Investigating the poor match among different precessing gravitational waveforms

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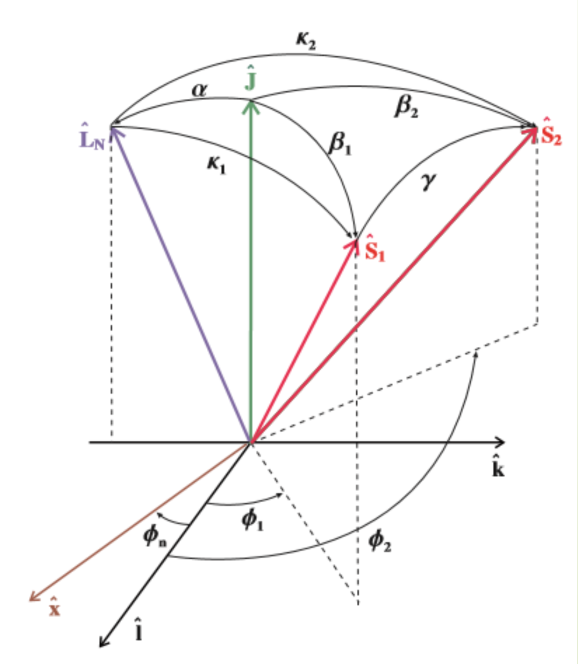
Binary black holes (BBH)

- phases of gravitational radiation from BBH:
  - Inspiral → analytically described
  - Merger → numerical methods required
  - Ringdown → analytically described

Binary black holes (BBH)

- Two cases:
  - spin-aligned: angle measured between the orbital angular momentum L_N and the spins S_i, $\kappa_i = 0$.
  - precessing: $\kappa_i \neq 0$ or $\kappa_i \neq \pi$

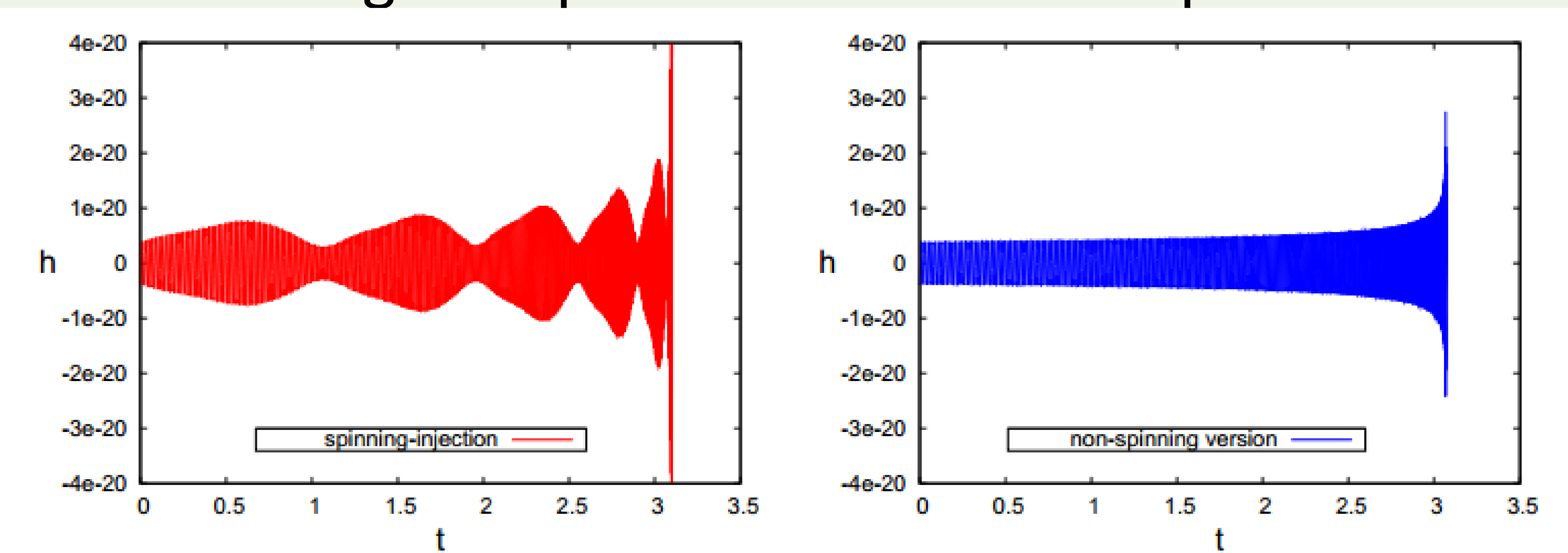
- Precessing waveforms have more parameters, and more difficult to recover



L. Á. Gergely, Phys. Rev. D 81, 084025 (2010).

Gravitational waves

- Non aligned Spin   no spin



2010 J. Phys.: Conf. Ser. 228 012003 L. Veréb et al.

Motivation

- Motivation:
  - Serous mismatch among various precessing waveforms → needs to be sorted out before any precessing search by the LIGO Scientific Collaboration

Compared waveforms

- Spin-dominated waveform (SDW):
  spinning, small mass ratio (<<1) inspiral waveform for black hole binaries
  larger spin dominates over the orbital angular momentum
  second spin negligible → 1 spin waveform, uses evolution equations simplified for the approximation

M. Tápai, Z. Keresztes, L. Á. Gergely, Phys. Rev. D 86, 104045 (2012).

Compared waveforms

- SpinTaylorT4 (ST4):
  spinning inspiral waveform for all mass ratios, uses evolution equations for the vectors $\mathbf{L}_N$, $\mathbf{S}_i$ and orbital frequency ω

A. Bounanno, Y. Chen, M. Vallisneri Phys.Rev.D70:104003,2004; Erratum-ibid.D74:029902,2006

- SEOBNRv3:
  spinning inspiral-merger-ringdown waveform, uses the effective one body approach.

A. Taracchini et al. Phys. Rev. D 89, 061502 (2014)

Investigations

- SDW and ST4 comparison by Viktória Pintér
- V. Pintér „Comparing spinning gravitational waveforms” MSC thesis

SDW vs ST4

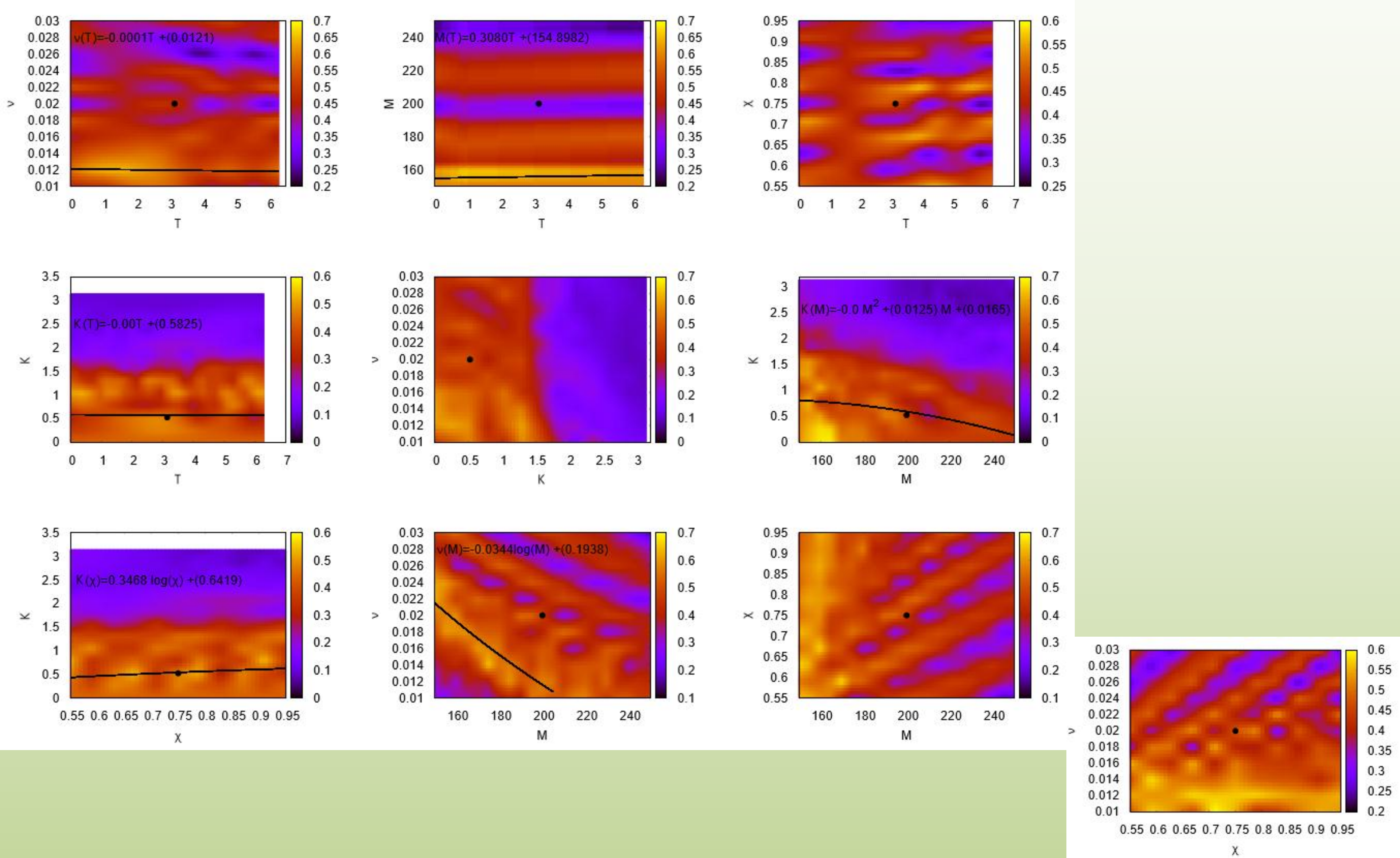
- Method of comparison:
  - Compare the waveforms using matched filtering
  - Fix one of the waveforms parameters, choose the parameter space around the fixed value (stable), and search which parameter combination produces the highest match value (between 0 and 1) → produce a heat map and fit trend-line
- Variables: ν mass ratio, M total mass
  - χ dimensionless spin parameter of the dominant spin
  - κ spin polar angle, T spin azimuthal angle

SDW vs ST4

	ν_{min}	ν_{max}	ν_{stable}	M_{min}	M_{max}	M_{stable}	χ_{min}	χ_{max}	χ_{stable}	κ_{min}	κ_{max}	κ_{stable}	T_{min}	T_{max}	T_{stable}
1	0.01	0.03	0.02	150	250	200	0.55	0.95	0.75	0	π	$\pi/6$	0	$2*\pi$	π
2	0.01	0.03	0.02	150	250	200	0.55	0.95	0.75	0	π	$\pi/6$	0	$2*\pi$	$\pi/2$
3	0.01	0.03	0.02	150	250	200	0.55	0.95	0.75	0	π	$\pi/6$	0	$2*\pi$	0
4	0.01	0.03	0.02	150	250	200	0.55	0.95	0.75	0	π	$\pi/6$	0	$2*\pi$	$3*\pi/2$
5	0.01	0.03	0.02	150	250	200	0.55	0.95	0.75	0	π	$\pi/4$	0	$2*\pi$	π
6	0.01	0.03	0.02	150	250	200	0.55	0.95	0.75	0	π	$\pi/4$	0	$2*\pi$	$\pi/2$
7	0.01	0.03	0.02	150	250	200	0.55	0.95	0.75	0	π	$\pi/4$	0	$2*\pi$	0
8	0.01	0.03	0.02	150	250	200	0.55	0.95	0.75	0	π	$\pi/4$	0	$2*\pi$	$3*\pi/2$

	χ	ν	M	T	κ	best match value
1	0.59	0.02	155	5.69413668463	0.785398163397	0.756224870914
2	0.91	0.024	150	6.2838530718	0	0.842712395051
3	0.59	0.02	150	6.08683576633	0.523598775598	0.777652663132
4	0.91	0.024	150	6.28318530718	0	0.772804436968
5	0.63	0.022	160	5.69413668463	0.523598775598	0.808710449536
6	0.91	0.026	150	6.28318530718	0	0.853677556535
7	0.63	0.026	150	5.10508806208	0.785398163397	0.845586741642
8	0.59	0.02	170	4.71238898038	0.785398163397	0.849652323853

SDW vs ST4



v(T)=-0.0001T +(0.0121)
M(T)=0.3080T +(154.8982)
K(T)=-0.00T +(0.5825)
K(M)=-0.0 M^2 +(0.0125) M +(0.0165)
K(χ)=0.3468 log(χ) +(0.6419)
v(M)=-0.0344log(M) +(0.1938)
T
M
K
v
χ

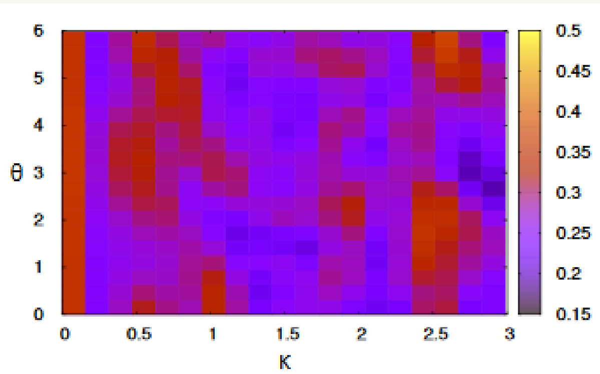
Investigations

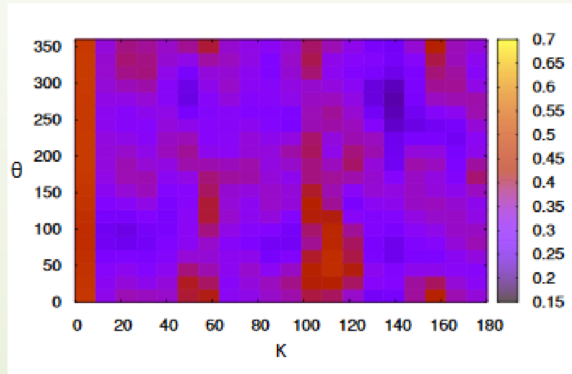
- SDW and SEOBNRv3 comparison by Tamás Tarjányi
- T. Tarjányi „Comparison of gravitational waveforms and dynamics obtained in the spin-dominated and effective-one-body approaches of the black hole binary systems" MSC thesis

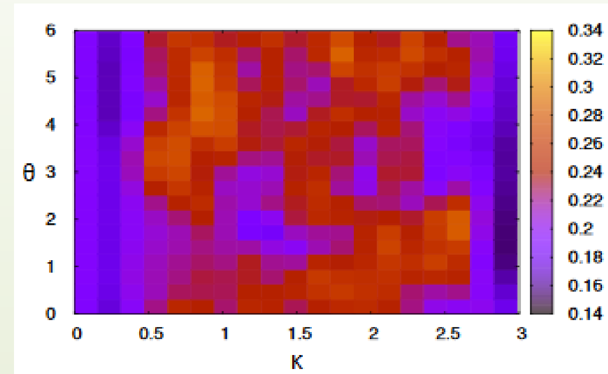
SDW vs SEOBNRv3

- Matches were calculated between SEOBNRv3 and SDW for different spin orientations for total mass values of 50, 100 and 150 solar mass [5]:
- Here κ is the polar angle, and θ is the azimuthal angle of the dominant spin
- The match values are low for all of the spin orientations except the spin-aligned case

SDW vs SEOBNRv3





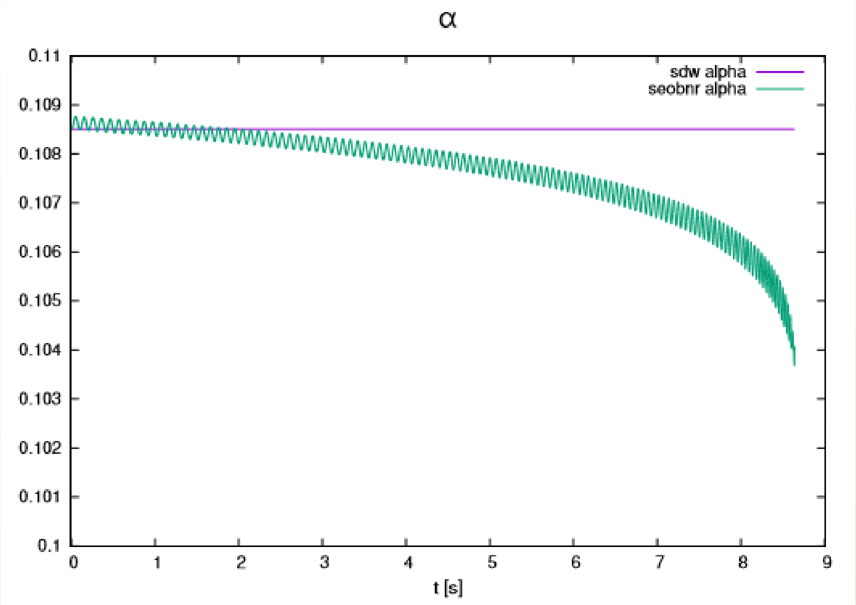


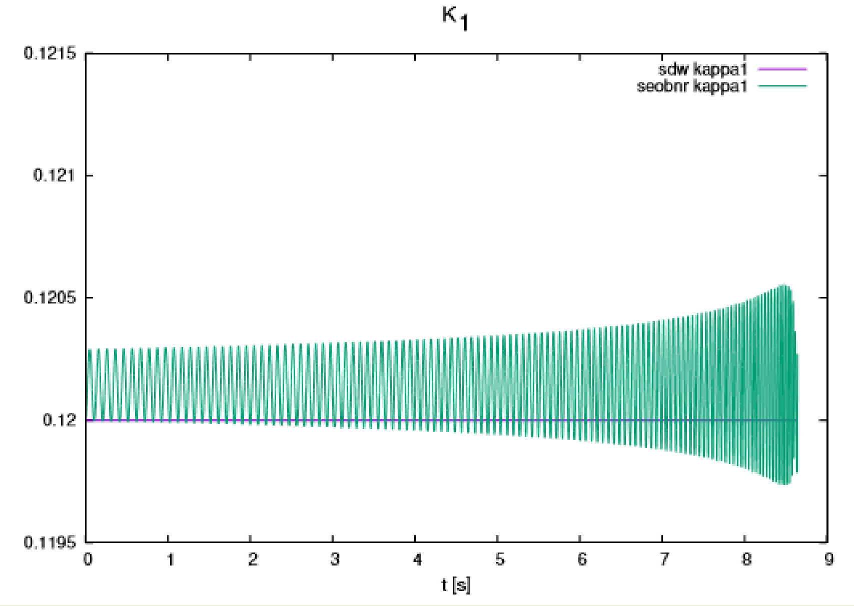
- Here κ is the polar angle, and θ is the azimuthal angle of the dominant spin
- The match values are low for all of the spin orientations except the spin-aligned case

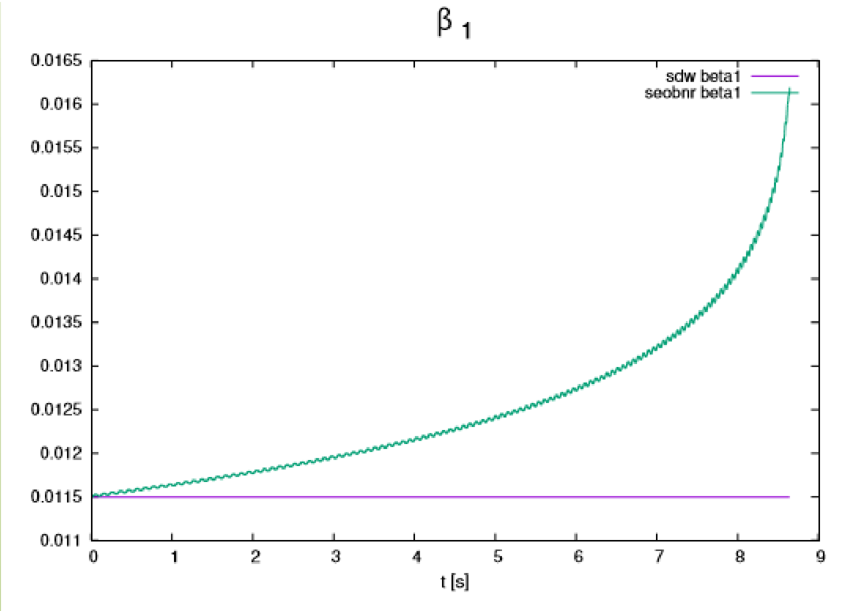
SDW vs SEOBNRv3

- Next step: investigate the difference among the waveform dynamics [5]:
  - Plot the evolution of the same variables for the two waveforms from the same initial parameters
  - Used variables $\kappa = \alpha + \beta$, ϕ_n and ψ where
  - α the angle between the total angular momentum and the orbital angular momentum
  - β the angle between the total angular momentum and the dominant spin
  - ϕ_n the longitude of the ascending node
  - ψ the argument of the periastron

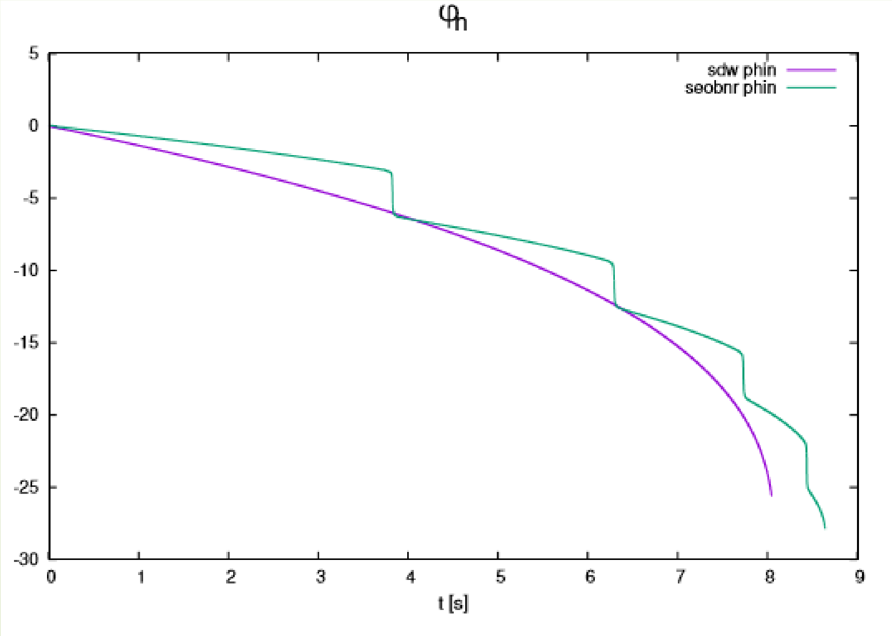
SDW vs SEOBNRv3

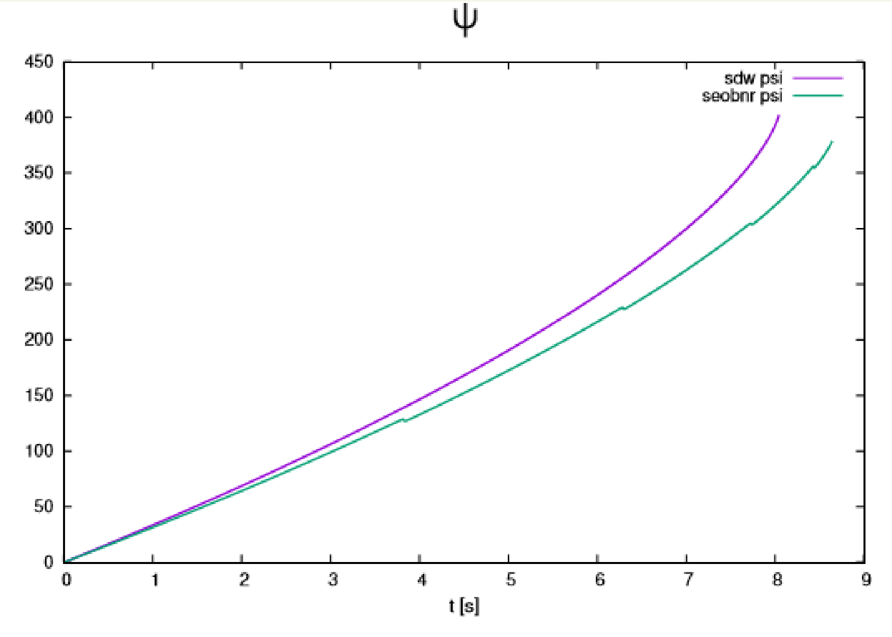






SDW vs SEOBNRv3





SDW vs SEOBNRv3

- The SDW evolution equations are averaged over an orbital period, while the figures clearly show that the SEOBNRv3 dynamics is not
- The secular values of spin and orbital angular momentum angles (α,β and κ) differ within only with 10^{-3} at the end of the inspiral, this is negligible
- The largest difference is in the ϕ_n parameter, while by the end of the inspiral, the difference between the ψ parameter is noticeable also

Conclusion

- The equations of the waveform dynamics used to evolve the binary parameters are taken to different accuracy, thus at the end of the inspiral the waveforms differ too, hence the poor match values. The sudden changes in ϕ_n could be related to the coding of the waveform.

- Further investigations to determine the exact cause is planned

Thank you for your attention!