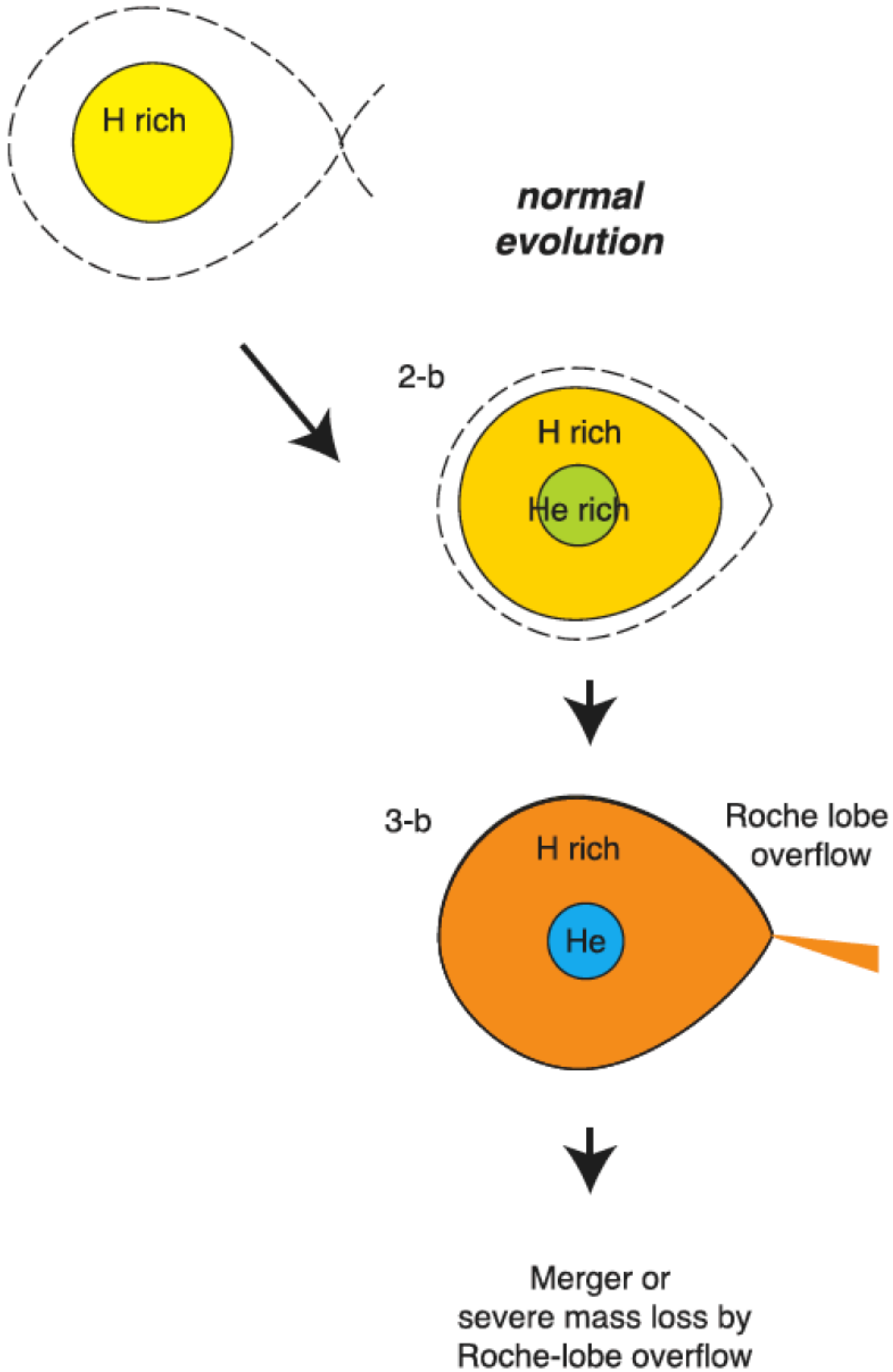
Merging binary black holes through chemically homogeneous evolution in short-period stellar binaries

Mandel & de Mink (2016)

Black hole seminar, March 1st, 2021
Dillon Dong

The standard way of making close binaries



- Hydrogen burns in core,
  expands during MS
  expands during post MS

- Eventually stars
  fill Roche Lobe

- Roche Lobe overflow,
  common envelope evolution
  double supernovae

- close compact object binary
  after heavy mass loss

Stellar rotation can affect close binary formation

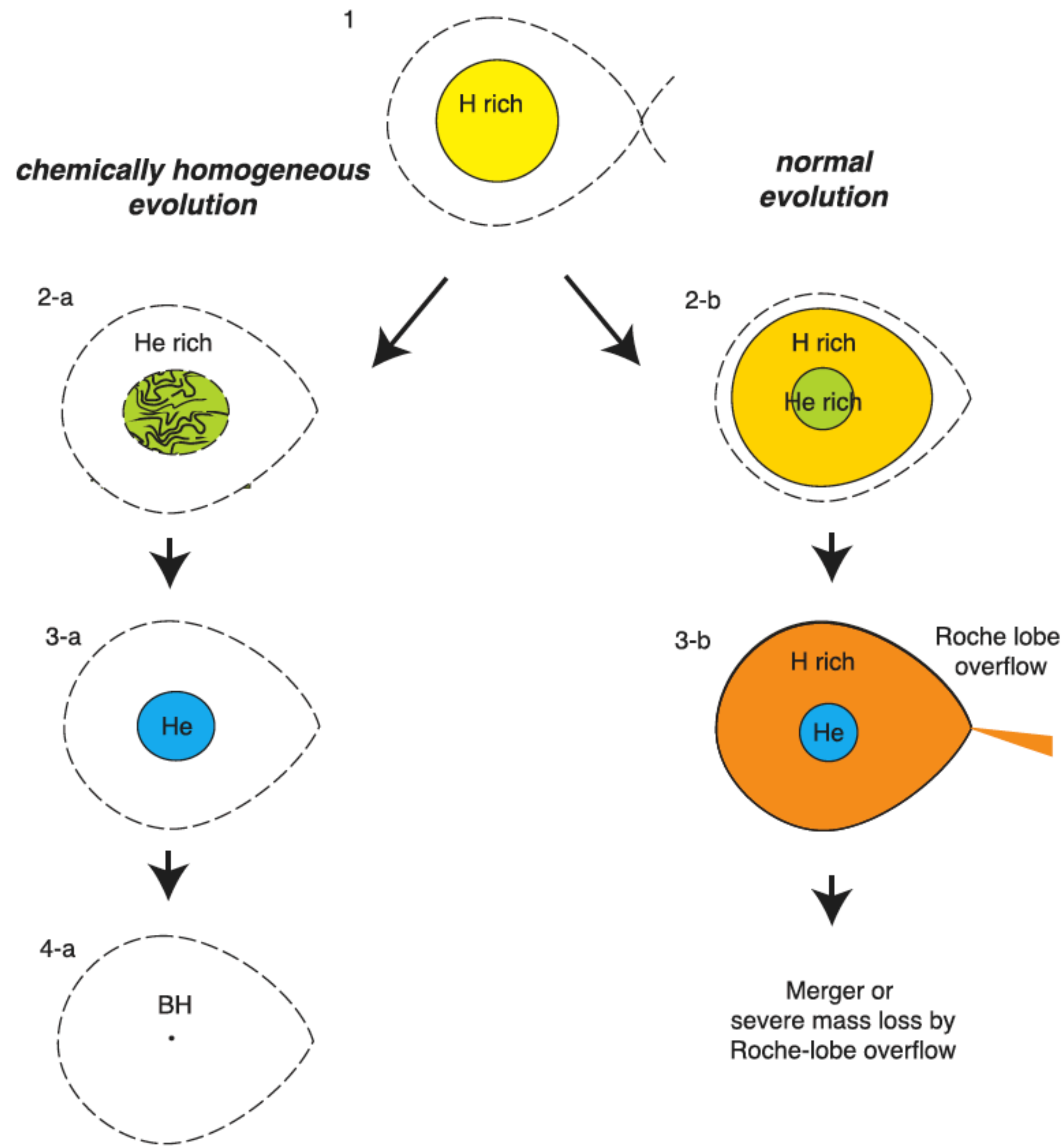
Chemically homogeneous evolution
(case M; de Mink et al. 2009)

- Very **rapid rotation** mixes hydrogen from envelope heavy elements from core

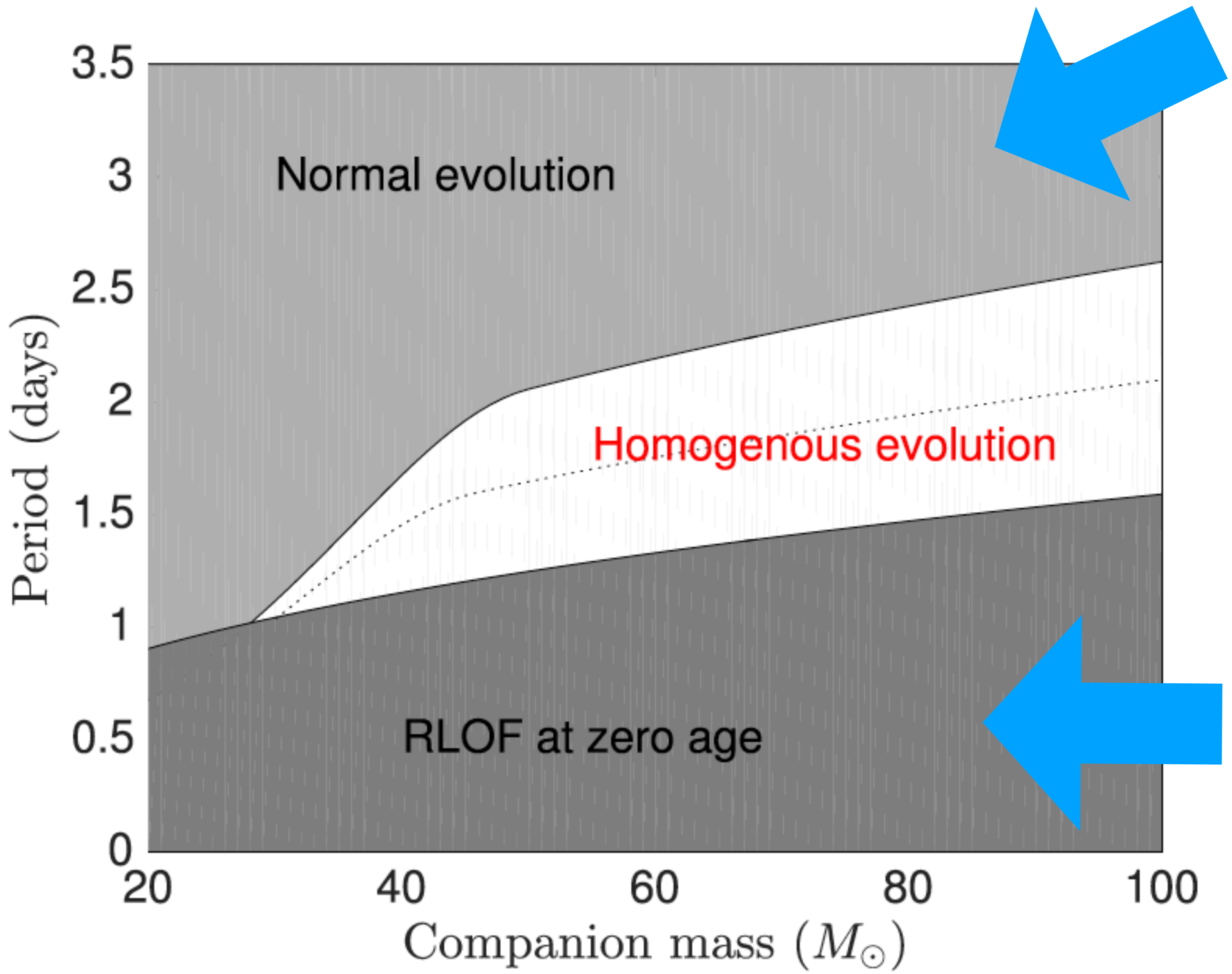
- Rather than expanding, star burns **hot, luminous and small**

- Favored at low metallicity (winds)
  Near contact binaries (tidal locking)

- Possible evidence from overcontact binary VFTS 352 (too hot/compact for dynamically inferred masses)



What periods and masses allow chemically homogeneous evolution?



Too far apart for homogeneous evolution

Stars have finite size at ZAMS

Order of magnitude, how important is this?

MW equivalent galaxies (MWEG) ~ 0.01 Mpc^{-3}

SFR in MWEGs ~ 2 $M_\odot$/year

3% at z = 0
10% cumulatively below Z = 0.004

3e-4 above 60 $M_\odot$
1/3 with companions > 40 $M_\odot$

~0.1 assuming period distribution is flat in log space

$$\frac{\mathrm{d}N}{\mathrm{d}V\,\mathrm{d}t} = \frac{\mathrm{d}N_{\mathrm{gal}}}{\mathrm{d}V} \dot{N}_{\mathrm{SF}} f_Z f_{\mathrm{mass}} f_{\mathrm{sep}},$$

where $\mathrm{d}N_{\mathrm{gal}}/\mathrm{d}V$ is the number density of galaxies; $\dot{N}_{\mathrm{SF}}$ is the rate of stars formed per galaxy per unit time; f_Z is the fraction of stars formed at metallicities of interest; f_{mass} is the fraction of stars formed in binaries in the mass range of interest and f_{sep} is the fraction of binaries in the required range of separations.

Altogether:

$$\frac{\mathrm{d}N}{\mathrm{d}t} \sim \frac{0.01}{\mathrm{Mpc}^3} \times \frac{2}{\mathrm{yr}} \times 0.1 \times 10^{-4} \times 0.1 \sim 20\ \mathrm{Gpc}^{-3}\mathrm{yr}^{-1}.$$

LIGO constraints: 10 - 100

Binary population synthesis inputs

Initial binary distributions

- **Kroupa IMF**
- **flat distribution in mass ratio q**
- $\mathrm{d}N/\mathrm{d}\log_{10}P \propto (\log_{10}P)^{-0.5}$ (Sana+2012)

Rotation threshold for chem. hom. evol.

$$\omega_c = \begin{cases} 0.2 + 2.7 \times 10^{-4} \left(\frac{m}{\mathrm{M}_\odot} - 50\right)^2 & \text{for } m < 50\,\mathrm{M}_\odot, \\ 0.2 & \text{for } m \geq 50\,\mathrm{M}_\odot. \end{cases}$$

analytic fit to Yoon+2006 simulations for Z = 0.004

Mass loss

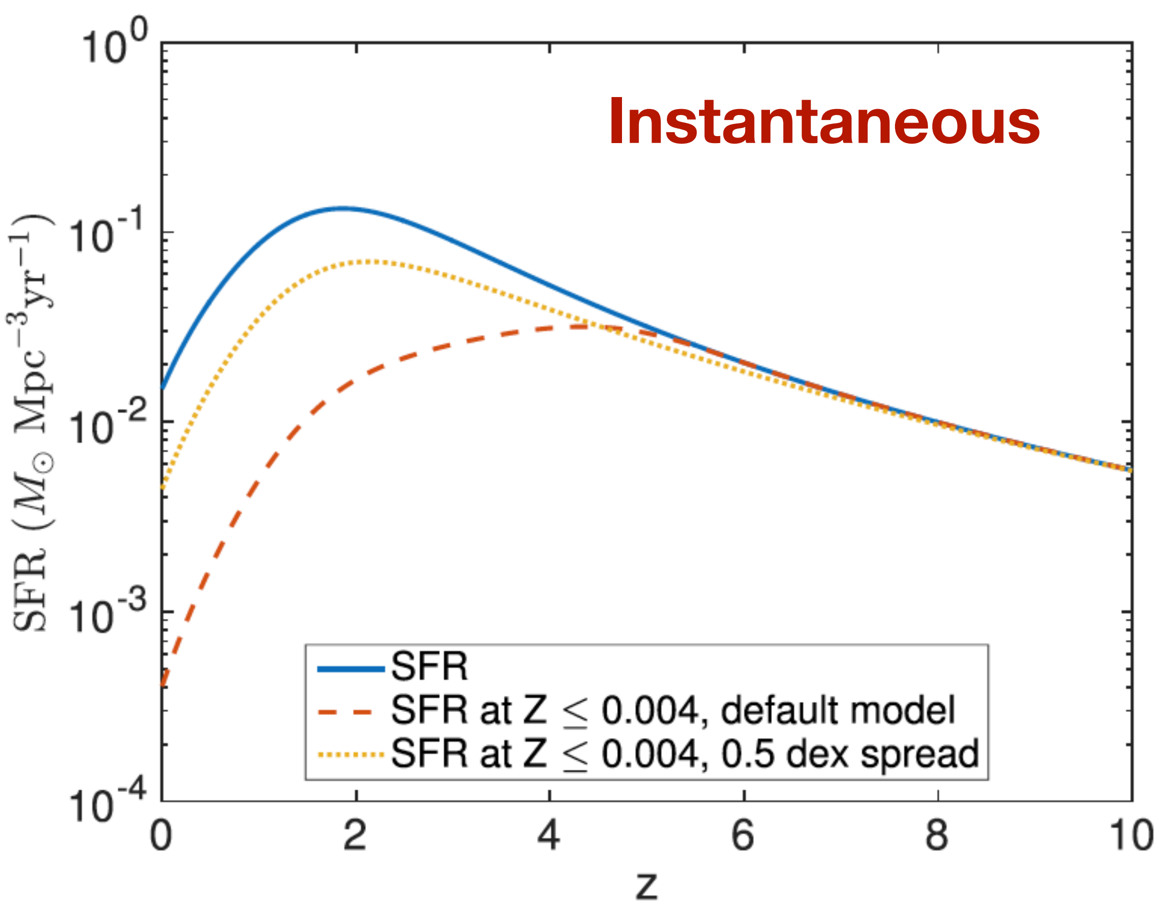
- **10% loss during MS (winds)**
- **25% loss during WR (winds)**
- **10% loss during SN (ejecta)**

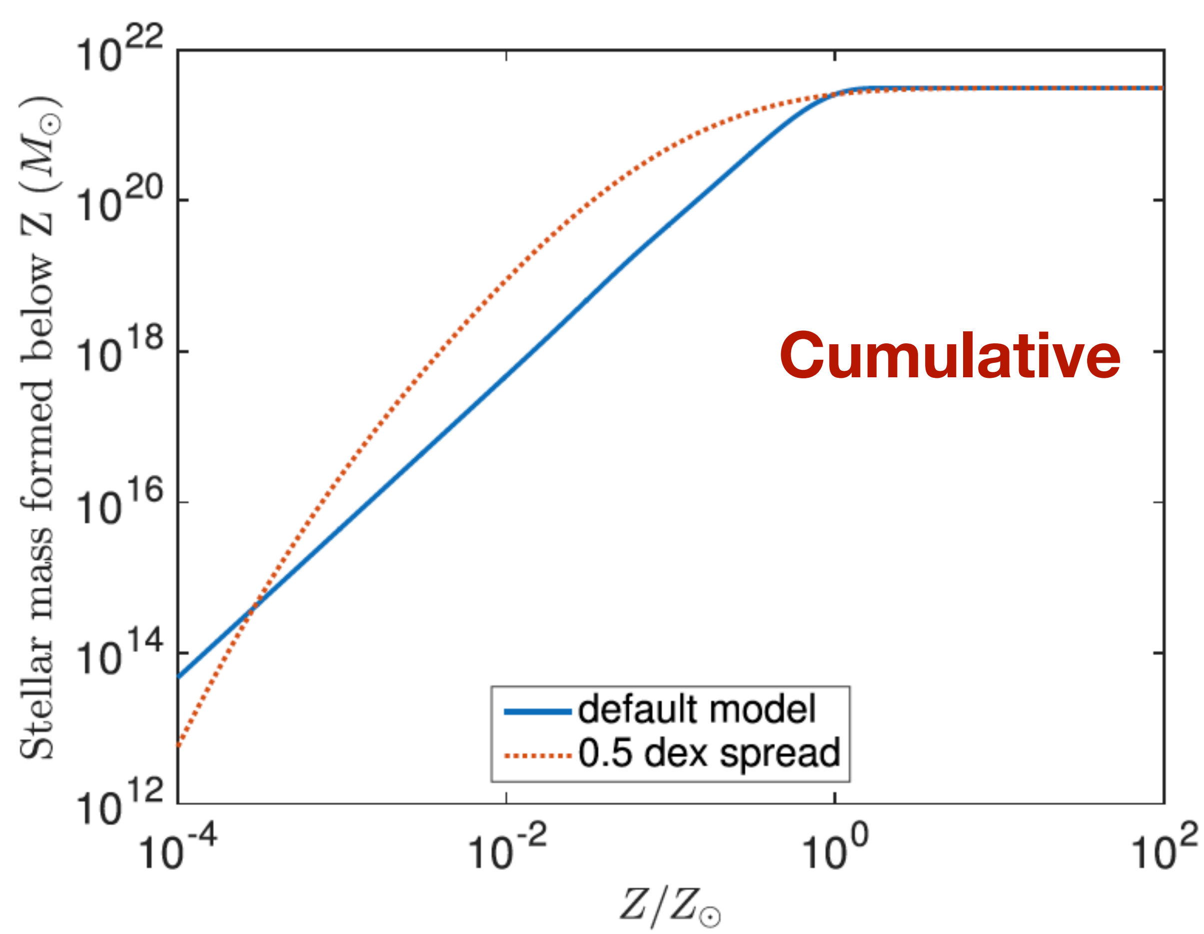
Binary population synthesis inputs

Orbital evolution

- **Assume circular orbits**
- **Orbit widens due to wind and SN mass loss**
- **Assume winds are spherical, fast compared to orbital motion**
- **Low kicks**

Star formation & metallicity





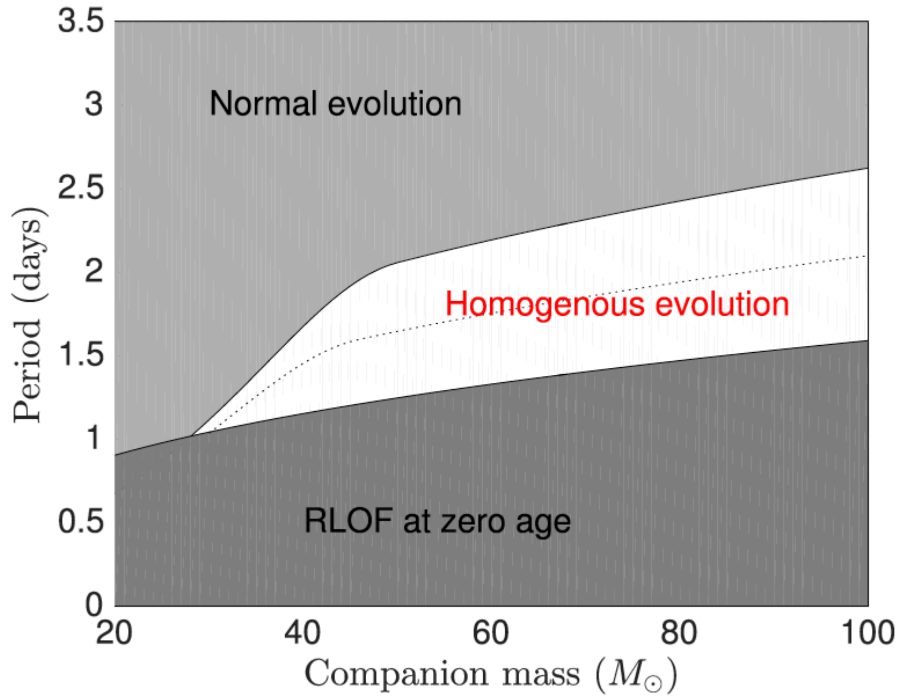
Sample from all these distributions in a Monte Carlo simulation to estimate the BBH merger rate

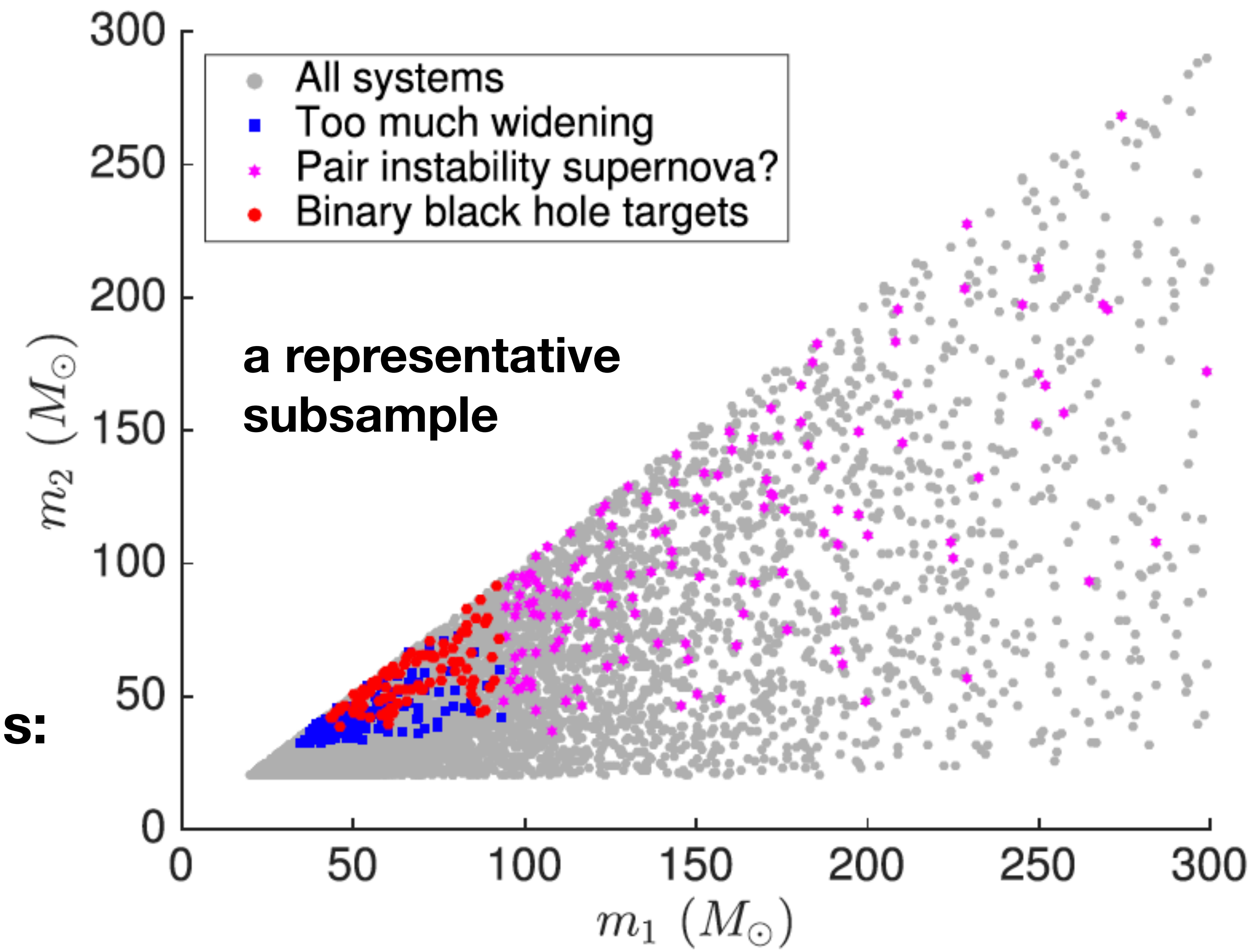
$$\frac{\mathrm{d}^4 N_{\mathrm{merge}}}{\mathrm{d}V_{\mathrm{c}}\,\mathrm{d}t\,\mathrm{d}m_1\,\mathrm{d}m_2}(t_{\mathrm{m}}) = \int_{P_{\mathrm{min}}}^{P_{\mathrm{max}}} \mathrm{d}P \int_0^1 \mathrm{d}Z \int_0^{t_{\mathrm{m}}} \mathrm{d}t\; p(t_{\mathrm{m}}; m_1, m_2, P, Z, t_{\mathrm{b}})\, \frac{\mathrm{d}^2 M_{\mathrm{SFR}}}{\mathrm{d}t\,\mathrm{d}V_{\mathrm{c}}}(t_{\mathrm{b}})\, \frac{\mathrm{d}^5 N_{\mathrm{binaries}}}{\mathrm{d}m_1\,\mathrm{d}m_2\,\mathrm{d}P\,\mathrm{d}Z\,\mathrm{d}M_{\mathrm{SFR}}}(t_{\mathrm{b}})\,. \quad (8)$$

Basically a fancier version of:

$$\frac{\mathrm{d}N}{\mathrm{d}V\,\mathrm{d}t} = \frac{\mathrm{d}N_{\mathrm{gal}}}{\mathrm{d}V}\,\dot{N}_{\mathrm{SF}}\, f_Z\, f_{\mathrm{mass}}\, f_{\mathrm{sep}}\,,$$

The simulated results

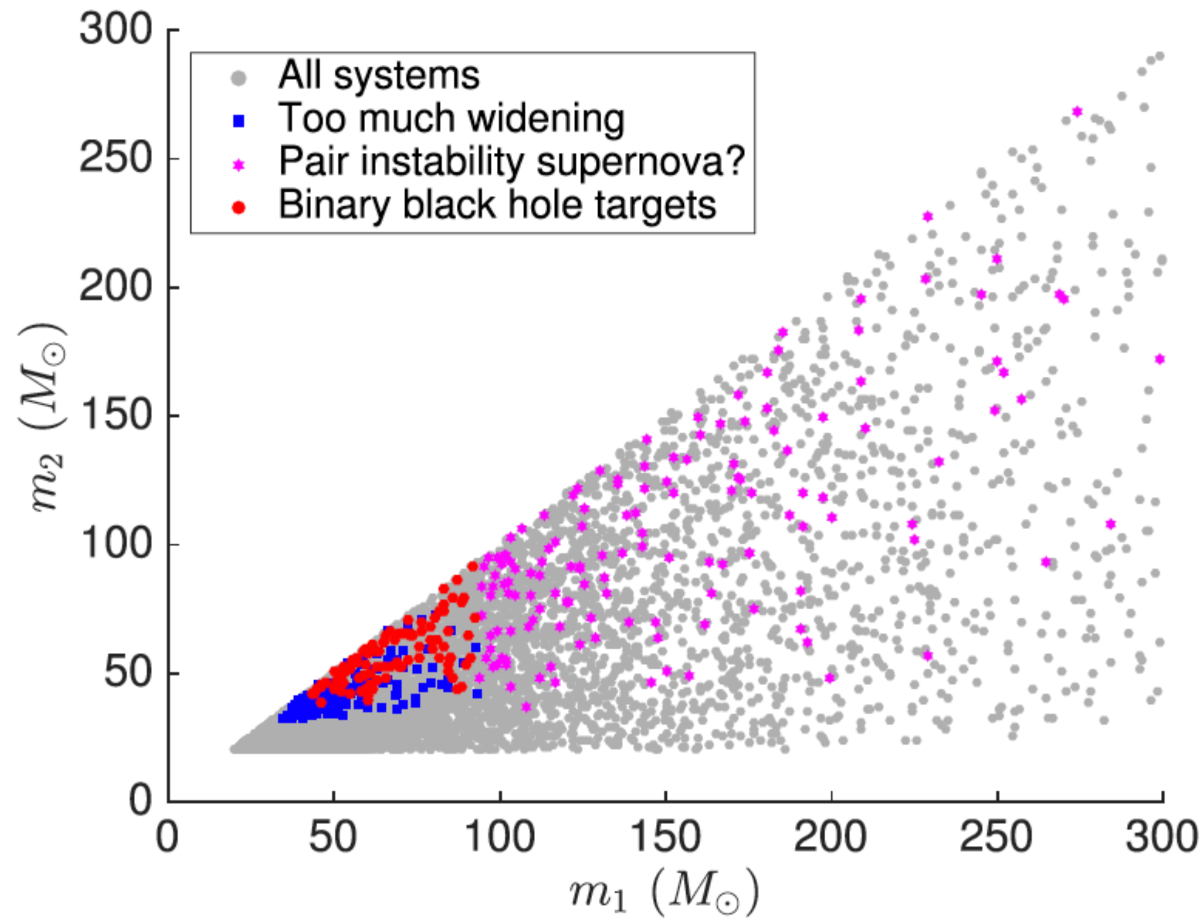




Out of 10^8 simulated systems:

- Vast majority are too wide or too close
- ~1900 satisfy case M conditions at ZAMS
- ~700 widen out of case M zone from winds
- ~700 have one component massive enough to explode as a pair instability SN
- ~500 form BBH systems (all merge within a Hubble time)

The simulated results



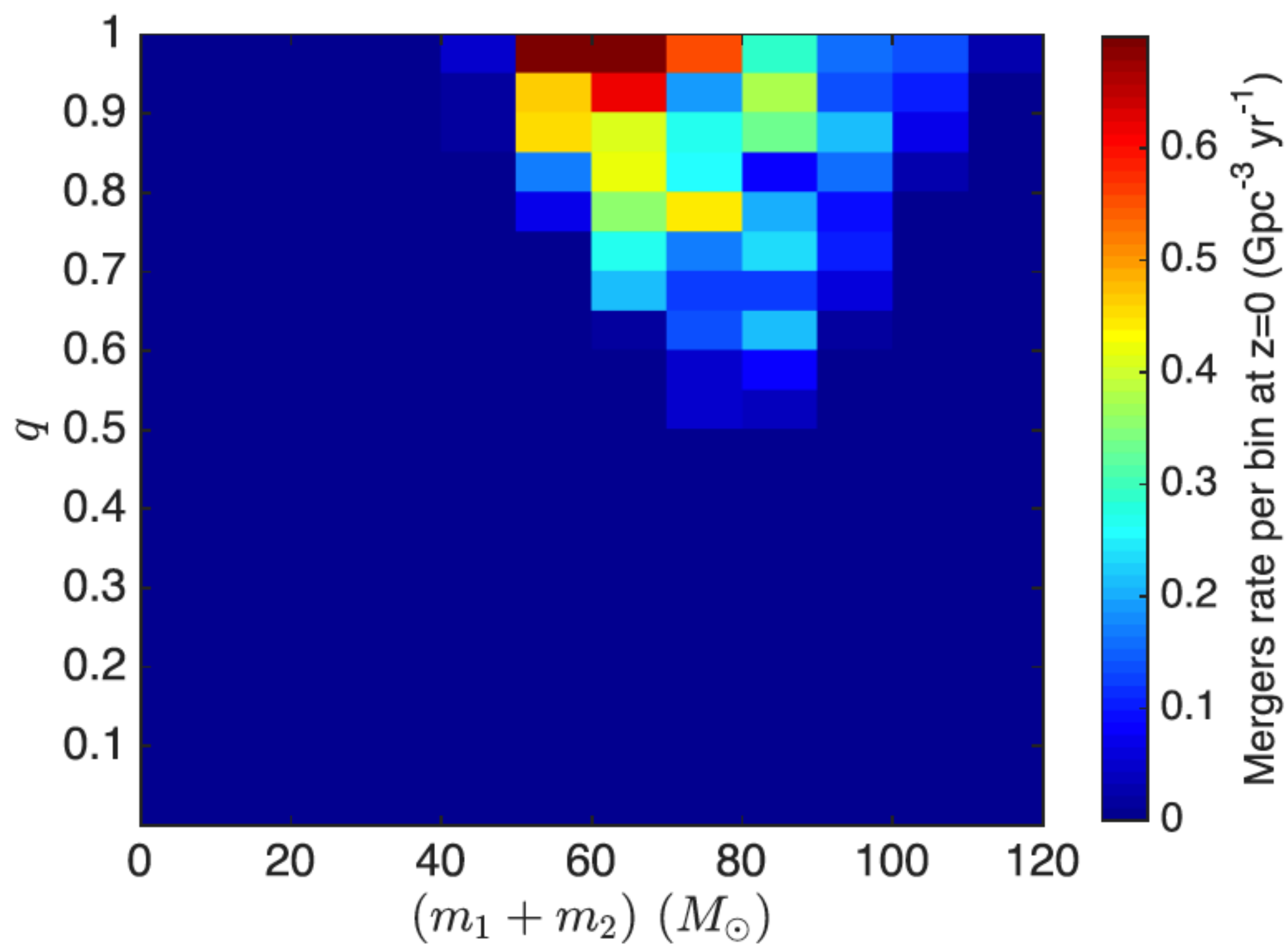
Overall rate:

- **10.5 +/- 0.5 mergers/year (numerical uncertainties in Monte Carlo)**

LIGO constraints: 10 - 100

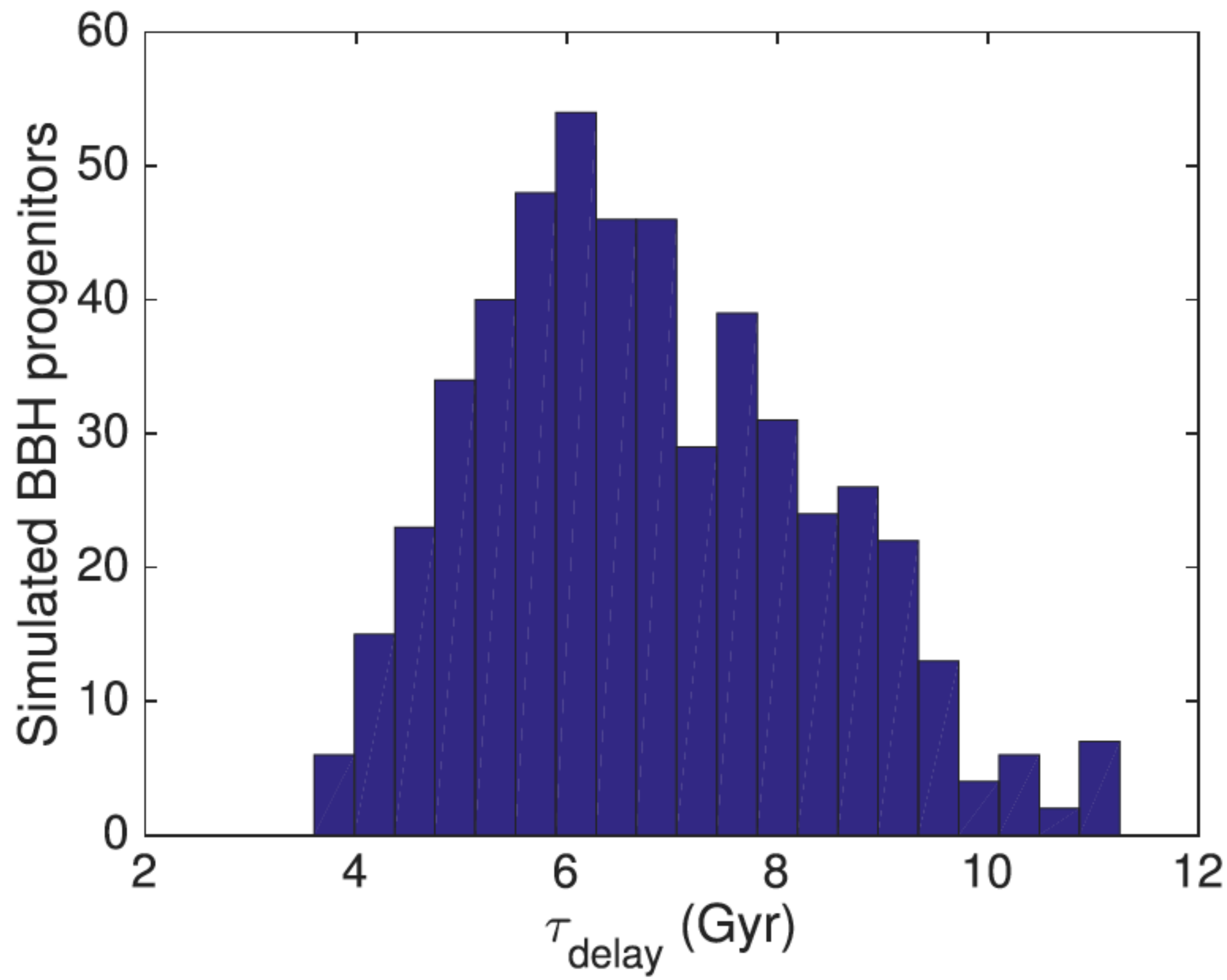
Mass ratios of BBH mergers

- Lower mass systems tend to have a mass ratio close to 1
- Intermediate mass systems go all the way down to q = 0.5
- The highest mass systems also have q ~ 1

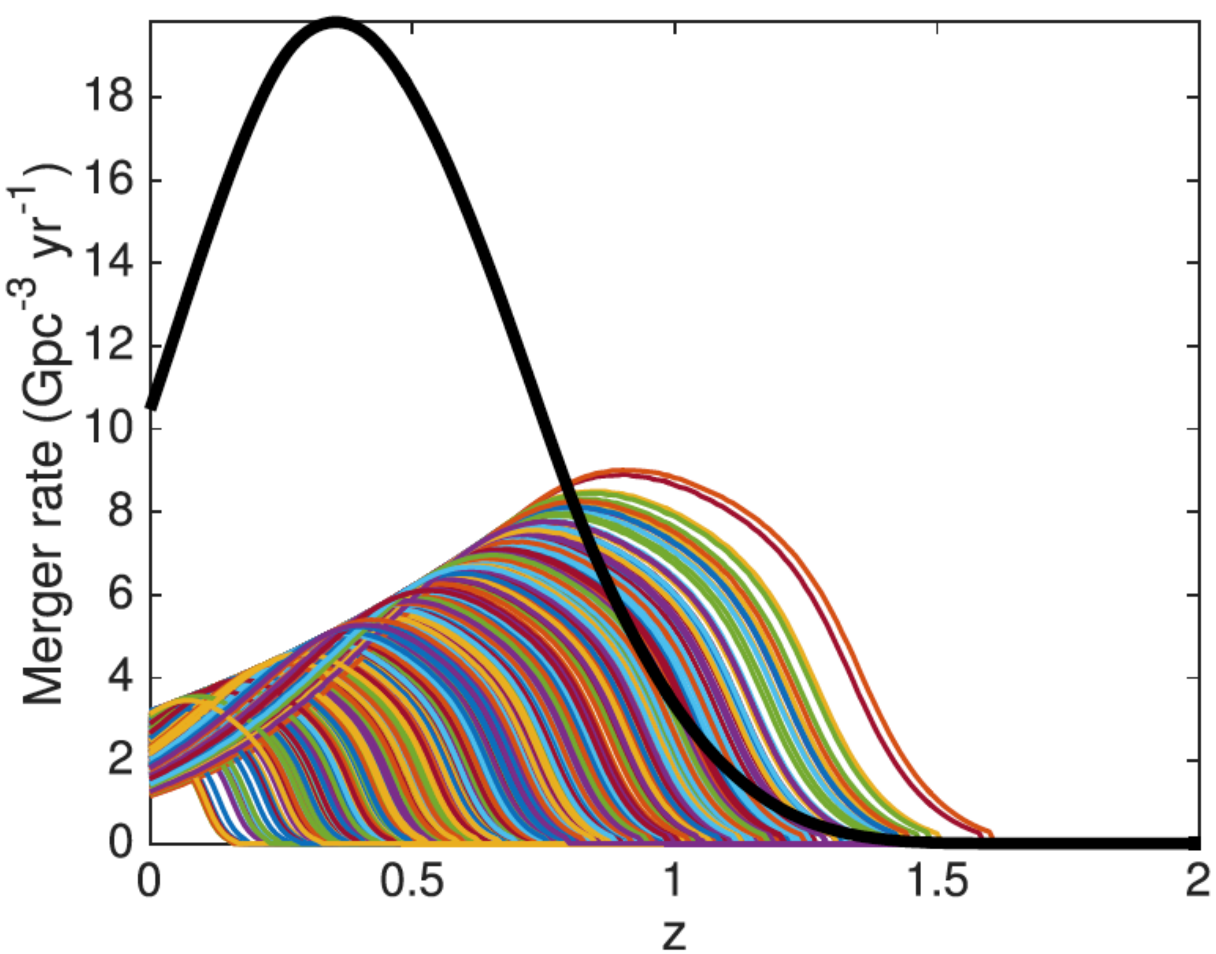


Delay times of BBH mergers

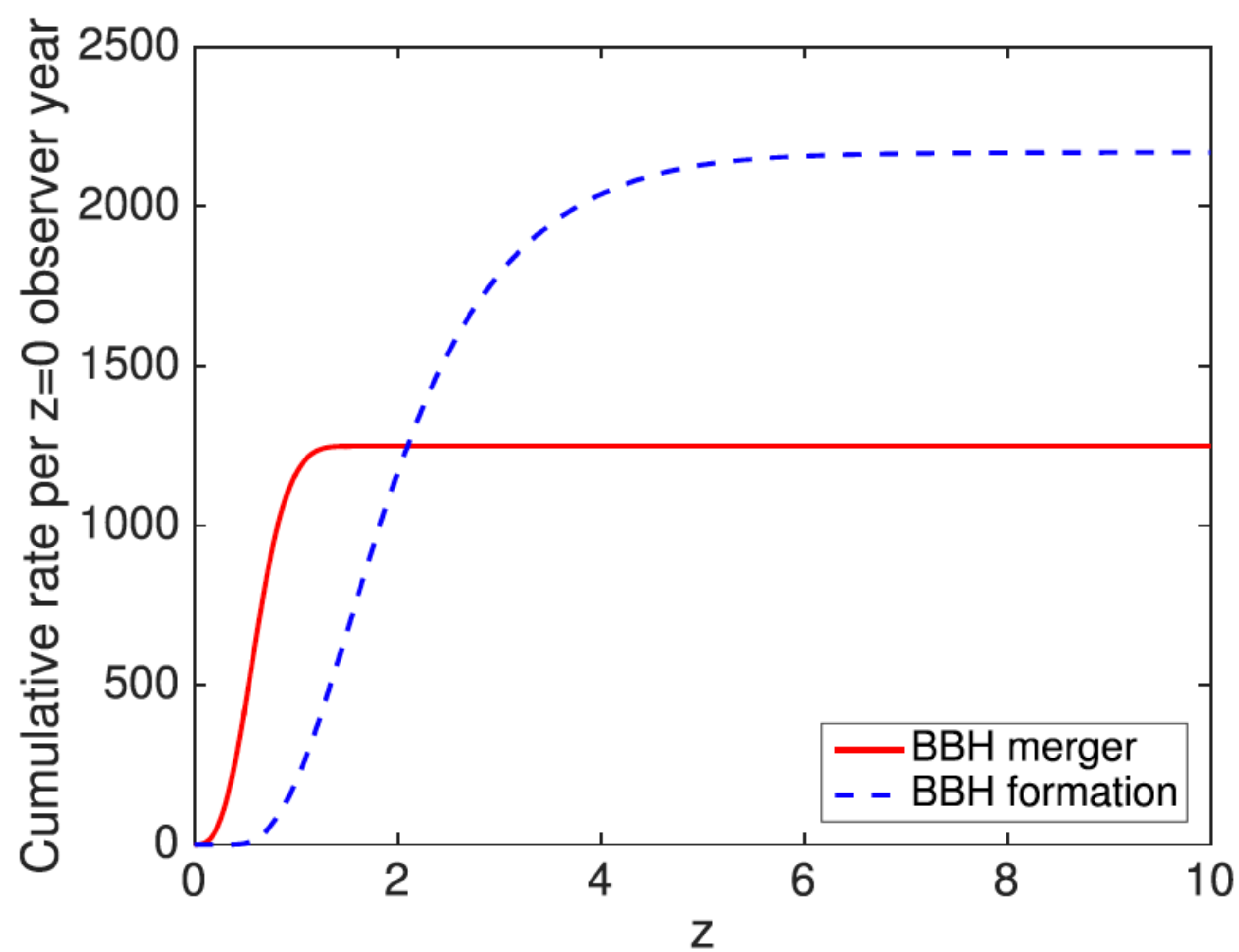
- **Minimum delay time = 3.5 Gyr**
- **No case M mergers before z = 1.6**



Most case M mergers happen at low redshift

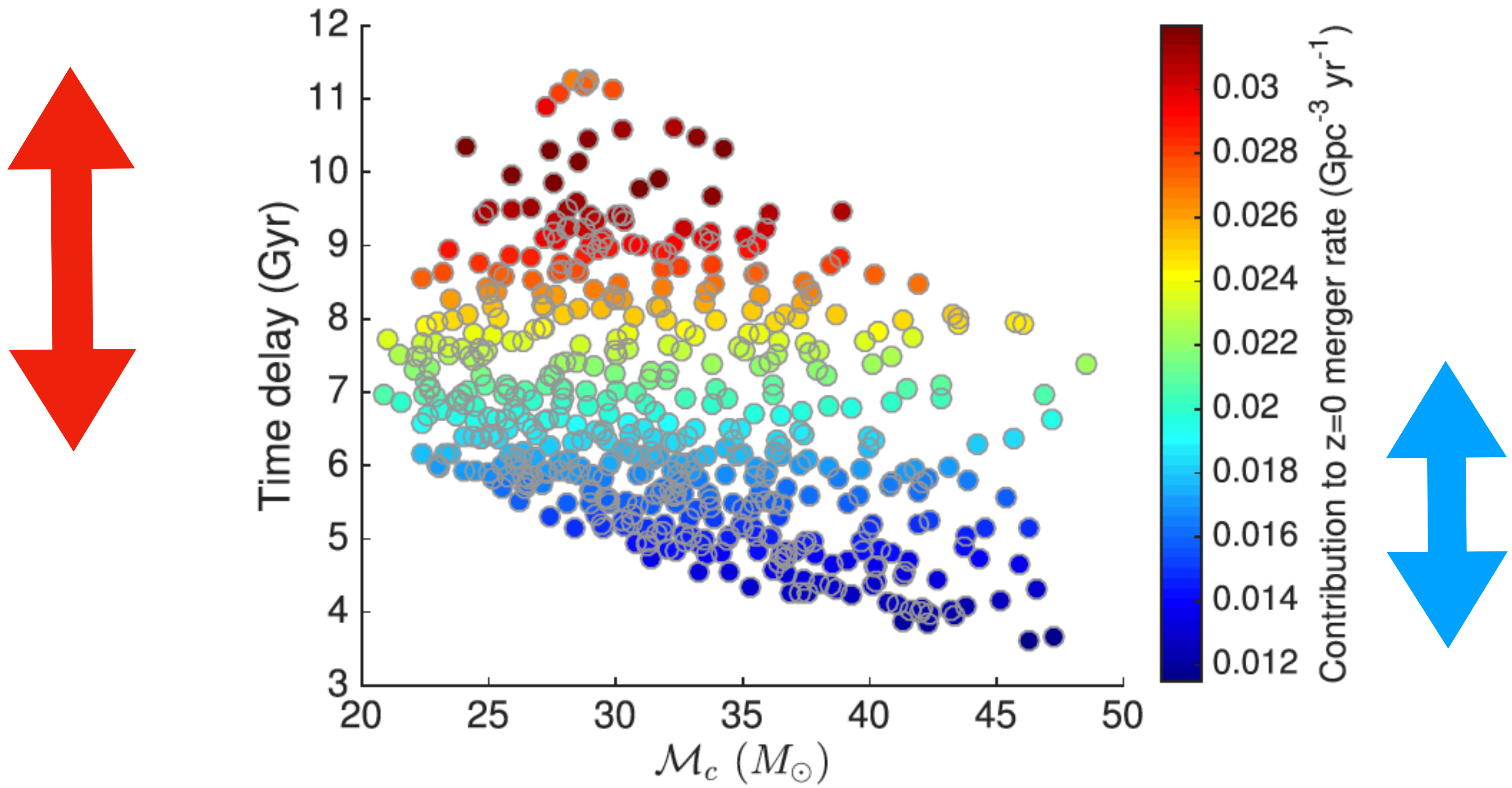


Instantaneous



Cumulative

Time delays and chirp masses of z = 0 mergers



- Low-ish chirp mass systems are common and span a large range of time delays
- High chirp mass systems are more rare & were mostly formed recently

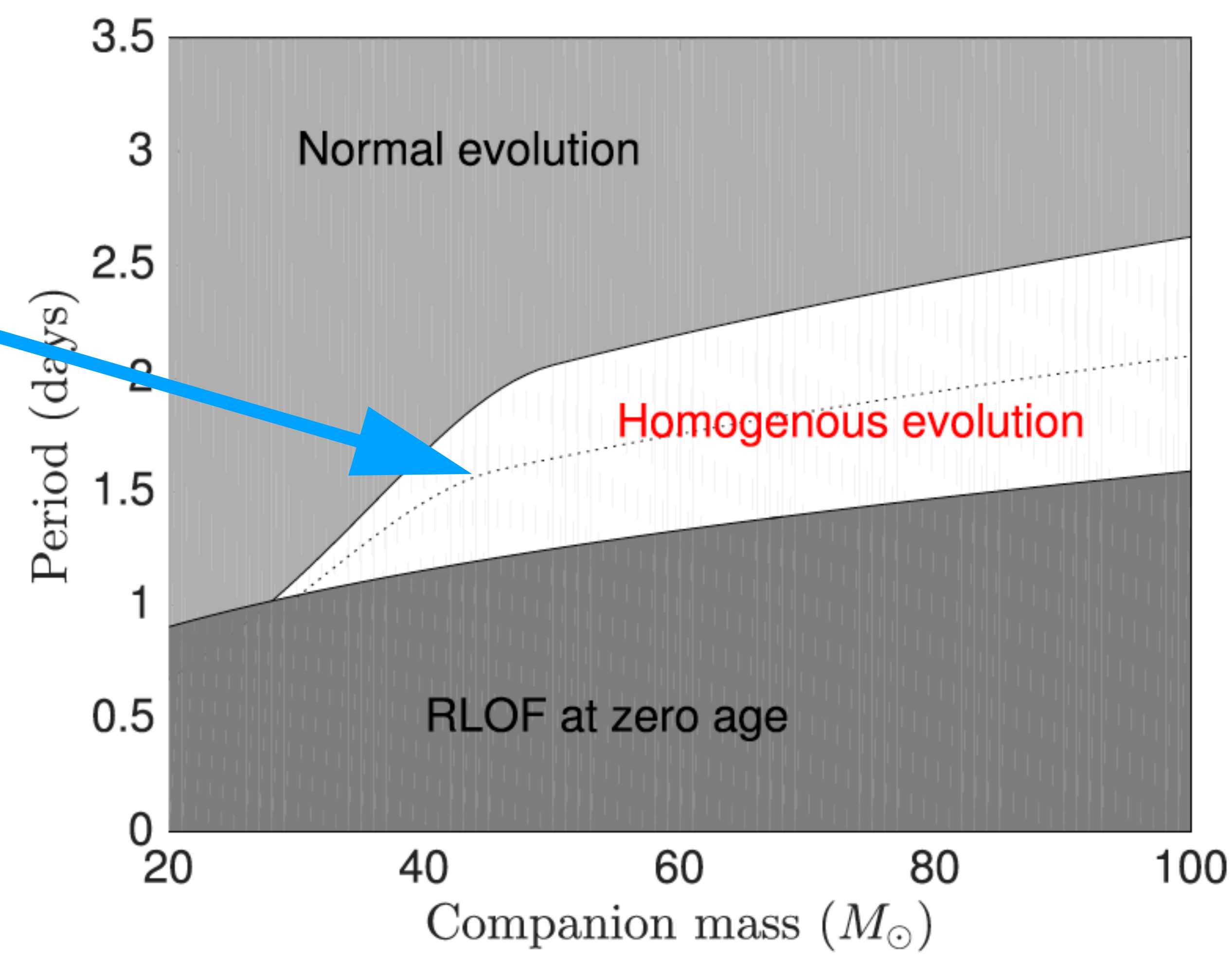
Uncertainties in the model

- **Uncertainties in mixing**

Estimated with more conservative fit to Yoon et al.

$$\omega_c = \begin{cases} 0.25 + 3.2\times10^{-4}\left(\frac{m}{\mathrm{M}_\odot} - 46\right)^2 & \text{for } m < 46\,\mathrm{M}_\odot, \\ 0.25 & \text{for } m \geq 46\,\mathrm{M}_\odot. \end{cases}$$

Reduces window for case M systems



Uncertainties in the model

- **Uncertainties in mixing**

Table 1. Cosmic merger rate in our default model and the impact of various uncertainties.

Simulation	R_{local} (Gpc^{-3} yr^{-1})	R_{max} (Gpc^{-3} yr^{-1})	$z(R_{max})$	Description	Comment
Default	10	20	0.5	Section 4	Standard simulation
Alternative 1	3	10	0.5	Section 7.1	Reduced Case M window
Alternative 2.1	2	3.5	0.3	Section 7.1	Reduced Metallicity threshold ($Z \leq 0.002$)
Alternative 2.2	15	30	0.3	Section 7.1	Relaxed metallicity threshold ($Z \leq 0.008$)
Alternative 3.1	7	200	2	Section 7.2	Slow winds (fixed separation)
Alternative 3.2	7	500	4	Section 7.2	Slow winds (halving separation)
Alternative 4.1	–	–	–	Section 7.3	Enhanced mass loss (doubled)
Alternative 4.2	25	50	0.4	Section 7.3	Enhanced mass loss and slow winds
Alternative 4.3	5	500	3	Section 7.3	Reduced mass loss (by factor of 5)
Alternative 5	10	20	0.5	Section 7.4	Increased PISN threshold (80 $M_{\odot}$)
Alternative 6	80	10	0.15	Section 7.5	Enhanced metallicity spread (0.5 dex)

Uncertainties in the model

- Wind-driven orbital evolution
- Wind velocities in the WR stage (1000 km/s) are comparable to the orbital velocity
  - May carry away significant orbital angular momentum from system
  - Results in tighter binaries, reducing delay times
  - More mergers at high z, marginally fewer at z = 0 (7 vs 10 Gpc^{-3})

Table 1. Cosmic merger rate in our default model and the impact of various uncertainties.

Simulation	R_{local} (Gpc^{-3} yr^{-1})	R_{max} (Gpc^{-3} yr^{-1})	$z(R_{max})$	Description	Comment
Default	10	20	0.5	Section 4	Standard simulation
Alternative 1	3	10	0.5	Section 7.1	Reduced Case M window
Alternative 2.1	2	3.5	0.3	Section 7.1	Reduced Metallicity threshold ($Z \leq 0.002$)
Alternative 2.2	15	30	0.3	Section 7.1	Relaxed metallicity threshold ($Z \leq 0.008$)
Alternative 3.1	7	200	2	Section 7.2	Slow winds (fixed separation)
Alternative 3.2	7	500	4	Section 7.2	Slow winds (halving separation)
Alternative 4.1	–	–	–	Section 7.3	Enhanced mass loss (doubled)
Alternative 4.2	25	50	0.4	Section 7.3	Enhanced mass loss and slow winds
Alternative 4.3	5	500	3	Section 7.3	Reduced mass loss (by factor of 5)
Alternative 5	10	20	0.5	Section 7.4	Increased PISN threshold (80 $M_{\odot}$)
Alternative 6	80	10	0.15	Section 7.5	Enhanced metallicity spread (0.5 dex)

Uncertainties in the model

- **Stronger or weaker mass loss**
  - **If mass loss is 2x stronger and winds are fast, all binaries widen too much**
    - **No BBH mergers**
  - **If mass loss is 2x stronger and winds are slow, fewer pair instability SNe**
    - **Higher rates (25 Gpc^{-3} at z = 0)**
  - **If mass loss is 5x weaker, less binary expansion during evolution**
    - **Time delays reduced**
    - **Large peak at z ~ 3 (500 Gpc^{-3})**
    - **Lower rate today (5 Gpc^{-3})**

Table 1. Cosmic merger rate in our default model and the impact of various uncertainties.

Simulation	R_{local} (Gpc^{-3} yr^{-1})	R_{max} (Gpc^{-3} yr^{-1})	$z(R_{max})$	Description	Comment
Default	10	20	0.5	Section 4	Standard simulation
Alternative 1	3	10	0.5	Section 7.1	Reduced Case M window
Alternative 2.1	2	3.5	0.3	Section 7.1	Reduced Metallicity threshold ($Z \leq 0.002$)
Alternative 2.2	15	30	0.3	Section 7.1	Relaxed metallicity threshold ($Z \leq 0.008$)
Alternative 3.1	7	200	2	Section 7.2	Slow winds (fixed separation)
Alternative 3.2	7	500	4	Section 7.2	Slow winds (halving separation)
Alternative 4.1	–	–	–	Section 7.3	Enhanced mass loss (doubled)
Alternative 4.2	25	50	0.4	Section 7.3	Enhanced mass loss and slow winds
Alternative 4.3	5	500	3	Section 7.3	Reduced mass loss (by factor of 5)
Alternative 5	10	20	0.5	Section 7.4	Increased PISN threshold (80 $M_{\odot}$)
Alternative 6	80	10	0.15	Section 7.5	Enhanced metallicity spread (0.5 dex)

Uncertainties in the model

- **Lower mass threshold for pair instability**
- **Larger spread in metallicities**
    - **Fairly similar to default scenario**

Table 1. Cosmic merger rate in our default model and the impact of various uncertainties.

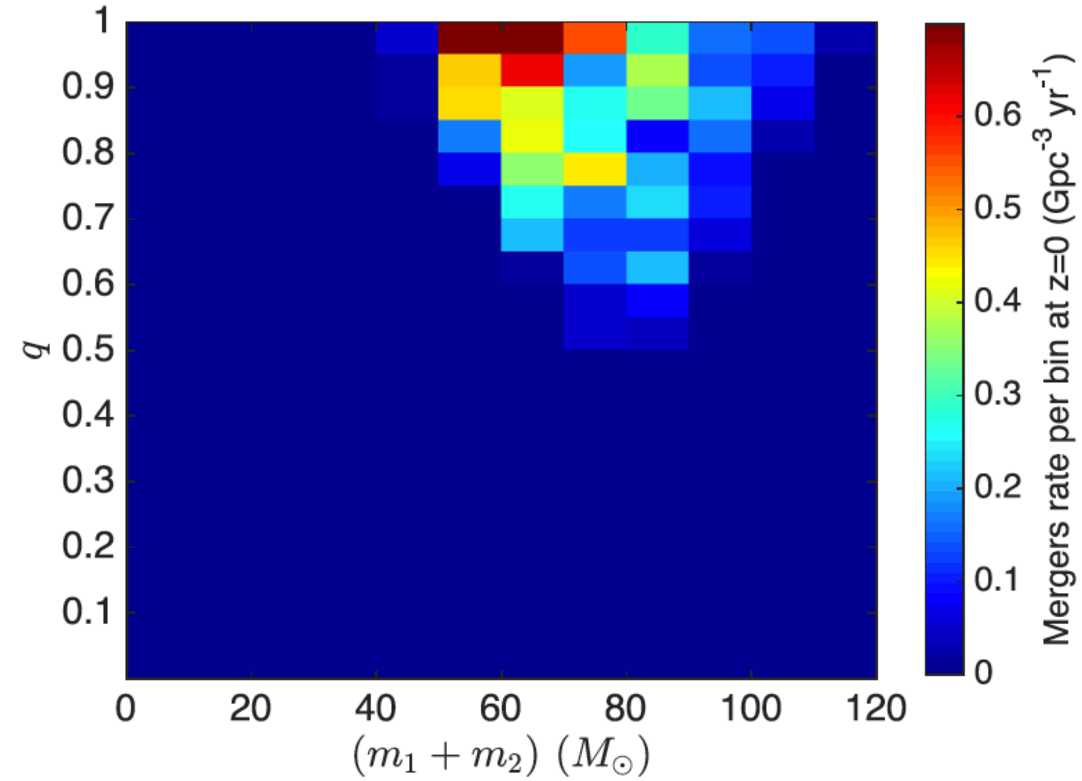
Simulation	R_{local} ($Gpc^{-3}\ yr^{-1}$)	R_{max} ($Gpc^{-3}\ yr^{-1}$)	$z(R_{max})$	Description	Comment
Default	10	20	0.5	Section 4	Standard simulation
Alternative 1	3	10	0.5	Section 7.1	Reduced Case M window
Alternative 2.1	2	3.5	0.3	Section 7.1	Reduced Metallicity threshold ($Z \leq 0.002$)
Alternative 2.2	15	30	0.3	Section 7.1	Relaxed metallicity threshold ($Z \leq 0.008$)
Alternative 3.1	7	200	2	Section 7.2	Slow winds (fixed separation)
Alternative 3.2	7	500	4	Section 7.2	Slow winds (halving separation)
Alternative 4.1	–	–	–	Section 7.3	Enhanced mass loss (doubled)
Alternative 4.2	25	50	0.4	Section 7.3	Enhanced mass loss and slow winds
Alternative 4.3	5	500	3	Section 7.3	Reduced mass loss (by factor of 5)
Alternative 5	10	20	0.5	Section 7.4	Increased PISN threshold (80 $M_\odot$)
Alternative 6	80	10	0.15	Section 7.5	Enhanced metallicity spread (0.5 dex)

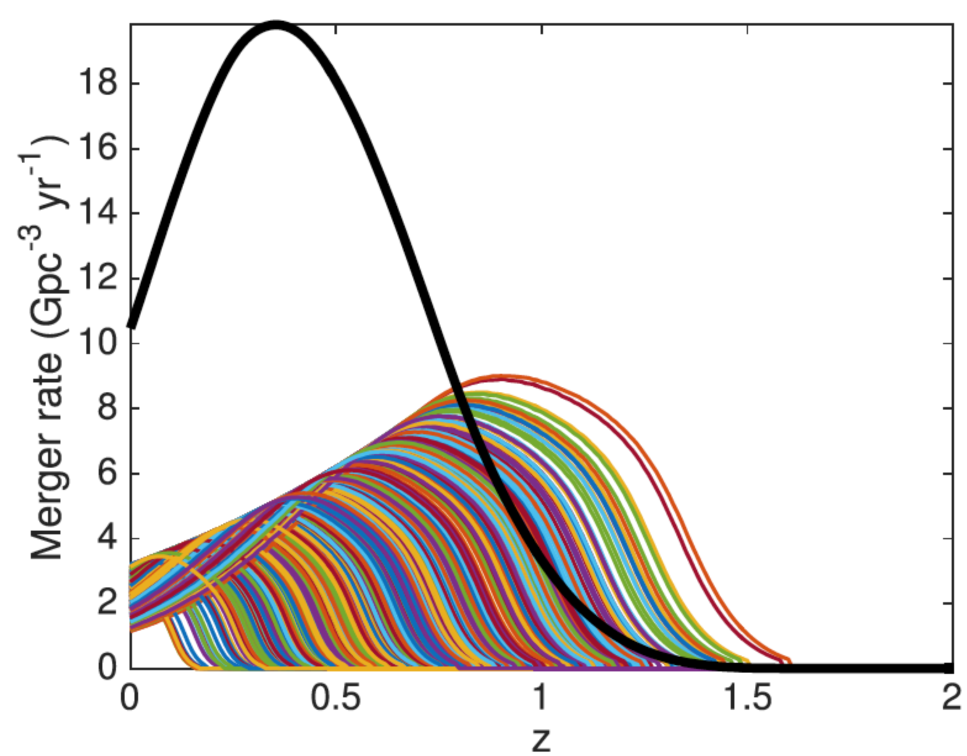
- **Differences in initial binary P's and q's**
    - **Affects overall rate normalization but not properties**

(de Mink & Belczynski 2015)

Conclusions of paper I

- Case M evolution can produce a significant fraction of BBH mergers ~ 10 Gpc^{-3}
- Typical mergers are equal mass ratio total binary mass ~50 - 110 $M_{\odot}$
- SN natal kicks are expected to be low, so BH spins are expected to be aligned
- Delay times are long, so most mergers are at low redshift
    - Can possibly be tested with a stochastic GW background





Mechanisms producing merging BH binaries

- Dynamical evolution within a dense stellar cluster

- Isolated binary evolution through mass transfer/ejection of common envelope

- Chemical evolution of stars in near-contact binaries with strong internal mixing

Mechanisms producing merging BH binaries

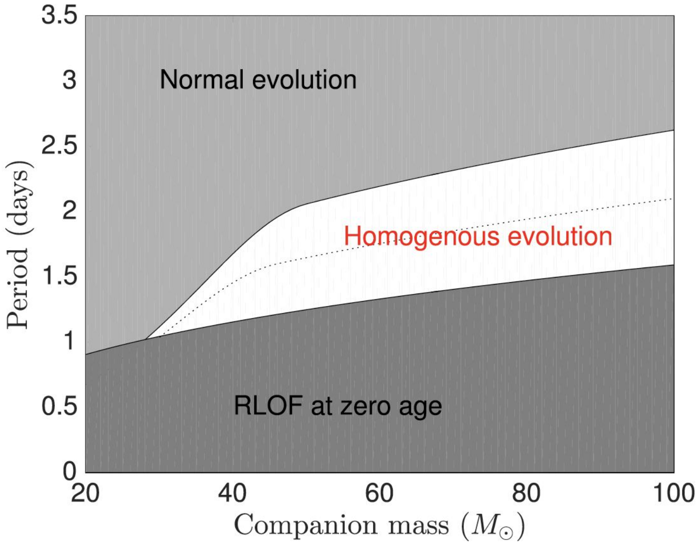
- Dynamical evolution within a dense stellar cluster
- Isolated binary evolution through mass transfer/ejection of common envelope
- Chemical evolution of stars in near-contact binaries with strong internal mixing
    - Primary formation pathway we will consider

Mixing of nuclear material by instabilities induced by tidal deformation

- Can lead to enrichment of stellar envelope with helium
- Prevents the buildup of a chemical gradient within the star
- Stars remain compact through their evolution
- Possible observational examples include VFTS 352 (Almeida et al. 2015) and HD 5980 (Koenigsberger et al. 2014)

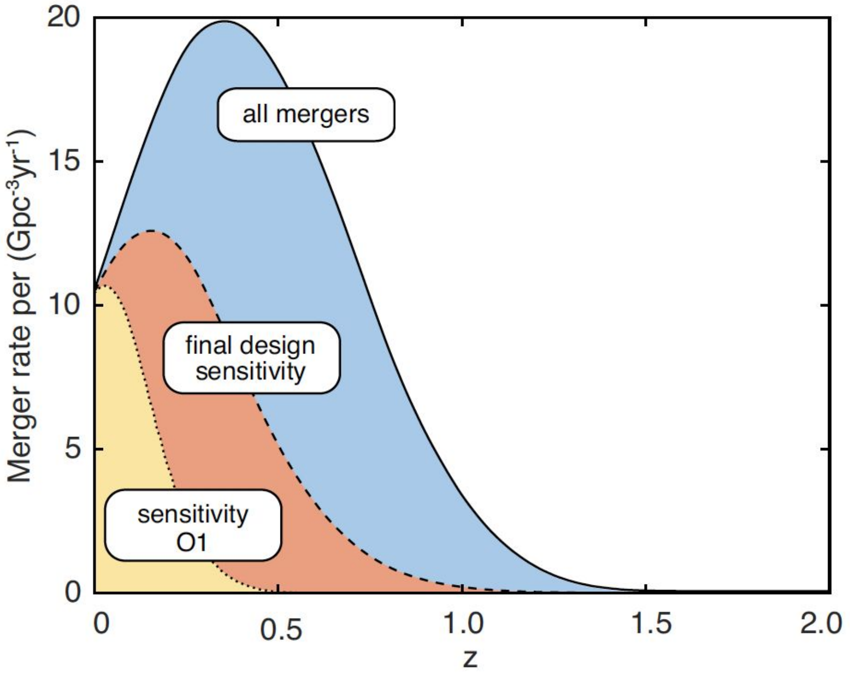
Chemically homogeneous evolution simulations

- Merger times within 4-11 Gyr,
- Total mass to exceed 50-100 $M_\odot$
- Mass ratio q > 0.75
- Assumes circular orbits
- Maximum Z = 0.004



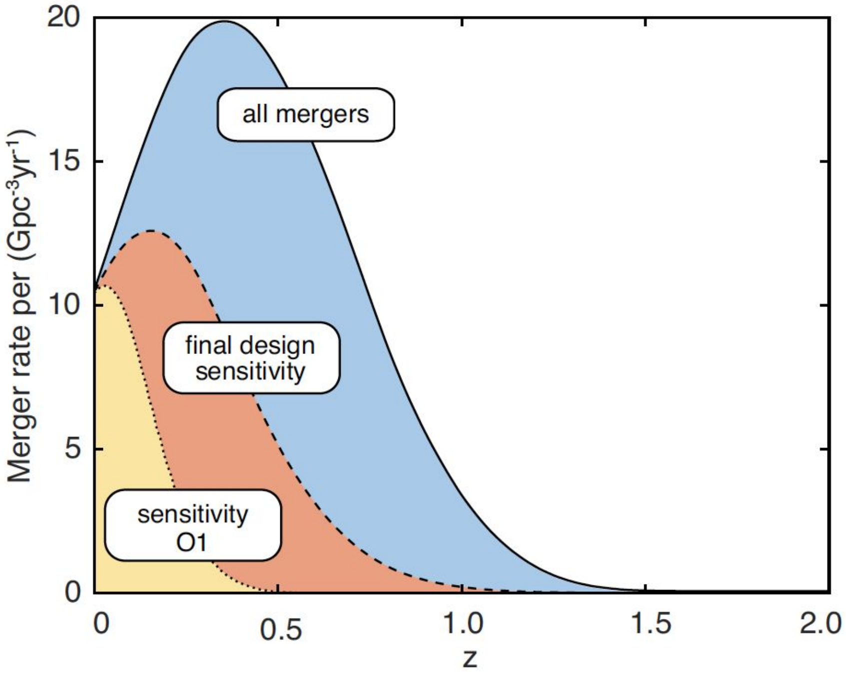
Cosmology and Merger rate

- Assumes flat cosmology with Ω_Λ = 0.718 and H_0 = 69.7 km/s/Mpc
- Initial orbital period $10^{0.075}$ d to $10^{5.5}$ d
- Delay time 4-11 Gyrs, earliest mergers z~1.5
- Maximum at z~0.4
- Varies with mass loss rate, wind speed, metallicity distribution etc.

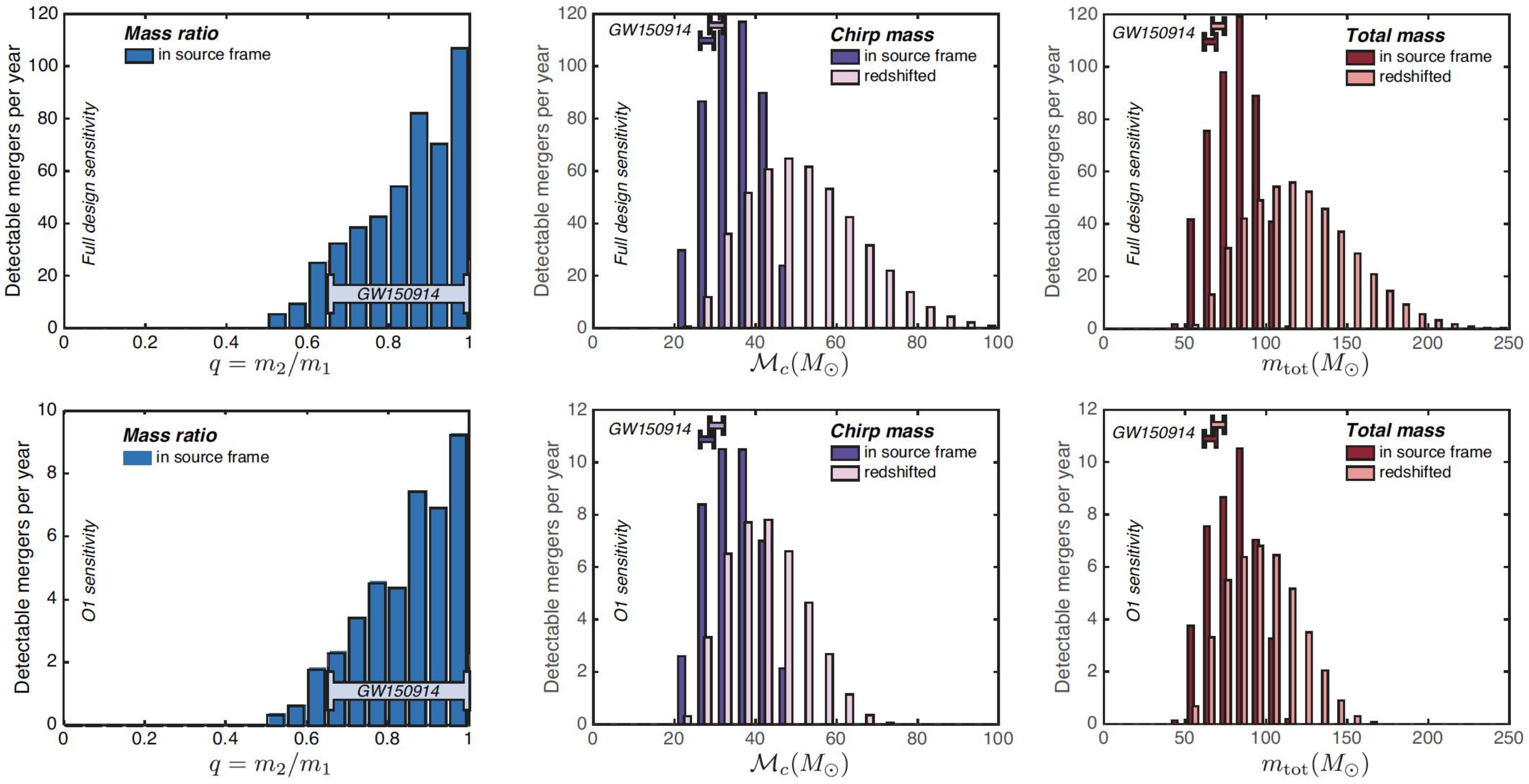


Detection rate

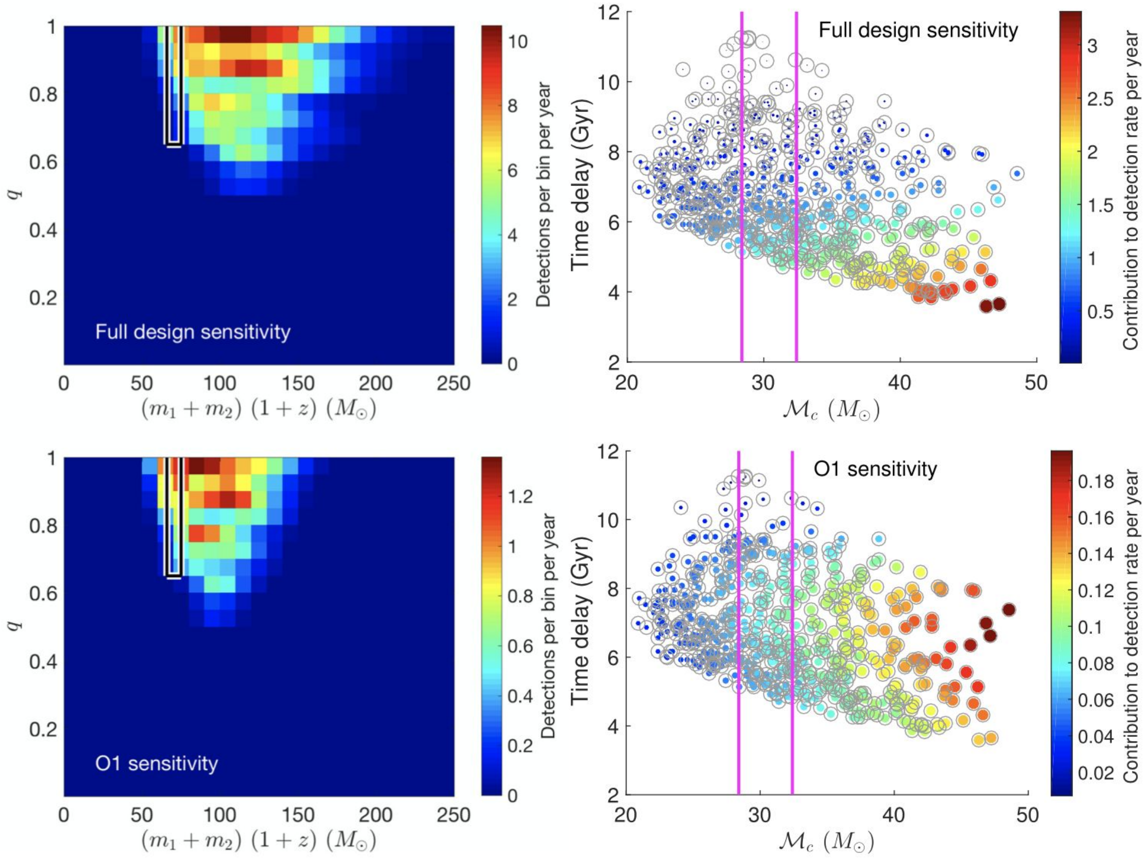
- For O1, median z~0.2
- GW150914 z~0.1, lower 10th percentile
- Full sensitivity, median z~0.5
- 500 events detectable per year with full sensitivity



Mass ratio, chirp mass, total mass



Mass ratio, chirp mass, total mass



Model variations

ID	Model	R_{detect}(full) (yr^{-1})	N_{detect} (O1) (per 16 d)	$\mathcal{M}_c$ ($M_\odot$)	m_{tot} ($M_\odot$)	q	m_1 ($M_\odot$)	m_2 ($M_\odot$)	Description
0	`DefaultFull`	470	–	35^{+10}_{-10}	82^{+21}_{-25}	>0.66	44^{+11}_{-15}	36^{+15}_{-10}	Standard, full design sensitivity
0	`DefaultO1`	–	1.8	34^{+11}_{-10}	80^{+24}_{-24}	>0.68	44^{+12}_{-14}	35^{+15}_{-9}	Standard, O1 sensitivity
1	`PoorMixing`	230	0.6	32^{+10}_{-6}	74^{+24}_{-14}	>0.72	41^{+14}_{-11}	34^{+9}_{-7}	Red. Case M window
2.1	`Zmin0.002`	91	0.3	35^{+9}_{-9}	84^{+17}_{-22}	>0.65	47^{+9}_{-14}	35^{+12}_{-9}	Red. metallicity threshold (0.002)
2.2	`Zmin0.008`	540	2.5	35^{+9}_{-10}	80^{+20}_{-24}	>0.68	47^{+8}_{-18}	36^{+14}_{-10}	Inc. metallicity threshold (0.008)
3.1	`ConstA`	1200	1.4	34^{+10}_{-11}	79^{+22}_{-25}	>0.68	42^{+14}_{-14}	35^{+13}_{-10}	Slow winds (fixed sep.)
3.2	`HalvedA`	1000	1.2	34^{+10}_{-11}	78^{+23}_{-25}	>0.69	44^{+10}_{-16}	35^{+12}_{-10}	Slow winds (halving sep.)
4.1	`Mdot2`	0.0	0.0	–	–	–	–	–	Enh. mass-loss (doubled)
4.2	`Mdot2ConstA`	620	1.5	26^{+14}_{-12}	59^{+32}_{-27}	>0.55	34^{+15}_{-17}	26^{+19}_{-11}	Enh. mass-loss and slow winds
4.3	`Mdot0.2`	1500	1.6	39^{+11}_{-9}	91^{+23}_{-22}	>0.74	50^{+10}_{-14}	42^{+14}_{-9}	Red. mass-loss (by factor of 5)
5	`PISN80`	600	2.1	40^{+8}_{-16}	93^{+17}_{-37}	>0.59	51^{+16}_{-19}	37^{+18}_{-11}	Enh. PISN threshold (80 $M_\odot$)
6	`Dex0.5`	1400	10	34^{+10}_{-10}	77^{+24}_{-22}	>0.71	43^{+11}_{-14}	37^{+13}_{-11}	Enh. metallicity spread (0.5 dex)
Combined		0–1500	0–10	14–50	32–114	>0.55	17–67	15–56	Union of 90 per cent ranges
GW150914			1	28^{+2}_{-2}	65^{+5}_{-4}	>0.65	36^{+5}_{-4}	29^{+4}_{-4}	Abbott et al. (2016f)

Conclusions

- Occurrence of GW150914 consistent with predictions of BH mergers via chemically homogenous evolution
- Should expect several hundred BH mergers consisting of ~equal mass BH ~40 $M_\odot$ each per year in full sensitivity LIGO.
- ~40 per year in O1