Gravitational-wave astronomy with LIGO/Virgo: the SPINSPIRAL code

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Outline

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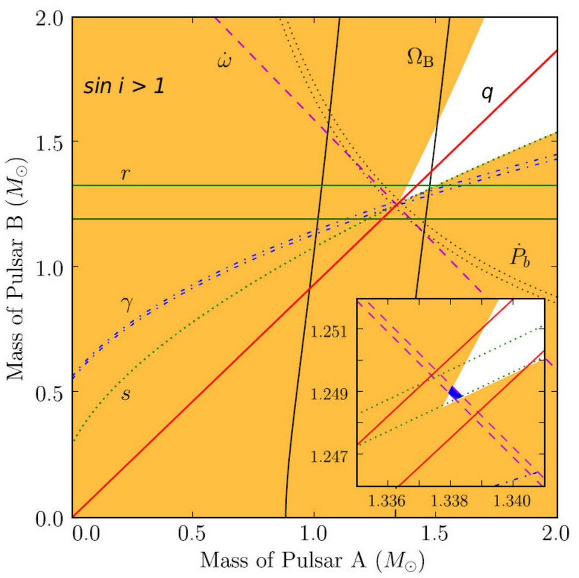
   - LIGO/Virgo
2. Estimation of astrophysical parameters
   - Signal and noise
   - Analysis of a BH-NS signal
   - Analysis of a BH-BH signal
   - The importance of having spins
   - Using astrophysical information
3. Conclusions

Gravitational waves

GWs:

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



(Breton et al., Science, 2008)

Electromagnetic vs. gravitational waves

EM:

- are waves that propagate through spacetime
- are produced incoherently by many (small) atoms
- have a short wavelength compared to the source size
- use the relatively strong EM force
- have frequencies $\gtrsim 10^6$ Hz
- are measured by energy $\rightarrow \quad L(r) \sim 1/r^2$

GW:

- are waves in the metric of spacetime
- are produced coherently by a few large masses
- have a long wavelength compared to the source size
- use the weak gravitational force
- have frequencies $\lesssim 10^3$ Hz
- are measured by amplitude $\rightarrow \quad L(r) \sim 1/r$

Why detect them?

Physics:

- direct measurement of GWs and verification of GR
- direct observation of black holes
- verify that GWs travel at the speed of light, *i.e.* that the graviton rest mass = 0
- verify that GWs act transversely, *i.e.* that the graviton spin = 2

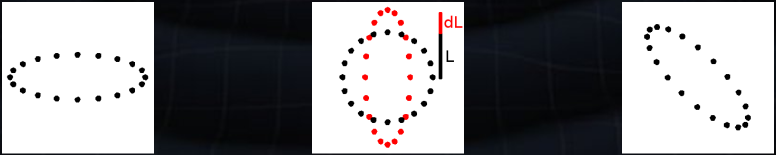
Astrophysics:

- whole new window to the universe!
- the ripping apart of neutron stars, their implosion to a black hole
- black holes eating neutron stars, BH-BH collisions
- core-collapse supernovae
- hills on pulsars
- primordial GWs as a probe to the Big Bang
- the unexpected. . .

Gravitational waves

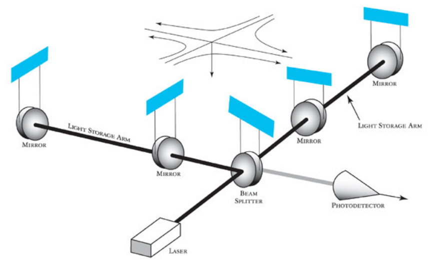
Gravitational waves. . .

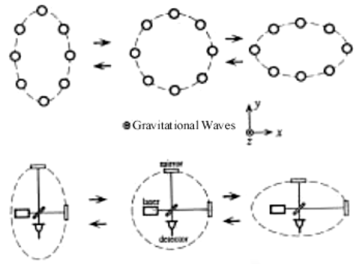
- propagate transversely at the speed of light
- are quadrupole radiation at the lowest order
- stretch and squeeze spacetime in two polarisations
- allow us to measure their amplitude



- 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)





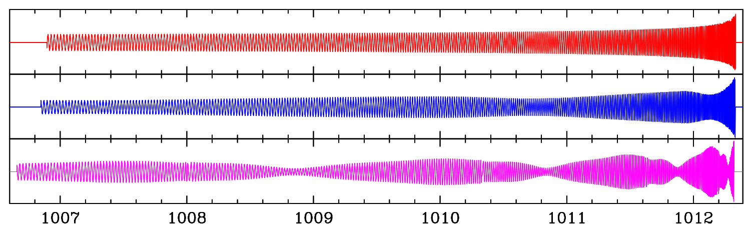
Laser Interferometer GW Observatory (LIGO)

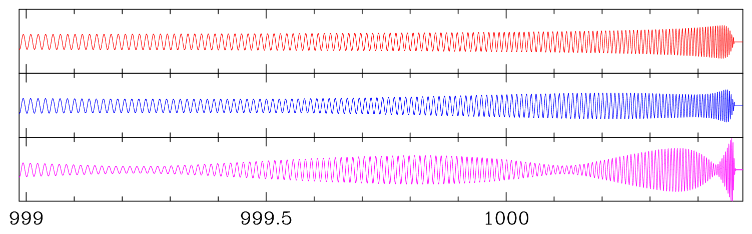
- LLO: Livingston, Louisiana (L1: 4 km)
- LHO: Hanford, Washington (H1: 4 km, H2: 2 km)
- Virgo: Pisa, Italy (V: 3 km)

- Michelson interferometers
- Frequency sensitivity: $f \sim 40 - 1600\,\mathrm{Hz}$
- $\delta L = 10^{-22} \times L \approx 10^{-16}\,\mathrm{cm}$ (atomic nucleus $\sim 10^{-13}\,\mathrm{cm}$)

Inspiral waveforms with increasing spin

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



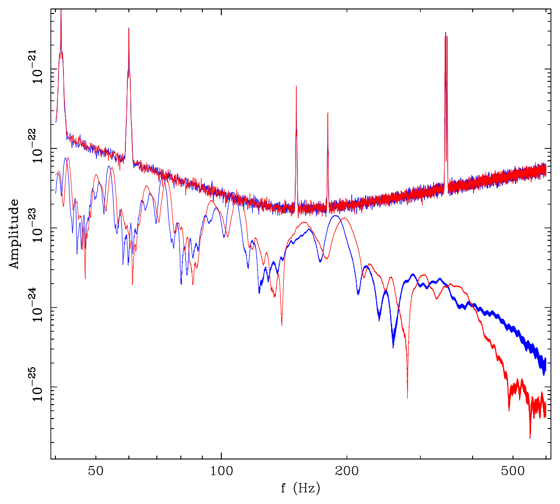


$a_{\rm spin} \equiv S/M^2 = 0.0$, 0.1 and 0.5

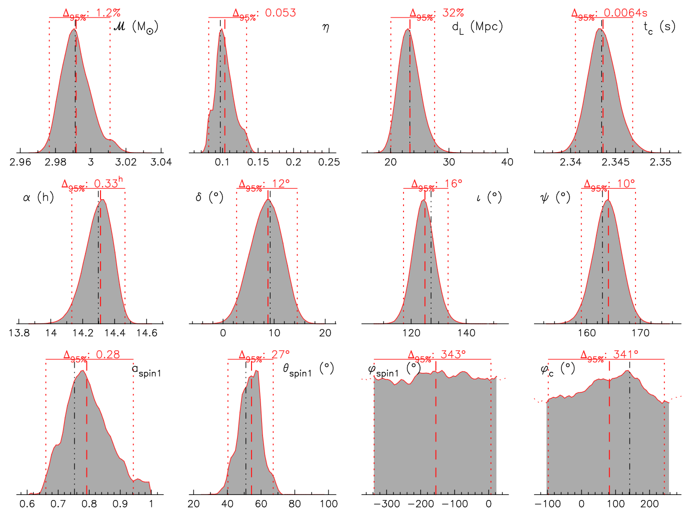
Signal injection into detector noise

Example:

- Using two 4-km detectors H1, L1
- Gaussian, stationary noise or LIGO/Virgo detector data
- Do software injections
- Retrieve physical parameters using MCMC
- ΣSNR = 17



MCMC results for the analysis of a BH-NS signal

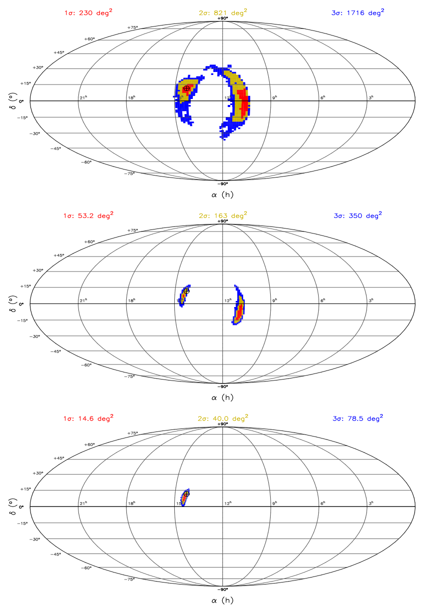


van der Sluys et al., 2008

Parameters:

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

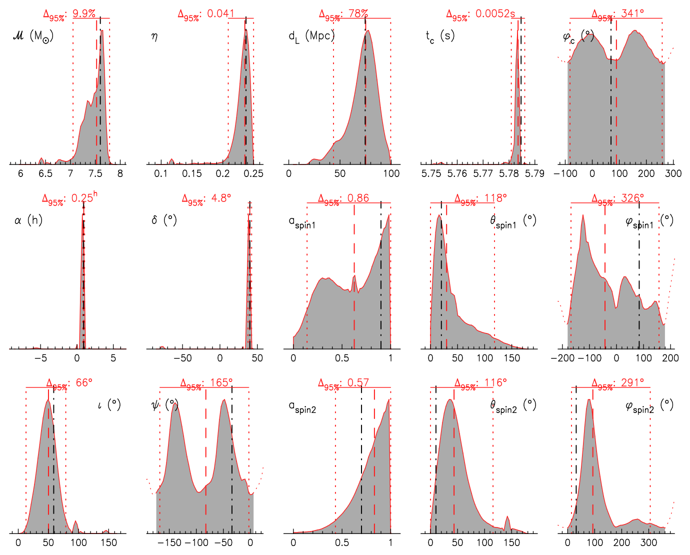
2 detectors, $a_{\rm spin} = 0.0$
2-σ accuracy: $821^{\circ 2}$

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

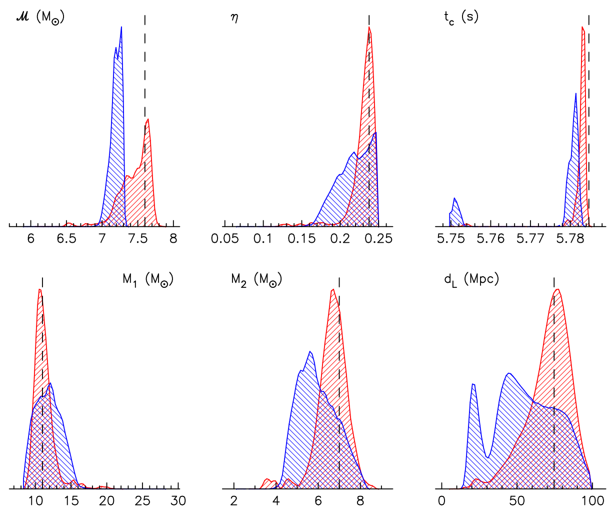


van der Sluys et al., in preparation

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

The importance of having spins in your analysis



Signal with spins

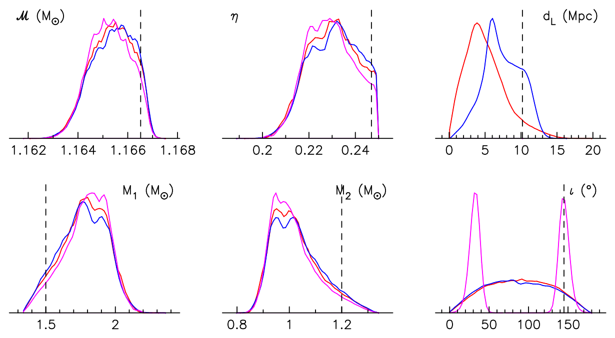
Analysis with spinning template

Analysis with non-spinning template

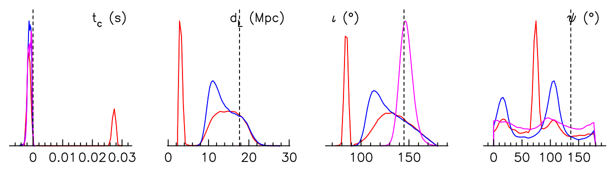
van der Sluys et al., in preparation

Using astrophysical data to constrain parameters

1 detector:



3 detectors:



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

No astrophysical information

Sky position known

Sky position and distance known

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Conclusions

- 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)

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

- Knowing the sky position of a source improves determination of distance, inclination
- Knowing the position and distance improves inclination further
- Effects may be stronger for signals with spin; in progress. . .

End. . .

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

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

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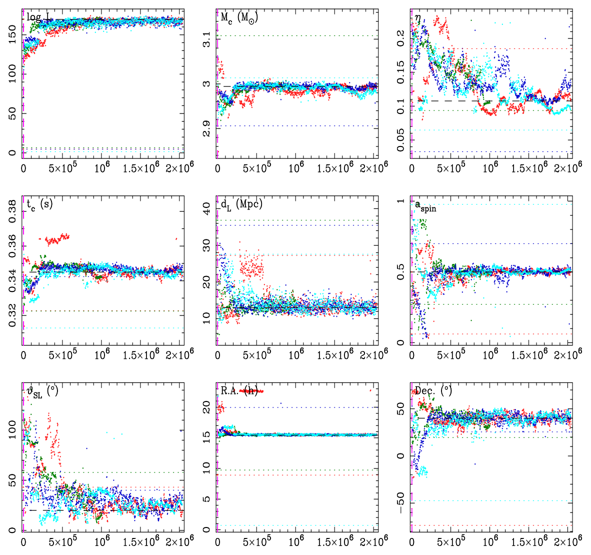
Analysis details: BH-NS signal

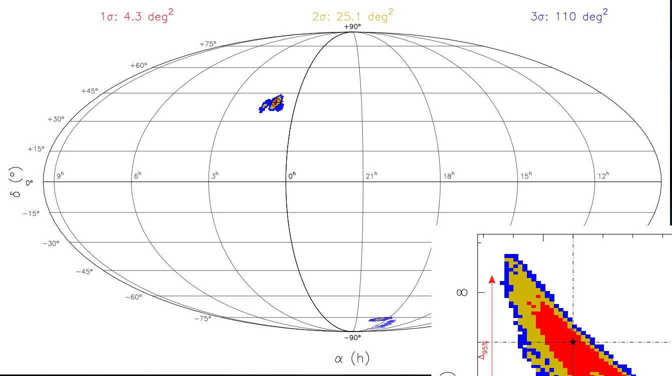
- Signals injected in simulated noise for H1L1V @ SNR $\approx$17.0
- Fiducial binary: $M_{1,2} = 10 + 1.4\, M_\odot$, $d_{\rm L} =$ 16–23 Mpc
- Spin: $a_{\rm spin} = 0.0, 0.1, 0.5, 0.8$, $\theta_{\rm SL} = 20^\circ, 55^\circ$

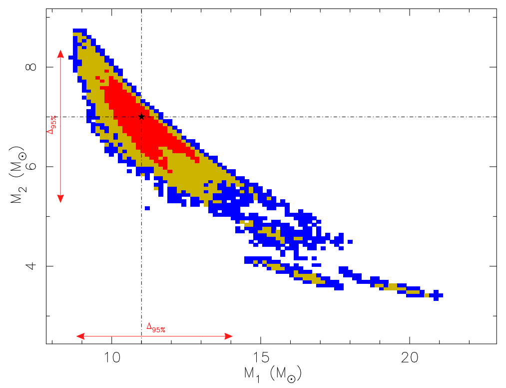
Convergence of chains



- Dots: starting values
- Dashes: injection values

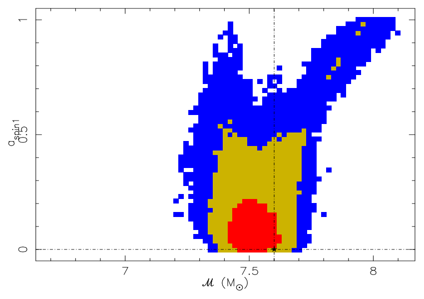
Analysis of a BH-BH signal with spins



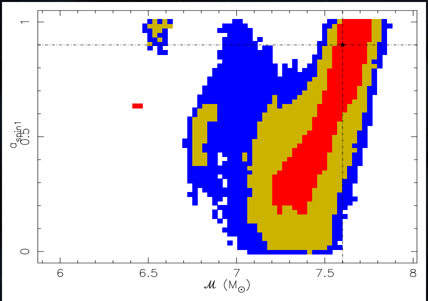


van der Sluys et al., in preparation

The nuisance of having spins in your analysis



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



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