The formation of single sdB stars through common-envelope mergers

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Outline

sdB stars

Basic properties:

- Core helium burning stars with very thin ($\lesssim 0.02\,M_\odot$) hydrogen-rich envelope
- In the field $\sim$ 40–70% are found in binaries
- In GCs mostly observed as **single** sdB stars
- Masses observed $\sim 0.39\,M_\odot - 0.7\,M_\odot$ (*e.g.* asteroseismology)

sdB stars

Possible formation channels:

In wide binaries:

- One or two phases of stable Roche-lobe overflow

In close binaries:

- One or two CE/spiral-in phases

Single sdB stars:

- He-WD–He-WD mergers ($M \gtrsim 0.4\,M_\odot$)
- Strong mass loss at tip of RGB (*e.g.* capture of planet; Soker & Harpaz, 2000, 2007; Livio & Siess, 1999a,b)
- **CE merger on the RGB** (Soker 1998, Soker & Harpaz 2000, 2007)

Input models

Eggleton code TWIN:

- 116: single-star models: 0.5, 0.6, . . . , 10.0, 10.5, . . . , 20.0 $M_\odot$
- Solar composition
- Core mass: $M_c \equiv$ central region where $X < 0.1$
- Envelope binding energy: $E_{\rm bind} \equiv \int_{M_c}^{M_s} \left(E_{\rm int}(m) - \frac{Gm}{r(m)} \right) {\rm d}m$
- Convective mixing: $l/H_P = 2.0$
- Convective overshooting: none for $M < 1.2\,M_\odot$, $\delta_{\rm ov} = 0.12$ for $M \geq 1.2\,M_\odot$
- Stellar wind: Reimers-like ($\eta = 0.2$), De Jager
- *Helium-flash-avoidance routine*

Treatment of evolution

- Randomly select 10^7 binaries:
  - M_p: Miller-Scalo IMF
  - $q \equiv M_\mathrm{s}/M_\mathrm{p}$: $g(q)\,\mathrm{d}q = \{1, q, q^{-0.9}\}\,\mathrm{d}q$
- Follow the evolution of track closest in mass to primary
- When mass comes closer to next track, jump with conservation of M_c
- Assume synchronous, rigid rotation on RGB, AGB
- If $v_\mathrm{rot} > v_\mathrm{crit}$: lose additional mass and AM until $v_\mathrm{rot} \leq v_\mathrm{crit}$
- $v_\mathrm{crit} \equiv \{0.1, 1/3, 1.0\}\,v_\mathrm{br}$

CE and spiral-in

- CE occurs if:
  - $R_p > R_{RL,p}$ and $q > q_{crit}(M_p, M_c)$ (Hurley et al.)
  - Darwin instability
- Classical energy formalism to determine post-CE orbit:

$$E_{bind} = \alpha_{CE} \left(\frac{G M_p M_s}{2\, a_i} - \frac{G M_c M_s}{2\, a_f} \right)$$

- $\alpha_{CE} = \{0.1, 0.5, 1.0\}$
- Merger occurs if: $R_{RL,s,postCE} < R_{s,postCE}$

Merger product

The merged object has:

- the core mass of the original primary
- the maximum mass for which the star is spinning subcritically (and $M \leq M_{\mathrm{p}} + M_{\mathrm{s}}$)
- the evolutionary state of the primary, or later

The merged object does:

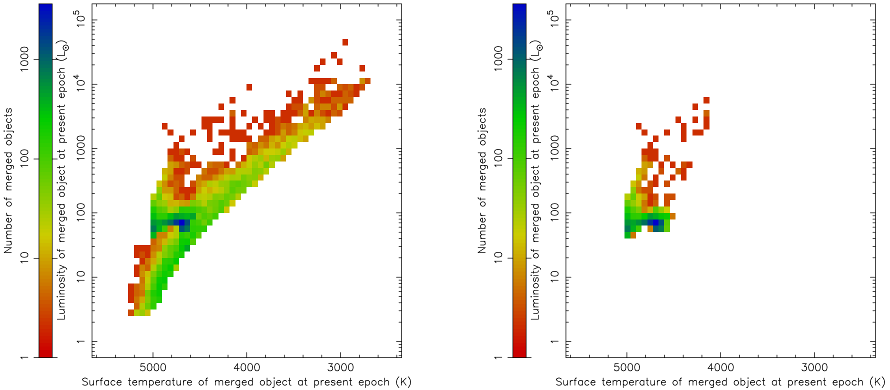
- evolve in the same way as a single star
- lose additional mass to ensure that $v_{\mathrm{rot}} \leq v_{\mathrm{crit}}$

Population-synthesis results

	Number	Fraction of previous group	Fraction of total
Total binary population:	**10,000,000**	**100%**	**100%**
No MT	7,094,523	71%	71%
Stable MT	1,267,854	13%	13%
Unstable MT:	**1,637,623**	**16%**	**16%**
CE Survivors:	789,807	48%	7.9%
Mergers:	**847,816**	**52%**	**8.5%**
Mergers due to RLOF	689,815	81%	6.9%
Mergers due to tidal capture	158,001	19%	1.6%
Mergers on RGB	738,385	87%	7.4%
Mergers on AGB	109,431	13%	1.1%
WDs	822,773	97%	8.2%
GB/HB stars:	**25,042**	**3%**	**0.25%**
RGB	9,301	37%	0.09%
HB:	**14,306**	**57%**	**0.14%**
AGB	1,435	6%	0.01%
Critically rotating HB stars	**4,504**	**31%**	**0.05%**

HRD with merger population

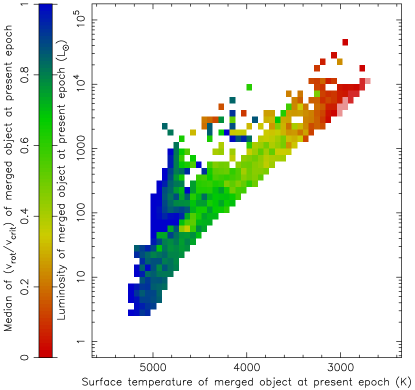
All merged objects: **Merged objects on HB:**



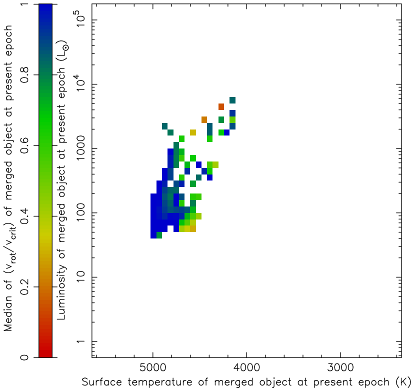
$$v_{\rm crit} = \frac{1}{3} v_{\rm br}$$

HRD with rotational velocities

All merged objects:

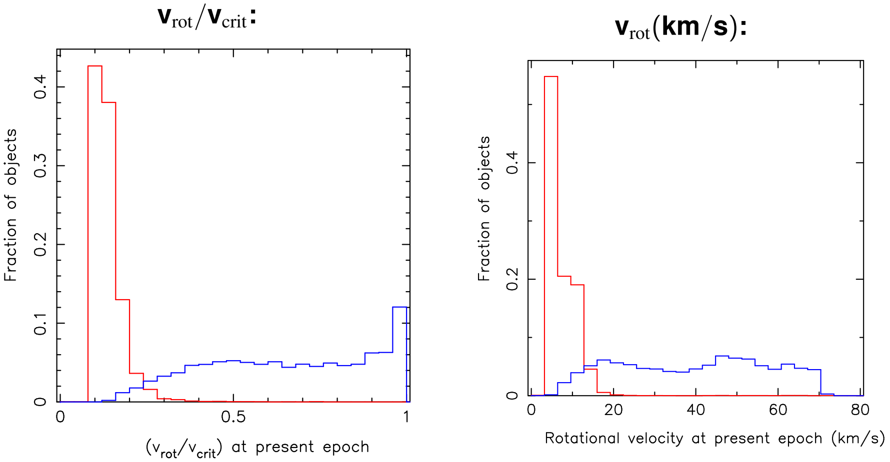


Merged objects now on HB:



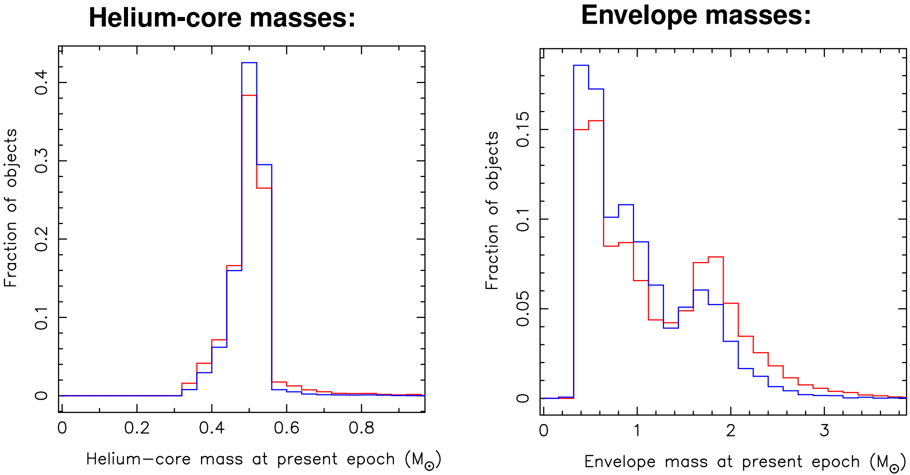
$$v_{\rm crit} = \frac{1}{3} v_{\rm br}$$

Rotational velocities



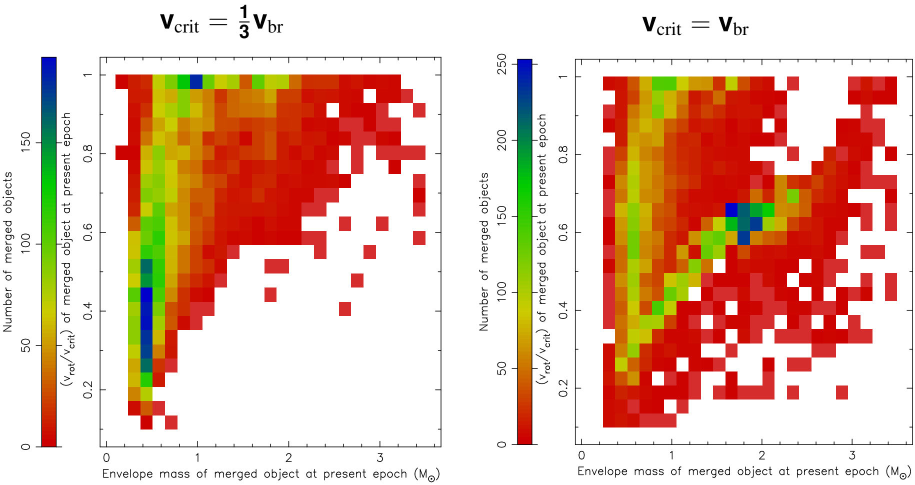
Merged objects, single stars, $v_{\rm crit} = \frac{1}{3} v_{\rm br}$

Core and envelope masses



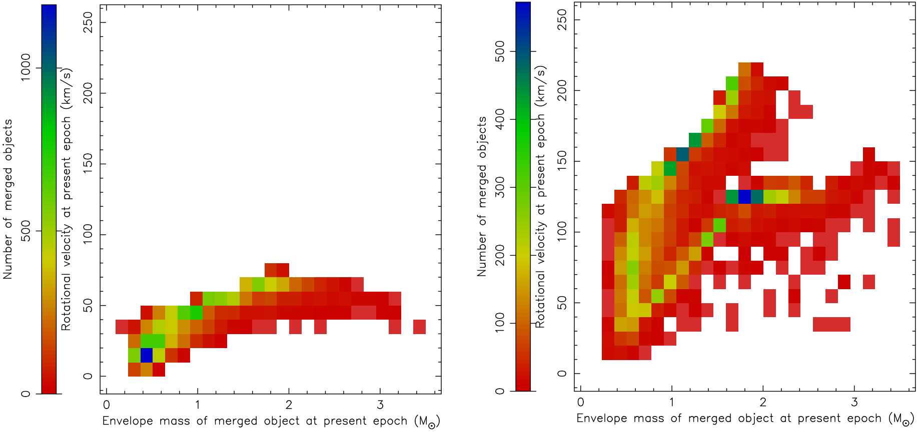
Merged objects, single stars

Rotational velocity vs. envelope mass



Rotational velocity vs. envelope mass

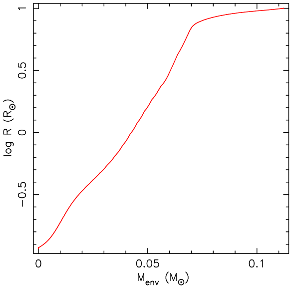
$\mathbf{v}_{\rm crit} = \frac{1}{3}\mathbf{v}_{\rm br}$ $\mathbf{v}_{\rm crit} = \mathbf{v}_{\rm br}$



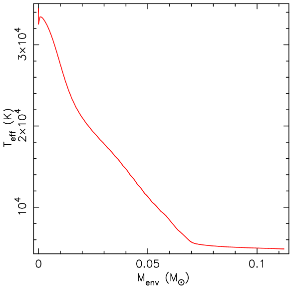
Losing the envelope

Detailed model of an HB star with initial parameters M $\approx$ 0.59 $M_\odot$, $M_{env} \approx 0.11\,M_\odot$ and $v_{rot} \approx 25$ km/s:

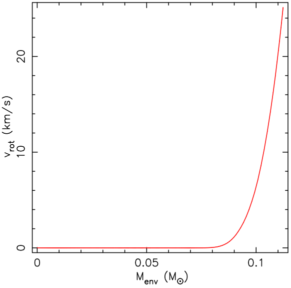
M_{env} vs. log R:



M_{env} vs. T_{eff}:



M_{env} vs. v_{rot}:



Conclusions

- Common-envelope mergers on the RGB lead to rapidly rotating merger products
- Contraction of such a merged object due to helium ignition provides a natural way for the star to spin up and experience enhanced mass loss
- This leads to a population of rapidly rotating HB stars
- A small fraction of these HB stars have thin envelopes
- With some additional mass loss, these stars may become single sdB stars

Future work

- Use more flexible implementation for mass loss due to winds and rotation
- Include magnetic braking for merged object
- Look for mechanism to remove last bit of HB-star envelope (perhaps on RGB?)
- Combine population synthesis and entropy sorting:
  - do population synthesis to get the mergers
  - use entropy sorting to get a merged object
  - interpolate to create an evolution model
  - evolve it with a detailed stellar-evolution code (including rotation)

And now for something completely different...

How to measure gravitational waves from quite a long way away

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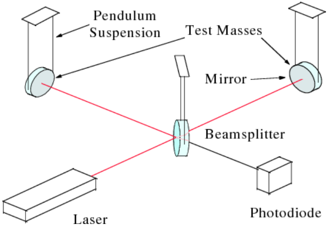
September 29, 2009

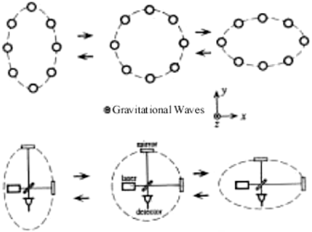
Outline

1. The formation of single sdB stars
   - Properties of sdB stars
   - Population-synthesis models
   - Population-synthesis results
   - Conclusions and future work

2. GW binary inspirals with LIGO/Virgo
   - LIGO/Virgo
   - Binary inspirals
   - Markov-chain Monte Carlo
   - Conclusions

Laser Interferometer GW Observatory (LIGO)





Predicted detection rates

Realistic estimate:

	Rates (yr^{-1})			Horizon (Mpc)		
	NS-NS	BH-NS	BH-BH	NS-NS	BH-NS	BH-BH
Initial	0.015	0.004	0.01	32	67	160
Enhanced	0.15	0.04	0.11	71	149	349
Advanced	20	5.7	16	364	767	1850

Plausible, optimistic estimate:

	Rates (yr^{-1})			Horizon (Mpc)		
	NS-NS	BH-NS	BH-BH	NS-NS	BH-NS	BH-BH
Initial	0.15	0.13	1.7	32	67	160
Enhanced	1.5	1.4	18	71	149	349
Advanced	200	190	2700	364	767	1850

Estimates assume $M_{\rm NS} = 1.4\,M_{\odot}$ and $M_{\rm BH} = 10\,M_{\odot}$

CBC group, rates document

Goals of this project

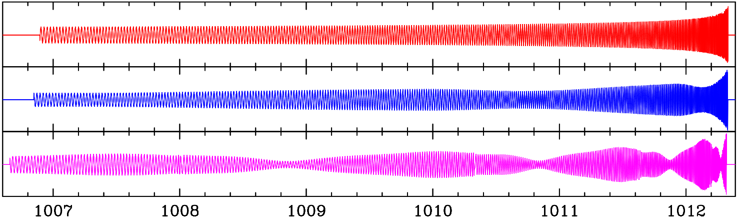
LIGO

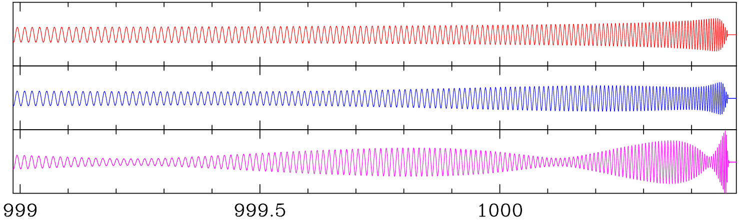
- Show that Markov-Chain Monte Carlo (MCMC) with a large number of parameters (12–15) on LIGO data can be done
- Automated parameter estimation on detected inspiral signal:
  - Confirm spinning inspiral nature of signal
  - Determine *physical* parameters (masses, spin, position, . . .)

Astrophysics

- BH/NS mass distributions, BH spins and spin alignments
- Association of GW and EM events, *e.g.* GRB
- Merger rates, NS-NS/BH-NS/BH-BH merger ratios
- Evolution of massive stars (in binaries), CEs
- Initial-mass range for BH progenitors

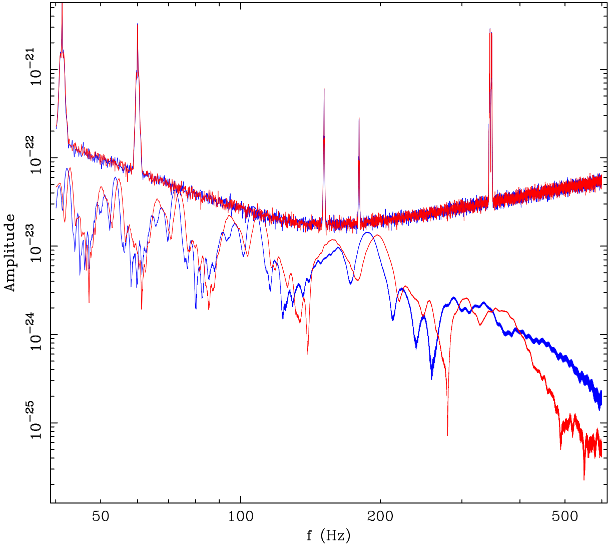
Inspiral waveforms with increasing spin





$a_{\mathrm{spin}} \equiv S/M^2 = 0.0$, 0.1 and 0.5

Signal injection into detector noise



- Using 2 4-km detectors H1, L1
- Gaussian, stationary noise
- Do 1.5-pN software injections
- Retrieve physical parameters with 1.5-pN template

Here, ΣSNR = 17

Compute posterior distribution

- Find posterior density of the model parameters
- Bayesian approach
- The likelihood for each detector i is:

$$L_i(d|\vec{\lambda}) \propto \exp\left(-2\int_0^\infty \frac{\left|\tilde{d}(f) - \tilde{m}(\vec{\lambda}, f)\right|^2}{S_n(f)}\,\mathrm{d}f\right)$$

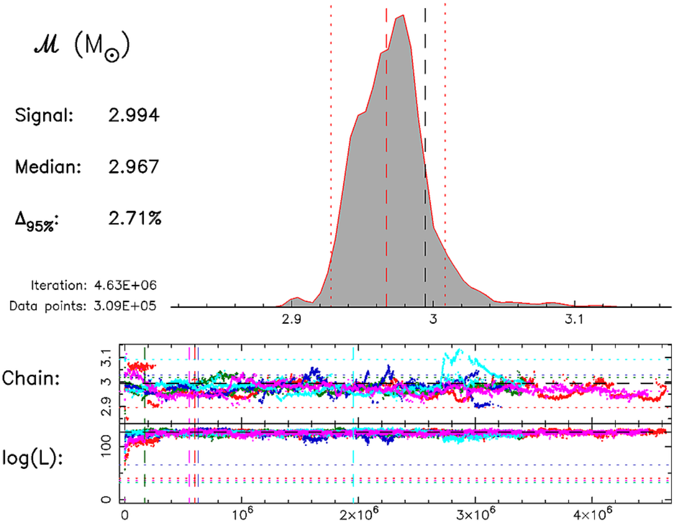
- Coherent network of detectors:
  - $\mathrm{PDF}(\vec{\lambda}) \propto \mathrm{prior}(\vec{\lambda}) \times \prod_i L_i(d|\vec{\lambda})$

- Use Markov-Chain Monte Carlo to sample the posterior

Markov chains

- Choose starting point for chain: $\vec{\lambda}_1$
- Compute its likelihood: $L_j \equiv L(d|\vec{\lambda}_j)$ and prior: $p_j \equiv p(\vec{\lambda}_j)$
- do $j = 1, N$
  - draw random jump size $\Delta\vec{\lambda}_j$ from Gaussian with width $\vec{\sigma}$
  - consider new state $\vec{\lambda}_{j+1} = \vec{\lambda}_j + \Delta\vec{\lambda}_j$
  - calculate $L_{j+1} \equiv L(d|\vec{\lambda}_{j+1})$ and $p_{j+1} \equiv p(\vec{\lambda}_{j+1})$
  - if($\frac{p_{j+1}}{p_j} \frac{L_{j+1}}{L_j} >$ ran_unif[0,1]) then
    - Accept new state $\vec{\lambda}_{j+1}$
    - Increase jump size $\vec{\sigma}$
  - else
    - Reject new state; $\vec{\lambda}_{j+1} = \vec{\lambda}_j$
    - Decrease jump size $\vec{\sigma}$
  - end if
  - save state $\vec{\lambda}_{j+1}$
- end do (j)

MCMC example



MCMC runs

MCMC parameters

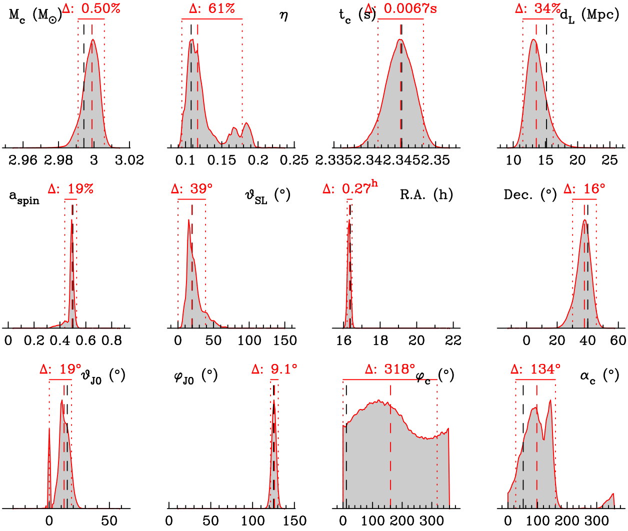
Masses: $\mathcal{M} \equiv (M_1 + M_2)\,\eta^{3/5}$ & $\eta \equiv \frac{M_1 M_2}{(M_1+M_2)^2}$, distance: $\log d_{\rm L}$, time and phase at coalescence: $t_{\rm c}$ & $\varphi_{\rm c}$, position: R.A. & sin Dec, spin magnitude: $a_{\rm spin_{1,2}}$, spin orientation: $\cos\theta_{\rm spin_{1,2}}$ & $\varphi_{\rm spin_{1,2}}$, orientation: $\cos(\iota)$ & ψ

MCMC set-up

- 5 serial chains per run, starting from the true parameter values
- Chain length: 5×10^6 states, burn-in: 5×10^5 states
- Run time: 10 days on a 2.8 GHz CPU for 1.5-pN waveform ($\sim 2.5\times$ longer for 3.5-pN)

- Signals injected in simulated noise for H1L1V @ SNR $\approx$17.0
- Fiducial binary: $M_{1,2} = 10 + 1.4\,M_\odot$, $d_{\rm L} =$ 16–21 Mpc
- Spin: $a_{\rm spin} = 0.0, 0.1, 0.5, 0.8$, $\theta_{\rm SL} = 20^\circ, 55^\circ$

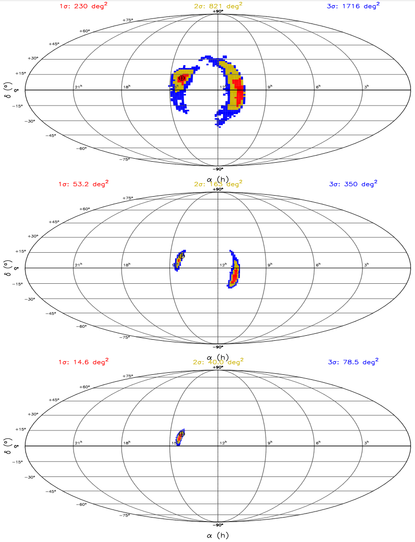
Spinning MCMC results



Parameters:

- H1 & L1
- $M = 10, 1.4\, M_\odot$
- $d_L = 18.7\,\mathrm{Mpc}$
- $a_{\mathrm{spin}} = 0.5$, $\theta_{\mathrm{SL}} = 20^\circ$
- $\Sigma\mathrm{SNR} \approx 17.0$
- Black dashed line: true value
- Red dashed line: median
- Δ's: 90% probability

Spinning MCMC results



Spinning BH, non-spinning NS:

$10 + 1.4\,M_{\odot}$, 16–22 Mpc, Σ SNR=17

2 detectors, $a_{\rm spin} = 0.0$

2 detectors, $a_{\rm spin} = 0.5$

3 detectors, $a_{\rm spin} = 0.5$

van der Sluys et al., 2008; Raymond et al., 2009

Accuracy of parameter estimation

2 detectors (H1 & V):

a_{spin}	θ_{SL} (°)	d_L (Mpc)	M_1 (%)	M_2 (%)	$\mathcal{M}$ (%)	η (%)	t_c (ms)	d_L (%)	a_{spin}	θ_{SL} (°)	**Pos.** (°^{2})	**Ori.** (°^{2})
0.0	0	16.0	95	83	2.6	138	18	86	0.63	—	537	19095
0.1	20	16.4	102	85	1.2	90	10	91	0.91	169	406	16653
0.1	55	16.7	51	38	0.88	59	7.9	58	0.32	115	212	3749
0.5	20	17.4	53[b]	42[a]	0.90	50[b]	5.4	46[a]	0.26	56	111[a]	3467[a]
0.5	55	17.3	31	24	0.62	41	4.9	21	0.12	24	19.8	178[a]
0.8	20	17.9	54[a]	42[a]	0.86[a]	54[a]	6.0	56	0.16	25[a]	104[a]	1540
0.8	55	17.9	21	16	0.66	29	4.7	22	0.15	15	22.8	182[a]

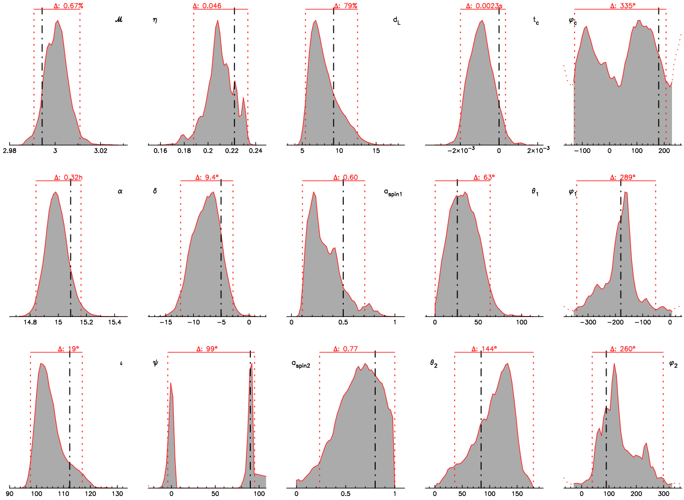
3 detectors (H1, L1 & V):

a_{spin}	θ_{SL} (°)	d_L (Mpc)	M_1 (%)	M_2 (%)	$\mathcal{M}$ (%)	η (%)	t_c (ms)	d_L (%)	a_{spin}	θ_{SL} (°)	**Pos.** (°^{2})	**Ori.** (°^{2})
0.0	0	20.5	114	90	2.6	119	15	69	0.98[b]	—	116	4827
0.1	20	21.1	70	57	0.92	72	7.0	60	0.49	160	64.7	3917
0.1	55	21.4	62	48	0.93	68	6.2	51	0.52	123	48.7	976
0.5	20	22.3	54[b]	44[a]	0.89[a]	48[b]	3.3	52	0.28[a]	69	28.8	849
0.5	55	22.0	33	25	0.62	43	4.6	23[a]	0.14	27	20.7	234[a]
0.8	20	23.0	53[b]	41[a]	0.85[a]	52[b]	3.8	55	0.17	23[a]	36.4[a]	645
0.8	55	22.4	30	22	0.86	40	5.0	26	0.21	21	27.2	288

90%-probability ranges, injection SNR = 17.0
[a] the true value lies outside the 90%-probability range
[b] idem, outside the 99%-probability range, but inside the 100% range

van der Sluys et al., 2008

MCMC with two spins



- 3.5-pN waveform
- 3 detectors
- $\mathcal{M} = 3.0\ M_\odot$, $\eta = 0.22$
- $a_{\rm spin} = 0.5, 0.8$
- Σ SNR=20

Conclusions GW parameter estimation

MCMC code:

We have developed an MCMC code that can recover the 12–15 parameters of a binary inspiral, including one or two spins

Accuracies:

- Detection with only 2 detectors can produce astronomically relevant information when spin is present, with typical accuracies for low/higher spin:
  - individual masses: $\sim 32\%/39\%$
  - dimensionless spin: $0.17 - 0.18$
  - distance: $\sim 55\%/45\%$
  - sky position: $\sim 500^{\circ^2}/40^{\circ^2}$
  - binary orientation: $\sim 2500^{\circ^2}/175^{\circ^2}$
  - time of coalescence: 11ms / 6ms
- Combination of the above can lead to association with an electromagnetic detection (*e.g.* gamma-ray burst)

End...