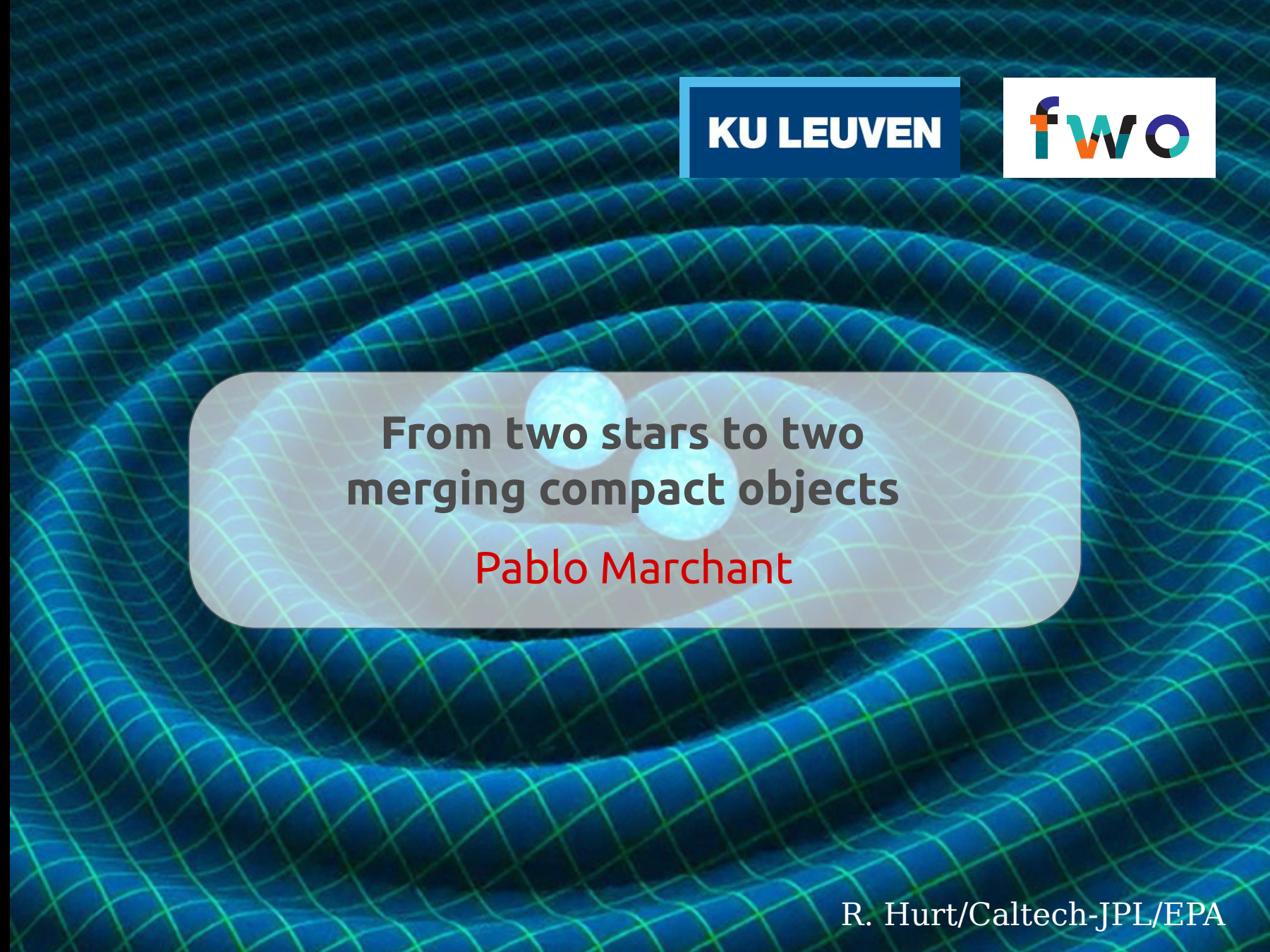

KU LEUVEN
fwo
From two stars to two
merging compact objects
Pablo Marchant
R. Hurt/Caltech-JPL/EPA

More and more GW detections



LIGO Hanford detector

More and more GW detections

- A gravitational wave produces a relative change in lengths

$$\frac{\Delta L}{L} = h(t) \propto \frac{1}{D_L}$$

- A gravitational wave produces a relative change in lengths

$$s(t) = n(t) + h(t)$$

More and more GW detections

- Main measured quantity, the chirp mass.

$$M_{\rm chirp} = \frac{(m_1 m_2)^{3/5}}{(m_1+m_2)^{1/5}}$$

- To second order, the mass ratio and the effective spin.

$$q = \frac{m_1}{m_2}, \qquad \chi_{\rm eff} = \frac{\chi_1 m_1 + \chi_2 m_2}{m_1+m_2}$$

  and there is a strong degeneracy between these two (Hannam et al. 2013)

- Eccentricities expected to be very small on the LIGO band.

More and more GW detections





More and more GW detections

Abbott et al. (2016), astro-ph/1606.04856

Black hole mergers in LIGOs 1st observing run

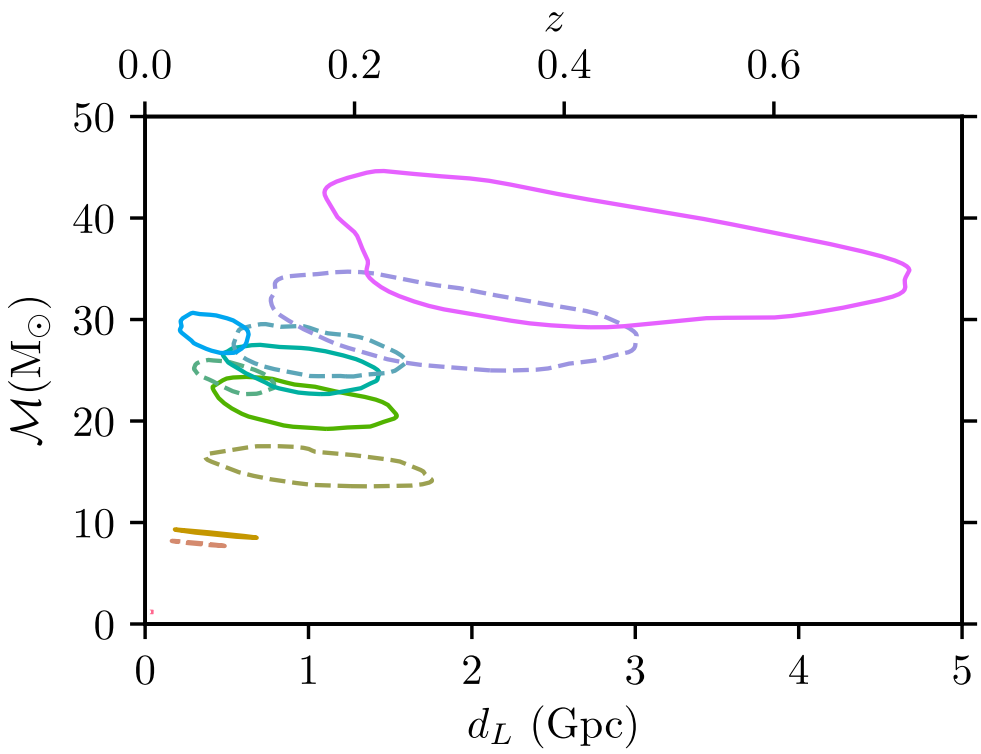
More and more GW detections

Abbott et al. (2018), astro-ph/1811.12907

Event	$m_1/M_\odot$	$m_2/M_\odot$	$\mathcal{M}/M_\odot$	$\chi_{\rm eff}$	$M_{\rm f}/M_\odot$	$a_{\rm f}$	$E_{\rm rad}/(M_\odot c^2)$	$\ell_{\rm peak}/({\rm erg\ s^{-1}})$	$d_L/{\rm Mpc}$	z	$\Delta\Omega/{\rm deg}^2$
GW150914	$35.6^{+4.8}_{-3.0}$	$30.6^{+3.0}_{-4.4}$	$28.6^{+1.6}_{-1.5}$	$-0.01^{+0.12}_{-0.13}$	$63.1^{+3.3}_{-3.0}$	$0.69^{+0.05}_{-0.04}$	$3.1^{+0.4}_{-0.4}$	$3.6^{+0.4}_{-0.4}\times10^{56}$	430^{+150}_{-170}	$0.09^{+0.03}_{-0.03}$	180
GW151012	$23.3^{+14.0}_{-5.5}$	$13.6^{+4.1}_{-4.8}$	$15.2^{+2.0}_{-1.1}$	$0.04^{+0.28}_{-0.19}$	$35.7^{+9.9}_{-3.8}$	$0.67^{+0.13}_{-0.11}$	$1.5^{+0.5}_{-0.5}$	$3.2^{+0.8}_{-1.7}\times10^{56}$	1060^{+540}_{-480}	$0.21^{+0.09}_{-0.09}$	1555
GW151226	$13.7^{+8.8}_{-3.2}$	$7.7^{+2.2}_{-2.6}$	$8.9^{+0.3}_{-0.3}$	$0.18^{+0.20}_{-0.12}$	$20.5^{+6.4}_{-1.5}$	$0.74^{+0.07}_{-0.05}$	$1.0^{+0.1}_{-0.2}$	$3.4^{+0.7}_{-1.7}\times10^{56}$	440^{+180}_{-190}	$0.09^{+0.04}_{-0.04}$	1033
GW170104	$31.0^{+7.2}_{-5.6}$	$20.1^{+4.9}_{-4.5}$	$21.5^{+2.1}_{-1.7}$	$-0.04^{+0.17}_{-0.20}$	$49.1^{+5.2}_{-3.9}$	$0.66^{+0.08}_{-0.10}$	$2.2^{+0.5}_{-0.5}$	$3.3^{+0.6}_{-0.9}\times10^{56}$	960^{+430}_{-410}	$0.19^{+0.07}_{-0.08}$	924
GW170608	$10.9^{+5.3}_{-1.7}$	$7.6^{+1.3}_{-2.1}$	$7.9^{+0.2}_{-0.2}$	$0.03^{+0.19}_{-0.07}$	$17.8^{+3.2}_{-0.7}$	$0.69^{+0.04}_{-0.04}$	$0.9^{+0.05}_{-0.1}$	$3.5^{+0.4}_{-1.3}\times10^{56}$	320^{+120}_{-110}	$0.07^{+0.02}_{-0.02}$	396
GW170729	$50.6^{+16.6}_{-10.2}$	$34.3^{+9.1}_{-10.1}$	$35.7^{+6.5}_{-4.7}$	$0.36^{+0.21}_{-0.25}$	$80.3^{+14.6}_{-10.2}$	$0.81^{+0.07}_{-0.13}$	$4.8^{+1.7}_{-1.7}$	$4.2^{+0.9}_{-1.5}\times10^{56}$	2750^{+1350}_{-1320}	$0.48^{+0.19}_{-0.20}$	1033
GW170809	$35.2^{+8.3}_{-6.0}$	$23.8^{+5.2}_{-5.1}$	$25.0^{+2.1}_{-1.6}$	$0.07^{+0.16}_{-0.16}$	$56.4^{+5.2}_{-3.7}$	$0.70^{+0.08}_{-0.09}$	$2.7^{+0.6}_{-0.6}$	$3.5^{+0.6}_{-0.9}\times10^{56}$	990^{+320}_{-380}	$0.20^{+0.05}_{-0.07}$	340
GW170814	$30.7^{+5.7}_{-3.0}$	$25.3^{+2.9}_{-4.1}$	$24.2^{+1.4}_{-1.1}$	$0.07^{+0.12}_{-0.11}$	$53.4^{+3.2}_{-2.4}$	$0.72^{+0.07}_{-0.05}$	$2.7^{+0.4}_{-0.3}$	$3.7^{+0.4}_{-0.5}\times10^{56}$	580^{+160}_{-210}	$0.12^{+0.03}_{-0.04}$	87
GW170817	$1.46^{+0.12}_{-0.10}$	$1.27^{+0.09}_{-0.09}$	$1.186^{+0.001}_{-0.001}$	$0.00^{+0.02}_{-0.01}$	≤ 2.8	≤ 0.89	≥ 0.04	$\geq 0.1\times10^{56}$	40^{+10}_{-10}	$0.01^{+0.00}_{-0.00}$	16
GW170818	$35.5^{+7.5}_{-4.7}$	$26.8^{+4.3}_{-5.2}$	$26.7^{+2.1}_{-1.7}$	$-0.09^{+0.18}_{-0.21}$	$59.8^{+4.8}_{-3.8}$	$0.67^{+0.07}_{-0.08}$	$2.7^{+0.5}_{-0.5}$	$3.4^{+0.5}_{-0.7}\times10^{56}$	1020^{+430}_{-360}	$0.20^{+0.07}_{-0.07}$	39
GW170823	$39.6^{+10.0}_{-6.6}$	$29.4^{+6.3}_{-7.1}$	$29.3^{+4.2}_{-3.2}$	$0.08^{+0.20}_{-0.22}$	$65.6^{+9.4}_{-6.6}$	$0.71^{+0.08}_{-0.10}$	$3.3^{+0.9}_{-0.8}$	$3.6^{+0.6}_{-0.9}\times10^{56}$	1850^{+840}_{-840}	$0.34^{+0.13}_{-0.14}$	1651

BHBH and NSNS mergers in the 2nd observing run
(see also Zackay et al. 2019)

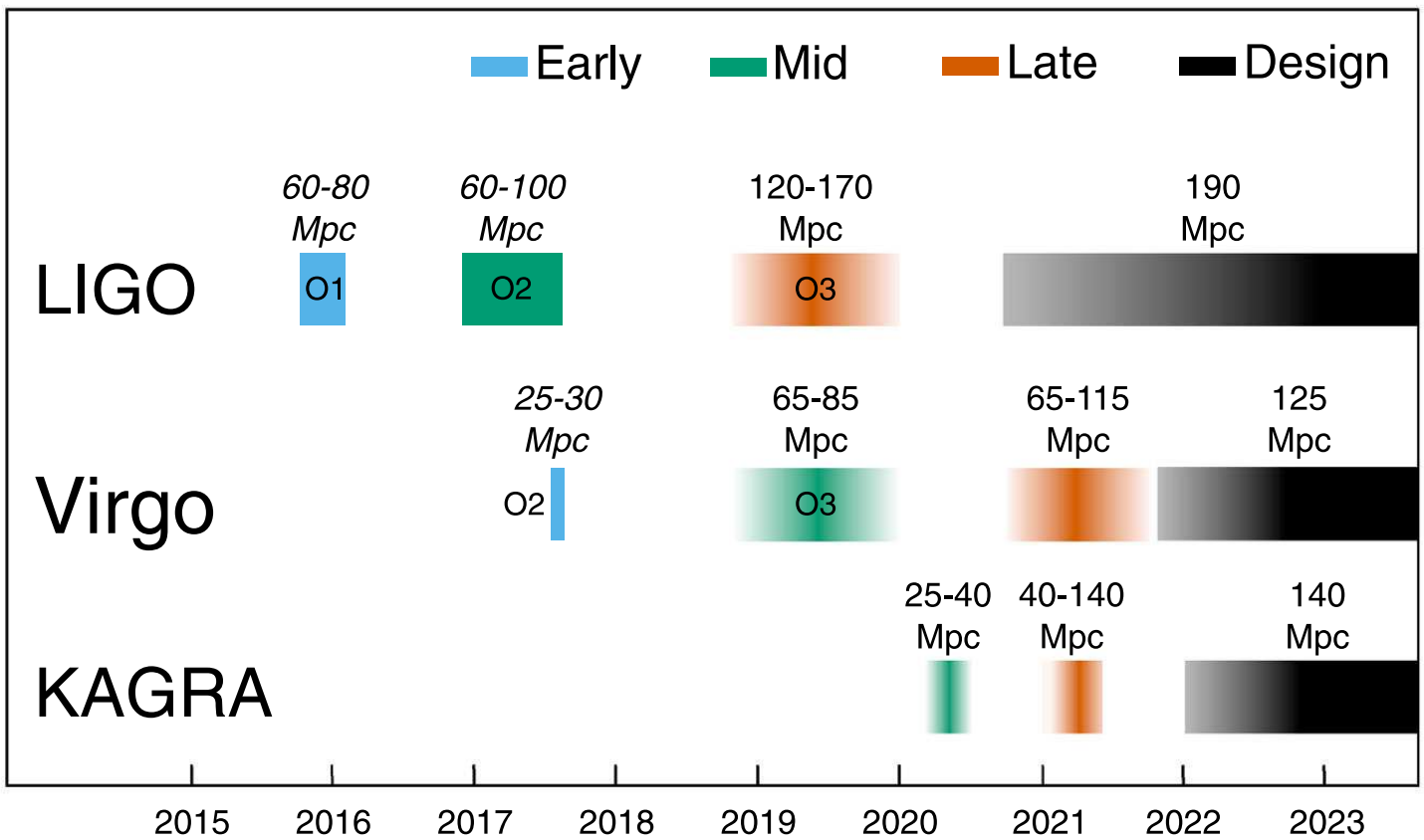
More and more GW detections



GW170817 GW151226 GW170104 GW170809 GW150914 GW170729
GW170608 GW151012 GW170814 GW170818 GW170823

The near future

Abbott, B.P., et al. Living Rev Relativ (2018) 21: 3.

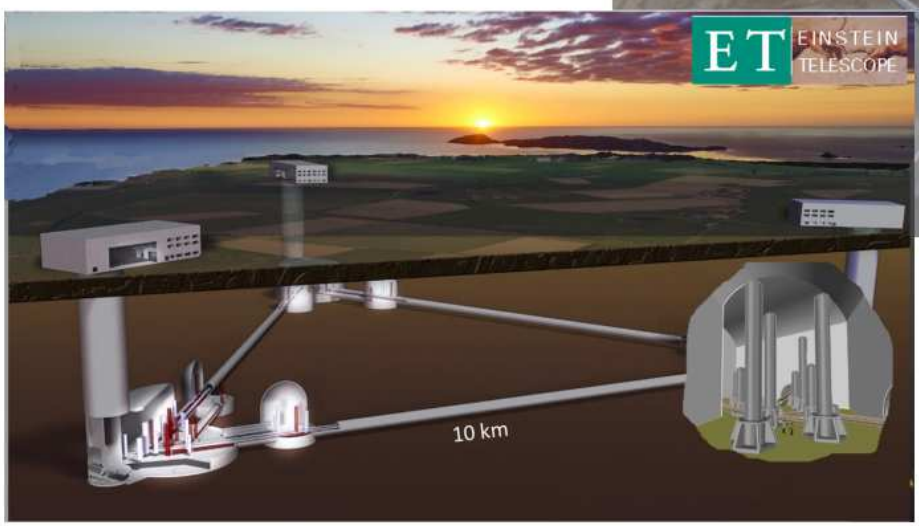


O3 detecting tons of stuff! (gracedb.ligo.org)

The far future



Punturo et al. (2010)



Abbott et al. (2017)
(astro-ph/1607.08697)

The far future

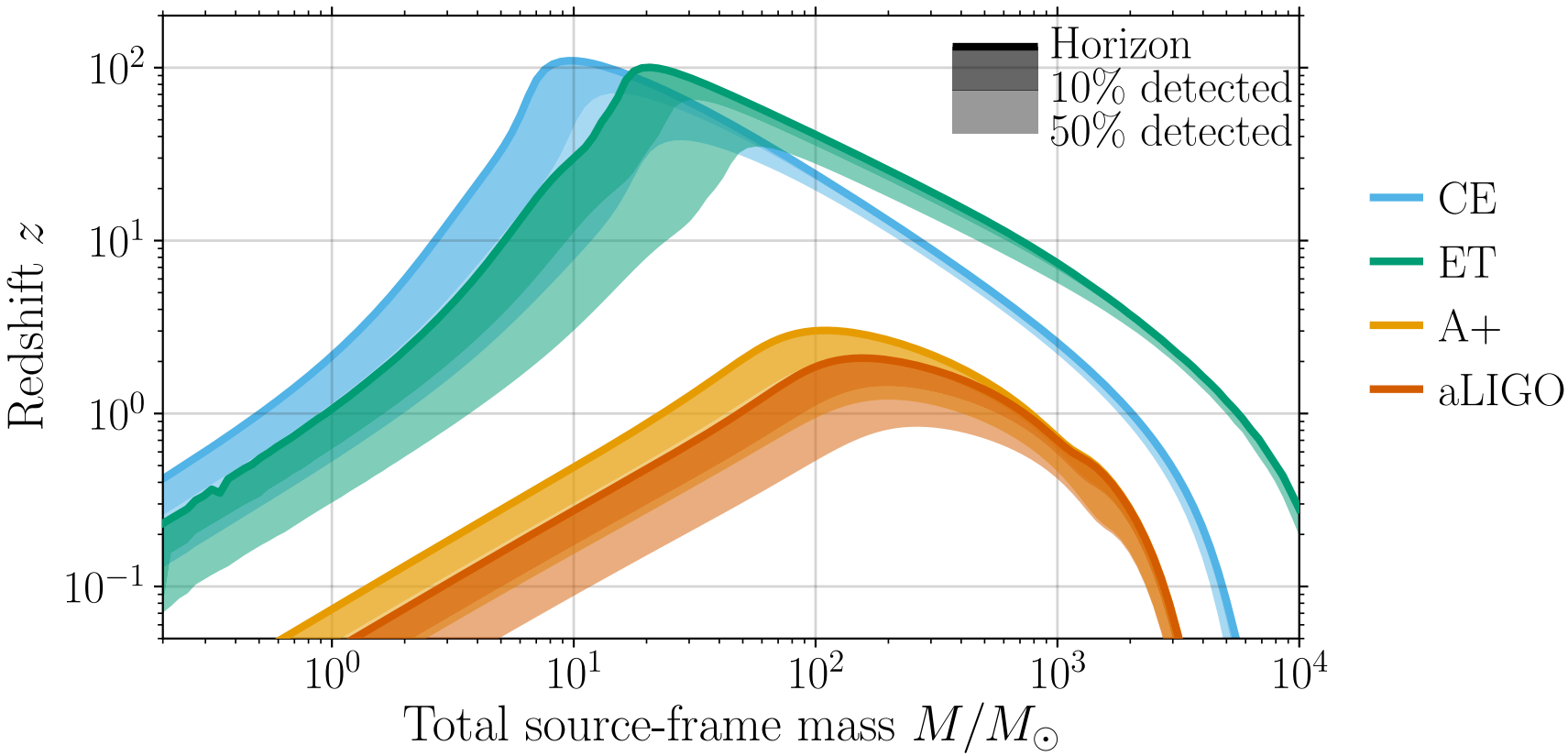
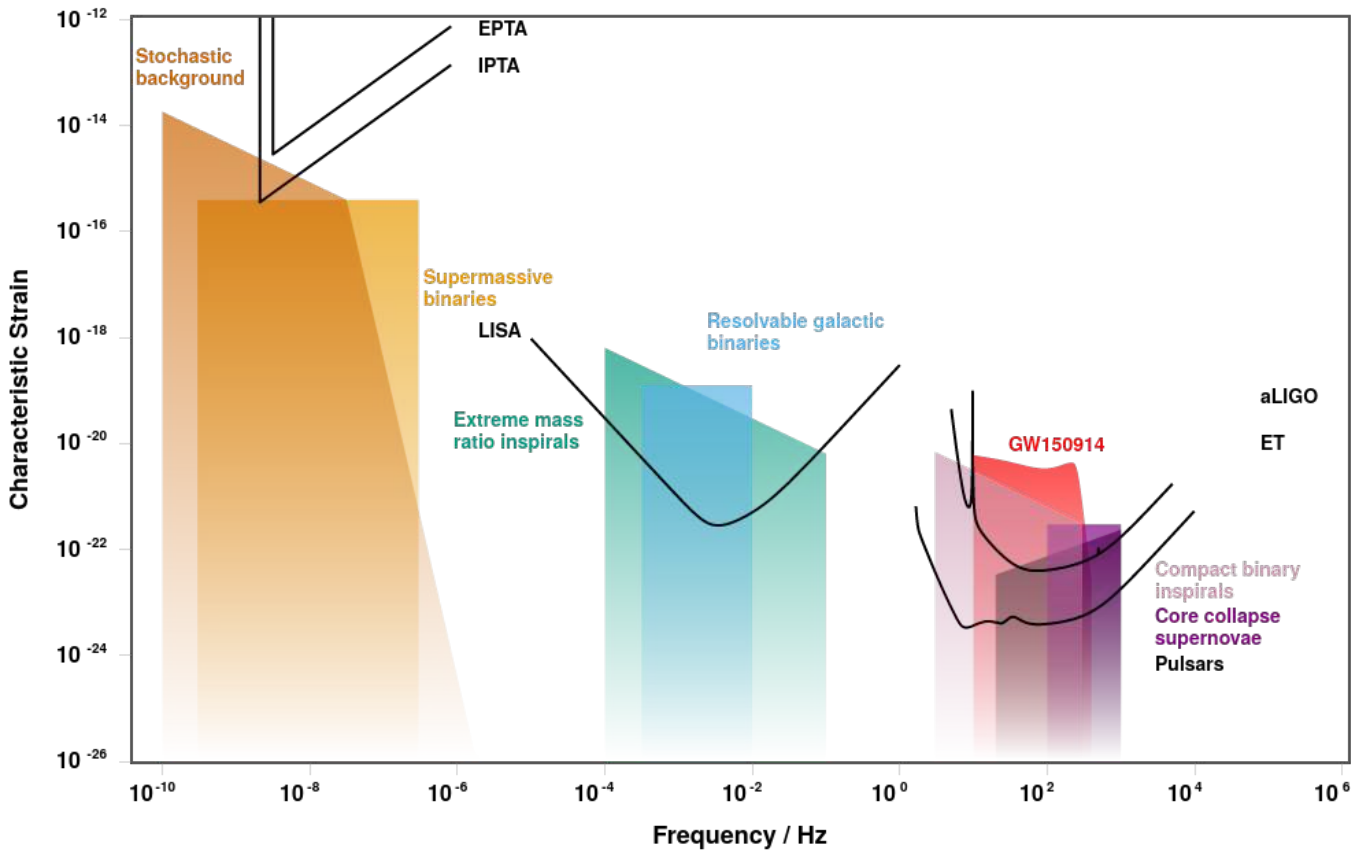


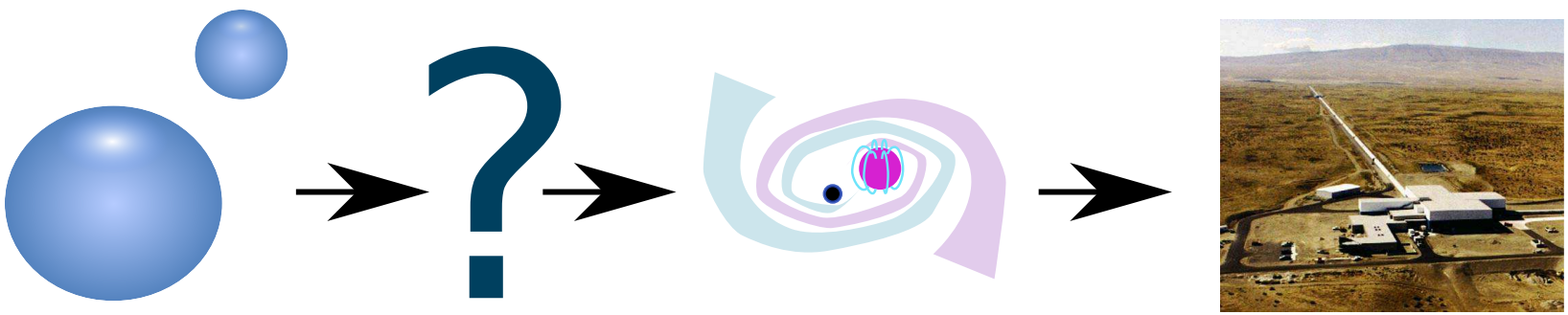
Figure courtesy of Christopher P.L. Berry, based on the calculations of Hall & Evans 2019

The far future



gwplotter.com Moore et al. (2014)

What can we learn from this?



1. Form two stars
2. ?
3. Merge them
4. Profit

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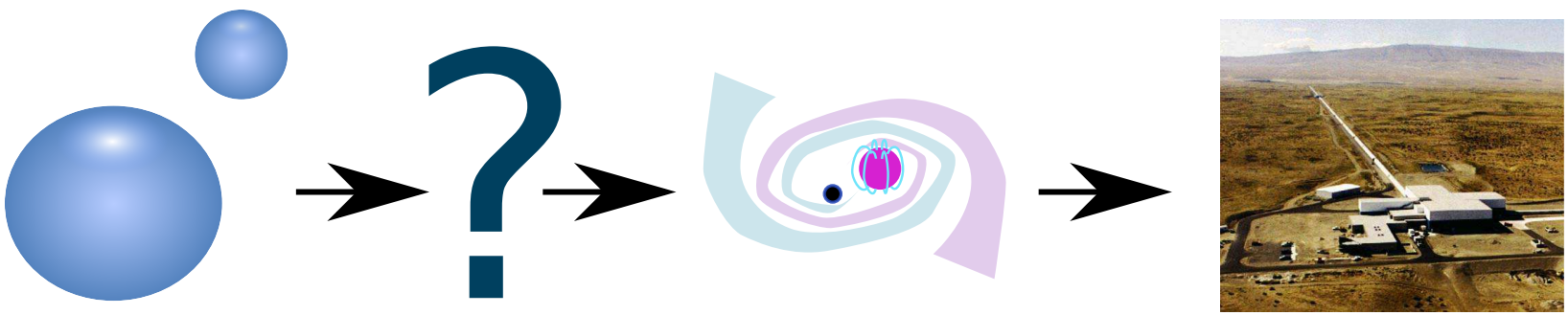
What are the progenitors of these sources?
(cf. Marchant et al. 2016)



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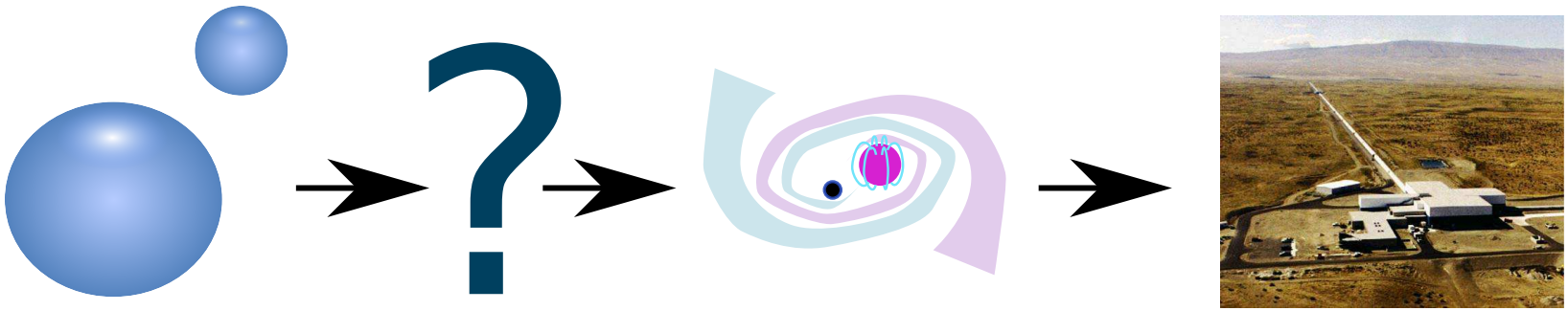

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Is GR broken?
(cf. Abbott et al. 2019, 1903.04467)

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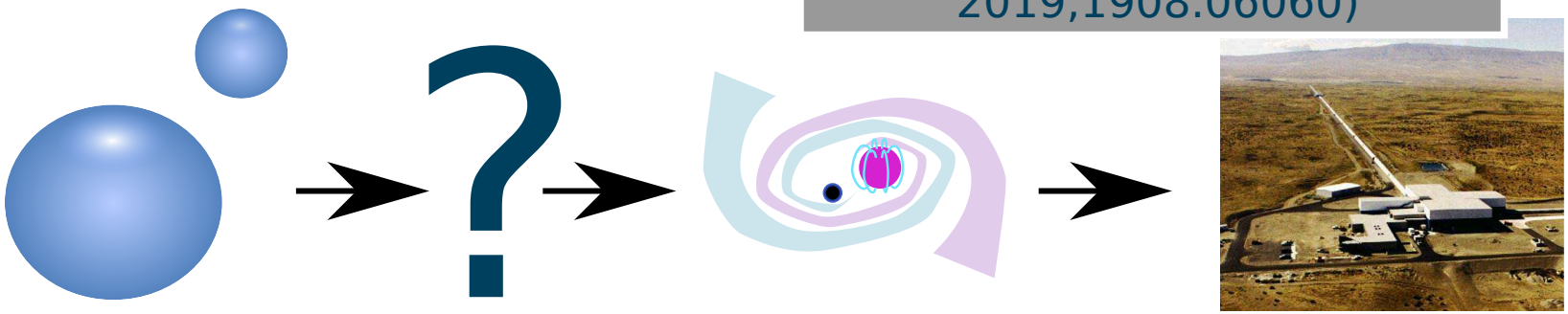

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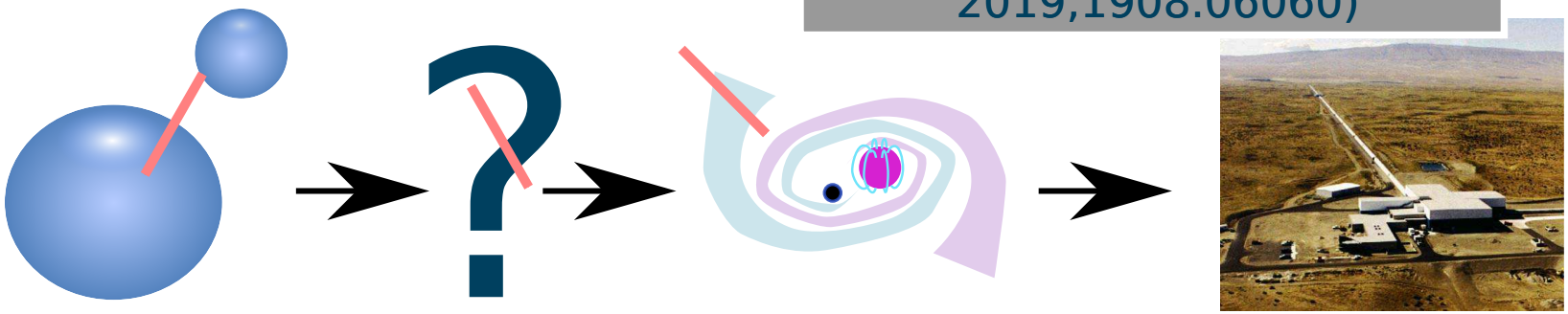

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Dynamical

Kulkarni et al. 1993,
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CE

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CHE

Mandel & de Mink 2016
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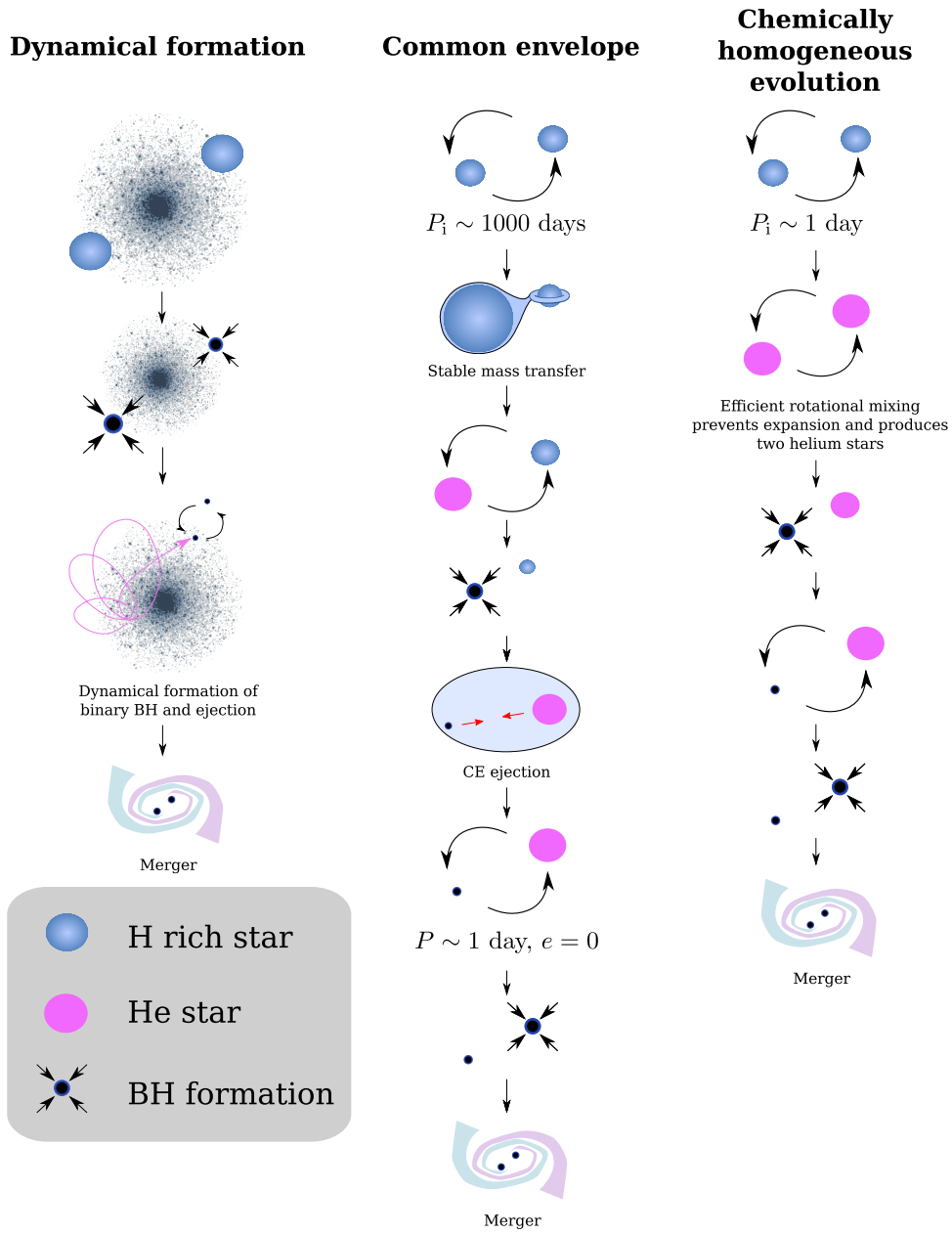

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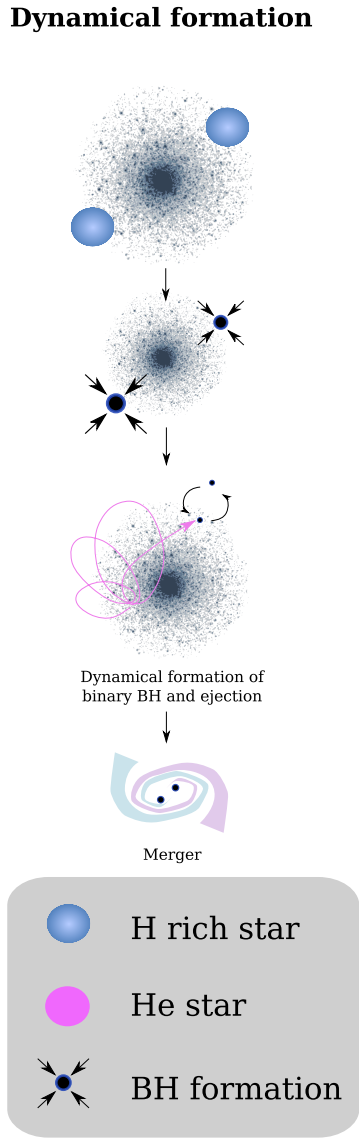
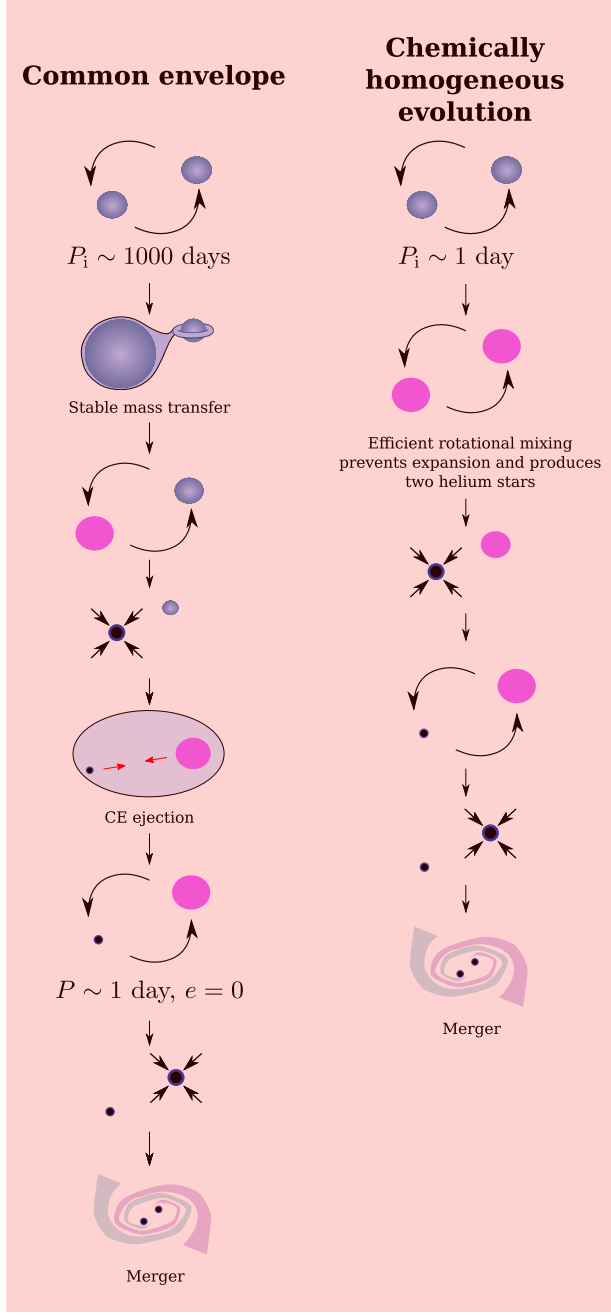
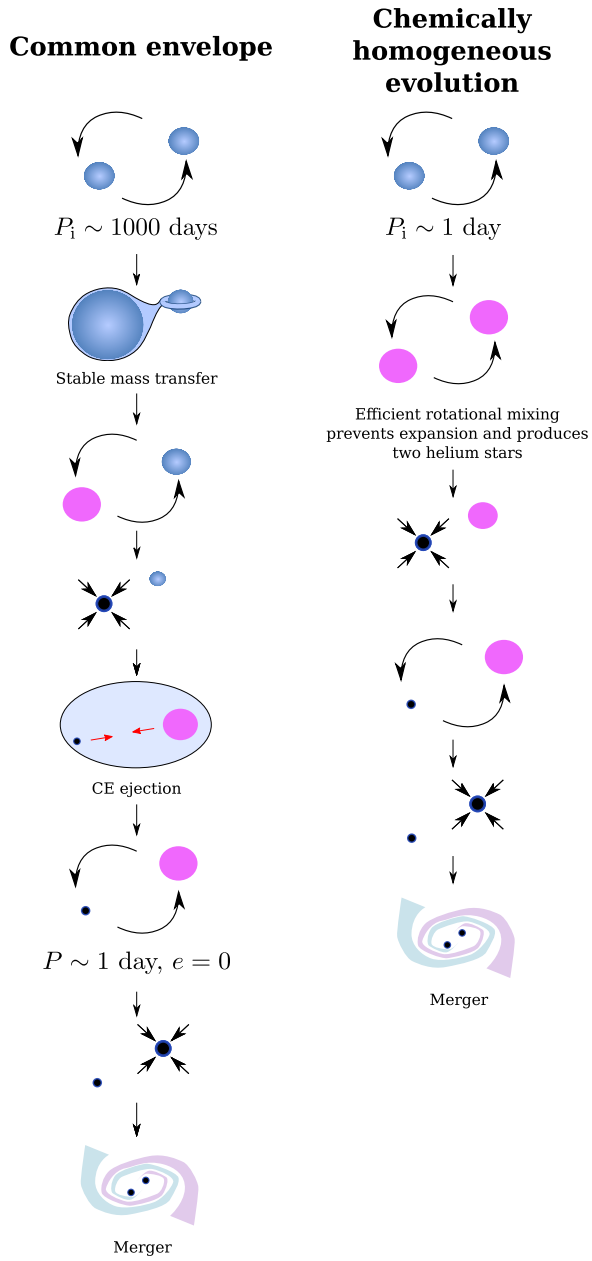
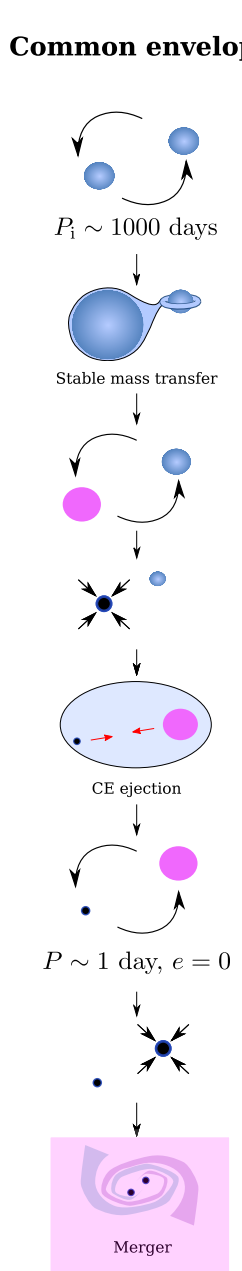
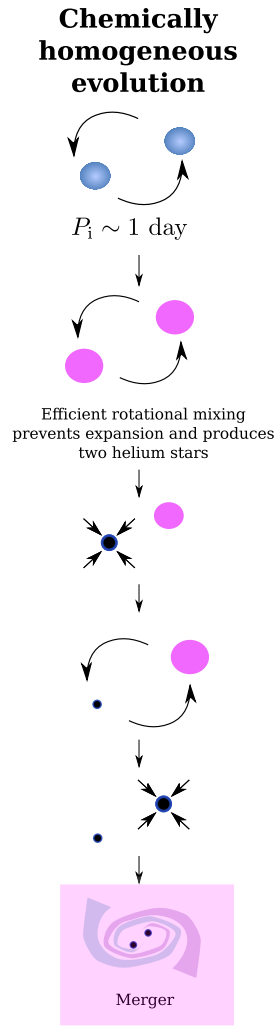


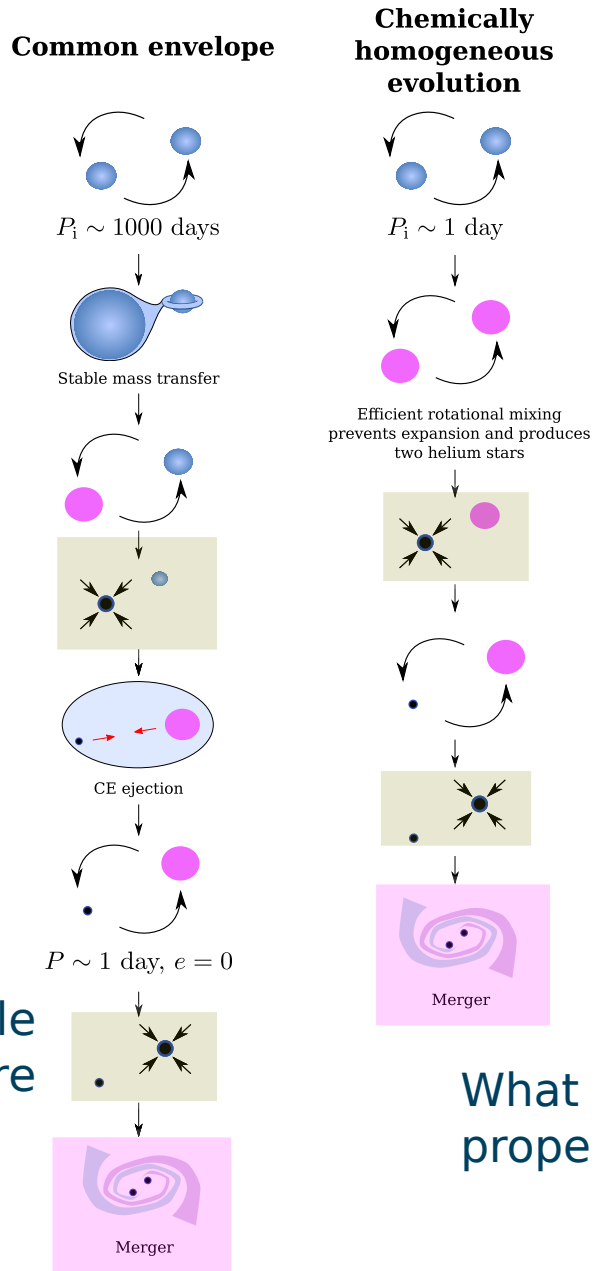



Common envelope
$P_{\rm i} \sim 1000$ days
Stable mass transfer
CE ejection
$P \sim 1$ day, $e = 0$
Merger
Chemically homogeneous evolution
$P_{\rm i} \sim 1$ day
Efficient rotational mixing prevents expansion and produces two helium stars
Merger





What are the predicted properties of GW sources



Are there observable transients when BHs are formed?

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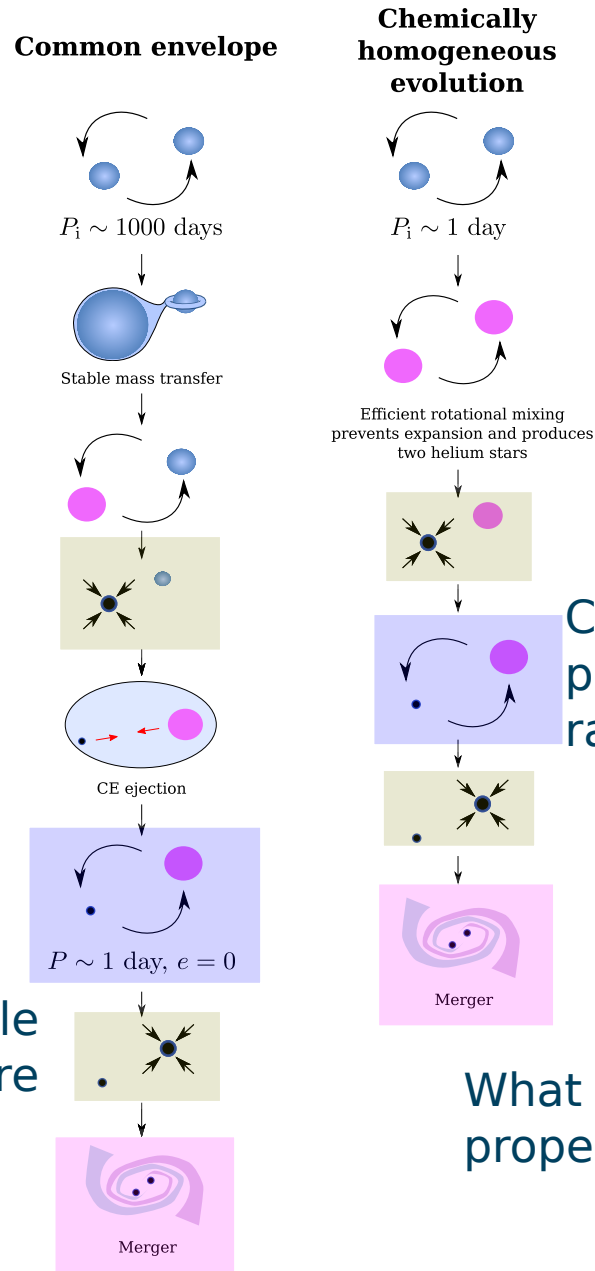
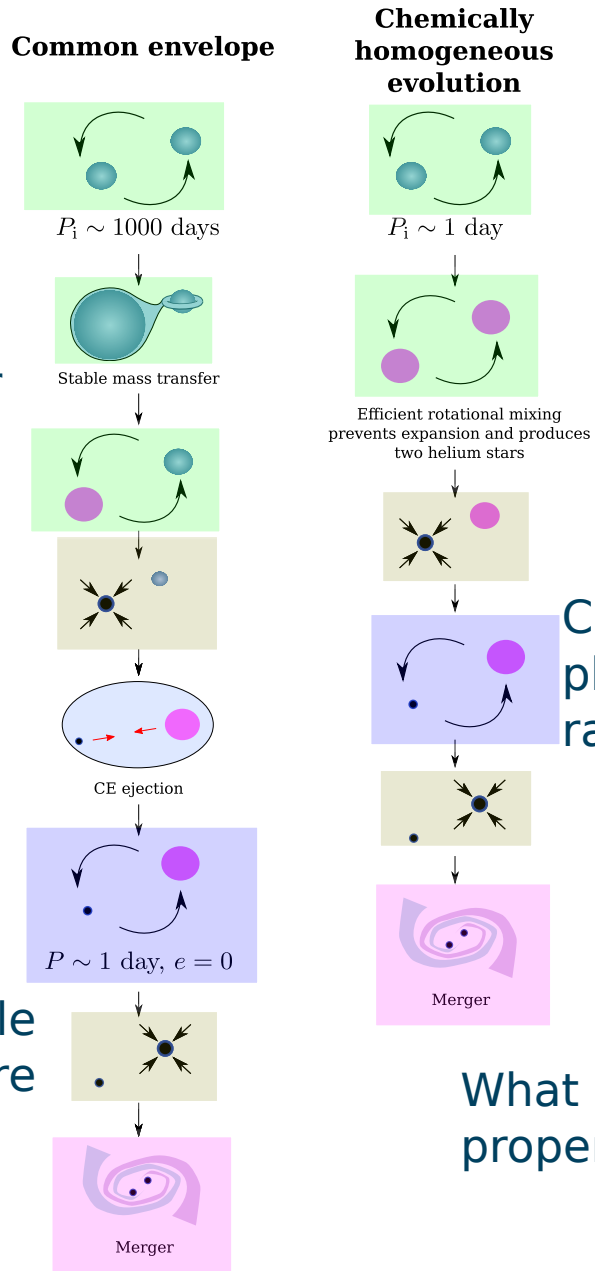


Are there observable transients when BHs are formed?

Can single degenerate phases be observed as X-ray sources?

What are the predicted properties of GW sources

Can we infer something from directly observing potential binary star progenitors?



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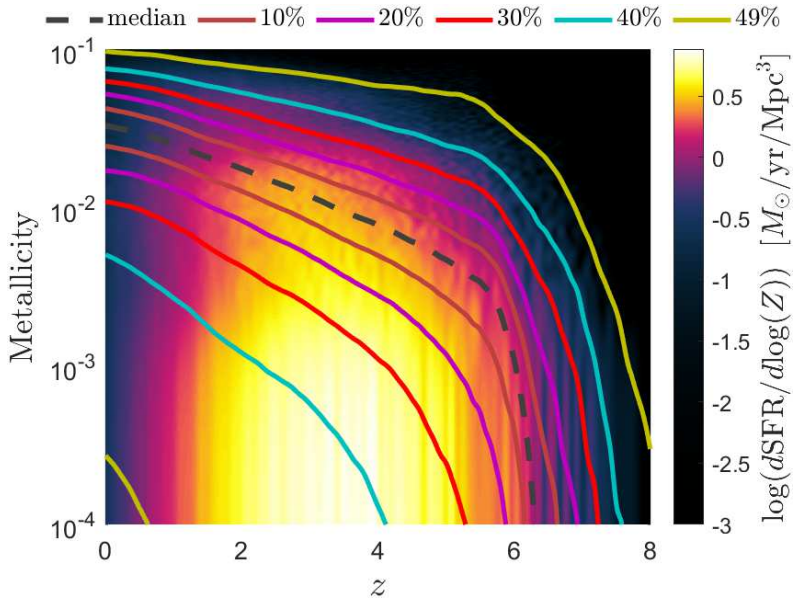

Metallicity distribution of the star formation rate throughout the lifetime of the universe, from the simulations of Kobayashi & Taylor 2015

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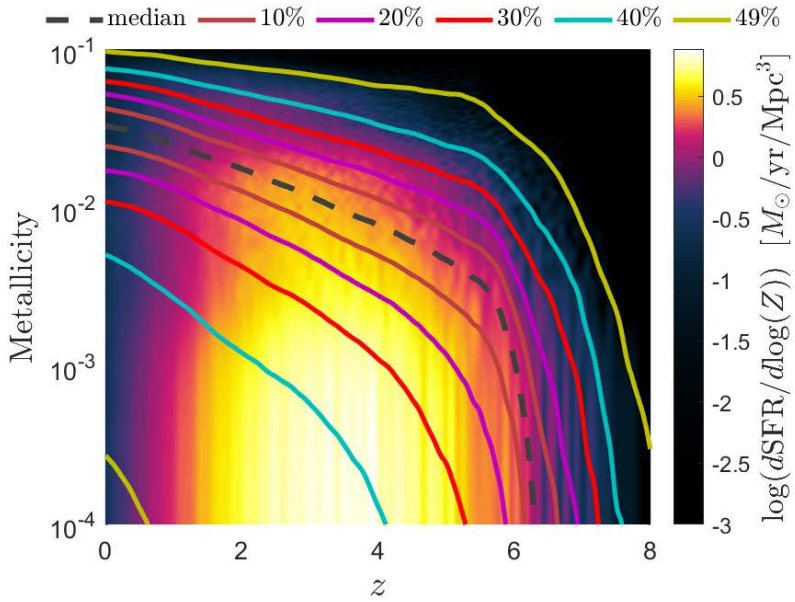

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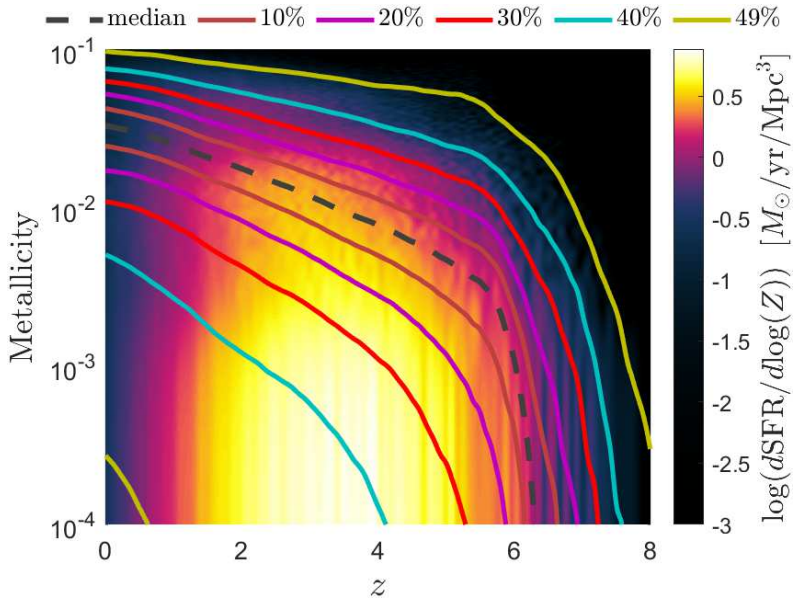

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- We need to know how much stars are formed in the universe, when they're formed, and with what metallicity.
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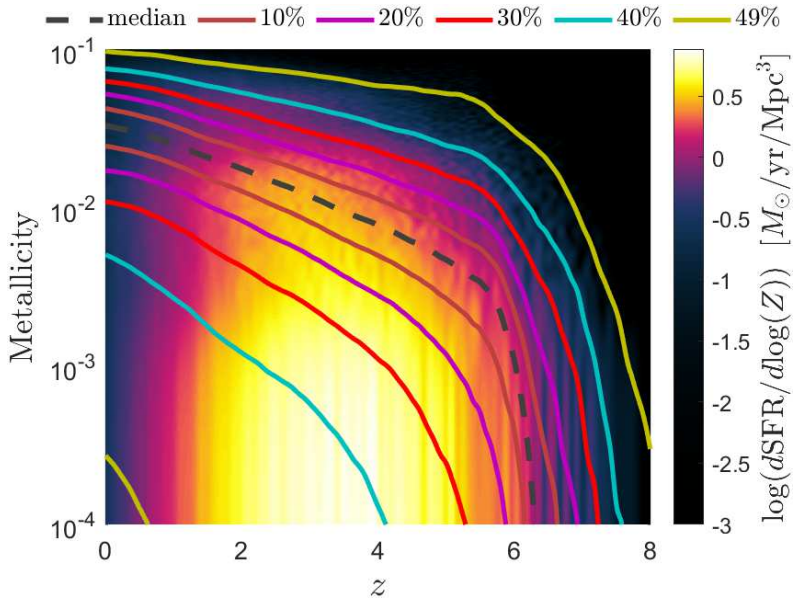
- Given a predicted merger event, the likelihood of it being detected.



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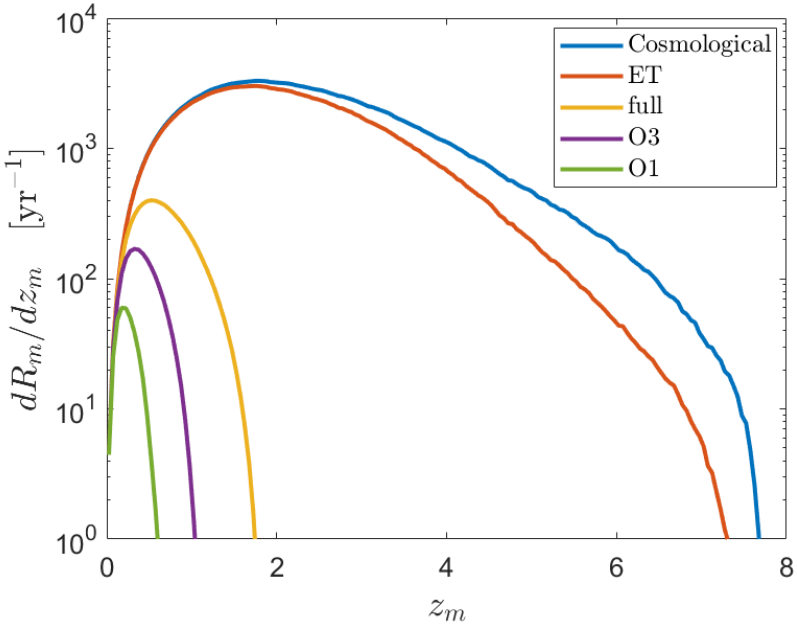
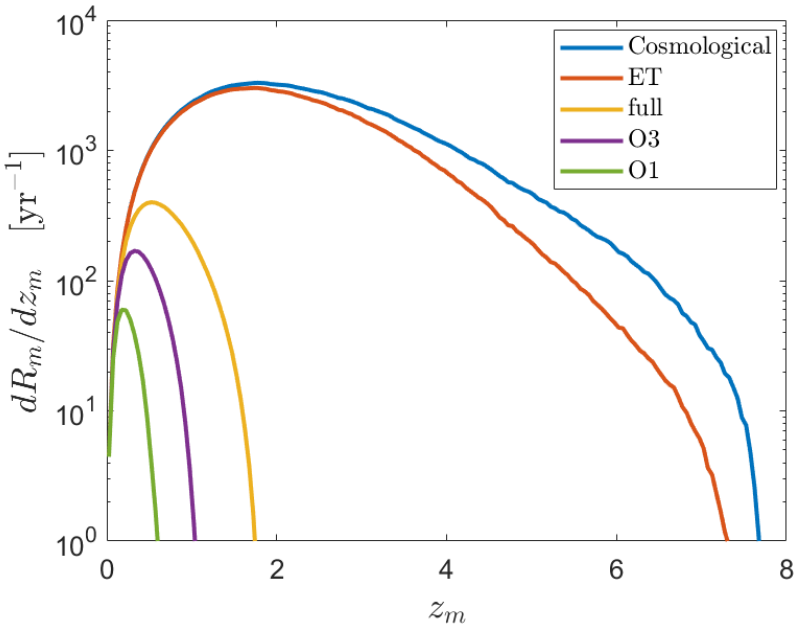
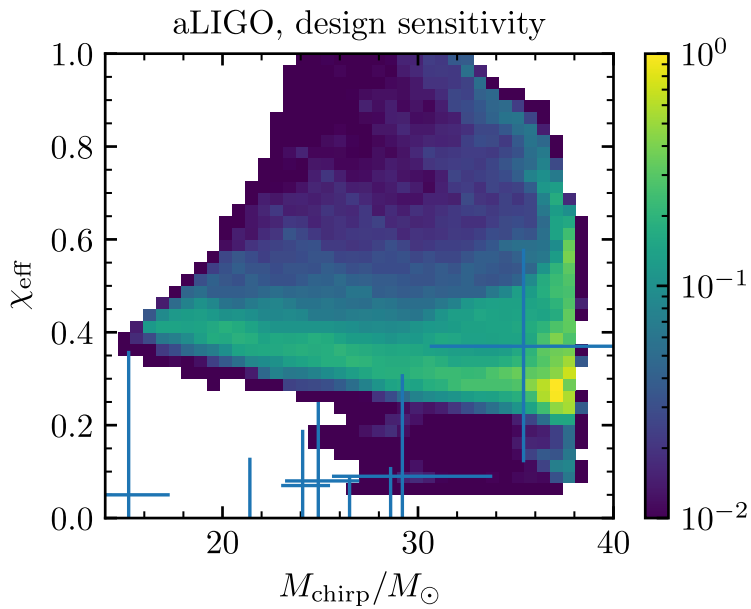
Rates of GW (for CHE)



du Buisson, Marchant et al. 2020
(in preparation)

Rates of GW (for CHE)





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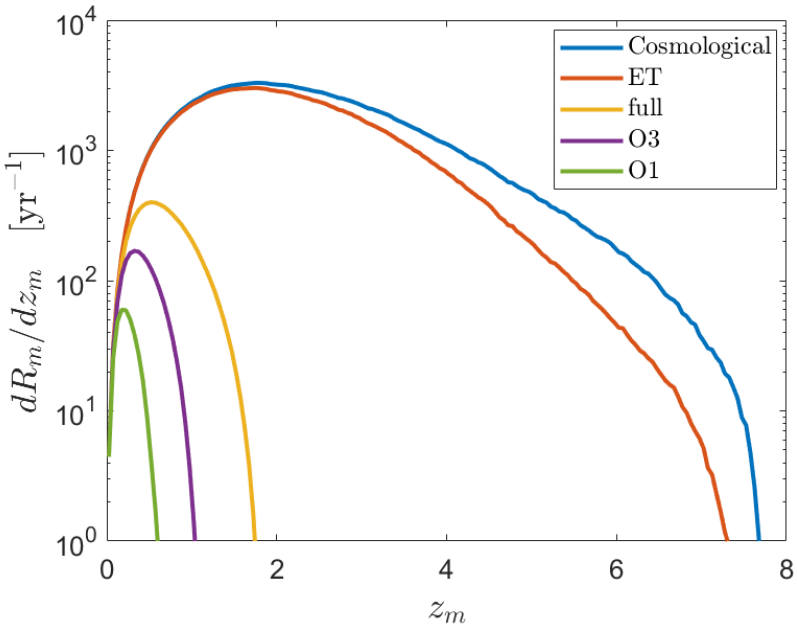

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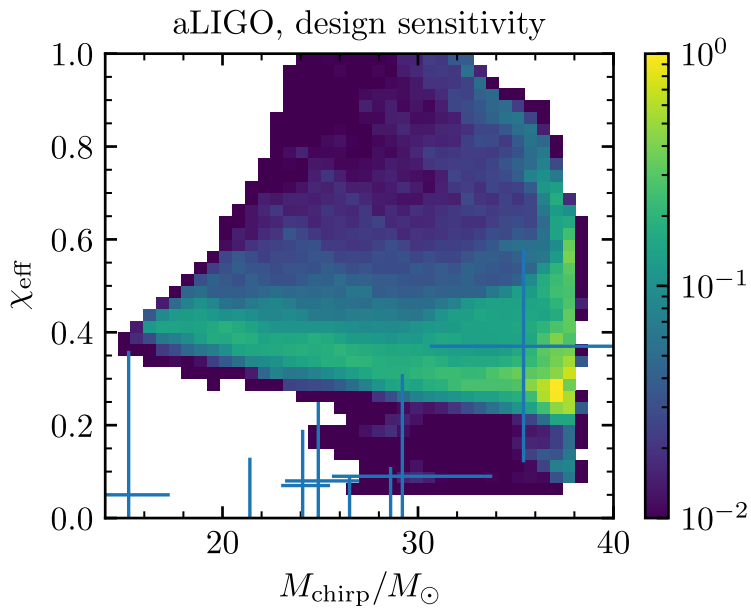
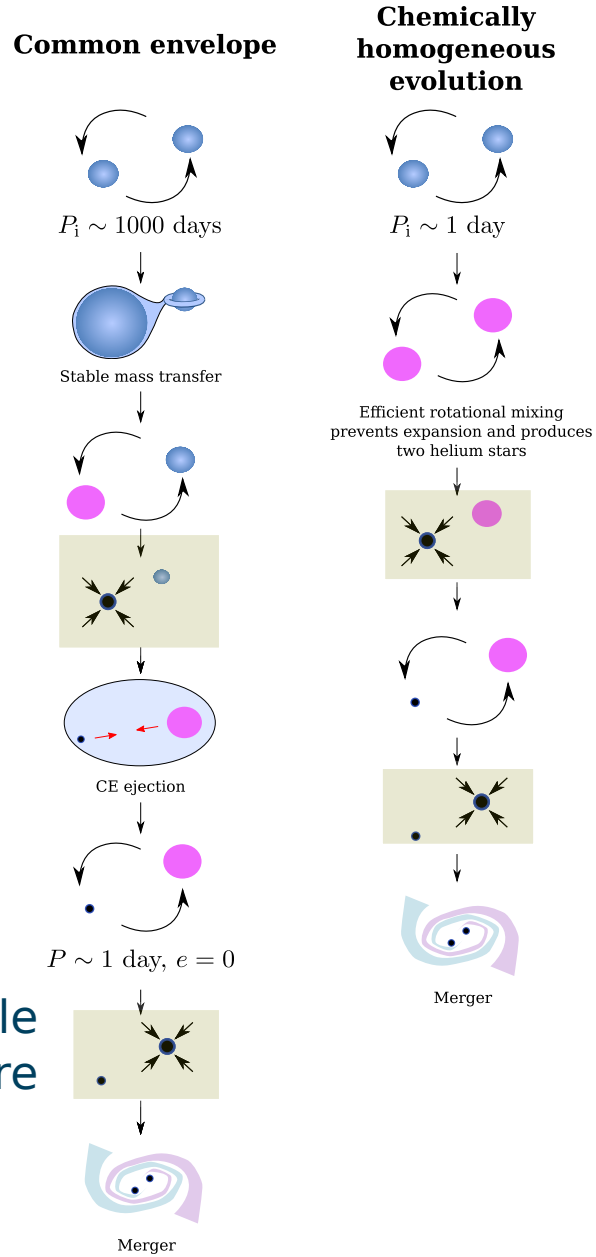


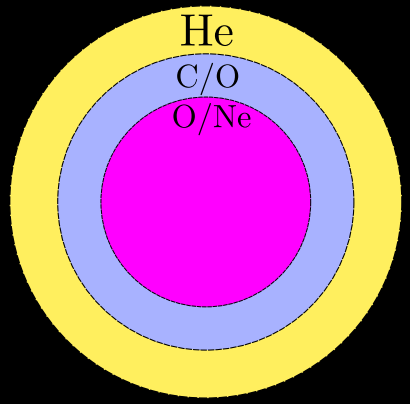
(See cf. Bavera et al. 2019 for predictions from CE evolution)

Are there observable transients when BHs are formed?



$\sim 60M_\odot - 120M_\odot$

Fowler & Hoyle 1964
Rakavi & Shaviv 1967
Woosley & Heger 2002

He → 

→ Collapse

$2\gamma \longleftrightarrow e^+e^-$

Final outcome



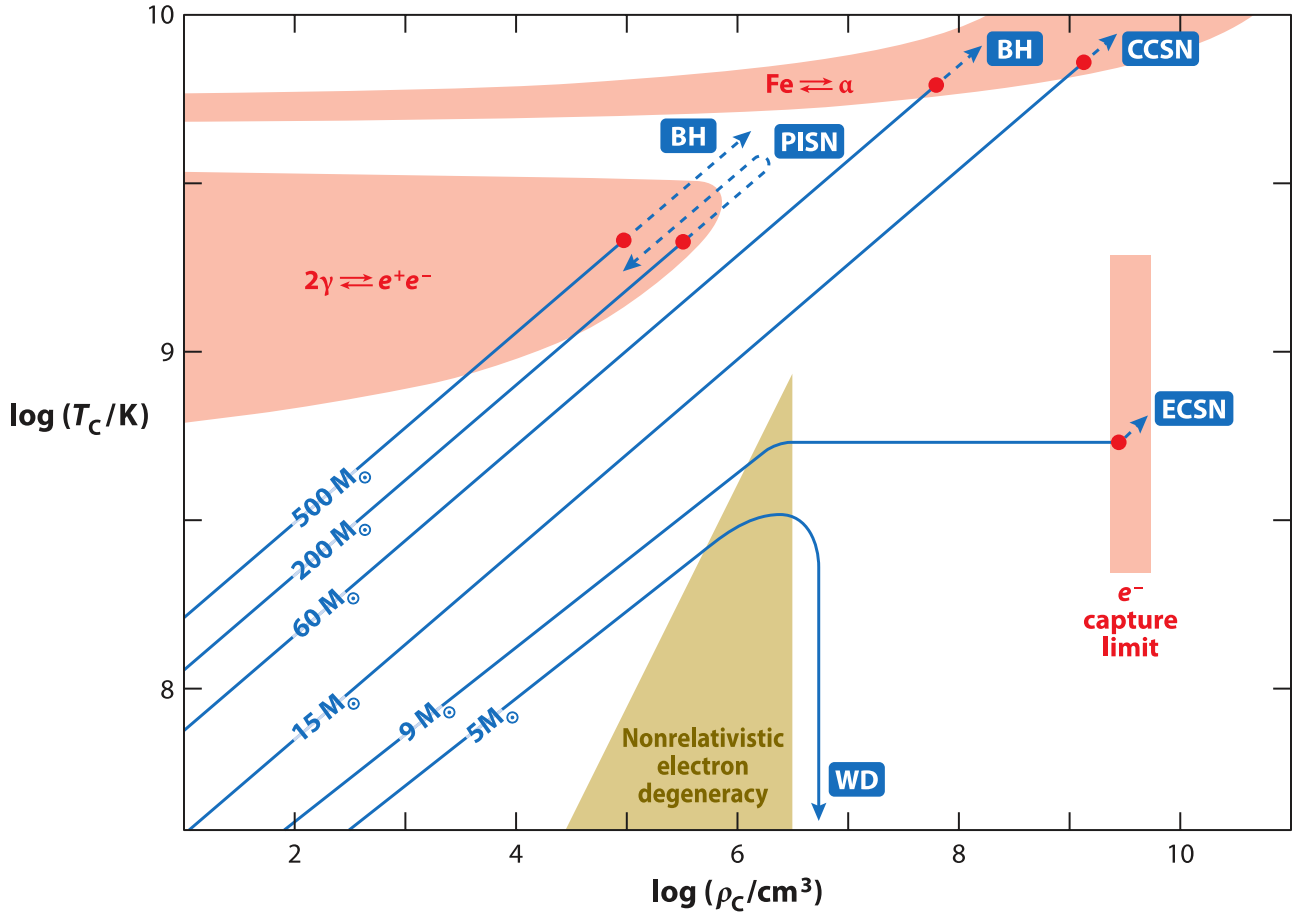
NOTHING

←



PISN

An expected gap in BH masses



Langer 2012

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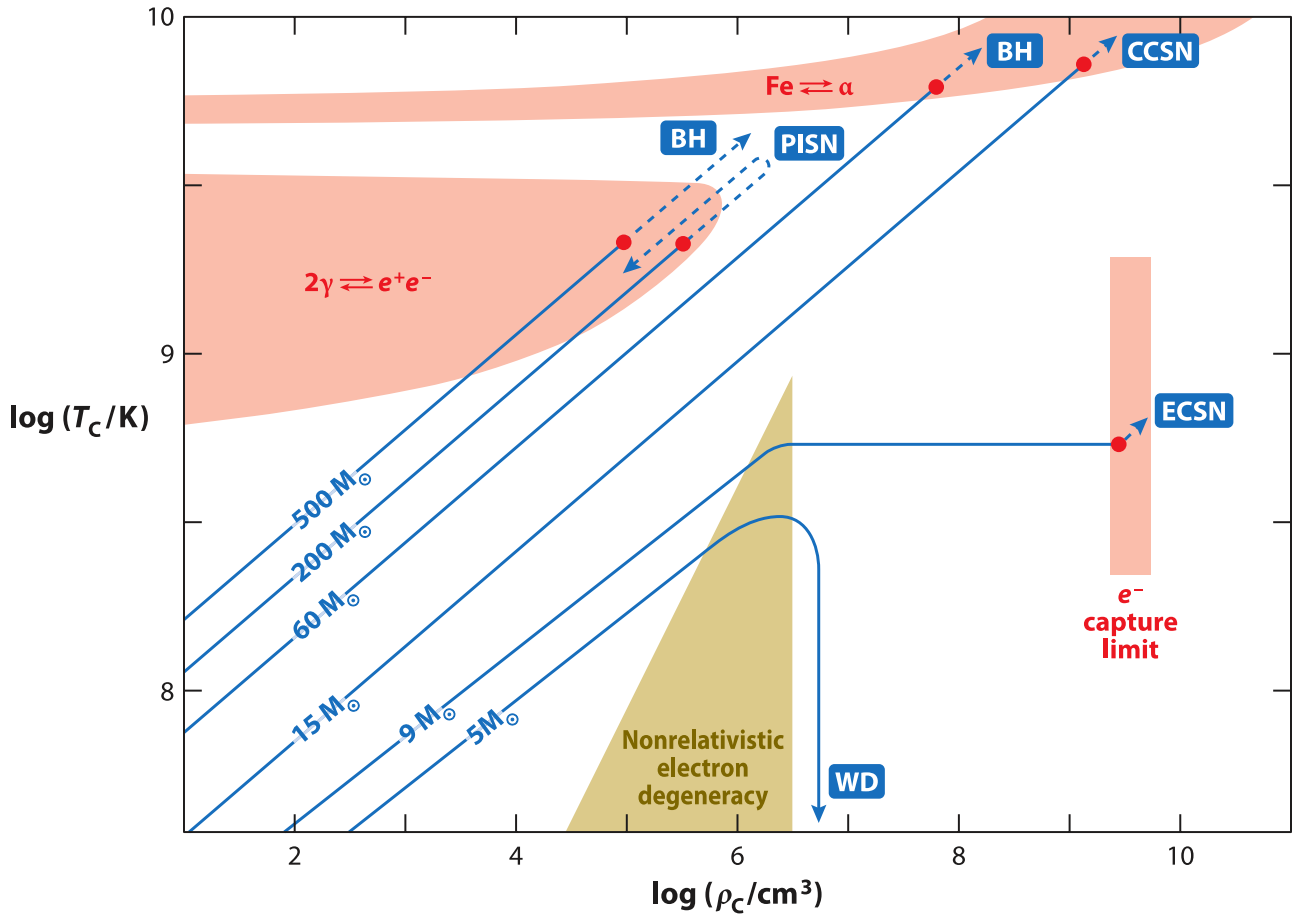
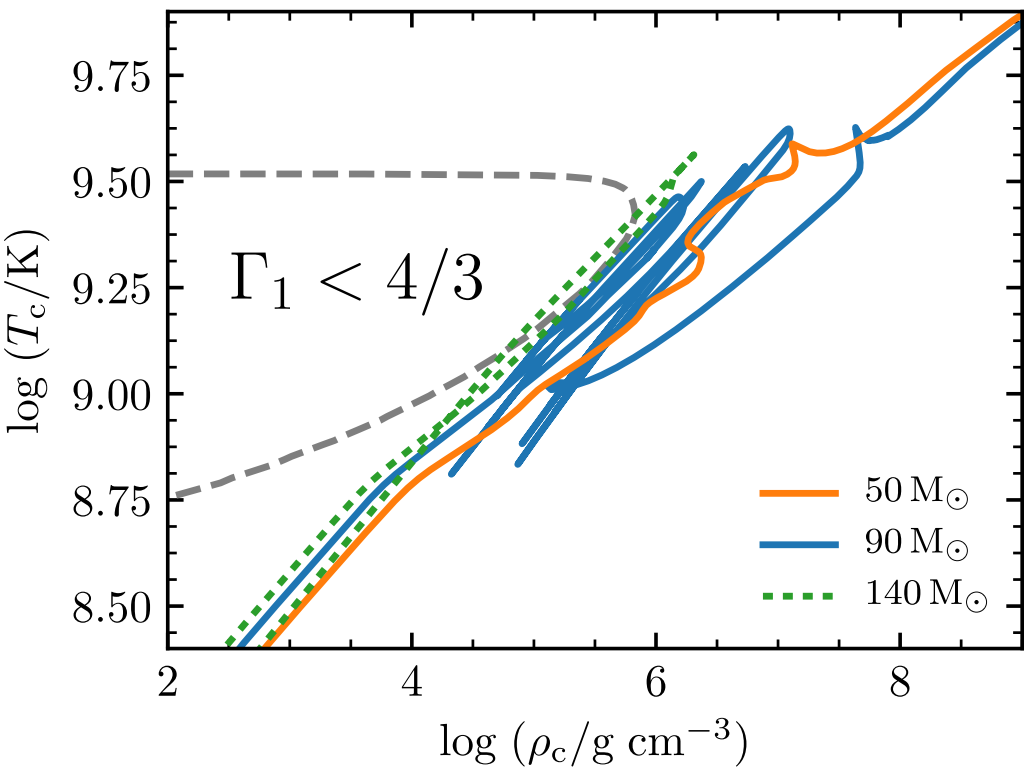


Langer 2012

No BHs with masses between ~60-130 Msun expected from hydrogen free progenitors (Heger & Woosley 2002)

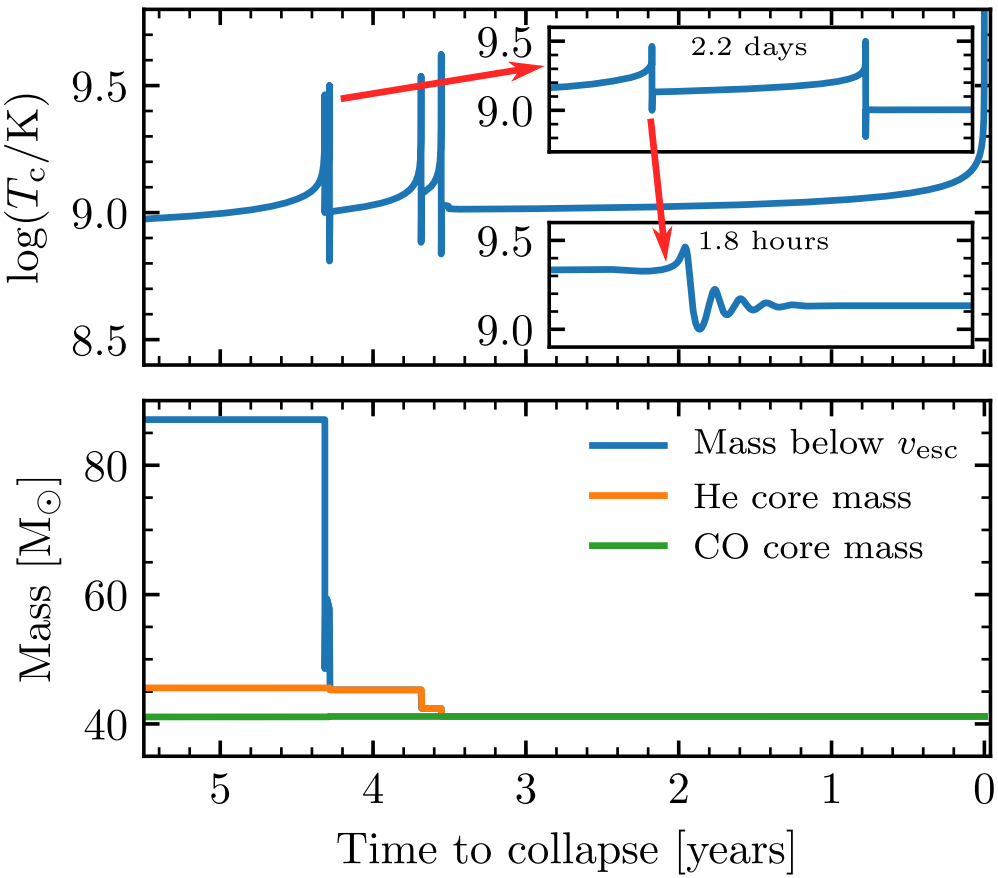
Pulsational-PISN



Paxton,...,Marchant,... 2018

- Collapse can produce a pulse and mass ejection instead of disruption (Fraley 1968, Woosley 2017)
- Ejected shells can catch up to each other leading to shock heating (cf. Renzo et al. 2020).

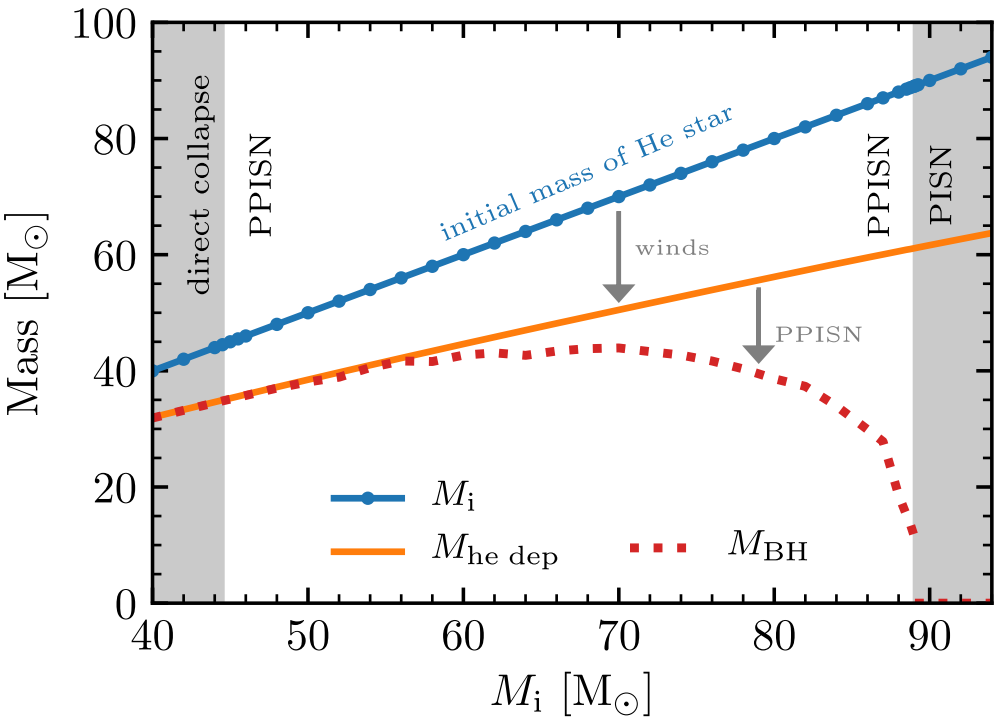
Pulsational-PISN



Paxton,...,Marchant,... 2018

- Collapse can produce a pulse and mass ejection instead of disruption (Fraley 1968, Woosley 2017)
- Ejected shells can catch up to each other leading to shock heating (cf. Renzo et al. 2020).

Pulsational-PISN



Marchant et al. 2019

Relationship between initial mass and expected black hole mass becomes non-monotonic (see also Woosley 2017).

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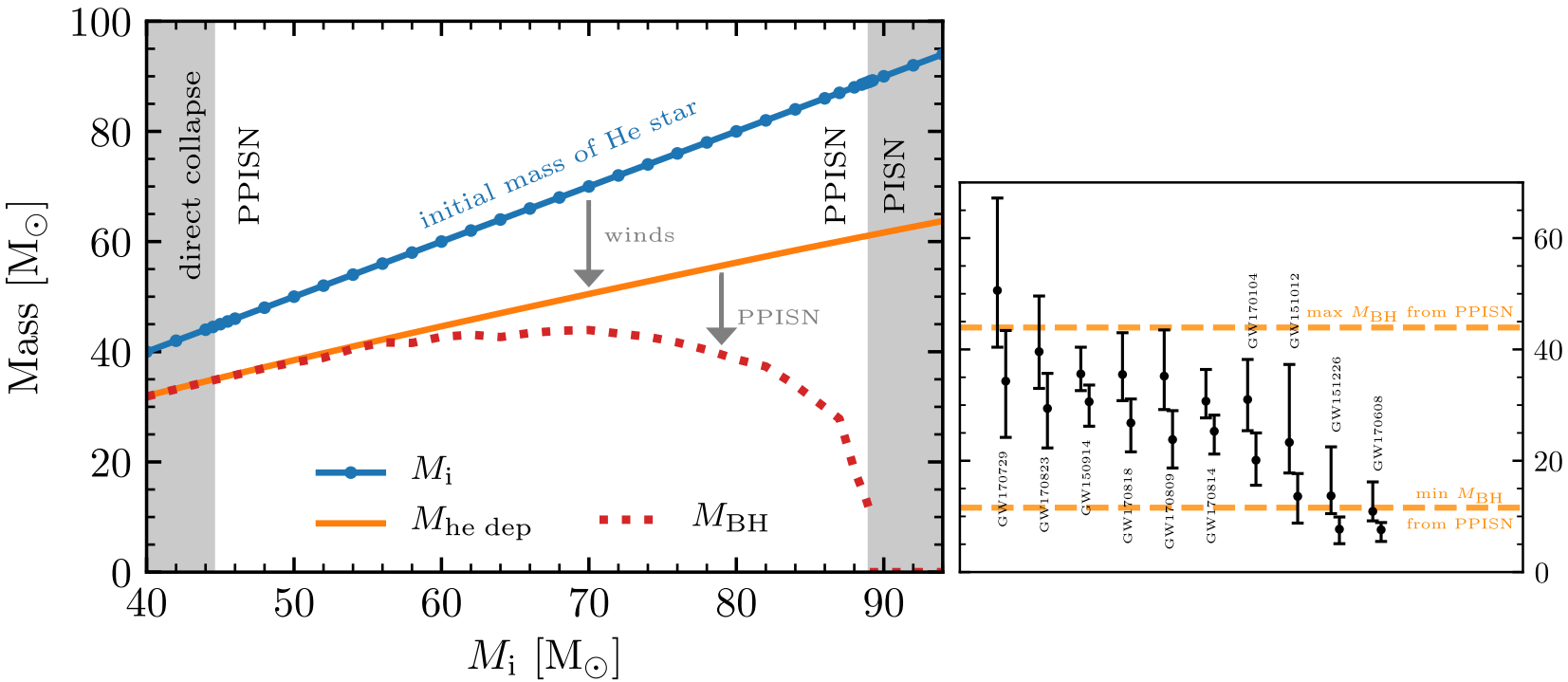

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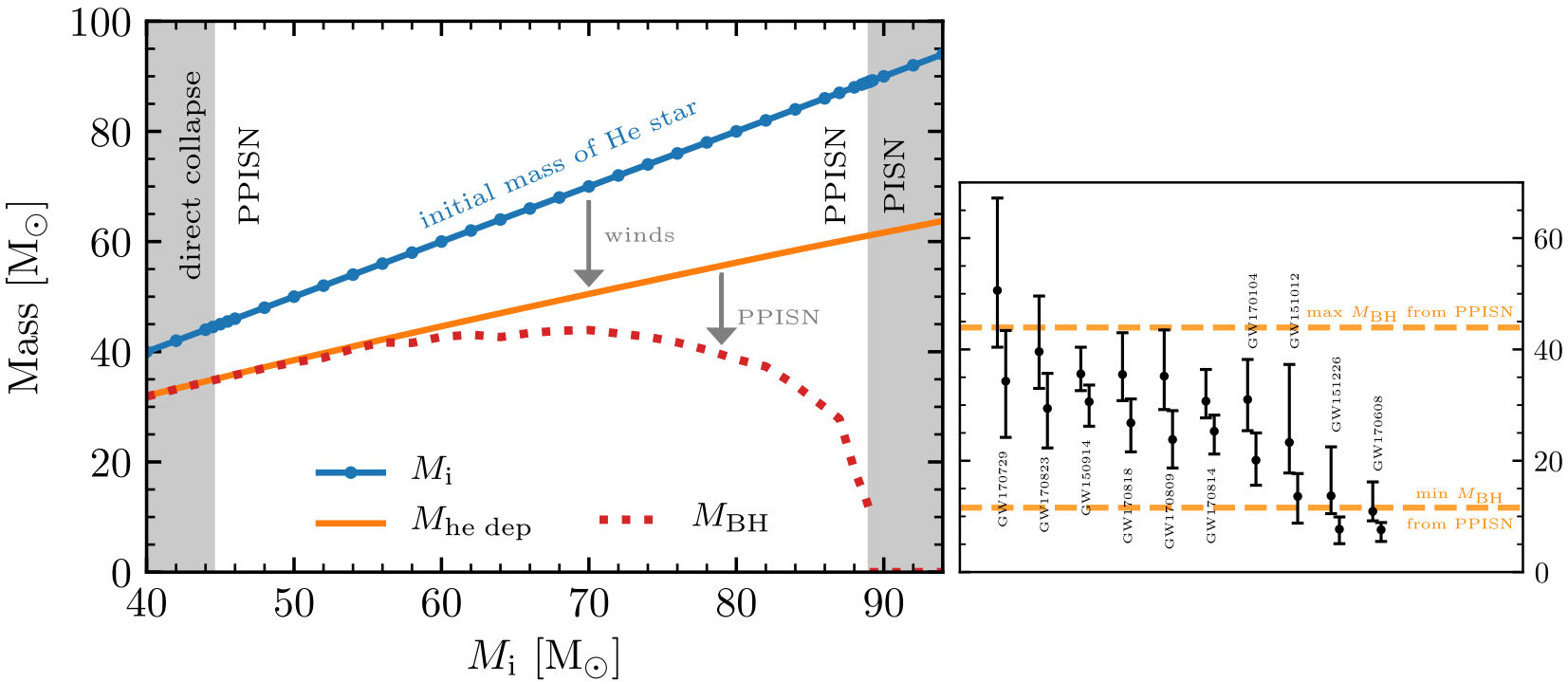

Marchant et al. 2019

Relationship between initial mass and expected black hole mass becomes non-monotonic (see also Woosley 2017).

The GWTC-1 data strongly supports a hard cutoff in BH masses at 45 Msun! (Abbott et al. 2018, astro-ph/1811-12940.)

Observing PISN

- du Buisson, Marchant et al. (in preparation): Coupled predictions of merging BBHs and PISN.

Table 2. PISN and CCSNe rates (for the intrinsic/cosmological and magnitude limited cases) in units of yr^{-1} for the default configuration: bright PISNe have an absolute peak bolometric magnitude $M_{\mathrm{bol}}^{\mathrm{peak}} \leqslant -19$, while faint PISNe have $M_{\mathrm{bol}}^{\mathrm{peak}} > -19$. The last column shows the total number of PISNe expected per 1000 CCSNe for each of the magnitude limited cases, as well as for the cosmological case. The values in this table are given for the whole sky.

	Bright PISNe	Faint PISNe	CCSNe	CC ratio
Cosmological	8070	12000	7.51×10^8	0.027
$m_{\mathrm{bol}}^{\mathrm{lim}} = 25$	2970	44.4	2.46×10^6	1.23
$m_{\mathrm{bol}}^{\mathrm{lim}} = 23$	643	4.15	2.28×10^5	2.84
$m_{\mathrm{bol}}^{\mathrm{lim}} = 21$	79.5	0.335	17500	4.56
$m_{\mathrm{bol}}^{\mathrm{lim}} = 19$	7.79	0.0243	1240	6.32
$m_{\mathrm{bol}}^{\mathrm{lim}} = 17$	0.659	0.00164	82.5	8.01

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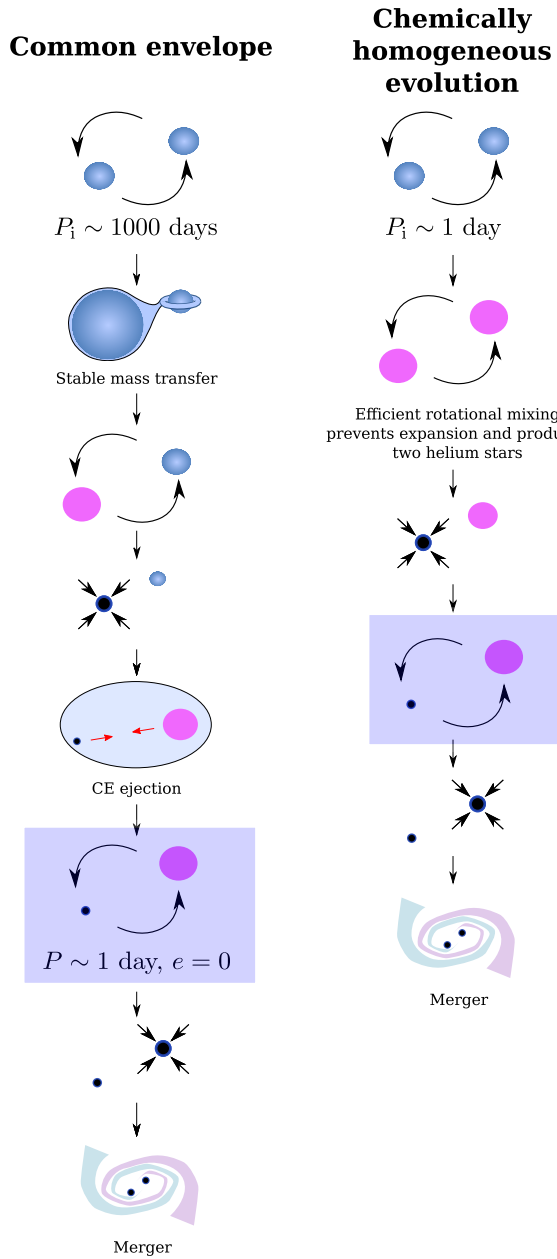
LSST

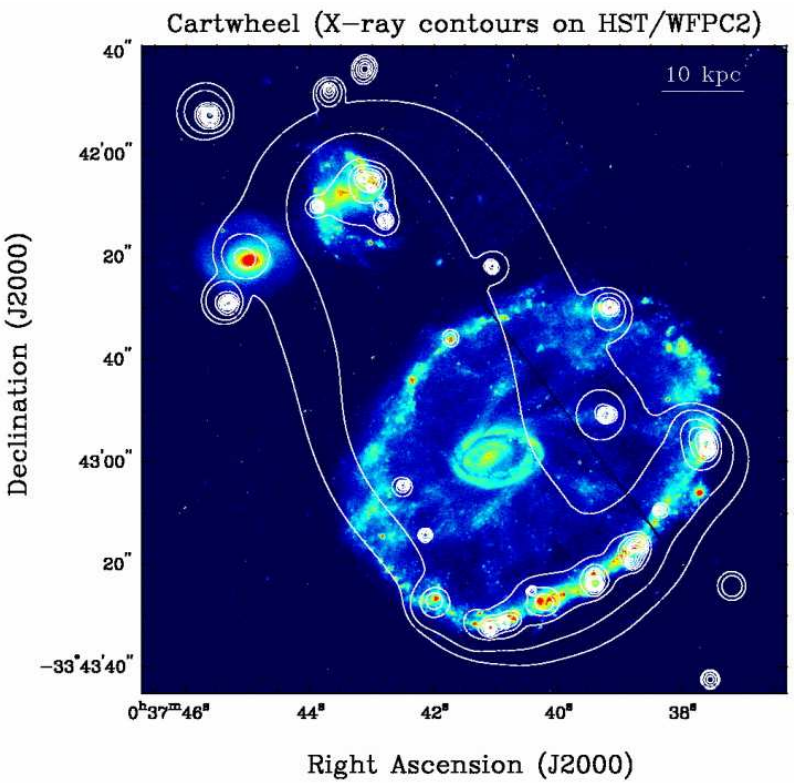
PAN-STARRS, Subaru HSC

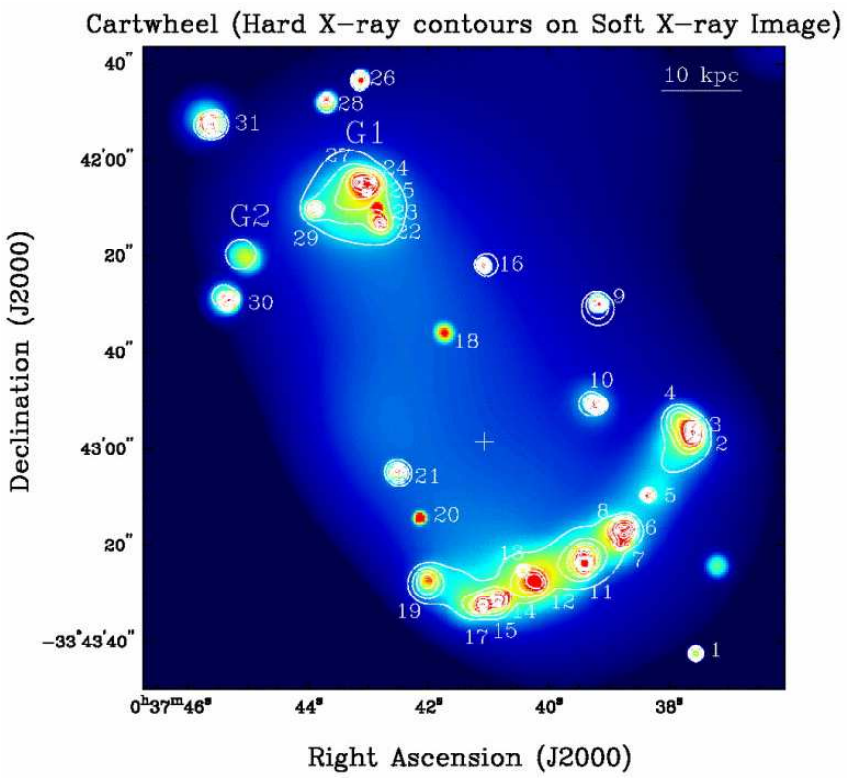
PTF



Can single degenerate phases be observed as X-ray sources?

ULXs, $L_X > 10^{39}$ erg s^{-1}





First detected with the Einstein telescope (Long & van Speybroeck 1983)

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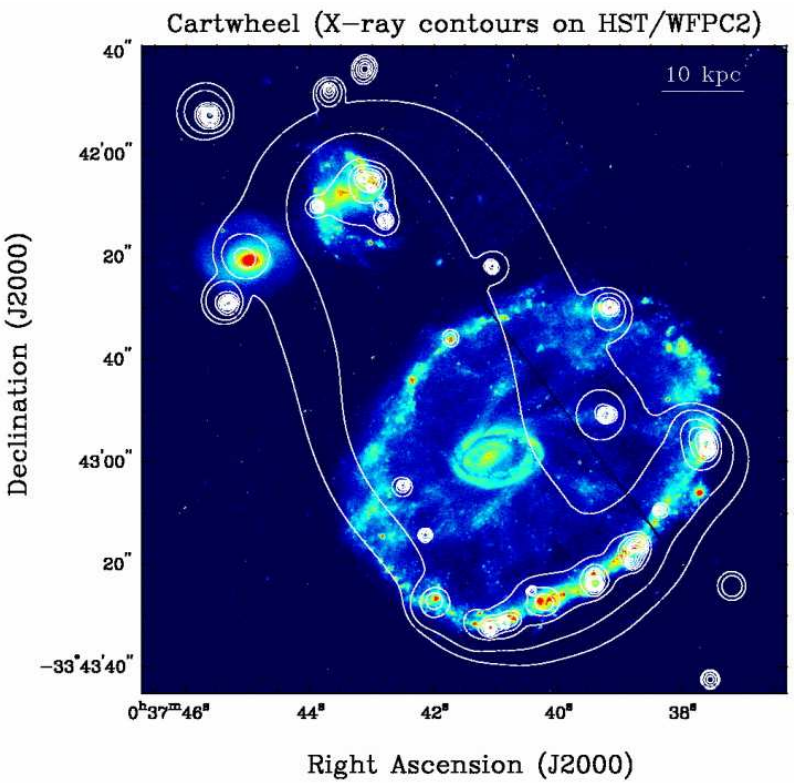
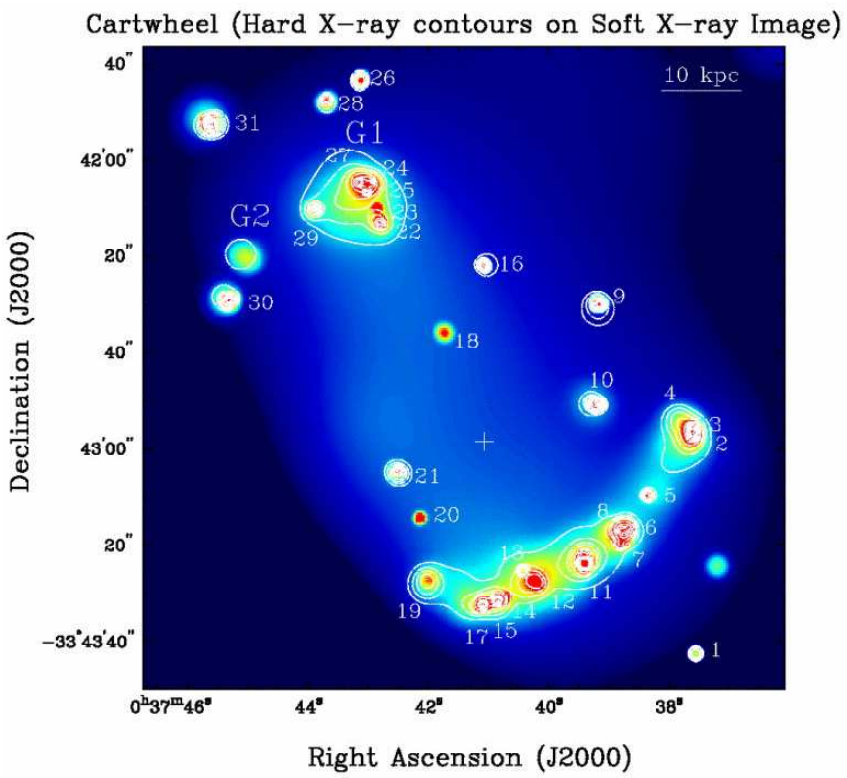


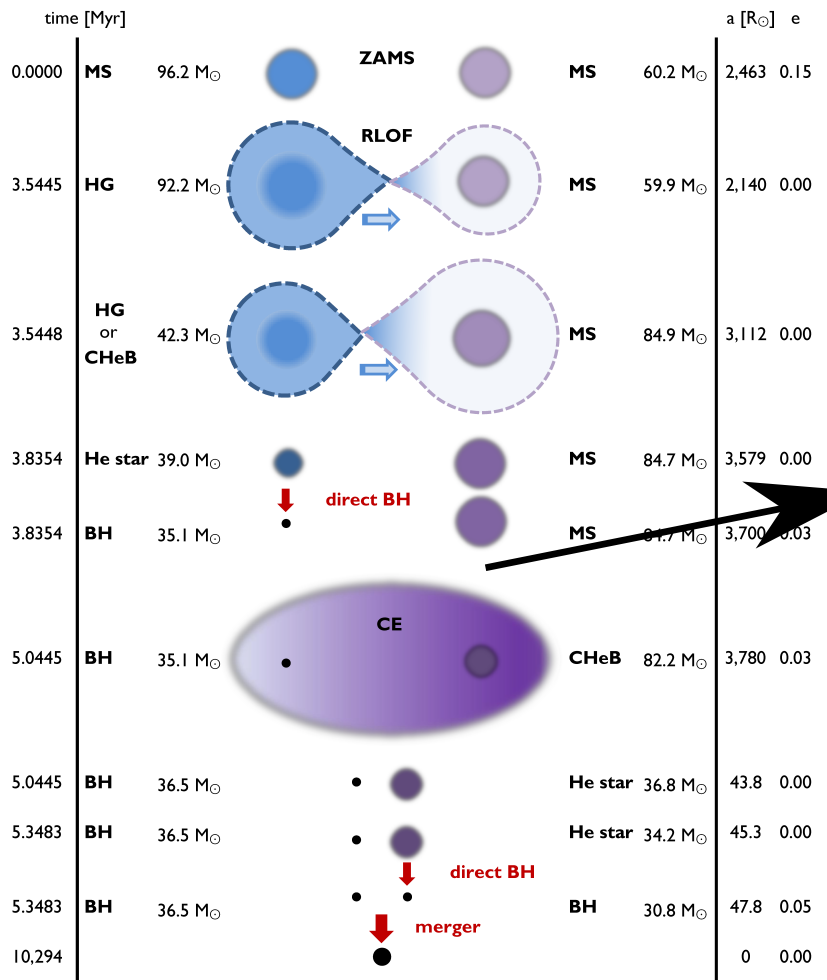


First detected with the Einstein telescope (Long & van Speybroeck 1983)

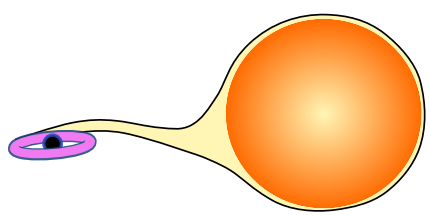
$$L_{\rm edd} \simeq 1.5 \times 10^{39} \left(\frac{M_{\rm BH}}{10 M_\odot} \right) \ {\rm erg \ s^{-1}}$$

ULXs associated to CE channel

Belczynski et al. 2016

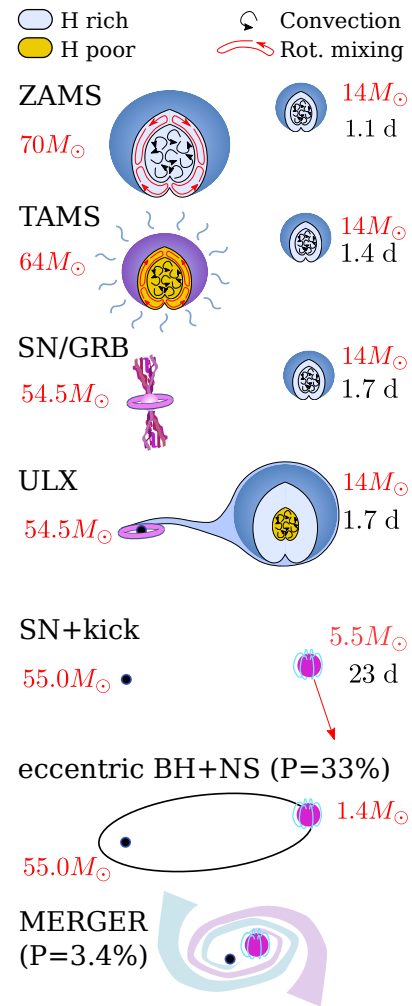


CE channel can branch into ULXs with yellow supergiant companions (cf. Pavlovski et al. 2017)



ULXs associated to CHE channel

- A similar branch on the CHE channel leads to ULXs. Donor in this case is most likely a MS star.
- Sources expected to dominate the total X-ray luminosity in very metal poor star forming galaxies (absent an AGN).
- Potential source of BH+NS binaries, including merging systems!



Marchant et al. 2017

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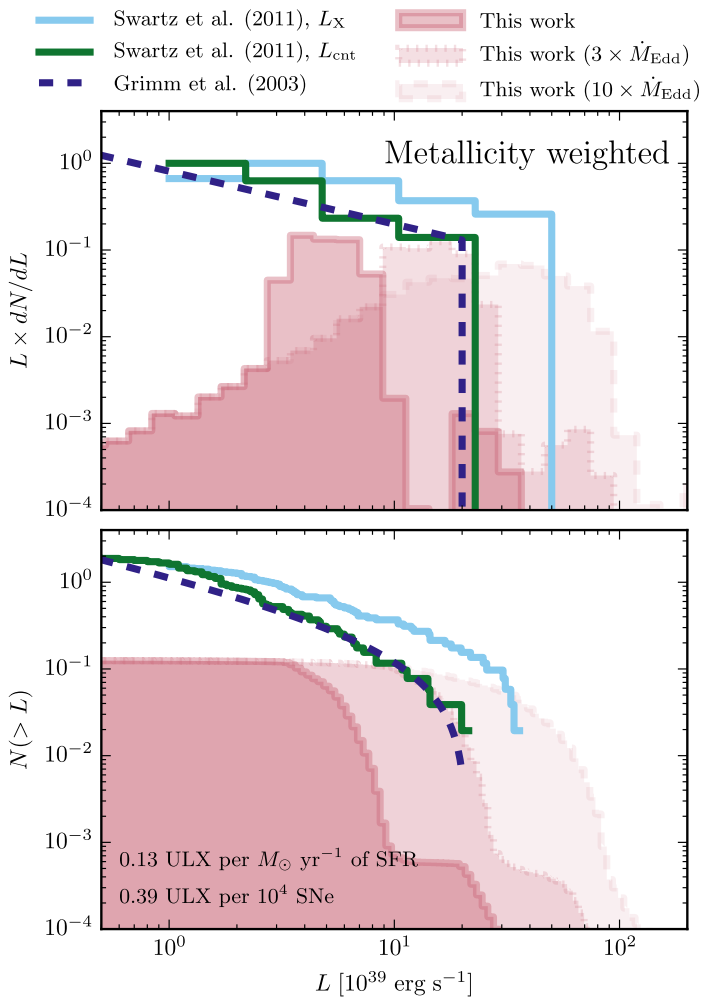
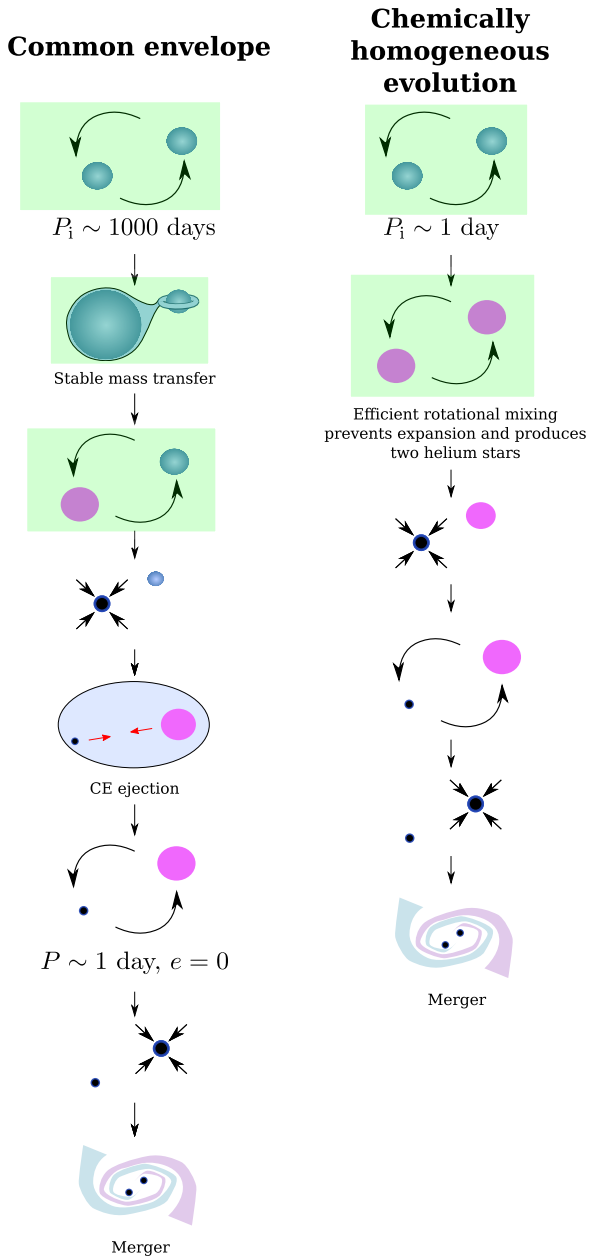
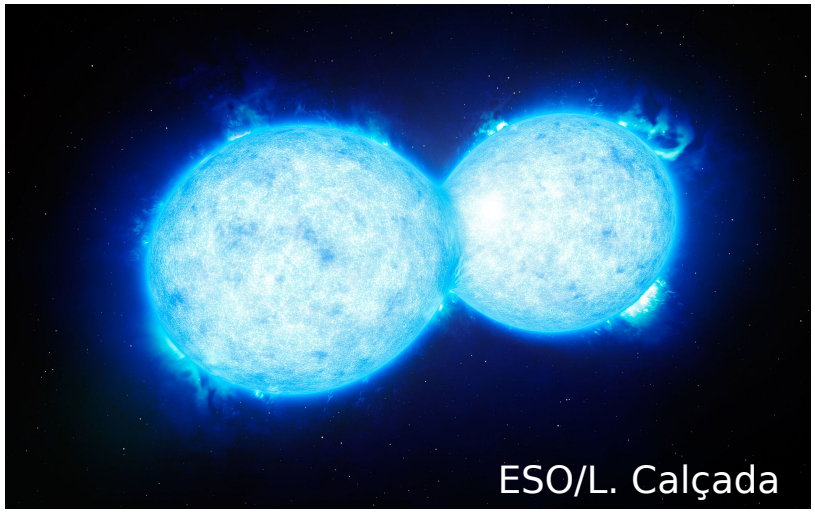


Marchant et al. 2017

Can we infer something from directly observing potential binary star progenitors?



Mixing in overcontact binaries



- Almeida et al. 2015: VFTS 352, most massive overcontact binary known.

$$m_1 \simeq m_2 \simeq 30 M_\odot,\ P_{\rm orb} = 1.12\ {\rm d}$$

- Stars hotter and more compact than expected, signs of helium enhancement!

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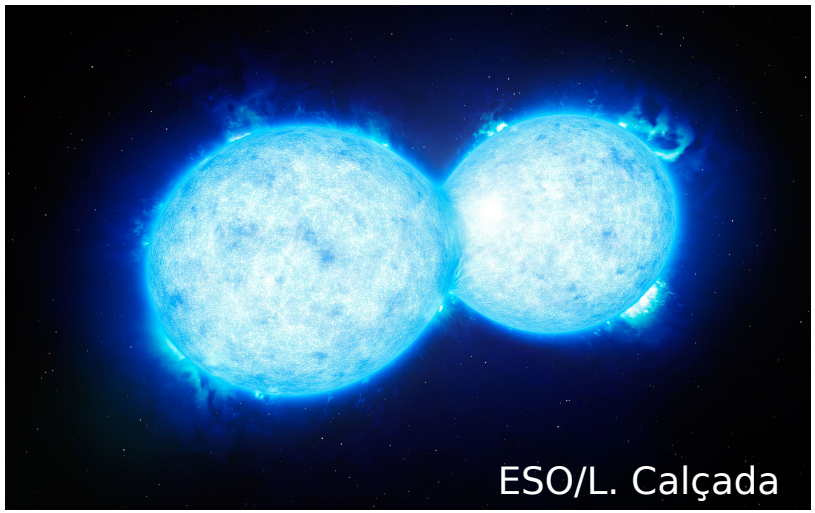

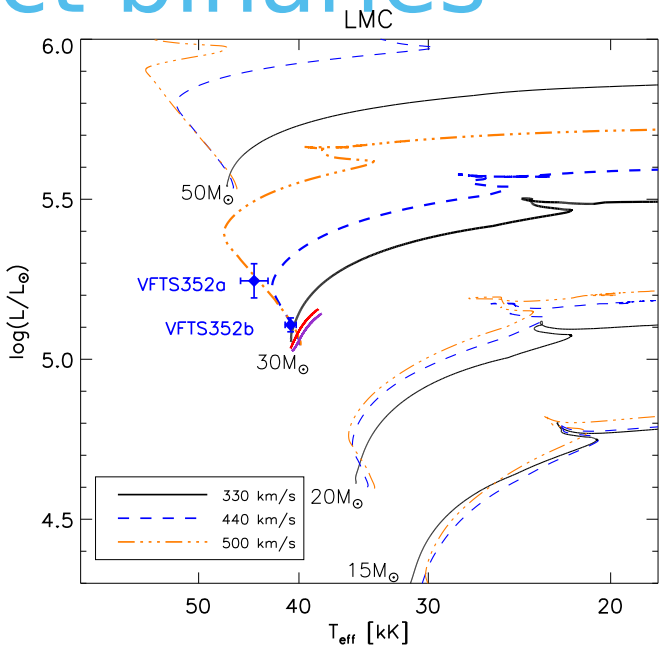

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- Abdul-Masih et al. 2019: Spectral disentangling and atmosphere analysis of VFTS 352.
- One component indeed hotter and overluminous, but no clear signs of mixing!

In Summary

- Predictions on the observed population convolve all uncertainties in the entire lifetime of a binary system, large uncertainties!
- General trends in observable properties of merging BBHs will be crucial to disentangle origin (masses, spins, redshifts).
- Indication of a mass gap consistent with pair-instability supernovae already observed, how will it hold with O3?
- If the gap arises from (P)PISN, and these BHs are formed at low redshift, transient surveys should detect them.
- Branches in the evolution can result in the formation of ULXs, with very distinct donor stars.