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

Marc van der Sluys

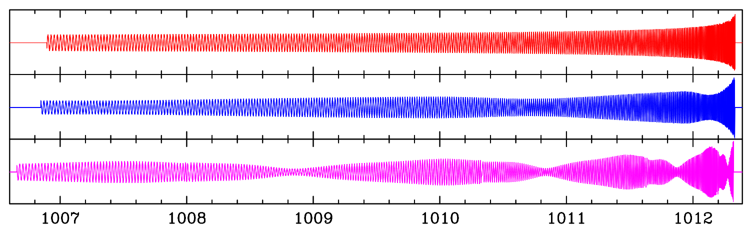
Radboud University Nijmegen / FOM / NIKHEF

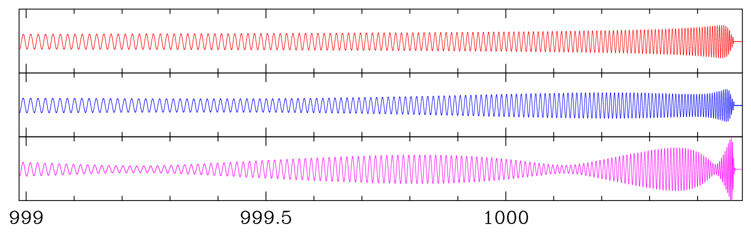
Vivien Raymond, Ben Farr, Ilya Mandel, Vicky Kalogera
Gijs Nelemans, Sweta Shah, Chris Chambers
Christian Röver, Nelson Christensen, Alberto Vecchio

Outline

Inspiral waveforms with increasing spin

Initial LIGO and Virgo can detect the last $\sim 10\,\mathrm{s}$ of a binary inspiral:





$10\,M_\odot$ BH + $1.4\,M_\odot$ NS; $a_{\mathrm{spin,BH}} \equiv S/M^2 = 0.0$, 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}):

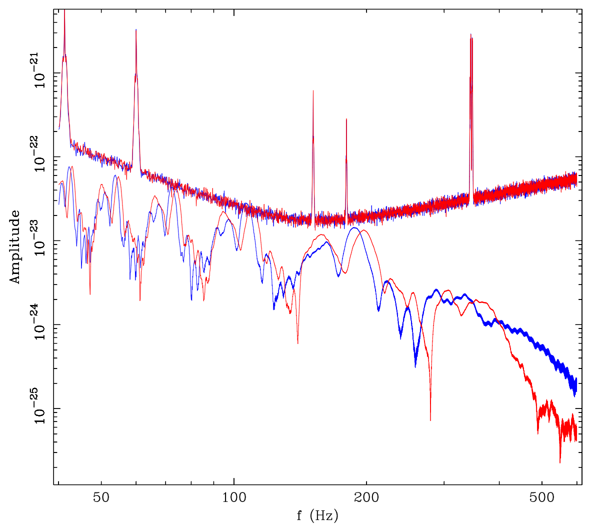
	NS-NS	BH-NS	BH-BH
Initial LIGO/Virgo	2×10^{-4} – 0.2	7×10^{-5} – 0.1	2×10^{-4} – 0.5
Advanced LIGO/Virgo	0.4 – 400	0.2 – 300	0.4 – 1000

Estimates assume $M_{\mathrm{NS}} = 1.4\,M_\odot$ and $M_{\mathrm{BH}} = 10\,M_\odot$
Abadie et al. (2010)

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 → LALinference

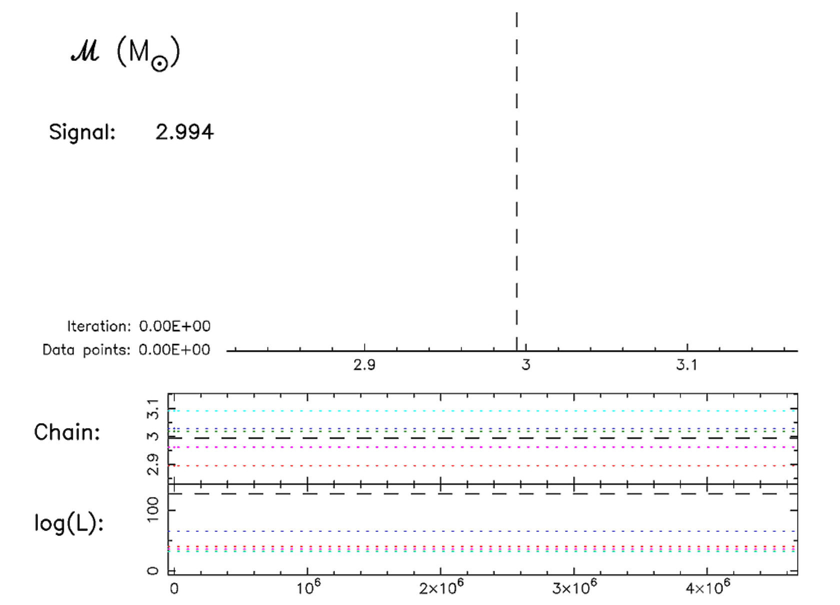
Purpose:

- Use Markov-Chain Monte Carlo for parameter estimation
- Follow-up after detection
- Gaussian, stationary noise or LIGO/Virgo/other 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:
  - $\mathrm{PDF}(\vec{\lambda}) \propto \mathrm{prior}(\vec{\lambda}) \times \prod_i L_i(d|\vec{\lambda})$

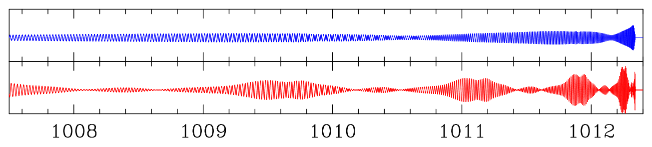
Output:

- 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

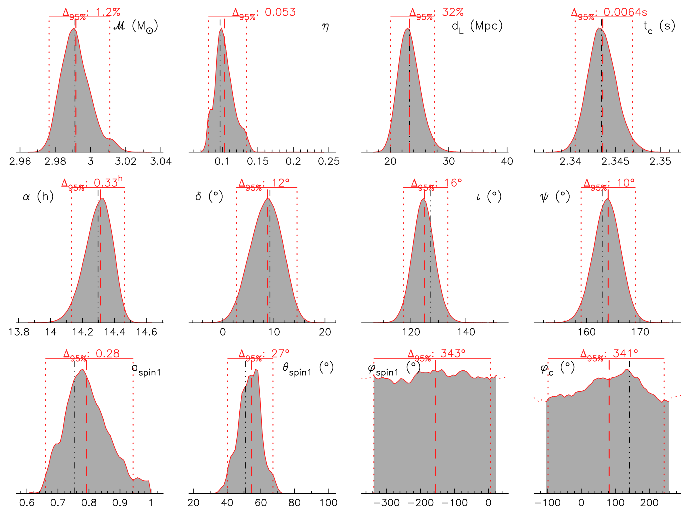


	M_c	η	a_{spin}	ϑ_{SL}	R.A.	Dec.
M_c		0.22	0.42	0.17	−0.40	0.19
η	−0.27		−0.34	−0.53	−0.07	−0.04
a_{spin}	−0.61	0.89		−0.04	0.11	0.62
ϑ_{SL}	0.66	−0.87	−0.99		0.02	−0.34
R.A.	−0.36	0.01	0.02	−0.02		0.12
Dec.	−0.23	0.08	0.18	−0.20	−0.05	

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 ≈ 25

MCMC results for the analysis of a BH-NS signal



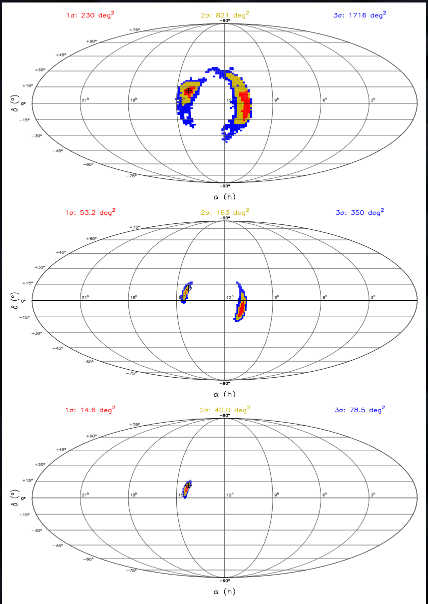
van der Sluys et al., 2008

Parameters:

- H1, L1, V
- $M = 10, 1.4\, M_{\odot}$
- $d_L = 22.4$ Mpc
- $a_{\rm spin} = 0.8$, $\theta_{\rm SL} = 55°$
- Σ SNR ≈ 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, $a_{\rm spin} = 0.5$

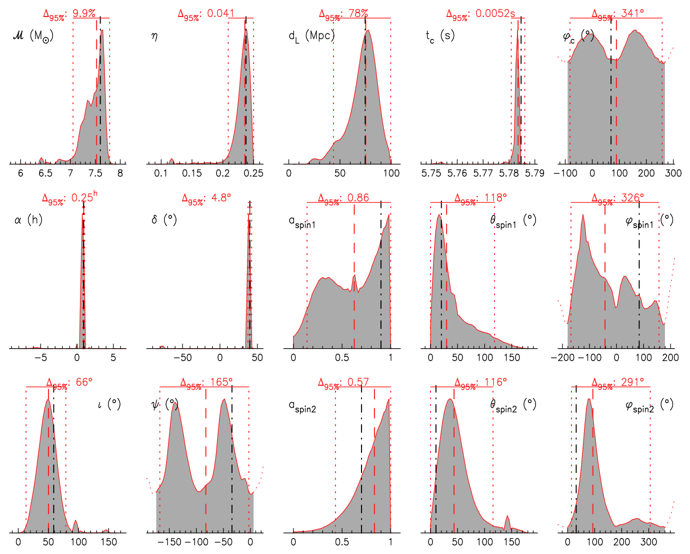
2-σ accuracy: $163^{\circ 2}$

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

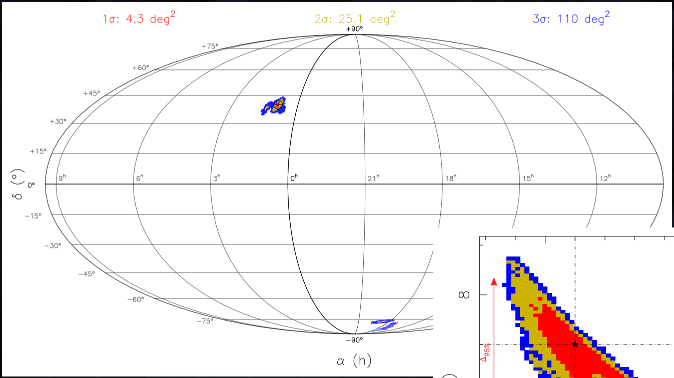


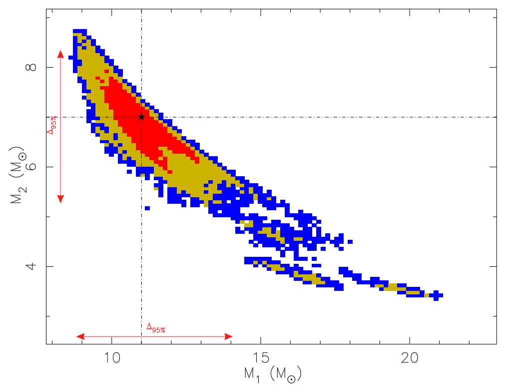
van der Sluys et al., in preparation

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

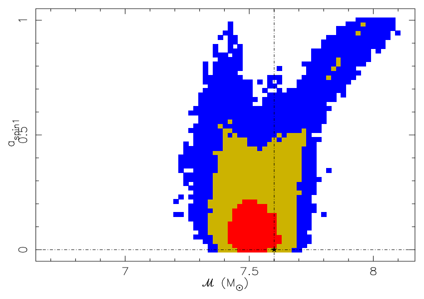
Analysis of a BH-BH signal with spins



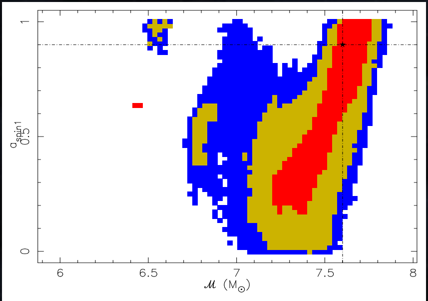


van der Sluys et al., in preparation

The nuisance of having spins in your analysis

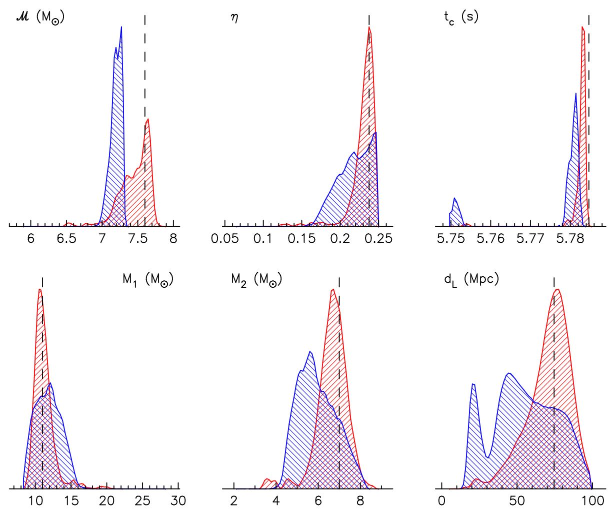


Signal **without** spins,
analysis with spinning template



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

The importance of having spins in your analysis



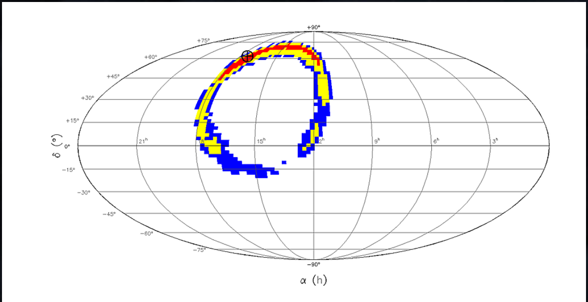
Signal with spins

Analysis with spinning template

Analysis with non-spinning template

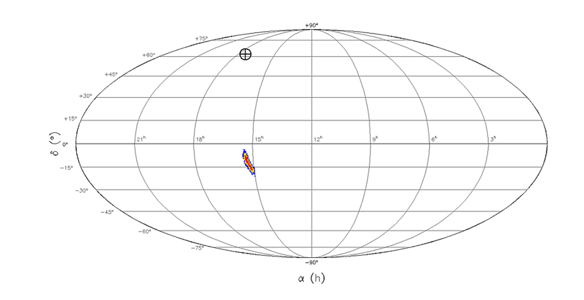
van der Sluys et al., in preparation

The importance of having spins in your analysis



2 detectors

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

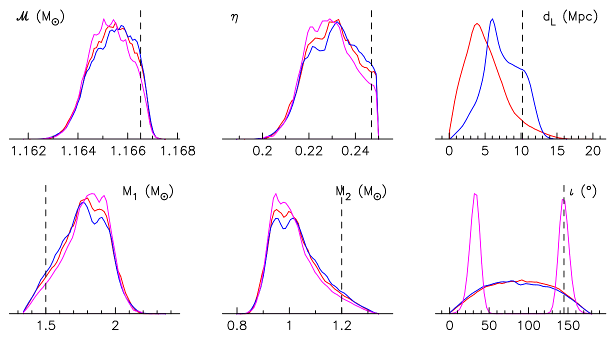


3 detectors

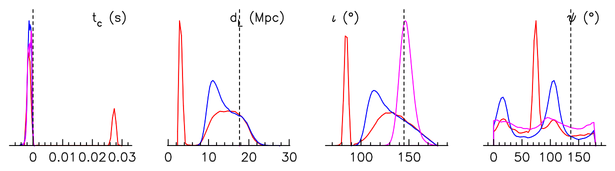
See also: poster by Riccardo & Salvatore at GWPAW

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

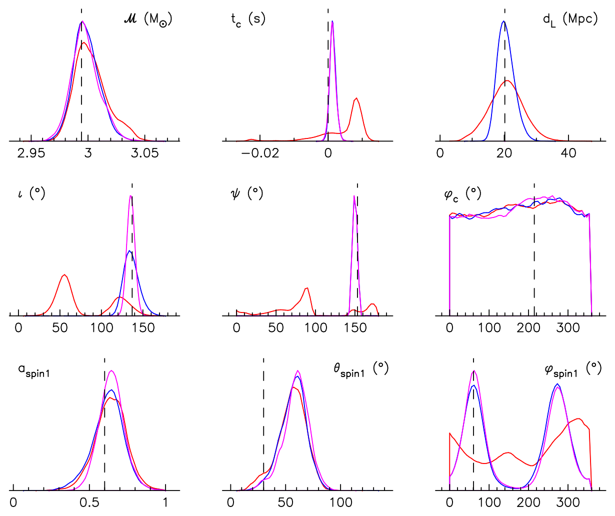
Sky position and distance known

van der Sluys et al., in preparation
See also: **Nissanke et al., 2010**

Equal-mass binaries: **Chris Chambers**

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

- can recover the 12–15 parameters of a binary inspiral, including one or two spins, using an MCMC technique
- has now been integrated in the LALinference package

- 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 in biases in *e.g.* mass and sky-position 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 (≥ 2 detectors)
- Knowing the position *and distance* improves inclination further, also in 1-detector analysis

Using astrophysical knowledge for GW data analysis: spins

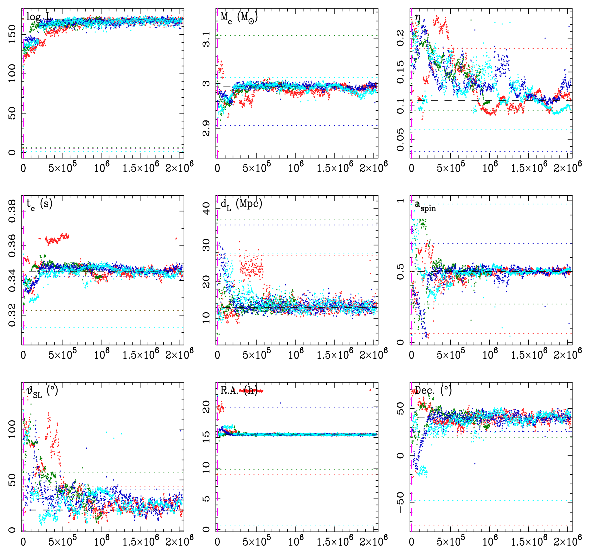
- Knowing the sky position of a source improves determination of:
  - distance ($\sim 50\%$)
  - inclination, polarisation angle ($50 - 90\%$)
  - masses ($\sim 20\%$)
  - spin angles
- Knowing the position *and distance* improves:
  - spin magnitude ($\sim 20\%$)

Learn:

- whether SHGRBs are caused by CBCs
- about masses and spins of GRB progenitors
- get a handle on GRB beaming

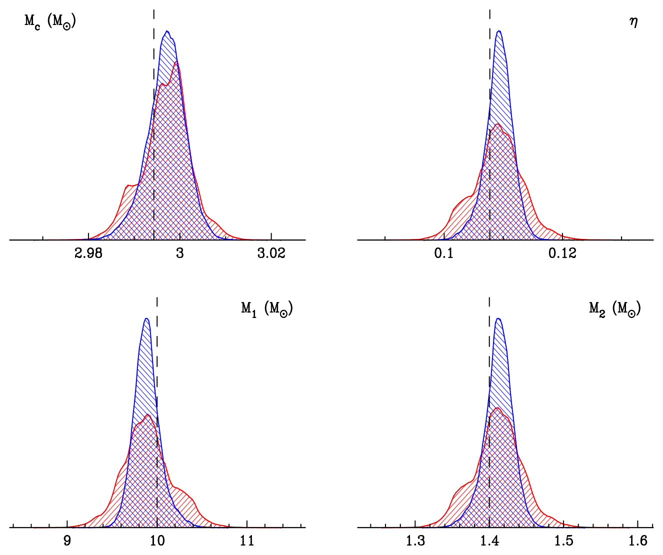
End. . .

Convergence of chains



- Dots: starting values
- Dashes: injection values

Effect of post-Newtonian approximation



Parameter estimation using:

- 1.5-pN waveform template
- 3.5-pN waveform template