Rate of iPTF 14gqr like ultra-stripped supernovae and binary evolution leading to DNS formation

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arXiv:1903.07575
Hijikawa et al. (2019), ApJ, 882, 93

Introduction

Gravitational wave from NS-NS

- **GW170817 (binary NS merger) was detected (Abbott *et al.* 2017).**
- **3rd observing run (O3) of a LIGO & Virgo has started from this April.**
- **3 or 4 new NS-NS merger events (candidates)**

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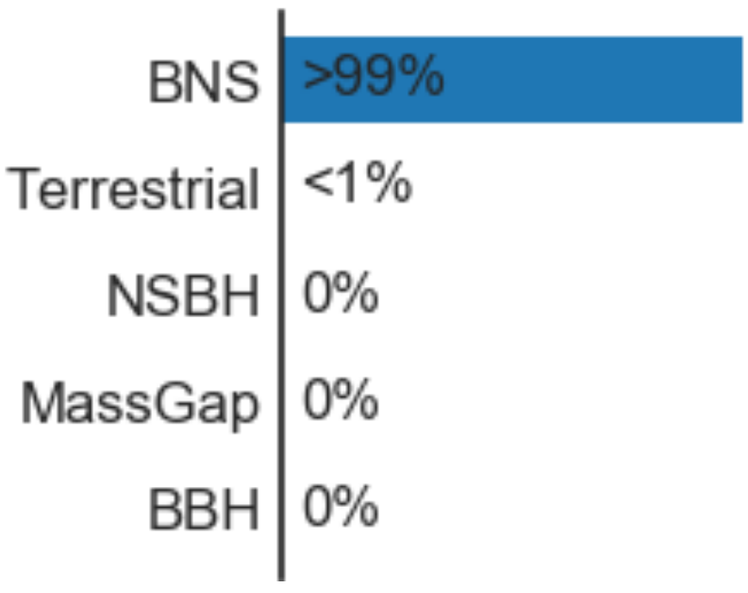

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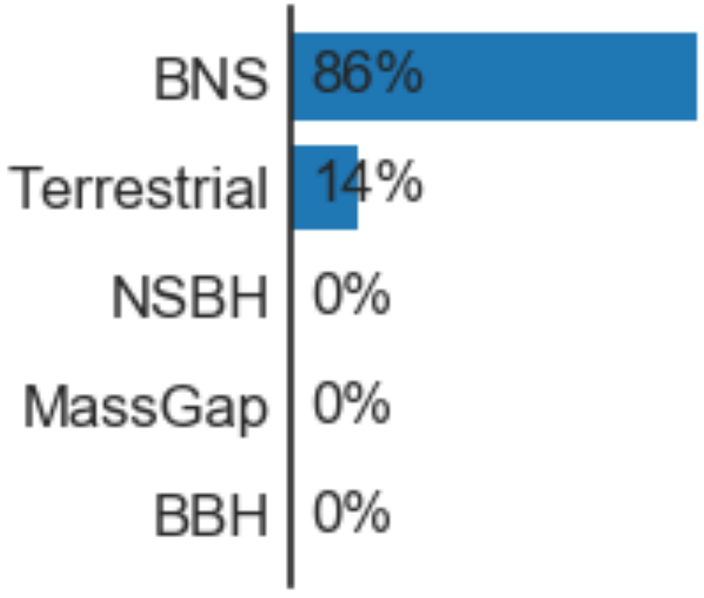

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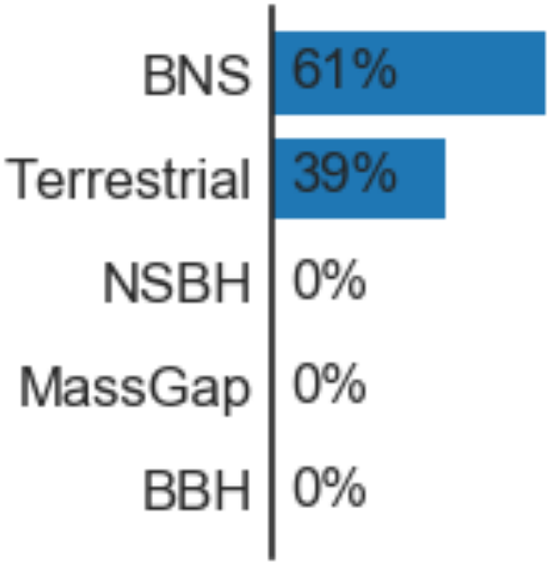


Double NS systems

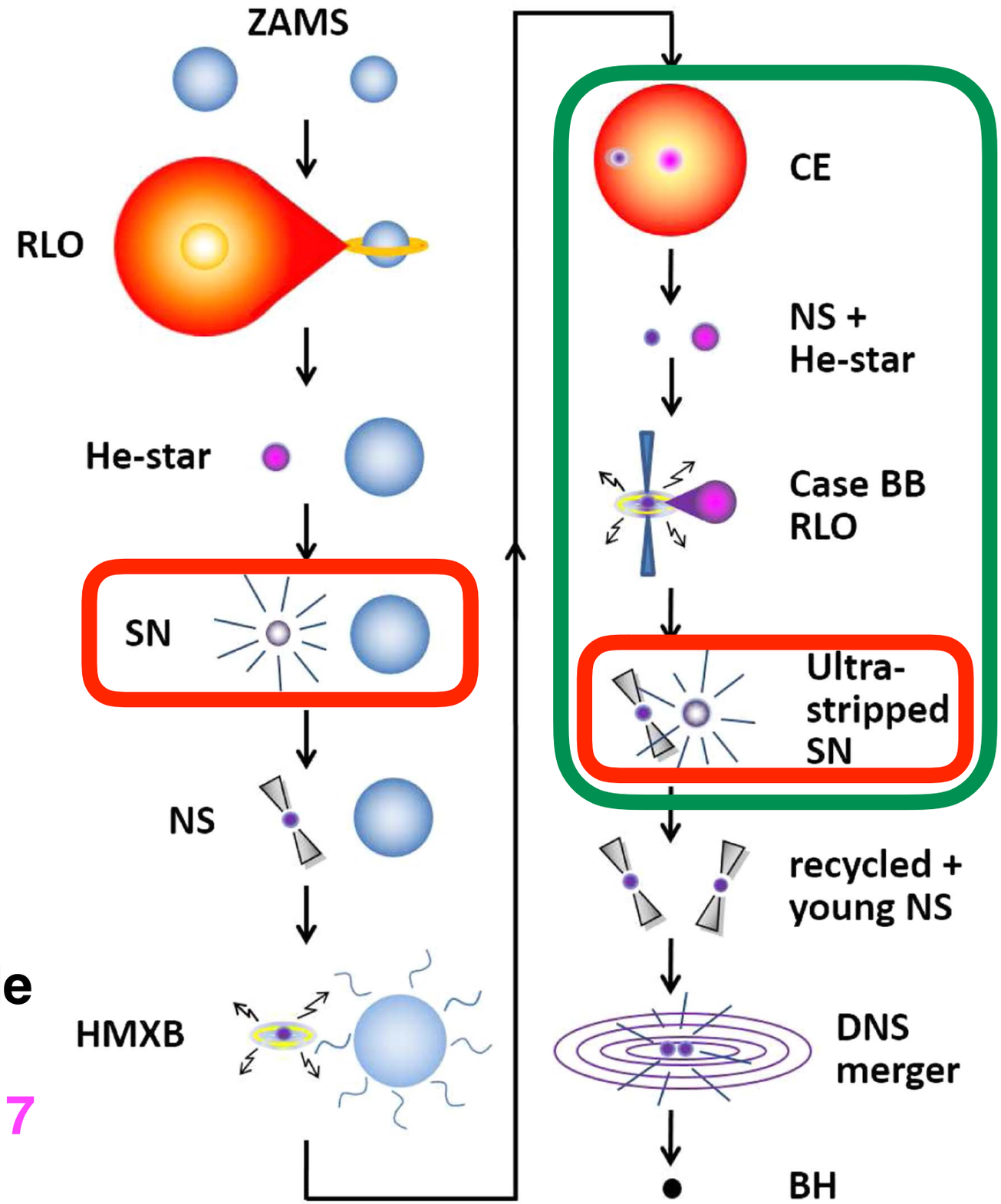
- **Gravitational wave (GW) source**
- **GW is a tool to explore strong gravitational field.**
- **GW observation allows us to constrain the EoS of the dense nuclear matter.**
- **sGRB, FRB, r-process, …**
- **It is important to deepen our knowledge about DNS systems that will merge within a Hubble time.**

A formation channel

- 2 SN explosions occur until DNS formation.
- Ultra-stripped SN (USSN) = progenitor is extremely stripped by binary interaction
- It had not been observed from CE to USSN.

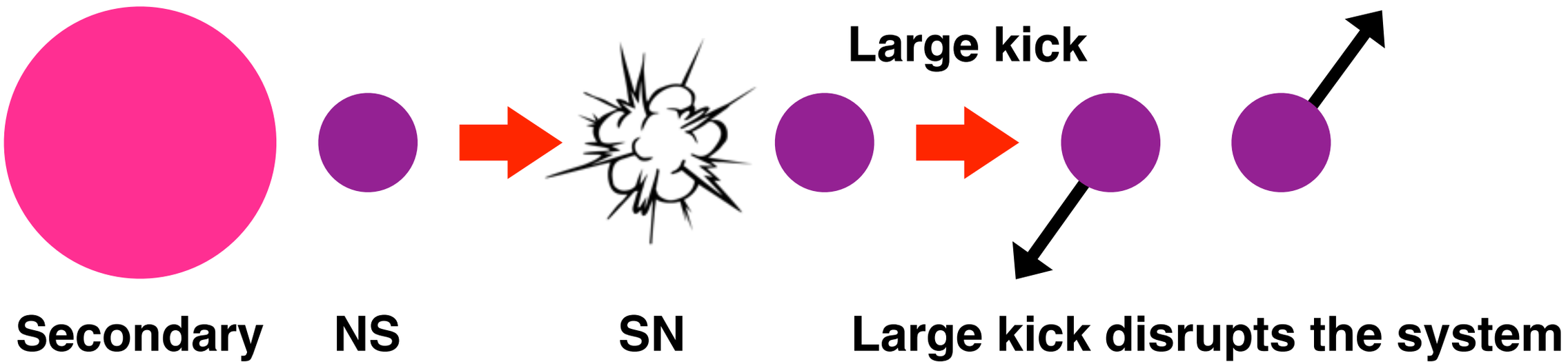
A formation channel leading to DNS systems that merge within the Hubble time

Fig. 1 in Tauris *et al*. 2017



Pulsar kick

- **Asymmetry of explosion causes pulsar kick.**
- **Kick velocity of canonical CCSN ~ several × 100 km s^{-1}**
- **Close binaries are hard to form with such a large kick.**
- **SNe with small kick are essential.**



Pulsar kick of USSNe

- **Kick of USSNe is small (Tauris *et al.* 2015).**

- **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.**

- **Hydrodynamical simulation shows that kick of USSNe ~ 30 km s^{-1} (Suwa *et al.* 2015).**

Model	t_{final} [a] (ms)	R_{sh} [b] (km)	E_{exp} [c] (B)	$M_{NS,\,baryon}$ [d] ($M_\odot$)	$M_{NS,\,grav}$ [e] ($M_\odot$)	M_{ej} [f] ($10^{-1}\,M_\odot$)	M_{Ni} [g] ($10^{-2}\,M_\odot$)	v_{kick} [h] (km s^{-1})
CO145	491	4220	0.177	1.35	1.24	0.973	3.54	3.20
CO15	584	4640	0.153	1.36	1.24	1.36	3.39	75.1
CO16	578	3430	0.124	1.42	1.29	1.76	2.90	47.6
CO18	784	2230	0.120	1.49	1.35	3.07	2.56	36.7
CO20 [i]	959	1050	0.0524	1.60	1.44	3.95	0.782	10.5

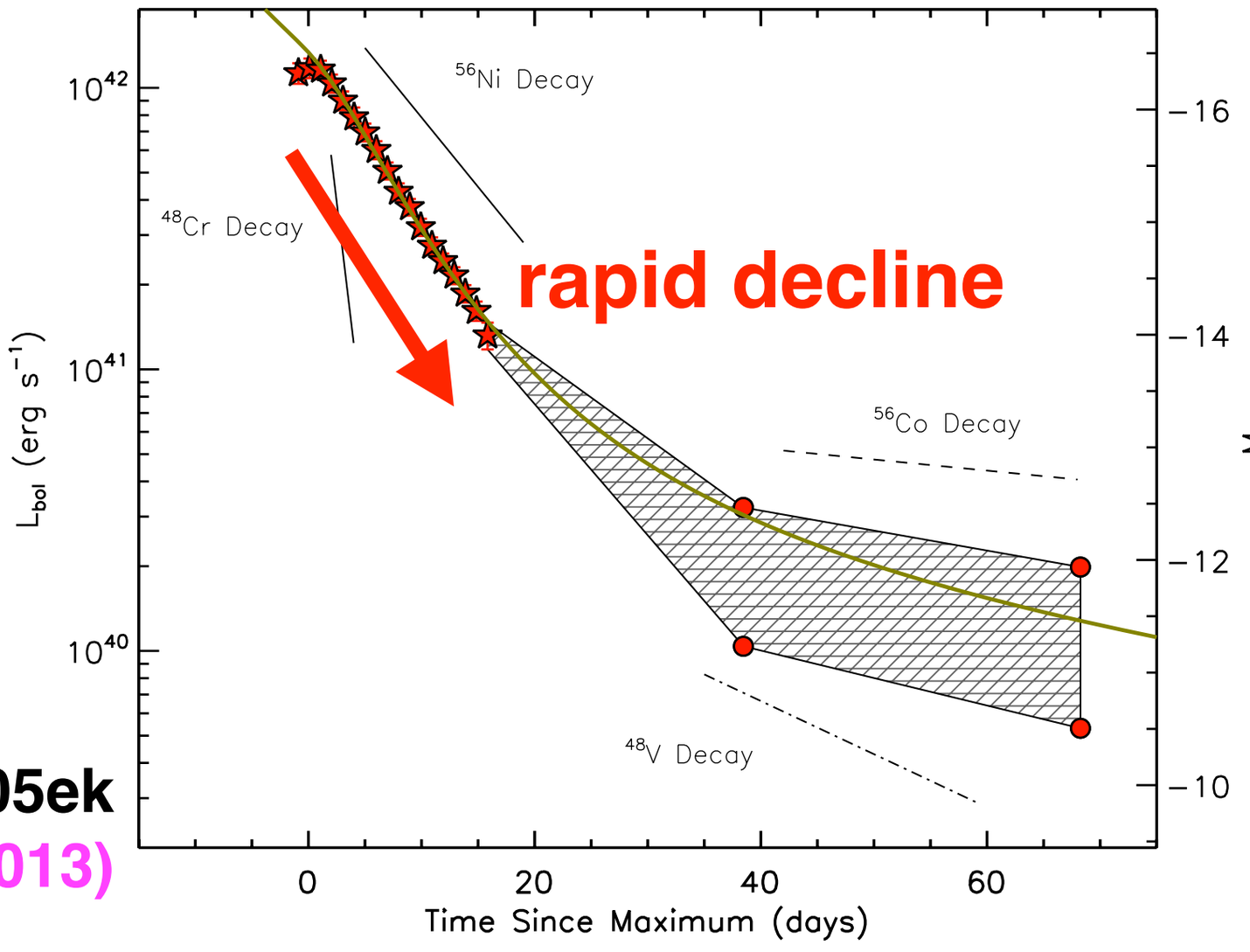
Table 2 in Suwa *et al.* (2015)

USSNe candidates

- **Type Ic SNe, SN 2005ek (Drout *et al.* 2013) and SN 2010X (Kasliwal *et al.* 2010) are candidates of USSNe.**

- **Ejecta mass ~ 0.3 $M_\odot$**

- **These events were observed only at the radioactively powered peak, and the origins of these SNe remain uncertain.**



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

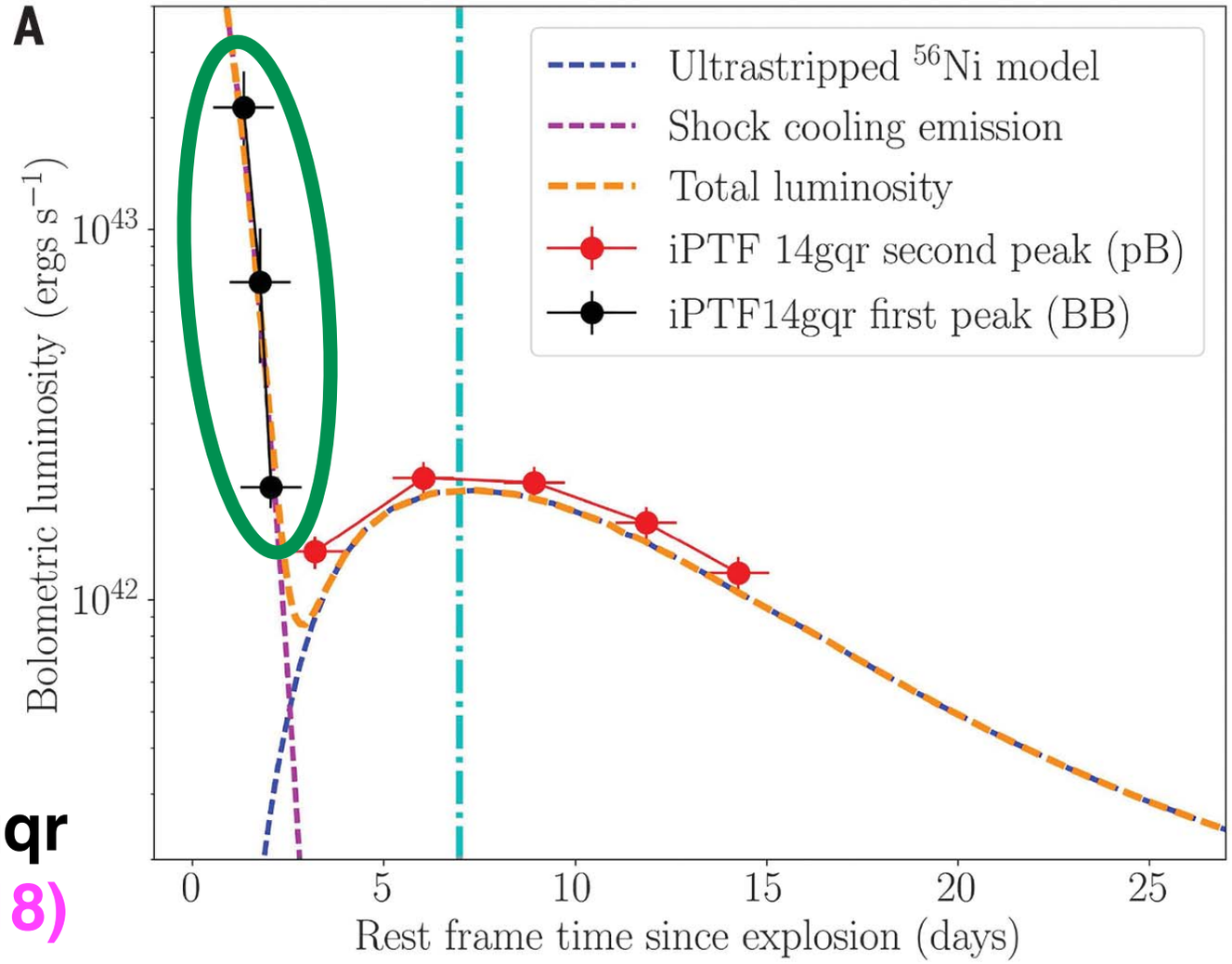
iPTF 14gqr (SN 2014ft)

- **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 = 0.2 $M_\odot$,**
  He envelope ~ 0.01 $M_\odot$

- **We estimate the rate of iPTF 14gqr like USSNe.**



Bolometric light curve of iPTF 14gqr
Fig. 5 in De *et al.* (2018)

Method

How to estimate the rate of USSNe

INPUT

$N = 10^6$

IMF : $M^{-2.35}$

q : flat

a : log-flat

$e = 0$

$Z = Z_\odot$

SFR = 2 $M_\odot$ yr^{-1}

BINARY PARAMETERS

β = 0.0, 0.5, 0.7, 0.9

CE while donor is HG

8 models

Population synthesis

Hurley *et al.* (2002)

Calculate the likelihood of each model

Estimate the rate of USSNe using the best model

Results

Detection rate

- **Rate of USSNe ~ 0.1%-1% of total SNe (Using Galactic total SNe rate $4.6^{+7.4}_{-2.7}$ century^{-1}; Adams *et al.* 2010)**

- **Short cadence surveys are essential.**

Survey	Limiting mag	Survey area (deg^2) (cadence < 2days)	Reference
iPTF	21	~1000	Rau *et al.* (2009) Law *et al.* (2009)
ZTF	20.5	~30000	Bellm *et al.* (2014)
LSST	26.5	~10	Ivezic *et al.* (2008)

Detection rate

- **ZTF can detect and identify iPTF 14gqr like USSNe at the rate of 10 yr^{-1}.**

Survey	Detection rate (yr^{-1})	Reference
iPTF	0.3	Rau *et al*. (2009) Law *et al*. (2009)
ZTF	10	Bellm *et al*. (2014)
LSST	1	Ivezic *et al*. (2008)

Companion stars of USSNe

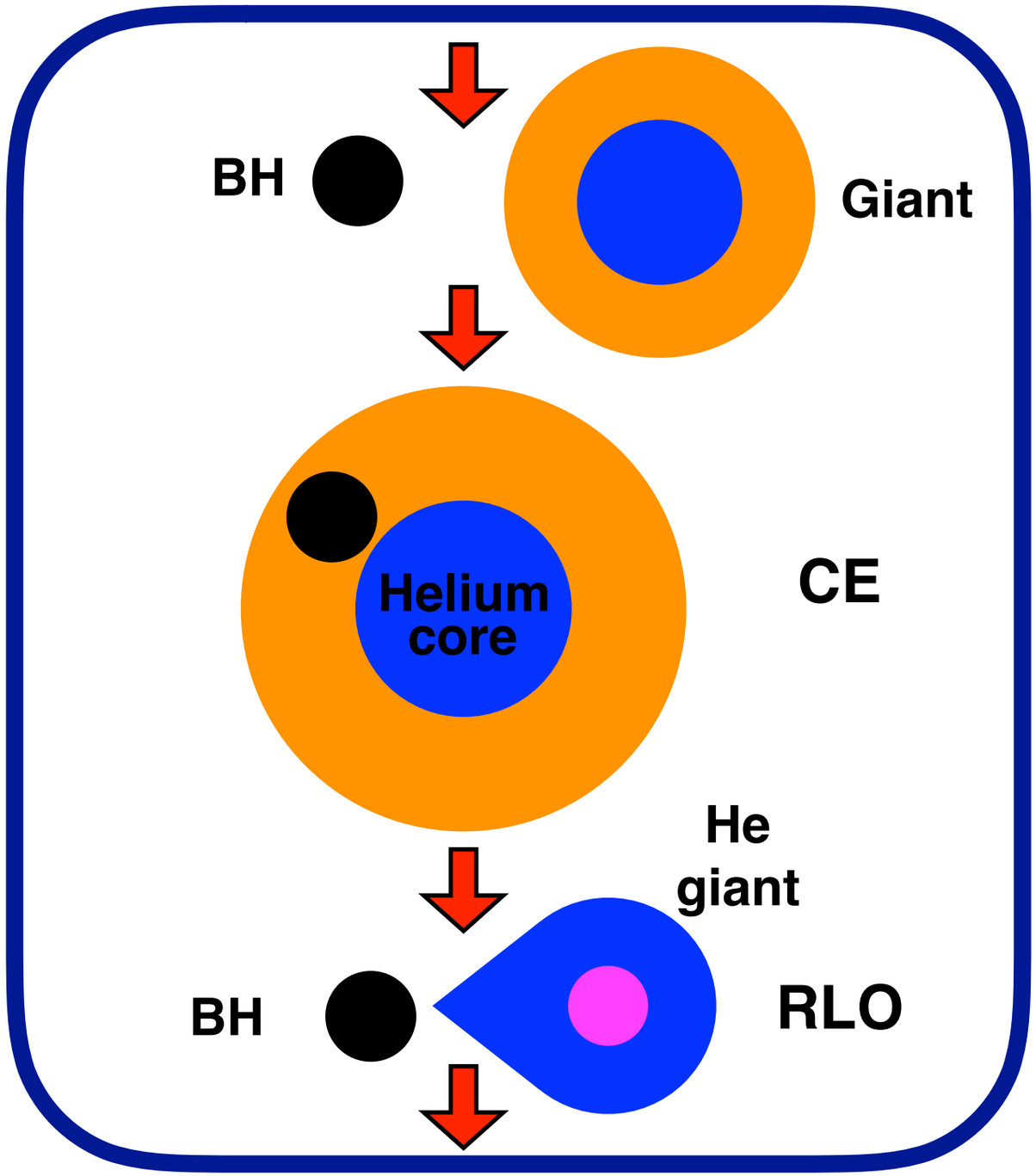
- **7.1 % of all USSNe have a NS companion and 99.8 % of these can form a DNS system, and 67.8 % lead to DNS merger.**

Companion	Ratio (%)
MS	19.5
WD	72.8
NS	7.1
BH	0.3
Others	0.3

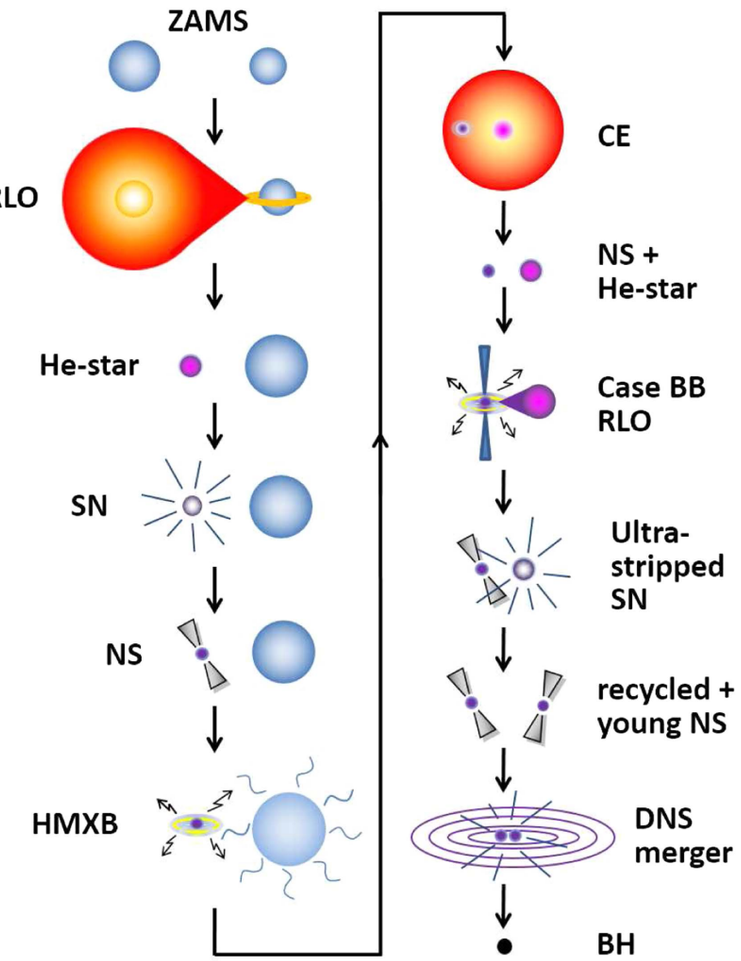
4.8%	Form DNS and merge
2.3%	Form DNS but not merge
0.01%	Disrupt

Various paths leading to USSNe

Companion of USSN = BH



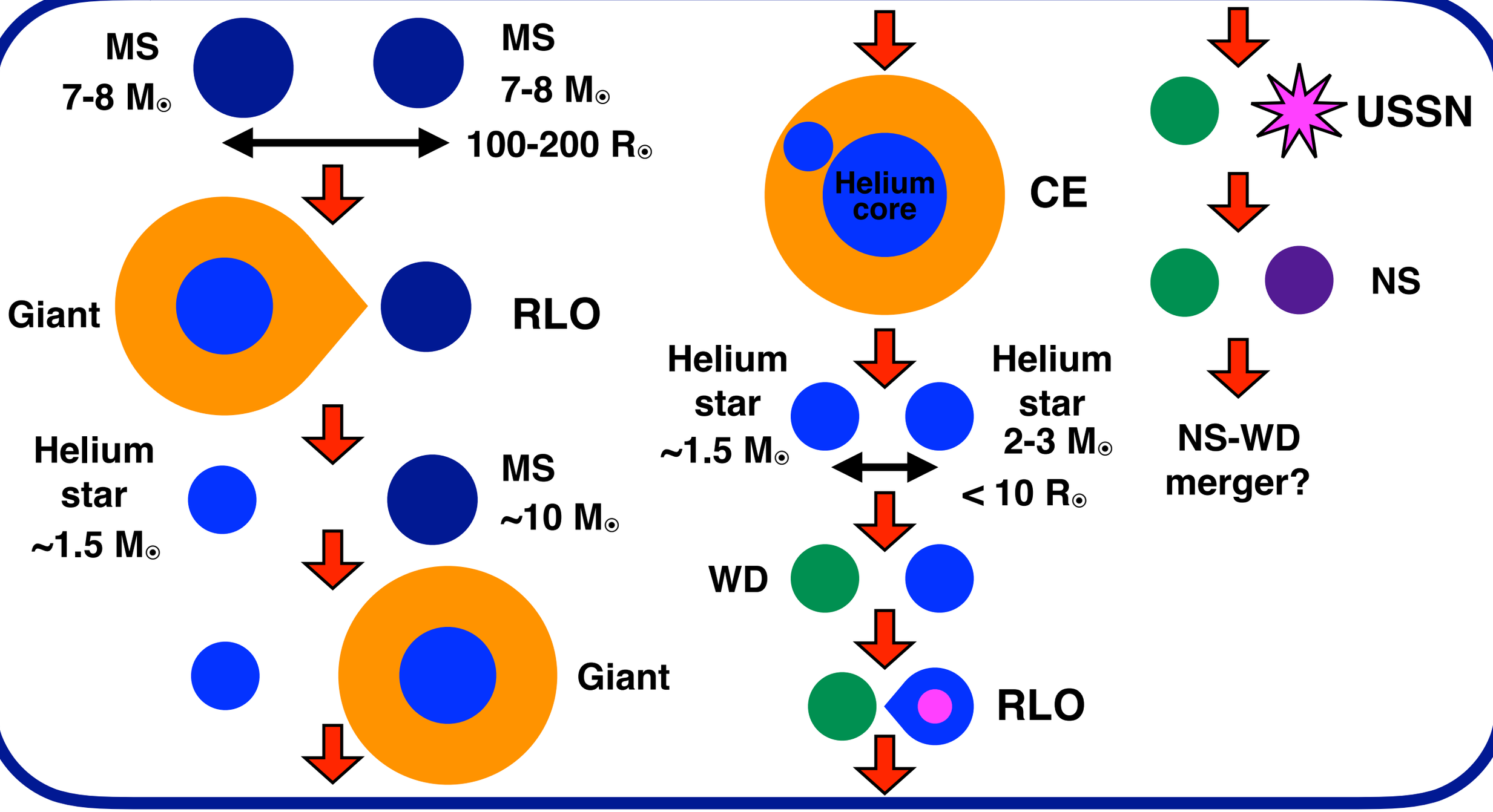
Same as Fig. 1 in Tauris *et al.* (2017)



Note: These results are based on population synthesis calculation

Various paths leading to USSNe

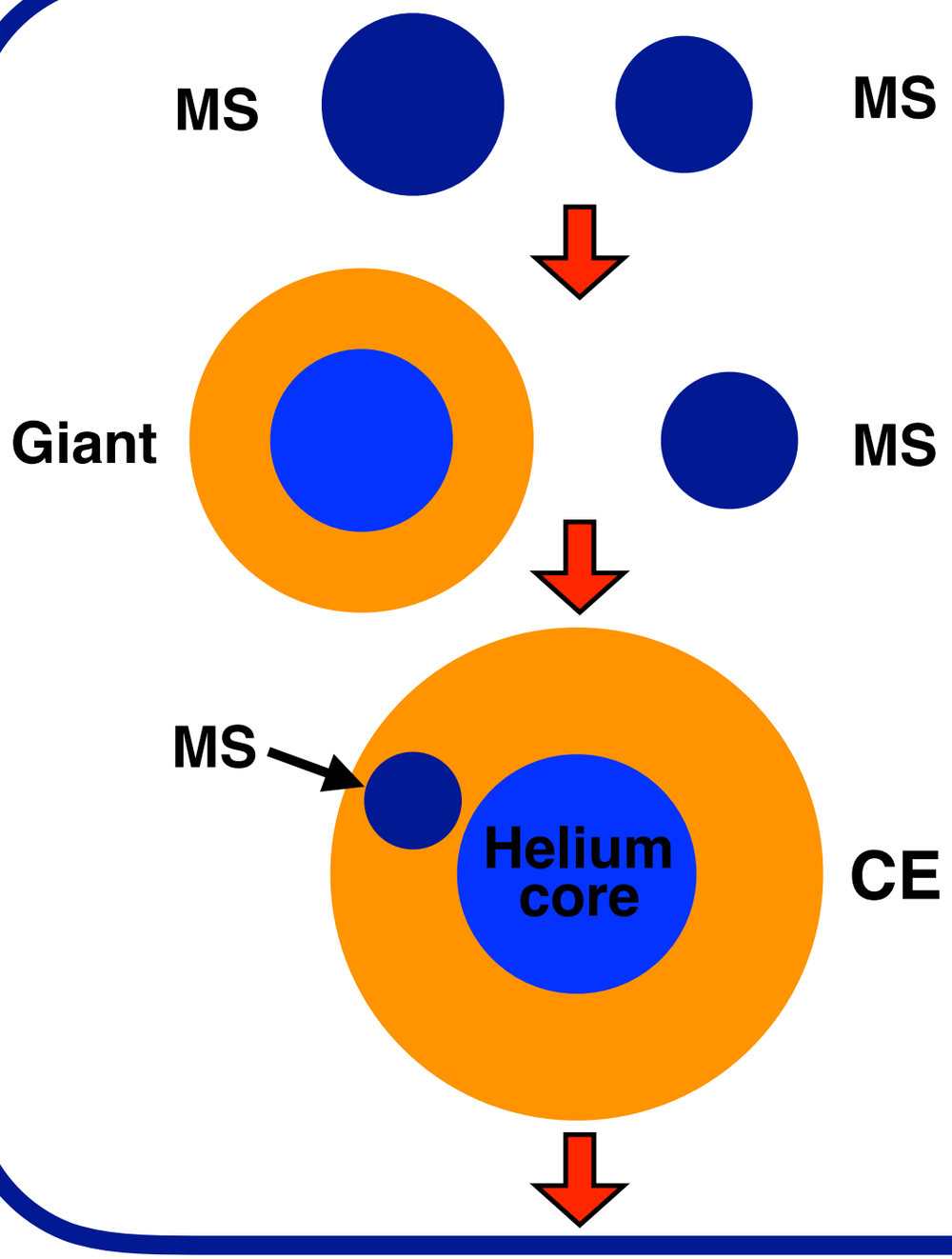
Companion of USSN = WD

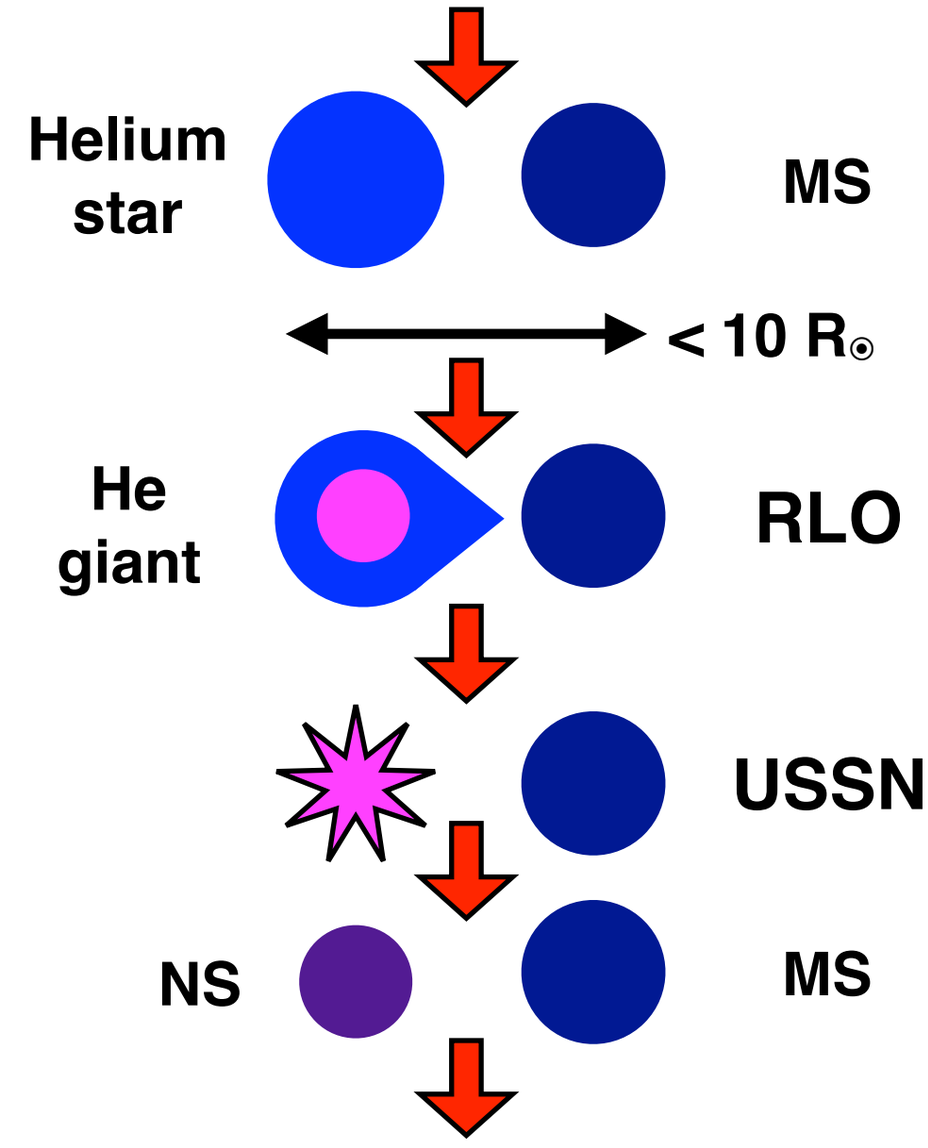


Note: These results are based on population synthesis calculation

Various paths leading to USSNe

Companion of USSN = MS





The secondary's fate depends on its mass and the orbital separation

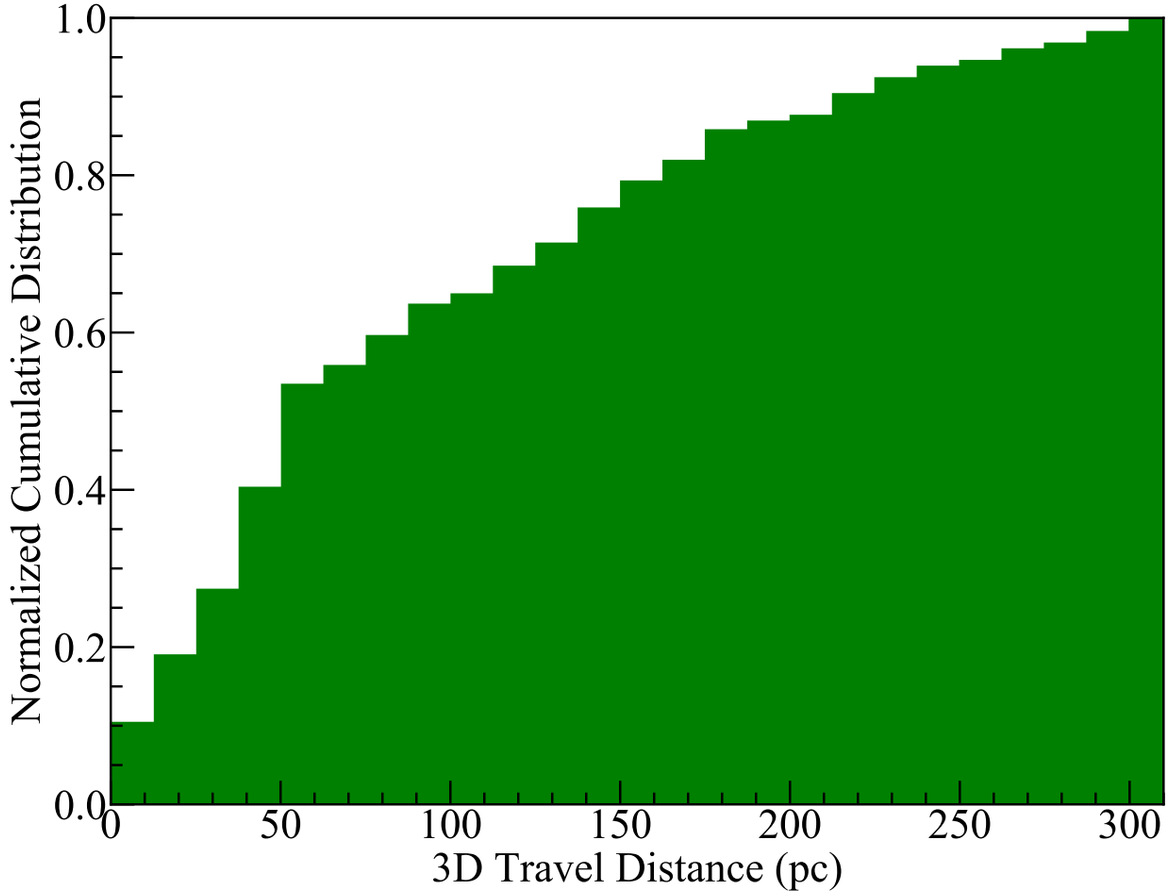
Note: These results are based on population synthesis calculation

Location of USSNe

- **The location of USSNe whose companion is not NS is almost same as its birth place.**

- **The travel distance of USSNe whose companion is NS is shorter than ~ 0.3 kpc.**

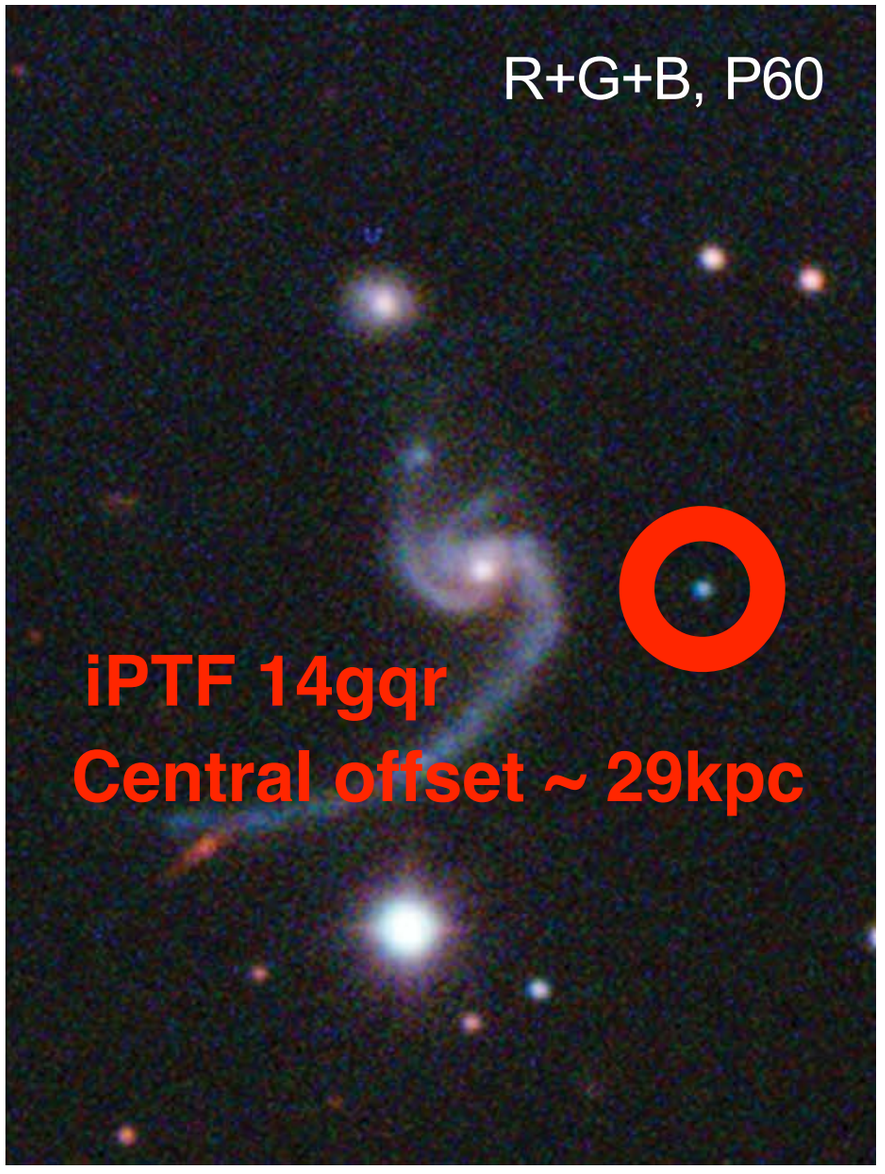
- **Therefore, the location is expected to be near a star forming region.**



Location of USSNe

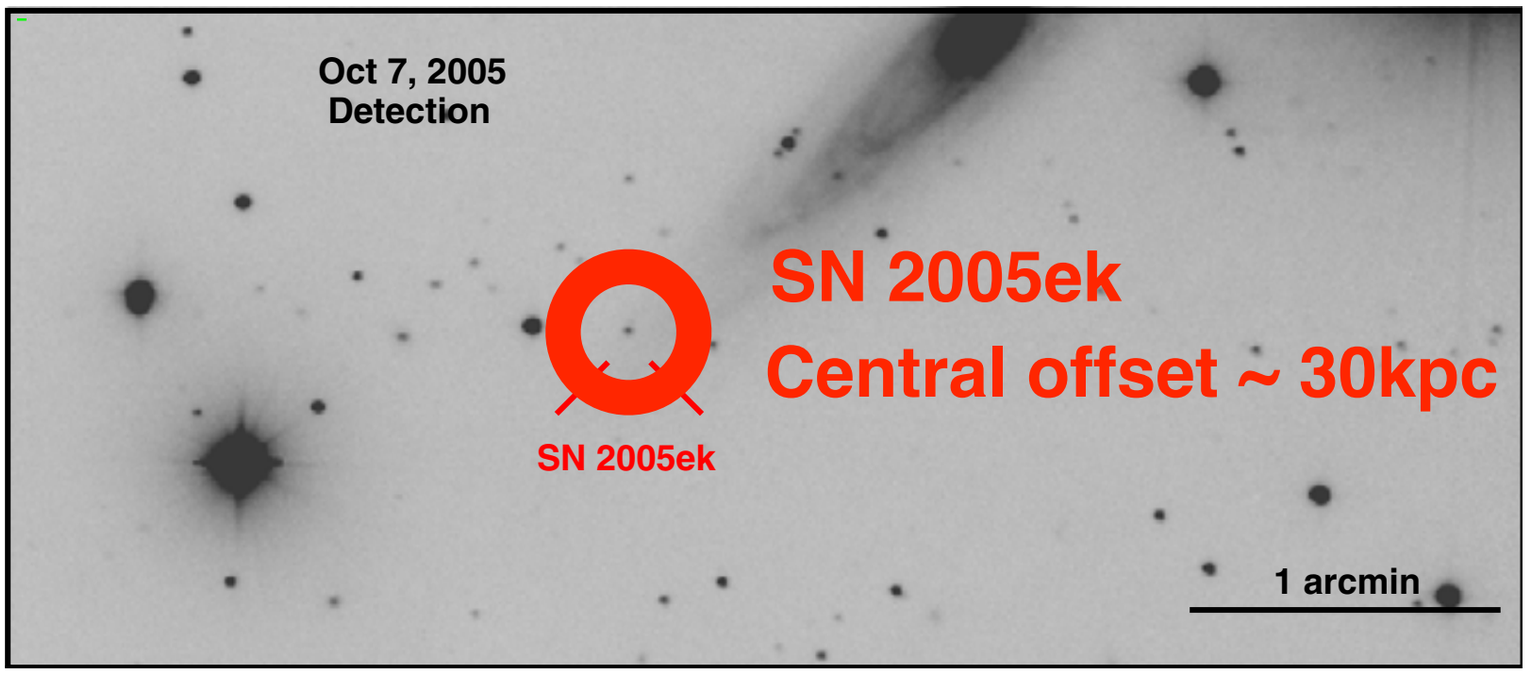
- **iPTF 14gqr and USSN candidate, SN 2005ek, are located in the outskirt of their host.**

- **It is suggested that HII region has already faded away within the progenitor lifetime.**



↑Fig. 1(B) in De *et al.* (2018)

←Fig. 1(top) in Draut *et al.* (2013)



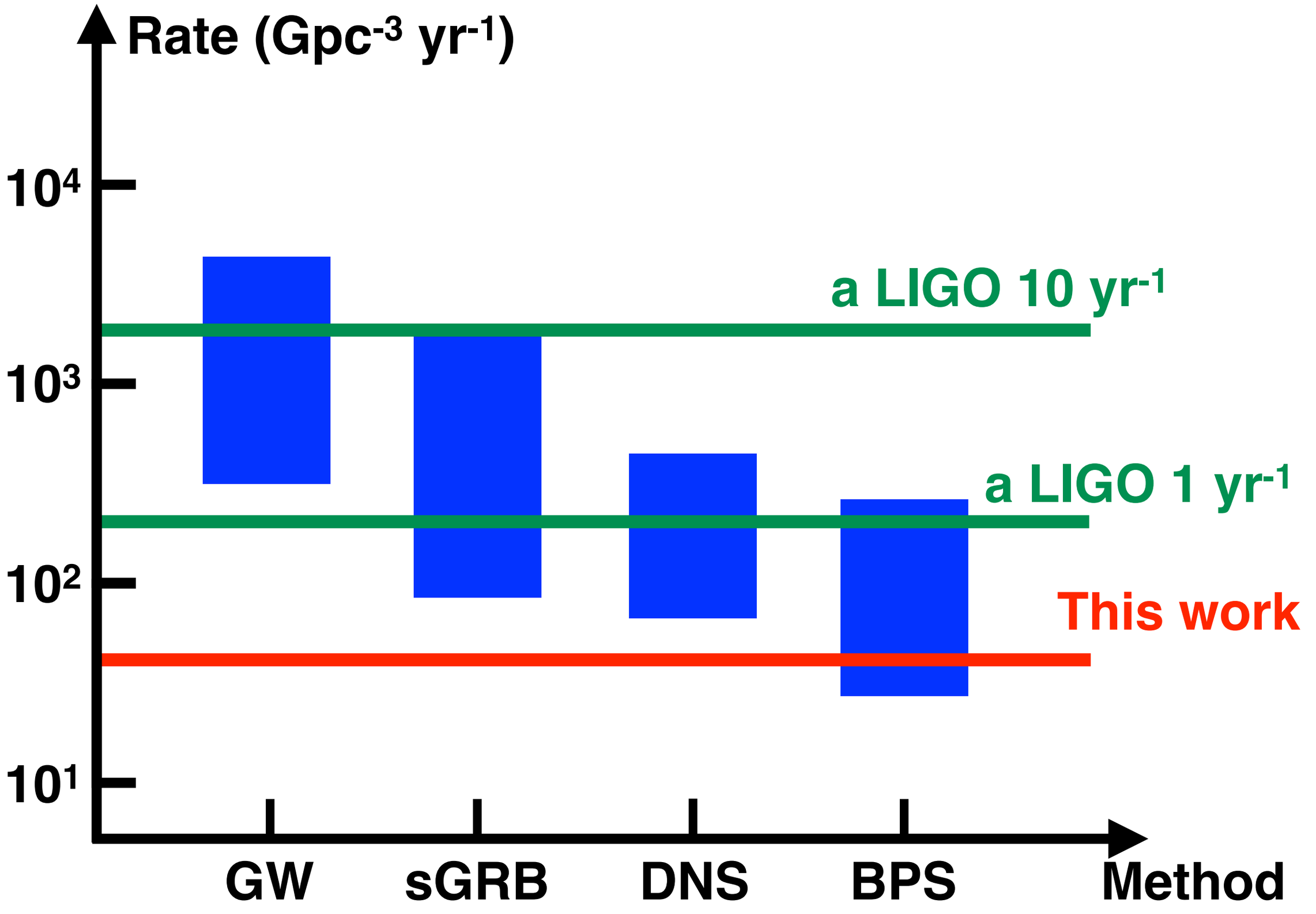
DNS merger rate

- **Our merger rate = 5 galaxy^{-1} Myr^{-1} (~ 50 Gpc^{-3} yr^{-1})**

- **This is consistent with other binary population synthesis (BPS) studies.**

Method	Merger rate (Gpc^{-3} yr^{-1})	Reference
BPS	~50	This work
BPS	~40	Shao & Li (2018)
Galactic DNS	$\sim 210^{+280}_{-140}$	Kim *et al.* (2015)
sGRB	270^{+1580}_{-180}	Fong *et al.* (2015)
GW	1540^{+3200}_{-1220}	Abbott *et al.* (2017)

DNS merger rate density



Summary

- **We perform a population synthesis calculation and estimate the rate of USSNe.**
- **The rate of USSNe in the Galaxy is 0.1-1% of all SNe.**
- **It is suggested that iPTF 14gqr like USSNe can be detected at 10 yr^{-1} by a next generation survey Zwicky Transient Facility (ZTF).**
- **However, all USSNe not necessarily have NS companions.**
- **The location of USSNe is expected to be near a star formation region.**