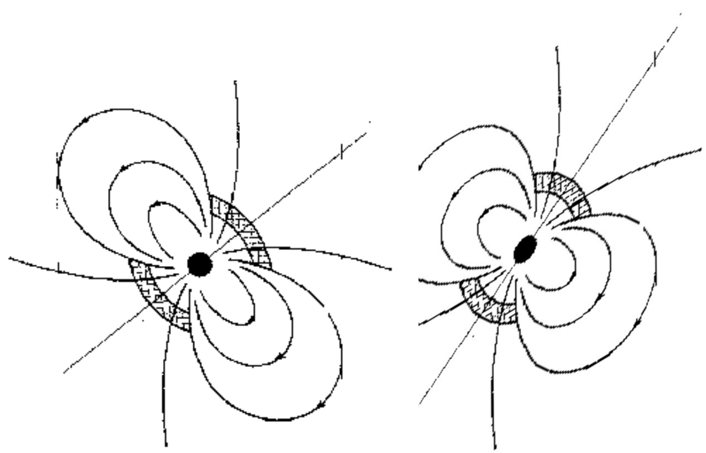
How to merge neutron stars?



Martyna Chruślińska
(read: *hroo-shlin-ska*)
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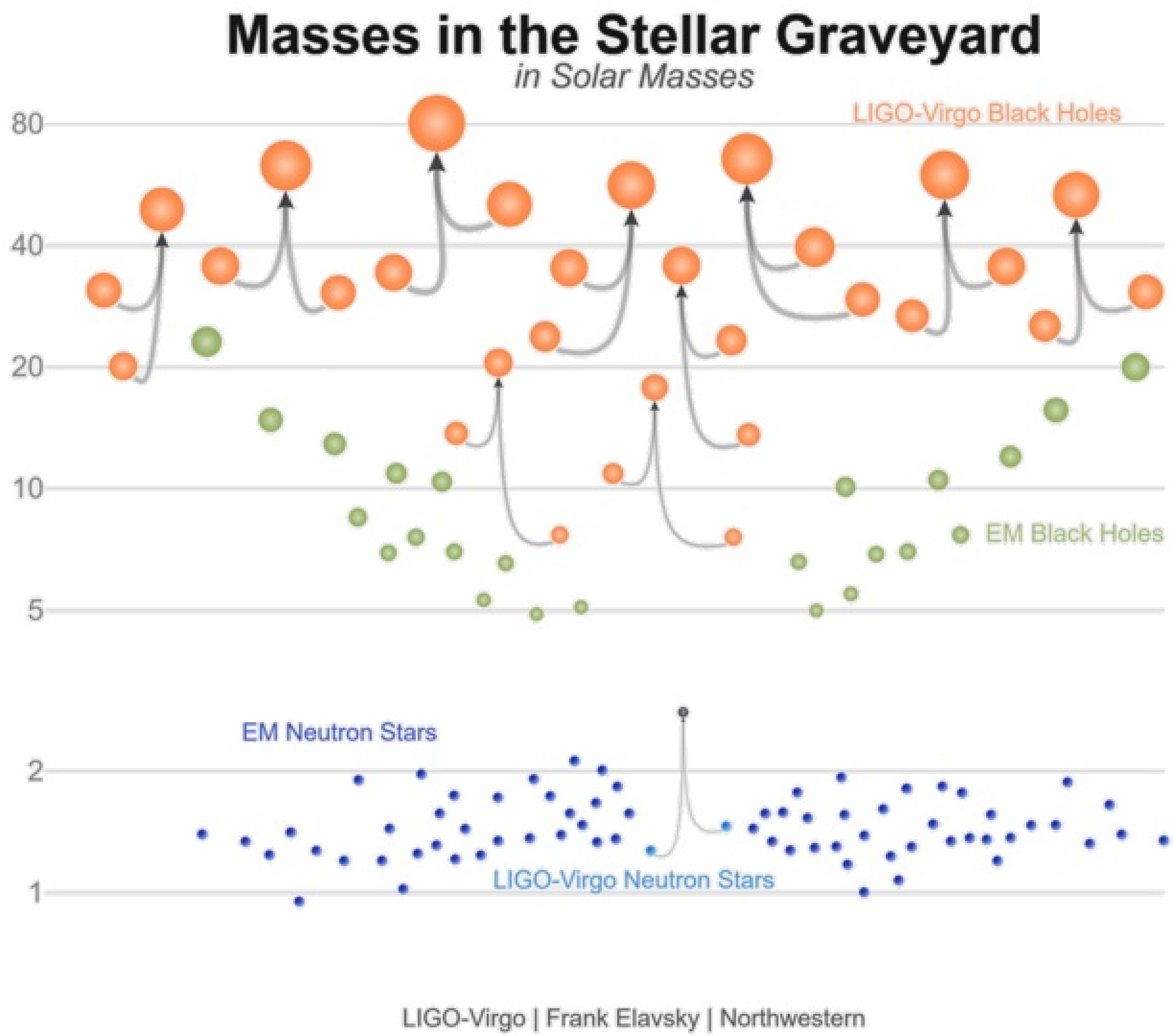
Radboud University,
Nijmegen NL

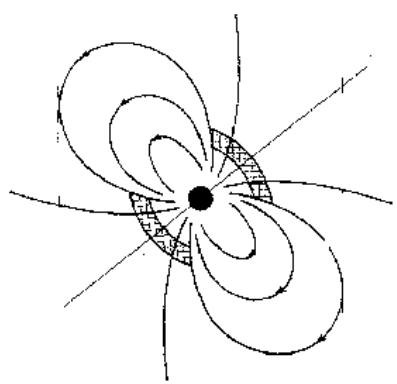
NS vs BH

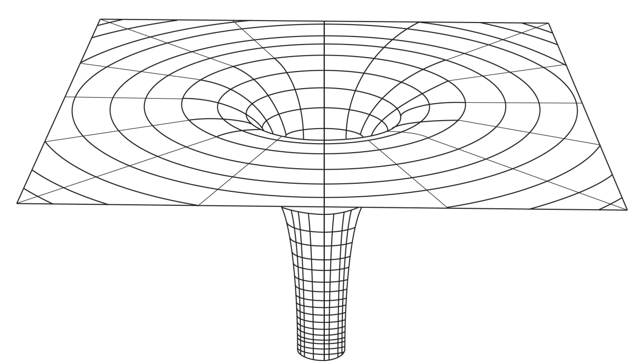

Masses in the Stellar Graveyard
in Solar Masses
LIGO-Virgo Black Holes
EM Black Holes
EM Neutron Stars
LIGO-Virgo Neutron Stars
80
40
20
10
5
2
1
LIGO-Virgo | Frank Elavsky | Northwestern

NS vs BH

→ from less massive progenitors ~8-20 Msun
→ more common than BH progenitors
→ 10 – 30 Myr time to NS formation (a few Myr for BH)

→ during the NS formation:
– eject the remaining envelope,
– leave ~1 - <3 Msun compact remnant,
– **gain velocity** (*natal kick*)





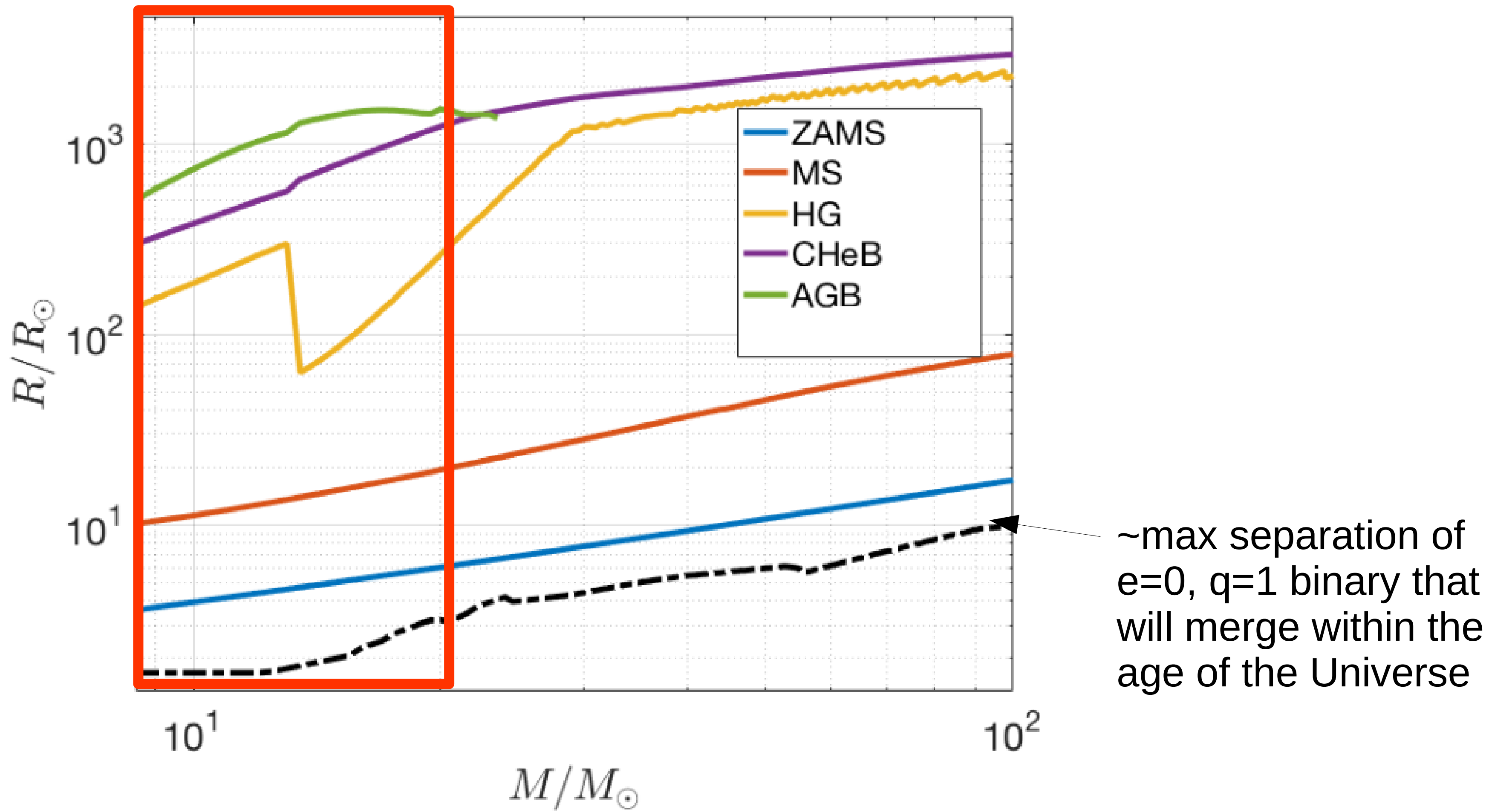
NS-NS vs BH-BH

$$T_{GW} = 0.15 \left(\frac{a}{\mathrm{R}_{\odot}} \right)^4 \left(\frac{\mathrm{M}_{\odot}^3}{M_1 M_2 (M_1 + M_2)} \right) \mathrm{Gyr}$$

→ to merge within the age of the Universe, NS-NS binary needs separation ~a few $\mathrm{R}_{\odot}$ (~10*smaller than BH-BH)

NS-NS vs BH-BH

→ the “separation problem” remains!



maximum radius at different phases of evolution, example from Mandel & Farmer (2018)

NS-NS vs BH-BH

→ the “separation problem” remains!

… but we know that close NS-NS *exist* (10 examples in our Galaxy) and *merge* (GW170817 + a few candidates in O3)

How to produce a merging NS-NS binary?

-Isolated binary evolution
- "common envelope" channel
- chemically homogeneous evolution

-Dynamical evolution
- globular clusters
- nuclear clusters
- AGN disks

-Triple systems

How to produce a merging NS-NS binary?

-Isolated binary evolution
- "common envelope" channel
(e.g. Tutukov&Yungelson'93, Tauris+17, Chruslinska+18, Mapelli &Giacobbo'18, Vigna-Gomez+19 ...)
- chemically homogeneous evolution

-Dynamical evolution
- globular clusters
- nuclear clusters
- AGN disks

-Triple systems

How to produce a merging NS-NS binary?

-Isolated binary evolution

- "common envelope" channel
- ~~chemically homogeneous evolution~~

(not discussed for NS-NS; more likely for more massive BH progenitors – but still rather exotic e.g. de Mink+09, Marchant+16,17)

-Dynamical evolution

- globular clusters
- nuclear clusters
- AGN disks

-Triple systems

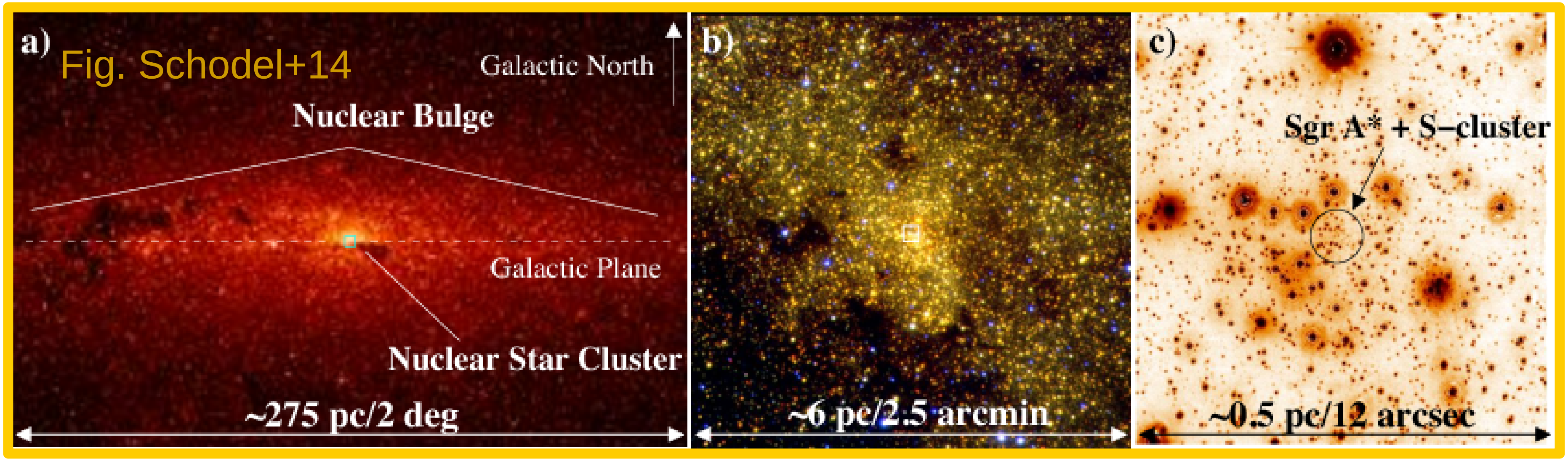
How to produce a merging NS-NS binary?

-Isolated binary evolution
- “common envelope” channel
- ~~chemically homogeneous evolution~~

-Dynamical evolution
- ~~globular clusters~~
  (dynamical interactions in globular clusters do not play a significant role for NS-NS e.g. Belczynski+18, Zevin+19, Ye+19)
- nuclear clusters
- AGN disks

-Triple systems

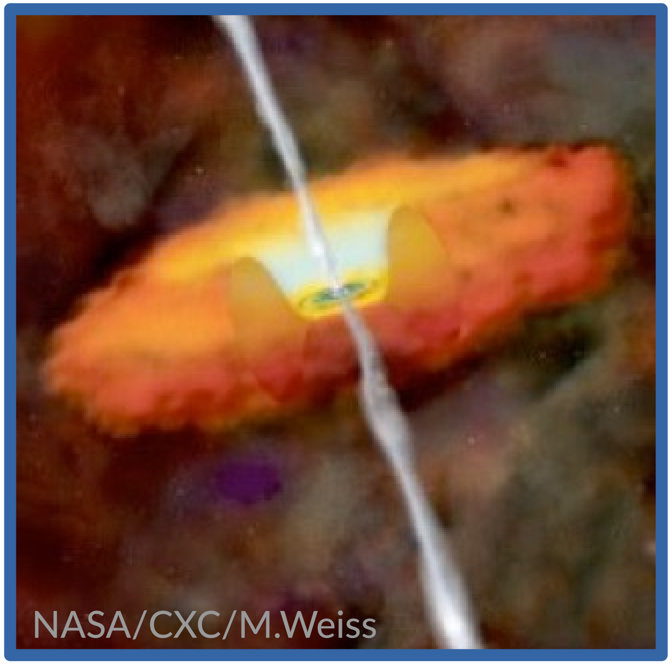
How to produce a merging NS-NS binary?



- ~~nuclear clusters~~
  (depends on how the nuclear cluster is formed, but current estimates show rather negligible contribution to NS-NS mergers from this channel, e.g. Belczynski+18, Panamerev+19, Fragione+19)
- AGN disks

-Triple systems

How to produce a merging NS-NS binary?



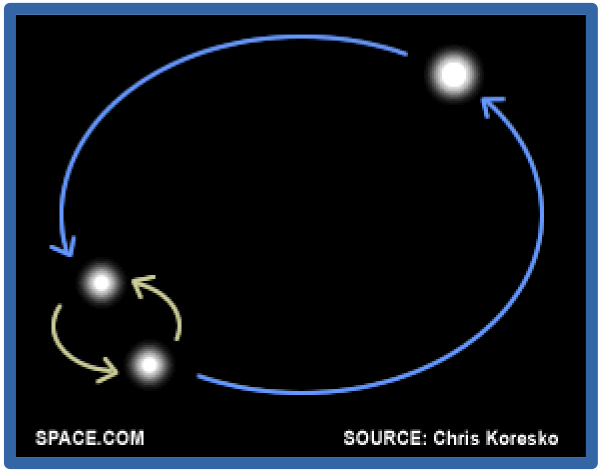
-Isolated binary evolution
- "common envelope" channel
- ~~chemically homogeneous evolution~~

-Dynamical evolution
- ~~globular clusters~~
- ~~nuclear clusters~~
- AGN disks (?)

(not discussed in the literature in the context of NS-NS, if there is a significant population of NS in the AGN disk potentially an interesting channel; but less efficient than for BH-BH e.g. McKernan+18)

-Triple systems

How to produce a merging NS-NS binary?

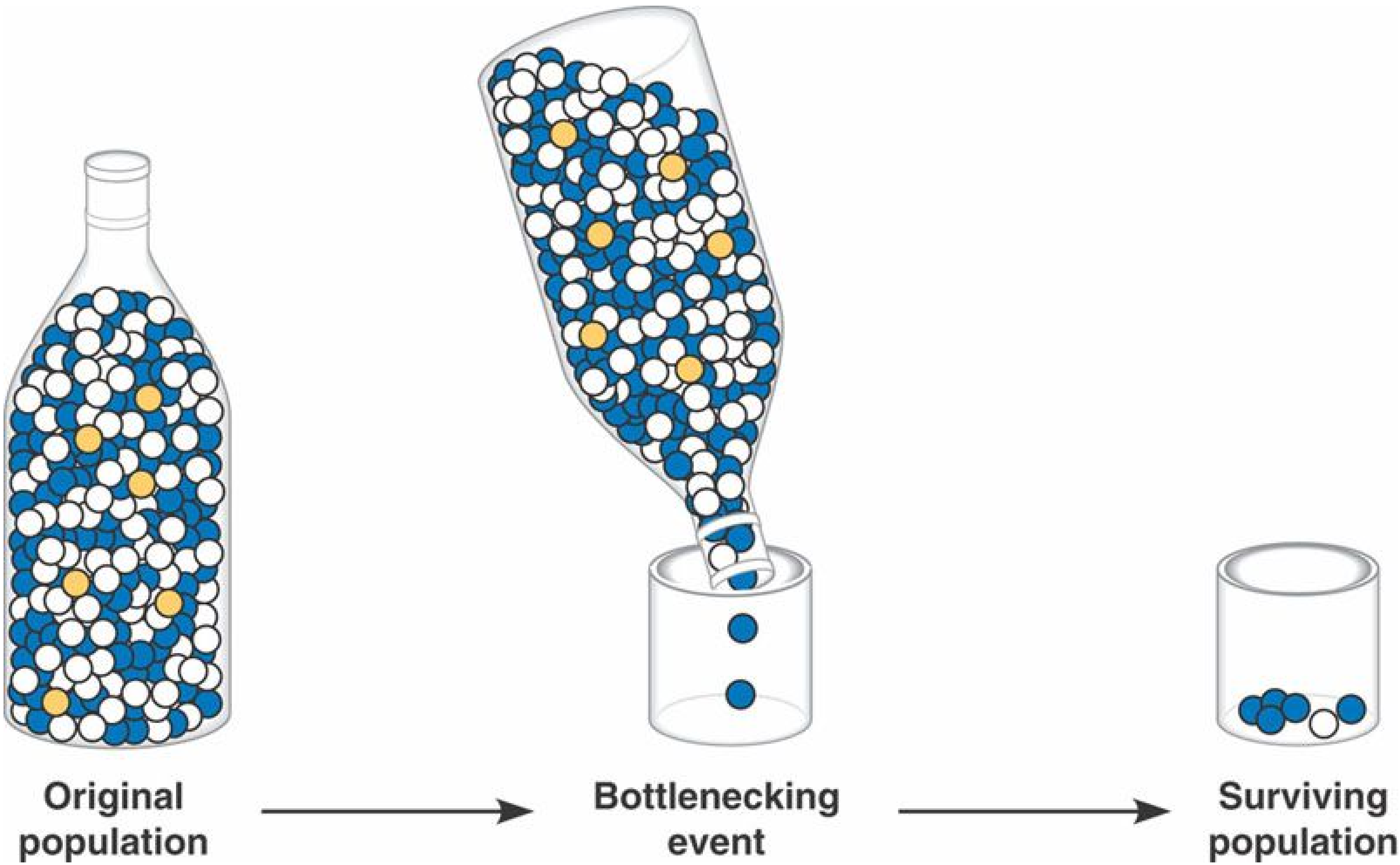


-Isolated binary evolution
- "common envelope" channel
- ~~chemically homogeneous evolution~~

-Dynamical evolution
- ~~globular clusters~~
- ~~nuclear clusters~~
- AGN disks (?)

-Triple systems
(Hamers & Thompson (2019) – with some important simplifications in the treatment of stellar evolution; dynamical effects appear not crucial, ~CE channel)

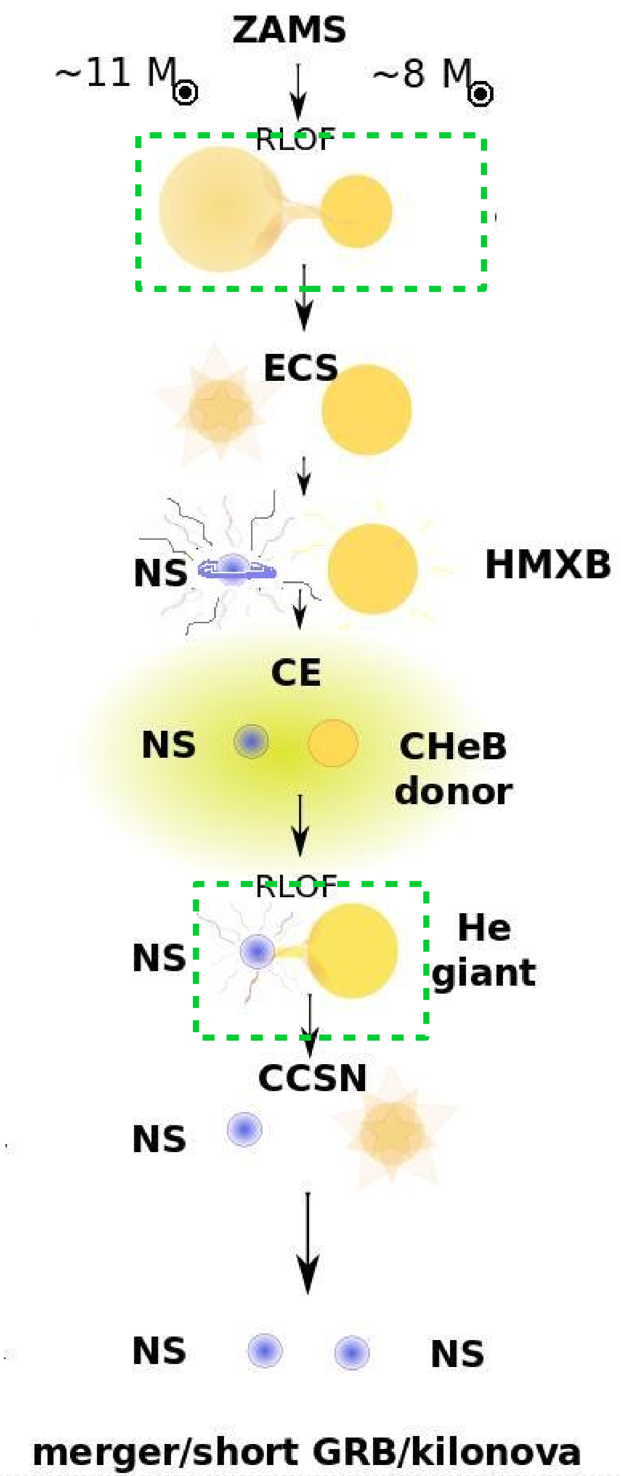
Isolated evolution: crucial phases & bottlenecks



http://bio1151.nicerweb.com/Locked/media/ch23/bottleneck.html

mass transfer:

- mass loss
- angular momentum loss

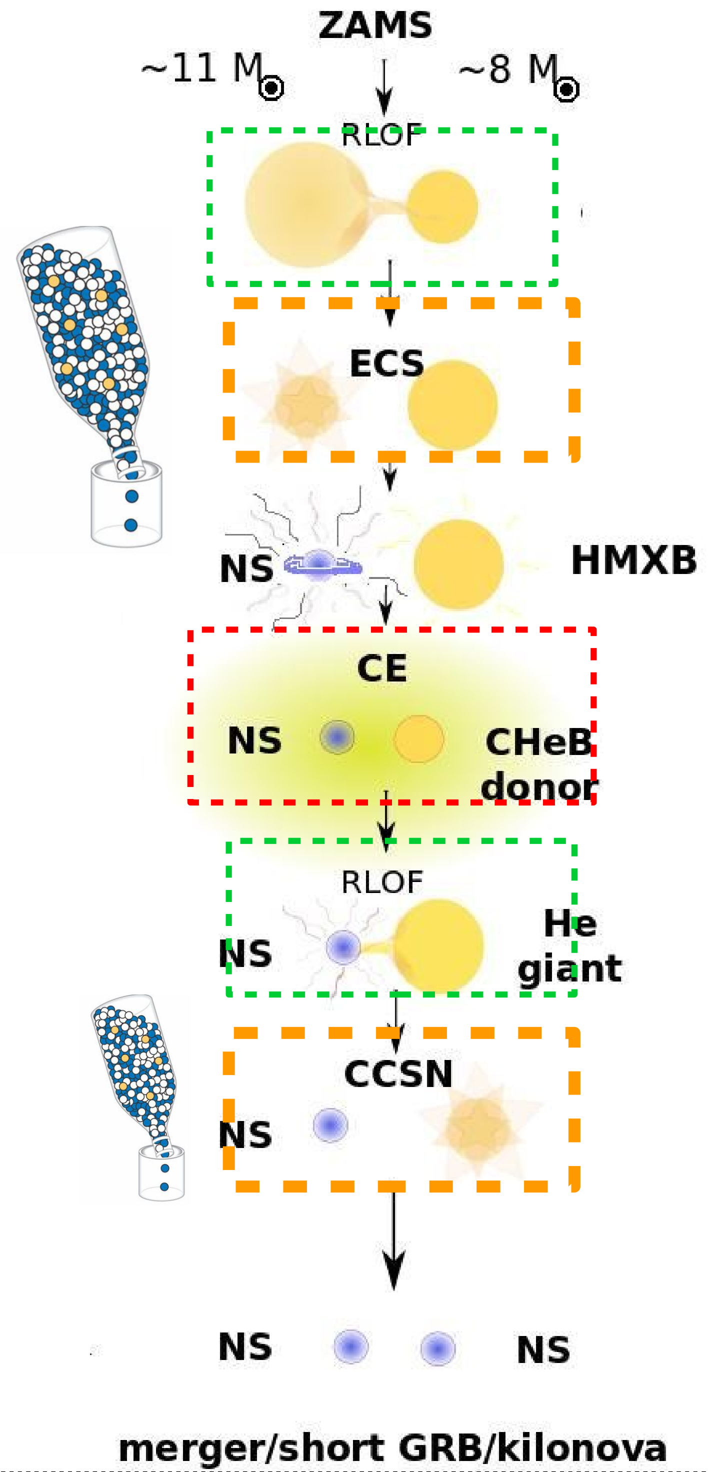


mass transfer:

- mass loss
- angular momentum loss

NS formation:

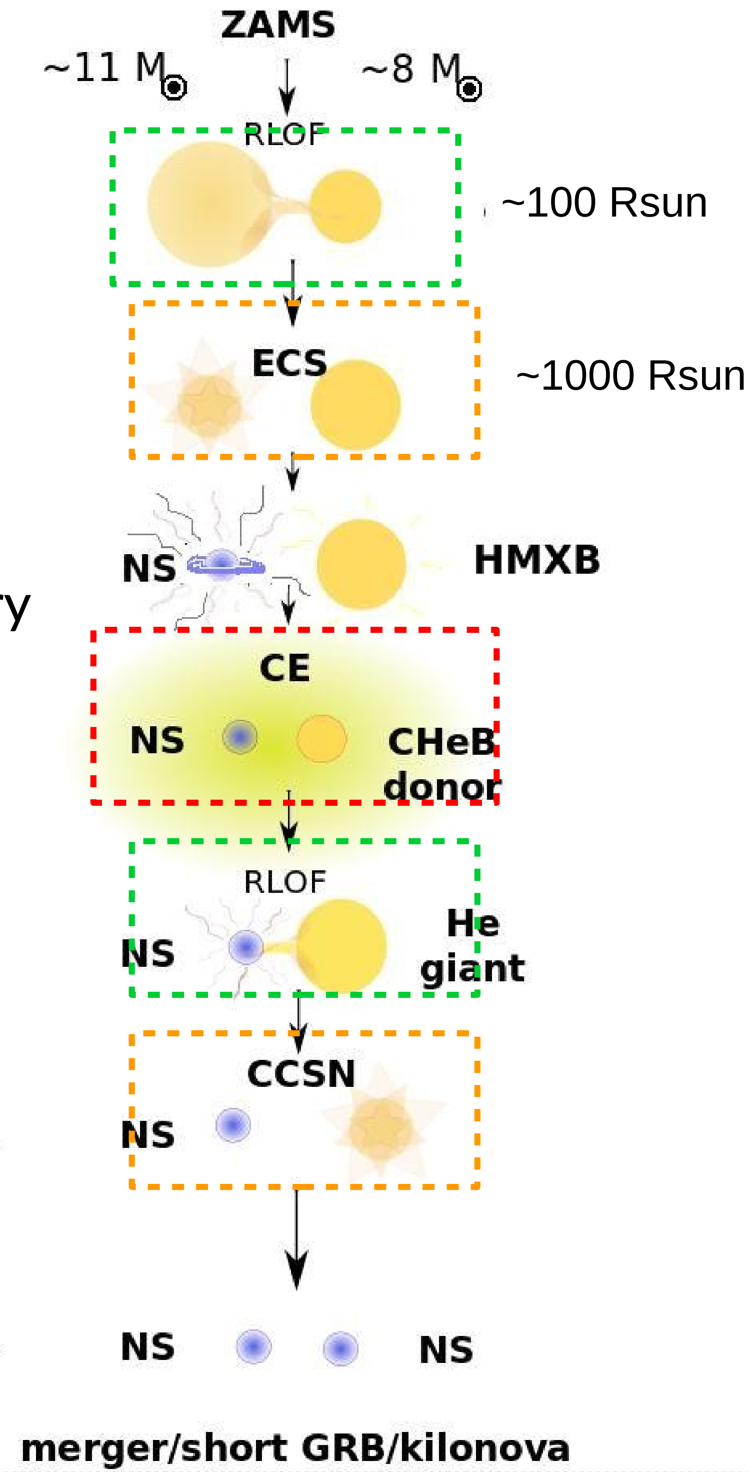
- natal kick velocity
- ejection of mass



mass transfer:
- mass loss
- angular momentum loss

NS formation:
- natal kick velocity
- ejection of mass

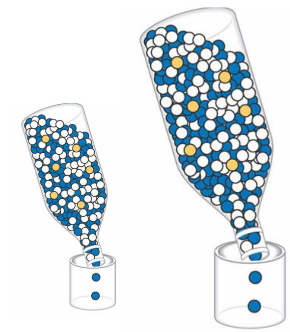
high mass
X-ray binary

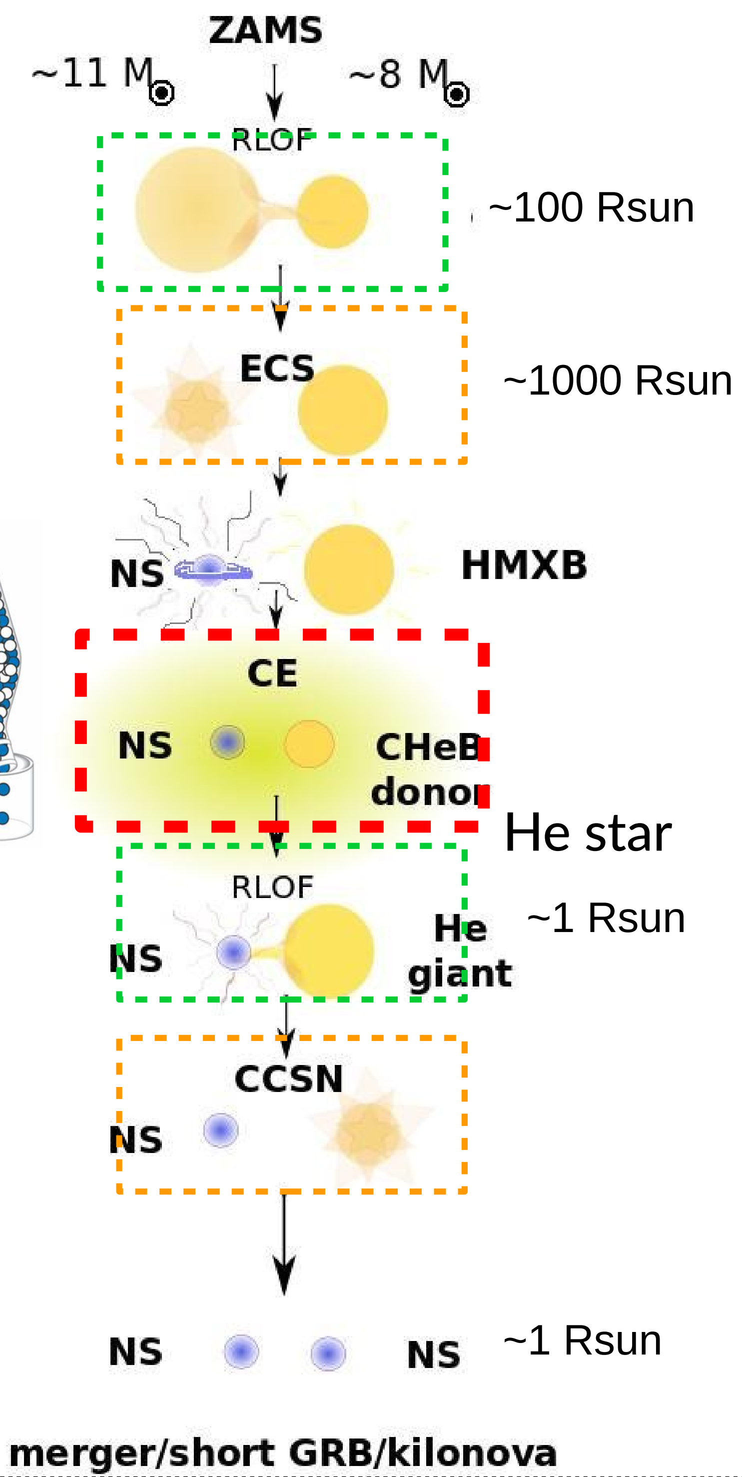


mass transfer:
- mass loss
- angular momentum loss

NS formation:
- natal kick velocity
- ejection of mass

common envelope
- conditions for occurrence
- survival criteria



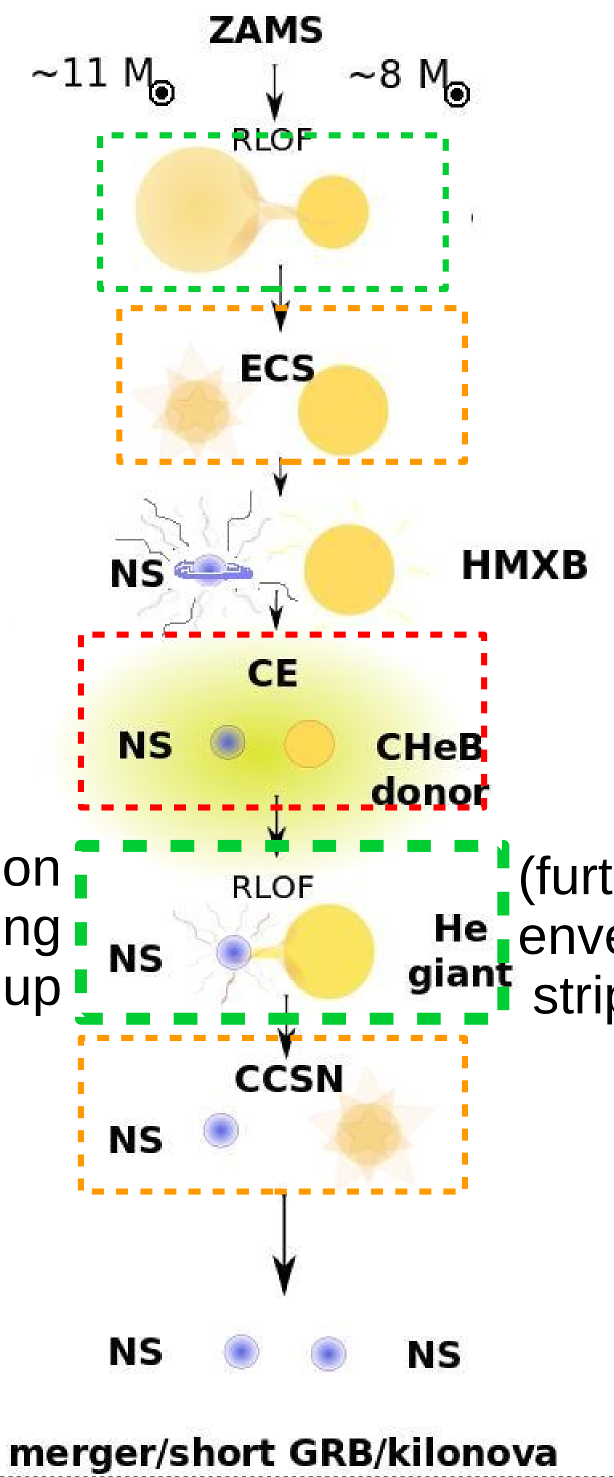


mass transfer:
- mass loss
- angular momentum loss

NS formation:
- natal kick velocity
- ejection of mass

common envelope
- conditions for occurrence
- survival criteria

NS mass accretion
recycling
spin up



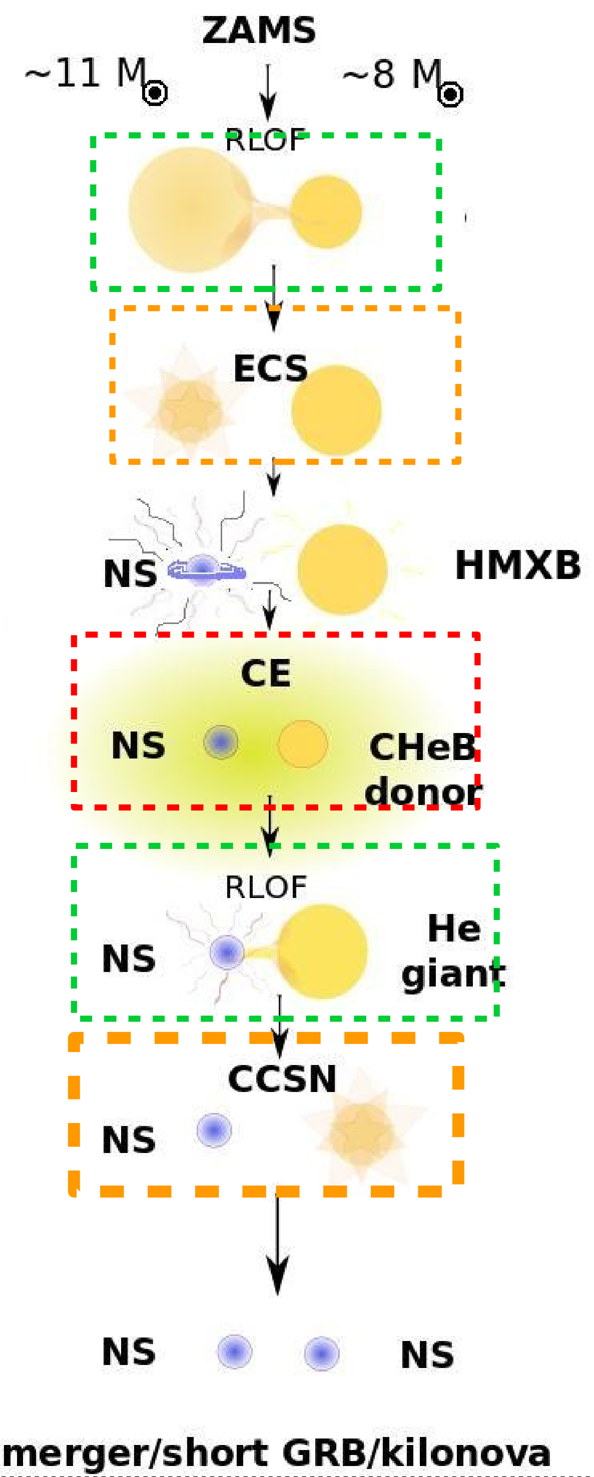
(further)
envelope
stripping

mass transfer:
- mass loss
- angular momentum loss

NS formation:
- natal kick velocity
- ejection of mass

common envelope
- conditions for occurrence
- survival criteria

(ultra) stripped SN



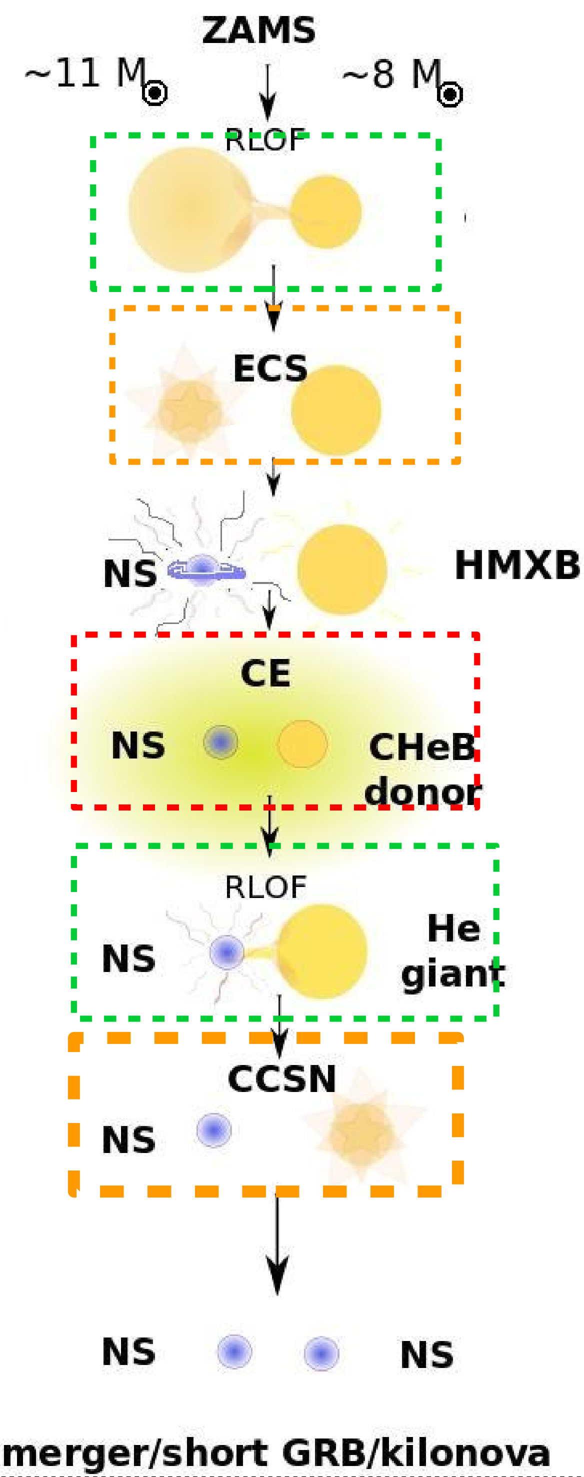
ASSUMPTIONS

mass transfer:
- mass loss
- angular momentum loss

NS formation:
- natal kick velocity
- ejection of mass

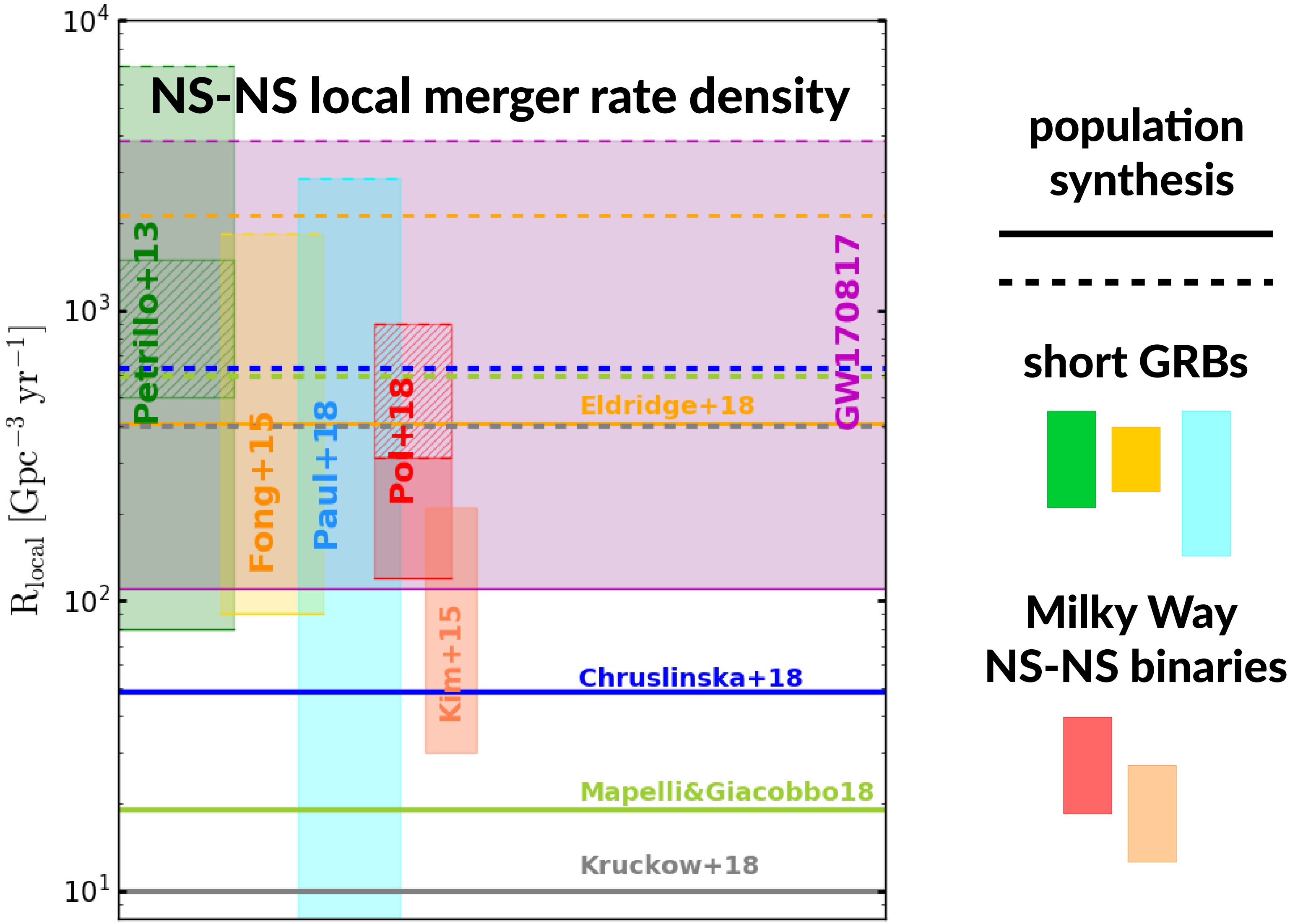
common envelope
- conditions for occurrence
- survival criteria

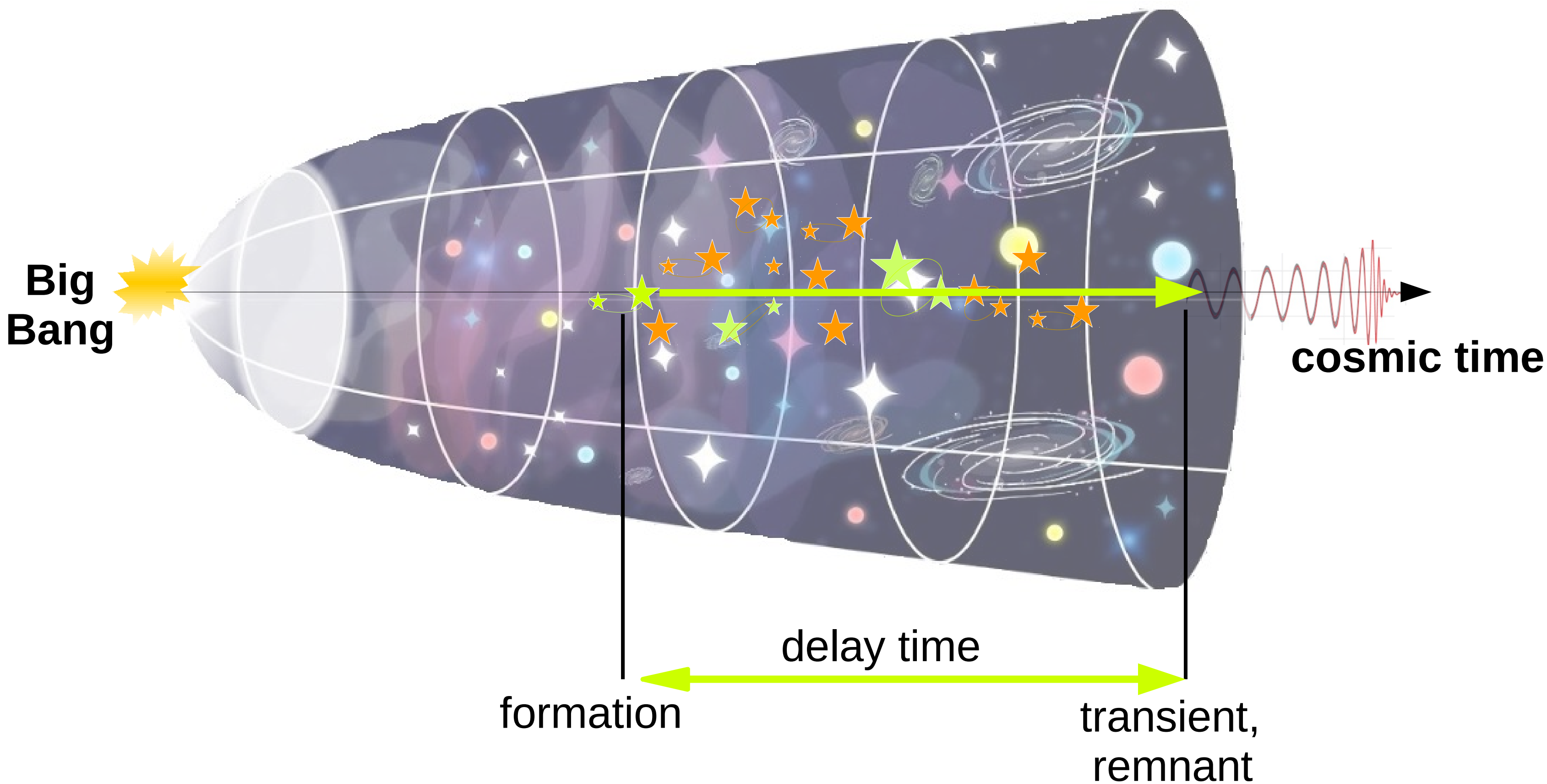
stellar wind mass loss



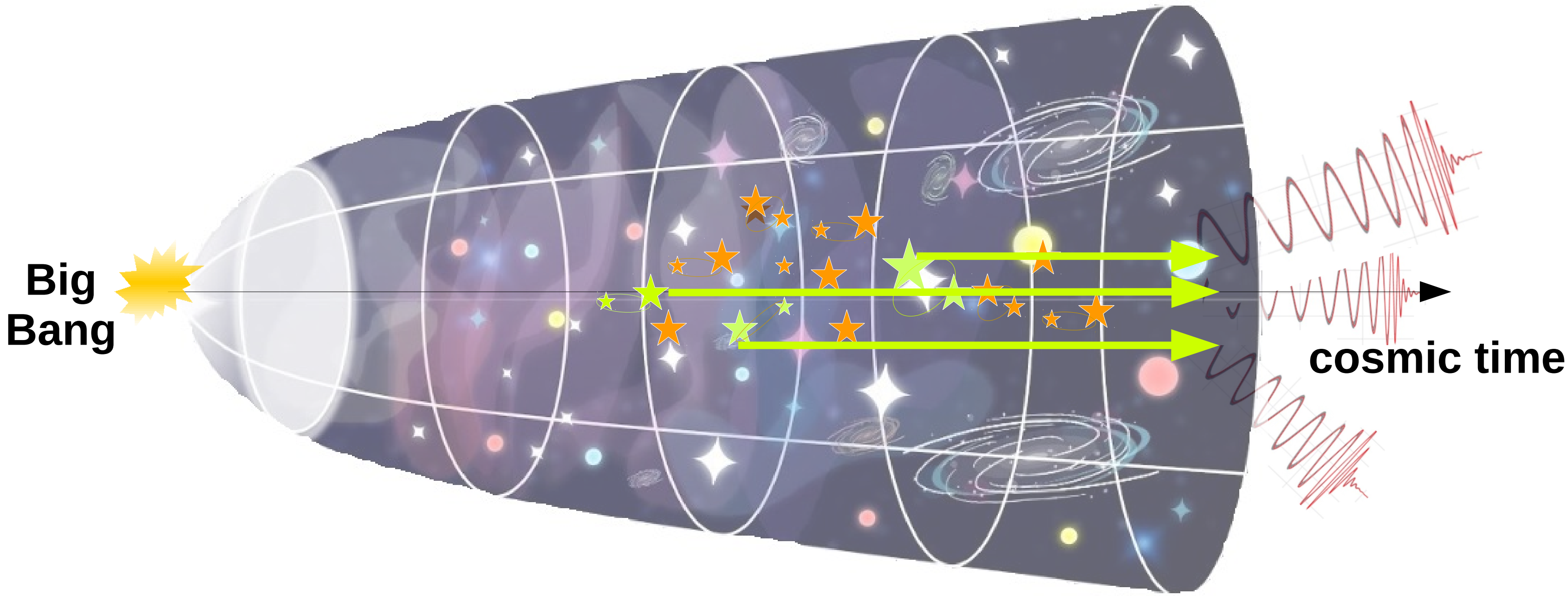
→ *can produce merging NS-NS*. Their number (rate) and properties of population *depend a lot* on our assumptions !
(e.g. Tutukov&Yungelson93, Voss&Tauris03, Dominik+12, Chruslinska+18,19, Kruckow+18, Mapelli & Giacobbo18, ...)

For certain combinations of assumptions can produce **enough** merging NS-NS




Big
Bang
cosmic time
delay time
formation
transient,
remnant

We observe a mixture of objects coming from progenitors formed at different z & **metallicities**



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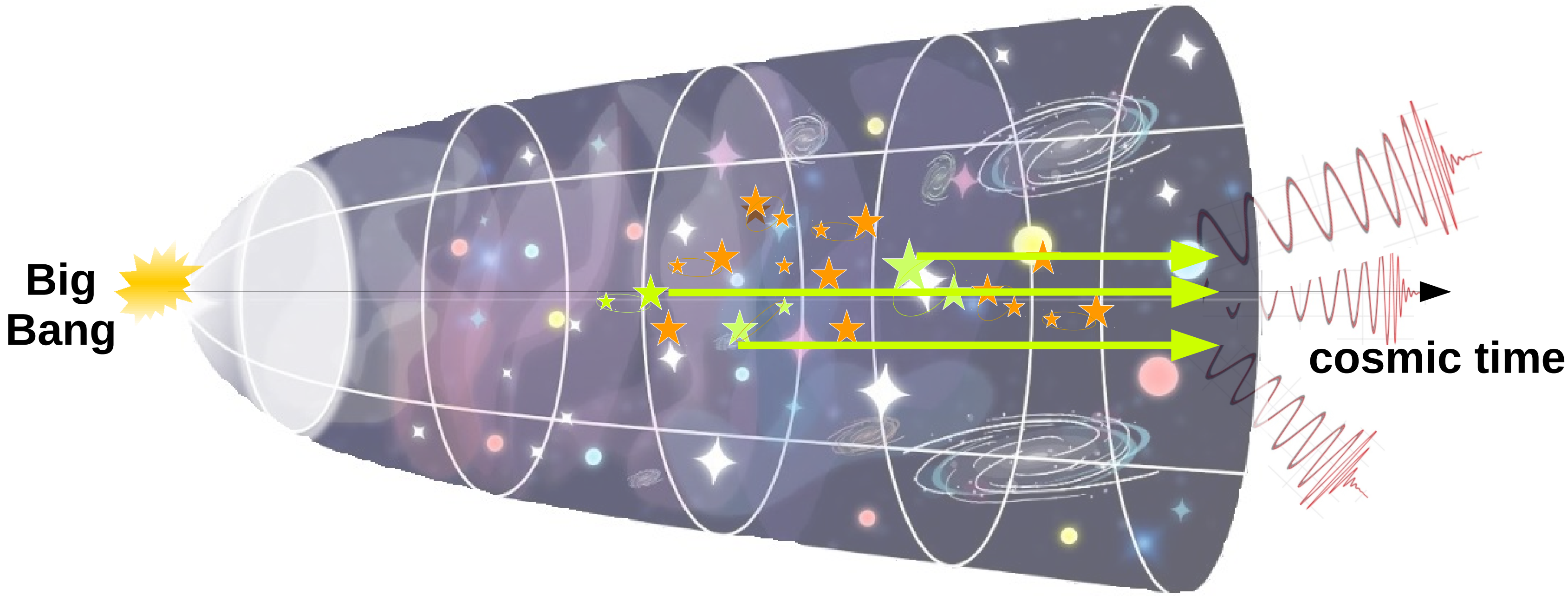


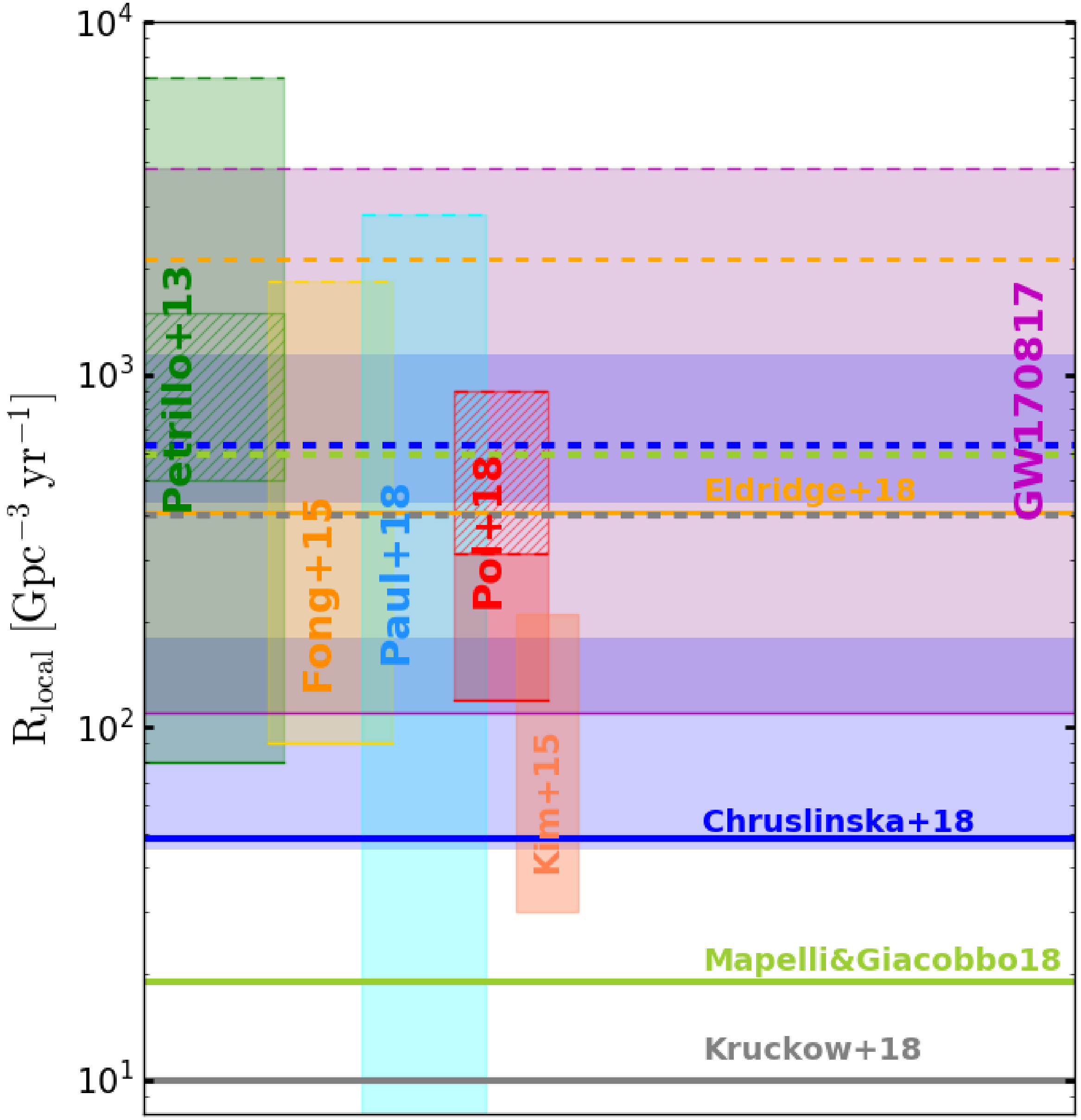
(very) different assumptions in the literature

→ even a factor of 10 difference in rates

→ **degeneracy with assumptions about the evolution**

→ ratio of rates of different mergers affected

Chruslinska et al. (2019a); also recently Neijssel et al. (2019), Tang et al. (2019)



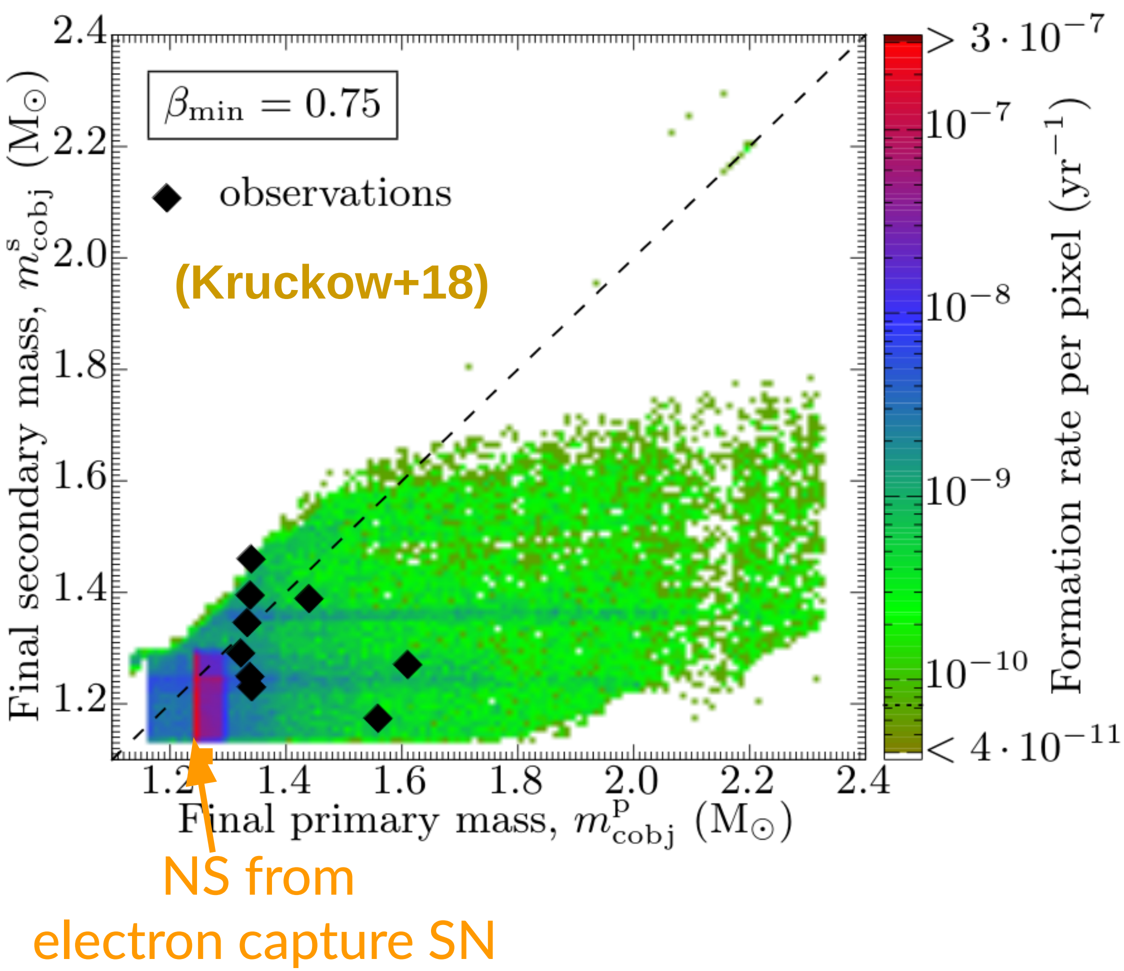
Uncertainty in the star formation history and chemical evolution of the Universe adds uncertainty to our estimates
Chruslinska et al. (2019a,b)

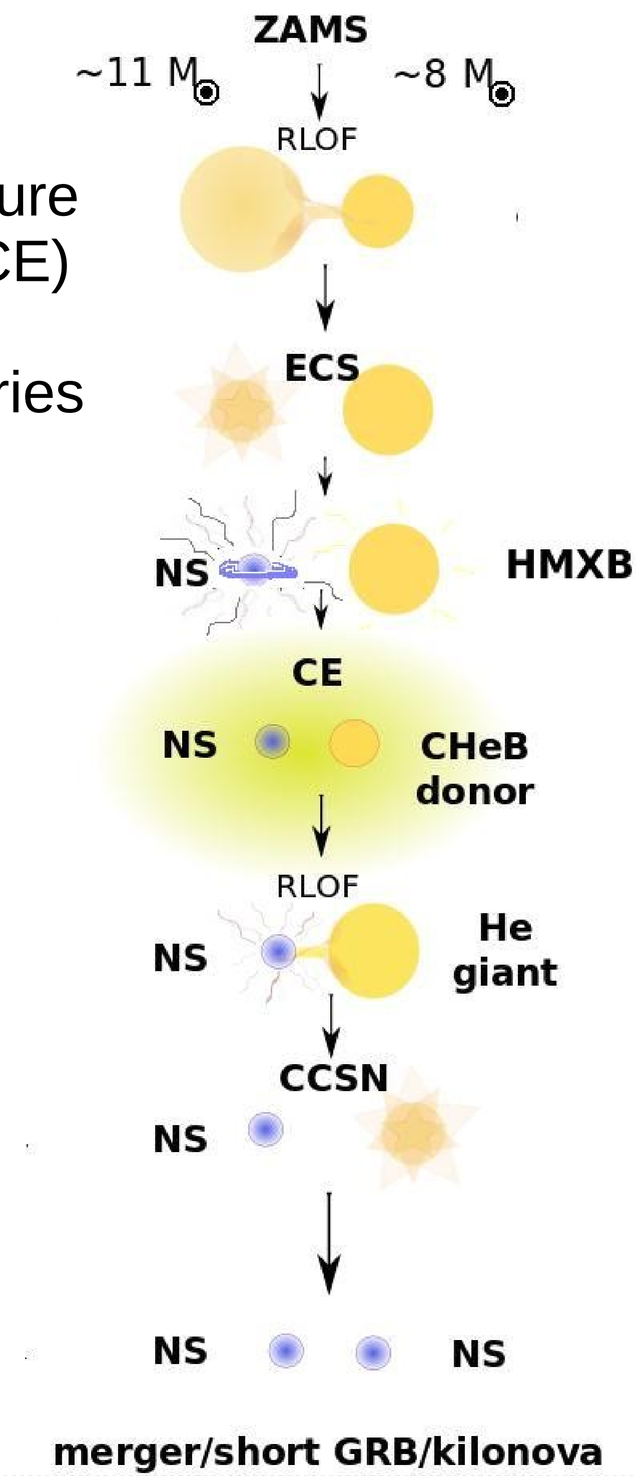
→ **degeneracies**
very limited gain from this kind of comparison...

Mass problem

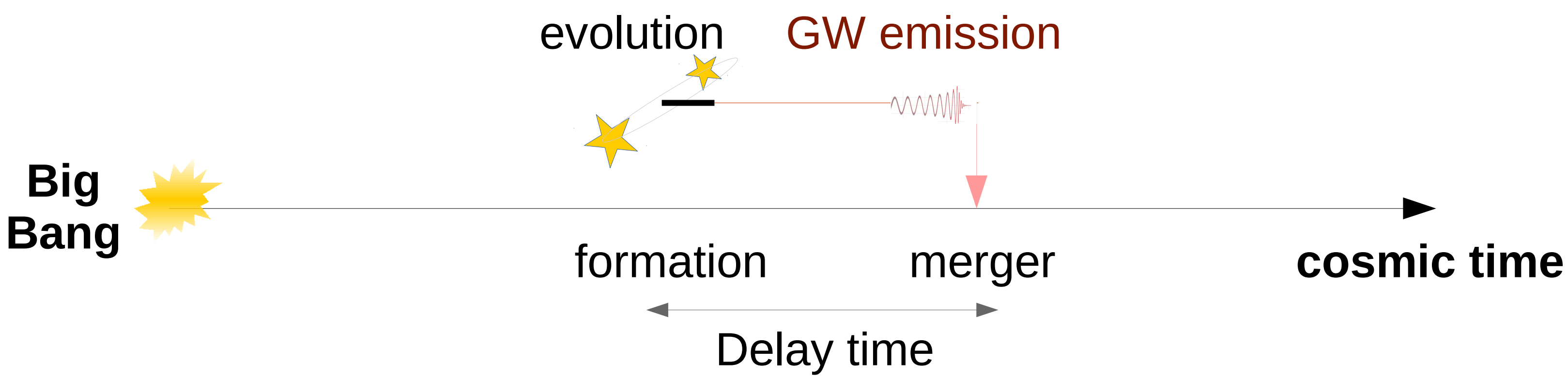
Theory: 1 st. SN: small kick required → electron capture (wide binary at this stage –> otherwise merger in CE) → *NS1 accretes <0.02 Msun* (Tauris+17)

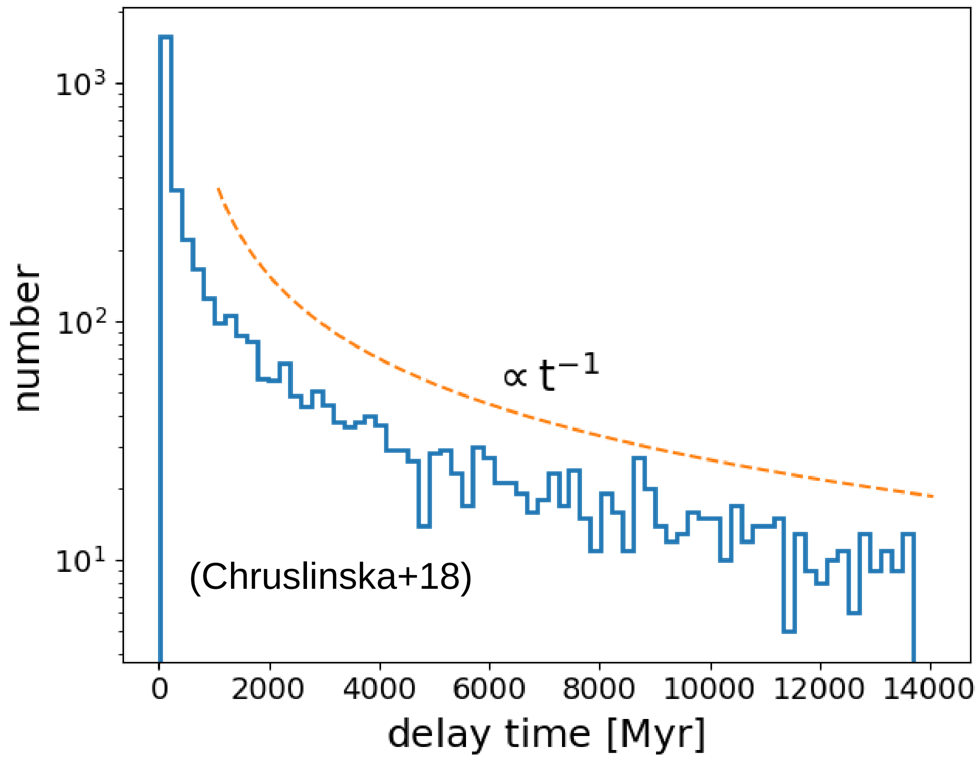
Observations: NS masses from Galactic NS-NS binaries





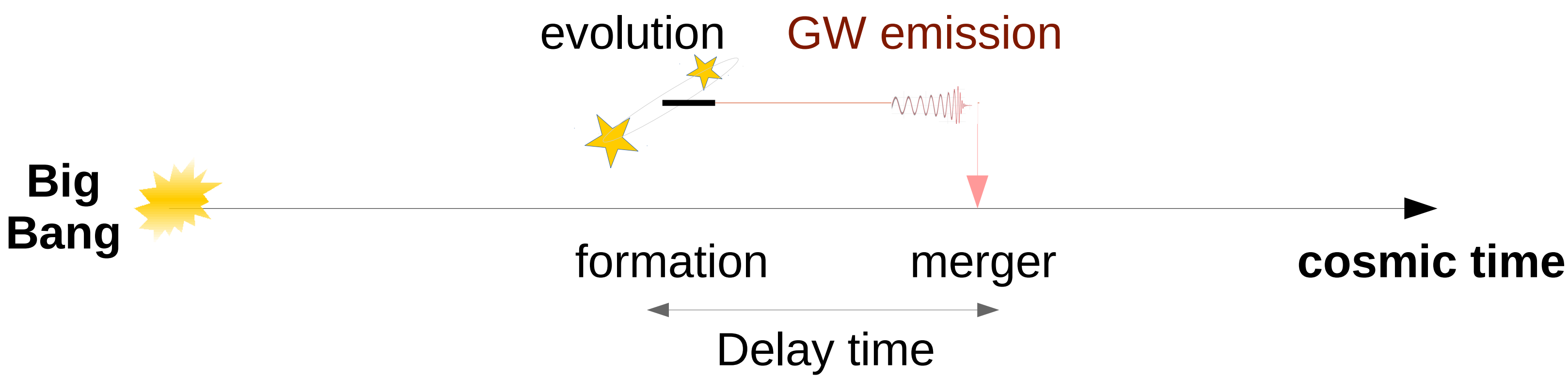
Delay time ‘surprise’: GW170817

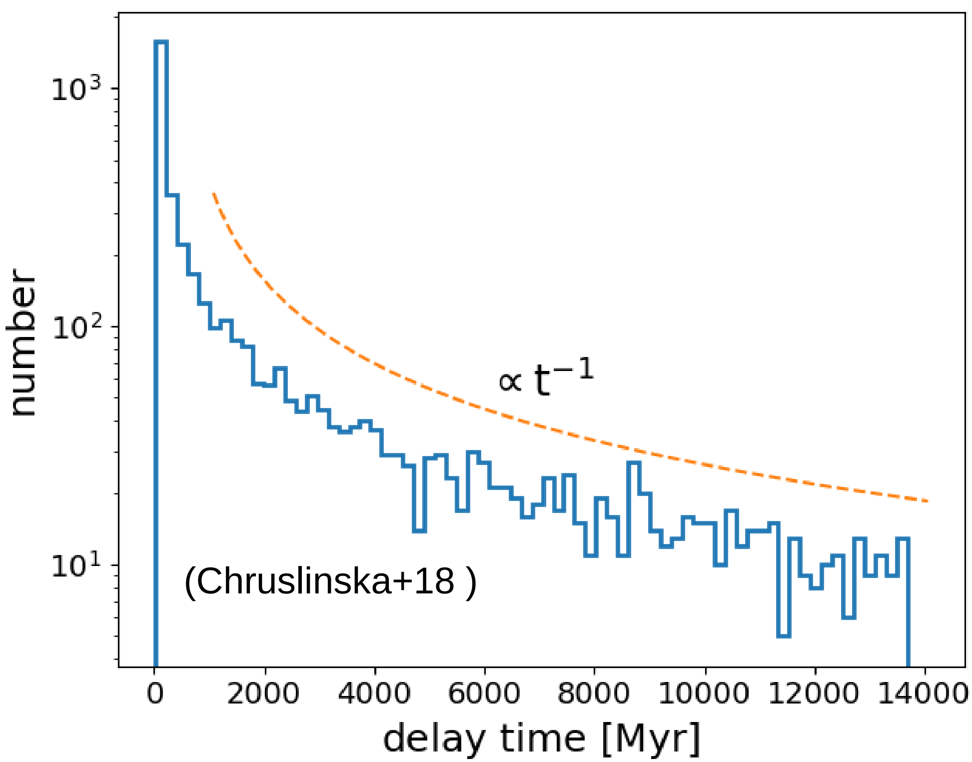




Population studies of the isolated channel find delay time distributions strongly peaked at short times (~a few 100 Myr)

Delay time 'surprise': GW170817

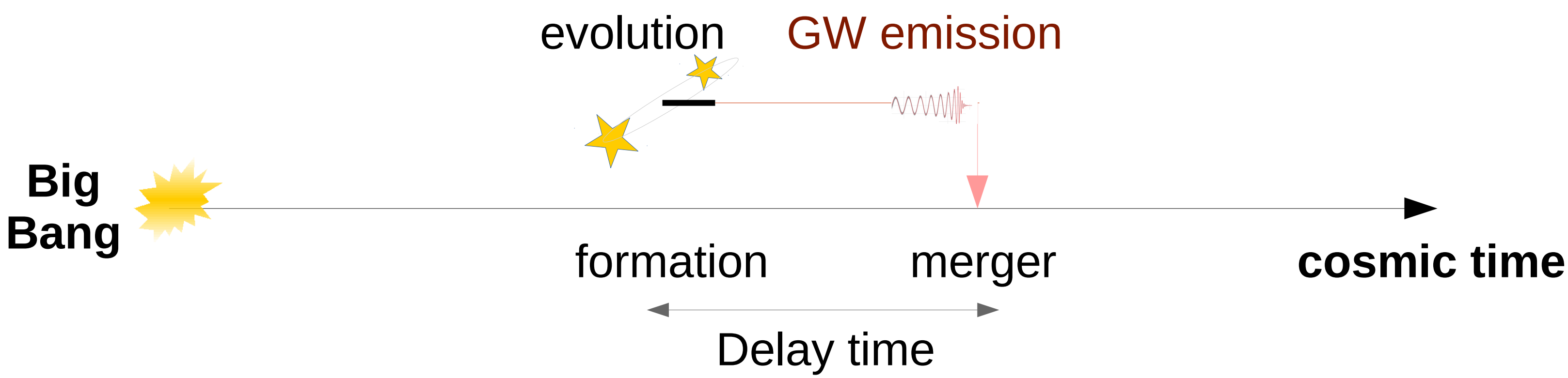


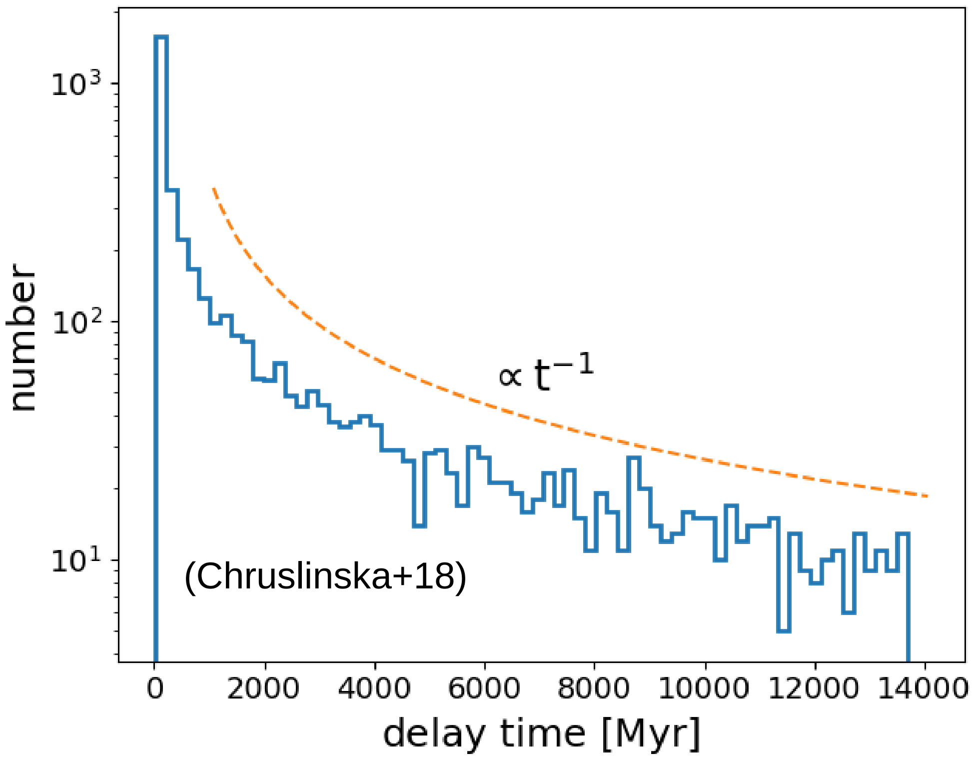


Population studies of the isolated channel find delay time distributions strongly peaked at short times (~a few 100 Myr)

→ NS-NS mergers are expected mostly in **young stellar populations** (starbursts, active spiral galaxies)

Delay time ‘surprise’: GW170817

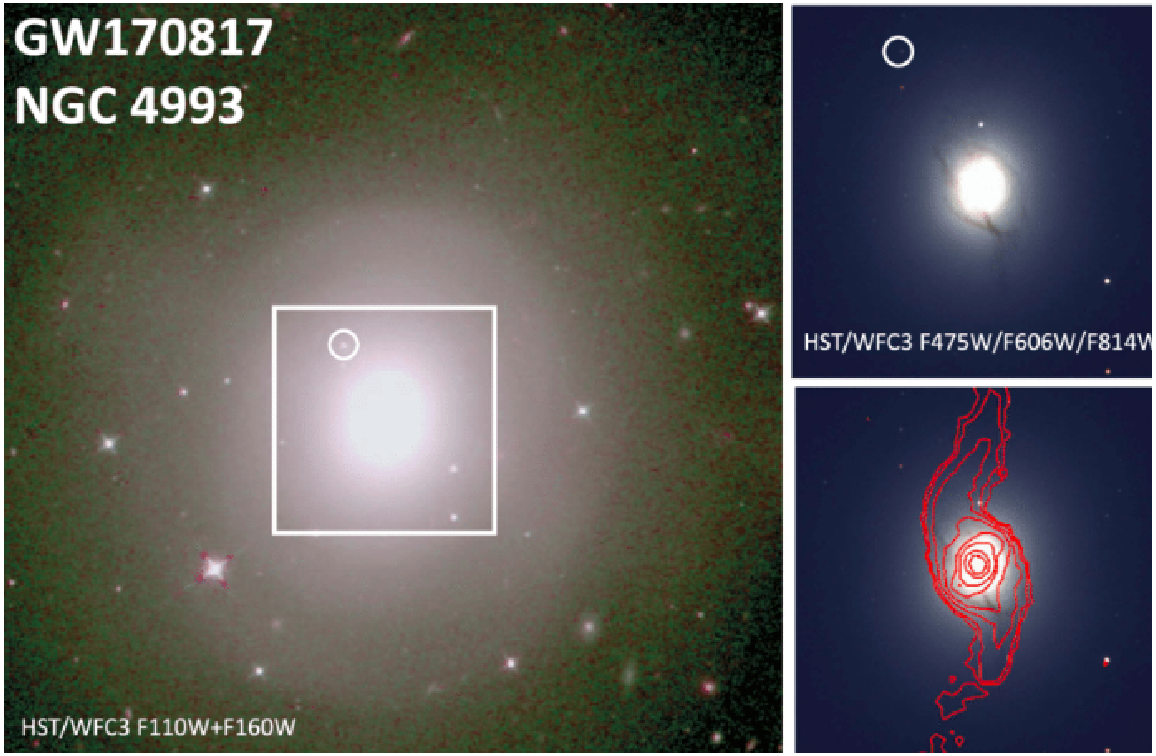




GW170817 was found in galaxy with **no star formation during the last >2 Gyr** (Blanchard+17; Troja+17; Palmese+17)

→ Belczynski, Askar, Arca-Sedda, Chruslinska et al. (2018)

GW170817 location



GW170817 “among the most centrally concentrated ~10% of short GRBs” (Levan+17)

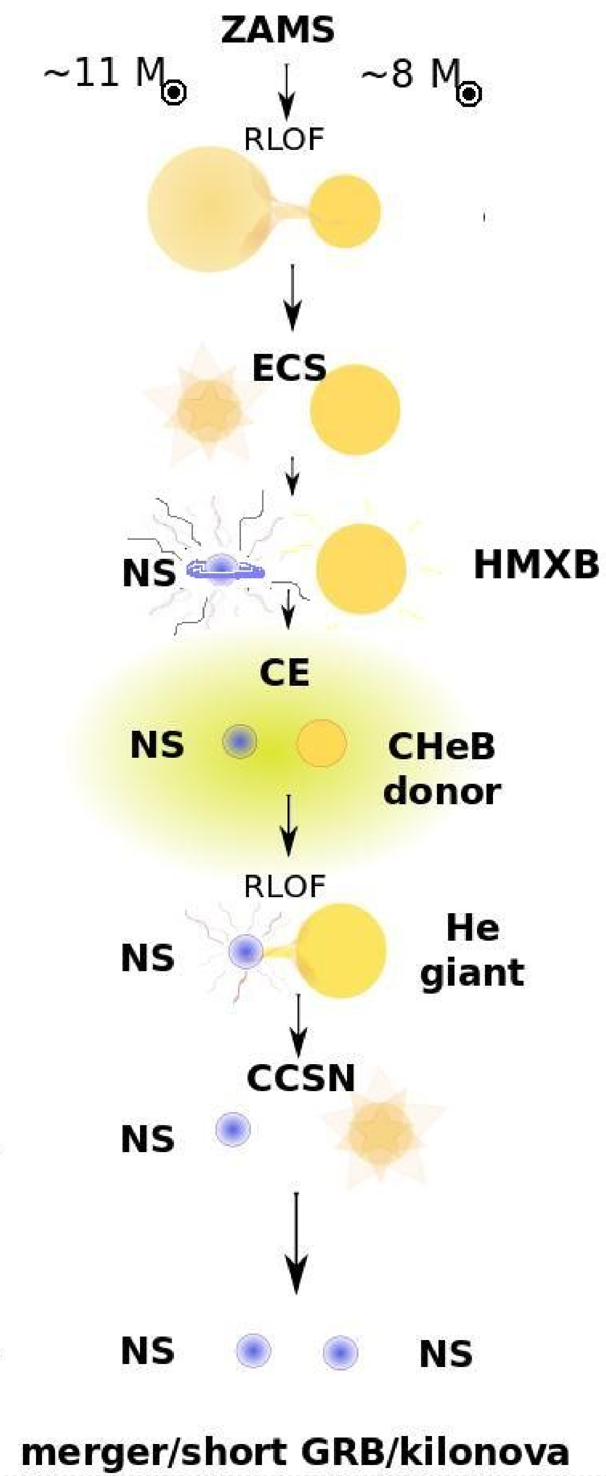
→ kick (unusually) small?
→ kick towards us/
just passing close to
core at merger ?
→ perturbed by galaxy merger?

Delay time problem: r-process elements

→ NS-NS mergers produce r-process elements
-- GW170817 kilonova

→ stars enriched in r-proc. are found in some globular clusters and ultra faint dwarf galaxies
e.g. Roederer 2011, Ji et al. 2016, Hansen et al. 2017

→ MW production history of r-proc. (traced by Eu) is similar to that of Mg (produced in normal SN) ---> r-process production seems to follow star formation with no (significant) delay
e.g. Hotokezaka et al. (2018)



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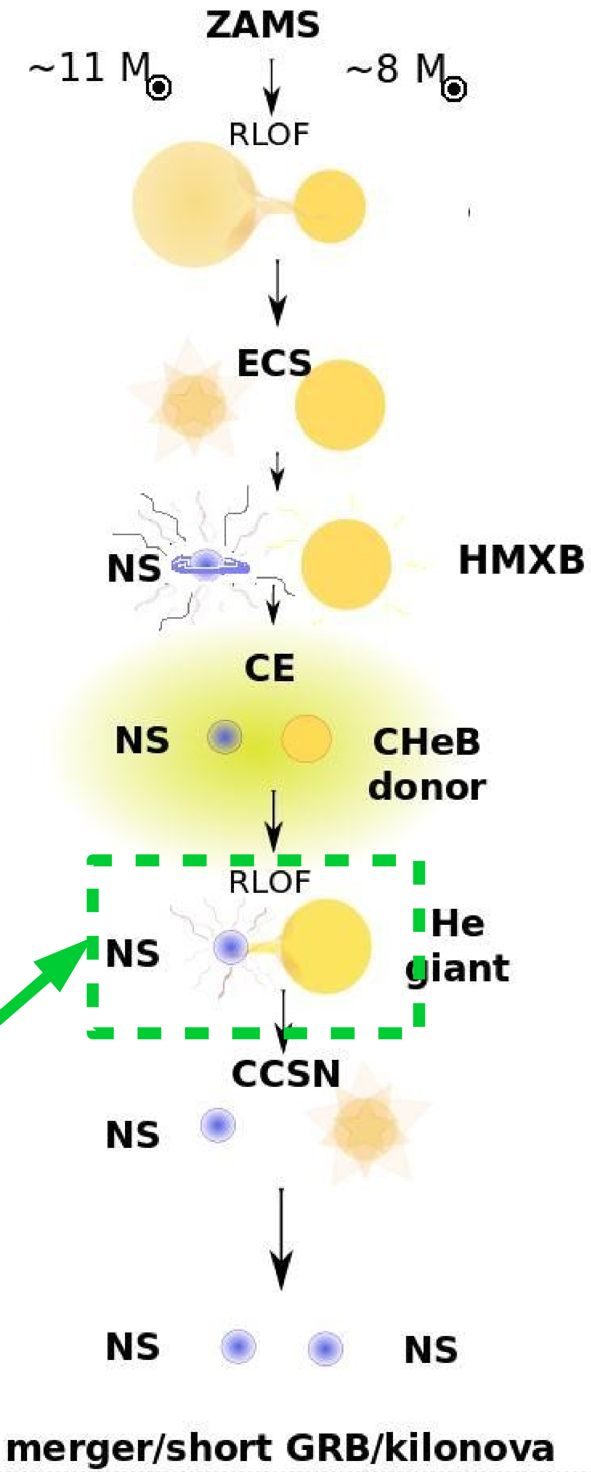
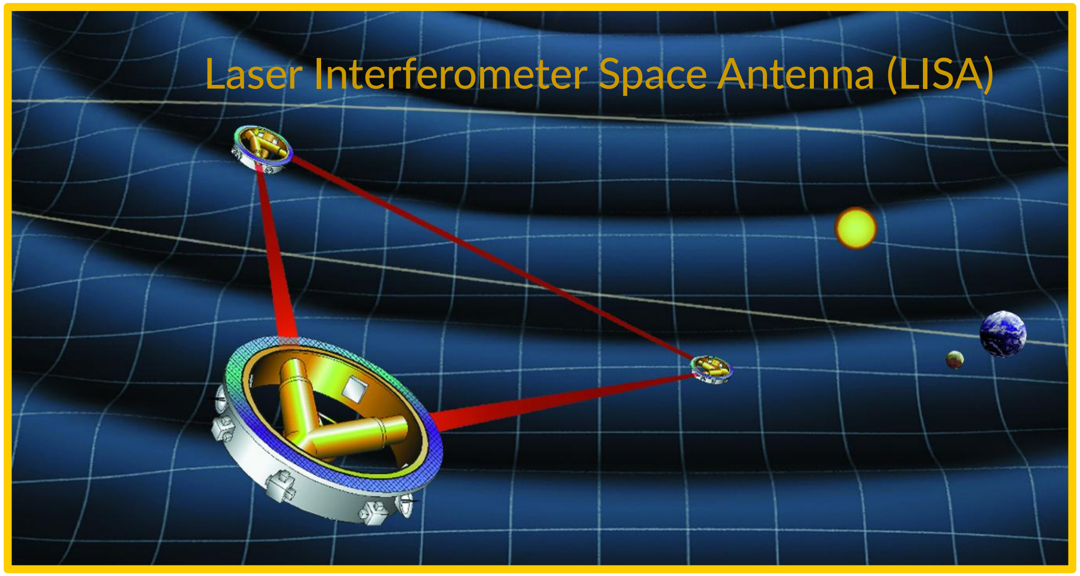
→ **if NS-NS mergers are responsible** for that r-proc., some must happen with *very short* delay times (~10 Myr)
- > implications for the case BB mass transfer phase
e.g. Safarzadeh et al. (2018), Zevin et al. (2019)

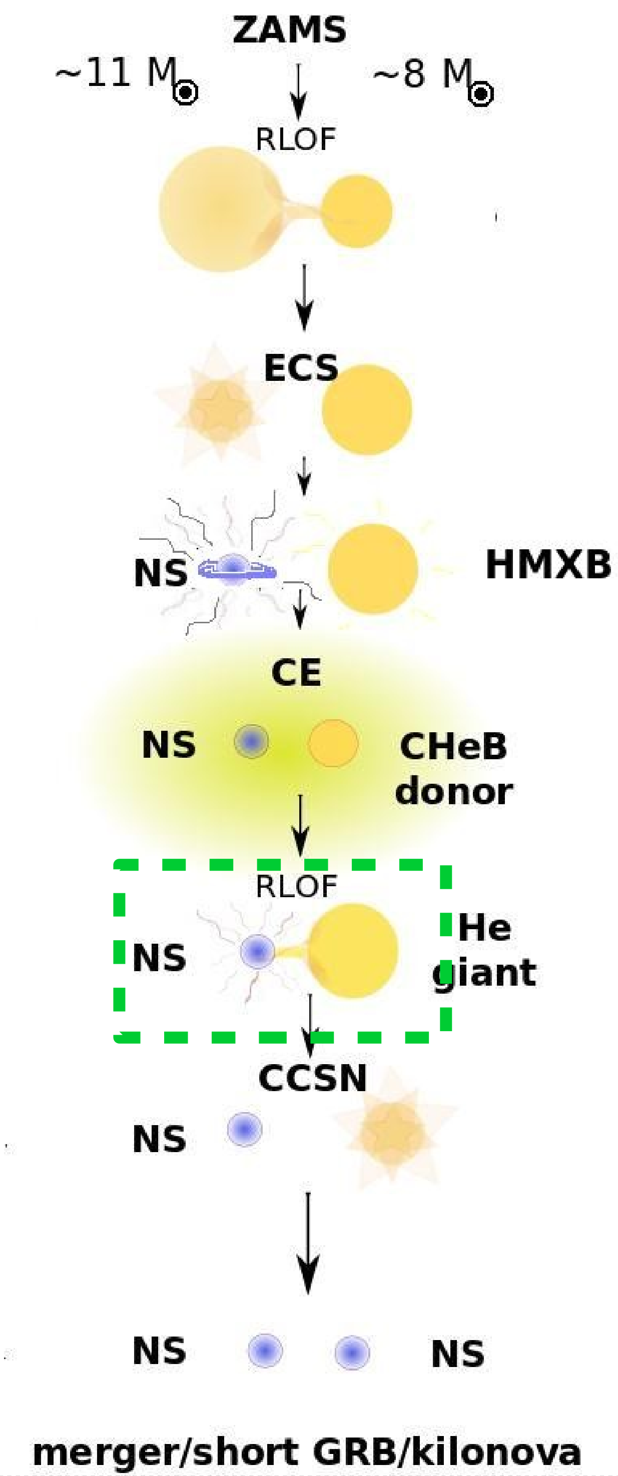


Delay time problem: r-process elements & LISA

→ NS-discovery methods based on radio observations are biased against very tight NS-NS binaries Porb <1 h (merger times <10 Myr; e.g Bagchi+13)

→ if they exist*, **LISA** should see them !
*in the Milky Way, *LMC, SMC*
e.g. Kyutoku+19, Andrews+19

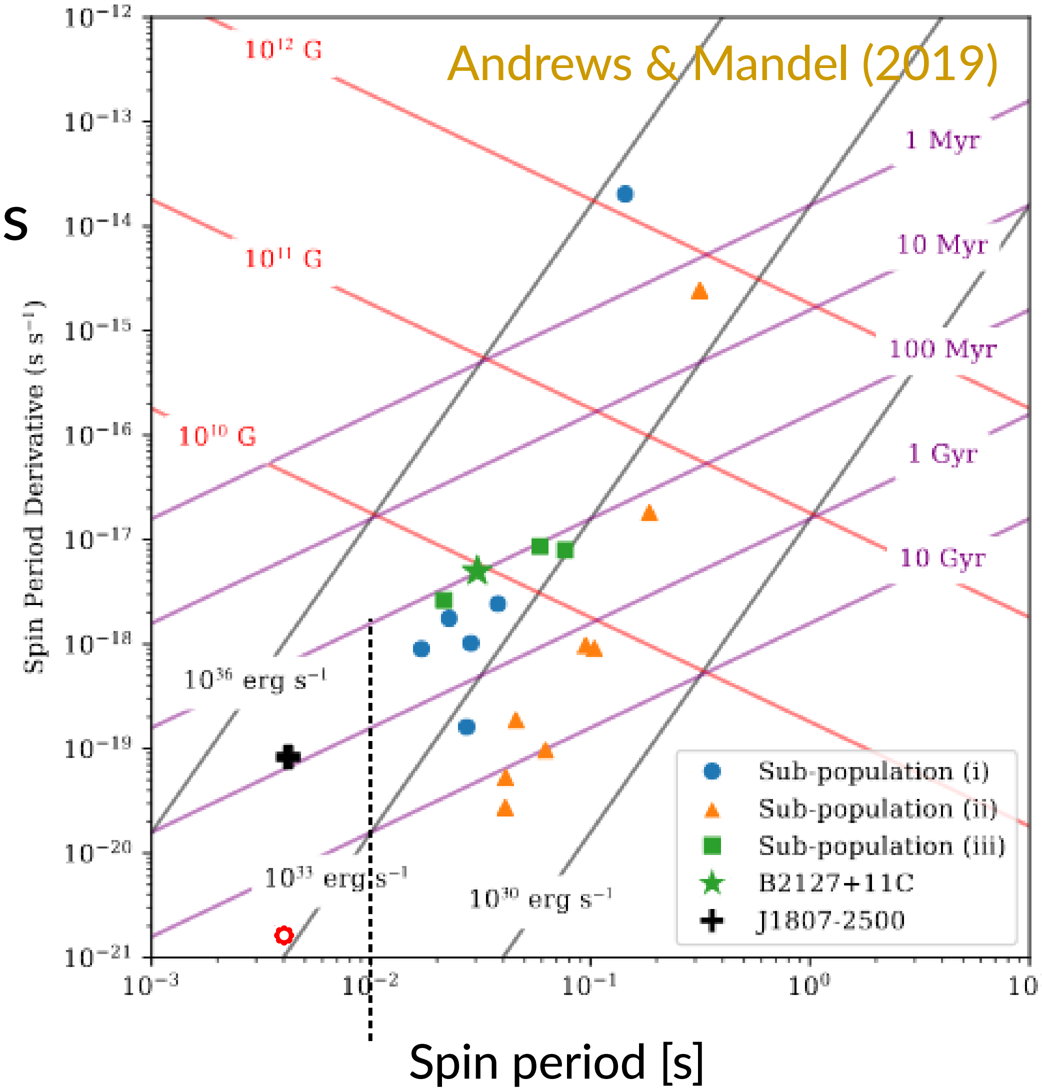




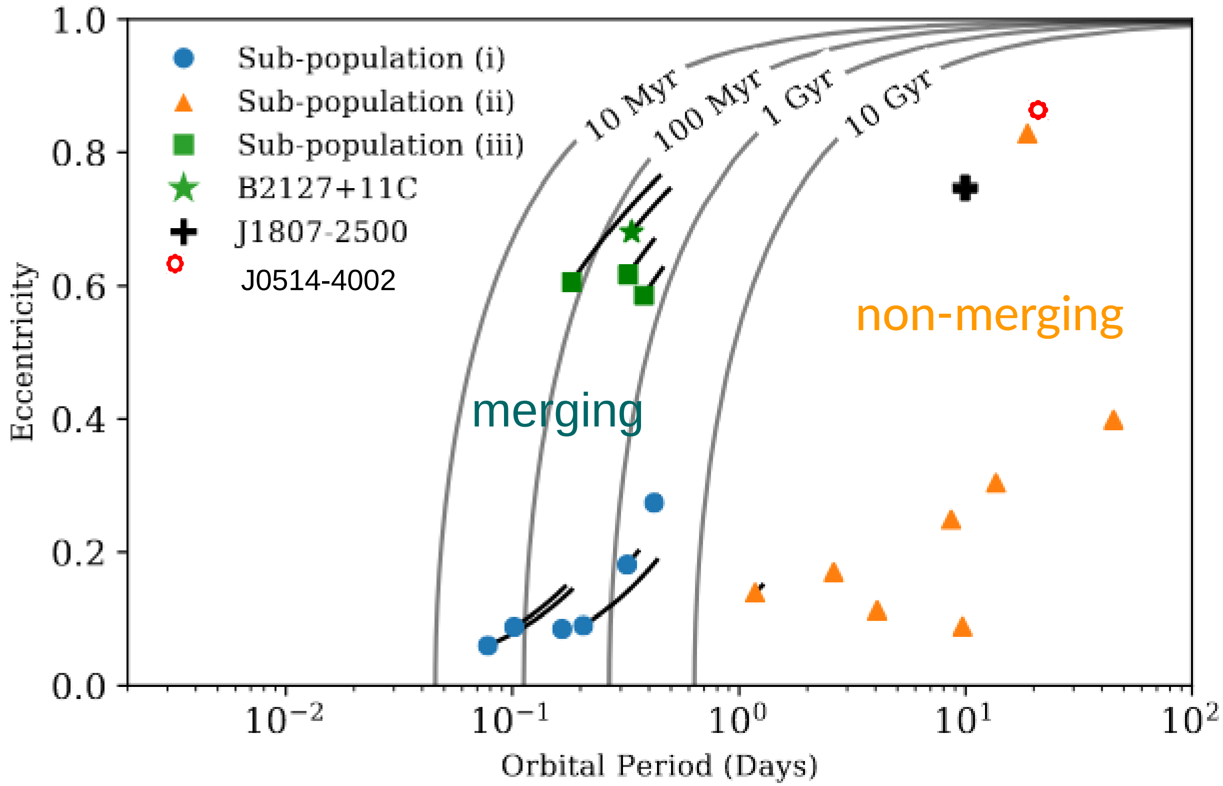
Galactic NS-NS: the return of dynamics?

Recycled NS in NS-NS are not expected to spin faster than ~10 ms (short timescale for mass transfer limits the amount of spin up)
e.g. Tauris+17

→ 2 NS-NS *candidates* in GC (J0514-4002A, **J1807−2500B**) contain pulsars that spin faster!



Galactic NS-NS:
the return of dynamics?



Andrews & Mandel (2019)

NS-NS with Porb < 1 day - a *tentative* gap in eccentricity 0.3 – 0.6 (*not seen in simulations*); also close to each other in P-dot – P diagram

→ similar formation histories?

→ dynamical scenario for e > 0.6 ? → problem with rates! (e.g. Ye+19)

Conclusions

Isolated binary evolution with common envelope can produce *enough* merging NS-NS (and likely is the dominant channel)

- the *details* are poorly understood (common envelope, natal kicks, mass transfer)
- not without *problems* (masses, delay time, eccentricity …)
- many parameters & degeneracies; need to use various observational constraints to improve our understanding of their formation
- NS-NS in our Galaxy can help

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