Science with Gravitational Wave Detections (NS-NS, BH-NS, BH-BH)

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Mass Gap: Fryer et al. 2012; Belczynski et al. 2012

Max. BH Mass: Belczynski, Bulik, Fryer, Ruiter, Valsecchi, Vink & Hurley 2010

DCO Rates (theory): Belczynski et al. 2010; Dominik et al. 2012

DCO Rates (empirical): Kim, Kalogera & Lorimer 2010 (NS-NS)
Belczynski, Bulik & Bailyn 2011 (BH-NS)
Bulik, Belczynski & Prestwich 2011 (BH-BH)

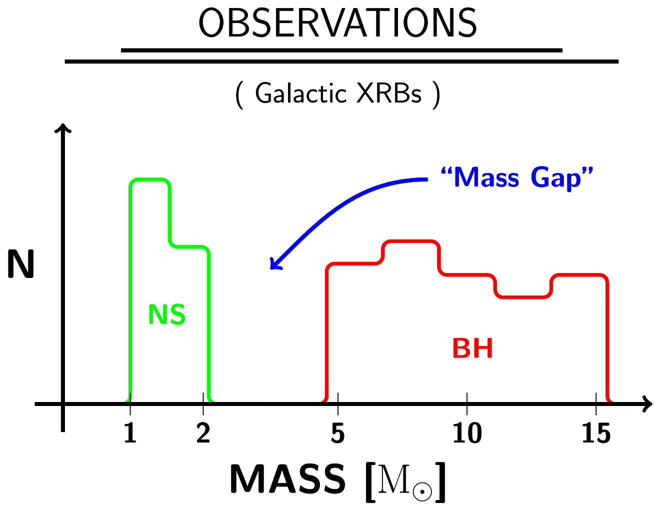
Population Synthesis Rate Estimates

TABLE 1
ADVANCED LIGO/VIRGO DETECTION RATES [YR^{-1}] [a]

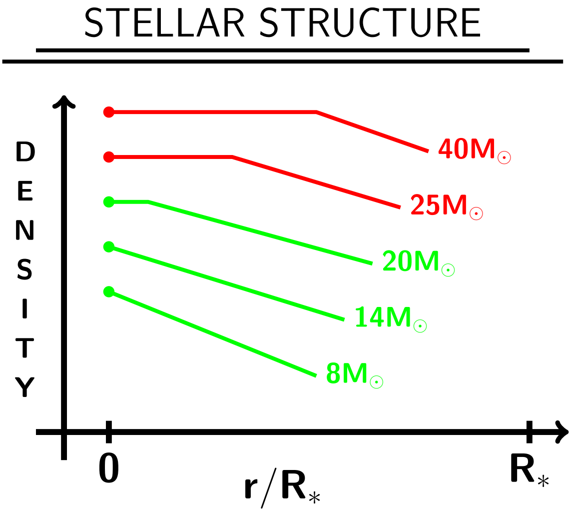
Model	NS-NS	BH-NS	BH-BH	comments
S	3.9 (1.3)	9.7 (5.1)	7993.4 (518.7)	standard
V5	3.9 (1.3)	9.4 (4.8)	8057.8 (533.7)	$M_{\rm NS,max} = 3\ M_\odot$
V6	3.9 (1.3)	9.3 (4.7)	8041.7 (523.6)	$M_{\rm NS,max} = 2\ M_\odot$
V7	5.0 (1.5)	14.8 (8.3)	8130.1 (574.2)	half NS kicks
V8	3.9 (1.3)	1.2 (0.3)	172.2 (14.0)	high BH kicks
V9	3.9 (1.3)	11.8 (6.7)	8363.6 (654.9)	no BH kicks
V10	5.2 (1.7)	5.7 (4.9)	7762.7 (487.0)	delayed SN
V11	3.9 (1.1)	10.5 (6.3)	12434.4 (888.1)	low winds
V12	11.7 (0.8)	7.6 (5.8)	8754.6 (275.3)	RLOF: conservative
V13	3.7 (0.9)	76.9 (62.1)	1709.6 (966.1)	RLOF: non-conservative

[a] Optimistic (realistic) rates are given under assumption that CE phase initiated by Hertzsprung gap donors with no clear core-envelope structure may lead to the formation of double compact object binary (always halts binary evolution).

Dynamical Mass Estimates: NS (50) and BH (20)

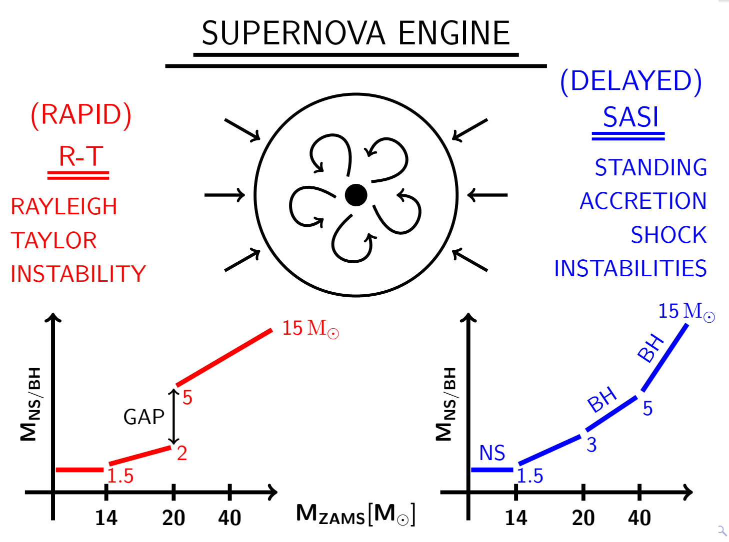


Burning: Radiative ($M_{\rm ZAMS} < 20 M_\odot$) vs Convective

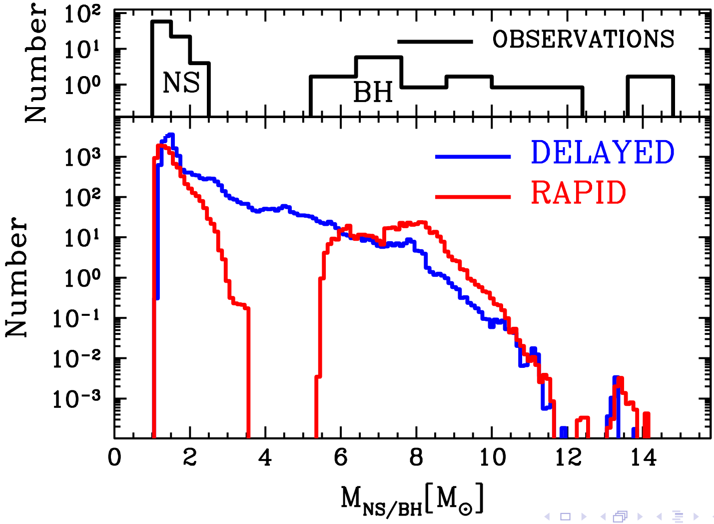


Explosion: Rapid ($t_{SN} < 0.2$s) vs Delayed ($t_{SN} \approx 1$s)

cold/dense
(low S)
on top of
hot/rare
(high S)



SN Model + IMF + Binary Evolution = Galactic XRBs



Observations: known BH masses

- $4 - 15 M_\odot$: Galactic BHs ($Z \sim Z_\odot$)
  – 17 transients: low mass companion
  – 3 persistent: massive companion
  (Casares, Bailyn, Orosz, Charles, Greiner, ...)
- $8, 11 M_\odot$: LMC X-3, X-1 ($Z \sim 30\% Z_\odot$)
  – HMXBs: massive companions (Orosz 02, Orosz et al. 09)
- $16 M_\odot$: M33 X-7 ($Z \sim 5 - 40\% Z_\odot$)
  – massive $70 M_\odot$ close companion (Orosz et al. 07)
- $\sim 20 M_\odot$: NGC300 X-1 ($Z \sim 60\% Z_\odot$)
  – massive $26 M_\odot$ close WR companion – (Crowther et al. 2010)
- $\sim 30 M_\odot$: IC10 X-1 ($Z \sim 30\% Z_\odot$)
  – massive $17 M_\odot$ close WR companion (Prestwich et al. 07)

Stars at low metallicity form massive BHs: How massive can a BH get?

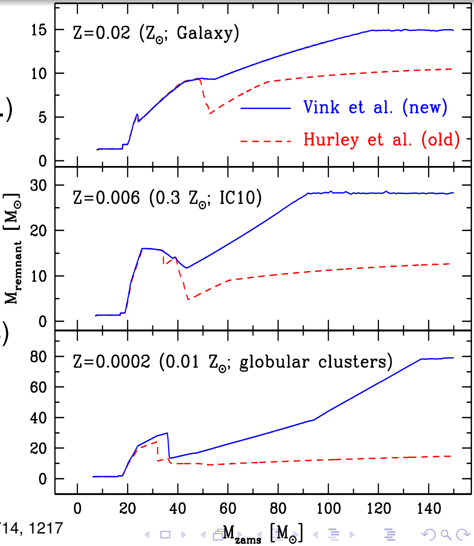
Predictions: calculation of BH masses

1) update on Hurley et al. stellar winds
- single star models
- new wind mass loss rates (Vink et al.)
- estimate BH mass (SN hydro)

2) new BH mass estimates:
- systematically higher BH mass
- steep increase of BH mass with decreasing metallicity (smaller winds)

New Winds (Vink et al.):

$Z = 1.0\ Z_\odot$: max. BH mass: $\sim 15 M_\odot$
$Z = 0.3\ Z_\odot$: max. BH mass: $\sim 30 M_\odot$
$Z = 0.01\ Z_\odot$: max. BH mass: $\sim 80 M_\odot$



Belczynski, Bulik, Fryer, Ruiter, Valsecchi, Vink & Hurley 2010, ApJ 714, 1217

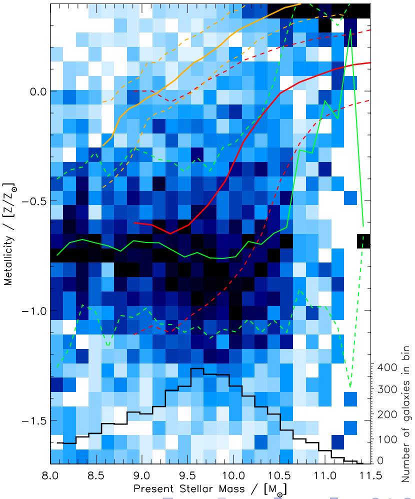
Observations: chemical composition of stars

Panter et al. 2008:

- SDSS sample: $\sim 30,000$ galaxies
- recent star formation: $\lesssim 1 Gyr$
  – 50%: solar metallicity ($Z_\odot$)
  – 50%: sub-solar metallicity (0.1 $Z_\odot$)

Stellar observations/models:

- solar metallicity:
  – max BH mass: $\sim 15\ M_\odot$ (GRS 1915)
  – large stellar radii -> messy interactions
- sub-solar metallicity:
  – max BH mass: $\sim 30\ M_\odot$ (IC10 X-1)
  – small stellar radii -> clean interactions

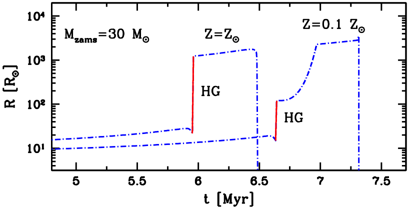


Common Envelope (CE) + Hertzsprung gap (HG) star

BH-BH formation: CE orbital contraction

1) HG: no clear core-envelope boundary
   – CE survival? YES (A) / NO (B)

2) Many HG stars in CE?
   – high metal.: YES -> very few BH-BH
   – low metal.: NO -> many BH-BH



LIGO/VIRGO detection rates:

- Initial LIGO: A close to upper limits
- Advanced LIGO: model B
  – NS-NS small contribution (1/500)
  – BH-NS moderate contribution (1/100)
  – BH-BH dominate (the first source)
- $d_{0,\mathrm{nsns}} = 50$–100 Mpc: 1–10 detections

Population Synthesis Detection Rates [yr^{-1}]
(2 stellar populations: 50% solar + 50% sub-solar metals)

Sensitivity	Type	Rate A (B)
450 Mpc (Advanced)	NS-NS	3.9 (1.3)
	BH-NS	9.7 (5.1)
	BH-BH	7993 (519)

Belczynski et al. 2010, ApJ 715, L138; Dominik et al. 2012, ApJ 759, 52

Science with Inspiral Detections

(1) First sources: type of binary?
- BH-BH: rates will discriminate CE models 1/hr vs 1/(day-month)
- NS-NS: only one model allows for this: high BH kicks (SN science)

(2) Many sources: average mass of merging binary?
- wind mass loss rates
- metallicity in local Universe

(3) Major (known) sources of uncertainty:
- Common envelope: $\sim$ 3000 (max change in rates)
- Supernovae: $\sim$ 1000 (max change in rates)

(4) Other (un-assessed) sources of uncertainty:
- rotation
- convection
- maximum mass of a star

Observations: known double compact objects

- BH-BH: not observed (but IC10 X-1, NGC300 X-1 -> 10^4 yr^{-1})
- BH-NS: not observed (Cyg X-1: 0.01 yr^{-1}, Cyg X-3: 0.1 yr^{-1})
- NS-NS: 9 Galactic systems. 6 are close binaries: 4 – 200 yr^{-1}

Phone #	t_{mrg}/Gyr	$M_{ns,1}/M_{\odot}$	$M_{ns,1}/M_{\odot}$	Comment
1) J0737-3039	0.09	1.34	1.25	field (double pulsar)
2) B2127+11C	0.22	1.36	1.38	cluster
3) J1906+0746	0.30	1.25	1.37	field
4) B1913+16	0.33	1.44	1.39	field
5) J1756-2251	1.7	1.39	1.18	field
6) B1534+12	2.7	1.33	1.35	field

– Empirical Galactic merger rate 3-190 $\times 10^{-6}$ yr^{-1} (Kim et al. 2010)
(population synthesis predictions: 0.3-77 $\times 10^{-6}$ yr^{-1})

– low contribution from cluster NS-NS binaries

Summary

– The Mass Gap: constraints on SN engine models -> rapid explosions (if light BHs found -> delayed explosions)

– Stellar Black Holes can reach upto $80 M_{\odot}$ (or more?) (and potentially explain the brightest ULXs?)

– Gravitational Radiation Detection (LIGO/VIRGO):

- signal dominated by BH-BH inspirals (observations + theory)
- moderate contribution of BH-NS mergers
- small contribution of NS-NS mergers
- first source: a massive BH-BH binary with chirp $10 - 30\ \mathrm{M}_{\odot}$ and high (aligned) spins

www.syntheticuniverse.org – population synthesis models

BH-BH progenitors: IC10 X-1/NGC300 X-1

1) Massive binaries: BH + WR

- $P_{\rm orb} \sim 30$ h ($V_{\rm orb} \sim 600$ km/s)
- $M_{\rm BH1} \sim 15 - 30\ {\rm M}_\odot$
- $M_{\rm WR} \sim 15 - 35\ {\rm M}_\odot$

2) Very simple evolution:

- WR: heavy mass loss
- WR: core collapse/supernova
- BH-BH: formed ($t_{\rm merger} \sim$ 1Gyr)

3) GR detection rate:

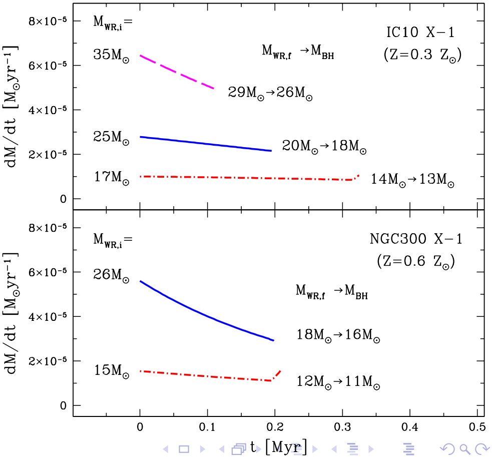
- Evolution: short lifetime 0.5 Myr
- Discovery: X-ray binary upto 2 Mpc
- Initial LIGO/VIRGO: upto 200 Mpc

GR detection rate: $\sim$ 0.4–10 yr^{-1}!!!

Bulik, Belczynski & Prestwich 2011, ApJ, 730, 140

IC BH-BH: 23 $\mathrm{M}_\odot$ + 13 $\mathrm{M}_\odot$ (M_c=15 $\mathrm{M}_\odot$)

NGC BH-BH: 15 $\mathrm{M}_\odot$ + 11 $\mathrm{M}_\odot$ (M_c=11 $\mathrm{M}_\odot$)



BH-NS progenitor: Cygnus X-1

1) Massive binary: BH + O star

- $M_{\rm BH1} \sim 15\ {\rm M}_\odot$ ($P_{\rm orb} = 5.6$d)
- $M_{\rm O} \sim 19\ {\rm M}_\odot$ ($R_{\rm O} \approx 16\ {\rm R}_\odot$, $R_{\rm Roche} \approx 17\ {\rm R}_\odot$)

2) 2-step evolution/3 outcomes:

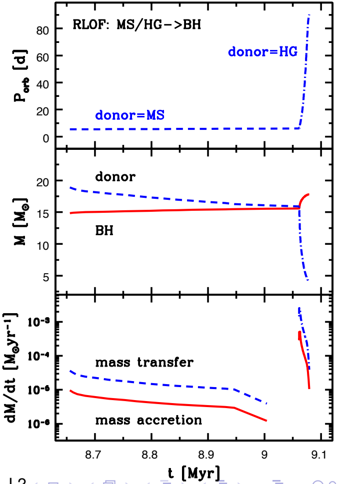
- RLOF: mass loss BH($18\ {\rm M}_\odot$) + WR($4\ {\rm M}_\odot$)
- SN: supernova WR($3.5\ {\rm M}_\odot$) -> NS($1.4\ {\rm M}_\odot$)
- disrupted BH/NS; wide BH-NS; close BH-NS
  ($\sim 70\%$) ($\sim 30\%$) ($\lesssim 1\%$)

3) GR detection rate:

- Evolution: lifetime 10 Myr
- Observations: only 1 system in Galaxy
- Advanced LIGO/VIRGO: upto 800 Mpc

Empirical GR detection: 1 per century (lower limit)
(population synthesis: $0.3 - 80$ per year)

BH-NS: $18\ {\rm M}_\odot + 1.4\ {\rm M}_\odot$ ($M_{\rm c}=4\ {\rm M}_\odot$)



Belczynski, Bulik & Bailyn 2011, ApJ, 742, L2