

# Remnant Mass, Spin, and Recoil From Spin Aligned Black-hole Binaries

James Healy

Carlos Lousto and Yosef Zlochower

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# Fitting Model

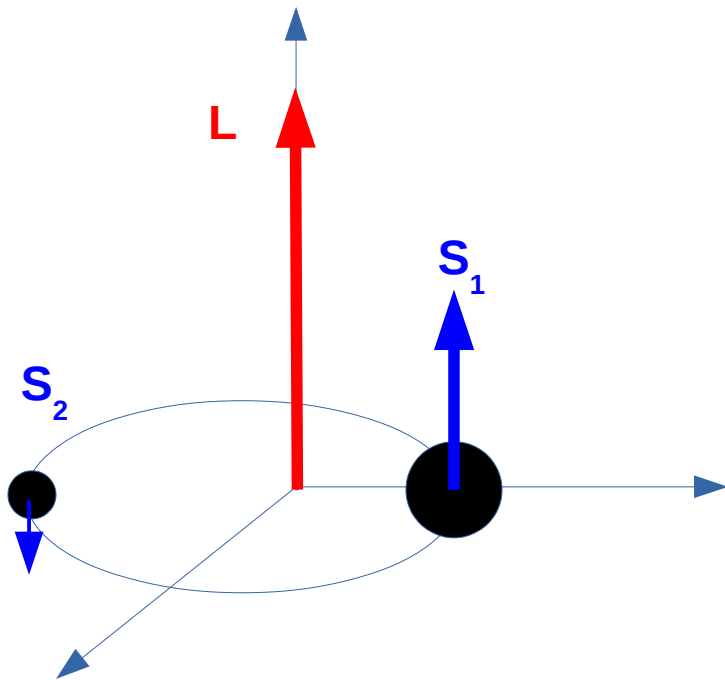
- PN motivated series expansion in  $\delta m$ ,  $S$ , and  $\Delta$

$$\begin{aligned} m &= m_1 + m_2 & \vec{S} &= \vec{S}_1 + \vec{S}_2 \\ \delta m &= \frac{m_1 - m_2}{m} & \vec{\Delta} &= m(\vec{S}_2/m_2 - \vec{S}_1/m_1) \end{aligned}$$

- Fitting order determined by combinations of  $\delta m$ ,  $S$ , and  $\Delta$
- Which combinations occur in fit determined by symmetry
- Explicit enforcement of particle limit

# NR Simulation Setup

- 36 spin-aligned configurations
- Additional runs from SXS catalog for mass and spin fit (<http://www.black-holes.org/waveforms>)



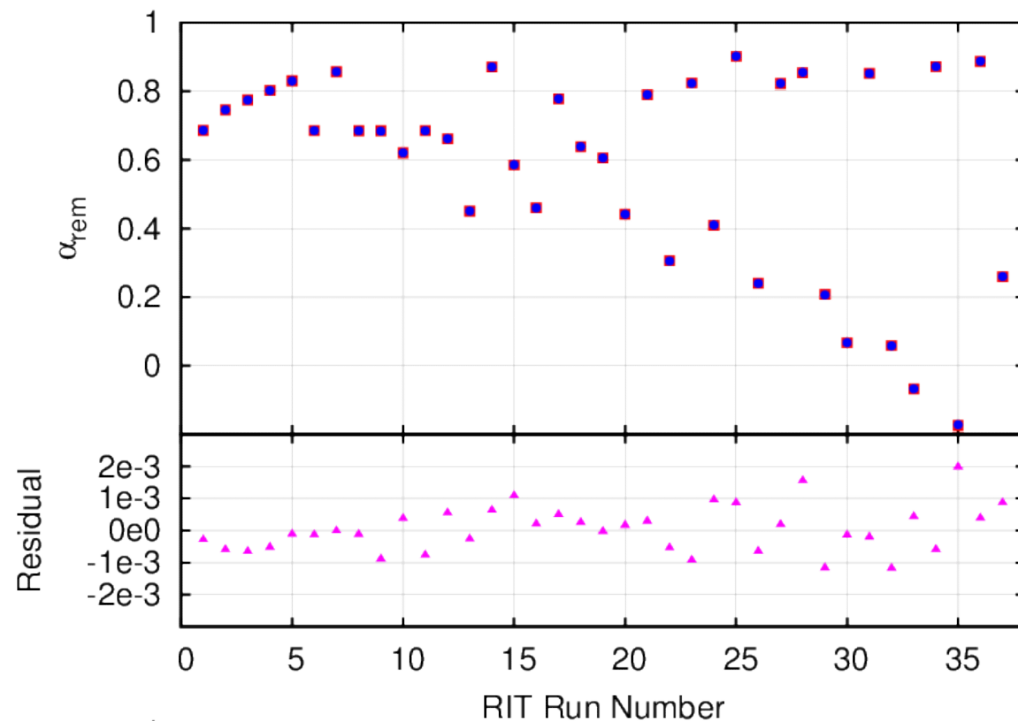
Category	Number of runs
$\delta m = S = \Delta = 0$	1
$\delta m = 0$	5
$S = 0$	4
$\Delta = 0$	4
$\delta m = S = 0$	3
$\delta m, S, \Delta \neq 0$	19

# Mass and Spin Fits

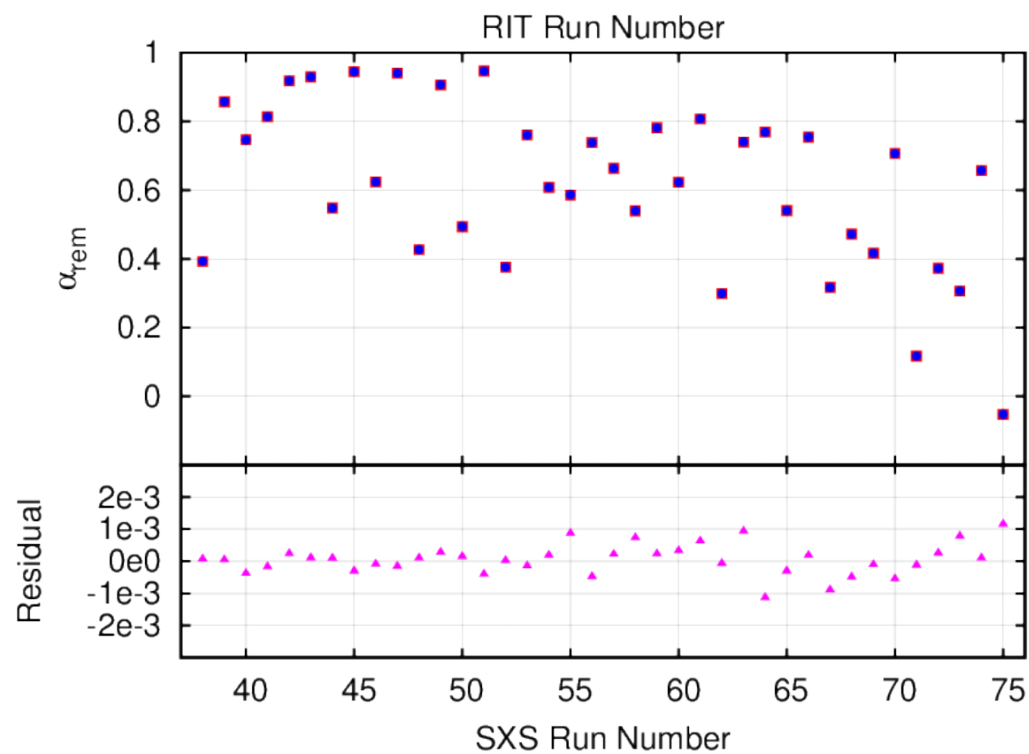
- 75 runs for 4<sup>th</sup> order fit (37 RIT + 38 SXS)
- Highly spinning, equal-mass systems included in SXS catalog runs
- Particle limit is enforced explicitly in fitting formula
- Robustness of fits between 3<sup>rd</sup> and 4<sup>th</sup> order
- Mass and spin calculated locally on apparent horizon

# Spin Fits

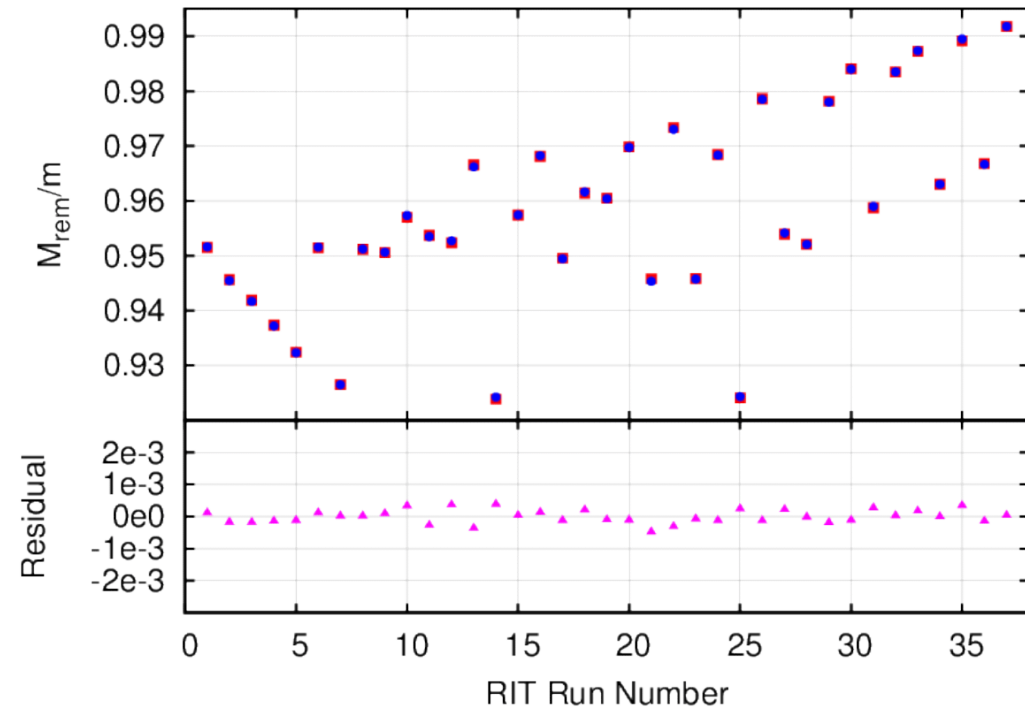
RIT Spin residual RMS:  
 **$7.16\text{e-}4$**



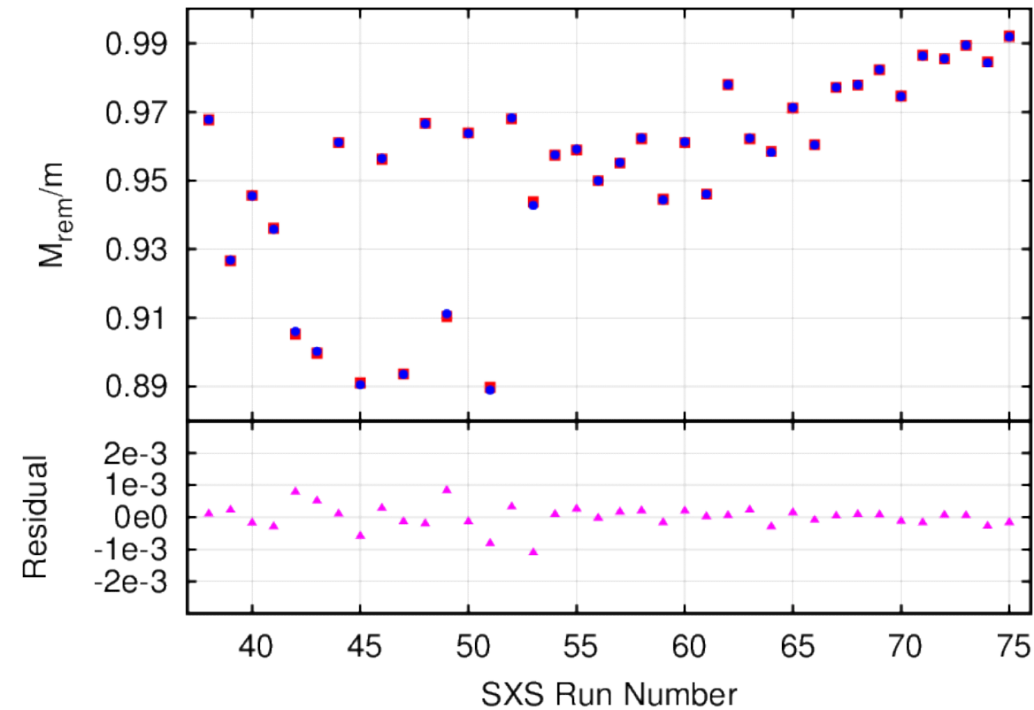
SXS Spin residual RMS:  
 **$4.73\text{e-}4$**



# Mass Fits



RIT Mass residual RMS:  
 **$2.07e-4$**



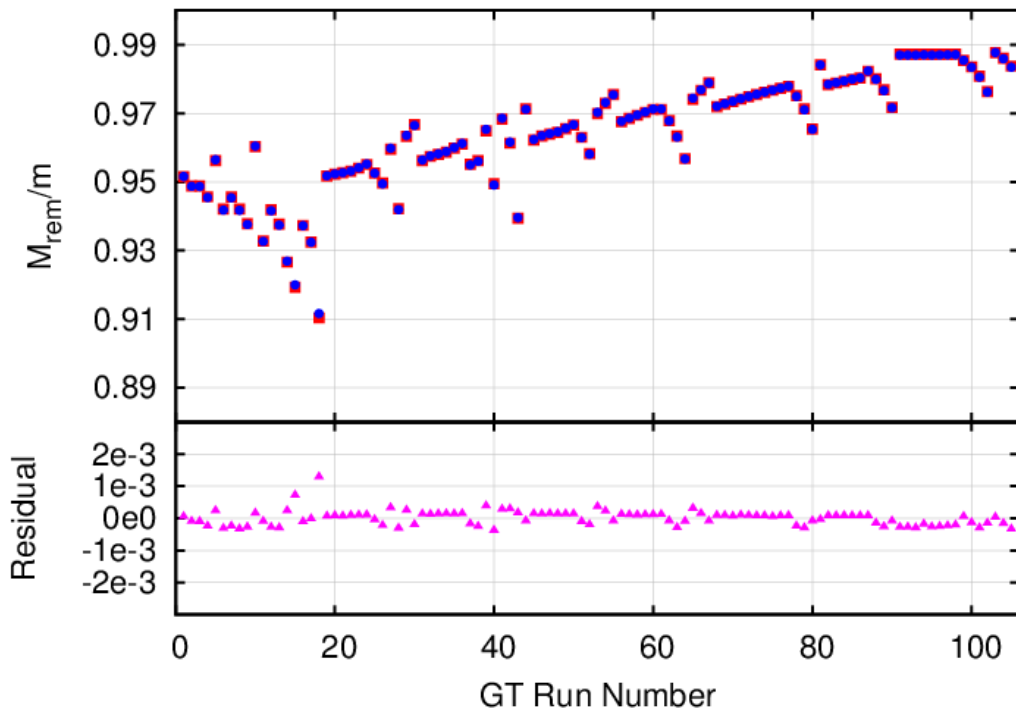
SXS Mass residual RMS:  
 **$3.56e-4$**

# Independent Verification

- 105 Georgia Tech aligned-spin simulations from GT Catalog (Jani et al., in preparation)
- Mass ratios between 1:1 and 1:7, spins as high as 0.8

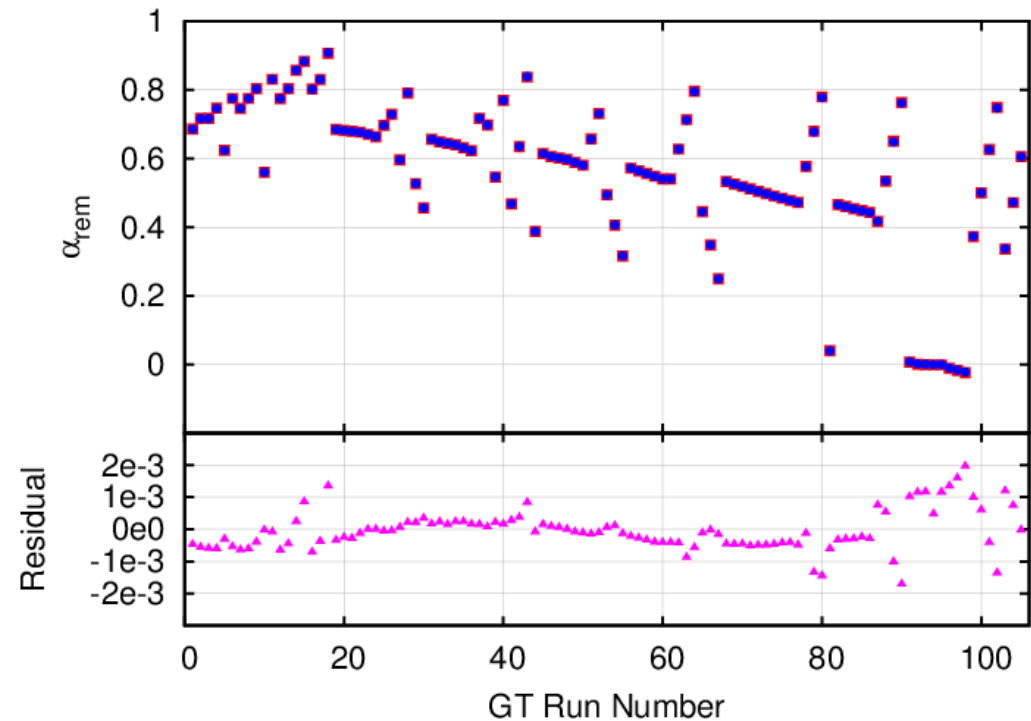
GT Mass residual RMS:

$2.35\text{e-}4$



GT Spin residual RMS:

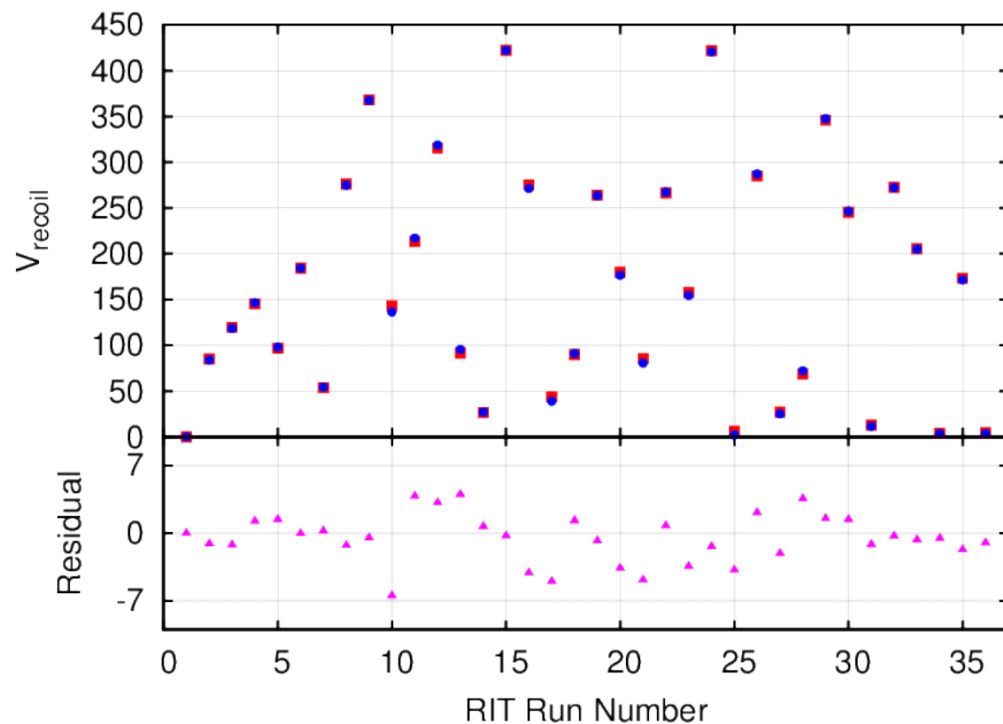
$6.24\text{e-}4$



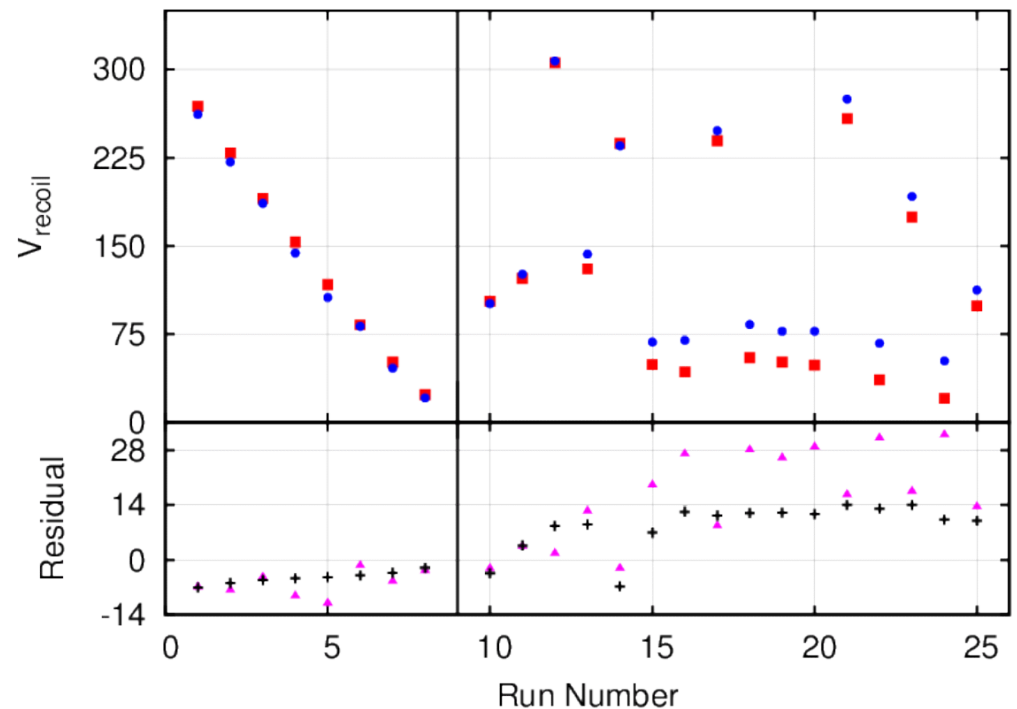
# Recoil Velocity Fit

- 36 simulations for 4<sup>th</sup> order fit
- Calculation of kicks from waveforms
- 8 AEI runs (Pollney et al., 2007) and 15 SXS catalog runs

RIT kick residual RMS:  
**2.5 km/s**



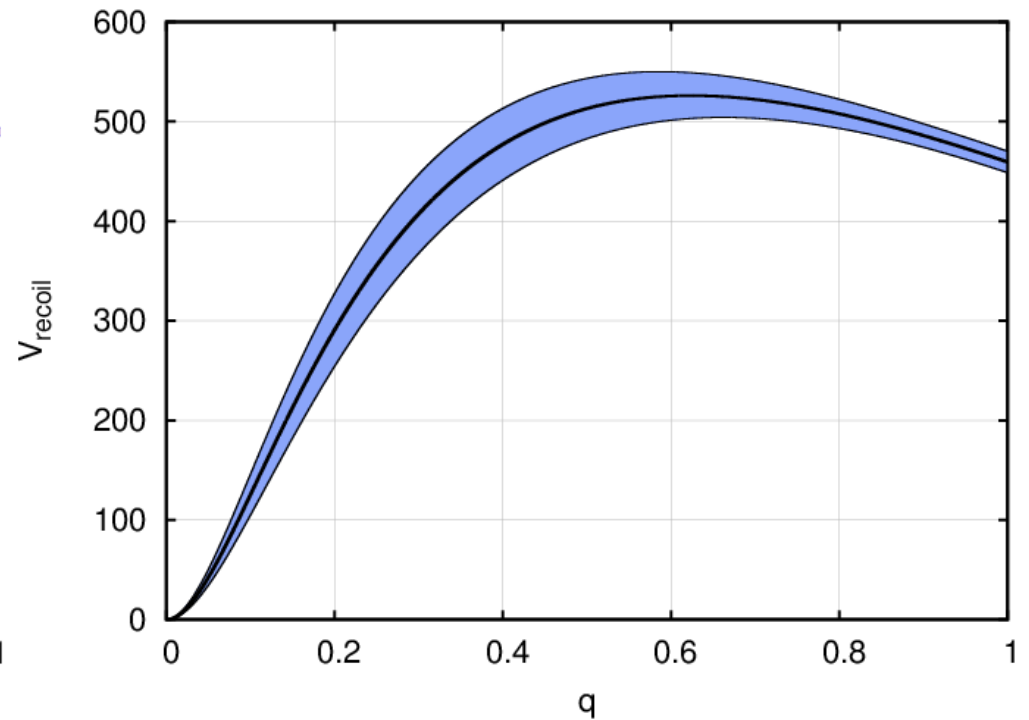
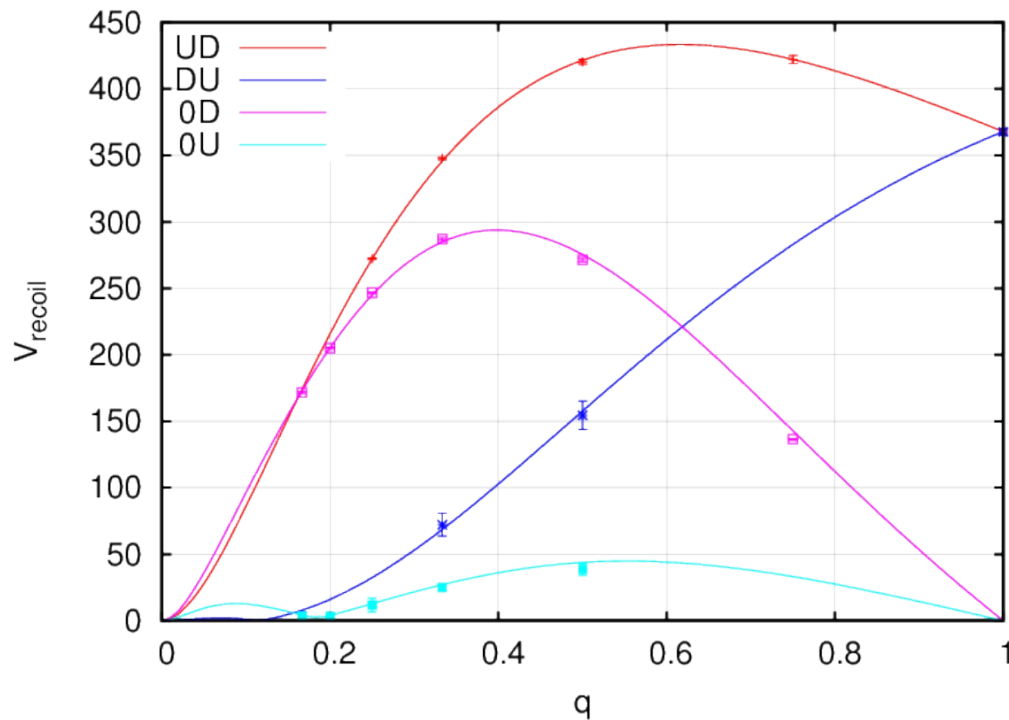
AEI RMS: **6.8 km/s**  
SXS RMS: **20 km/s**





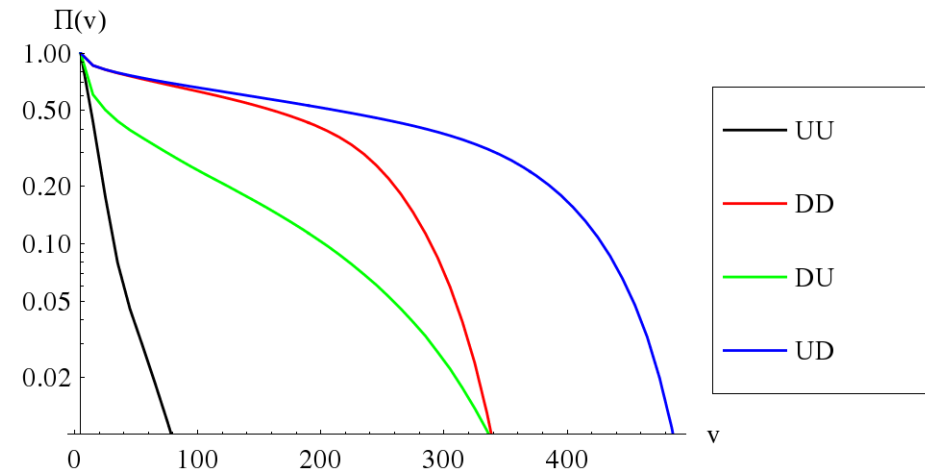
# Maximum Kick

- $V = 526 \pm 23 \text{ km/s}$  at  $q = 0.623 \pm 0.038$  in maximally spinning UD configuration
- 17% higher than previous estimates

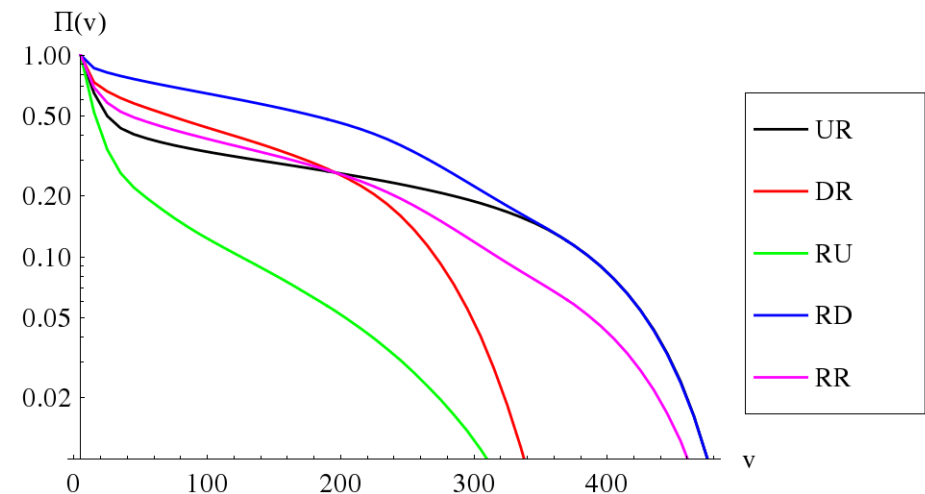


# Probability

UD: 45% chance  $V > 250$  km/s  
17% chance  $V > 400$  km/s



UR: 23% chance  $V > 250$  km/s  
8.4% chance  $V > 400$  km/s



RR: 19% chance  $V > 250$  km/s  
4.2% chance  $V > 400$  km/s

# Conclusion

- Robust new fitting formulas for remnant mass, spin, and recoil velocity
- Maximum kick for maximally spinning UD configurations of  $V = 526 \pm 23$  km/s at  $q = 0.623 \pm 0.038$
- Roughly 20% probability of recoil velocities higher than 250 km/s for RR case and as high as 45% for UD case.