Nearly extremal binary black hole simulations

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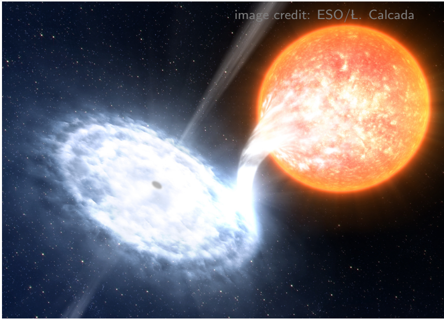
Black hole spin



Spin defined:

- $\chi = S/M^2$
- $0 \leq |\chi| \leq 1$

Where does spin come from?

- Collapsed progenitor stars
- Accretion disks

Do black holes spin fast?

- $\chi \approx 0.998$ (thin disk model, without MHD) Thorne, ApJ 191:507 (1974)
- $\chi \approx 0.95$ (thick disk model, with MHD) Gammie, et al., ApJ 602:312 (2004)
- GRS 1915+105: $\chi > 0.98$ McClintock+ (2006)
- Cygnus X-1: $\chi = [\ > 0.983\ ,\ > 0.95\ ,\ \sim 0\ ]$

  Gou+ (2013), Fabian+ (2012), Miller+ (2009)

Numerical simulations of high spin BHs allow us to study...

- The effect of high BH spin on BH/NS binaries.
  Lovelace et al., CQG 30:135004 (2013)
- Remnant properties as a function of initial parameters.
  Hemberger et al., PRD 88:064014 (2013)
- Calibration of analytical waveform models.
  Taracchini et al., PRD 89:061502 (2014)
- Do horizons violate spin limit?
  Lovelace et al., CQG 32:065007 (2015)
- How high a spin can LIGO distinguish?
  Hemberger et al., in prep

Why are High Spins Difficult?

- Initial Data
  - Standard initial data cannot produce $\chi > 0.93$
  - Superposed Kerr-Schild (SKS) initial data up to $\chi = 0.9997$

    Lovelace+ (2008)

- Evolution
  - Large metric gradients
  - Excision difficulties

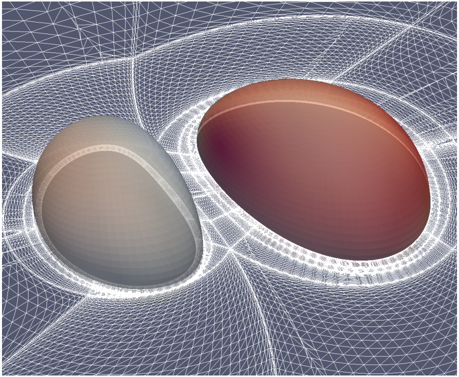
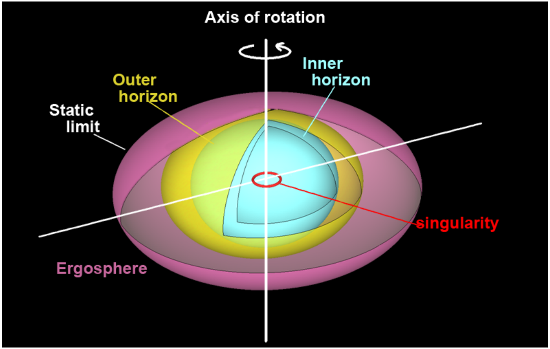


image courtesy Mark Scheel

$\chi = 0.2$ $\chi = 0.991$

Evolution Difficulties

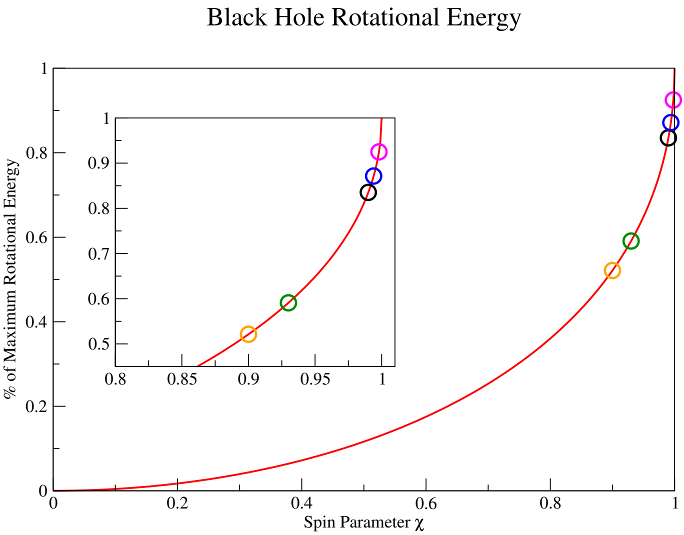


A heuristic explanation

- In the Kerr metric, as $\chi \to 1$:
  - the inner horizon r_- approaches the outer horizon r_+
  - $\Delta r = r_+ - r_- \sim \sqrt{1-\chi^2} \to 0$
  - higher spin $\to$ narrower 'safe zone'

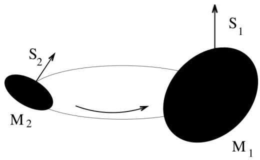
image credit nrumiano

What is 'high spin'? Isn't $\chi = 0.93$ high enough?

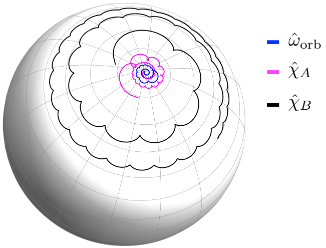


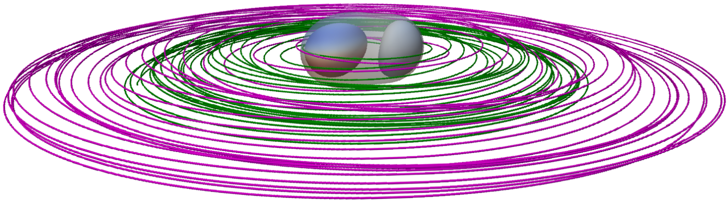
χ	:	$\%E_{rot}^{max}$
0.998	:	92.5
0.994	:	87.1
0.990	:	83.5
0.930	:	59.1
0.900	:	52.1

Nearly Extremal BBHs: Unequal Mass, Precessing



$\chi = 0.2$ $\quad$ $\chi = 0.991$

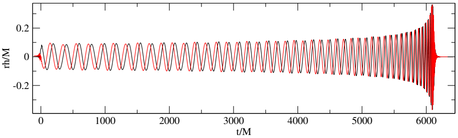


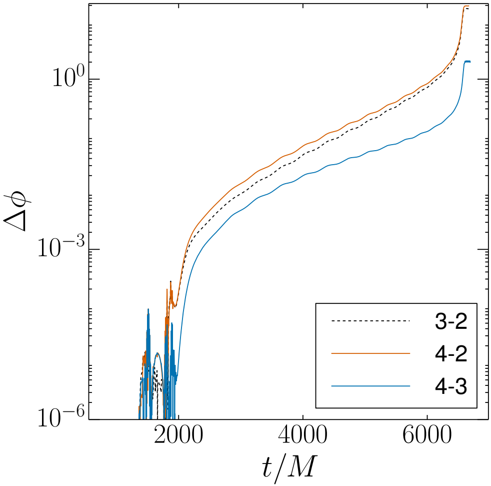


Nearly Extremal BBHs: Unequal Mass, Precessing

Convergence of the $(\ell = 2, m = 2)$ of the GW phase over 23.8 orbits.

χ_f	0.89692(5)
E_{rad}	7.8560(8) %

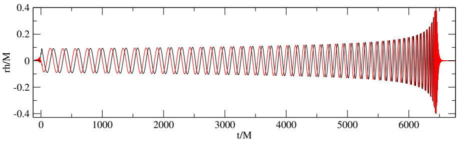


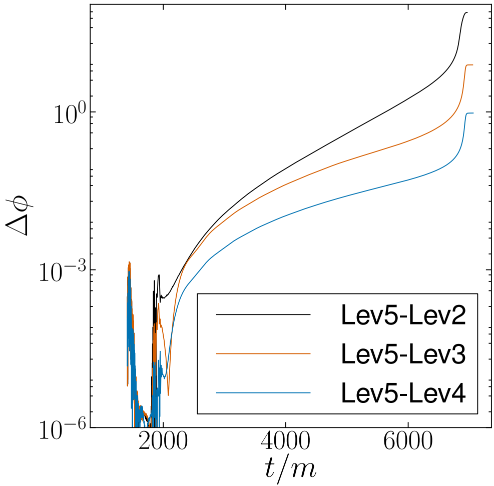


Nearly Extremal BBH: Equal Mass, aligned spin $\chi = 0.994$

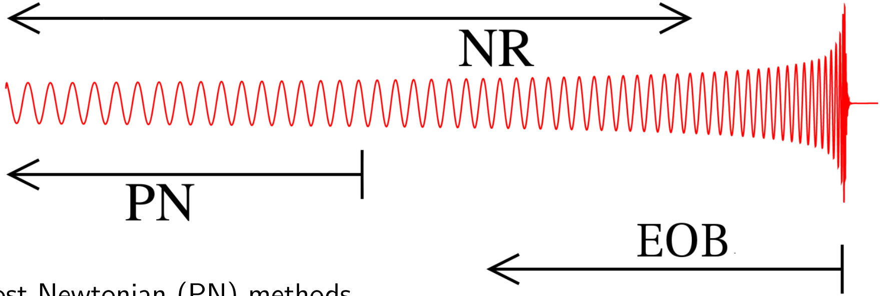
Convergence of the ($\ell = 2, m = 2$) of the GW phase over 25.4 orbits.

χ_f	0.949931(5)
E_{rad}	11.351(5) %





Analytic Approximants (PN & EOB)



Post-Newtonian (PN) methods

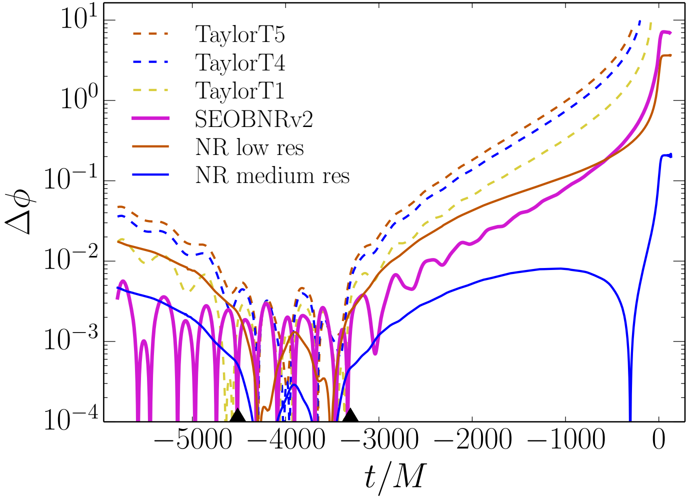
- perturbative expansion in $\frac{v}{c}$
- works during early inspiral
- breaks down before merger

Effective One-Body (EOB) approach

- maps two-body problem $\rightarrow$ an effective one-body problem
- i.e. the motion of a test particle in some effective external metric

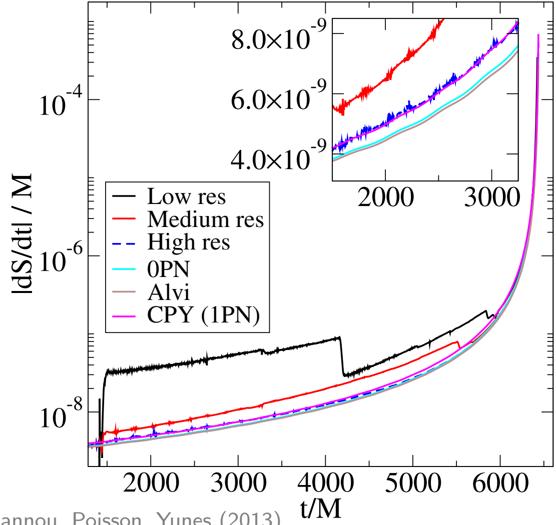
Comparison with Analytic Approximants (PN & EOB)

$\chi = 0.994$



Comparison with Analytic Approximants (PN)

$\chi = 0.994$ inspiral spin evolution



CPY: Chatziioannou, Poisson, Yunes (2013)

Alvi (2001)

Results

- Better overall agreement with EOB (specifically SEOBNRv2) than with TaylorT PN
- Offer opportunity for improving future approximants.
- BBH up to ~~0.994~~ 0.998 (just finished) now possible with SpEC! (preliminary results for $\chi = 0.998$: $E_{rad} \approx 11.72\%$ and $\chi_f \approx 0.9816$)

Further detail available @ arXiv:1412.1803