Binary black holes: formation scenarios and merger rates

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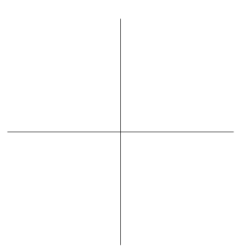
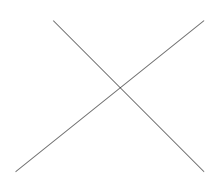
Gravitational waves: physical background

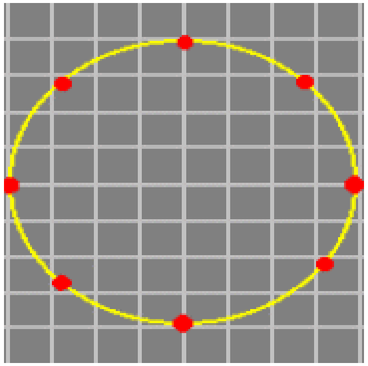
- Spacetime oscillations
- Gravitational waves are transverse
- Two polarisations: EM 90 deg; GW 45 deg

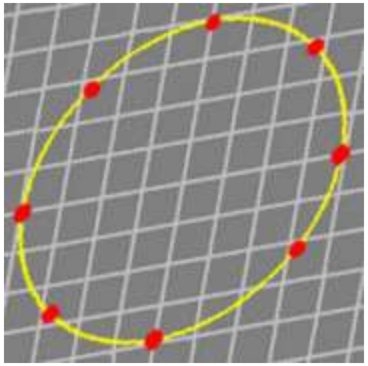




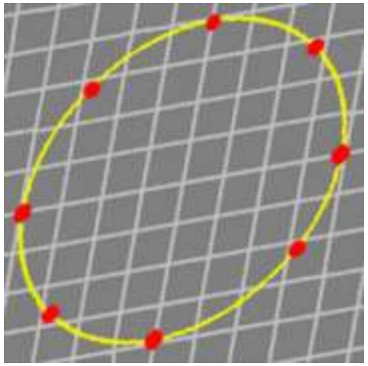
Gravitational wave polarisations

Llinear





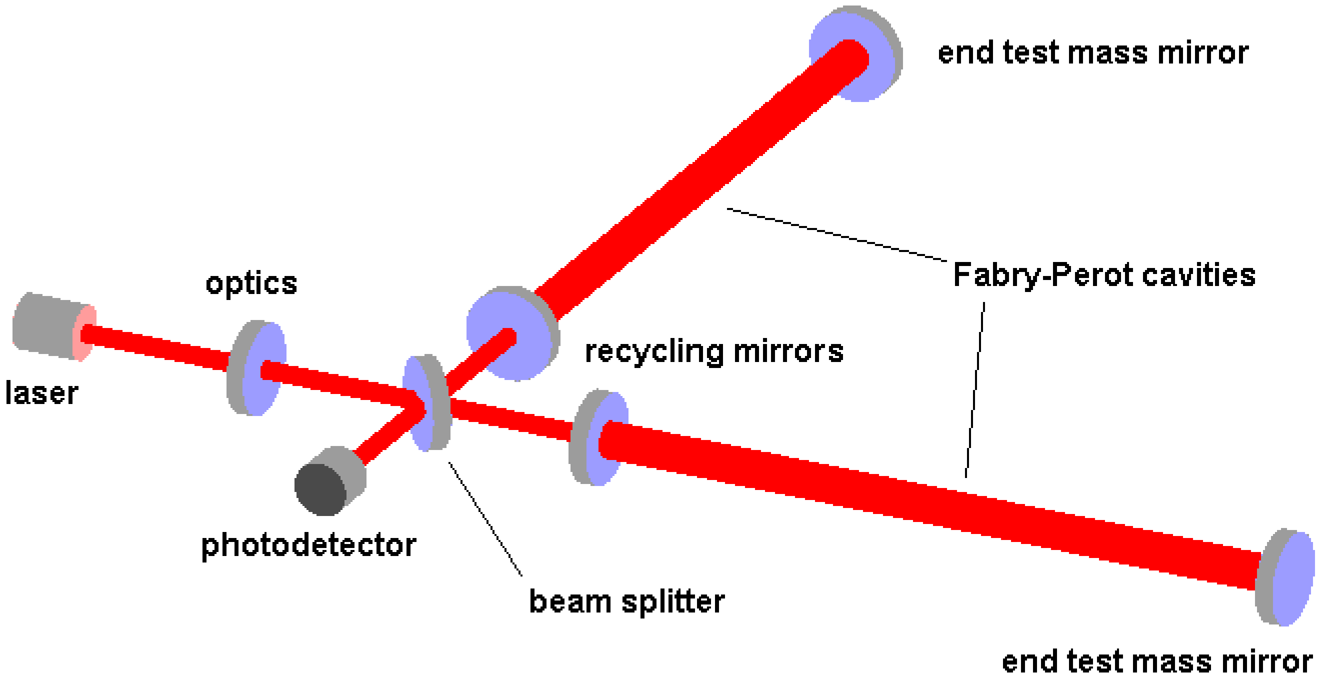
Curcular



Detection of gravitational waves

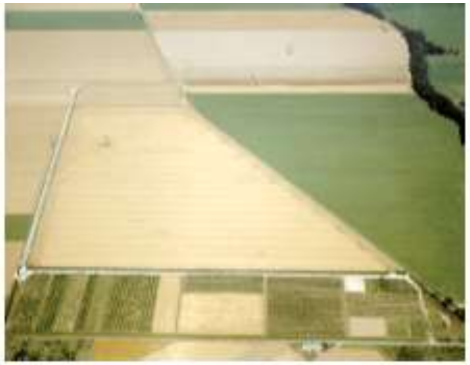
- Test masses
- Measurement of distances between them
- using light beams
- A network of detectors needed: to confirm detections independently

Interferometers



High frequency instruments

VIRGO: Pisa, Italy [Italy/France]



GEO600, Hanover Germany [UK, Germany]

TAMA300, Tokyo [Japan]

AIGO, Jin-Jin West Australia

Stellar mass binary black holes

Possible detection methods:

- Gravitational lensing
  - Signal depends on total mass
- Gravitational waves – coalescences
  - Strength of the inspiral signal depends on the chirp mass:
- $$\mathcal{M} = \frac{M_1^{3/5} M_2^{3/5}}{(M_1 + M_2)^{1/5}}$$

The range of gravitational wave detectors

- Signal to noise ratio

$$\frac{S}{N} \approx \frac{\mathcal{M}^{5/6}}{D}$$

- Volume

$$V \approx D^3 \approx \mathcal{M}^{5/2}$$

- Small formation rates may be compensated by large detectability volume

How to make a binary black hole system?

The critical point:
Common envelope mass transfer

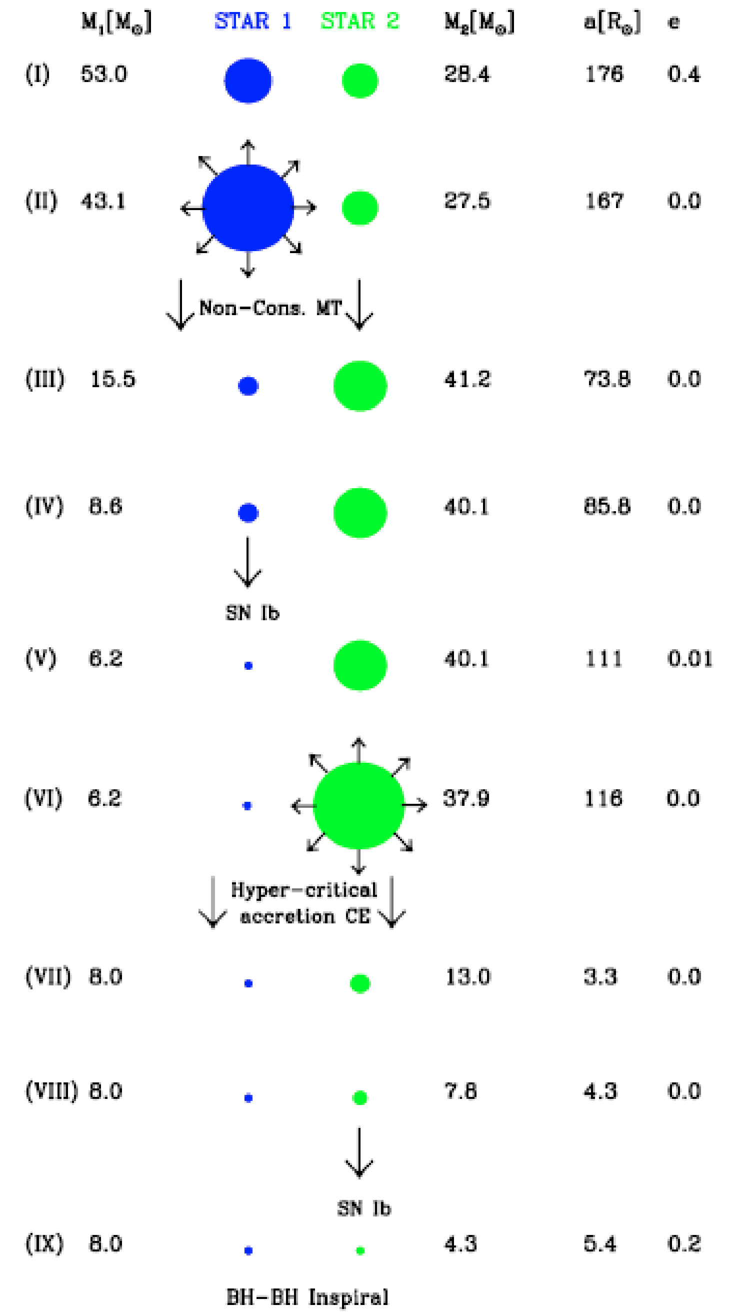


Fig. 1. An example evolutionary scenario leading to formation of a double black hole binary. For details see the text.

So what is the common envelope phase?

- More massive star fills its Roche lobe
- Convective envelope → inverse mass radius relation
- Unstable transfer, inspiral
- Can stop if the star has a clear core-envelope structure
- Otherwise leads to a merger

No binary black holes?

Negligible formation rate of merging binary black holes..

(2007)

THE ASTROPHYSICAL JOURNAL, 662:504–511, 2007 June 10

ON THE RARITY OF DOUBLE BLACK HOLE BINARIES: CONSEQUENCES FOR GRAVITATIONAL WAVE DETECTION

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Received 2006 December 1; accepted 2007 January 31

The case of IC10 X-1

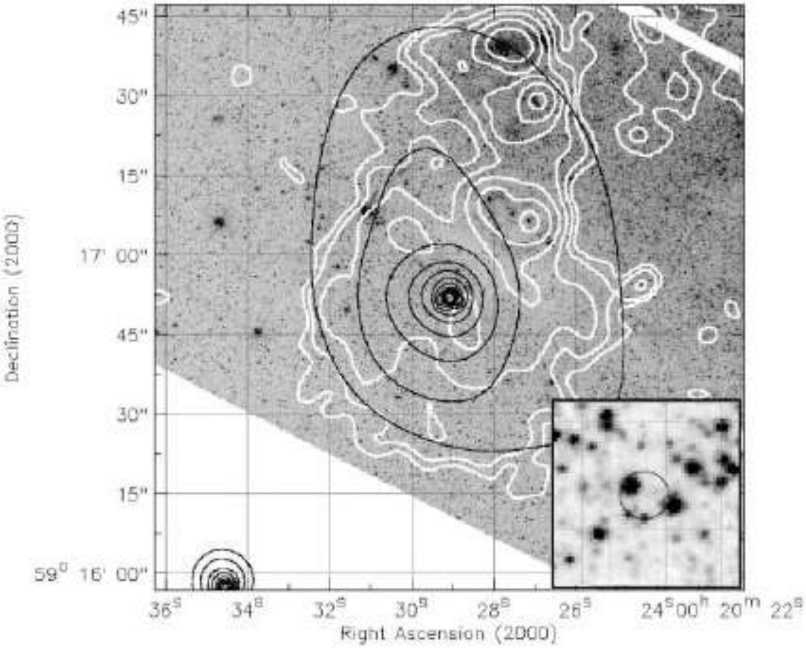


FIG. 1.—X-ray (*dark*) and radio (*light*) contours in the vicinity of X-1 overlaid on the *HST* ACS F814W image. The image shows X-1 in relation to the X-ray and radio emission from the surrounding superbubble. *Inset*: 50 pixel (≈2″.2) close-up of X-1 indicating the 0″.30 X-ray error circle (statistical+systematic), relative to the ACS F814W counterparts. X-1 lies 0″.23 from the confirmed W-R star [MAC92] 17A (slightly above and to the left of the X-ray centroid; Crowther et al. 2003).

Bauer, Brandt 2004

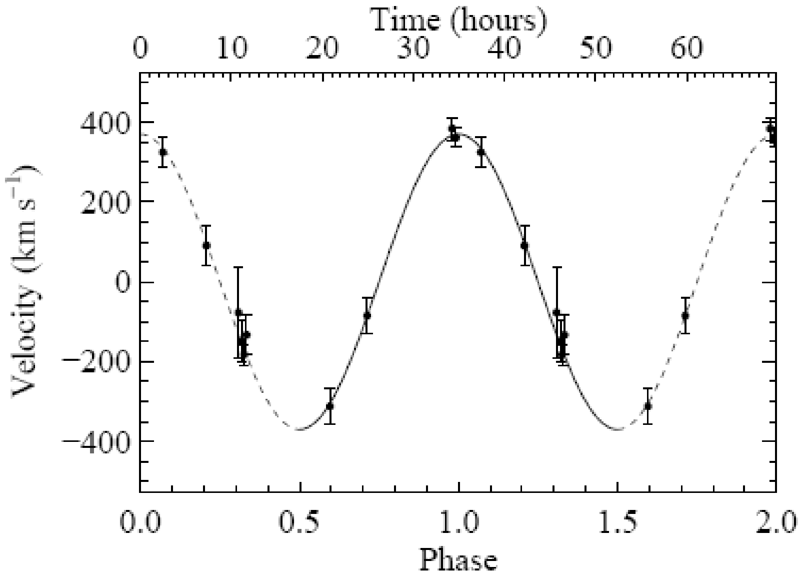


FIG. 3.— Radial-velocity curve of [MAC92] 17A using velocities relative to the [O III] λ5007 spectral line. Two cycles are shown for clarity. Formal velocity error bars are 1σ. See the text for values of the fit parameters.

Silverman Filipenko, 2008

- 32 hour period, well established distance,
- bright X-ray source, X-ray eclipses

Parameters of IC10X-1

TABLE 2
Derived Black Hole Mass ($M_\odot$)

Inclination (deg)	Wolf-Rayet Mass ($M_\odot$) 17	25	35
90	23.1 ± 2.1	27.7 ± 2.3	32.7 ± 2.6
78	23.9 ± 2.1	28.6 ± 2.4	33.8 ± 2.8
65[a]	27.1 ± 2.5	32.3 ± 2.8	37.9 ± 3.2

[a] If the mass of [MAC92] 17A is 35 $M_\odot$, inclinations less than $\sim 78^\circ$ will not yield X-ray eclipses.

Silverman Filipenko, 2008

This system survived the critical point in the evolution!

The future of IC10 X-1

- Mass transfer for 100-300kyrs
- Explosion of the WR* $\rightarrow$ second black hole
- Survival and creation of the binary BH
- Tight system – colescence time of 1-3Gyr
- Large chirp mass ~ more than 13 Msun

- How much mass shall the WR star loose?

Estimate of the rate

Merger rate density

$$\mathcal{R} = (V_{obs} t_{obs})^{-1} = 0.06\mathrm{Mpc}^{-3}\mathrm{Myr}^{-1}$$

Expected detection rate

$$\mathcal{N} = 0.69 \left(\frac{D_{DNS}}{18Mpc}\right)^3 \left(\frac{\mathcal{M}}{13M_\odot}\right)^{5/2} \mathrm{yr}^{-1}$$

Observational evidence for stellar mass binary black holes and their coalescence rate

T. Bulik[1,2] and K. Belczynski[1,3,4]

2009

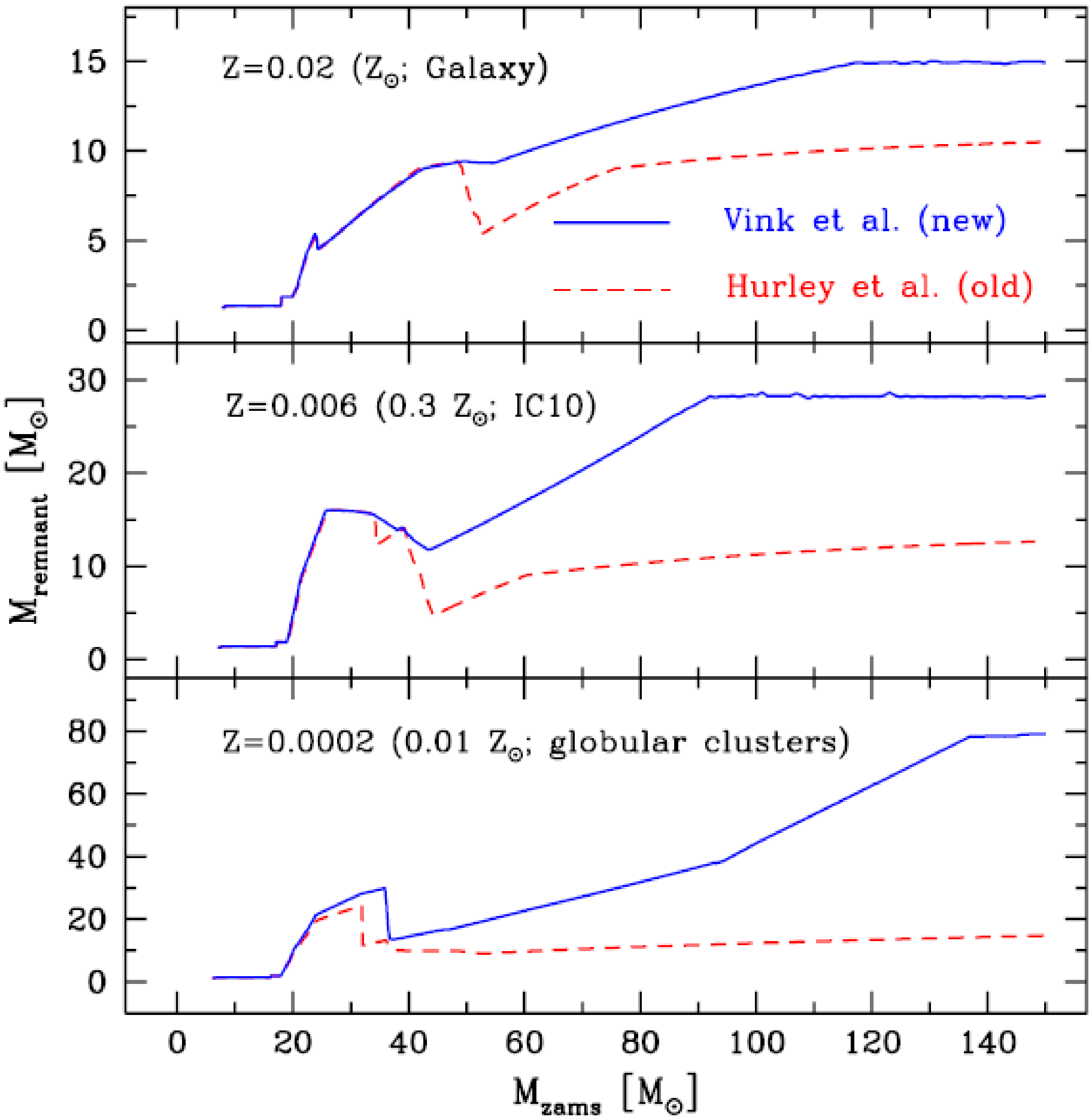
What is so special about IC10?

The dependence of stellar and binary evolution on metallicity

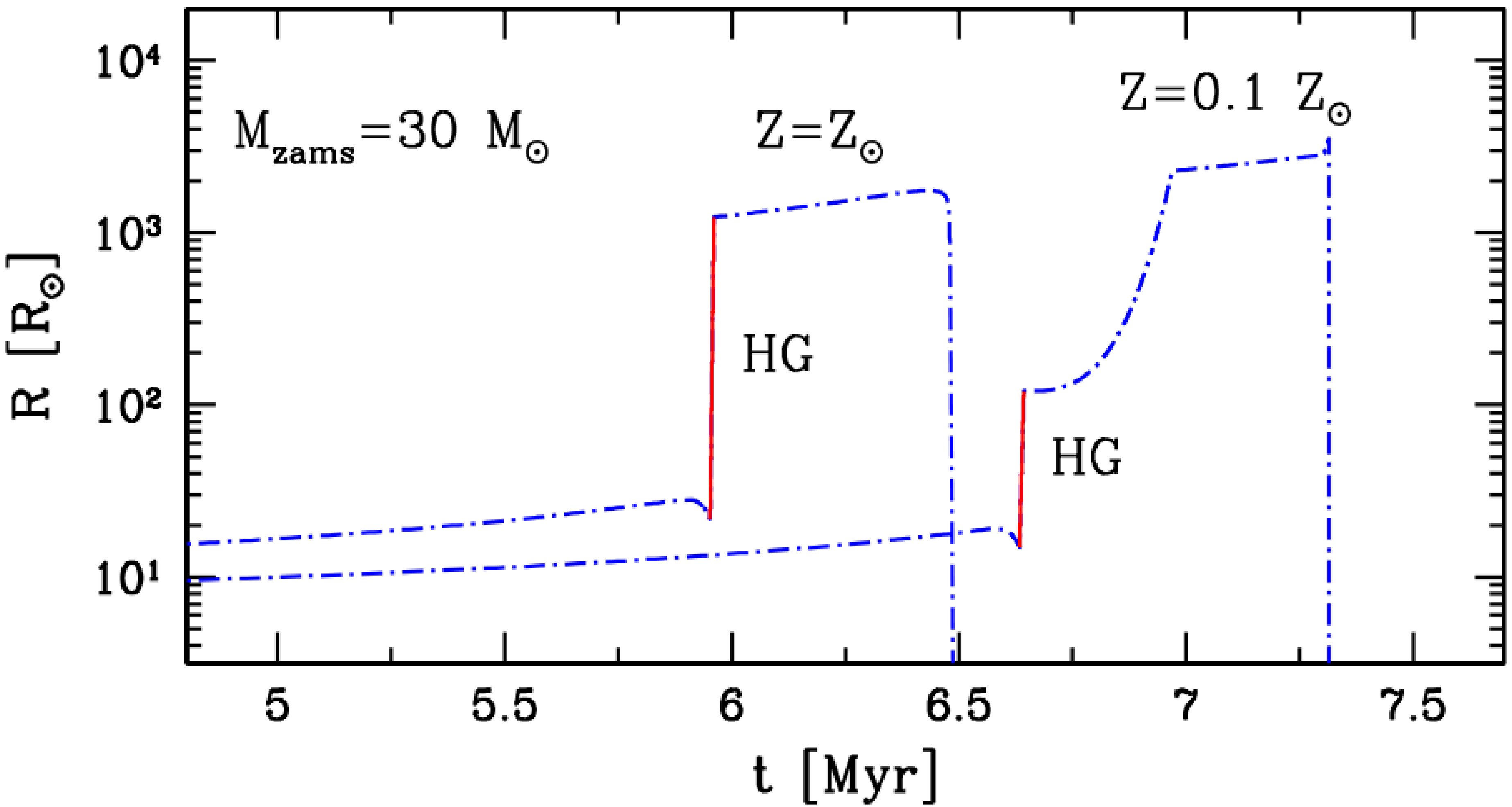
- Metallicity $\rightarrow$ opacity
- Stellar winds $\rightarrow$ mass loss rates
- Mass loss $\rightarrow$ masses of compact objects
- Opacity $\rightarrow$ stellar radii

- The dependence can be strong, expecially for massive stars!

Masses of compact objects



Stellar radii



Low metallicity star are typically smaller. Hertzsprung Gap smaller

Consequences of low metallicity

- Black hole masses larger – mass ratios in binaries closer to unity
- Stellar radii – probability of common envelope on the Hertzsprung Gap smaller
- Easy to jump through the critical point of the evolution
- Effective formation of binary black holes in low metallicity regions

Population synthesis results

Table 2
LIGO/VIRGO Detection Rates (yr^{-1})

Sensitivity ($d_{0,\mathrm{nsns}} =$)	Type	$Z_\odot$ (100%)	$0.1\ Z_\odot$ (100%)	$Z_\odot + 0.1\ Z_\odot$ (50% + 50%)
4*18 Mpc	NS–NS	0.01 (0.003)	0.01 (0.001)	0.01 (0.002)
	BH–NS	0.007 (0.00002)	0.04 (0.02)	0.02 (0.01)
	BH–BH	0.02 (0.00005)	9.9 (0.1)	4.9 (0.05)
	Total	0.03 (0.003)	10.0 (0.1)	5.0 (0.06)

THE EFFECT OF METALLICITY ON THE DETECTION PROSPECTS FOR GRAVITATIONAL WAVES

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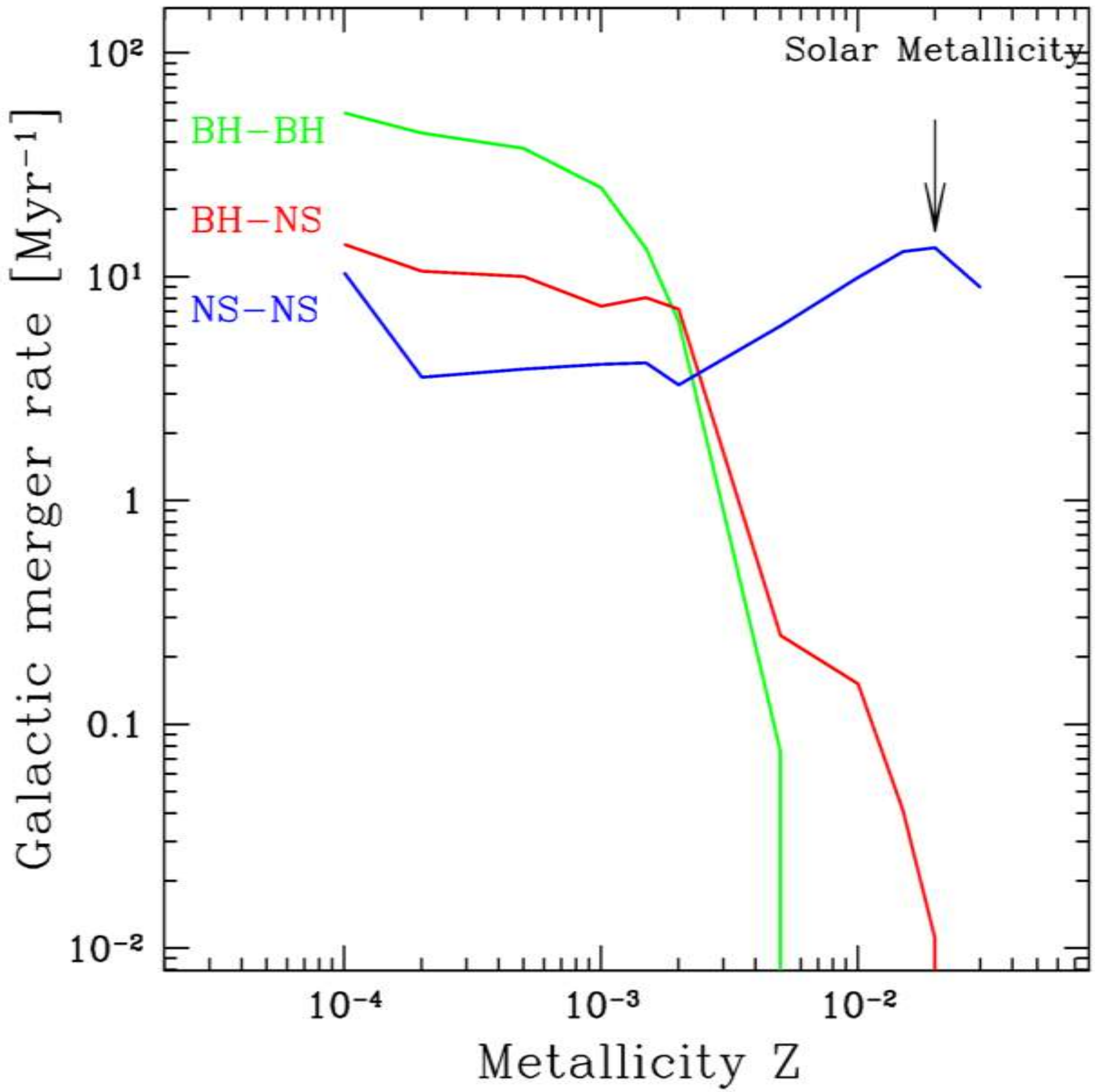
2010

Metallicity dependence of formation rate



Recent news - the twins

IC10 X-1

- M_{BH}=23-33 Msun
- M_{WR}=17-35 Msun
- P=35h
- Host metallicity=0.3

NGC300 X-1

- M_{BH}=14.5-20 Msun
- M_{WR}=15-26 Msun
- P=32h
- Host metallicity=0.6

Tight binaries with a massive BH accreting fro

Component masses in NGC300 X-1

- Mass estimate from mass function and identification of the WR star:

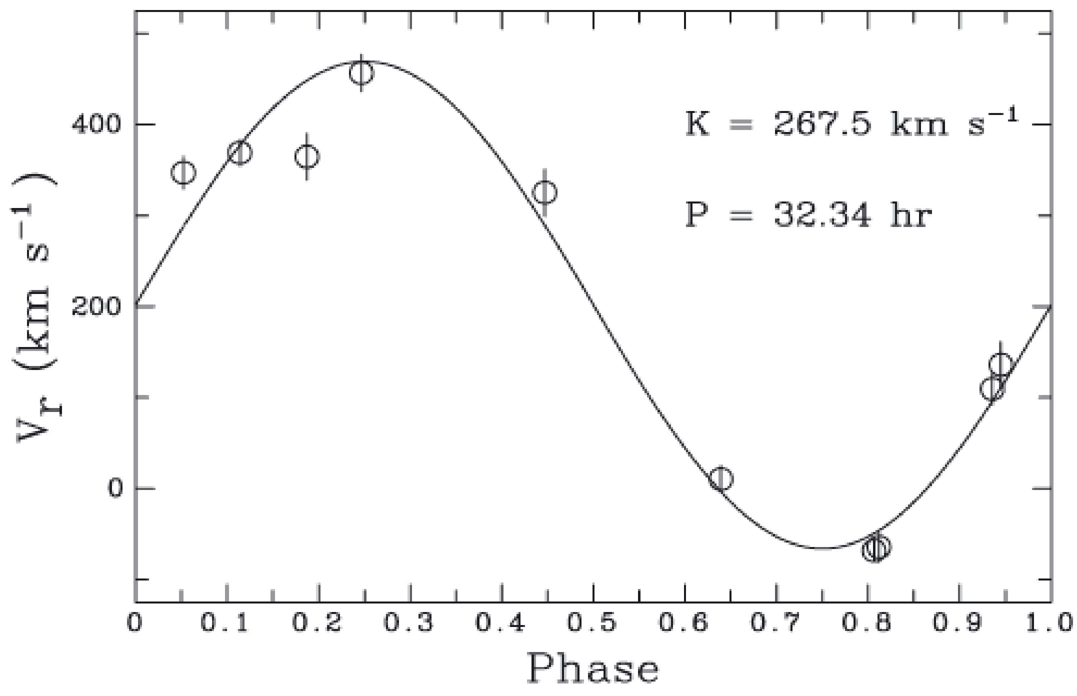


Figure 3. Radial velocity variations of λ4686 He II phased to 32.3 h, from which a systemic velocity of $v_r = 202 \pm 7\,\mathrm{km\,s^{-1}}$ and semi-amplitude of $K_2 = 267.5 \pm 7.7\,\mathrm{km\,s^{-1}}$ are obtained.

Crowther et al. 2010

BH masses vs metallicity

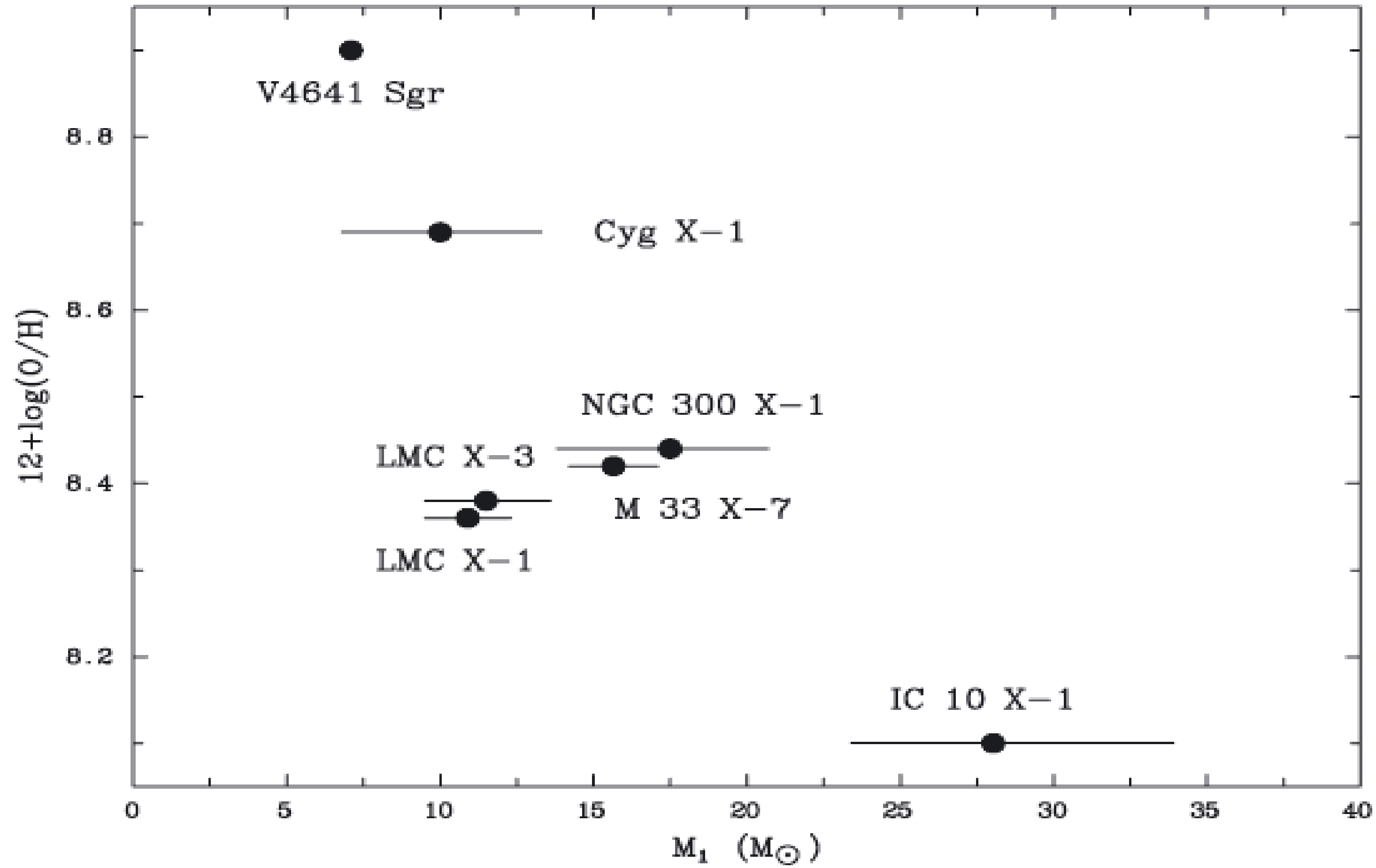
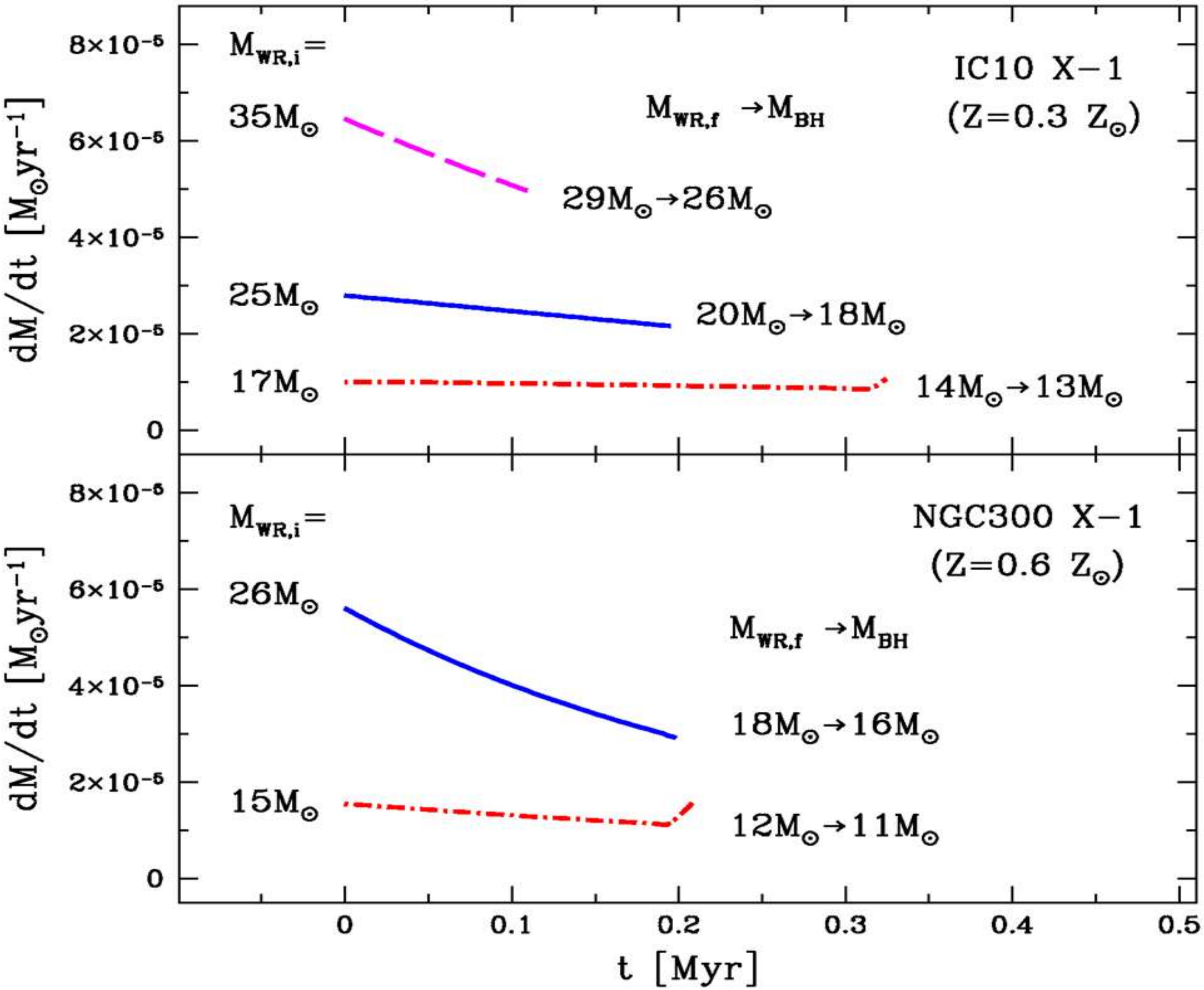


Figure 6. Comparison between inferred compact object masses, M_1, versus metallicity for all HMXB with $M_1 \geq 3\,M_\odot$ and $M_2 \geq 5\,M_\odot$. Black hole masses inferred for NGC 300 X-1 (IC 10 X-1) relate to a WR mass of $21^{+5}_{-6}\,M_\odot$ ($25^{+13}_{-8}\,M_\odot$) and an orbital inclination of 60°–75° (80°–90°).

Crowther et al. 2010

Detailed models of IC10 X-1 and NGC300 X-1



Future of NGC300 X-1 and IC10 X-1

- Mass loss < 20%
- Evolutionary time 100 – 300 kyrs
- Small kicks → formation of binary BHs
- Time to coalescence– 1-3 Gyrs.
- Formation rate = Coalescence rate, assuming constant star formation
- Chirp masses:
  - IC10X-1: 15-26 Msun
  - NGC300 X-1: 11-15 Msun

The estimate of the rate density

- Volume surveyed determined by the spectroscopy of the WR star (d<2Mpc)
- Detectability time – X-ray active phase – lifetime of WR star

$$R = 0.36^{+0.50}_{-0.26} Mpc^{-3} Myr^{-1}$$

Based on two(!) observed systems.

Estimate of the detection rate

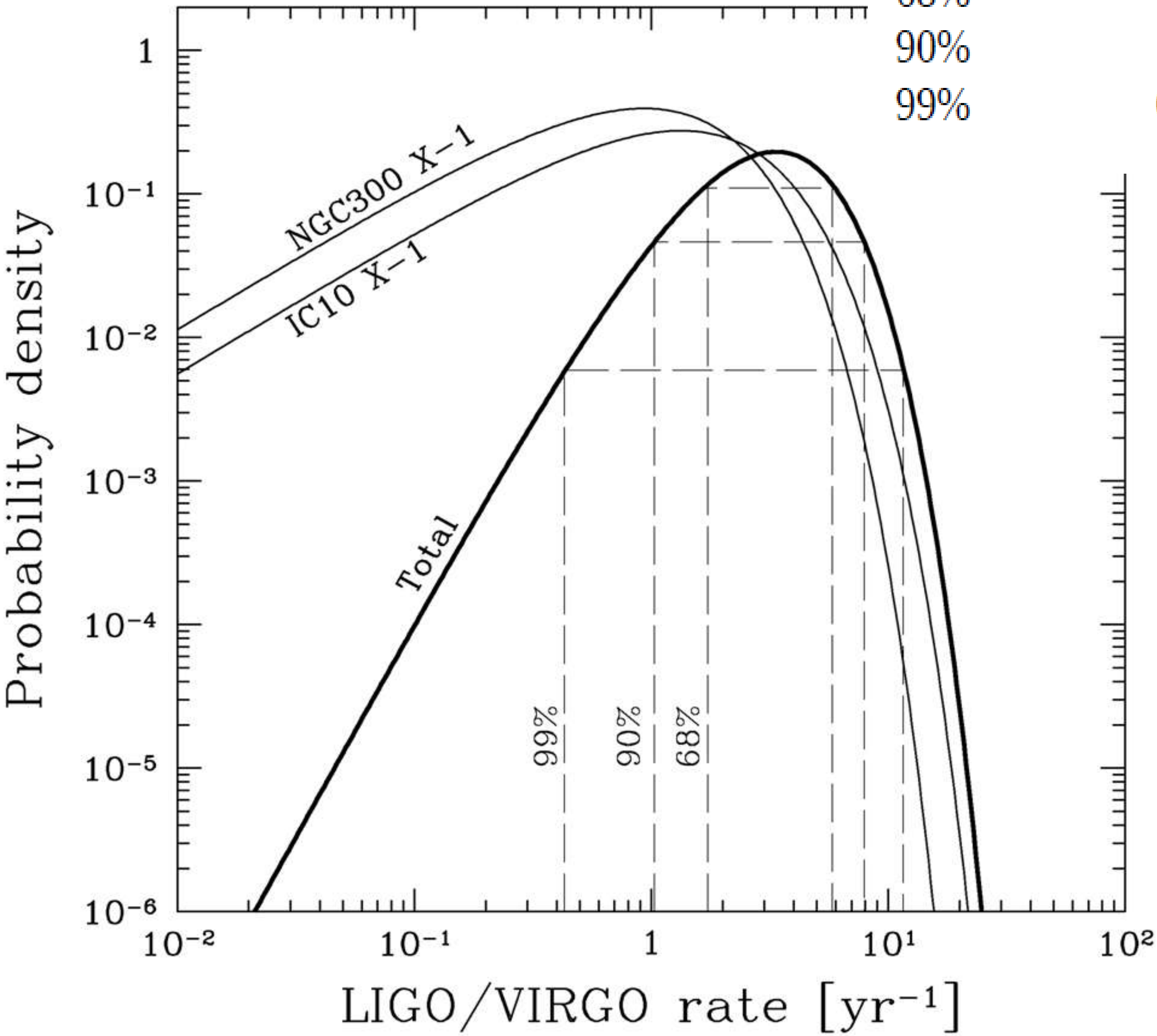
- Assume lowest chirp masses
- Assume that SNR is

$$\frac{S}{N} \approx \frac{\mathcal{M}_{chirp}^{5/6}}{D}$$

- Assume sensitivity to DNS up to 18Mpc
- Find the probability density of each rate
- Find the probability density of the sum of rates

Expected detection rate

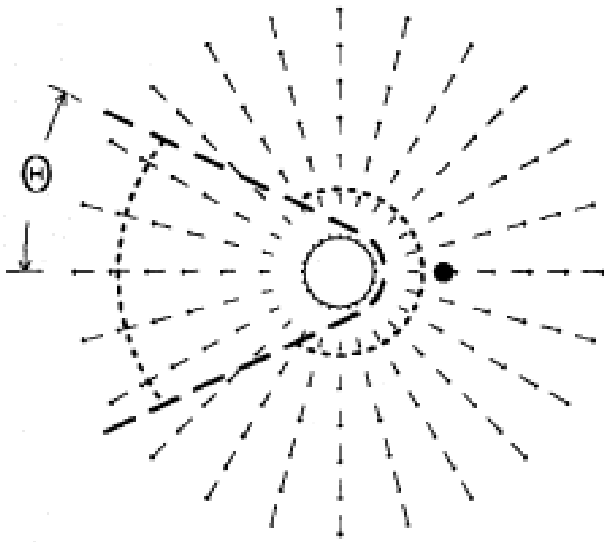
Conf level	lowest rate	highest rate per year
68%	1.73	5.80
90%	1.03	7.91
99%	0.43	11.6



Assuming best performance

Bulik, Belczynski, Prestw

Alternative explanation of the radial velocities



Ionized wind model – van Kerkwijk et al 1993 – for Cyg X-3

Wind – ionized except for the stellar shadow

Measure of wind speed and not radial velocity

Required simultaneous X-ray and optical observations

However -

Cyg X-3 is much tighter with P=4.8 hours

Observed radial velocity curves are sinusoidal

Summary

- Strong evidence for the existence of large population of binary black holes: are there more such systems as IC10 X-1? E.g. ULX?
- Expected colaescence rate density is large enough to suggest that we are close to the first detection

$$R_{LIGO/VIRGO} = 3.36^{+4.55}_{-2.32} yr^{-1}$$

- This estimate is based on <u>observations</u>
- BHBH-binaries form in low metallicity regions
- No detection – a challenge for the binary evolution models

Current status

- The estimate of the rate density is

$$\mathcal{R} = 0.36^{+0.50}_{-0.26}\mathrm{Mpc}^{-3}\mathrm{Myr}^{-1}$$

- Current (S5) observational limits are:

$$\mathcal{R} < 2\mathrm{Mpc}^{-3}\mathrm{Myr}^{-1}$$

Expected chirp mass distribution