Using astrophysical knowledge in gravitational-wave data analysis of binary inspirals

Marc van der Sluys

Radboud University Nijmegen / FOM

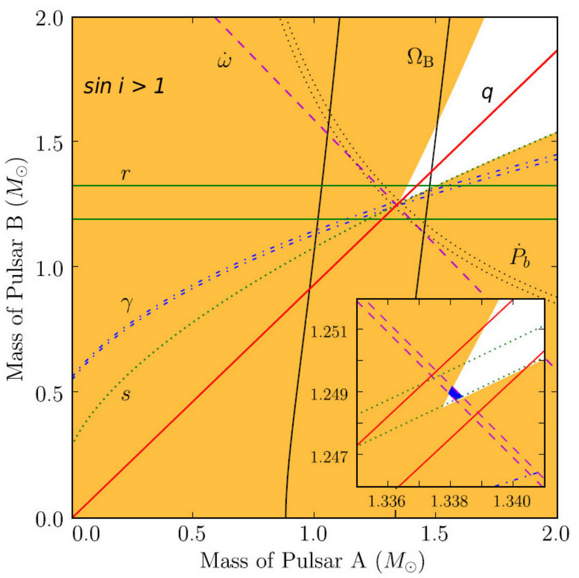
Vivien Raymond, Ben Farr, Ilya Mandel, Vicky Kalogera
Gijs Nelemans, Sweta Shah
Christian Röver, Nelson Christensen, Alberto Vecchio

Outline

Gravitational waves

GWs:

- "Ripples in spacetime"
- Predicted by Einstein's theory of General Relativity
- *Indirectly* observed for *e.g.* the binary pulsar:

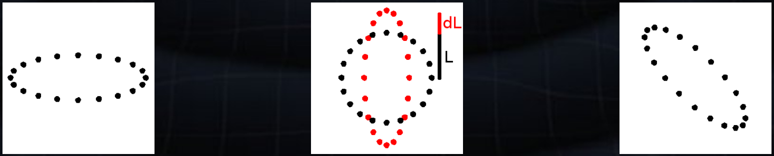


(Breton et al., Science, 2008)

Gravitational waves

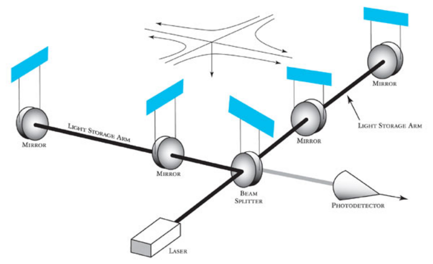
Gravitational waves...

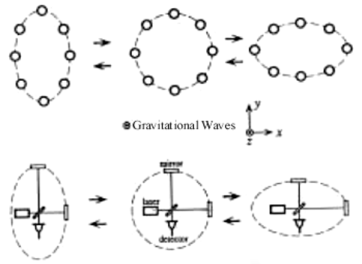
- propagate transversely at the speed of light
- are quadrupole radiation at the lowest order
- stretch and squeeze spacetime in two polarisations
- allow us to measure their amplitude



- Strain: $h(t) = h_+(t)F_+(t) + h_\times(t)F_\times(t) = \frac{\delta L(t)}{L} \sim 10^{-22}$

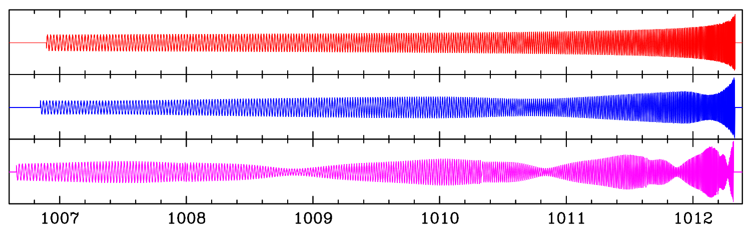
Laser Interferometer GW Observatory (LIGO)

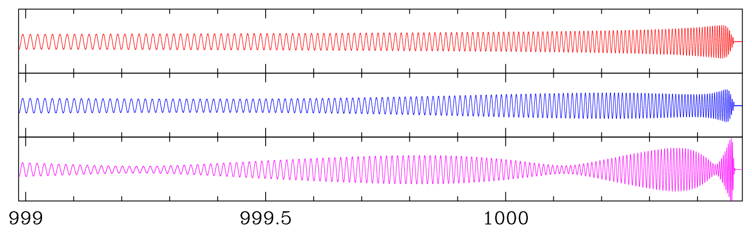




Inspiral waveforms with increasing spin

LIGO and Virgo can detect the last $\sim$10 s of a binary inspiral:





$10\,M_\odot$ BH + $1.4\,M_\odot$ NS; $a_{\rm spin,BH} \equiv S/M^2 = 0.0$, 0.1 and 0.5

Predicted detection rates of binary inspirals

Horizon distances (Mpc):

	NS-NS	BH-NS	BH-BH
Initial LIGO/Virgo	32	67	160
Advanced LIGO/Virgo	364	767	1850

Detection-rate estimates (yr^{-1}):

	NS-NS	BH-NS	BH-BH
Initial LIGO/Virgo	2×10^{-4} – 0.2	7×10^{-5} – 0.1	2×10^{-4} – 0.5
Advanced LIGO/Virgo	0.4 – 400	0.2 – 300	0.4 – 1000

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

Abadie 2010; talk by Ilya Mandel

Predicted detection rates of binary inspirals

Horizon distances (Mpc):

	NS-NS	BH-NS	BH-BH
Initial LIGO/Virgo	32	67	160
Advanced LIGO/Virgo	364	767	1850

Detection-rate estimates (yr^{-1}):

	NS-NS	BH-NS	BH-BH
Initial LIGO/Virgo	2×10^{-4} – 0.2	7×10^{-5} – 0.1	2×10^{-4} – 0.5
Advanced LIGO/Virgo	0.4 – 400	0.2 – 300	0.4 – 1000

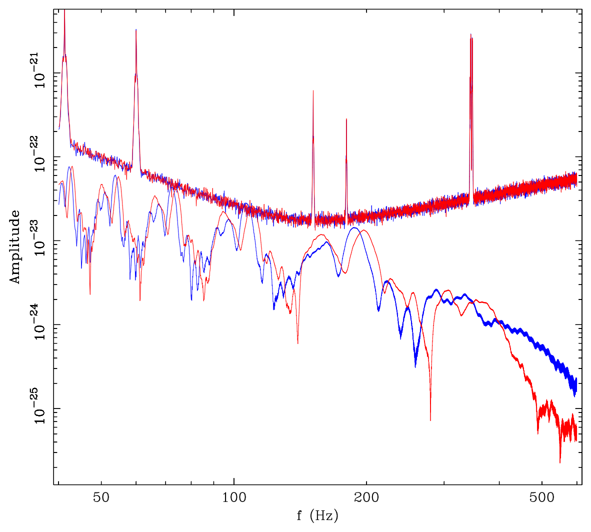
Estimates assume $M_{\rm NS} = 1.4\,M_\odot$ and $M_{\rm BH} = 10\,M_\odot$

Abadie 2010; talk by Ilya Mandel

Signal injection into detector noise

Example:

- Using two 4-km detectors H1, L1
- Inject signal coherently
- Σ SNR = 17
- Retrieve physical parameters using MCMC



SPINSPIRAL code

Purpose:

- Use Markov-Chain Monte Carlo for parameter estimation
- Follow-up after detection
- Gaussian, stationary noise or LIGO/Virgo detector data
- Analyse software injections, hardware injections, detection candidates/interesting events
- Include spin in injections and analysis
- Use any network composed of LIGO/Virgo detectors:
  - $\mathrm{PDF}(\vec{\lambda}) \propto \mathrm{prior}(\vec{\lambda}) \times \prod_i L_i(d|\vec{\lambda})$

Output:

- posterior probability-density function (PDF) of the parameter set that describes the model (9–12–15 D)

SPINSPIRAL code

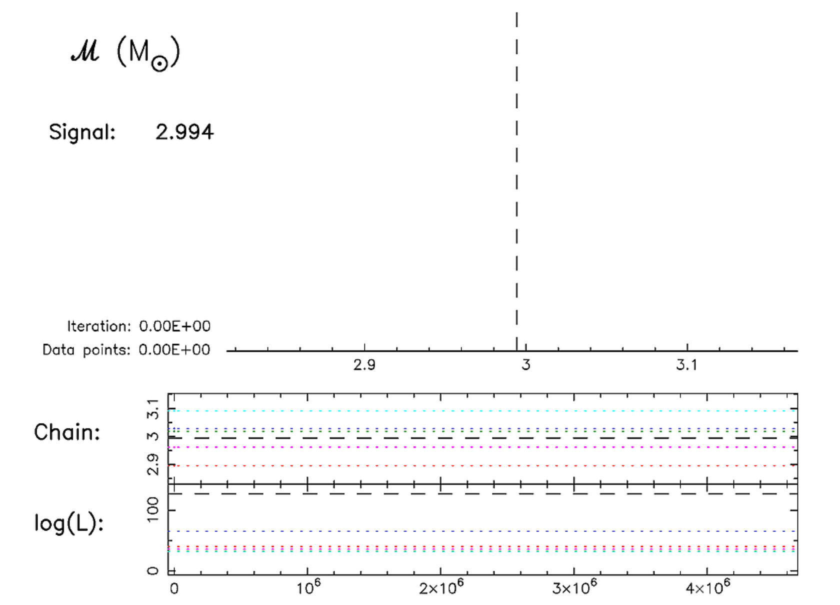
Purpose:

- Use Markov-Chain Monte Carlo for parameter estimation
- Follow-up after detection
- Gaussian, stationary noise or LIGO/Virgo detector data
- Analyse software injections, hardware injections, detection candidates/interesting events
- Include spin in injections and analysis
- Use any network composed of LIGO/Virgo detectors:
  - $\mathrm{PDF}(\vec{\lambda}) \propto \mathrm{prior}(\vec{\lambda}) \times \prod_i L_i(d|\vec{\lambda})$

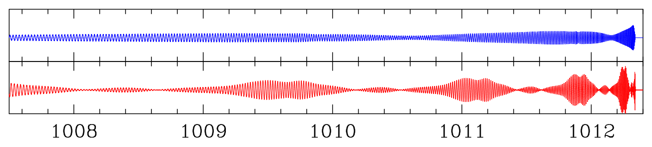
Output:

- posterior probability-density function (PDF) of the parameter set that describes the model (9–12–15 D)

SPINSPIRAL example



Information and correlations increase with spin

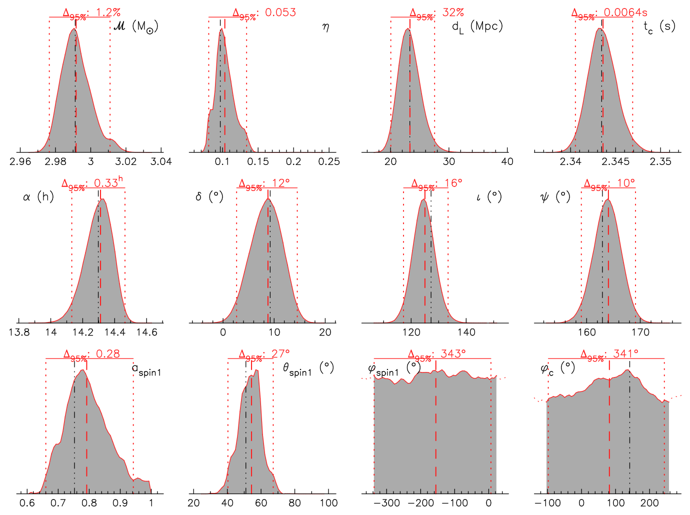


	M_c	η	a_{spin}	ϑ_{SL}	R.A.	Dec.
M_c		0.22	0.42	0.17	−0.40	0.19
η	−0.27		−0.34	−0.53	−0.07	−0.04
a_{spin}	−0.61	0.89		−0.04	0.11	0.62
ϑ_{SL}	0.66	−0.87	−0.99		0.02	−0.34
R.A.	−0.36	0.01	0.02	−0.02		0.12
Dec.	−0.23	0.08	0.18	−0.20	−0.05	

Parameters:

- BH-NS
- H1 & L1
- $M_1 = 10\, M_\odot$
- $M_2 = 1.4\, M_\odot$
- a_{spin} = 0.1, 0.8
- $\theta_{SL} = 55°$
- Network SNR $\approx$ 25

MCMC results for the analysis of a BH-NS signal



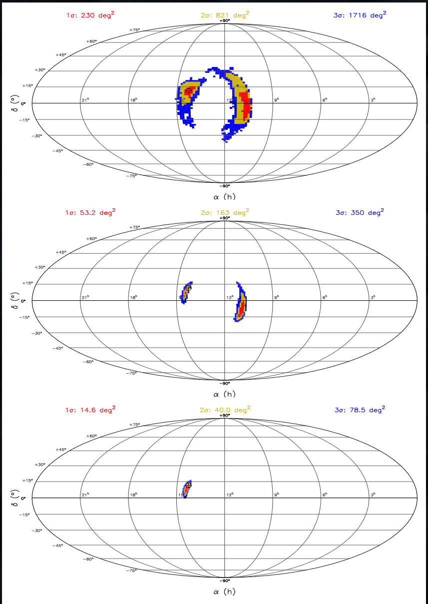
van der Sluys et al., 2008

Parameters:

- H1, L1, V
- $M = 10, 1.4\,M_\odot$
- $d_L = 22.4\,\mathrm{Mpc}$
- $a_{\mathrm{spin}} = 0.8$, $\theta_{\mathrm{SL}} = 55°$
- Σ SNR $\approx$ 17.0
- simulated noise

- Black dash-dotted line: injection
- Red dashed line: median
- Δ's: 95% probability

Sky position for signals with different spins



Spinning BH, non-spinning NS:

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

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

2-σ accuracy: $821^{\circ 2}$

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

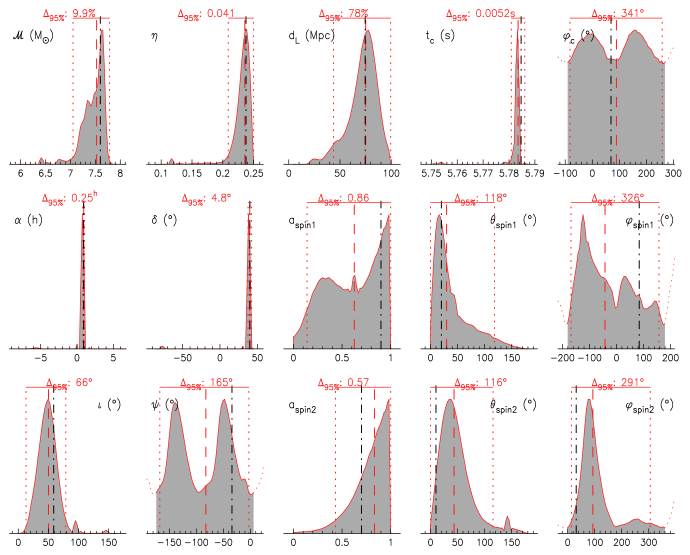
2-σ accuracy: $163^{\circ 2}$

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

2-σ accuracy: $40^{\circ 2}$

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

Analysis of a BH-BH signal with spins

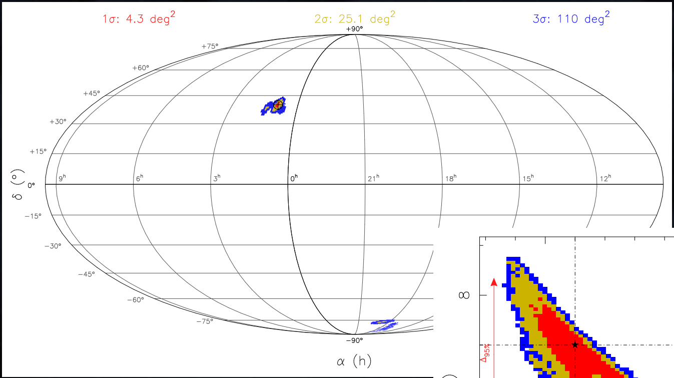


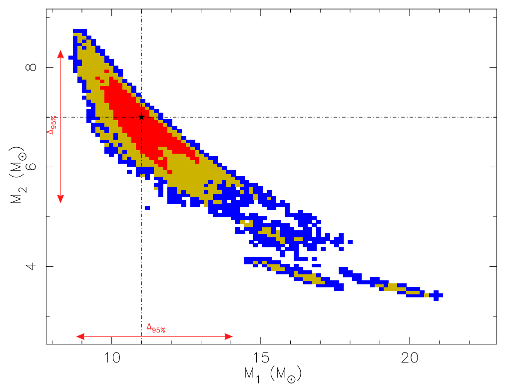
van der Sluys et al., in preparation

HS-2:

- 3.5-pN waveform
- 3 detectors (H1,L1,V)
- $\mathcal{M} = 7.6\,M_\odot$, $\eta = 0.238$; $M_1 = 11.0\,M_\odot$, $M_2 = 7.0\,M_\odot$
- $a_{s1,2} = 0.9, 0.7$
- $\theta_{s1,2} = 10, 20°$
- $d_L = 74.5$ Mpc
- Σ SNR=15
- simulated noise

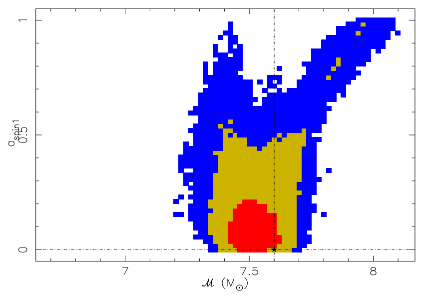
Analysis of a BH-BH signal with spins



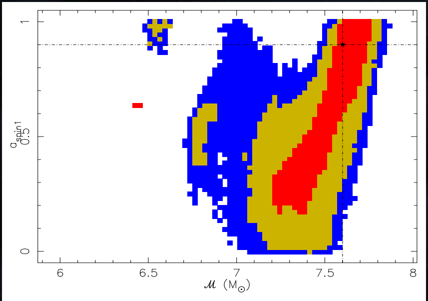


van der Sluys et al., in preparation

The nuisance of having spins in your analysis

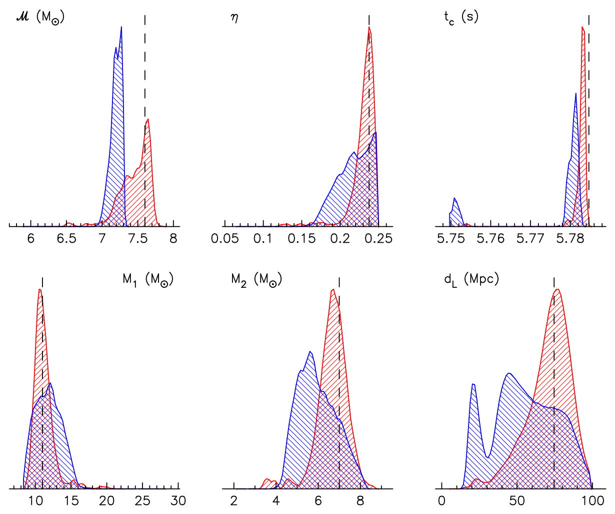


Signal **without** spins,
analysis with spinning template



Signal **with** spins,
analysis with spinning template

The importance of having spins in your analysis



Signal with spins

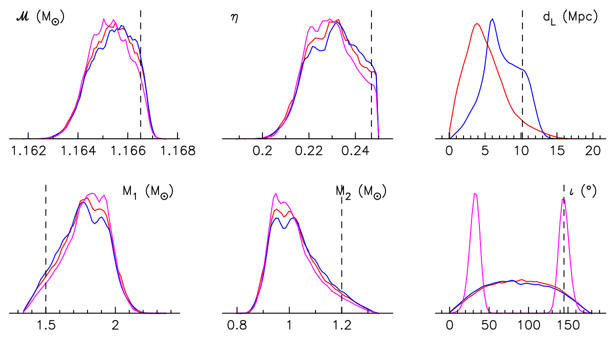
Analysis with spinning template

Analysis with non-spinning template

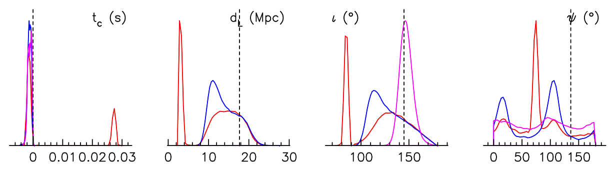
van der Sluys et al., in preparation

Using astrophysical data to constrain parameters: short GRB

1 detector (H1):



3 detectors (H1,L1,V):



NS-NS, non-spinning:
$1.2 + 1.5\, M_\odot$
$d_L \approx 10.2 - 17.8$ Mpc
(Σ SNR=15.0)

No astrophysical information

Sky position known

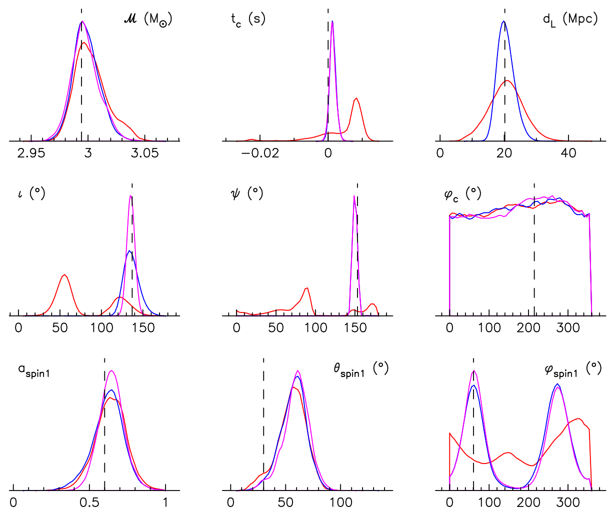
Sky position and distance known

van der Sluys et al., in preparation

See also: **Nissanke et al., 2010**

Using astrophysical data to constrain parameters: short GRB

2 detectors (H1,L1):



BH-NS, spinning BH:
$10 + 1.4\,M_\odot$, $a_{\rm spin} = 0.6$
$d_L \approx 20.2$ Mpc (Σ SNR=15.0)

No astrophysical information

Sky position known

Sky position and distance known

van der Sluys et al., in preparation

Conclusions

SPINSPIRAL

- SPINSPIRAL can recover the 12–15 parameters of a binary inspiral, including one or two spins, using an MCMC technique
- Sky-position reconstruction (few $\times 10^{\circ^{2}}$) is poor for astrophysical standards
- Combination of position, distance and time can lead to association with an electromagnetic detection (*e.g.* GRB)

Taking into account spins

- The inclusion of spin adds significantly to the number of dimensions (9–12–15) and introduces (strong) correlations
- Failing to take into account spin can result to biases in especially mass parameters

Conclusions

SPINSPIRAL

- SPINSPIRAL can recover the 12–15 parameters of a binary inspiral, including one or two spins, using an MCMC technique
- Sky-position reconstruction (few $\times 10^{\circ 2}$) is poor for astrophysical standards
- Combination of position, distance and time can lead to association with an electromagnetic detection (*e.g.* GRB)

Taking into account spins

- The inclusion of spin adds significantly to the number of dimensions (9–12–15) and introduces (strong) correlations
- Failing to take into account spin can result to biases in especially mass parameters

Conclusions (numbers are preliminary)

Using astrophysical knowledge for GW data analysis: no spins

- Knowing the sky position of a source improves determination of:
  - distance ($\sim 20-50\%$)
  - inclination
- Knowing the position *and distance* improves inclination further, also in 1-detector analysis

Using astrophysical knowledge for GW data analysis: spins

- Knowing the sky position of a source improves determination of:
  - distance ($\sim 50\%$)
  - inclination, polarisation angle ($50-90\%$)
  - masses ($\sim 20\%$)
  - spin angles
- Knowing the position *and distance* improves:
  - spin magnitude ($\sim 20\%$)

Conclusions (numbers are preliminary)

Using astrophysical knowledge for GW data analysis: no spins

- Knowing the sky position of a source improves determination of:
  - distance ($\sim 20 - 50\%$)
  - inclination
- Knowing the position *and distance* improves inclination further, also in 1-detector analysis

Using astrophysical knowledge for GW data analysis: spins

- Knowing the sky position of a source improves determination of:
  - distance ($\sim 50\%$)
  - inclination, polarisation angle ($50 - 90\%$)
  - masses ($\sim 20\%$)
  - spin angles
- Knowing the position *and distance* improves:
  - spin magnitude ($\sim 20\%$)

End. . .

MCMC analyses

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: $\log d_L$, time and phase at coalescence: t_c & φ_c, position: α & $\sin\delta$, spin magnitude: $a_{\mathrm{spin}_{1,2}}$, spin orientation: $\cos\theta_{\mathrm{spin}_{1,2}}$ & $\varphi_{\mathrm{spin}_{1,2}}$ & binary orientation: $\cos(\iota)$ & ψ

MCMC set-up

- $\geq$ 5 serial chains per run, starting from offset parameter values
- Chain length: $\sim$ few $\times 10^6$ states; burn-in: $\sim$ few $\times 10^5$ 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

MCMC analyses

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_c & φ_c, position: α & $\sin\delta$, spin magnitude: $a_{\mathrm{spin}_{1,2}}$, spin orientation: $\cos\theta_{\mathrm{spin}_{1,2}}$ & $\varphi_{\mathrm{spin}_{1,2}}$ & binary orientation: $\cos(\iota)$ & ψ

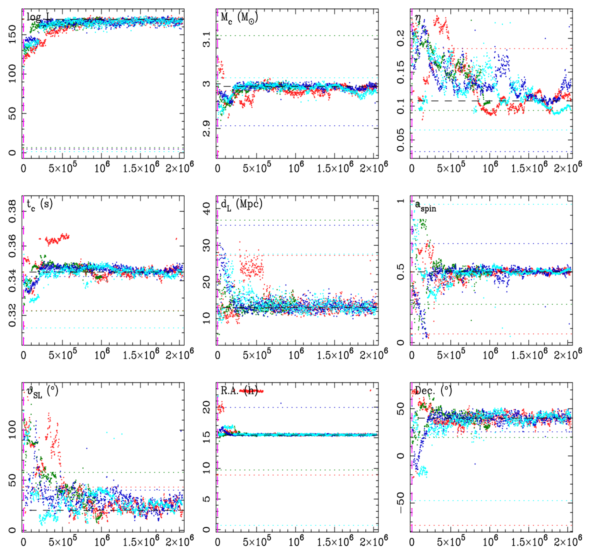
MCMC set-up

- ≥ 5 serial chains per run, starting from offset parameter values
- Chain length: $\sim$ few $\times 10^6$ states; burn-in: $\sim$ few $\times 10^5$ 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

Analysis details: BH-NS signal

- Signals injected in simulated noise for H1L1V @ SNR $\approx$17.0
- Fiducial binary: $M_{1,2} = 10 + 1.4\,M_\odot$, $d_{\rm L} = 16$–23 Mpc
- Spin: $a_{\rm spin} = 0.0, 0.1, 0.5, 0.8$, $\theta_{\rm SL} = 20^\circ, 55^\circ$

Convergence of chains



- Dots: starting values
- Dashes: injection values