Population models and rates

Where do we stand and the next challenges

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TUTT2024, 01 October 2024

Main collaborators: Mario Spera, Michela Mapelli, Giuliano Iorio, Andrea Lapi, Cristiano Ugolini …

EINSTEIN TELESCOPE

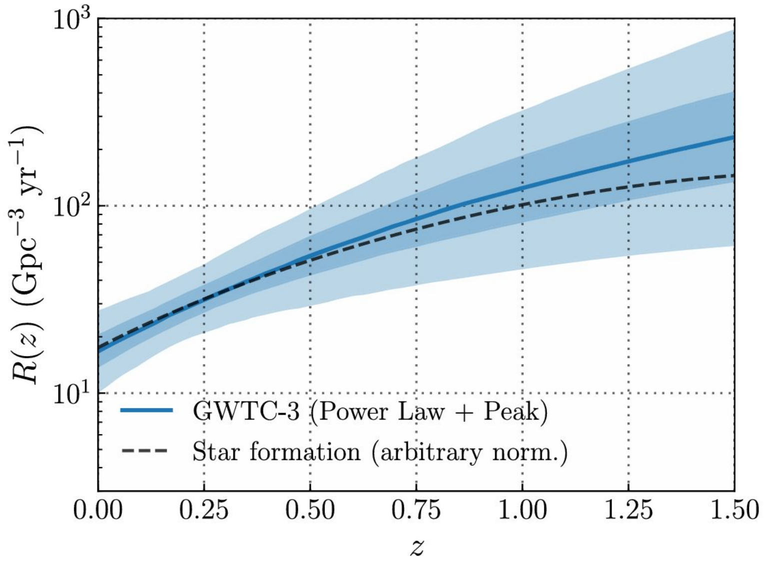
SISSA

Overview

1. Gravitational wave observations: where do we stand?
2. Binary population synthesis codes
3. The role of metallicity & SN kicks
4. Binary evolution: main uncertainties
5. The BNSs population
6. The cosmological context

GW observations: rates

We are starting to trace the merger rate evolution of BBHs with redshift



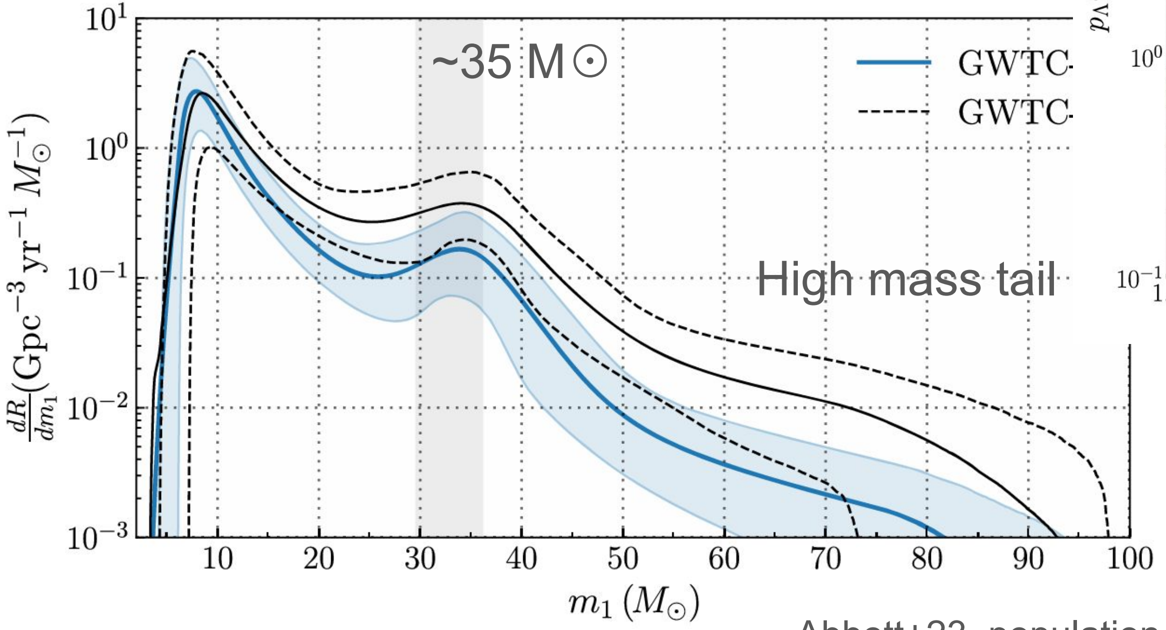
Abbott+23, population paper

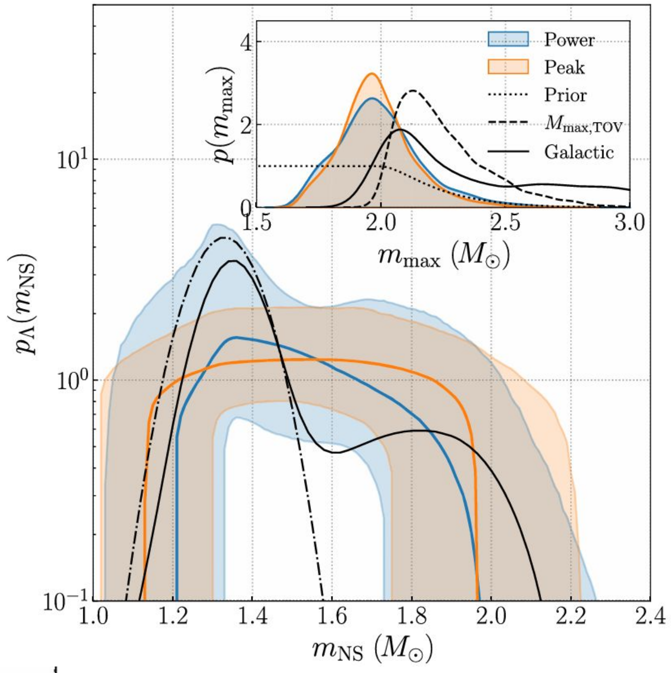
GW observations: masses

BHs

NSs

~10 M☉

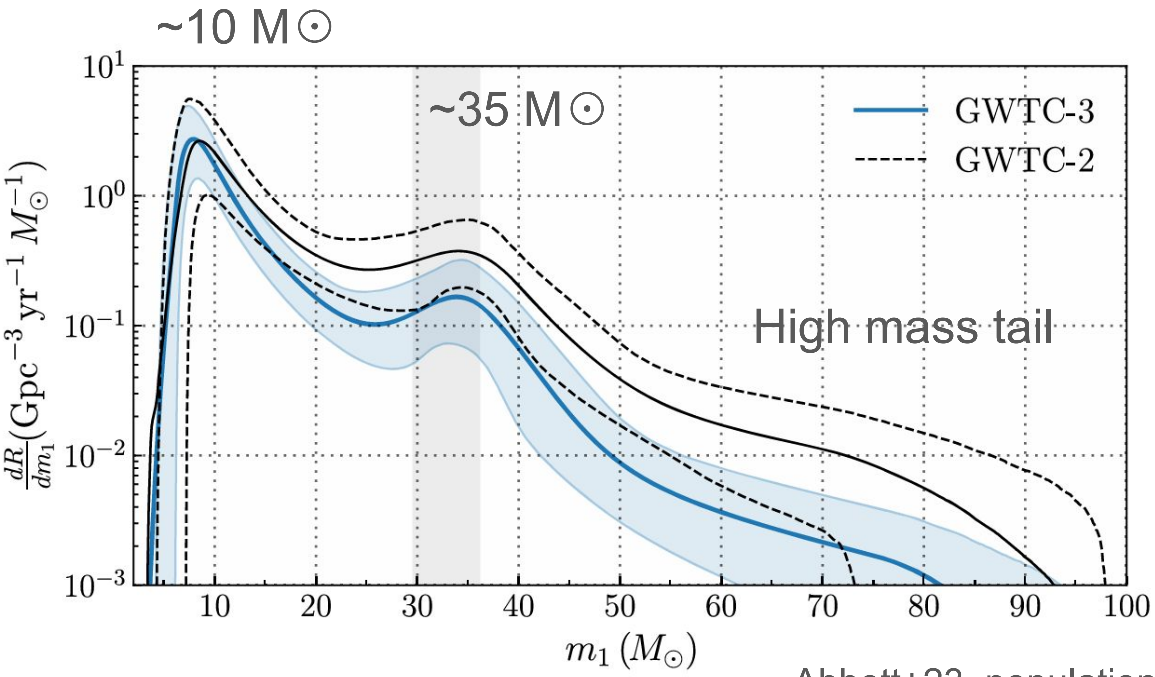




Abbott+23, population paper

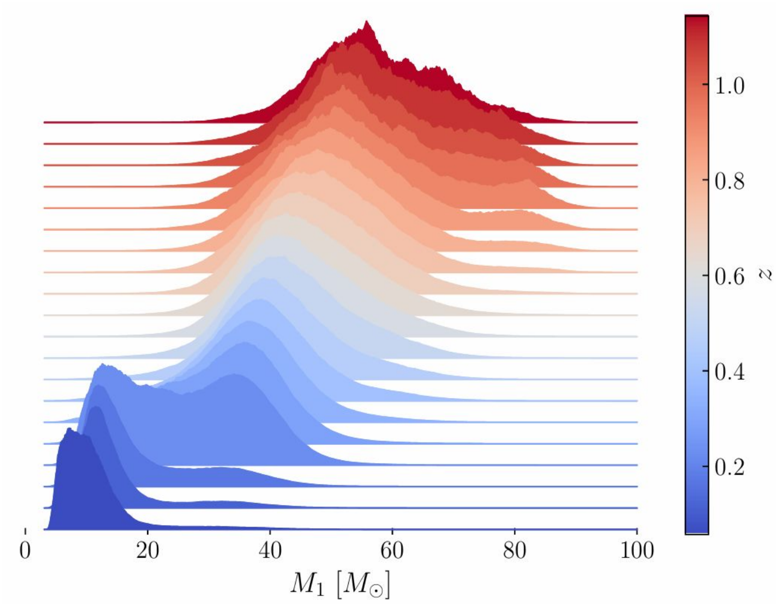
GW observations: masses

Where do these structures come from?

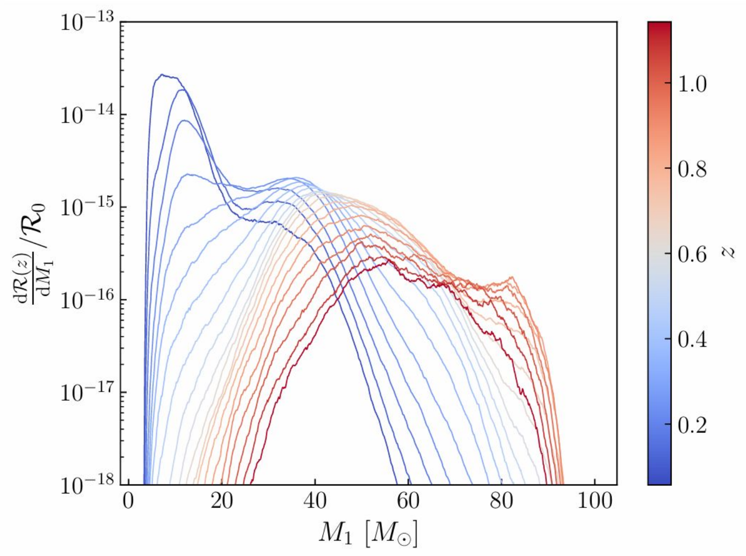


Abbott+23, population paper

Evolution with redshift?

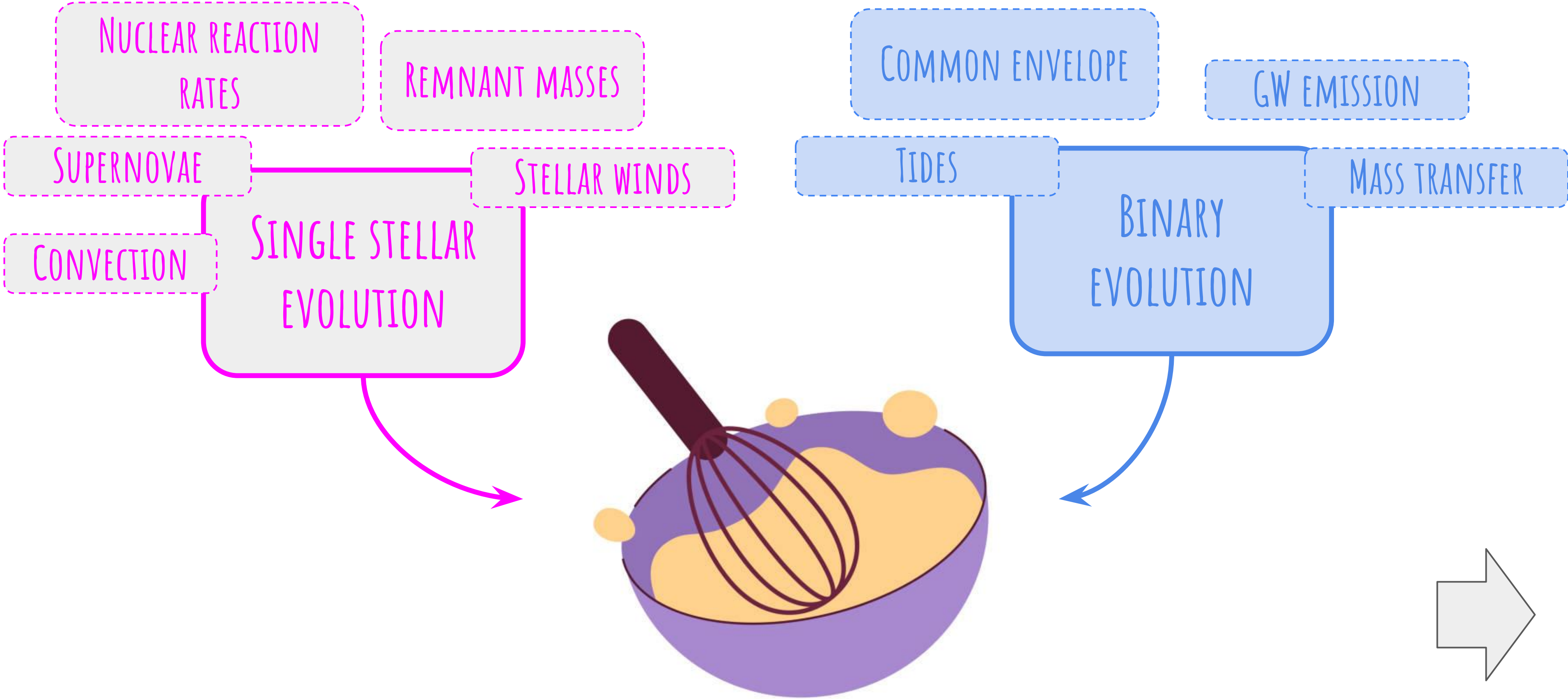


Rinaldi+23

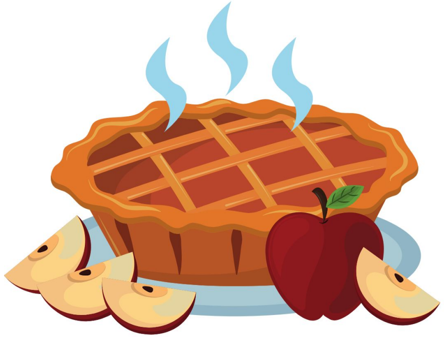


Data is still scarce, will future GW detections confirm this evolution?

Where does this evolution come from?

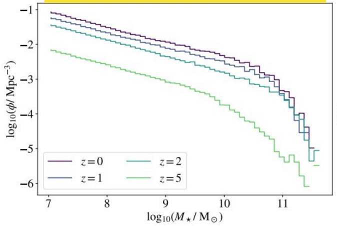


Binary population synthesis codes



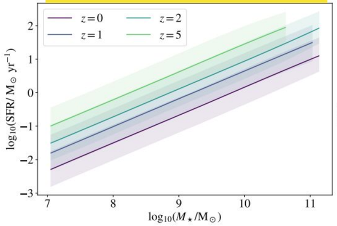
UNIVERSE EVOLUTION

Stellar mass



$\otimes$

Star-formation rate



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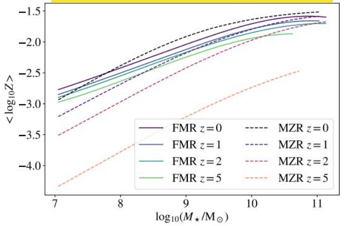
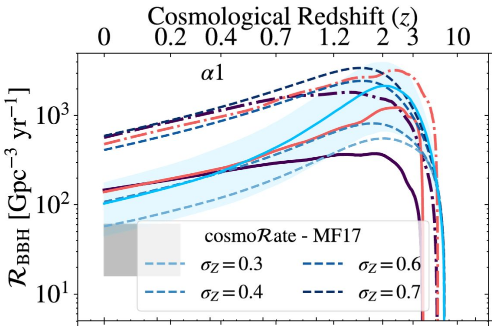
Metallicity

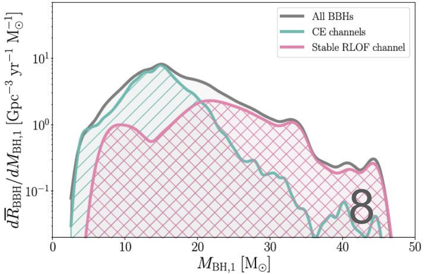


Santoliquido+22



Santoliquido+22

Van Son+22

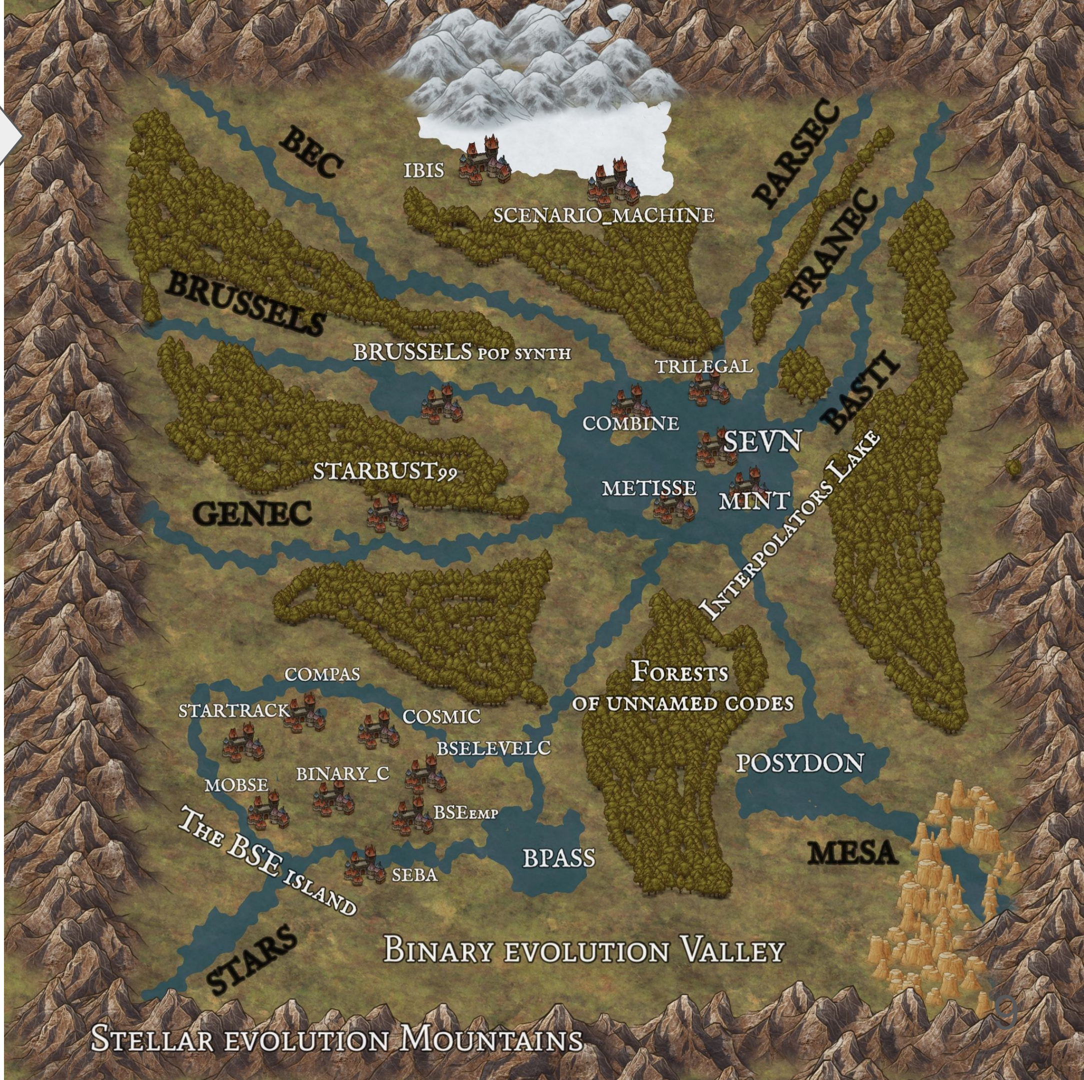


A lot of population synthesis codes …

Spera+17, Spera+19, Iorio+23

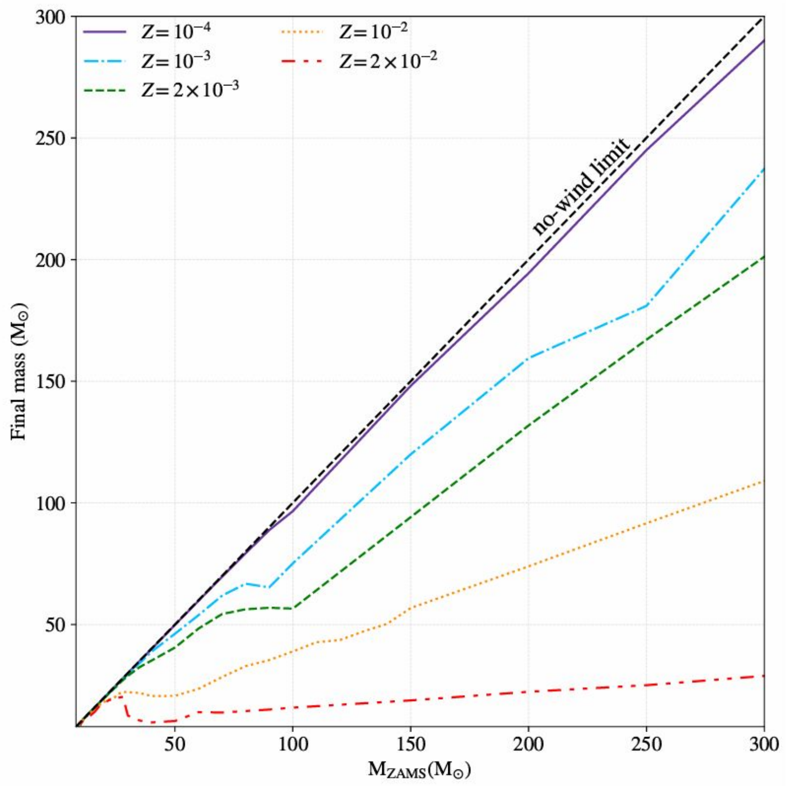
1. Interpolation on the fly of precomputed stellar tracks
2. Analytical and semi-analytical models for binary evolution

Credit: Giuliano Iorio



Single stellar evolution: metallicity

See talk by Cristiano Ugolini

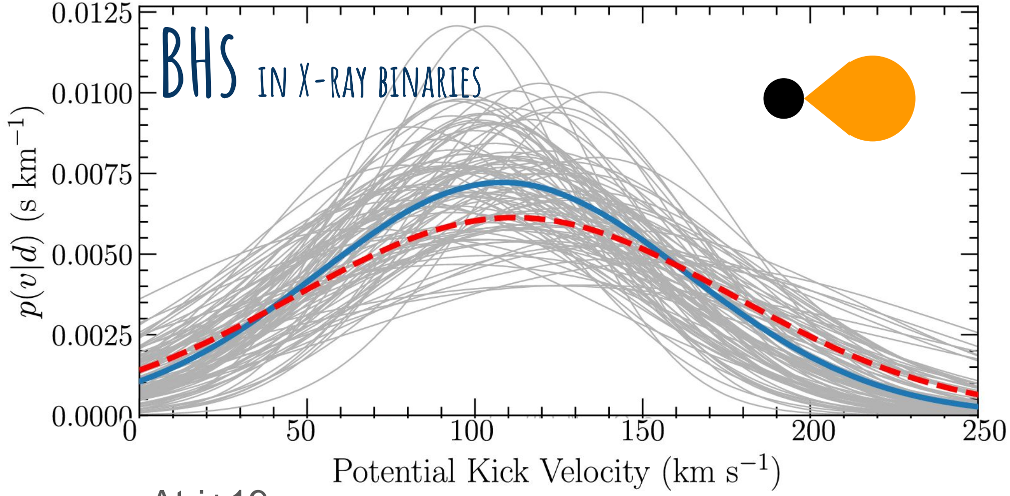


- Massive stars lose mass by stellar winds
- Mass loss higher for metal-rich than metal poor stars
- Metal-poor stars produces more massive black holes

(e.g. Vink et al. 2001; Graefener & Hamann 2008; Vink et al. 2011; Vink et al. 2021; Sabhahit et al. 2023)

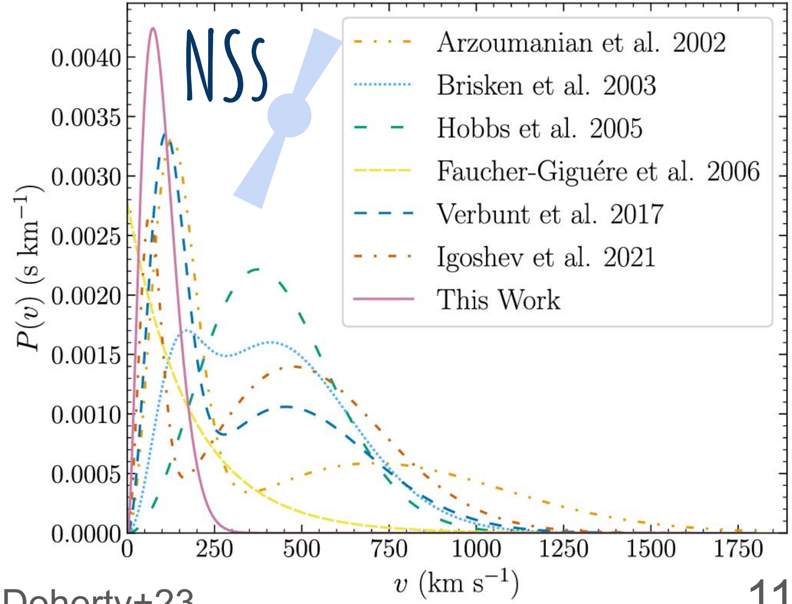
Spera+23 for a review

Single stellar evolution: SN kicks observations



Atri+19

SN kicks inferred from observations are affected by significant biases



O'Doherty+23

On the other hand…

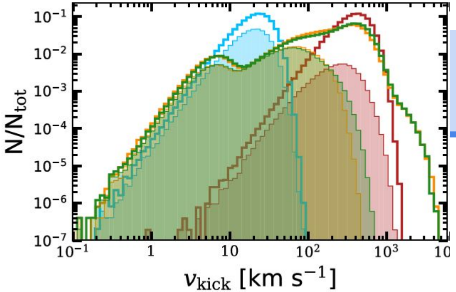
Single stellar evolution: SN kicks

Burrows2021

Hydrodynamical SN simulations predict high kicks due to **asymmetries** of explosion and **anisotropic neutrino emission**

Simplified approaches in pop. synth.

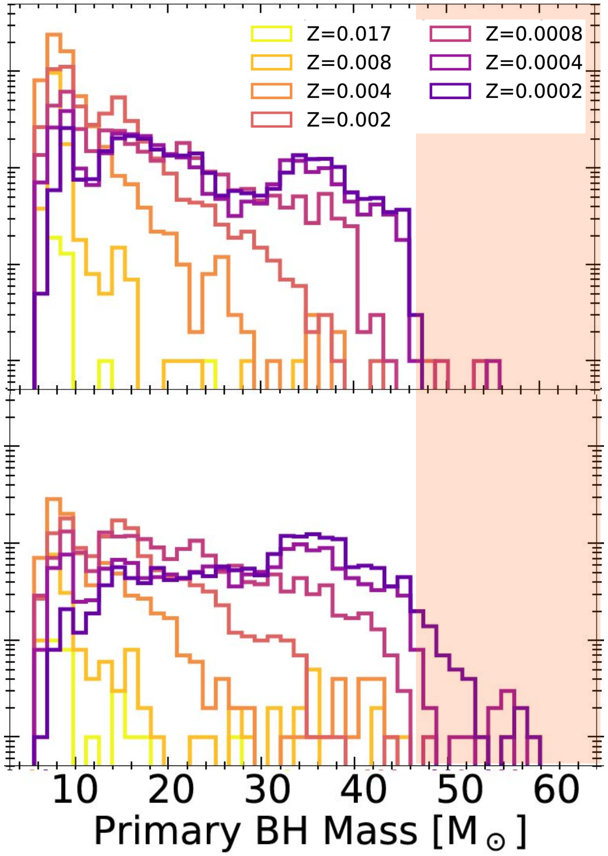
$$v_{\rm kick} = f_{\rm H05}\,\frac{m_{\rm ej}}{\langle m_{\rm ej}\rangle}\,\frac{\langle m_{\rm NS}\rangle}{m_{\rm rem}},$$



Giacobbo & Mapelli 2018

Single stellar evolution: SN kicks

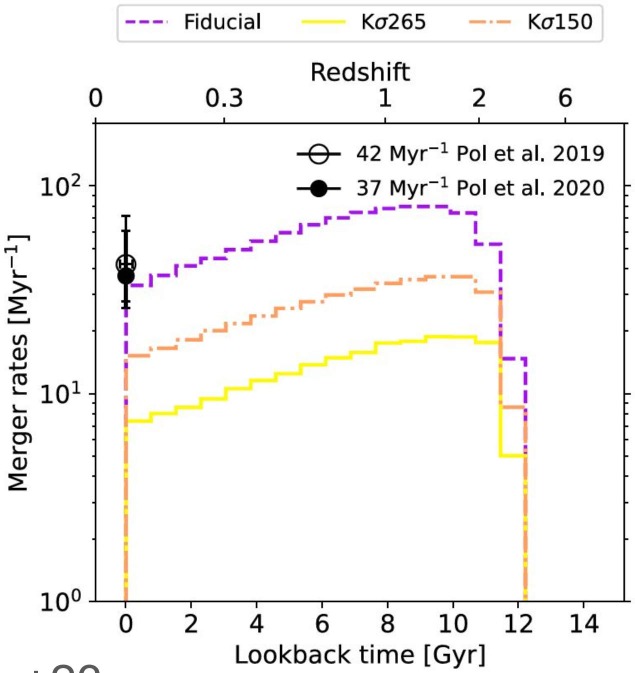
Iorio+23



Higher SN kicks:

1 - Disruption of wider binaries, lowering the merger rates

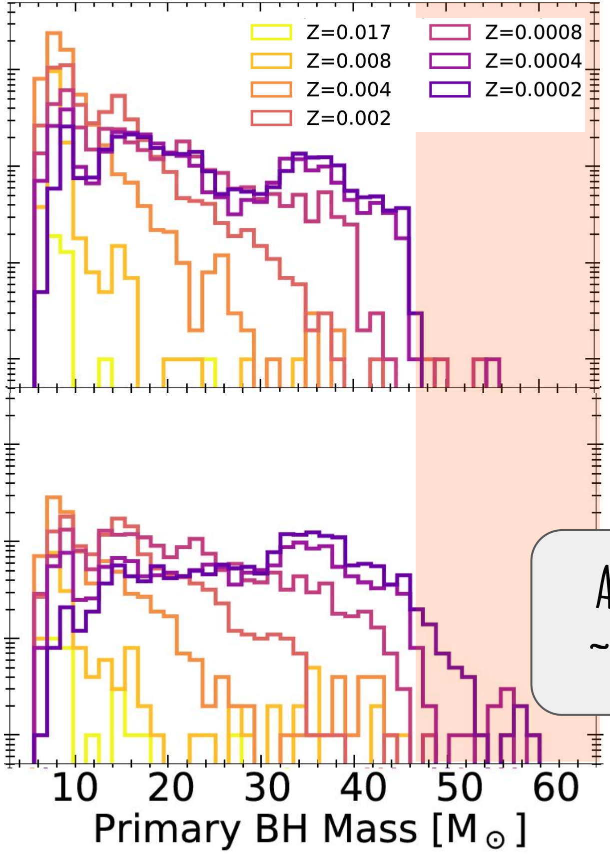
2 - Bias towards higher mass binaries



Sgalletta+23

Single stellar evolution: SN kicks

Iorio+23

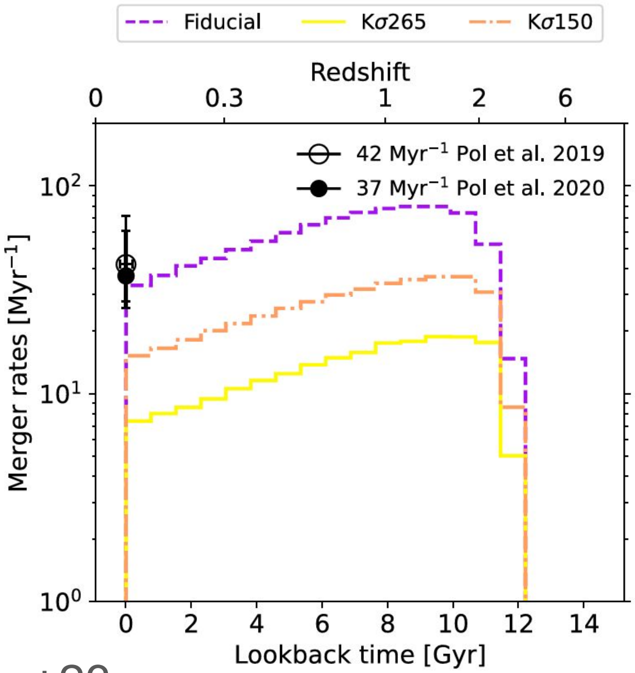


Higher SN kicks:

1 - Disruption of wider binaries, lowering the merger rates

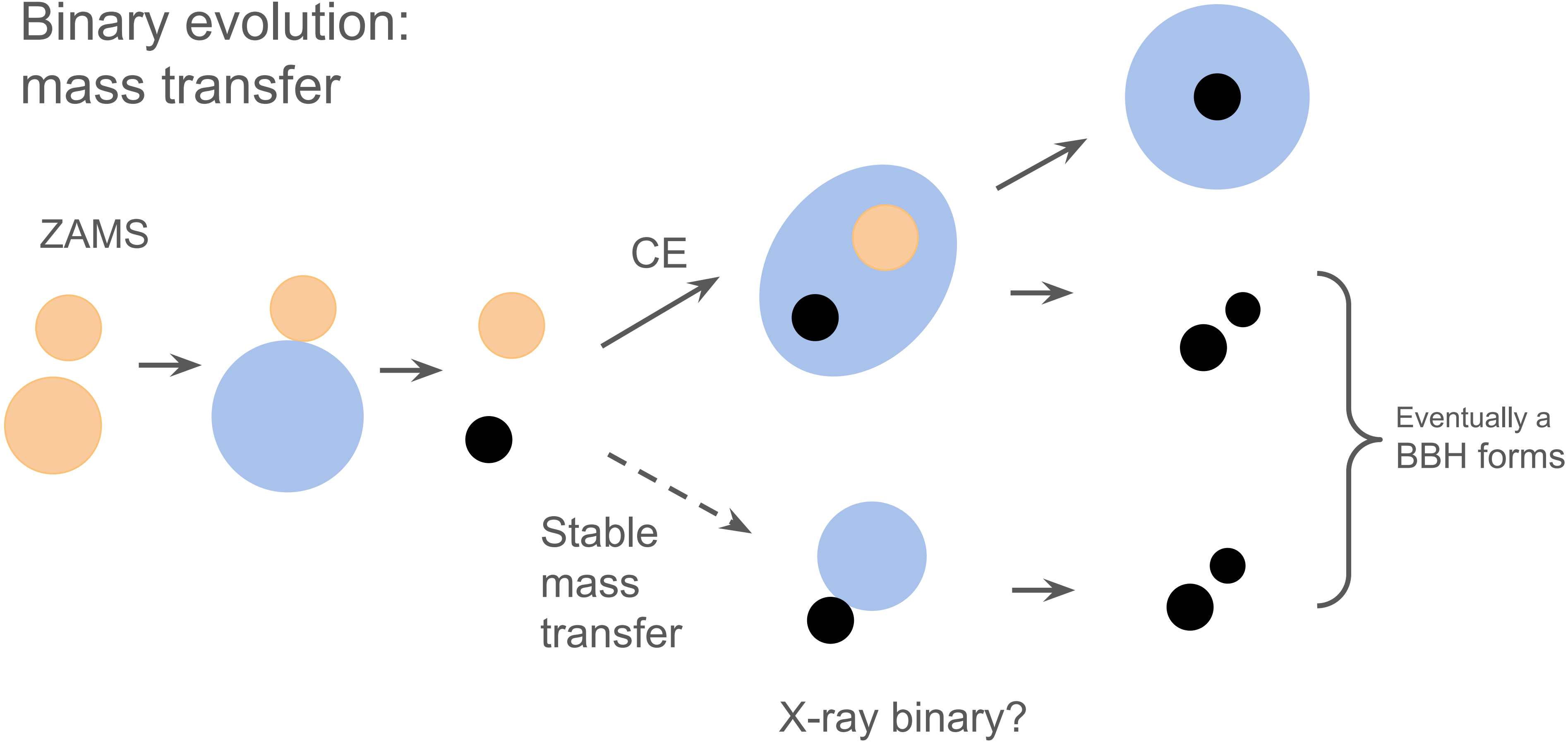
2 - Bias towards higher mass binaries

At low metallicities the ~10 $M_\odot$ peak disappears

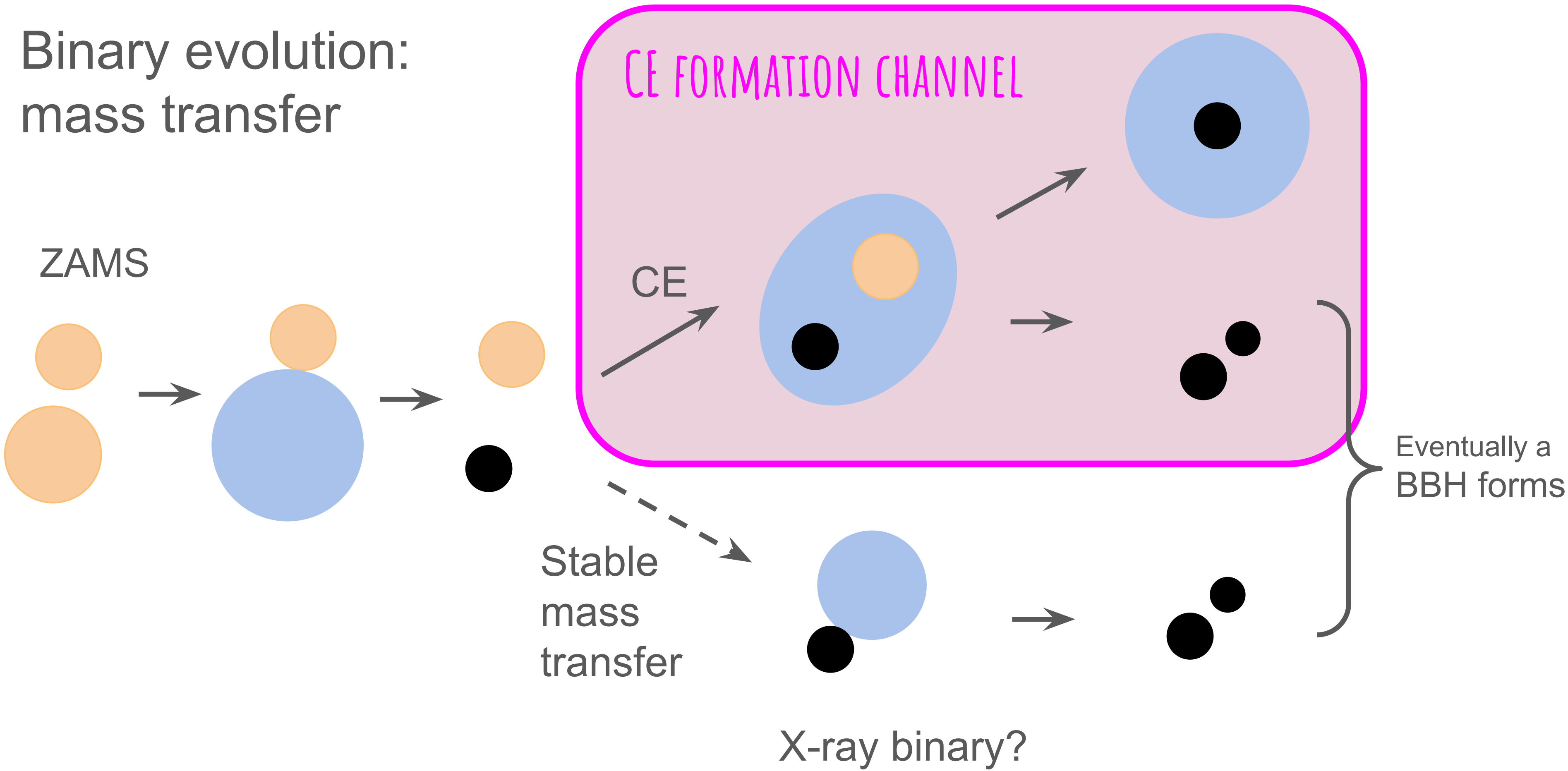


Sgalletta+23

Binary evolution: mass transfer

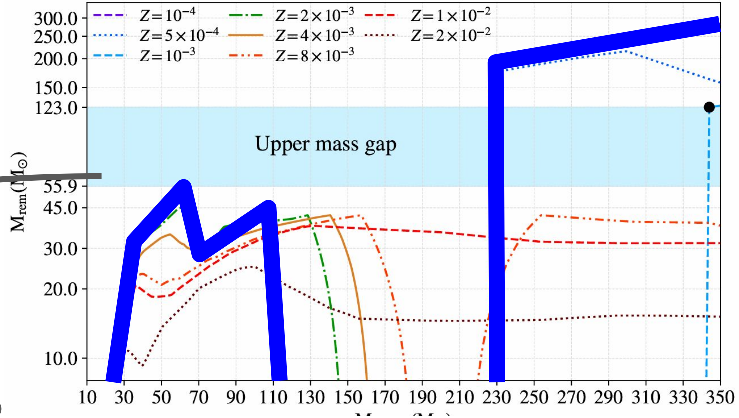


Binary evolution: mass transfer

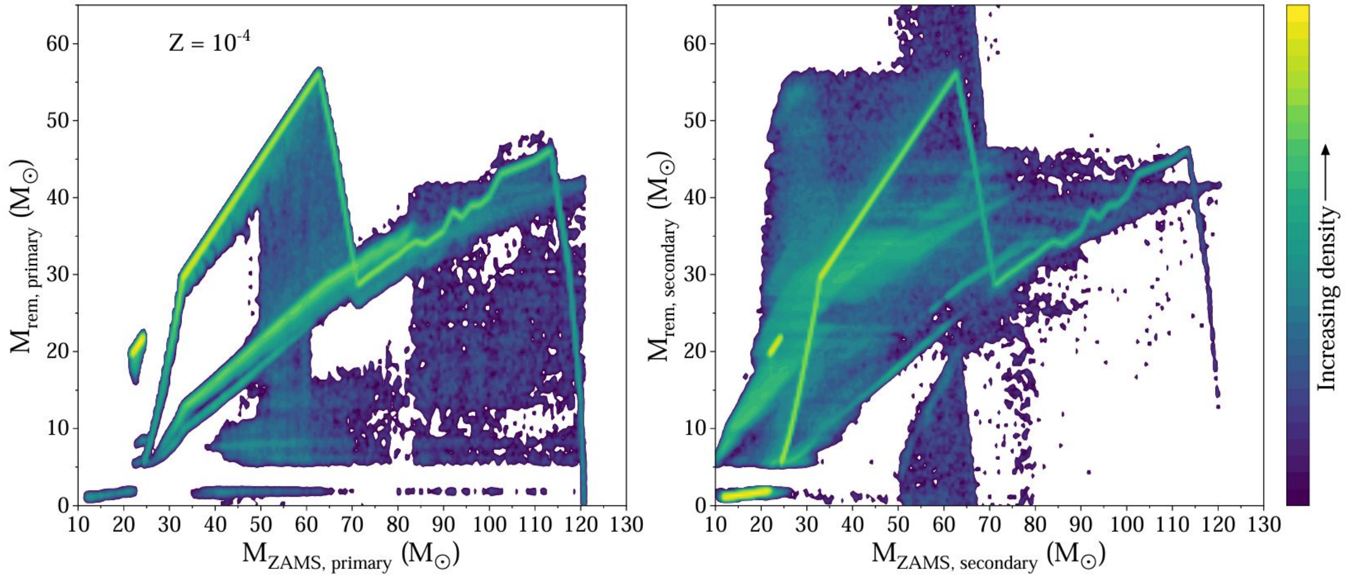


Binary evolution: mass transfer

Binary interactions wildly change the mass spectrum



Spera+23

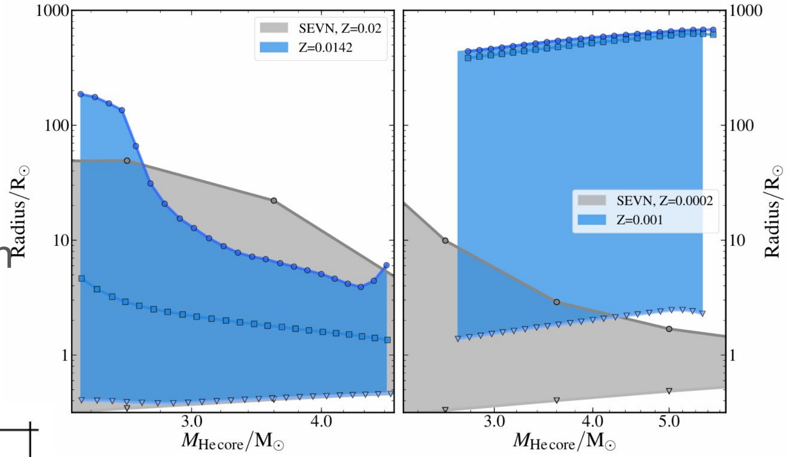


See Spera+23 for a review

Binary evolution: mass transfer uncertainties

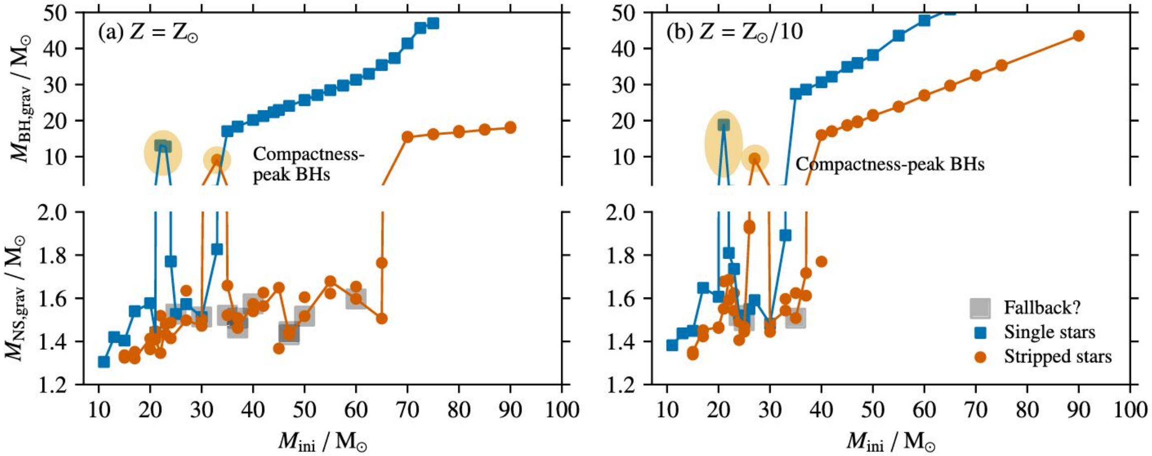
Stellar response to mass transfer

Laplace+20



→ Enhanced radial expansion as a consequence of mass stripping

Schneider+23

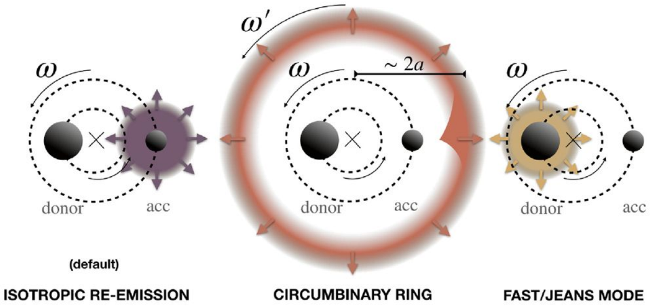


→The response of a star to mass stripping pushes upward the minimum BH mass

Circumbinary disks

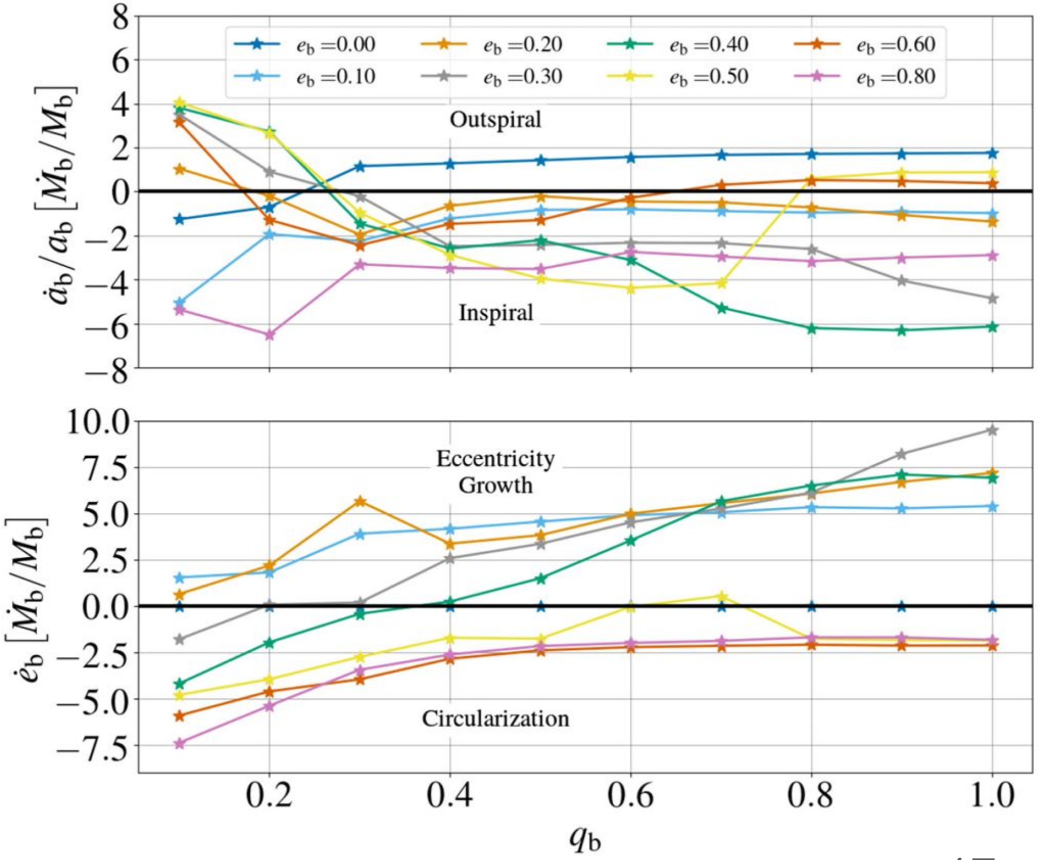
Siwek+23

… what are we missing?



Vinciguerra+20

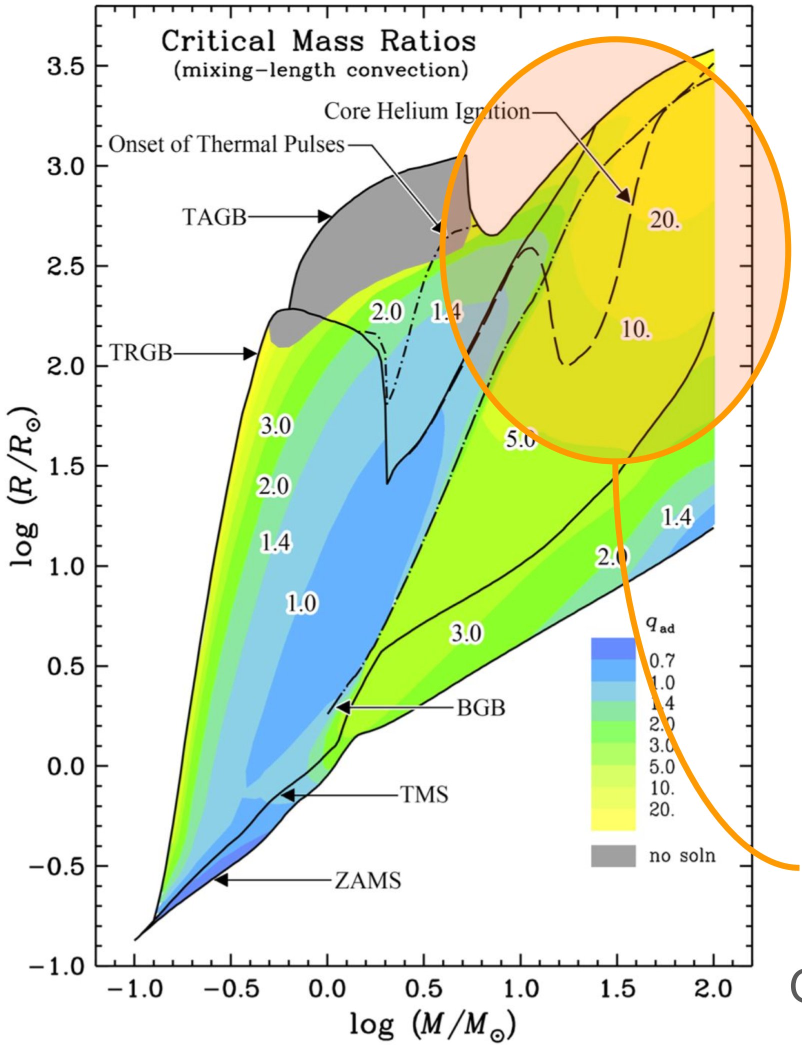
Most common in pop. synth.



Torques exerted from the circumbinary disks can affect the loss of angular momentum and in the end the evolution of the binary

Binary evolution: mass transfer uncertainties

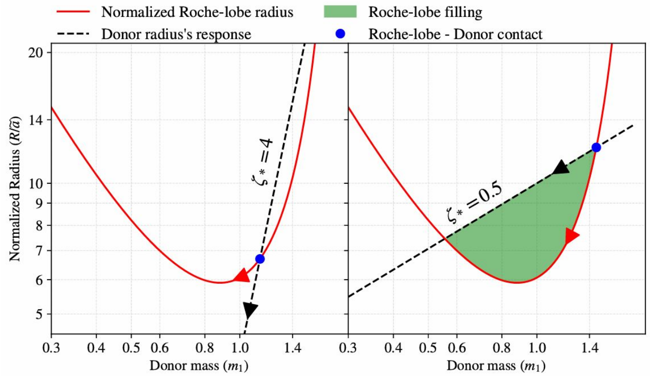
Stability of mass transfer



Ge+20

Pop synth use simplified formalism based on critical mass ratios
q=Md/Ma

Typical critical values:
q=1 – 5

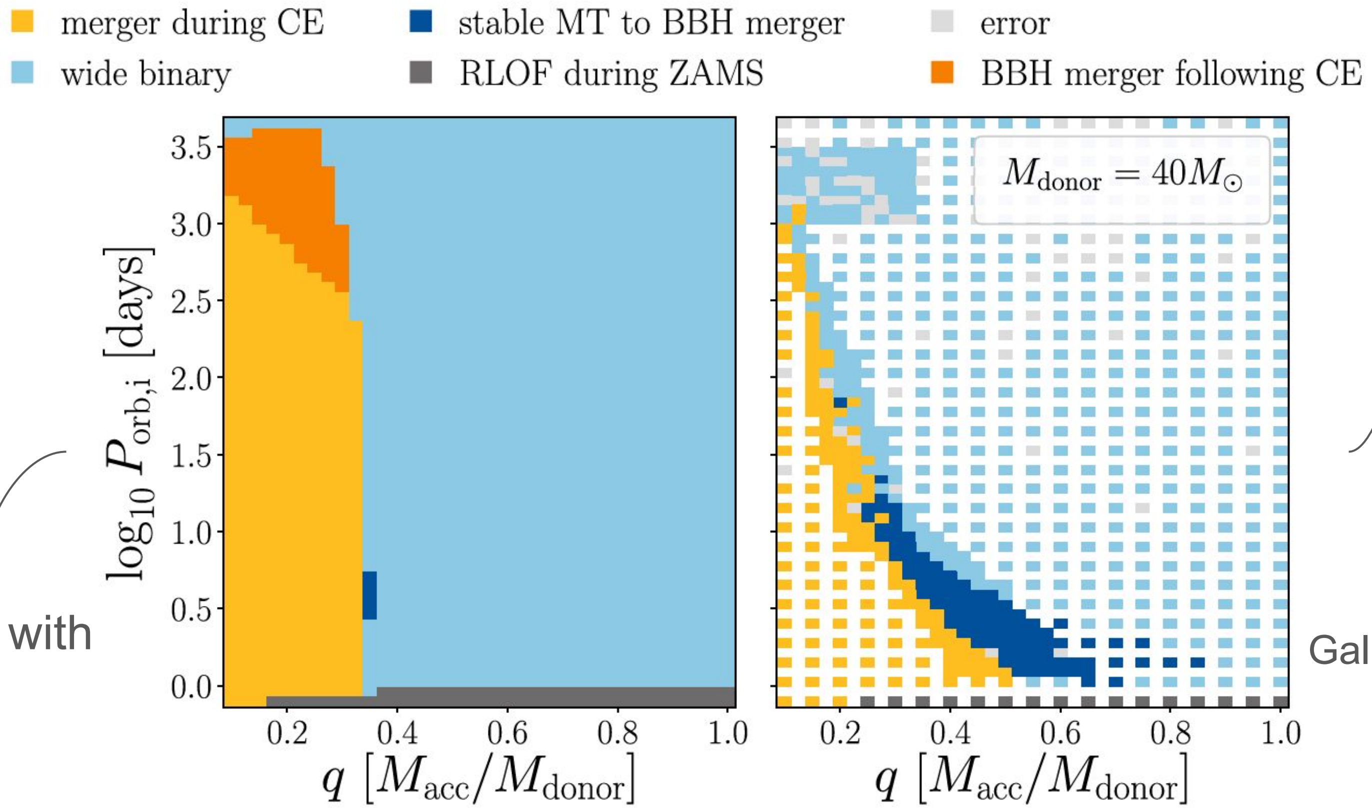


Spera+23

→ Massive donors might be responsible for **stable mass transfer episodes**

Binary evolution: mass transfer uncertainties

Detailed stellar evolution with MESA

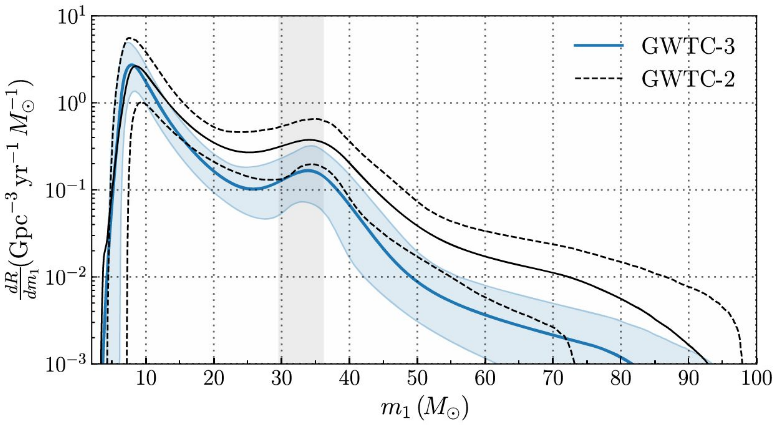


Evolution with COSMIC

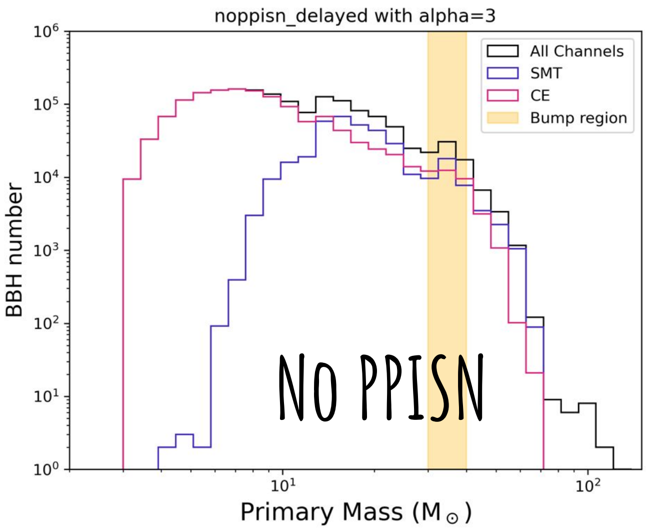
Gallegos-Garcia+21

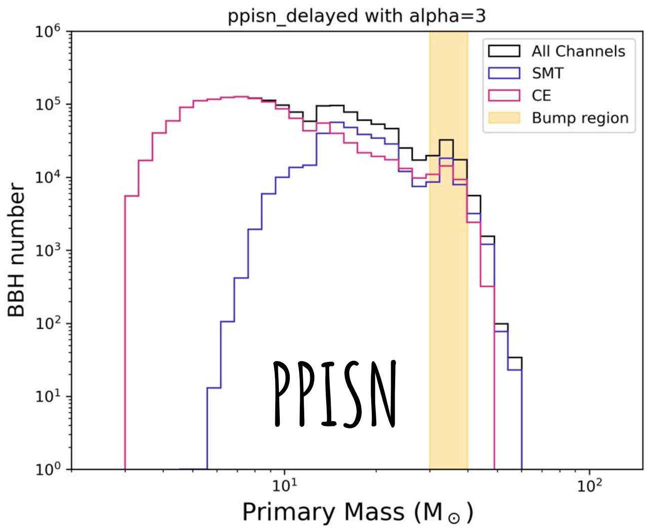
Does the formation channel play a role?

Ugolini et al. in prep



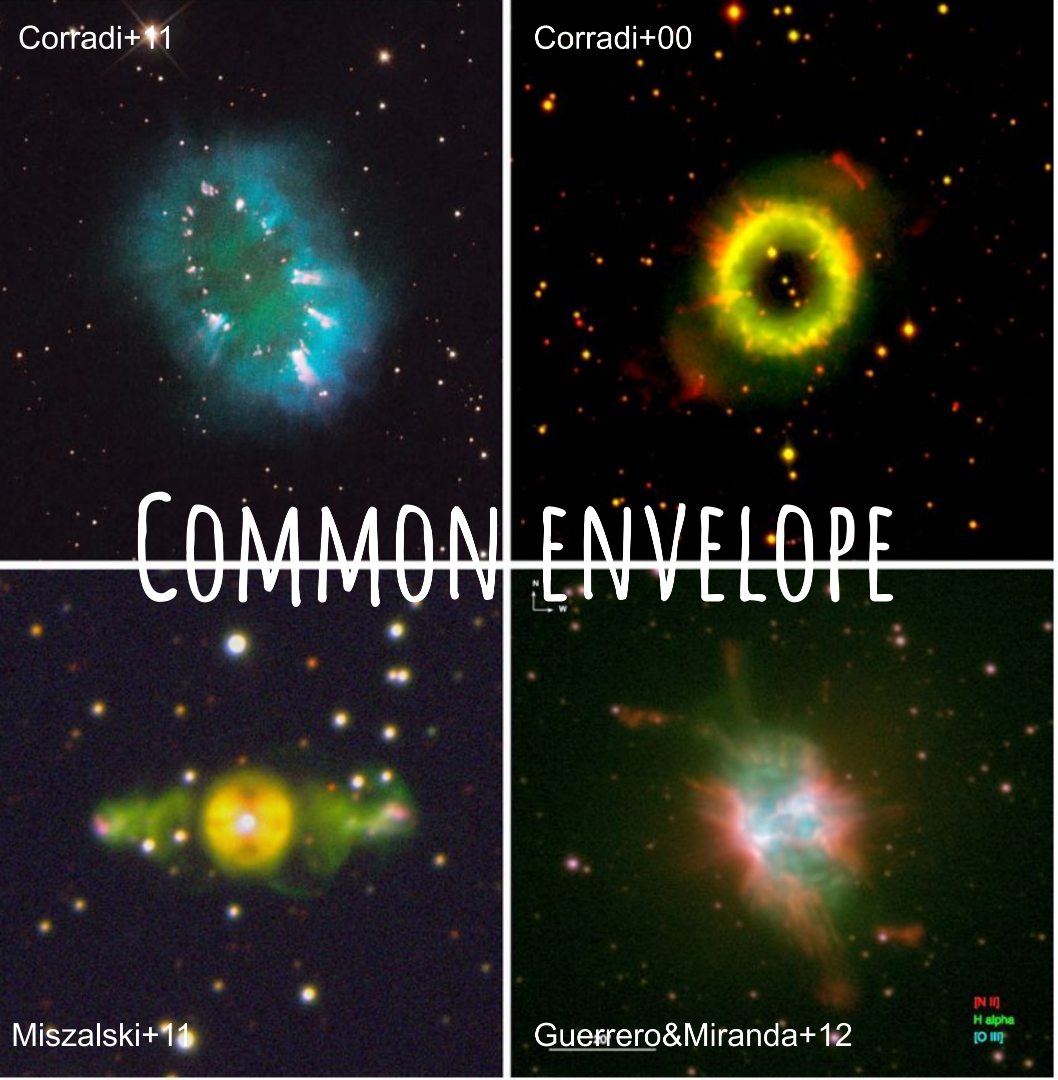
The peak is present also assuming no PPISN !





The stable mass transfer (SMT) channel mergers peak on the bump interval

Common envelope

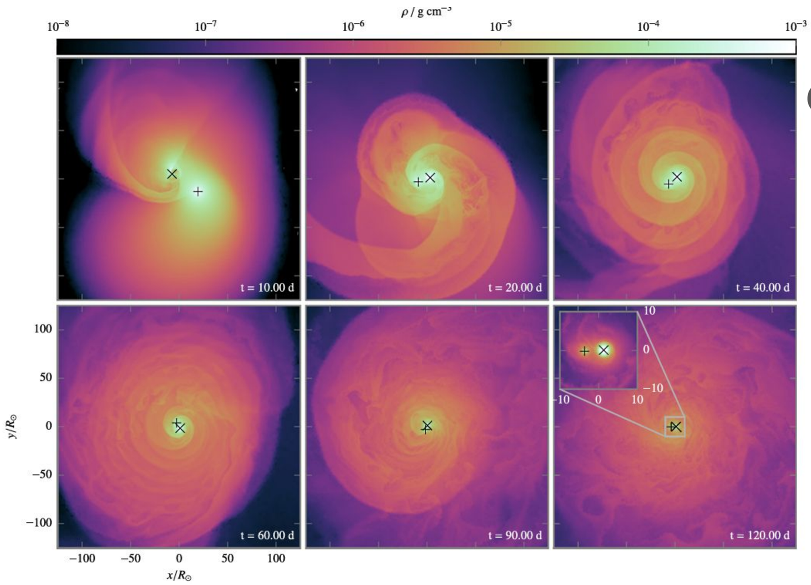


- Initially introduced to explain a compact binary with a white dwarf (Paczynski1976).
- Many more low-mass systems since then can only be explained with a CE
- CE is needed in most cases to explain binaries of remnant of massive stars

Post-CE planetary nebulae with known compact binaries as central objects.

Ivanova+13

Common envelope

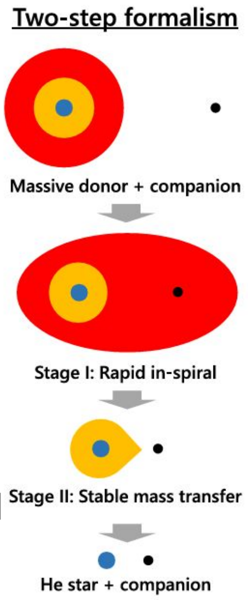


Ohlmann+2016

3D hydrodynamical simulations are needed to capture the asymmetries of this phase

Extremely tricky computationally

Wide range of spatial and timescales involved



Parametric models

Energy-conservation based
(αλ)-formalism

Van den Heuvel 1976, Webbink 1984

Two-stage formalism

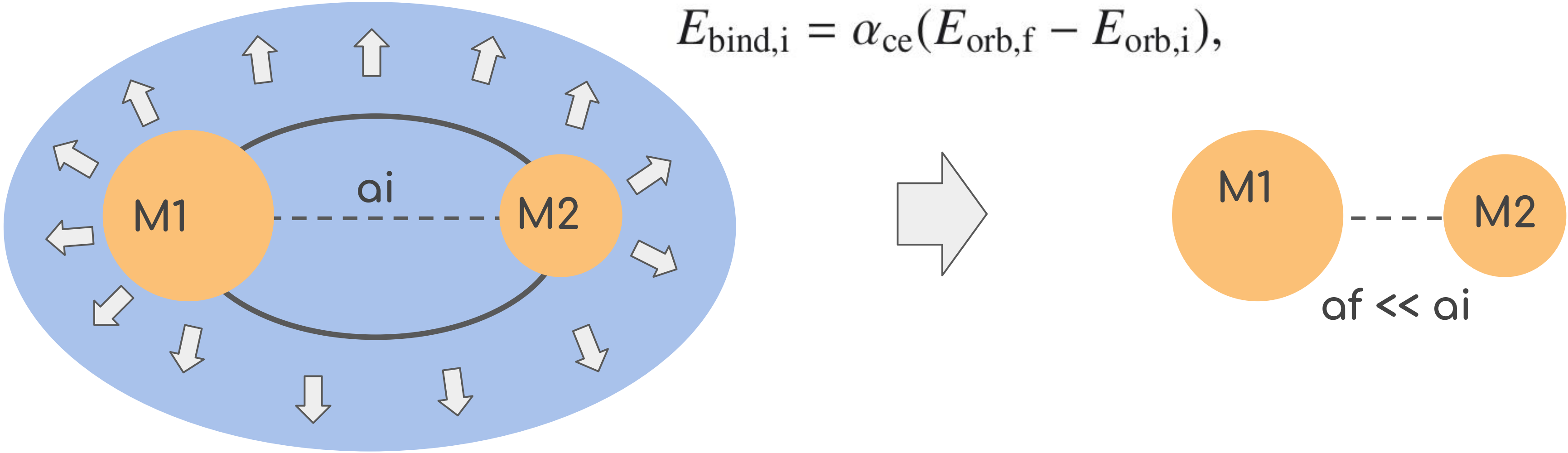
Hirai & Mandel 21

Angular momentum-conservation based
ɣ-formalism

Nelemans+00

(αλ)-formalism

Van den Heuvel 1976,
Webbink 1984



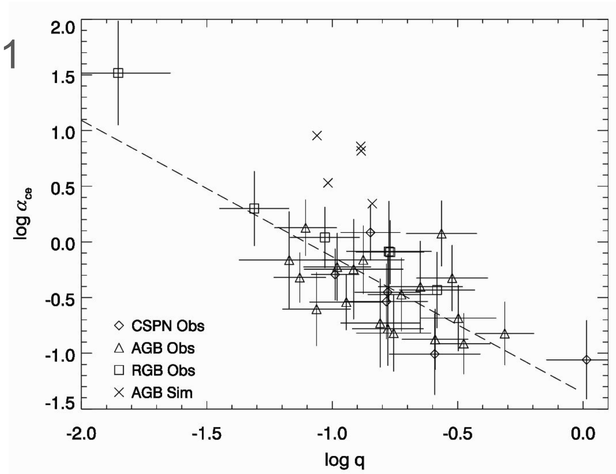
$$E_{\rm bind,i} = \alpha_{\rm ce}(E_{\rm orb,f} - E_{\rm orb,i}),$$

$$E_{\rm bind,i} = -G\left(\frac{M_1\, M_{\rm env1}}{\lambda_{\rm CE1} R_1} + \frac{M_2\, M_{\rm env2}}{\lambda_{\rm CE2} R_2}\right),$$

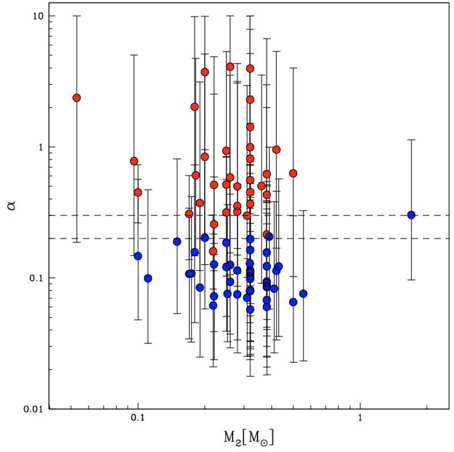
The second parameter is directly linked to the stellar structure of the star

Common envelope: uncertainties on the α parameter

De Marco+11

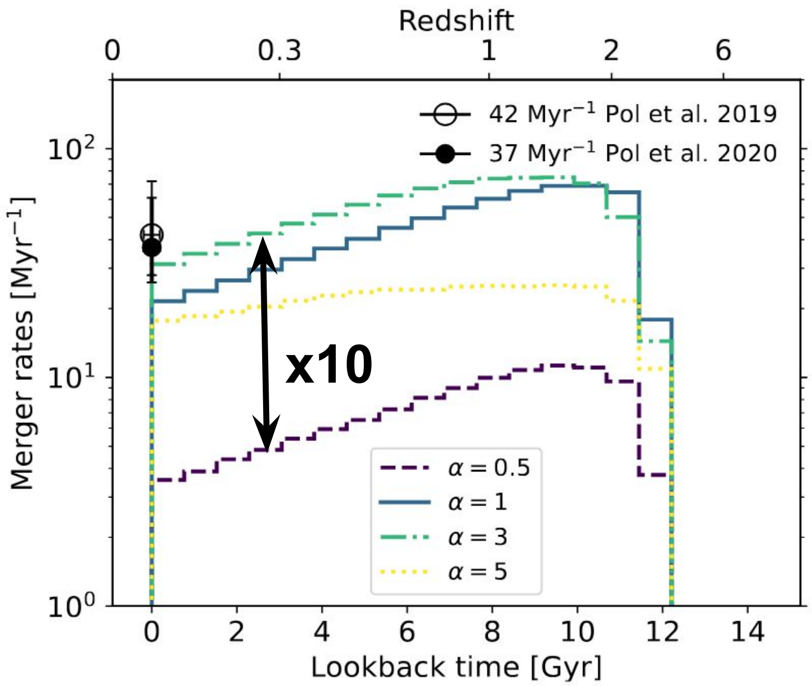


Zorotovic+10



WDs observations

- α smaller than 1
- possible dependence with masses?



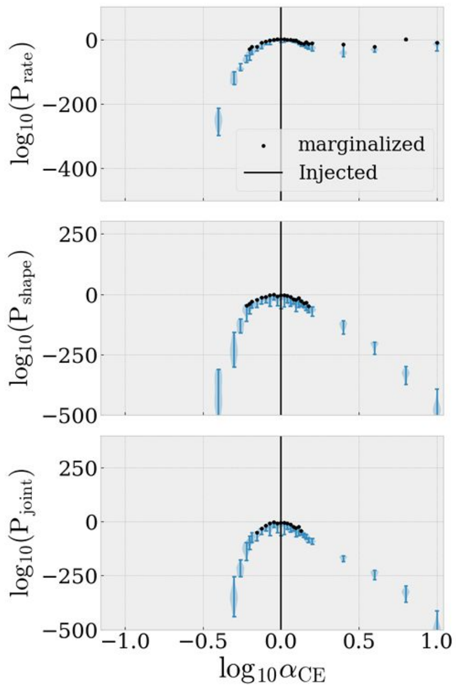
Sgalletta+23

BNSs binary population synthesis simulations

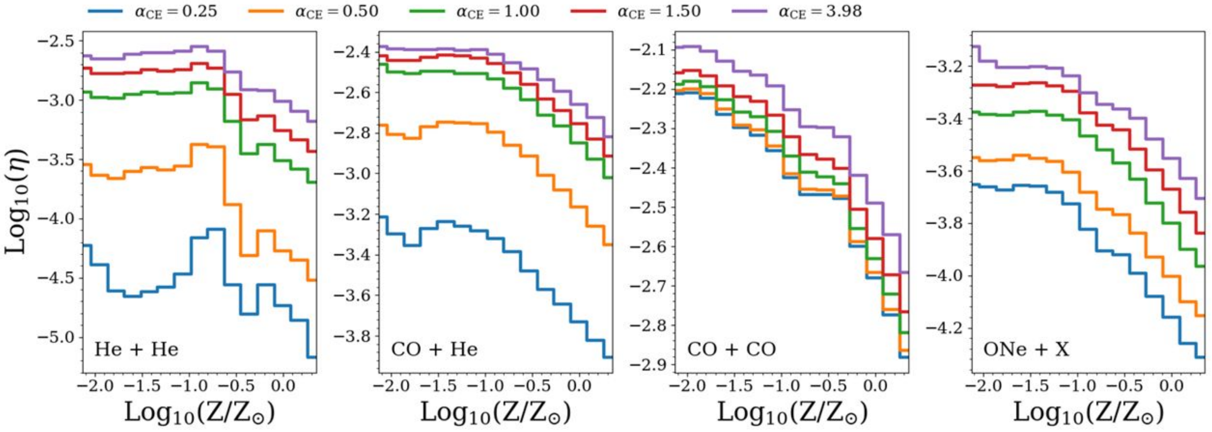
Common envelope: uncertainties on the α parameter

WILL WE BE ABLE TO RECOVER α FROM LISA OBSERVATIONS?

The joint likelihood of both the rate and shape of the different populations can be used to retrieve α

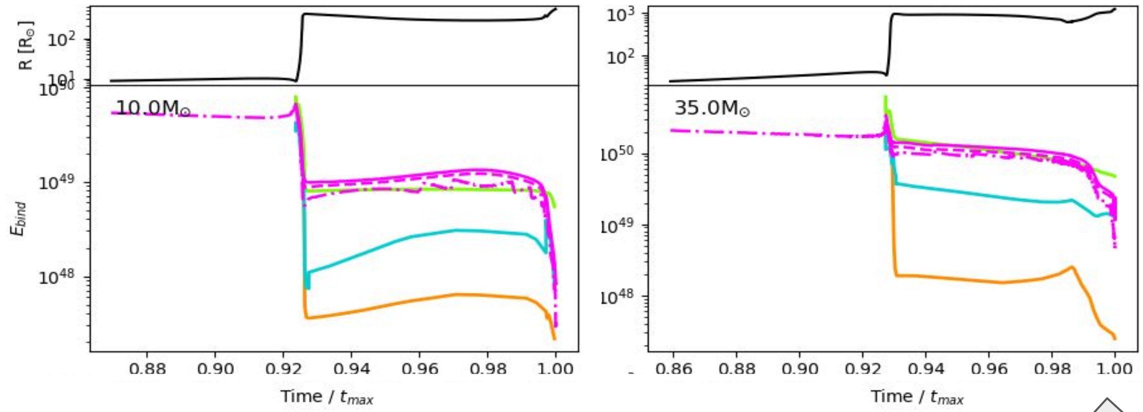


DWD FORMATION EFFICIENCY



Delfavero+24

Common envelope: the stellar structure problem

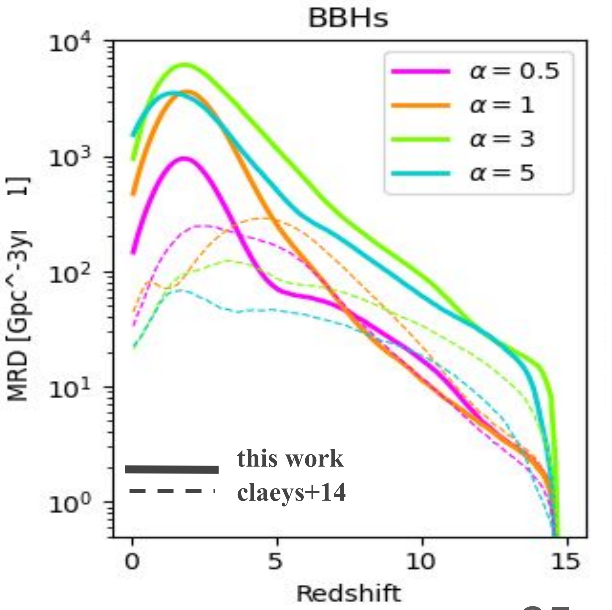


Sgalletta et al. in prep

- Core-envelope definitions uncertainties

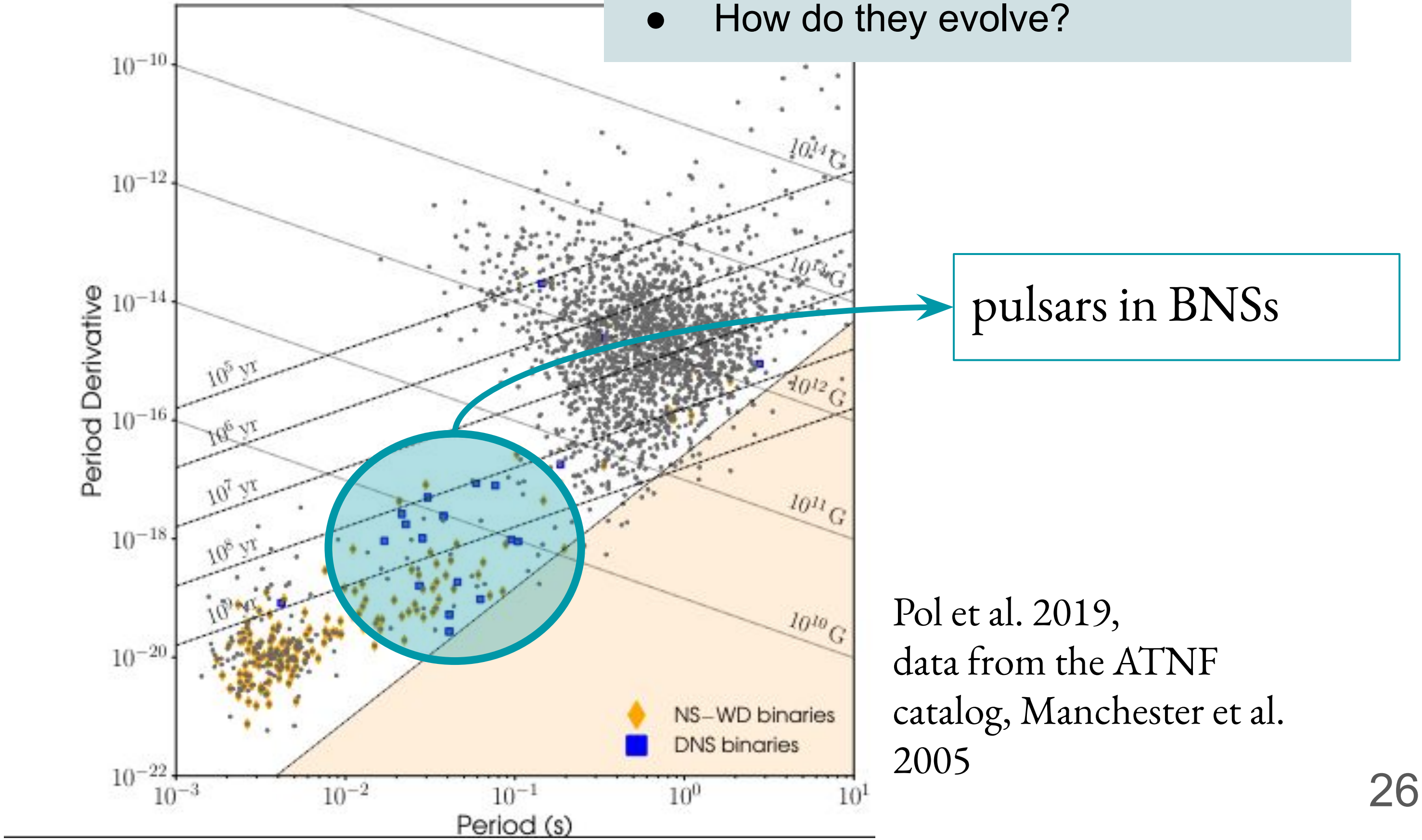
- Fits to different stellar tracks produce different results

Big changes in the merger rate density



Population of BNSs

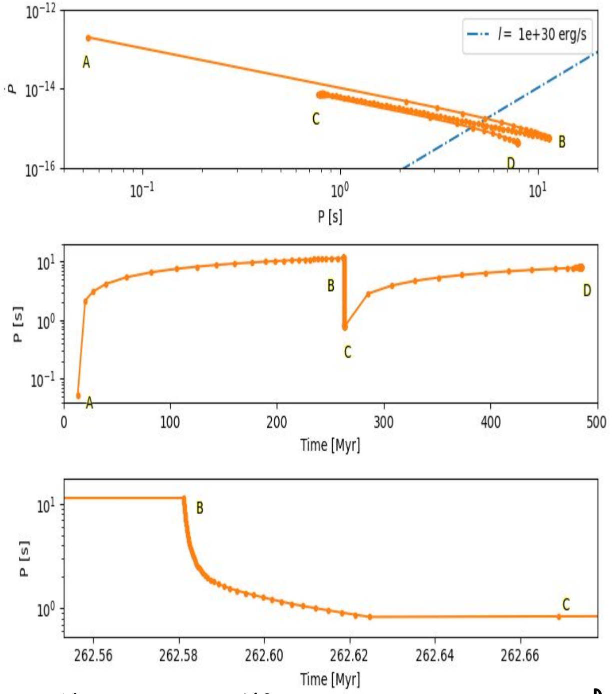
- What are the birth magnetic fields and spin periods?
- How do they evolve?



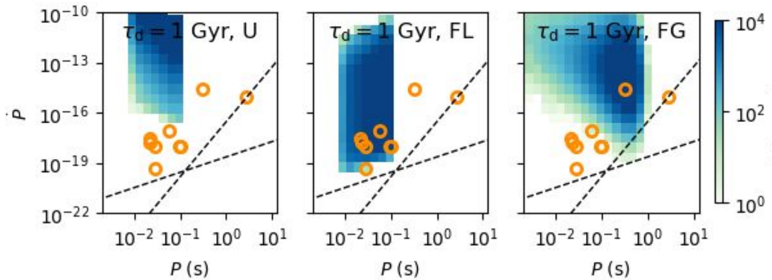
Pol et al. 2019,
data from the ATNF catalog, Manchester et al. 2005

Population of BNSs

Sgalletta+23

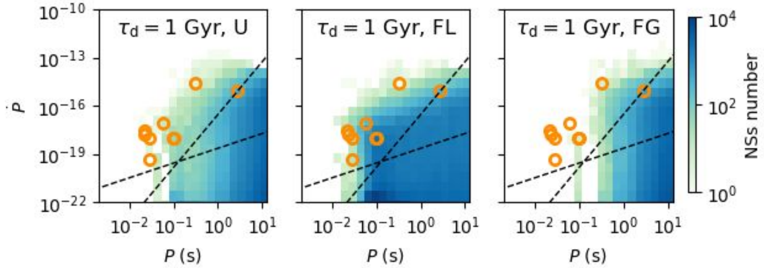


Modelling of NS spin-down and spin-up

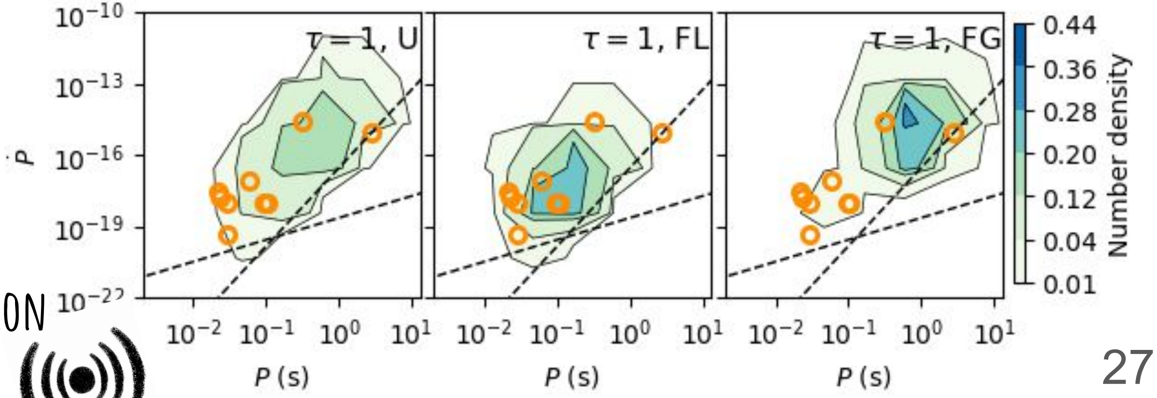


Initial distributions

Evolution in the MW

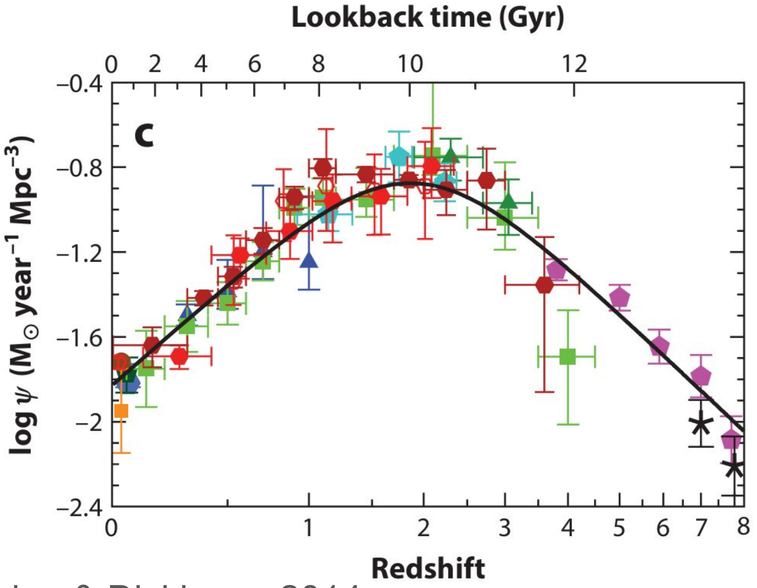


Radio selection effects

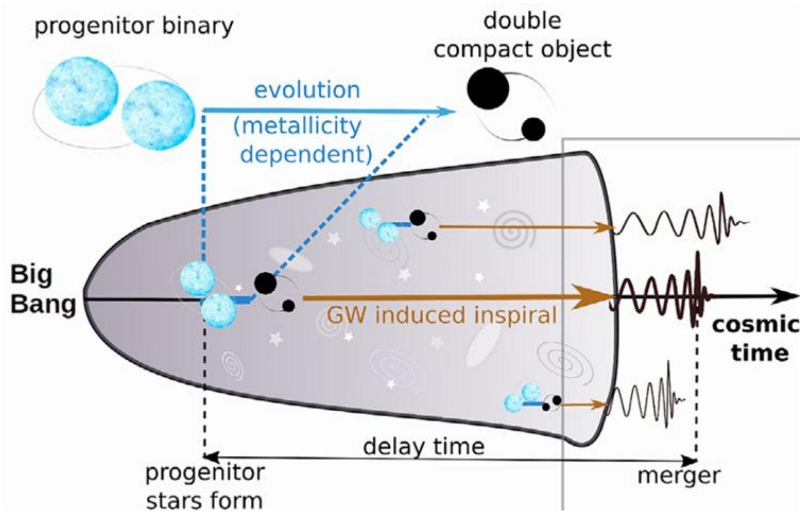


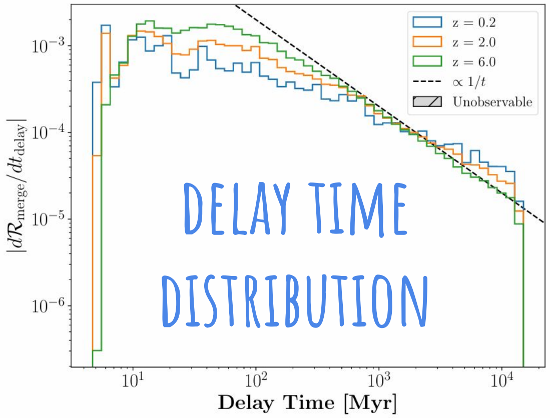
Cosmological context

The evolution of the universe and properties of the host galaxies is key in understanding the observations of GWs



Madau & Dickinson 2014





Boesky+24

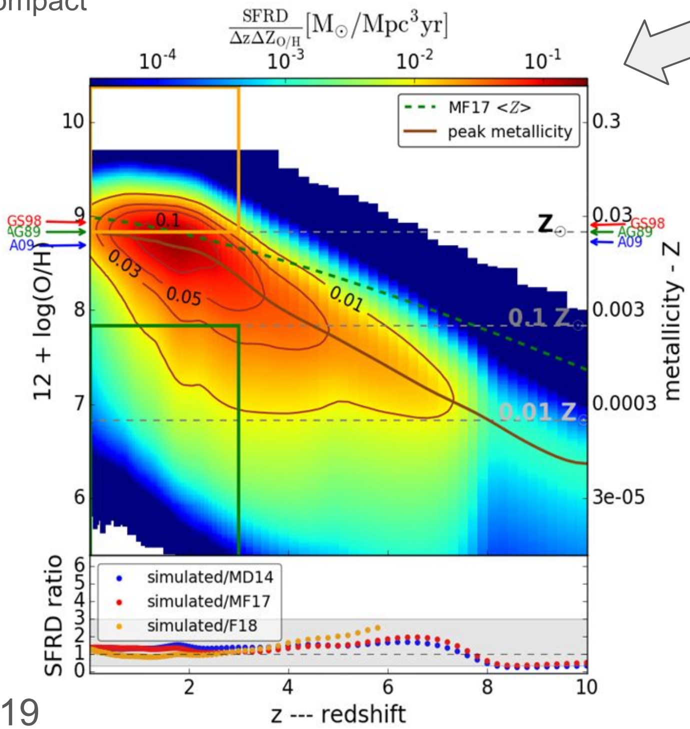
see Chruslinska2024 for a review

Cosmological context

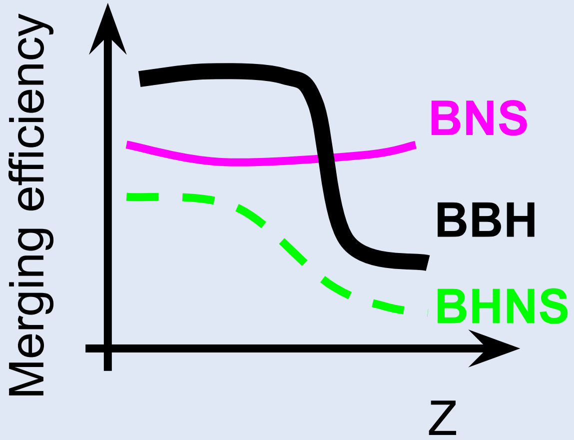
The metallicity-dependent cosmic star formation history can significantly affect the properties of binary compact object mergers

Major issues:

1. Star-forming metallicities are poorly constrained at z>3 (JWST will improve it!)
2. Low-mass galaxy properties are more difficult to observe and poorly constrained
3. Metallicity calibration issues



Chruslinska+19

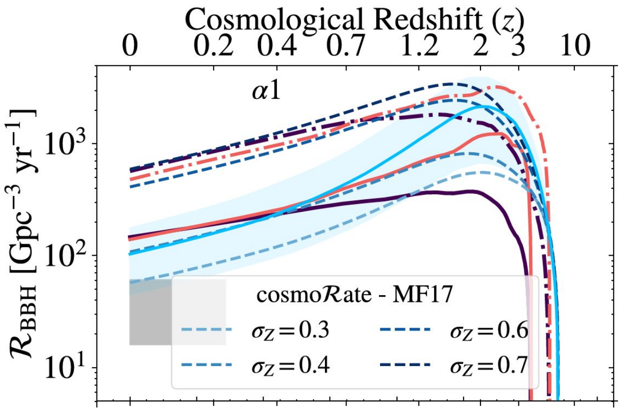


- stellar winds
- SN kicks
- radial expansion

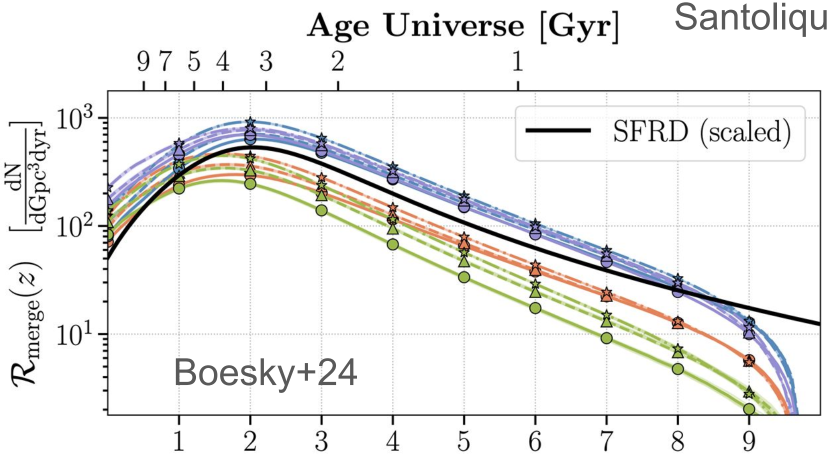
see Chruslinska2024 for a review

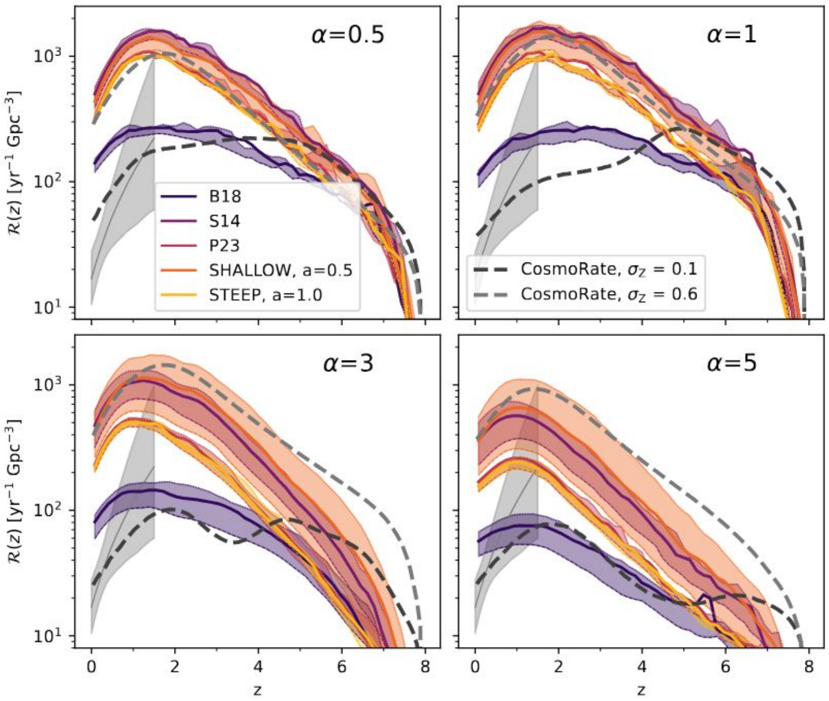
Cosmological context

Better models of the universe lead to higher BBHs merger rates, compared to the LVK data



Santoliquido+22

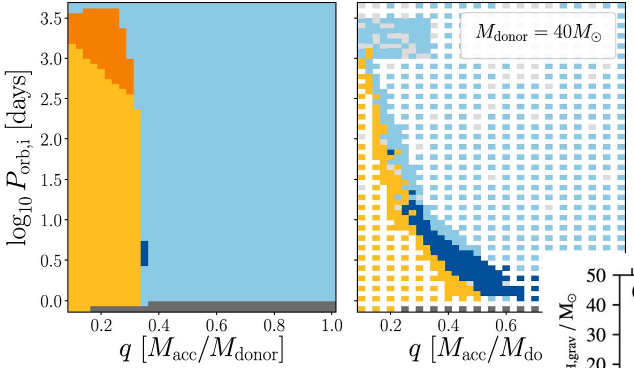




Sgalletta et al in prep.

Galaxy observational scaling relation uncertainties cannot account for the discrepancy

Cosmological context

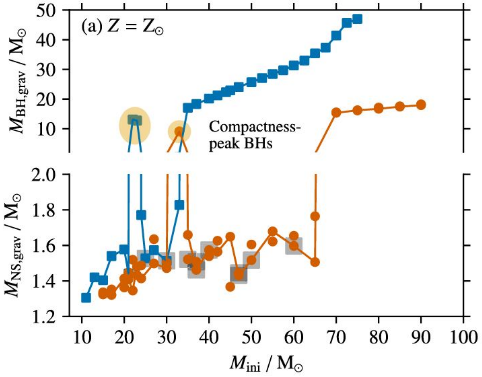


Gallegos-Garcia+21

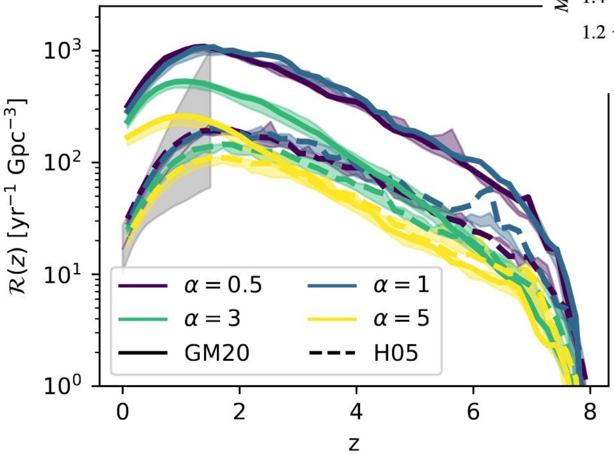
1. Too many systems survive CE?

2. Stripped stars should produce less BHs?

3. SN kicks should be higher?



Schneider+23



Sgalletta et al. in prep

Lots of parameters,

lots of degeneracies,

Lots of possibilities ...

How can we move forward?