possible to extract **the information on the progenitor binary?**
  Will the remnant DNS binary born in SN 2005ek or iPTF 14gqr merge within the cosmic age?
  => This talk (Matsuoka et al. 2020, published in ApJ)

- Why do we miss **the supernova remnant hosting a DNS binary** in our galaxy? (Matsuoka et al. 2021, in prep.)
  => Mildly short visible timescale, faint surface brightness
  => Talk in the ASJ meeting (N14a)

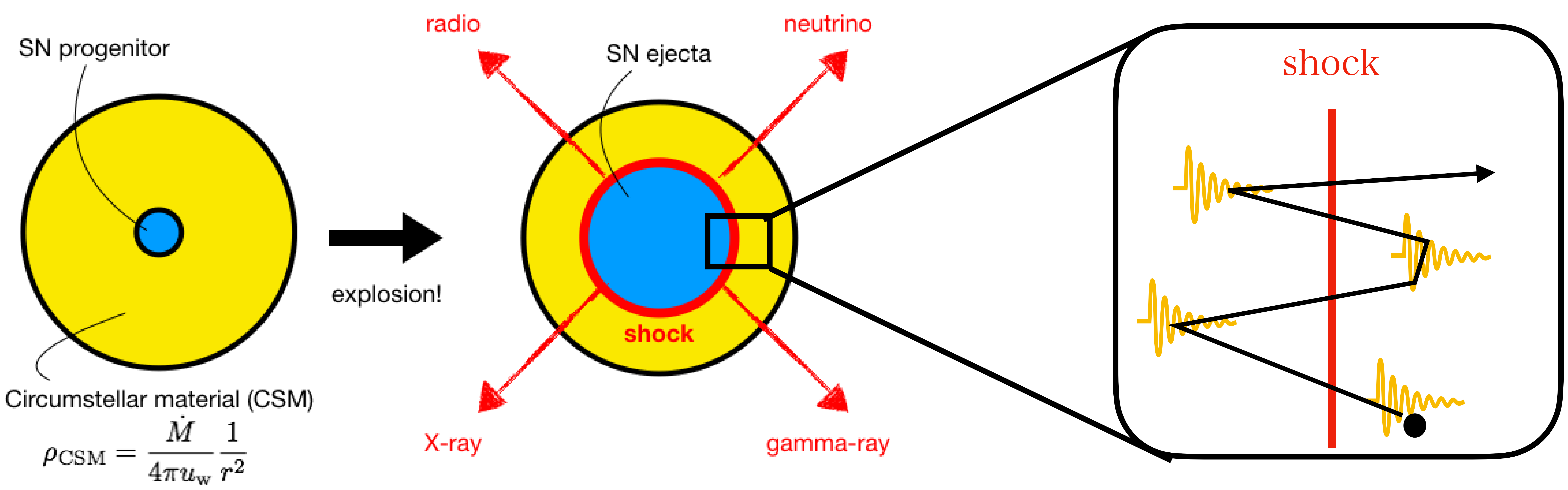
Mass-transfer rate v.s. binary separation

- High $\dot{M}_{RLO}$ => small separation
- $a \lesssim 3R_\odot$: the remnant DNS binary merging within the cosmic age
- High $\dot{M}_{RLO}$ => formation of the dense circumstellar material (CSM)
  - traced as a radio SN



Radio emission from the SN => Mass-transfer rate => possibility of the coalescence

Radio emission from SNe



- Particle acceleration (Drury 1983)
- Magnetic field amplification

=> Non-thermal emission

Radio emission from SNe can trace the nature of CSM

Analytical model of radio SNe

- Hydrodynamics : self-similar evolution (Chevalier+ 1982)

$$V_{\rm sh} = 1.1 \times 10^4 \; E_{50}^{0.45} M_{{\rm ej},0.1M_\odot}^{-0.35} \dot{M}_{\rm CSM}^{-0.10} u_{w,1000{\rm km/s}}^{0.10} t_{\rm 10days}^{-0.10} \; {\rm km/s}$$

- Particle acceleration & Magnetic field amplification

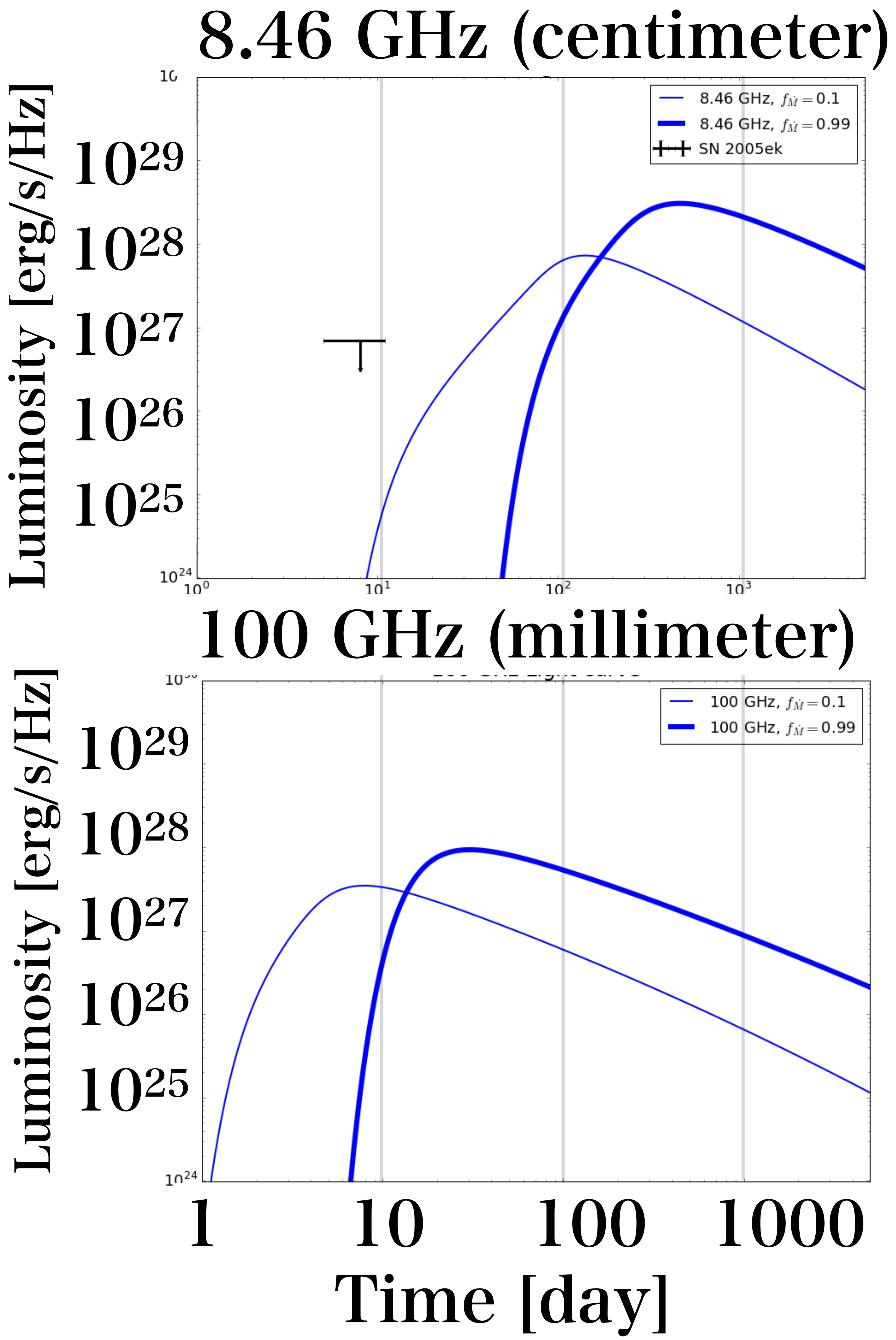
$$u_e = \epsilon_e \rho_{\rm sh} V_{\rm sh}^2 \Rightarrow N(E) = CE^{-p}, \; u_B = \epsilon_B \rho_{\rm sh} V_{\rm sh}^2 \Rightarrow B$$

- Quantities relevant to synchrotron emission

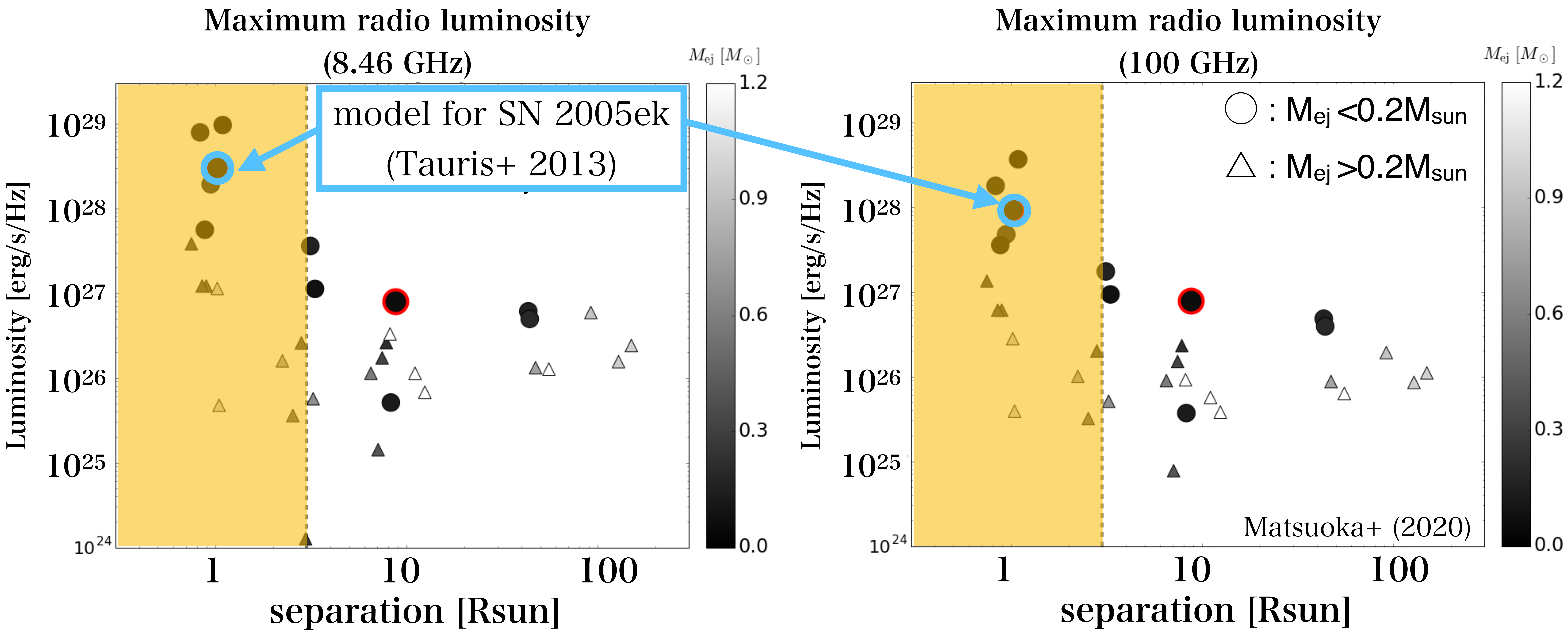
$$j_{\rm syn}(N(E), B), \; \alpha_{\rm syn}(N(E), B)$$

- Radio emission : Analytical solution

$$L_\nu = 4\pi^2 R_{\rm sh}^2 S_\nu (1 - e^{-\tau_{\nu,{\rm syn}}}) e^{-\tau_{\rm ff}}$$



Maximum radio luminosity v.s. binary separation



Radio emission from ultra-stripped SNe => binary separation, coalescence possibility

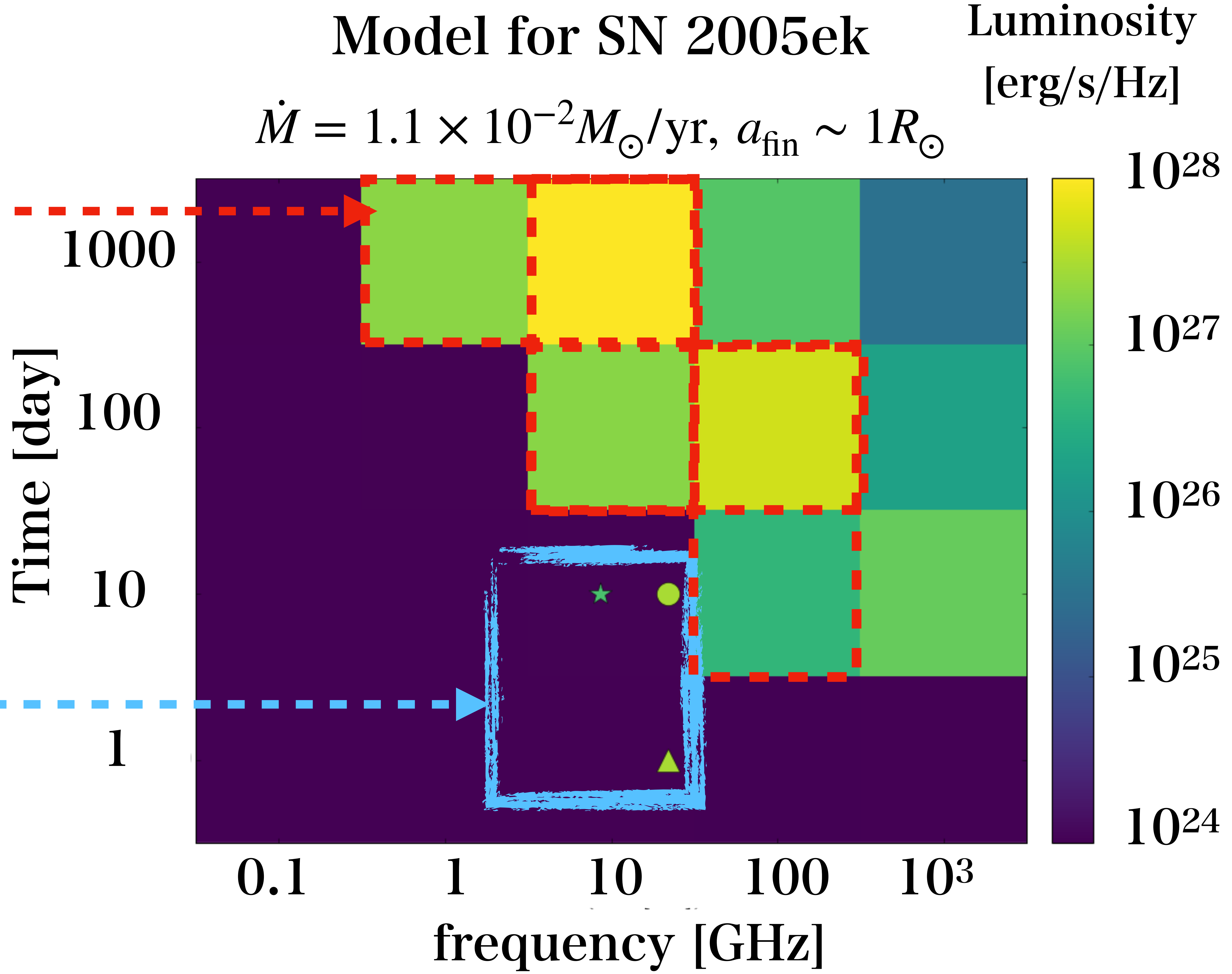
Feasible time/frequency window

~Optimized window~

- cm : $t_{obs} \gtrsim$ 100days
- mm : $t_{obs} \sim$ 10-100days

~Previous observations~

- upper limit
- in the centimeter range
- within 10 days



Summary

- Observational candidates for the ultra-stripped SNe have been reported, but their binary properties are not well constrained
- We showed that **binary separation is linked with mass-transfer rate, which can be traced by radio emission** from ultra-stripped SNe
- Our analytical modeling suggests the **optimized time/frequency window** to detect the radio signal from ultra-stripped SNe