The distribution of the delay times of Binary Neutron Stars Mergers

(Greggio, Simonetti & Matteucci 2021, MNRAS 500, 1755)

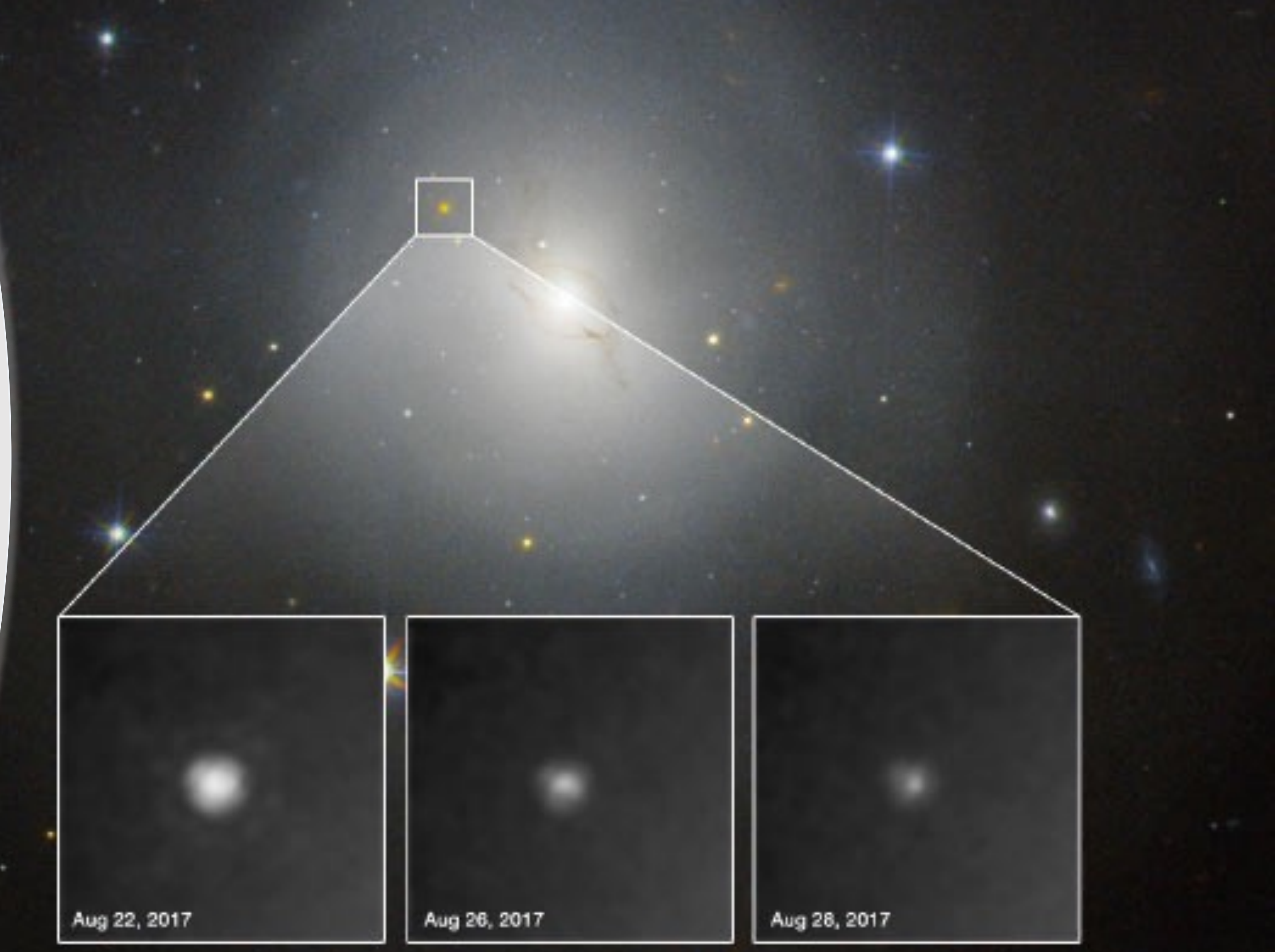
On Aug 17, 2017 a GW signal from a NSM was detected by LIGO/VIRGO (GW170817)

11 hr later Las Campanas detects one optical transient in the same region of the sky (AT2017gfo)

FERMI and INTEGRAL register a sGRB (GRB170817A) occurred shortly after GW170817 in the same sky region

9 days later CHANDRA detects it in x-rays

16 days later VLA detects it in the radio



HST images of NGC 4993 taken in August 2017

The merging of Double Neutron Stars is the event at the origin of short GRBs and Kilonovae.

Their rate → gravitational waves signal

cosmic evolution of sGRB rate

chemical enrichment of r-process elements

Fundamental to model the rate is the

DDT = distribution of the Delay Times ∝ rate MNS from one burst of SF

Delay Time = time elapsed between the formation of the original system and the merging of the double neutron star system

sGRBs observed in early and late type galaxies → The DDT of MNS is likely wide with early and late events

In the literature sometimes it is adopted DDT α $(DT)^{-1}$

The time it takes to merge the system due to GWR emission is:

$$\tau_{GW} = 0.15 \frac{A^4}{m_1 m_2 (m_1+m_2)} \times (1-e^2)^{7/2}$$

At fixed masses and eccentricity

$$n(\tau_{GW}) d\tau_{GW} = n(A) dA \quad : A = K\,\tau_{GW}^{0.25}$$

$$n(\tau_{GW}) \propto n(A) \frac{dA}{d\tau_{GW}} \propto A^{\beta} \tau_{GW}^{0.25-1} \propto \tau_{GW}^{0.25\beta-0.75}$$

For primordial binaries $\beta \approx -1$ → $n(\tau_{GW}) \propto \tau_{GW}^{-1}$

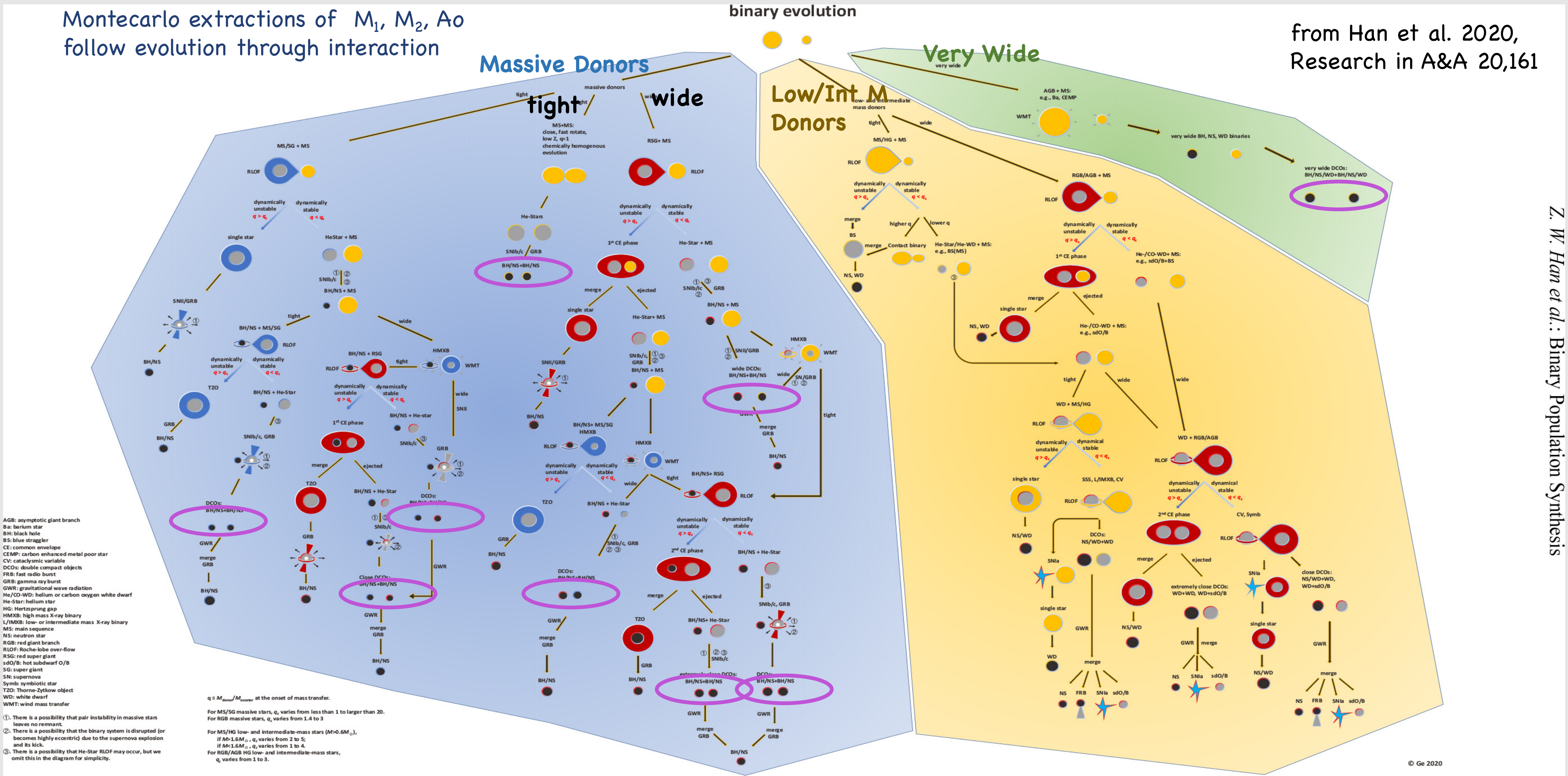
Assume that delay = GWR delay

trend dominated by distribution of A

distribution of A prop to a power law, with exponent -1

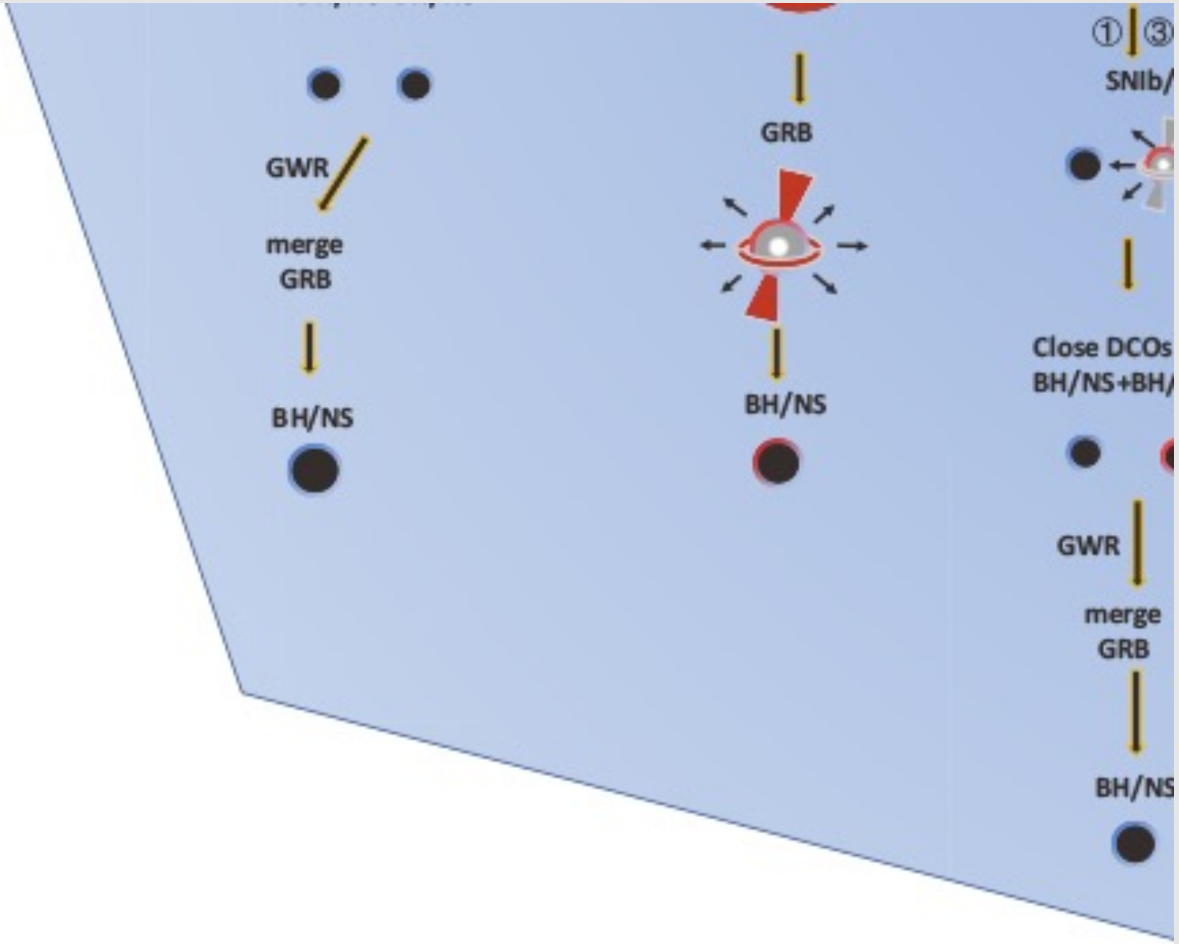
DDT from Binary Population Synthesis (BPS) computations

(e.g. Mapelli's team 2018 … 2022; Tang, Eldridge et al. 2020; Belczynski et al. 2020)



AGB: asymptotic giant branch
Ba: barium star
BH: black hole
BS: blue straggler
CE: common envelope
CEMP: carbon enhanced metal poor star
CV: cataclysmic variable
DCOs: double compact objects
FRB: fast radio burst
GRB: gamma ray burst
GWR: gravitational wave radiation
He/CO-WD: helium or carbon oxygen white dwarf
He-Star: helium star
HG: Hertzsprung gap
HMXB: high mass X-ray binary
L/IMXB: low- or intermediate mass X-ray binary
MS: main sequence
NS: neutron star
RGB: red giant branch
RLOF: Roche-lobe over-flow
RSG: red super giant
sdO/B: hot subdwarf O/B
SG: super giant
SN: supernova
Symb: symbiotic star
TZO: Thorne-Zytkow object
WD: white dwarf
WMT: wind mass transfer

①. There is a possibility that pair instability in massive stars leaves no remnant.
②. There is a possibility that the binary system is disrupted (or becomes highly eccentric) due to the supernova explosion and its kick.
③. There is a possibility that He-Star RLOF may occur, but we omit this in the diagram for simplicity.



$q \equiv M_{donor}/M_{accetor}$ at the onset of mass transfer.

For MS/SG massive stars, q_c varies from less than 1 to larger than 20.
For RGB massive stars, q_c varies from 1.4 to 3

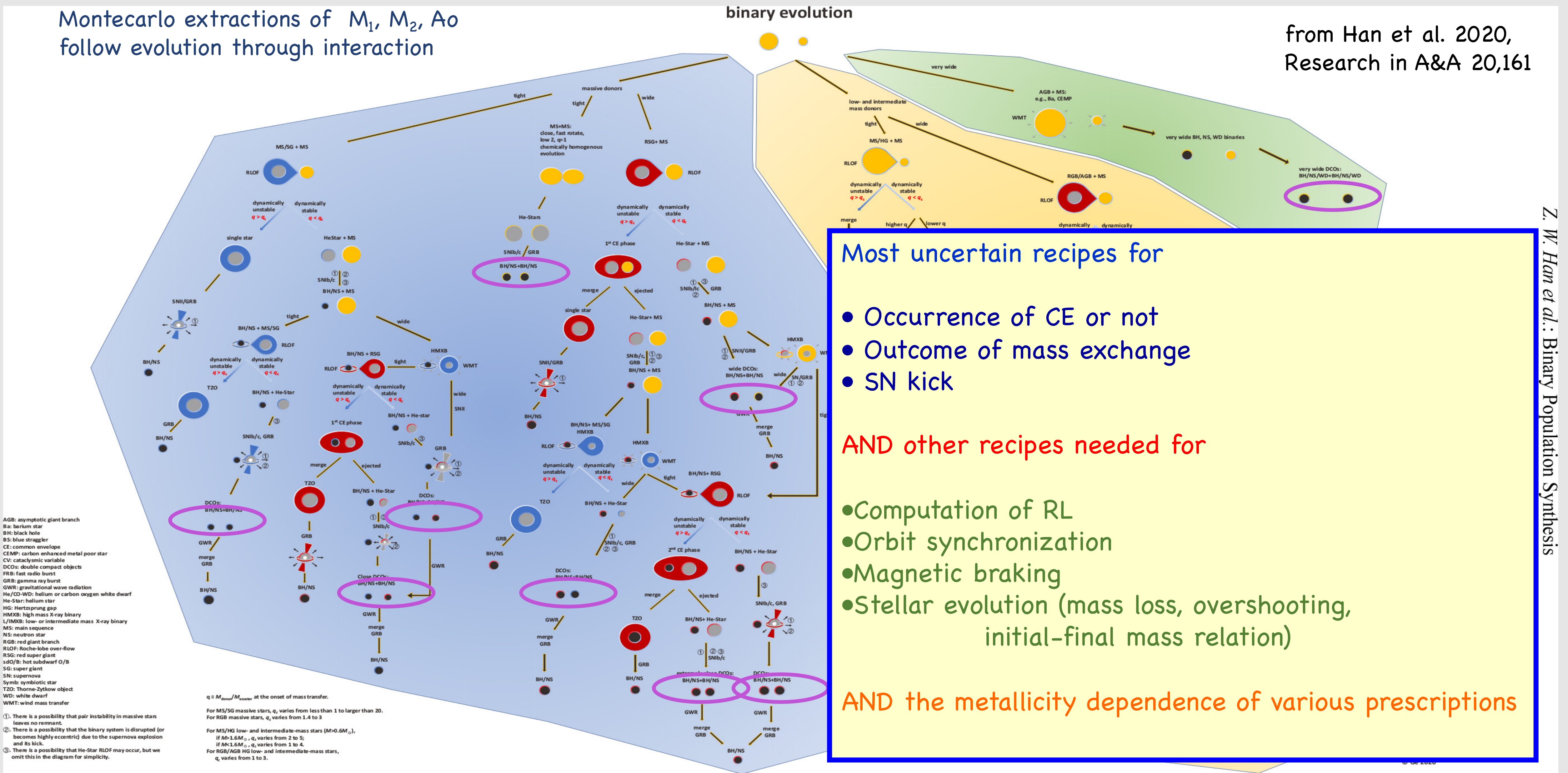
For MS/HG low- and intermediate-mass stars (M>0.6$M_\odot$),
if M>1.6$M_\odot$, q_c varies from 2 to 5;
if M<1.6$M_\odot$, q_c varies from 1 to 4.
For RGB/AGB HG low- and intermediate-mass stars,
q_c varies from 1 to 3.

DDT from Binary Population Synthesis (BPS) computations

(e.g. Mapelli's team 2018 … 2022; Tang, Eldridge et al. 2020; Belczynski et al. 2020)

Montecarlo extractions of M_1, M_2, Ao
follow evolution through interaction

from Han et al. 2020,
Research in A&A 20,161



Most uncertain recipes for

- Occurrence of CE or not
- Outcome of mass exchange
- SN kick

AND other recipes needed for

- Computation of RL
- Orbit synchronization
- Magnetic braking
- Stellar evolution (mass loss, overshooting, initial-final mass relation)

AND the metallicity dependence of various prescriptions

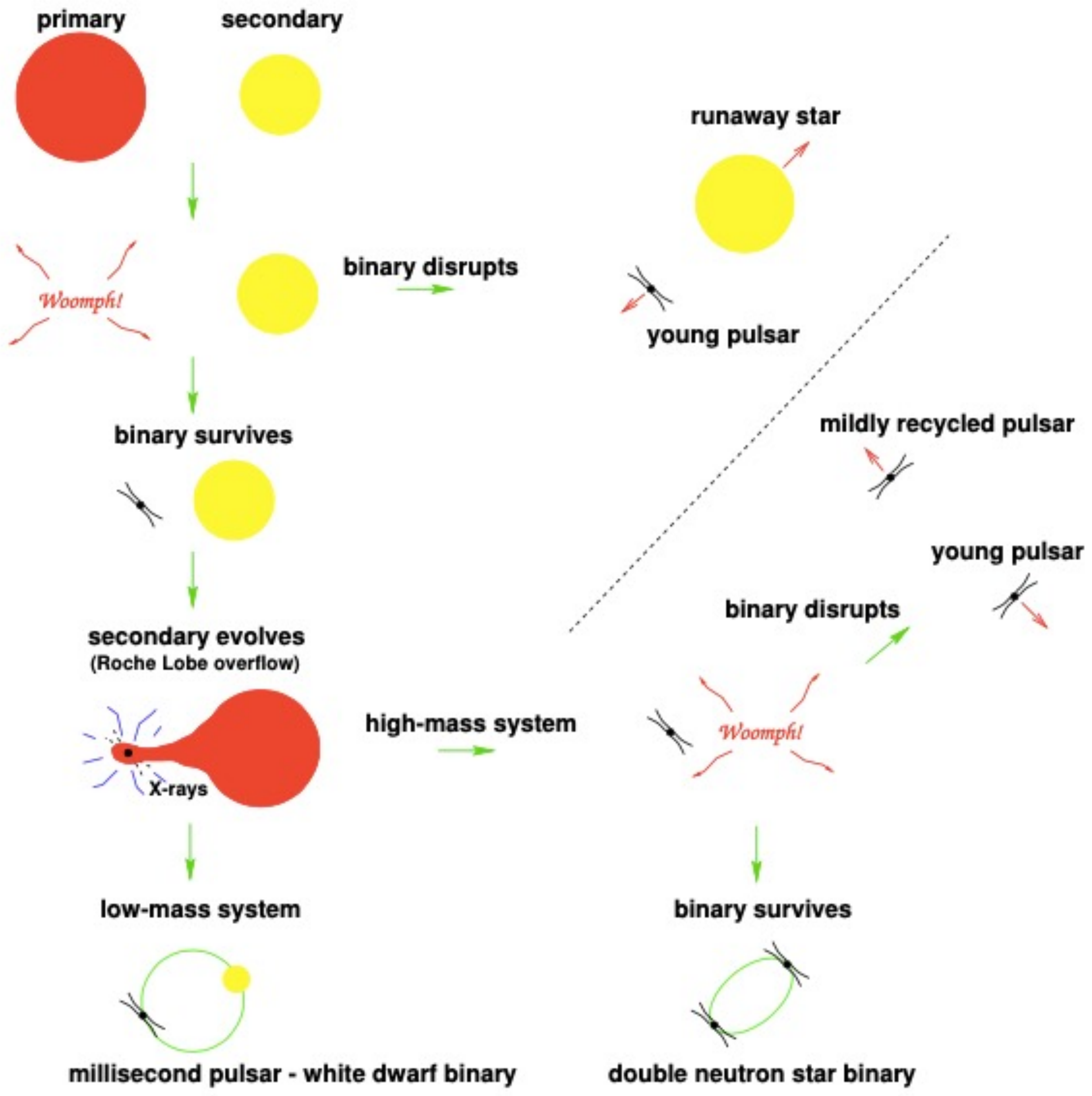


Figure 1: Cartoon showing standard formation channels for close NS-NS binaries through binary stellar evolution. Image reproduced from [178].

From Faber and Rasio (2012)

Evolutionary Paths of Massive Binaries

- A variety of products
- The double neutron stars are only a fraction

How many survive??
Impacts on the efficiency of MNS production

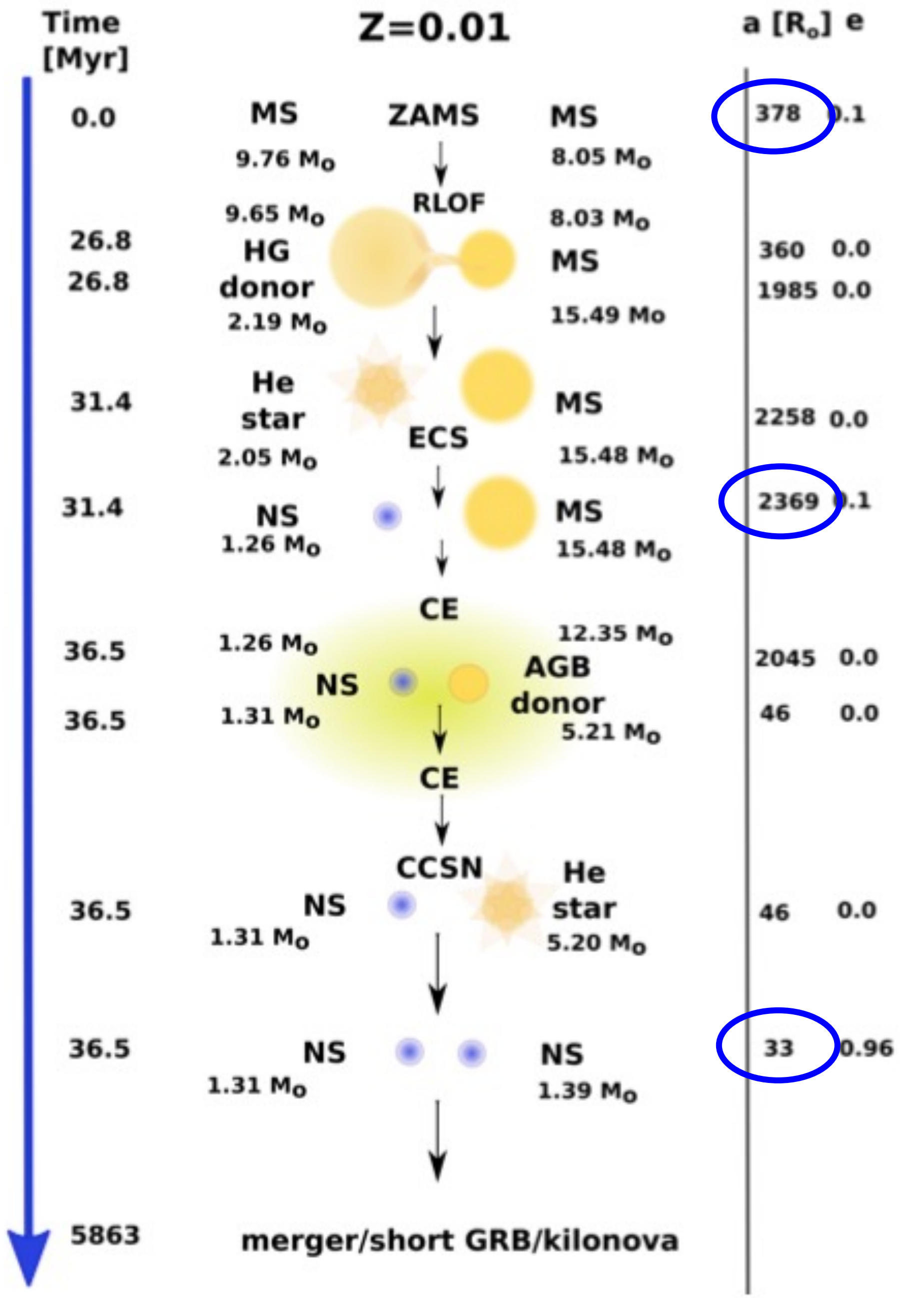


Fig. 1. Example of the formation of an NS-NS merger similar to GW170817 in the classical isolated binary evolution channel.

From Belczynski + (2018)

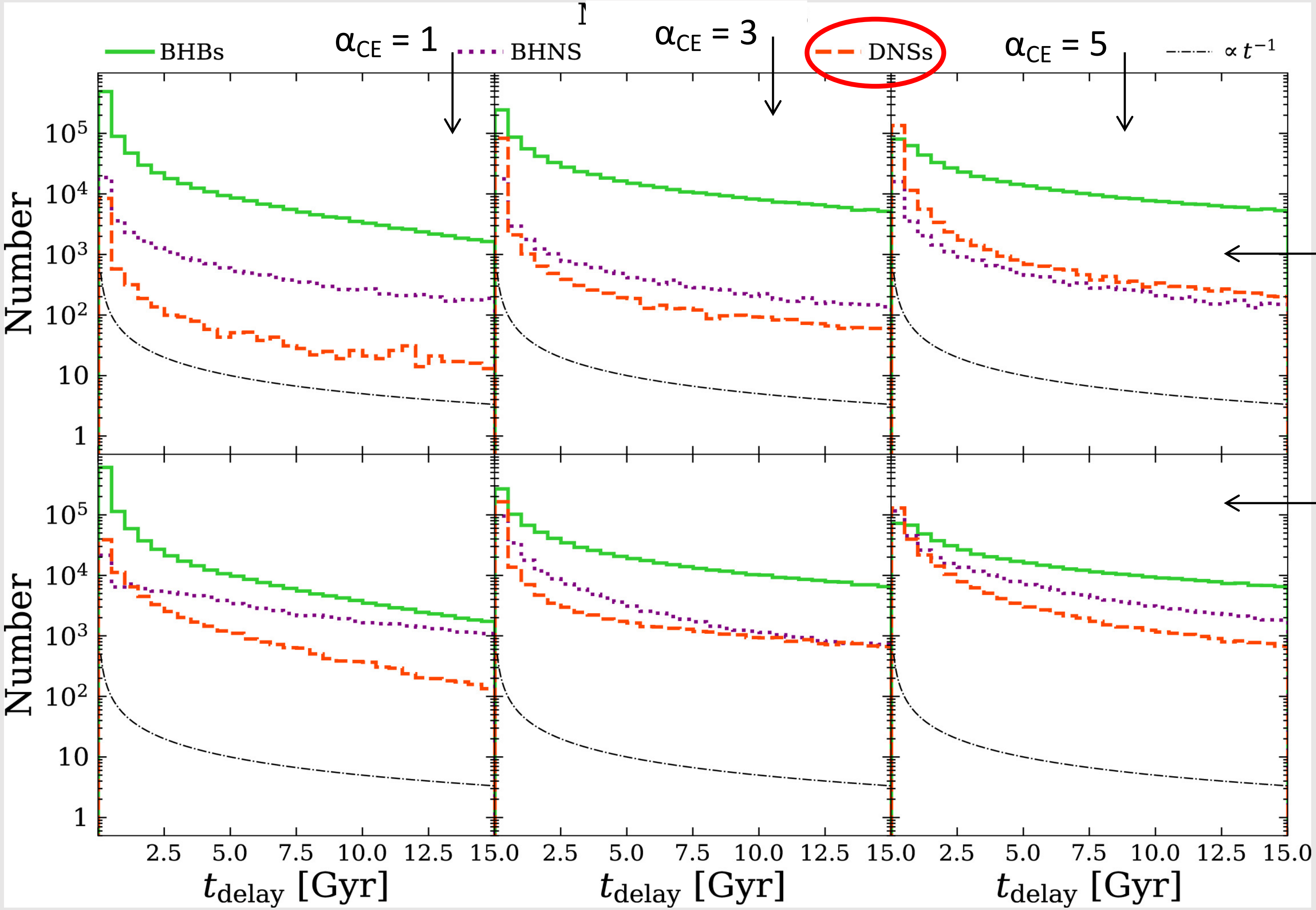
Evolutionary Path leading to GW170817

The separation goes from

1. few x 100 to enable 1RLOf
2. I RLOf happens to be conservative: the system gets wide (fewx1000)
3. the secondary fills the RL: CE the system shrinks to few x 10 Ro

How well do we describe this evolution?
This is crucial for the DDT

DDT from BPS : Giacobbo & Mapelli 2018, MNRAS 480, 2011



Monte Carlo simulations of 10^7 massive binaries

Large kick at CC explosion

Small kick at CC explosion

The DDT scales approx. as $(DT)^{-1}$

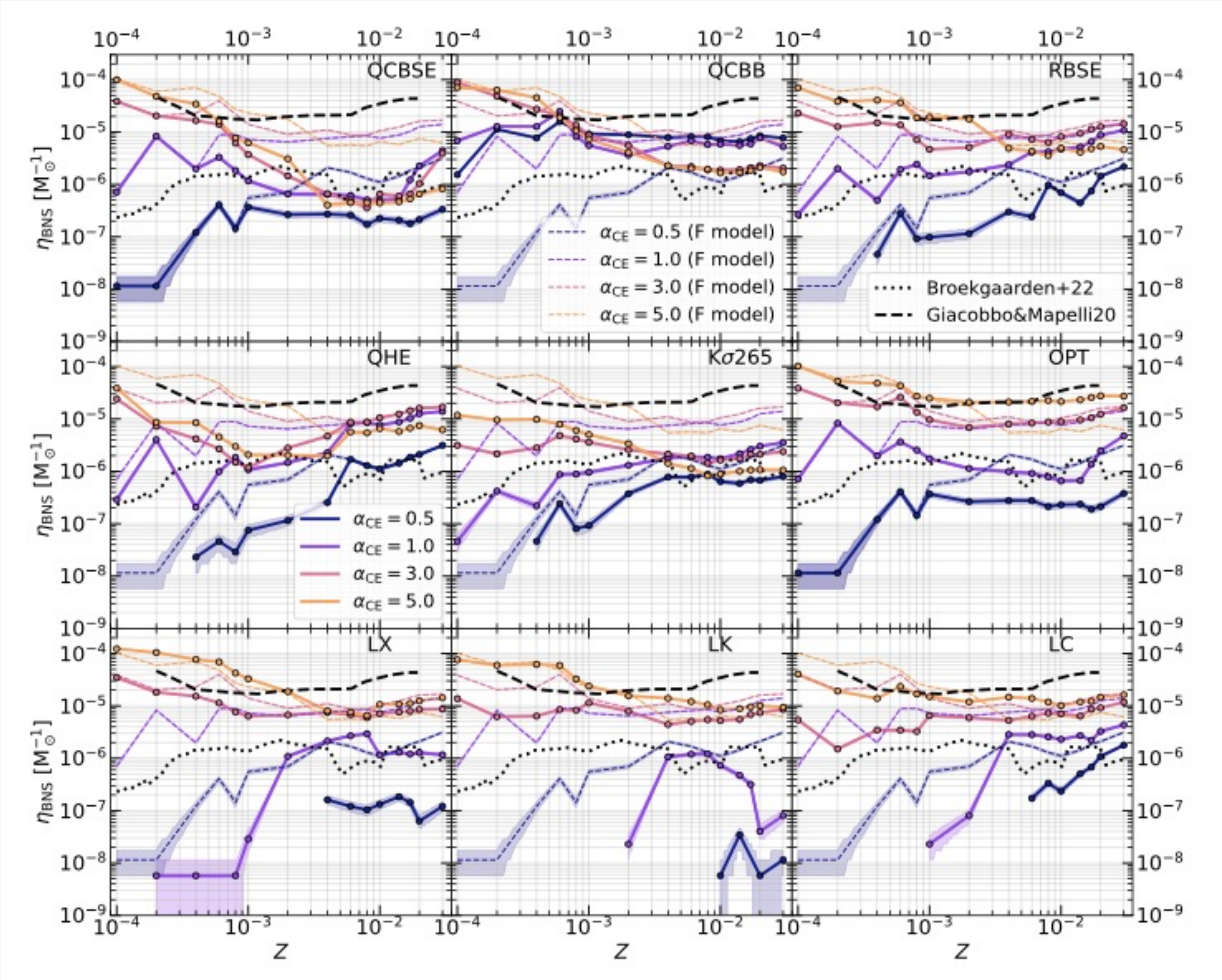
Great sensitivity of the realization probability from CE efficiency and CC SN kick

Realization probability of BPS : dependence on params and stellar evolution

(Iorio et al. 2022)

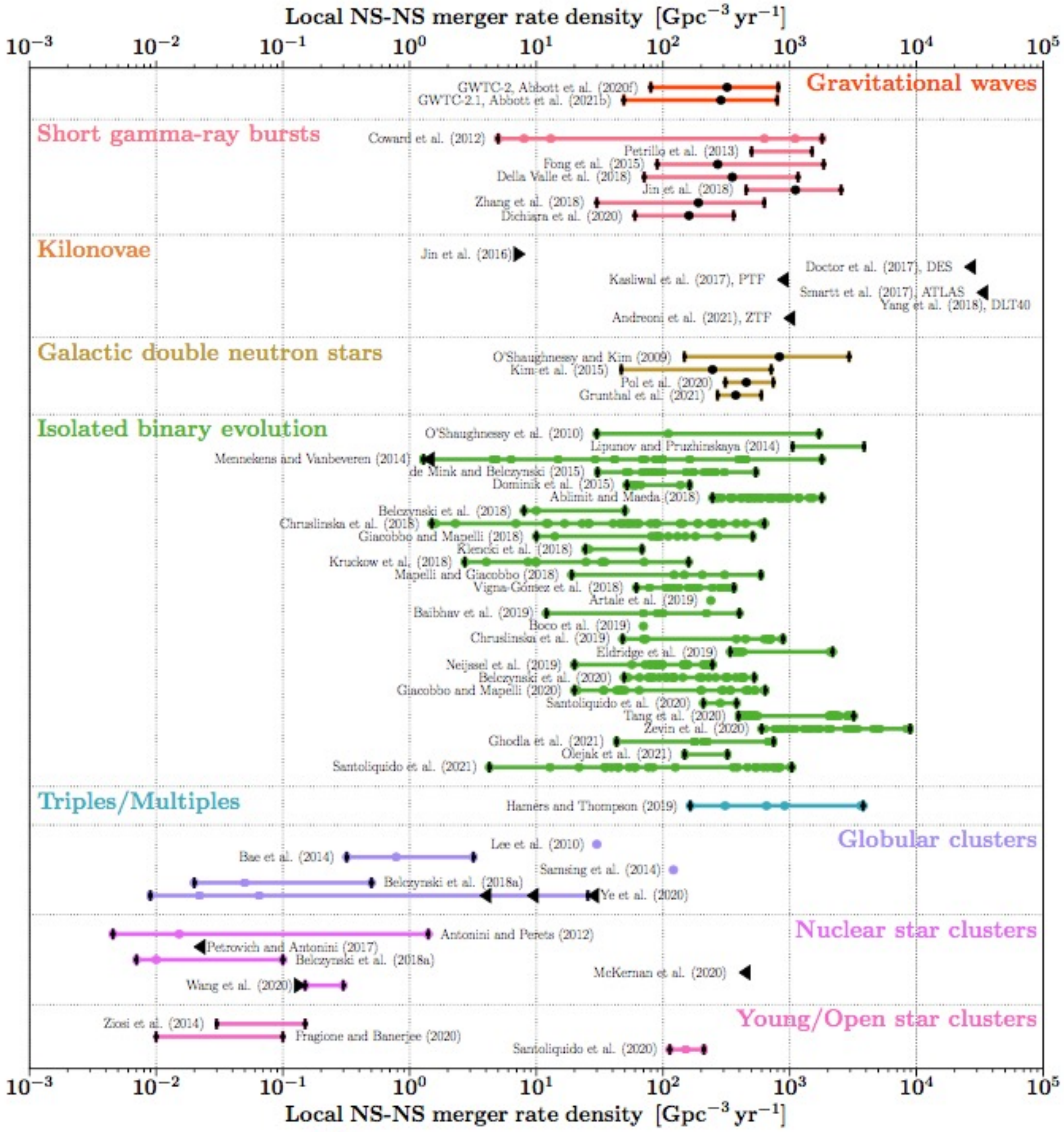
$\eta_{BNS} = N_{BNS}(DT<14\ \mathrm{Gyr})/M_{SSP}$

Model	Parameter variations
F	Fiducial model
QCBSE	Use QCBSE option for the RLO mass transfer stability (Table 3)
QCBB	Use QCBB option for the RLO mass transfer stability (Table 3)
QHE	Enable quasi-homogeneous evolution during RLO (Section 2.3.2)
RBSE	Use Equation 26 for mass accretion efficiency during the RLO (same as in Hurley et al. 2002)
Kσ265	Draw supernova kicks from a Maxwellian with σ = 265 kms^{-1}
Kσ150	Draw supernova kicks from a Maxwellian with σ = 150 kms^{-1}
F19	Use Farmer et al. (2019) PISN prescriptions (Section 2.2.2)
SND	Use the delayed supernova model with a Gaussian distribution for NS masses (Section 2.2.1)
NT	Disable tides (Section 2.3.4)
NTC	Disable tides and circularise when the RLO condition is valid at the pericentre (Section 2.3.5)
OPT	QCBSE + Optimistic CE assumption for HG stars (Section 2.3.3)
LX	Use λ_{CE} by Klencki et al. (2021) for CE (Equation 32)
LK	Use λ_{CE} by Xu & Li (2010b) for CE (Equation 32)
LC	Use λ_{CE} = 0.1 for CE (Equation 32)



The realization probability varies by large factors for different prescriptions adopted to follow the binary evolution

From Mandel and Broekgaarden 2022, in Living Reviews in Relativity, 25



Alternative approach: forget about the details of close binary evolution and split the DDT in two factors:

1. the average realization probability of the channel k_{Kn}
2. and the normalized distribution of the delay times f_{Kn}

The rate of merging binary neutron stars from a single burst stellar population is proportional to

- the original mass of the stellar population
- the overall efficiency with which this SP produces MNS within a Hubble time
- the fraction of systems with delay time = τ

$$R(\tau) = M_{SP} \times k_{Kn} \times f_{Kn}(\tau)$$

1) derive f_{Kn} from theoretical arguments

2) calibrate k_{Kn} directly on observations

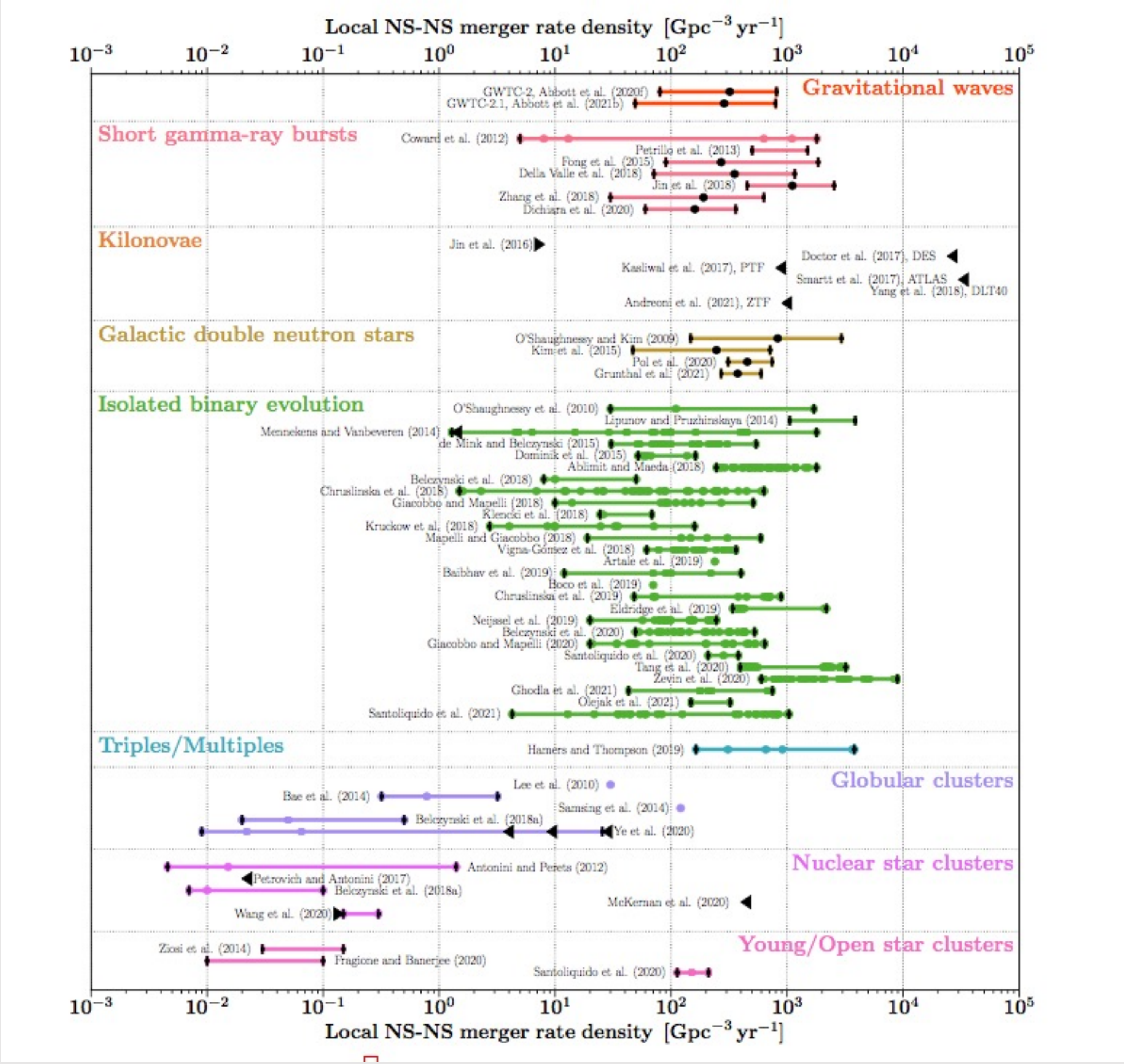
From Mandel and Broekgaarden 2022, in Living Reviews in Relativity, 25

$$R(t_H) = \int_0^{t_H} \psi_{cosmic}(t-\tau) \times DDT(\tau)\, d\tau$$

$$= k_{Kn} \times \int_0^{t_H} \psi_{cosmic}(t-\tau) \times f_{Kn}(\tau) d\tau$$

$$= k_{Kn} \times < \psi_{cosmic} > \times \int_0^{t_H} f_{Kn}(\tau) d\tau$$

= 1

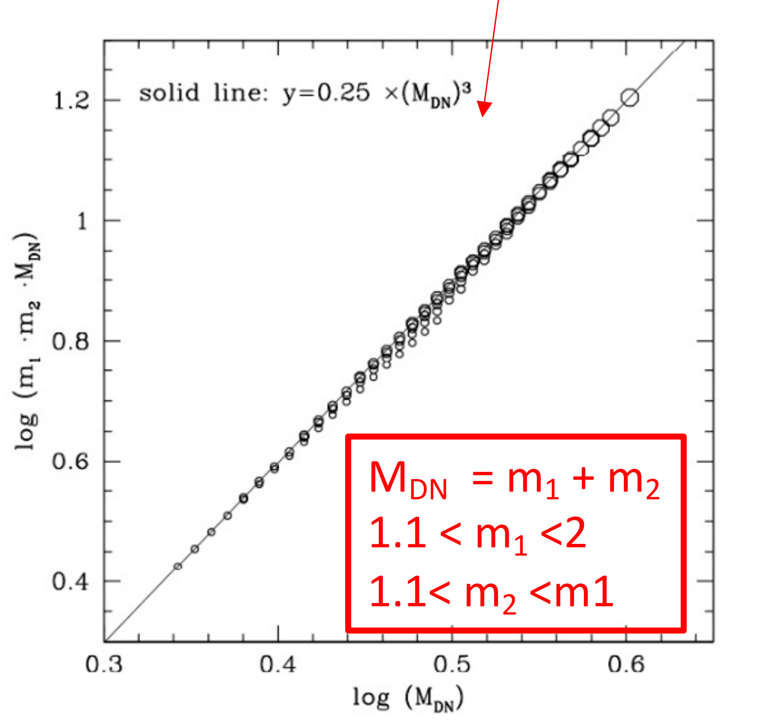


The clock: $\tau = \tau_{nuc} + \tau_{GW}$

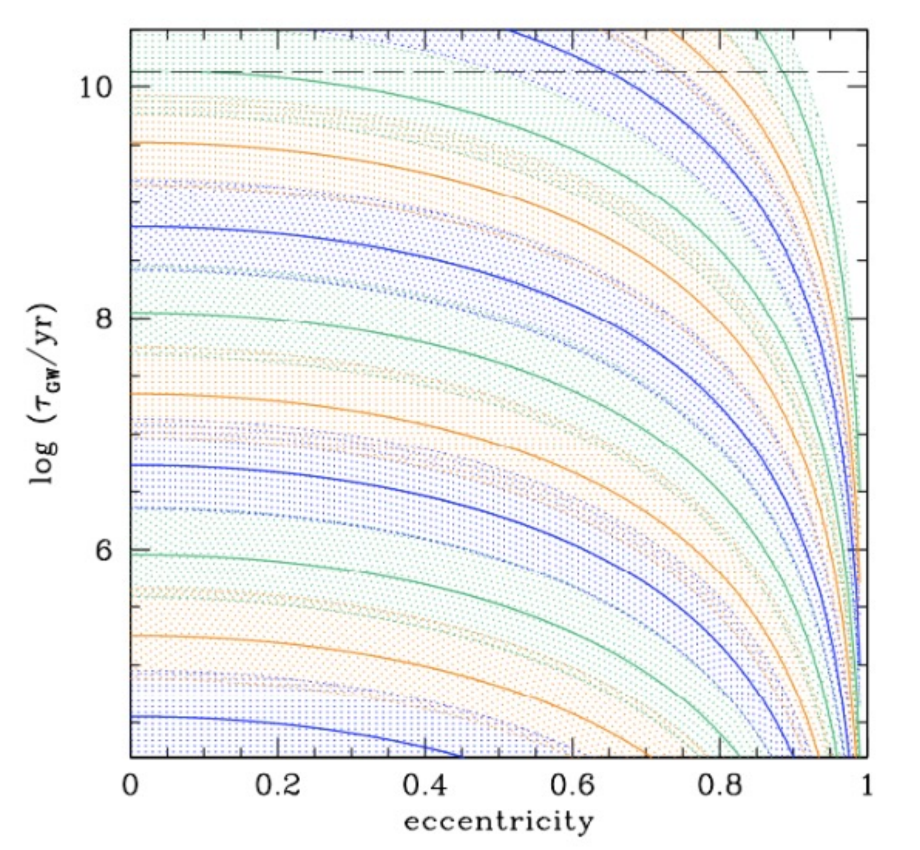
$$\tau_{nuc} = f(m_2)$$

$$\tau_{GW} = 0.15 \frac{A^4}{m_1 m_2 (m_1 + m_2)} (1 - e^2)^{7/2}$$

$$\tau_{GW} = 0.6 \frac{A^4}{M_{DN}^3} \times (1 - e^2)^{7/2}\ Gyr$$



$M_{DN} = m_1 + m_2$
$1.1 < m_1 < 2$
$1.1 < m_2 < m1$



A=(0.2,0.3….1…5….8,12,19) Ro
Solid M_{DN}=3; band 2.2 < M_{DN} <4

τ_{GW} decreases as e and M_{DN} increase and as A decreases

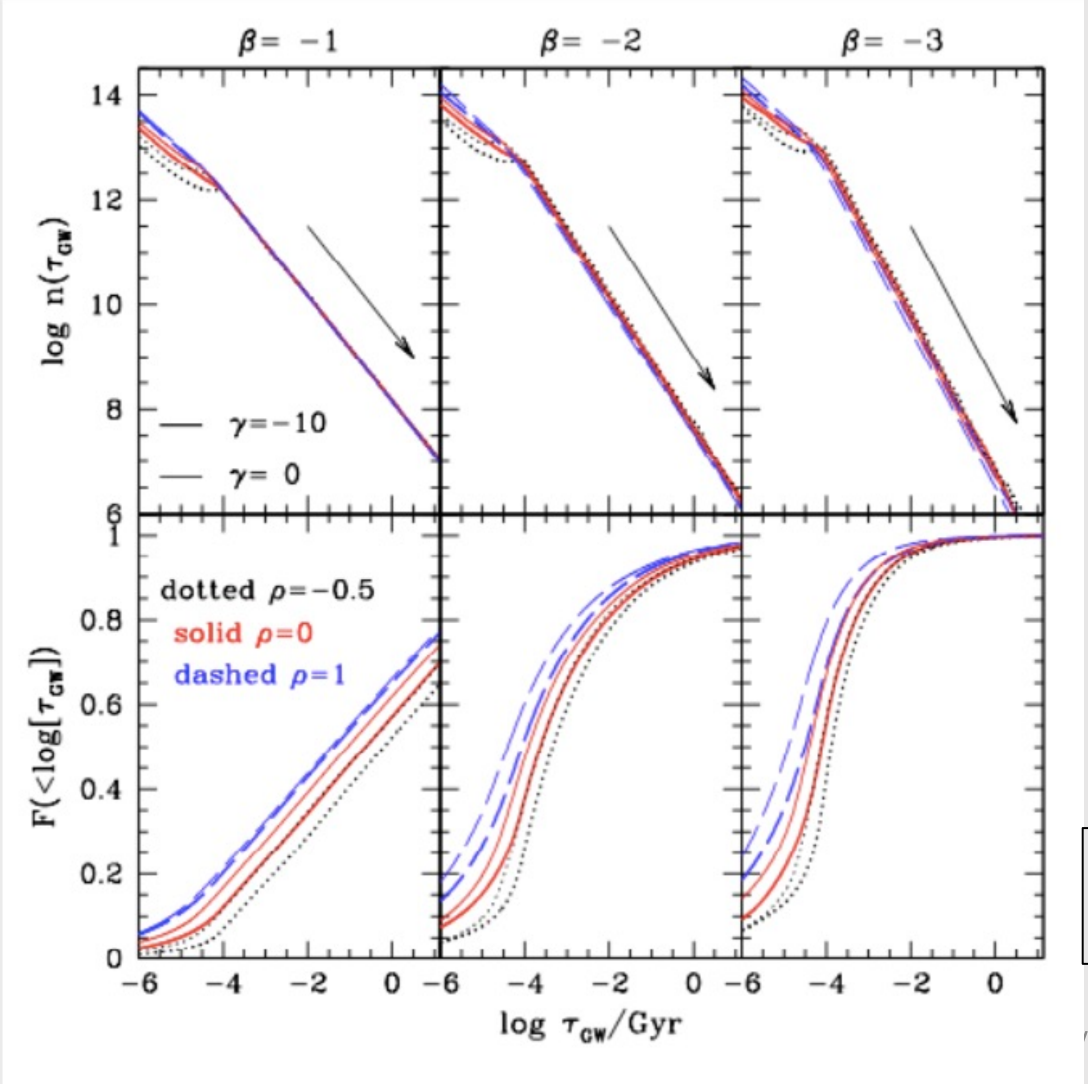
All close systems have short τ_{GW}

only wide systems have long τ_{GW}

Most of the relevant parameter space is limited to A < 10 Ro

Assume continuous distributions of (A , M_{DN} , e)
parametrized by the exponent of a power law.
Run Monte Carlo simulations to determine the distribution of τ_{GW}

$$\begin{cases} f(A) \propto A^{\beta} \\ f(M_{DN}) \propto M_{DN}^{\gamma} \\ f(e) \propto e^{\rho}. \end{cases}$$



Explore: β=-1, -2, -3
γ= -10, 0
ρ = -0.5, 0, 1

0.2 < A/Ro < 30
2.2 < M_{DN}/Mo < 4

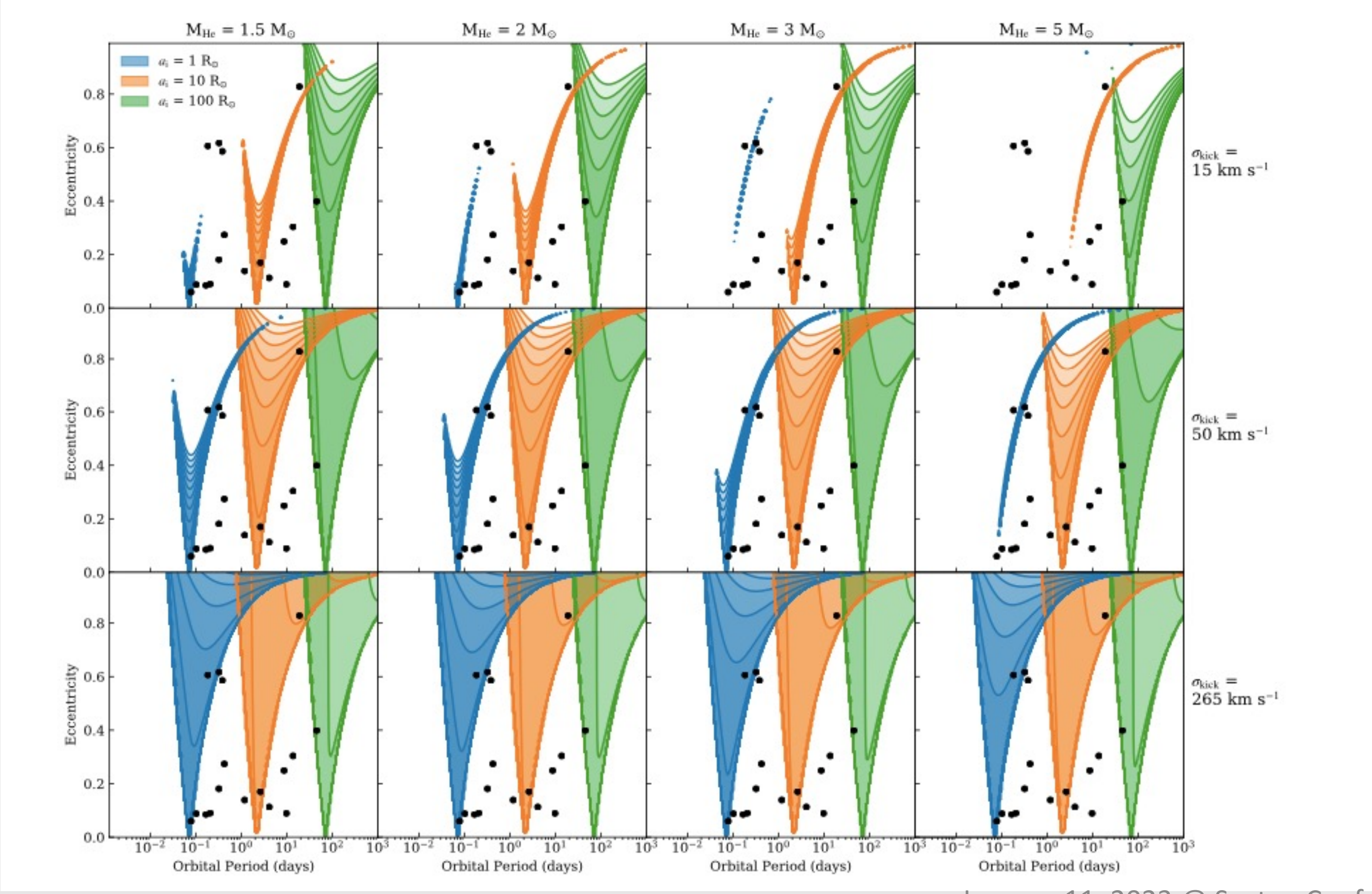
The shape of the distribution of τ_{GW} depends on the slope of the distribution of the separations (β)

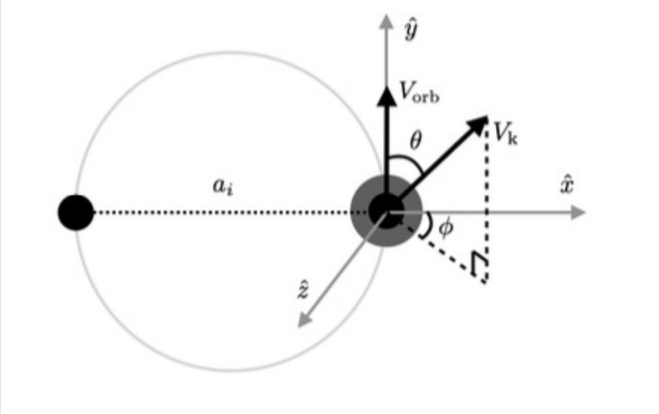
The distributions of mass (γ) and eccentricity (ρ) impact on the cumulative distribution, because they control the number of short lived (coalescence) systems

Arrows: power laws with s=-0.75+0.25β
β = -1,-2,-3 → s = -1,-1.25,-1.5

Effect of the Supernova Kick

Andrews and Zezas (2019) study the response of a NS + Helium star system when the Helium star goes SN
The asymmetric explosion imparts a kick and the separations and eccentricity of the system are changed
They consider a distribution of kicks, of masses and of separations.

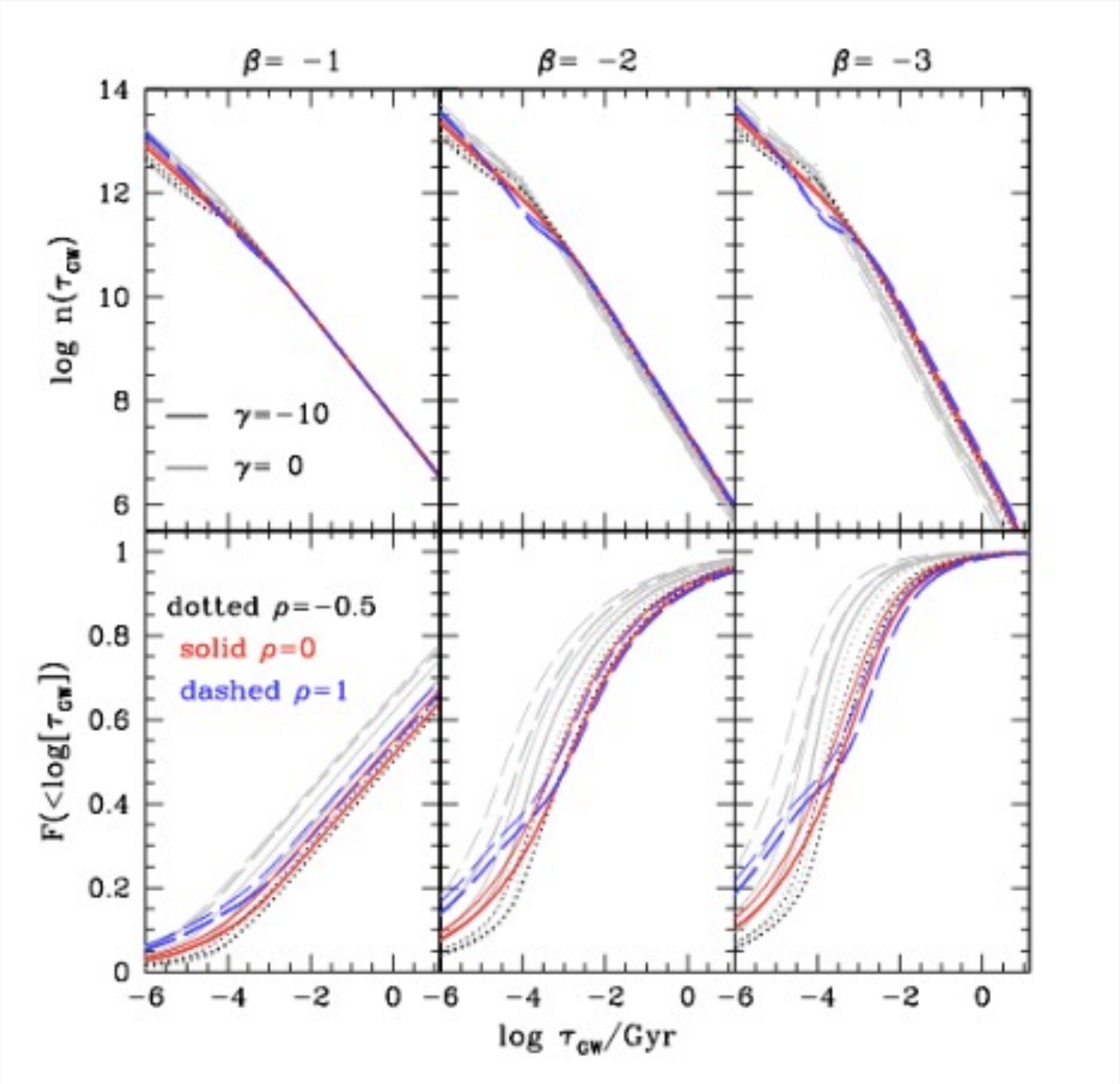




Systems which are not disrupted cluster along the loci

$A_f = A_i (1 + e)^{-1}$ $A_f = A_i (1 - e)^{-1}$

➡ systems may turn out with a mildly reduced separation (at most a factor of 2) or much wider, but then with a high eccentricity

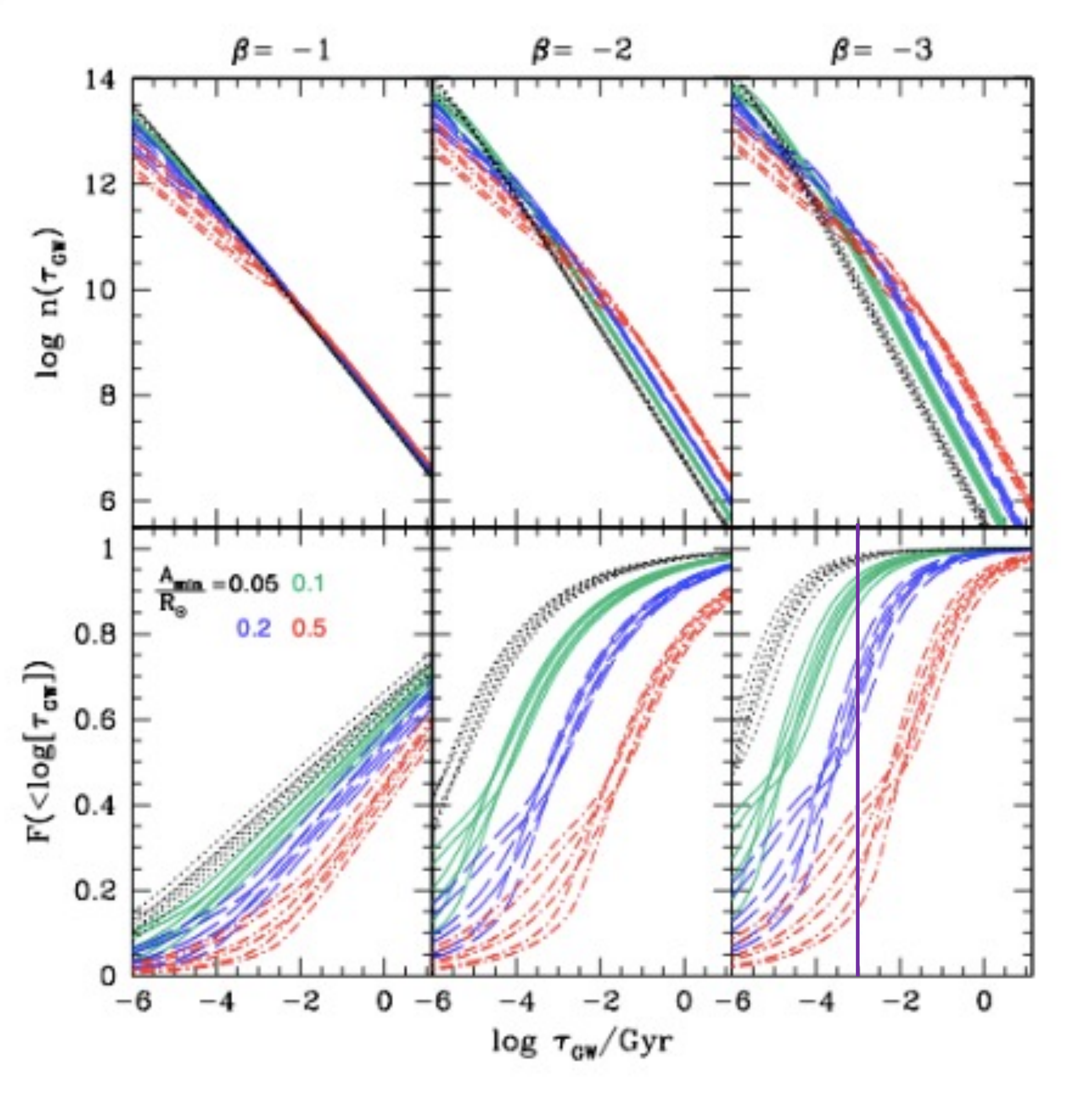


Extract independent couples A_i , e to which associate $A_f = A_i / (1 \pm e)$

Coloured lines: distributions when applying the above prescriptions to account for the effect of the SN kick

Wrt the previous case (grey lines) typical coalescence timescales get longer.

A crucial parameter: A_{min}



The sensitivity is more pronounced for steeper β.

In an extreme combination (β=-3, A_{min}=0.05 Ro) all DNS systems merge within 1 Myr from their formation

The larger the fraction of massive binaries and/or the fraction of eccentric systems, the larger the fraction of systems with short GW delay times.

β and A_{min} : what do BPS models tell us?

Belczynski + (2018)

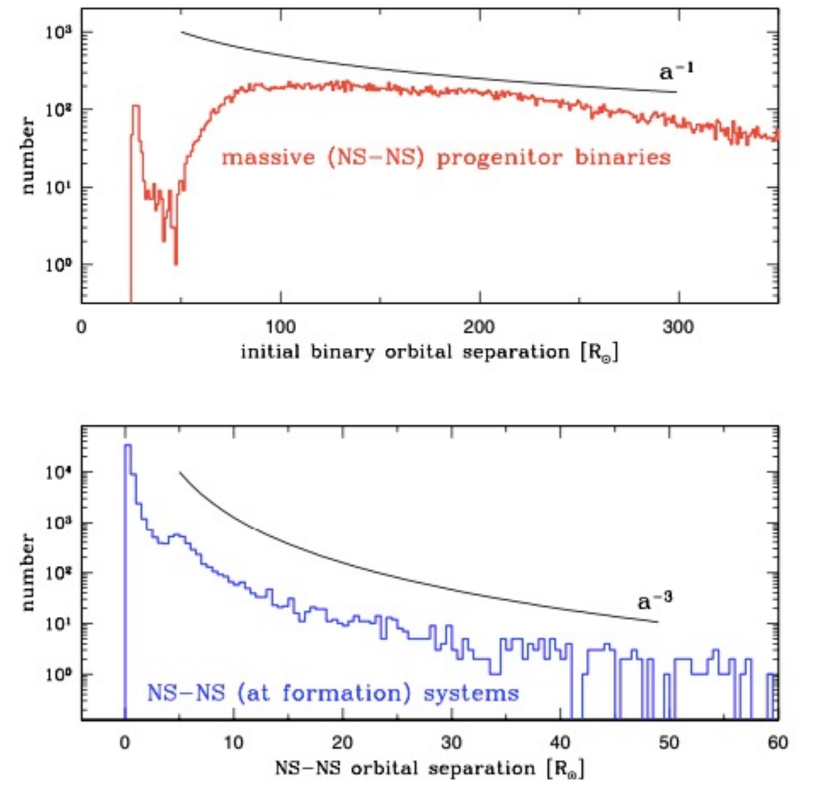
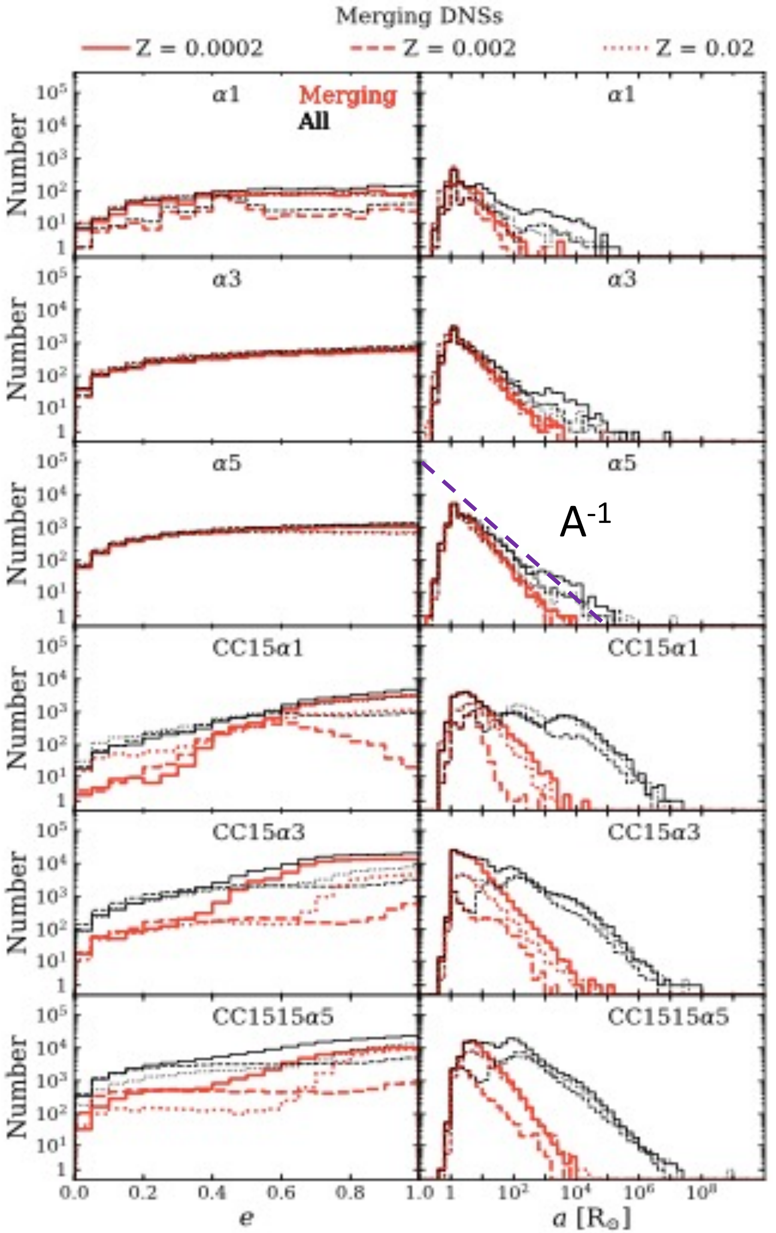


Fig. 2. Initial orbital separation of binaries that are progenitors of NS-NS mergers; we note that the distribution is close to a^{-1} (*top*). After binary evolution (mass transfers, supernovae, CE) close NS-NS systems form with much smaller orbital separations, and their orbital separation distribution may be approximated by a steep power-law: a^{-3} (*bottom*).

Discrepancies in the slopes

Difficult to tell A_{min} because of binning

GM models show a turn over at small separations



Giacobbo & Mapelli (2018)

Figure 5. Eccentricity (left-hand panels) and semi-major axis (right-hand panels) of DNSs after the second SN explosion has led to the formation of the second NS (hereafter initial eccentricity and initial semi-major axis). The bin width is 0.05 for the eccentricity and log (a/$R_\odot$) = 0.2 for the semi-major axis. All simulations are shown. Black thin lines: all simulated DNSs. Red thick lines: DNSs merging within a Hubble time. Solid lines: $Z = 0.0002$; dashed lines: $Z = 0.002$; dotted lines $Z = 0.02$.

Which minimum separation? Look at radii of Helium stars

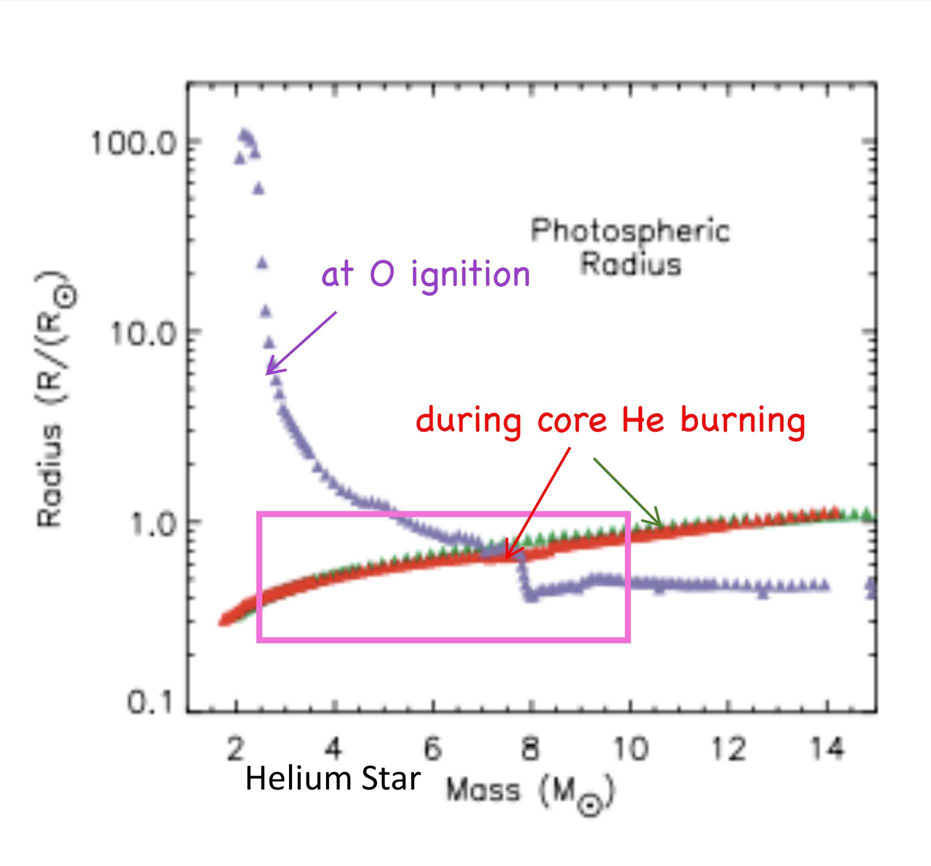
From Woosley, 2019, ApJ 878,49 : Evolution of non-rotating, solar metallicity He stars in CBs

If the Helium star fills the Roche lobe before exploding, mass is lost, evolution may be aborted.

Table 8
Critical Masses in Close Binary Systems

ZAMS Star [$M_\odot$]	Initial He Star [$M_\odot$]	Pre-SN Mass [$M_\odot$]	Characteristics
<13	<2.4	...	SAGB star, WD
13–13.5	2.4–2.5	2.0–2.1	SAGB star, rad-expansion ECSN, fast SN Ib, little ^{56}Ni
13.5–16	2.5–3.2	2.1–2.6	Si flash, rad-expansion, peculiar SN Ib
16–30	3.2–10	2.6–7	Ordinary SN Ib, Ic
30–120	10–60	7–30	Mostly BH, massive SN Ic
120–140	60–70	30–35	Weak PPISN, BH
140–250	70–125	35–62	Strong PPISN, BH
250–500	125–250	62–133	PISN, no remnant
>500	>250	>133	Black holes

Note. These are for nonrotating solar-metallicity stars using the standard mass-loss rate. The "initial He star masses" correspond to section headers in Sections 3 and 6. Equivalent main-sequence masses are particularly uncertain at very high mass, and crude estimates are given. The transition mass between NeO white dwarfs and electron-capture supernovae (ECSN), shown here as initial helium core mass = 2.4 $M_\odot$, is also very uncertain.

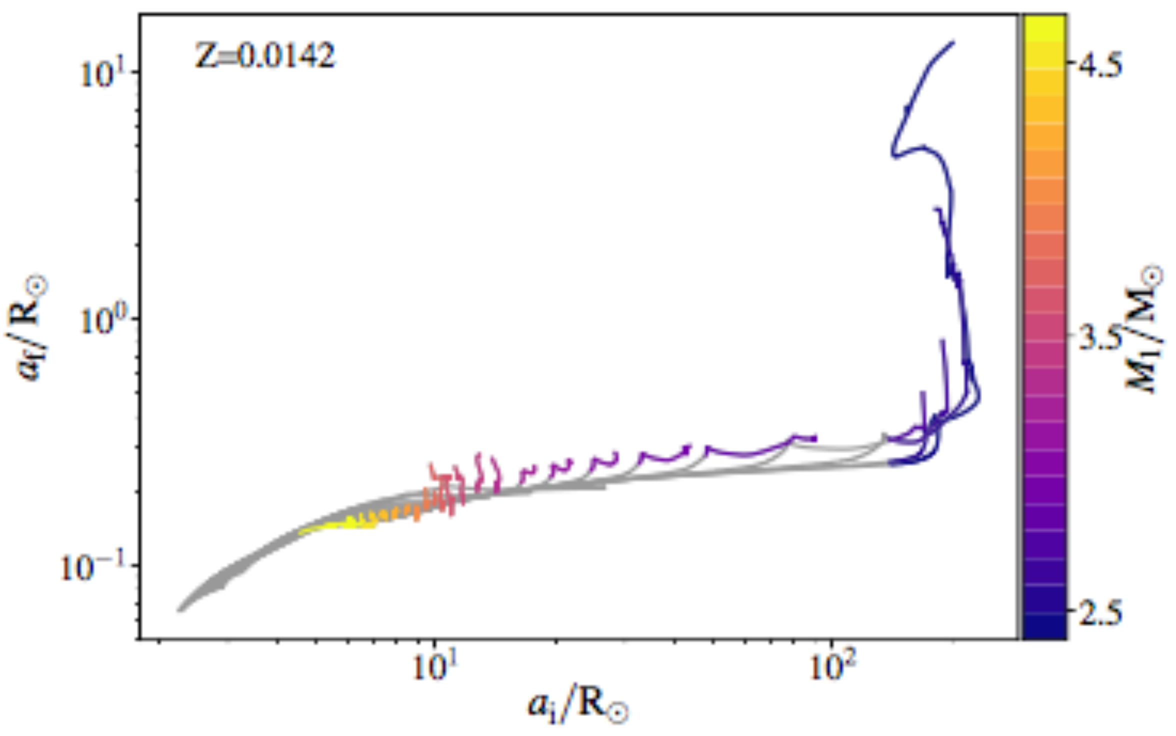


It makes sense to consider A_{min} ~ few tenths Ro, late CE could further reduce the separation

Which minimum separation?

From Laplace et al., 2020, A&A 637, A6 : Evolution of Massive stars in close binary systems following the mass exchange phases

Post-CE separation vs pre-CE separation of massive He stars with a neutron star companion

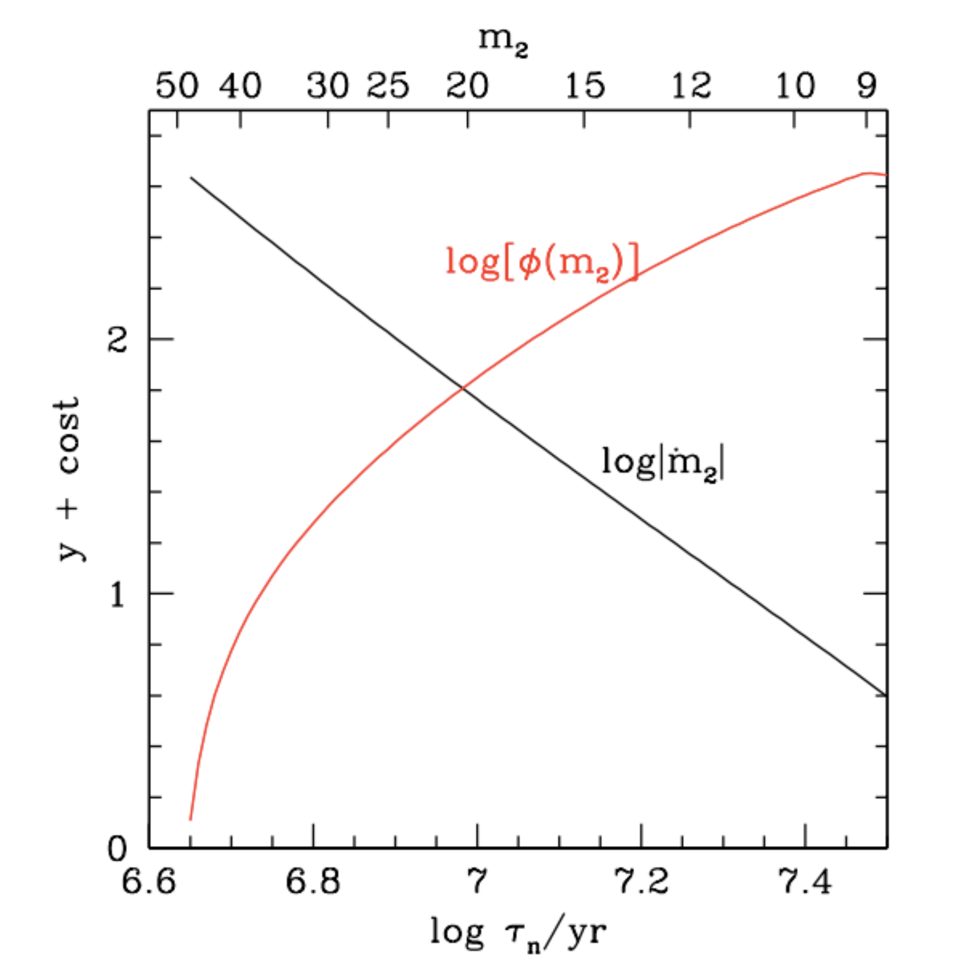


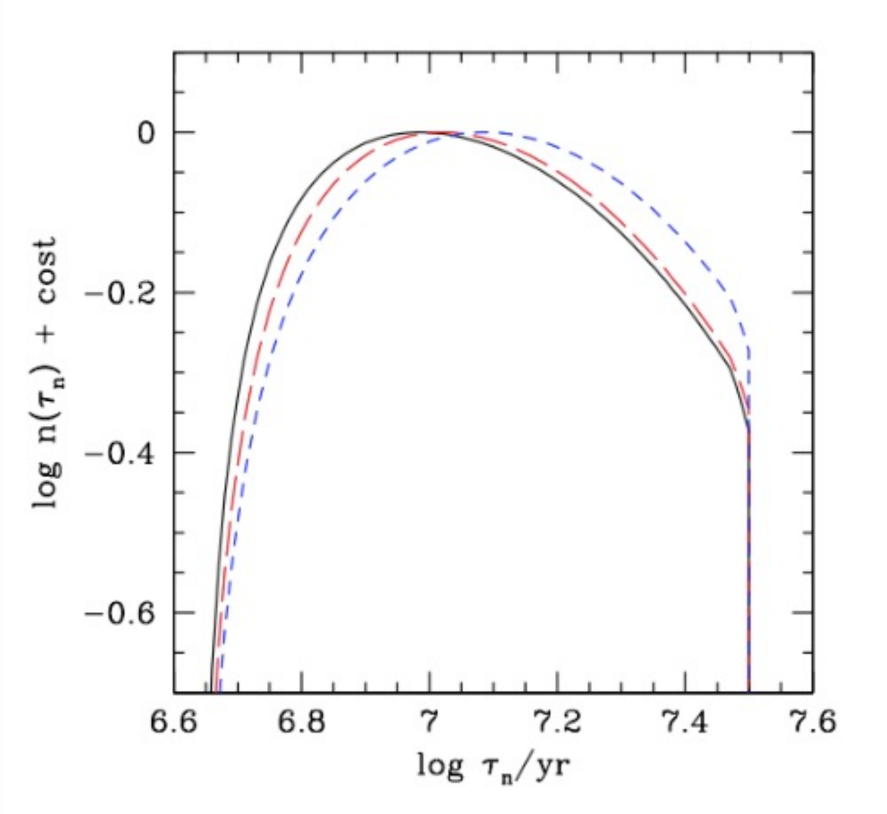
The final separation could be as low as 0.07 Ro

Back to the DDT: $\tau = \tau_{nuc} + \tau_{GW}$

$n(\tau_{nuc}) = |\dot{m}_2| \times \phi(m_2)$

$$\phi(m_2) \propto \int_{\max\{m_2,9\}}^{50} n(m_1) f(q) \frac{dm_1}{m_1}$$





Black: $n(m_1) \propto m_1^{-2.35}$ and $f(q) \propto q$

Red: $n(m_1) \propto m_1^{-2.3}$ $f(q) \propto q^{-0.1}$ most BPS

Blue: $n(m_1) \propto m_1^{-2.6}$ $f(q) \propto q^{0}$

Progenitors have masses between 50 and 9 Mo
Evolutionary lifetime ranges between 4.5 and 32 Myr

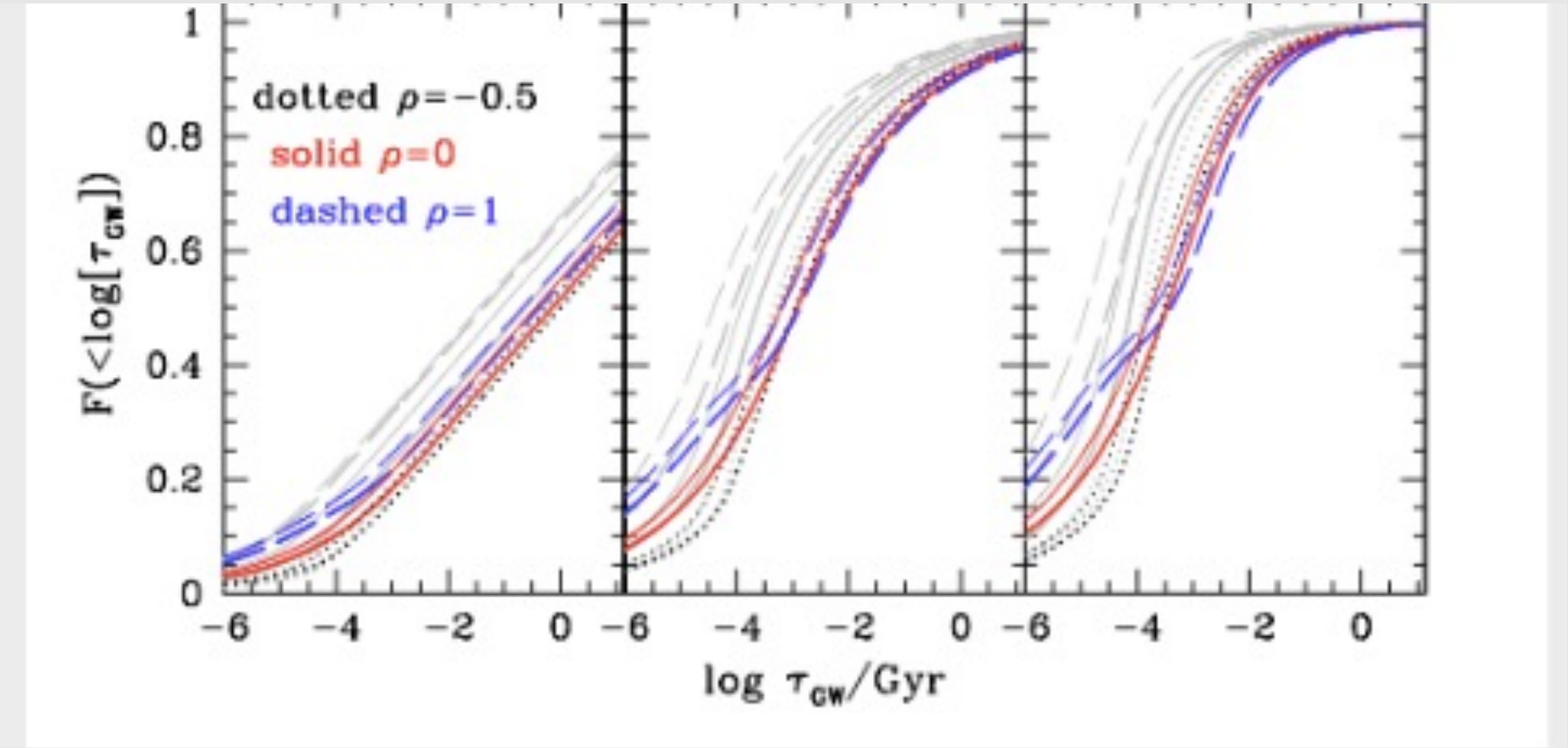
Back to the DDT

Fraction of systems which merge within τ is obtained by summing over all possible τ_{nuc} the corresponding contribution: $n(\tau_{nuc}) \times F(<\tau_{GW}=\tau-\tau_{nuc}) \times d\tau_{nuc}$

F is the fraction of systems with coalescence time shorter than the appropriate τ_{GW}

$$\mathcal{F}(<\tau) = \int_{\tau_{nuc,i}}^{\min(\tau,\tau_{nuc,x})} n(\tau_{nuc}) \times F(<\tau_{GW})\, d\tau_{nuc}$$

$$f_{Kn}(\tau) = \frac{d\mathcal{F}}{d\tau}$$



The DDT of Binary Neutron Stars Mergers

- No event earlier than 4.5 Myr (= min evolutionary delay)
- Early peak populated with systems with with 4.5< τ_{nuc}/Myr <32 and τ_{GW} varying such that $\tau=\tau_{nuc}+\tau_{GW}$
- Later than 32 Myr (= max evolutionary delay) only systems with sufficiently long τ_{GW} populate the DDT
- The level of the peak depends on (β,A_{min})
- At long delays (e.g. τ > 0.1 Gyr) the DDT scales as a power law with exponent $s = -0.75+0.25\ \beta$
- The fraction of 'prompt' mergings, (e.g. τ <=32 Myr) is sensitive to β and A_{min}

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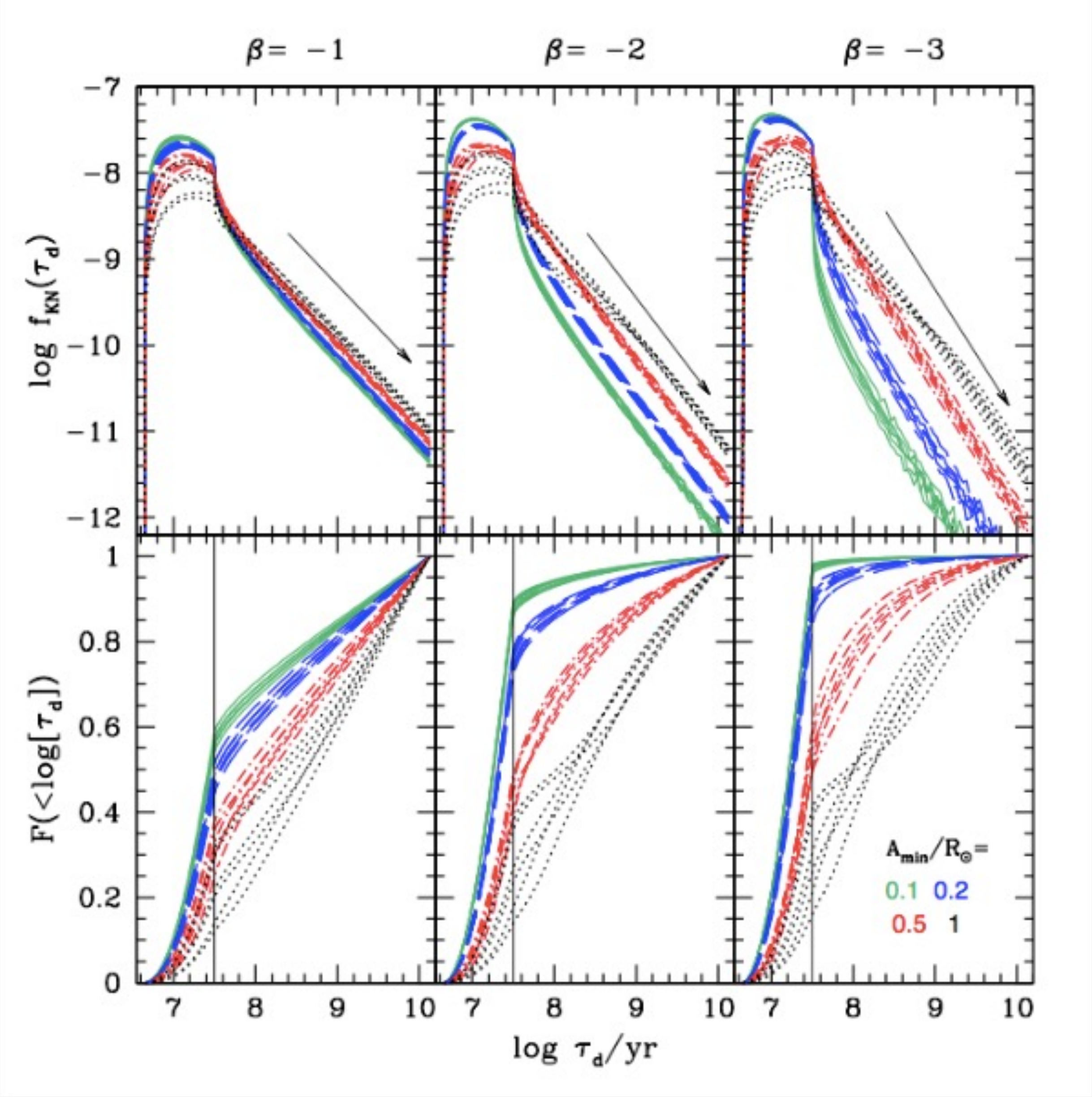
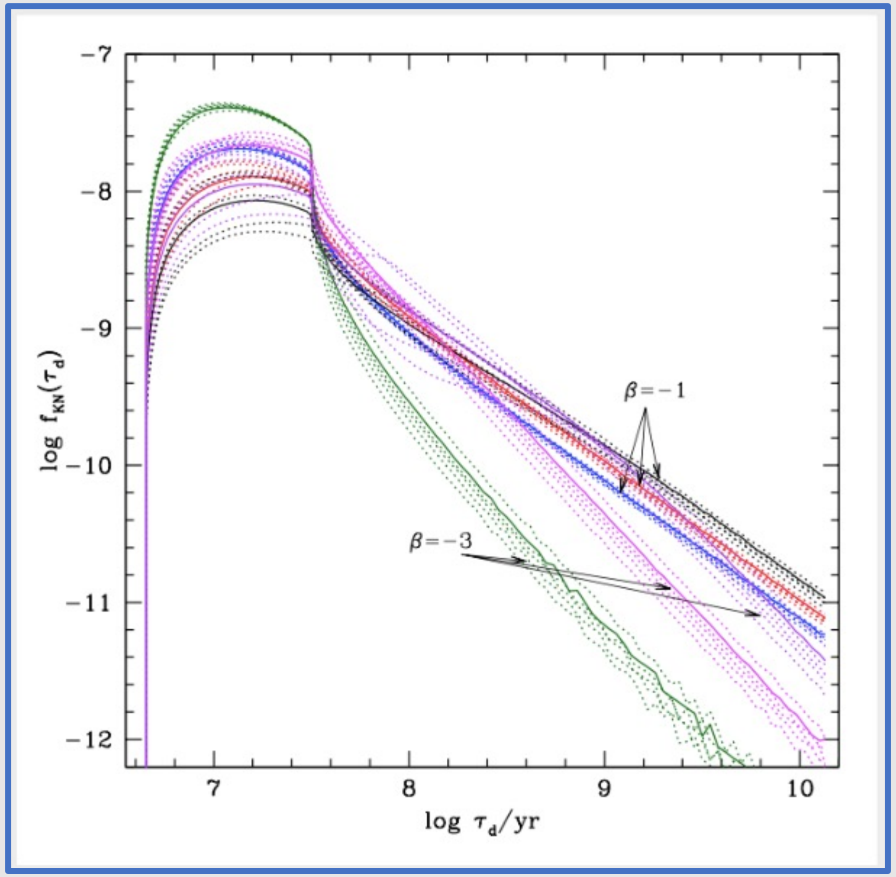
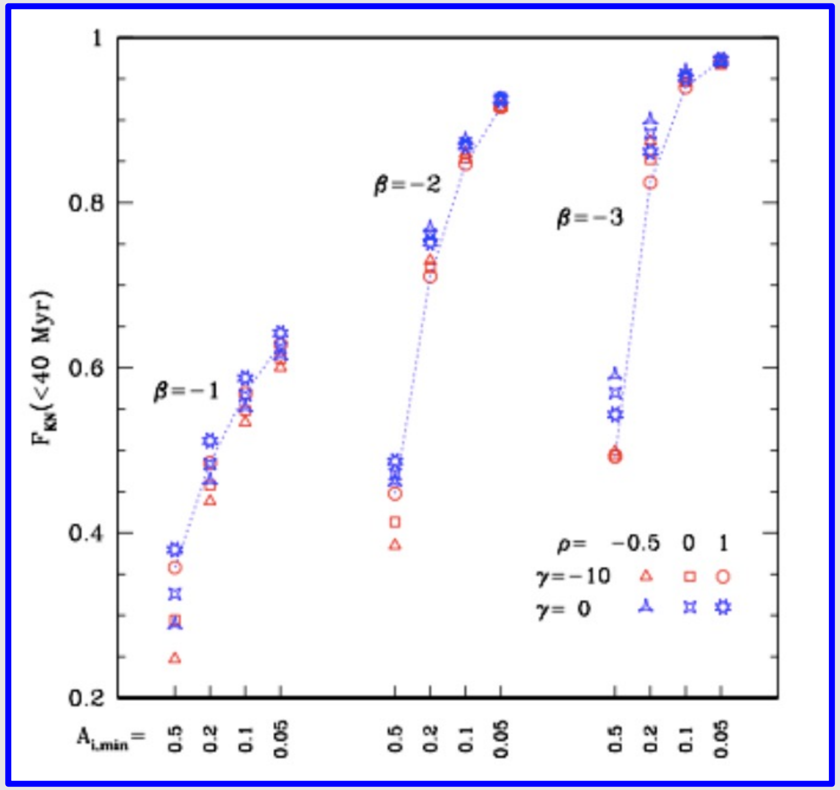


How much pollution from Kilonovae during the CC SN era?

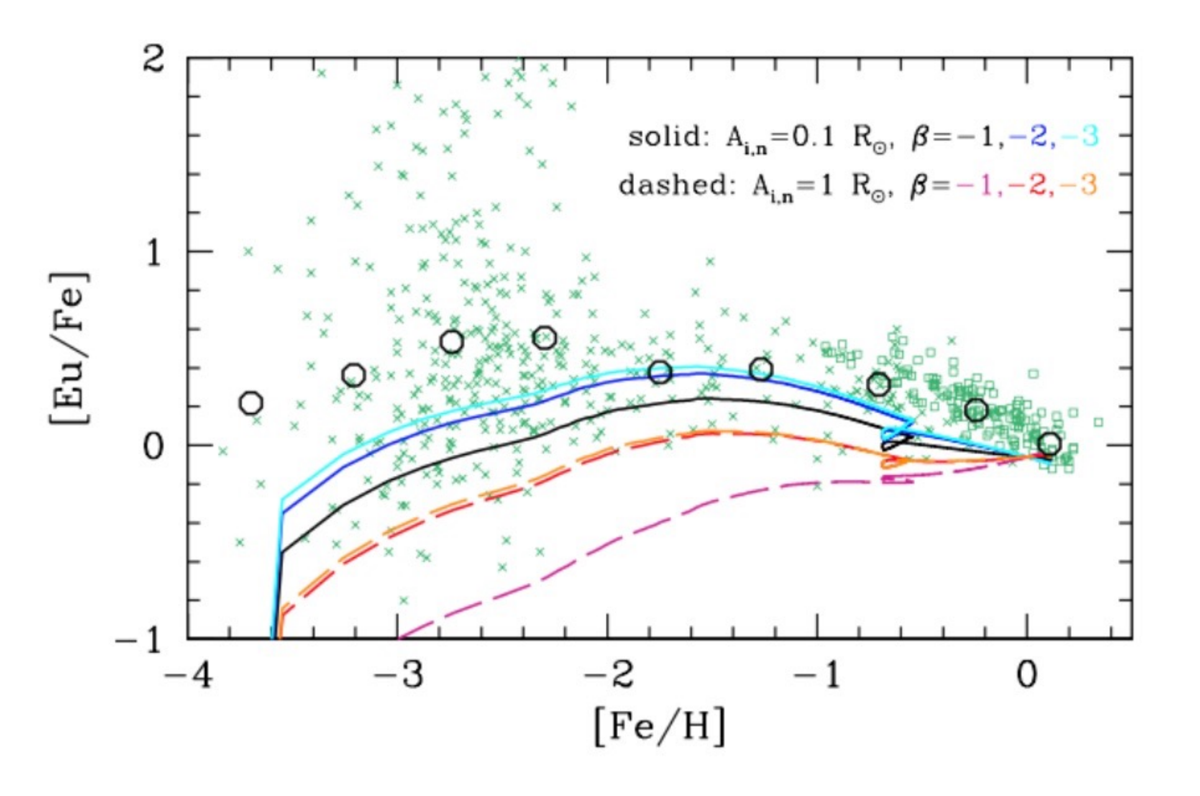




A steep distribution of the DNS separations coupled with a small A_{min} leads to a very prompt release of Kilonova products to the ISM.

In this case we expect an overabundance of, e.g., Eu/Fe already at very low Fe, i.e. in stars formed before SNIa give a sizable contribution to Fe.

Chemical properties of MW stars



Two infall model for the chemical evolution of the Milky Way (Chiappini et al. 1997, Matteucci 2012) with standard stellar yields:

- Europium from Kilonovae only
- Fe from CC and Type Ia SNe

The data favour models with small A_{min} and steep β but at low metallicities models underproduce Eu: another early source of Eu is needed

Conclusions

Based on the properties of the clock of the event, the DDT of merging DNS is characterized by an early peak from ≈ 4.5 to ≈30 Myr followed by a power law decline with exponent s=-0.75+0.25 β, where β describes the distribution of the separations of the DNS at birth

The strength of the peak depends on β and on the minimum value of the separation of the DNS systems. The timescale for kilonova pollution of the ISM depends on these parameters. e.g. for (β=-3, A_{min}=0.05 Ro) all systems merge within 30 Myr from birth

The [Eu/Fe] abundance ratio of low metallicity MW stars is too high to be explained just with the kilonovae yield and requires some Eu production from CC SNe

While current data do not allow us to constrain β and A_{min}, more GW and sGRB events will be detected to enhance the statistics and trace the rate of merging DNS as a function of redshift. At the same time more, and more accurate, data on the abundances of low metallicity stars will build up. Future data will then allow us to reach robust conclusions on the DDT.