Rate of ultra-stripped supernovae and binary evolution leading to double NS

Abstract

- A supernova (SN) iPTF 14gqr whose ejecta mass is 0.2 M_{sun}, and He envelope mass is ~ 0.01 M_{sun} was discovered (De et al. 2018).
- These types of SNe are called ultra-stripped SNe (USSNe), and are considered as the final stages in the formation of double neutron star (DNS) systems.
- We calculate the rate of USSNe like iPTF 14gqr and discuss the observability of USSNe by some optical transient surveys.

Introduction

Double Neutron Star systems

- Gravitational wave (GW) sources
  → GW170817 (NS-NS merger) was detected (Abbott et al. 2017)

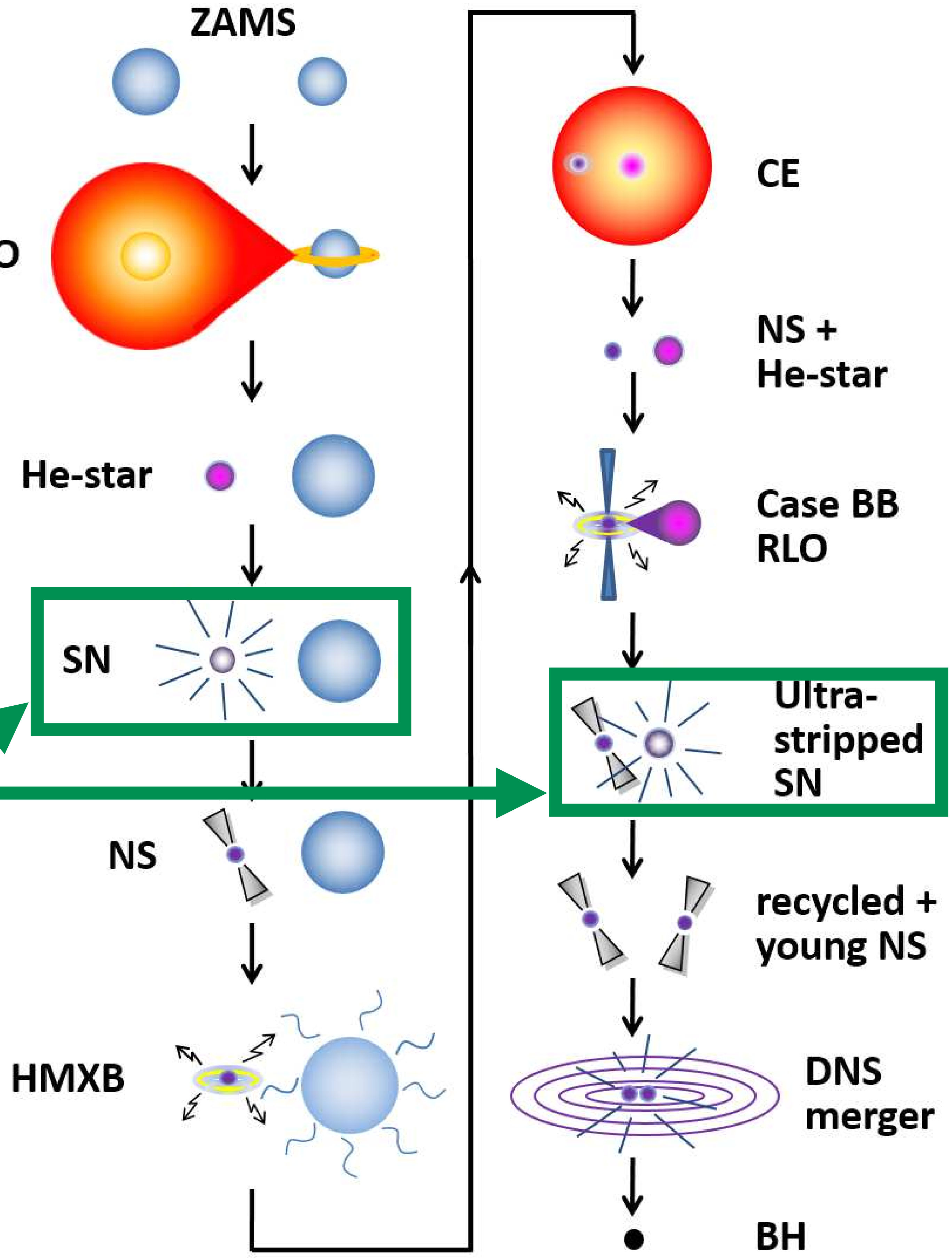
- GW is a tool to explore physical phenomena in a strong gravitational field.

- **It is important to deepen knowledge of DNS systems which are typical gravitational wave sources**.

- What are formation channels of DNS systems?

A formation channel of DNS systems

~ 10 M_{sun}



2 SN explosions occur until a DNS is formed

One of evolutionary path
leading to DNS systems
that merge within a Hubble time

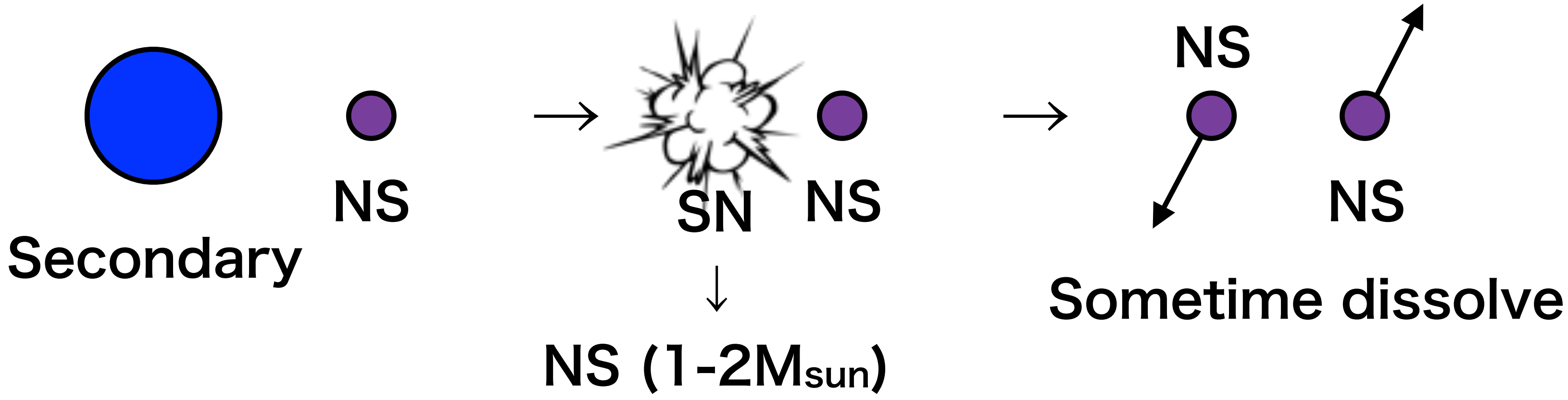
Fig1 in Tauris et al. 2017

Pulsar kick

- Pulsar kick caused by an asymmetry of explosion changes orbital parameters, and it is actually observed (Hobbs et al. 2005).

- Kick velocity of a standard core-collapse SN (CCSN) is several hundred km/s (cf. orbital velocity ~ several × 100 km/s), and it is too large to form DNS systems whose eccentricity < 0.6 (11 DNS systems of 14 have eccentricities less than 0.6).

- **SNe with small kick are essential**.



Pulsar kick of USSNe

- **Pulsar kick of USSN is small for 2 reasons** (Tauris et al. 2015).

  1. the binding energies of the envelopes are often only a few 10^{49} erg, such that even a weak outgoing shock can **quickly lead to their ejection, potentially before large anisotropies can build up**.

  2. the amount of ejecta is extremely small compared to standard SN explosions. This may likely lead to **a weaker gravitational tug** on the proto-NS.

- It is suggested that USSNe can explain the eccentricity of the observed DNS systems.

USSNe candidates

- Type Ic SNe **SN 2005ek** (Drout et al. 2013) and **SN 2010X** (Kasliwal et al. 2010) are candidates of USSNe.
- Ejecta mass ~ 0.1 M_{sun}
- **These events were observed only at the radioactively powered peak**, and the origins of these SNe remain uncertain.

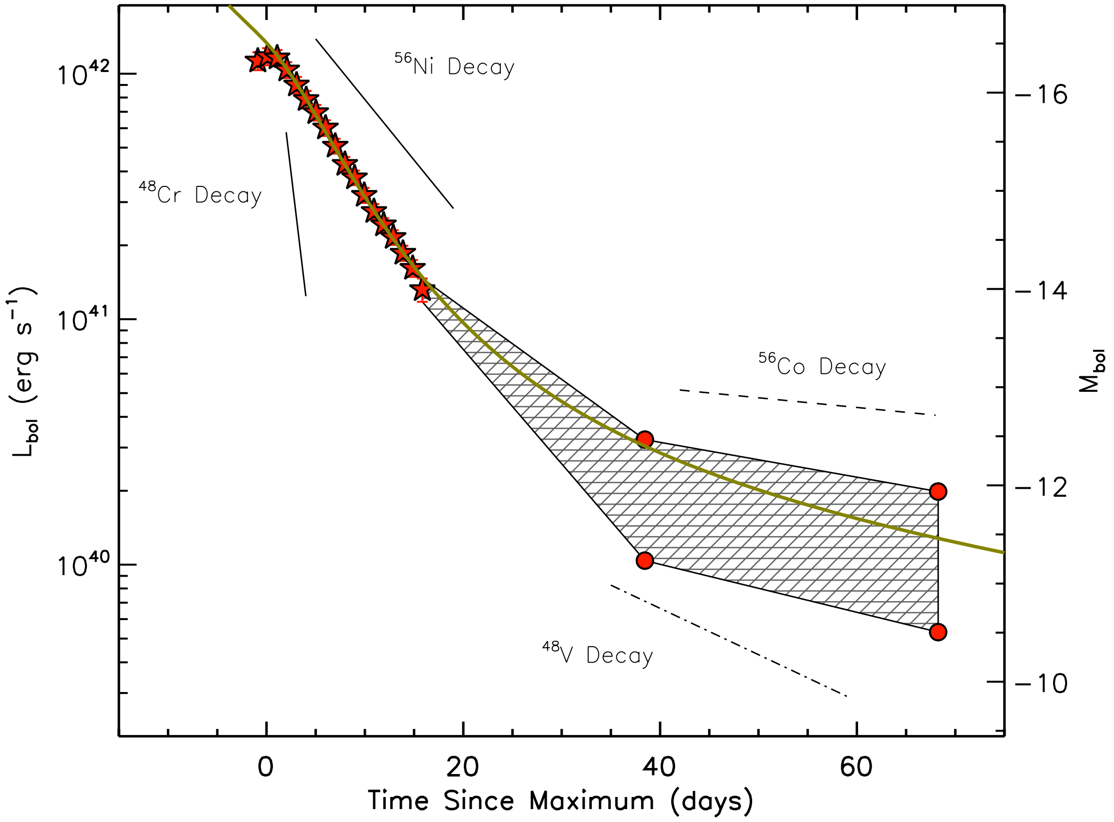


Figure 14. Radioactive models for the pseudo-bolometric light curve of SN 2005ek. Black lines show the decay rates for ^{56}Ni, ^{56}Co, ^{48}Cr, and ^{48}V, assuming full trapping of gamma-rays. The gold curve shows the best-fit model described in the text, assuming $\sim 0.03\,M_\odot$ of ^{56}Ni, a luminosity which tracks the instantaneous energy input, and incomplete gamma-ray trapping.

Bolometric light curve of SN 2005 ek.
Fig 14 in Drout et al. (2013)

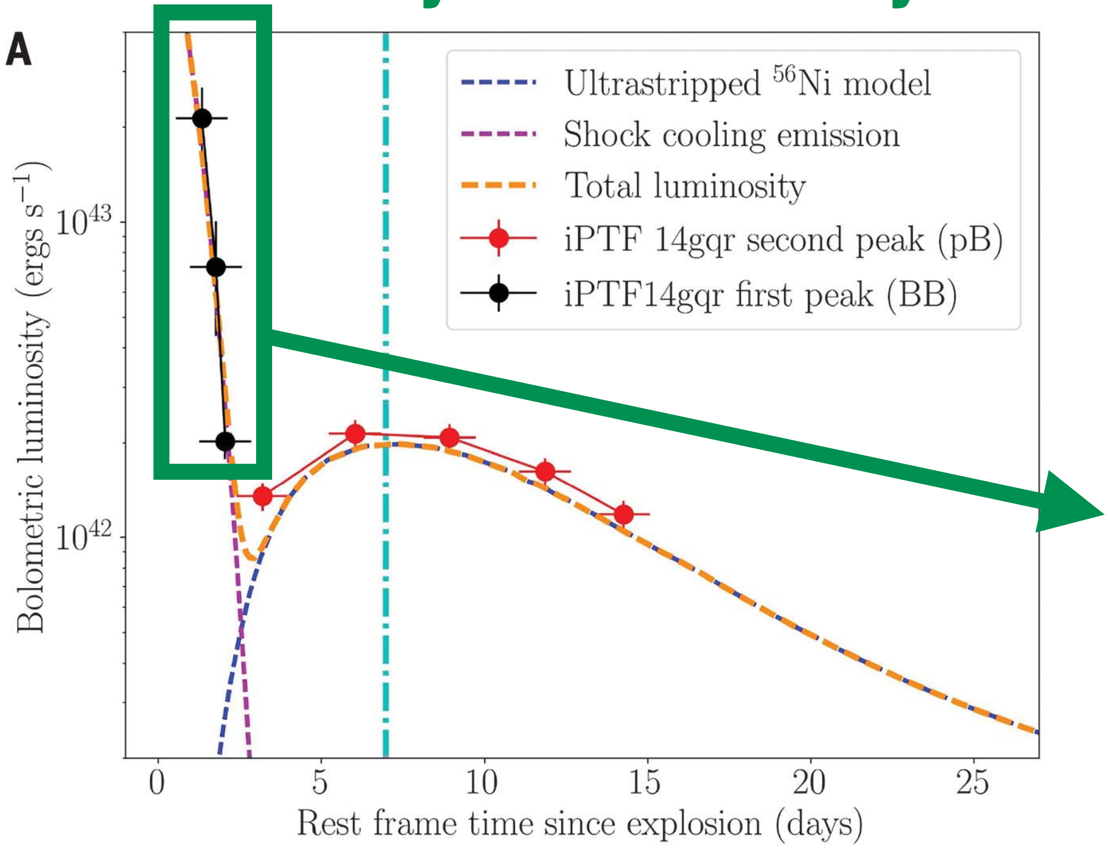
iPTF 14gqr

- **iPTF 14gqr (SN 2014ft) is the first discovered USSN** (De et al. 2018).

- **Rapid decline of the first peak due to the shock cooling emission was also observed.**

- ejecta mass = 0.2 M_{sun}, envelope mass ~ 0.008 M_{sun}

- In this work, we **calculate the rate of USSN like iPTF 14gqr** (ejecta mass = 0.15 - 0.30 M_{sun}, envelope mass = 0.003 - 0.013 M_{sun}) and **discuss the observability of USSNe by some optical transient surveys**.



Bolometric light curve of iPTF 14gqr (De et al. 2018)

Shock cooling emission component

Method

Population synthesis

- **We perform Monte Carlo simulation called population synthesis**.
- Our population synthesis code is based on BSE code (Hurley et al. 2002).
- We calculate the evolution of 10^6 binaries consisting of ZAMS.
- Initial conditions are as follows.

Metallicity Z	0.02
Initial primary mass M_1 (M_{sun})	5—50
Initial Mass Function (IMF)	Salpeter
Initial mass ratio $q = M_2 / M_1$	flat distribution (0-1)
Initial separation a (R_{sun})	flat-in-the-log distribution (a_{min}—10^6)
Initial eccentricity e	0

determine a_{min} not to fill the Roche lobe

Binary parameters

- We consider the following parameters.
  1. Mass transfer efficiency $\beta = \{0.0, 0.5, 0.7, 0.9\}$,
  2. Common envelope parameter $\alpha_{\rm CE}\lambda = \{0.1, 0.5, 1.0\}$
  3. After CE during HG, binary stars always coalesce or not (not much effect on the results).
  4. ECSNe are considered or not.

- 4 × 3 × 2 × 2 = 48 models.

- We calculate the probability distribution of orbital parameters of DNS systems for each model.

- Using the observed 14 DNS systems as samples, we obtained the likelihood of these probability distributions.

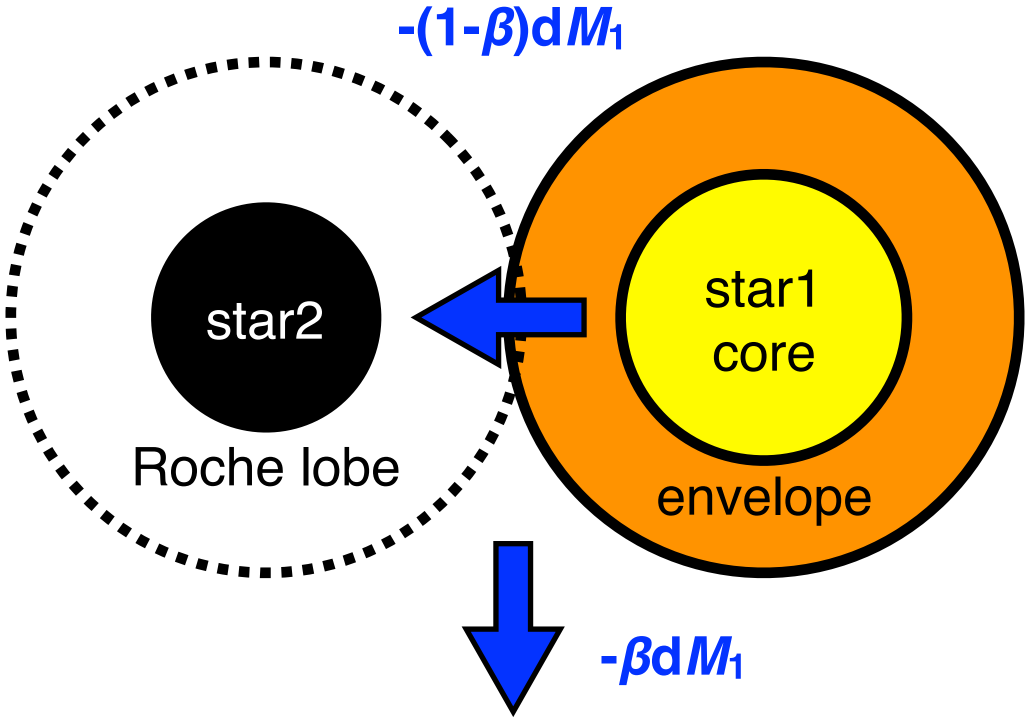
- Using the most favored model, we calculate the rate of USSNe like iPTF 14gqr (ejecta mass = 0.15 - 0.30 $M_{\rm sun}$, envelope mass = 0.003 - 0.013 $M_{\rm sun}$)

Input physics : mass transfer efficiency β

- Some of the parameters that determine the binary evolution are not well known.

- Mass transfer efficiency **β** (How many masses are lost from a binary system i.e., **$dM_2 = -(1-\beta)dM_1$**) remain uncertain.

- We use 4 constant values
  β = 0.0(conservative mass transfer), 0.5, 0.7, 0.9.



Input physics : CE parameter $\alpha_{\rm CE}\lambda$

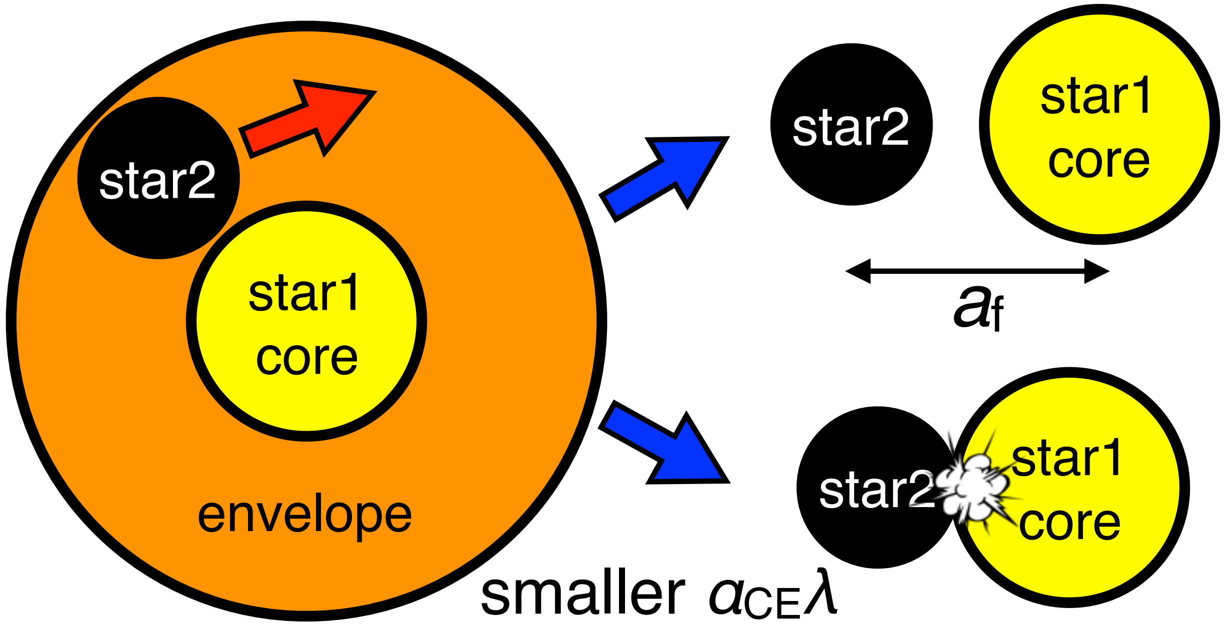
- We deal with common envelope(CE) phase using this description.

$$\alpha_{\rm CE}\left(\frac{GM_{\rm core,1}M_2}{2a_{\rm f}}-\frac{GM_1M_2}{2a_{\rm i}}\right)=\frac{GM_1M_{\rm env,1}}{\lambda R_1}$$

- CE parameter **$\alpha_{\rm CE}\lambda$** (determine the separation of the system after CE) has major uncertainties.

- The smaller the value of $\alpha_{\rm CE}\lambda$, the shorter the separation becomes.

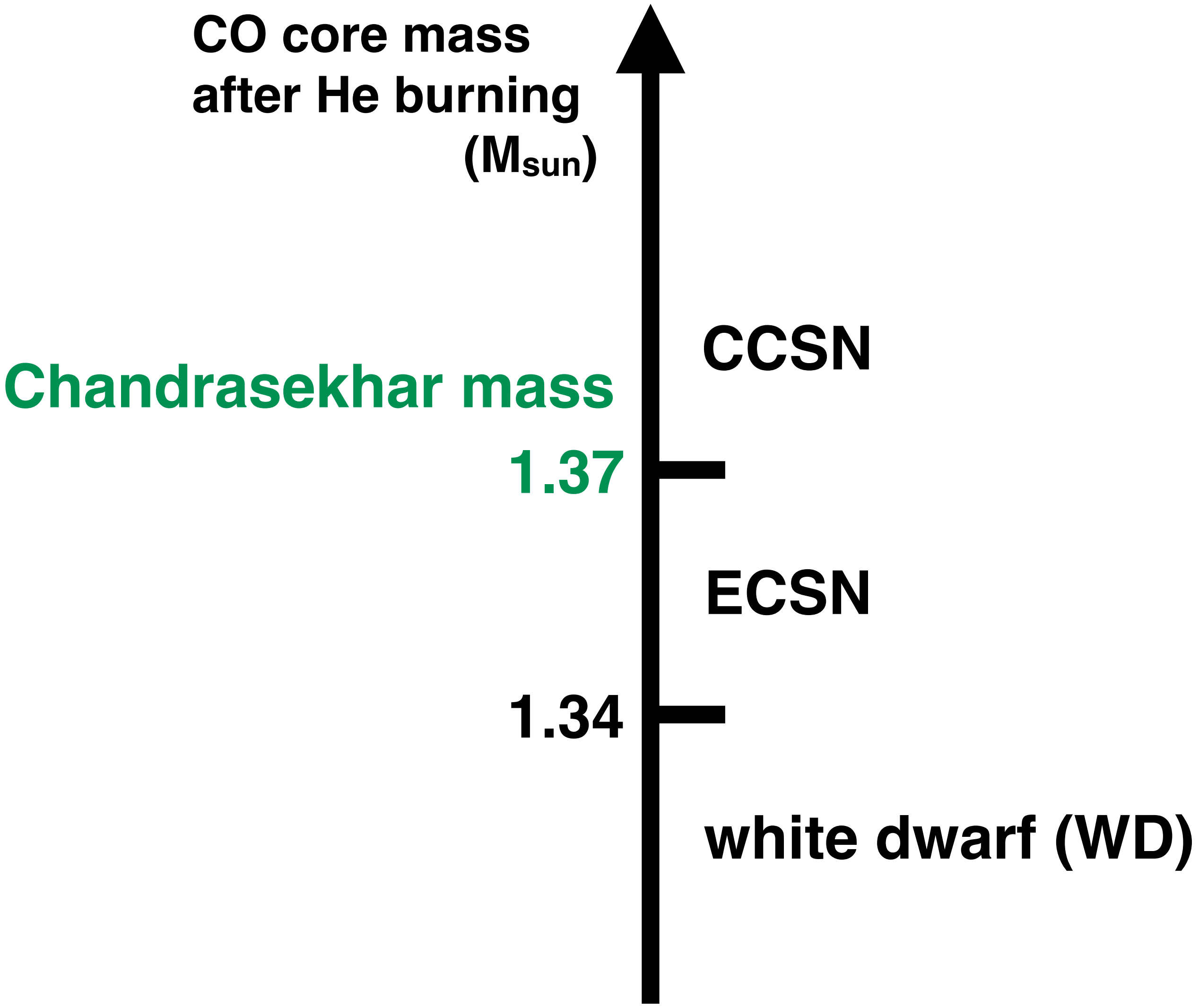
- We use 3 constant values **$\alpha_{\rm CE}\lambda = 0.1, 0.5, 1.0$**.



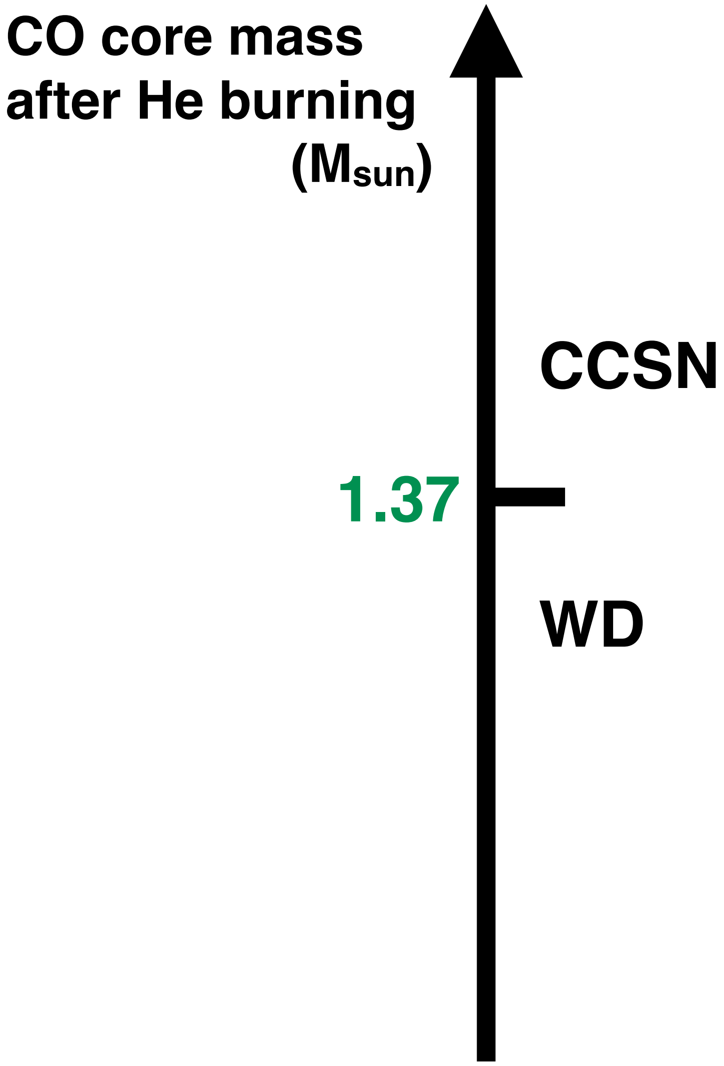
Input physics : electron-capture SN

- We deal with cases where **electron-capture SN (ECSN) is considered or not**.

ECSN is considered



ECSN is not considered



Input physics : kick velocity

- It is considered that kick velocity obeys Maxwell distribution (Hobbs et al. 2005).

- The dispersions we use are as follows.

type	σ(km/s)
CCSN	265
ECSN	30
USSN	30

- Definition of USSNe is that He envelope at time of SN < 0.2 M_{sun} (Tauris et al. 2015)

Results and Discussion

Results

The results of calculation are as follows.

rank	β	$\alpha_{\mathrm{CE}}\lambda$	ECSN	HG	R_{f} (/Myr/galaxy)	R_{m} (/Myr/galaxy)	iPTF 14gqr (/Myr/galaxy)	Likelihood ratio
1	**0.7**	**1.0**	**1**	**0**	**48.17**	**24.14**	**57.67**	**1 / 1**
2	0.7	1.0	0	0	46.75	24.13	57.56	1 / 1.8
3	0.7	0.5	1	0	37.67	20.93	52.46	1 / 4.2
4	0.7	0.5	1	1	33.58	17.27	46.99	1 / 4.7
5	0.9	1.0	0	0	26.94	8.48	16.61	1 / 7.4
6	0.9	1.0	1	0	28.38	8.48	16.55	1 / 9.3
7	0.7	0.5	0	0	36.41	20.78	52.27	1 / 15
8	0.7	0.5	0	1	32.24	17.05	46.76	1 / 17
9	0.9	0.5	0	0	25.10	10.54	25.54	1 / 72
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮

1 / 20

Significantly disfavored

The criterion "1/20" are used in Vigna-Gómez et al. (2018)

USSNe like iPTF 14gqr occur at 57.67 galaxy^{-1} Myr^{-1} for most favored model (rank = 1).

Rate of USSNe like iPTF 14gqr

- We assume that SNe with the same ejecta and envelope mass as iPTF 14gqr reproduce the light curve equivalent to iPTF 14gqr.

- To obtain the information about the envelope, we need to observe the shock cooling emission component.

- We assume that **a cadence < 2 days are needed to detect the USSNe like iPTF 14gqr**.

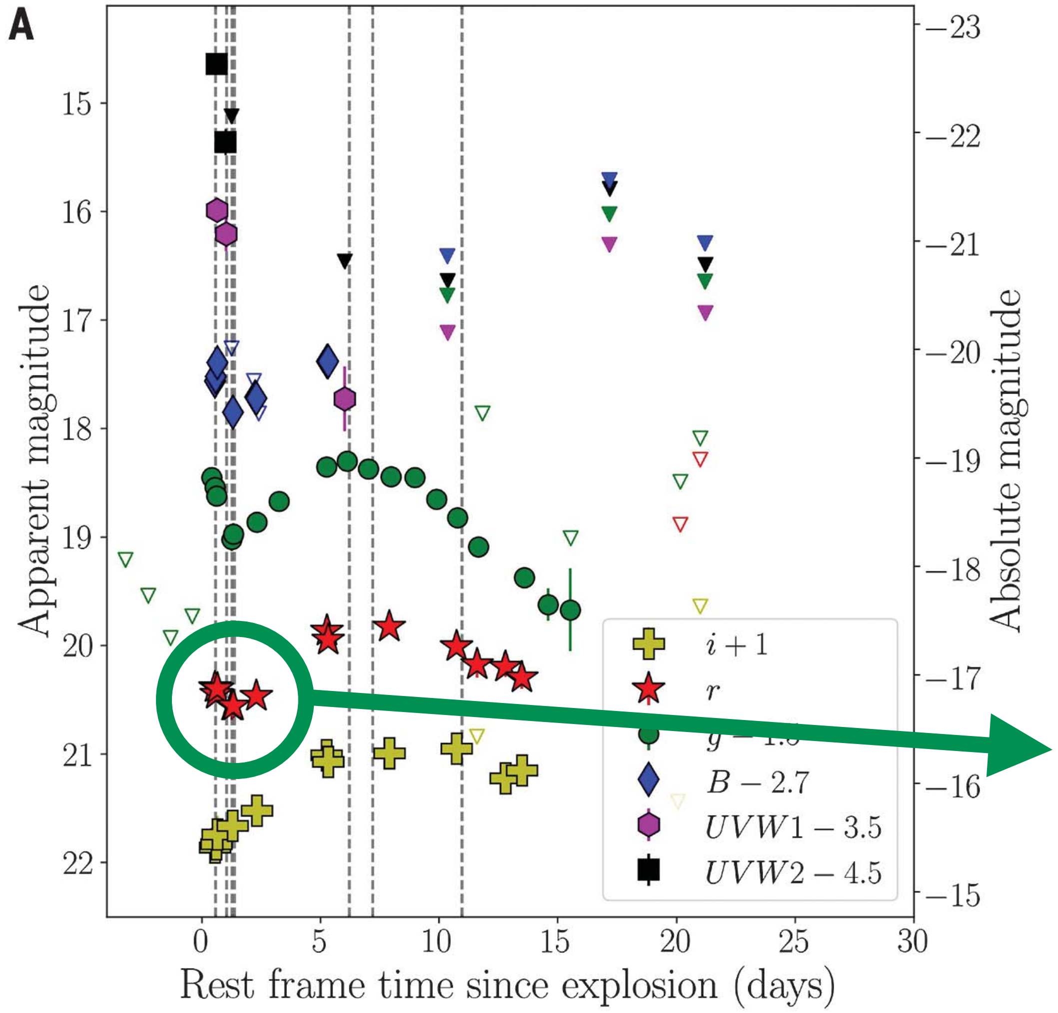


Fig 2. in De et al. (2018)

Shock cooling emission

Rate of USSNe like iPTF 14gqr

- Detection rate is as follows.

Survey	detection rate (yr^{-1})	reference
iPTF	**1**	Rau et al. 2009 Law et al. 2009
ZTF	**40**	Bellm et al. 2014
LSST	**5**	Ivezic et al. 2008

- **A next generation survey Zwicky Transient Facility (ZTF) can detect USSNe like iPTF 14gqr at 40 yr^{-1}**

Results

The results of calculation are as follows.

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⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮

1 / 20

Significantly disfavored

The criterion “1/20” are used in Vigna-Gómez et al. (2018)

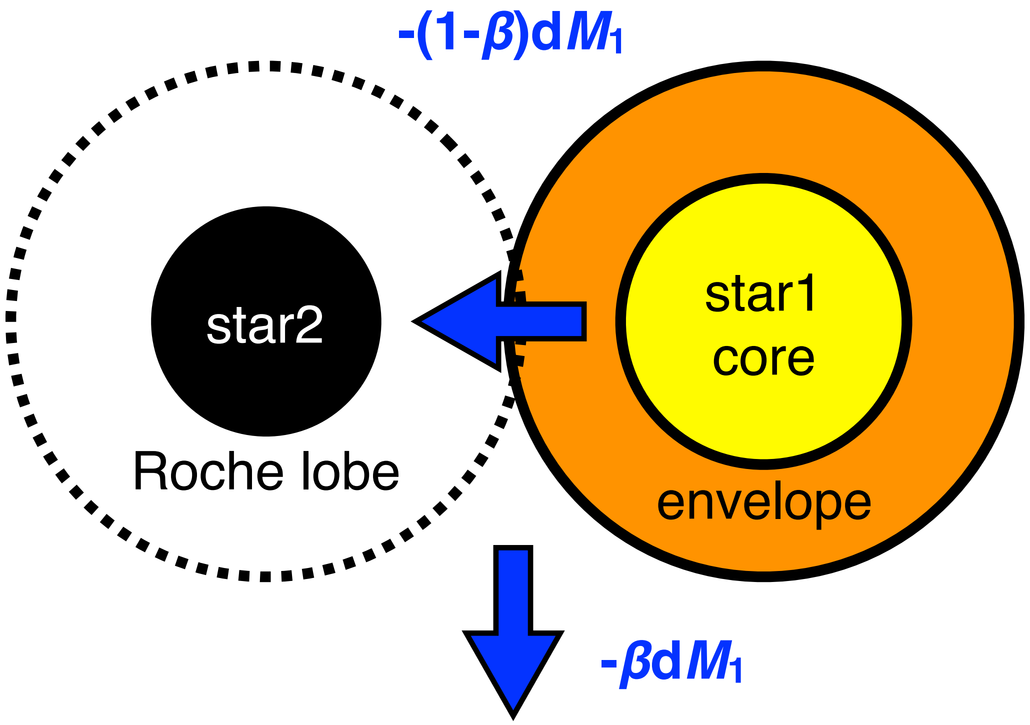
Mass transfer efficiency β

- We consider $\beta = 0.0$ (conservative mass transfer), 0.5, 0.7, 0.9.

- From the results, **$\beta = 0.0$ (conservative mass transfer) and 0.5 are not preferable** to explain the orbital period and eccentricity of the observed DNS systems.

- In order to form binaries like MWC656 (Be star-BH binary with $P_{\mathrm{orb}} = 60$ days), non-conservative mass transfer is essential (Shao et al. 2014)

- Our result is consistent with this.



Comparison with other studies

- We estimate the formation and merger rate of DNS systems.
- **Our values are the same order of magnitude as other values**.

Reference	R_f (/Myr/galaxy)	R_m (/Myr/galaxy)	Method
Shao et al. 2018	10	4	population synthesis
Vigna-Gómez et al. 2018	33	24	population synthesis
Kruckow et al. 2018		3	population synthesis
This work	**48.17**	**24.14**	**population synthesis**
Abbott et al. 2017		154^{+320}_{-122}	GW observation
Kim et al. 2013		21^{+28}_{-14}	Pulsar observation

Summary

- We perform Monte Carlo simulation called population synthesis.

- We estimate the rate of ultra-stripped supernovae (USSNe) like iPTF 14gqr (ejecta mass = 0.15 - 0.30 M_{sun}, He envelope mass = 0.003 - 0.013 M_{sun}).

- It is suggested that USSNe like iPTF 14gqr can be detected at 40 yr^{-1} by a next generation survey Zwicky Transient Facility (ZTF).

Supplementary materials

Comparison with other studies (detail)

	Z	SFR (M_{sun}/yr)	σ (km/s)	ECSN mass range	β	α	λ	R_f (/Myr/gal)	R_m (/Myr/gal)
Shao 2014		3	EC:40 CC:300	1.83-2.75(He)	Ω / Ω_c	1	Xu+2010	10	4
Vigna-Gómez 2018	0.0142	2	US,EC:30 CC:265			1	Xu+2010	33	24
Kurckow 2018	0.0088		EC:0-50 no H:120 no He(1st):60 no He(2nd):30 CC:265	1.37-1.435	0.95	0.5	self		3
This work	0.02	2	US,EC:30 CC:250	1.34-1.37	0.5	1	0.1	48.17	24.14

iPTF 14gqr

- The host galaxy of iPTF 14gqr is spiral galaxy IV Zw 155

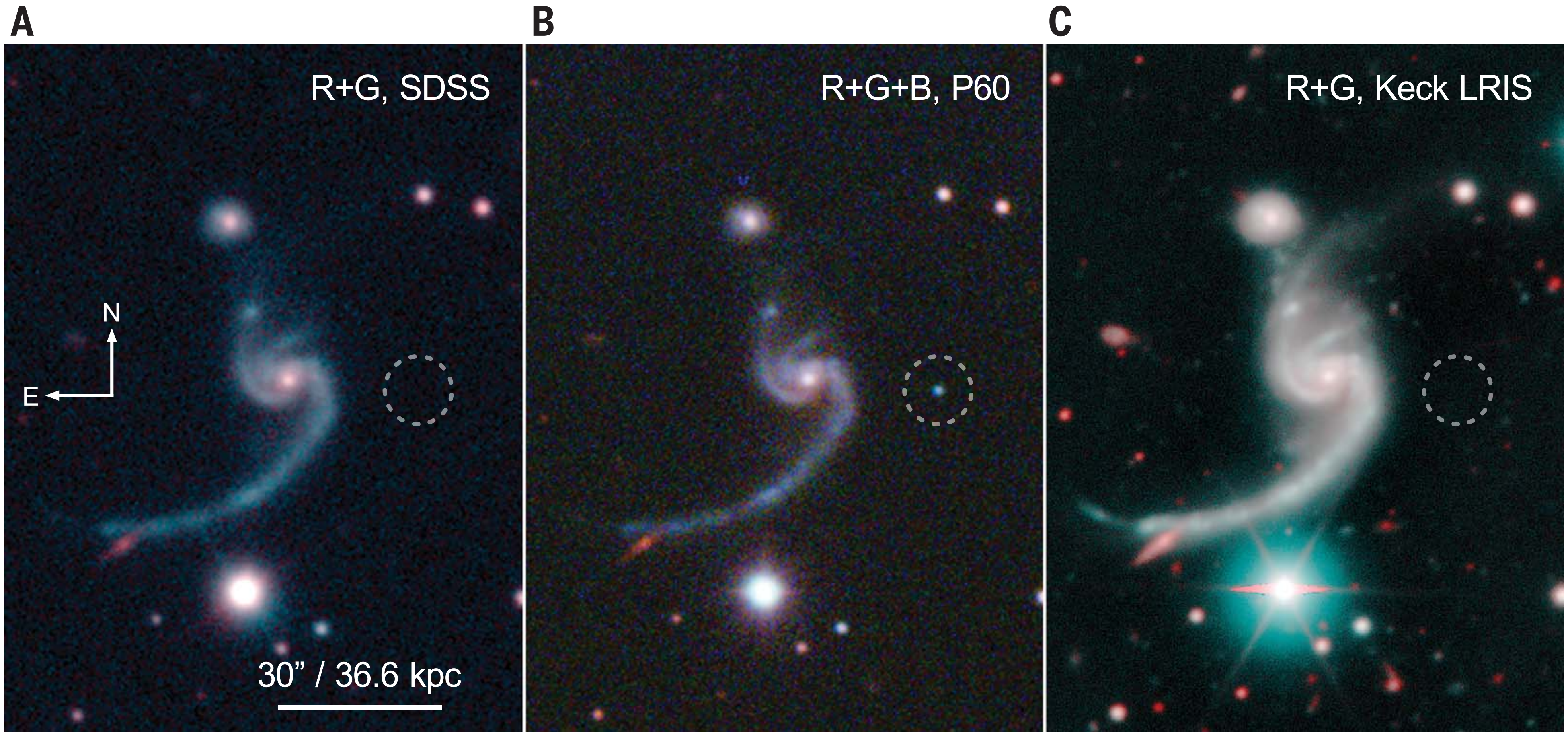


Fig. 1. Discovery field and host galaxy of iPTF 14gqr. (**A**) Optical image of the field from the Sloan Digital Sky Survey (SDSS) (*51*); R and G filter images have been used for red and cyan colors, respectively. (**B**) Composite RGB image (R, G, and B filter images have been used for red, green, and blue colors, respectively) of the iPTF 14gqr field from images taken near the second peak (19 October 2014) with the Palomar 60-inch telescope (P60), showing a blue transient inside the white dashed circle at the discovery location. (**C**) Late-time composite R+G image (R and G filter images have been used for red and cyan colors, respectively) of the host galaxy taken with the Low Resolution Imaging Spectrograph on the Keck I telescope.

Rate calculation

- We assume that **the absolute magnitude of iPTF 14gqr is -16.6 mag** in R band.

- The maximum distance *D* that USSNe like iPTF 14gqr can be observed is

$$D = 10\ [\mathrm{pc}]\ \times 10^{(m+16.6)/5}$$

limiting mag.

- The detection rate is

survey area with a cadence < 2 days

$$\frac{4\pi}{3} D^3 \times \rho_{\mathrm{gal}} \times\ 57.67\ [\mathrm{galaxy}^{-1}\ \mathrm{Myr}^{-1}] \times \frac{A\ [\mathrm{deg}^2]}{41253[\mathrm{deg}^2]}$$

galaxy density
= 0.01 galaxies Mpc^{-3}

rate of USSNe like iPTF 14gqr

The area of the sky

iPTF

- Limiting mag. is ***m* = 20.5 mag** in R band

- Survey strategy is as follows

cadence	exposure % of total	filter	target
5 days	41	R	
1 minutes - 3 days	**40**	**g, R**	
1 minitues	11	R	Orion
	8	Hα	

USSNe like iPTF 14gqr can be detected.
We must multiply a factor 0.4.
They call this experiment dynamical cadence (DyC).

- We assume that a cadence is always 1 day in DyC.

- iPTF can survey at 1000 $\mathrm{deg}^2\ \mathrm{day}^{-1}$, so that survey area is ***A* = 1000 deg^2**.

LSST

- Survey strategy is as follows

cadence	exposure % of total	limiting mag.
~ 4 days	90	24.5
~ 1 minutes	**10**	**26.5**

USSNe like iPTF 14gqr can be detected.
We must multiply a factor 0.1.
They call this experiment Deep Drilling fields (DDF).

- We assume that a cadence is always 1 minutes in DDF.
- We assume that survey area is equal to field of view **9.6 deg^2**.

ZTF

- Limiting mag. is **m = 20.5 mag** in R band.
- ZTF can scan all sky (survey area is **A = 30000 deg^2**)