Suppression of superkicks in BBH inspiral

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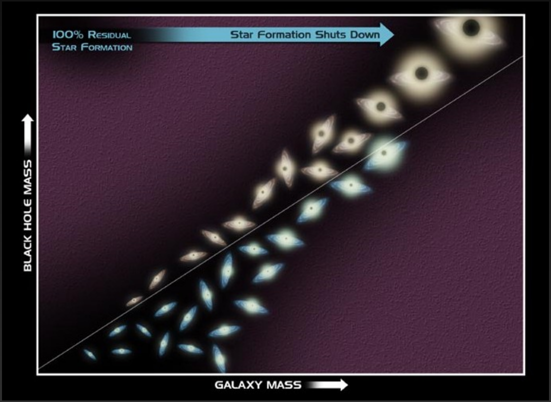
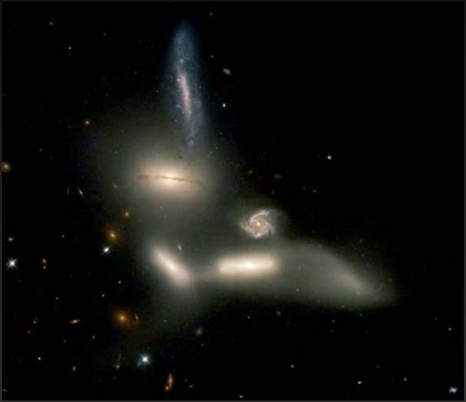
Introduction

- Galaxies ubiquitously harbor BHs
- BH properties correlated with bulge properties
  e. g. J.Magorrian *et al.*, AJ 115, 2285 (1998)



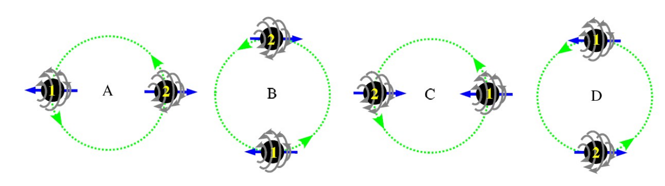
Introduction

- Most widely accepted scenario for galaxy formation: hierarchical growth; "bottom-up"
- Galaxies undergo frequent mergers, especially elliptic ones

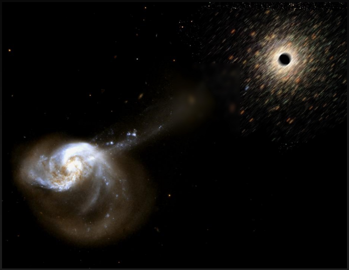


Superkicks

- Numerical relativity breakthroughs in 2005
  Pretorius, PRL 95, 121101 (2005)
  Campanelli, Lousto, Marronetti & Zlochower, PRL 96, 111101 (2006)
  Baker, Centrella, Choi, Koppitz & van Meter, PRL 96, 111102 (2006)
- NR now able to accurately calculate kicks
- Superkicks: up to several 1000 km/s
  González, Hannam, Sperhake, Brügmann & Husa, PRL 98, 231101 (2007)
  Campanelli, Lousto, Zlochower & Merritt, ApJ 659, L5 (2007)
- $>$ escape velocities from giant galaxies!



Ejection/displacement of SMBHs possible



- Doppler shifts of BLR vs. NLR: $2,650\ \mathrm{km/s}$
  Komossa *et al.*, ApJ 678, L81 (2008)
- Isophotal analysis of M87: central BH displaced
  Betcheldor *et al.*, ApJ 717, L6 (2010)
- Still: Virtually every E galaxy observed has a BH!

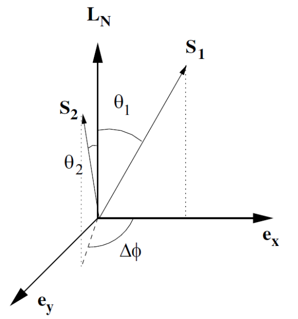
Possible explanations

- Superkicks are a relatively special configuration
  $q = \frac{1}{10} \ldots 1$ EOB study $\Rightarrow \sim 10$ % of kicks $\gtrsim 500 \ldots 1000\ \mathrm{km/s}$
  Schnittman & Buonanno, ApJ 662, L63 (2007)
- Torques from accreting gas can align $\vec{S}$ with $\vec{L}$: 10...30°
  Bogdanović, Reynolds & Miller, ApJ 661, L147
  Dotti *et al.*, MNRAS 402, 682 (2010)
- Efficiency depends on accretion flow and sufficient gas
- New mechanism to suppress superkicks:
  GW driven inspiral aligns $\vec{S}_1$ and $\vec{S}_2$ provided more massive BH is partially aligned.
  Kesden, Sperhake & Berti, PRD 81, 084054 (2010)
  Kesden, Sperhake & Berti, ApJ 715, 1006 (2010)

Framework

- PN equations of motion for precessing, qc BBHs
  Kidder, PRD 52, 821 (1995)
- Quadrupole-monopole interaction
  Poisson, PRD 57, 5287 (1997)
- Spin-spin interaction
  Mikoczi, Vasuth & Gergely, PRD 71, 124043 (2005)
- Adaptive stepsize integrator STEPPERDOPR5
- PN evolution from $R = 1000\,M$ on; sub-parsec scale
- Guided by resonances which act on timescales $\gg t_p$
  Schnittman, PRD 70, 124020 (2004)

Spin-orbit resonances; Schnittman (2004)



- Configurations for which $\mathbf{L}_N$, $\mathbf{S}_1$, $\mathbf{S}_2$ precess at same frequency
- One parameter family of solutions; R
- θ_1, θ_2 , $\Delta\phi$ remain fixed on precession time scale t_p
- These solutions have either $\Delta\phi = 0^\circ$ or $\Delta\phi = 180^\circ$

Evolution in $\theta_1,\ \theta_2$ plane for $q = 9/11$

$\theta_1 := \angle(\vec{S}_1, \vec{L}_N)$

$\theta_2 := \angle(\vec{S}_2, \vec{L}_N)$

$\theta_1 = \theta_2$

$\vec{S} \cdot \vec{L}_N = \mathrm{const}$

$\vec{S}_0 \cdot \vec{L}_N = \mathrm{const}$

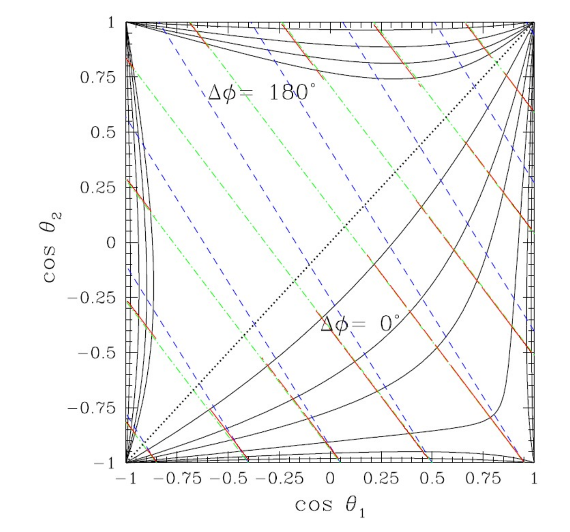
evolution

$\Rightarrow$ BHs approach

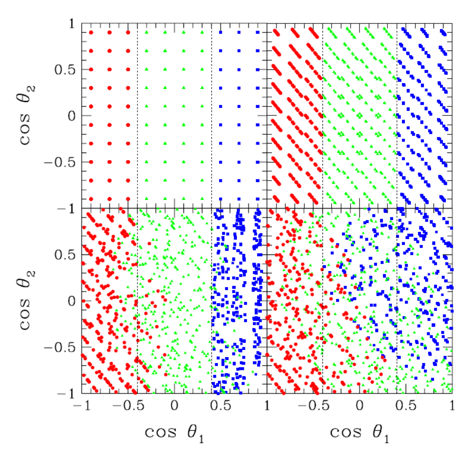
$\theta_1 = \theta_2$

$\Rightarrow$ $\vec{S}_1,\ \vec{S}_2$ align

if θ_1 small

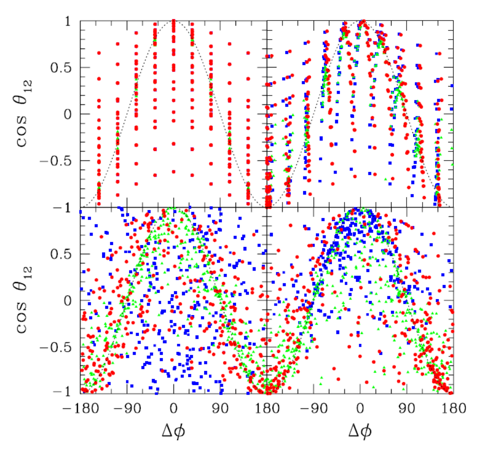


Distributions in $\theta_1, \ \theta_2$ plane at different R



- Isotropic $10 \times 10 \times 10$ grid of configurations
- At $R = 1000\ M + \epsilon,\ 1000\ M,\ 100\ M,\ 10\ M$

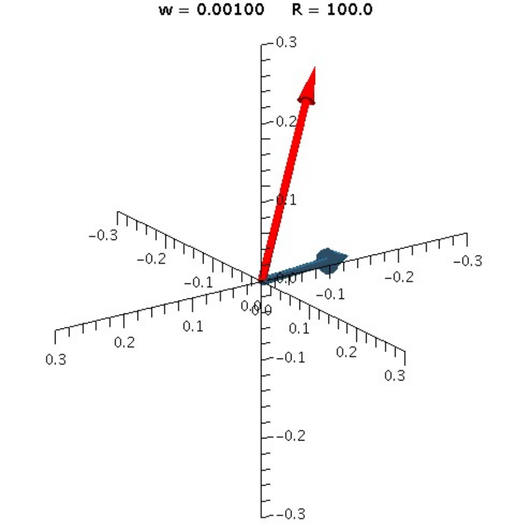
Distributions in θ_{12}, $\Delta\phi$ plane at different R



- Isotropic $10 \times 10 \times 10$ grid of configurations
- At $R = 1000\ M + \epsilon,\ 1000\ M,\ 100\ M,\ 10\ M$

Time evolution of $\vec{S}_1$, $\vec{S}_2$

$q = \frac{9}{11}$, $\theta_1 = 10^\circ$, $\theta_2 = 154^\circ$, $\Delta\phi = 264^\circ$



Calculation of kick

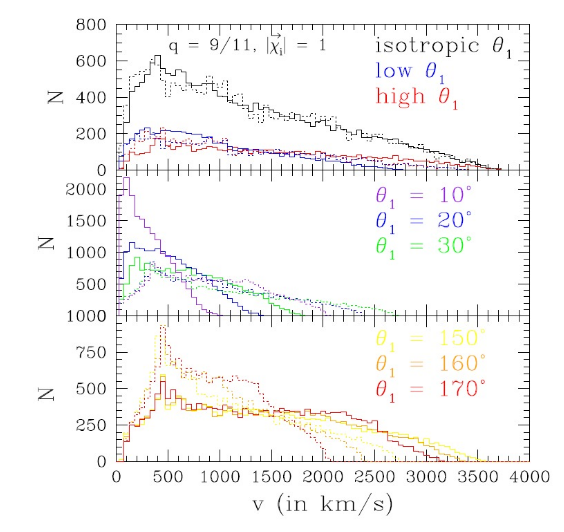
- Ensemble 1: $10 \times 10 \times 10$ in $\theta_1,\ \theta_2,\ \Delta\phi$
- Ensemble 2: $\theta_1 = 10^\circ,\ 20^\circ,\ 30^\circ$ with 30×30 in $\theta_2,\ \Delta\phi$
- Ensemble 3: $\theta_1 = 150^\circ,\ 160^\circ,\ 170^\circ$ with 30×30 in $\theta_2,\ \Delta\phi$
- Spin evolution gives us $\vec{S}_1,\ \vec{S}_2,\ \vec{L}$ at any time
- Use kick formula by RIT or Goddard group

  Campanelli, Lousto, Zlochower & Merritt, ApJ 659, L5 (2007)

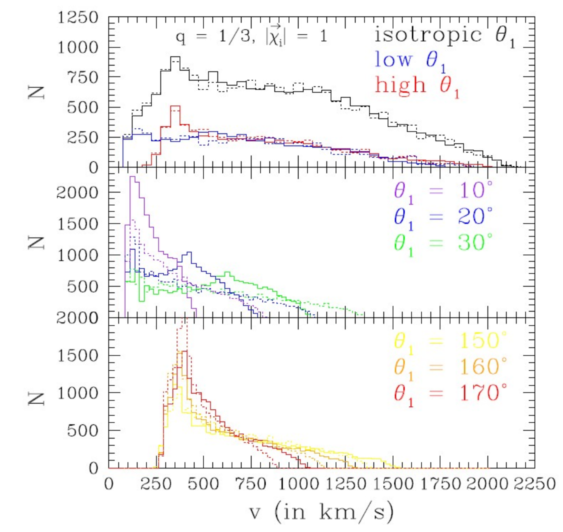
  Baker *et al.*, ApJ 682, L29 (2008)

  $\Rightarrow v_{\rm kick}(r)$
- Compare kick distribution with and without PN inspiral

Kick distributions with and without PN inspiral $q = \frac{9}{11}$



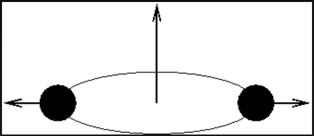
Kick distributions with and without PN inspiral $q = \frac{1}{3}$



Even larger kicks: superkick and hang-up

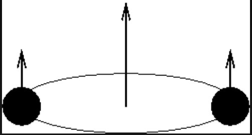
Lousto & Zlochower, arXiv:1108.2009 [gr-qc]

Superkicks

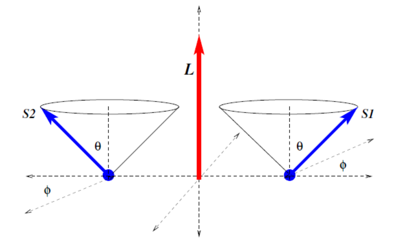


- Moderate GW generation
- Large kicks

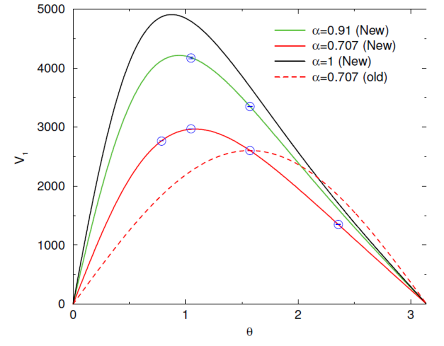
Hangup



- Strong GW generation
- No kicks

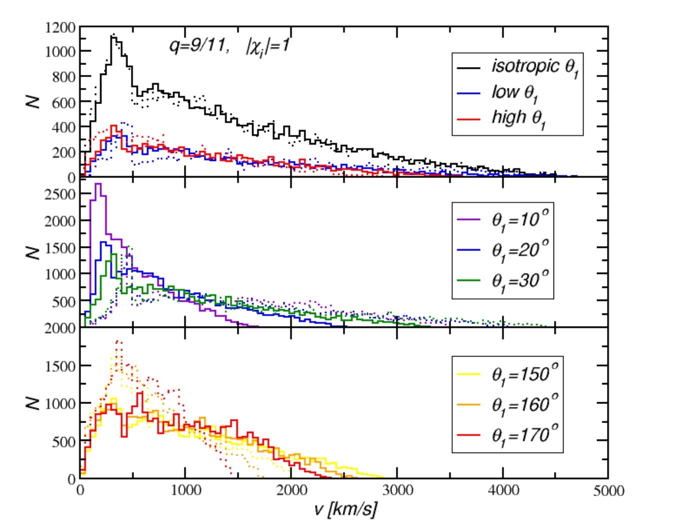


Superkicks and orbital hang-up

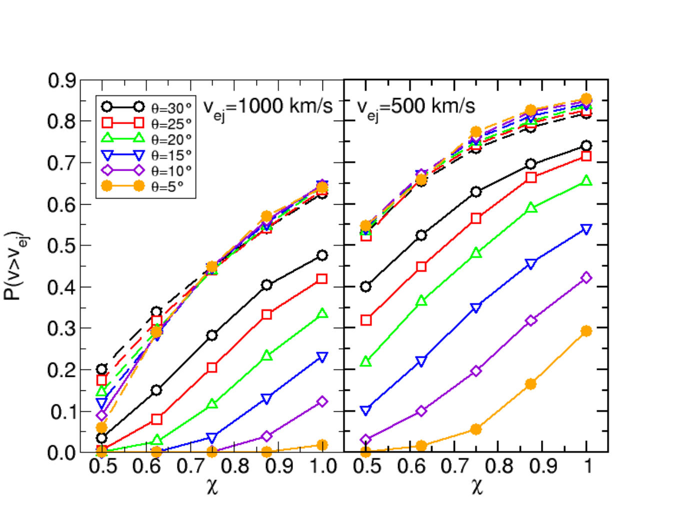


- Maximum kick about 25 % larger: $v_{\max} \approx 5\,000$ km/s
- Distribution asymmetric in θ
- Largest recoil for partial alignment

Kick distributions with and without PN inspiral $q = \frac{9}{11}$



Ejection probabilities for $v > v_{ej}$



Conclusions

- GW driven inspiral on subparsec scale aligns (anti aligns) $\vec{S}_1$, $\vec{S}_2$ if more massive BH initially partially aligned (anti aligned) with $\vec{L}_N$
- This is true for resonance and non-resonance binaries!
- Resonances attract aligned (anti aligned) configurations towards $\Delta\phi = 0^\circ$ (180°)
- Accretion torque will partially align $\vec{S}_1$ with $\vec{L}_N$
- $\Rightarrow$ spin alignment likely to dominate
- The GW driven alignment substantially suppresses superkicks
- Reconciles superkicks with observation of SMBHs in galaxies
- Superkick suppression still efficient for hang-up kicks