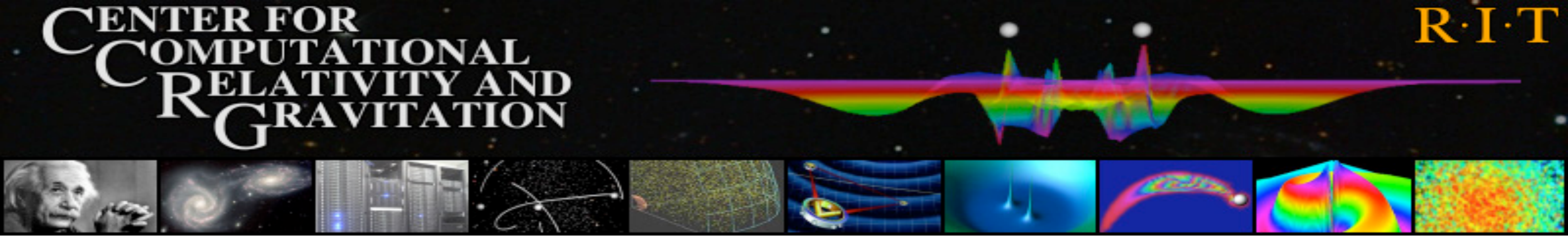

Astrophysical Gravitational Recoils of Binary Black Hole Mergers

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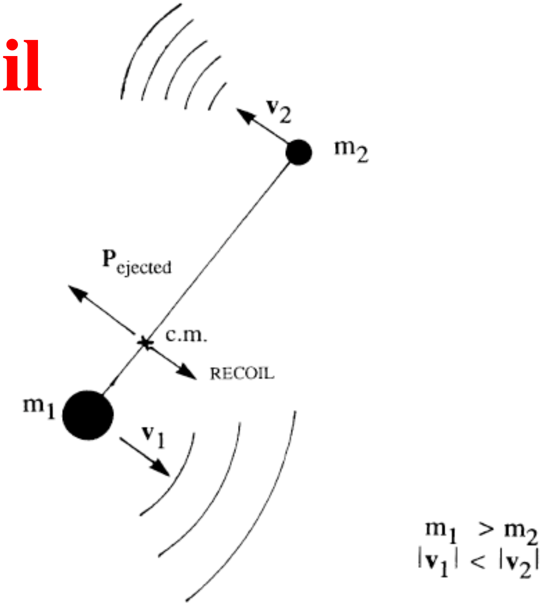
R·I·T

Gravitational Radiation Recoil



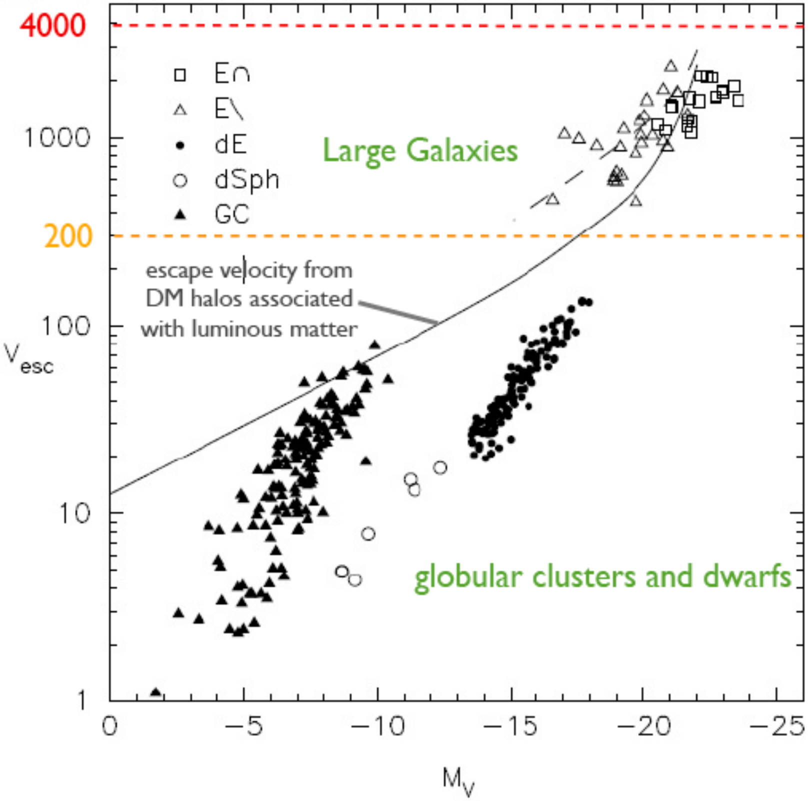
- In binary black-hole (BH) coalescences, asymmetrical gravitational radiation carries a net linear momentum, causing center-of-mass recoil. To conserve momentum the merged BH is given a kick in the opposite direction.

- The magnitude of the kick has an impact in astrophysics:
  - galactic population synthesis models
  - massive black hole formation scenarios

- If large enough (compared to escape velocity), the final BH remnant could be kicked out from the host structure …

- Escape velocities:
  - < 100 km/so for globular clusters
  - ~ 500-1000 km/s for spiral galaxy bulges
  - ~ 2000 km/s for giant elliptical galaxies

- There are a number of possible observational consequences: off-set galactic nuclei, displaced active galactic nuclei, population of galaxies without SMBHs, x-rays afterglows, feedback trails,



Kicks: non-spinning black-hole binaries

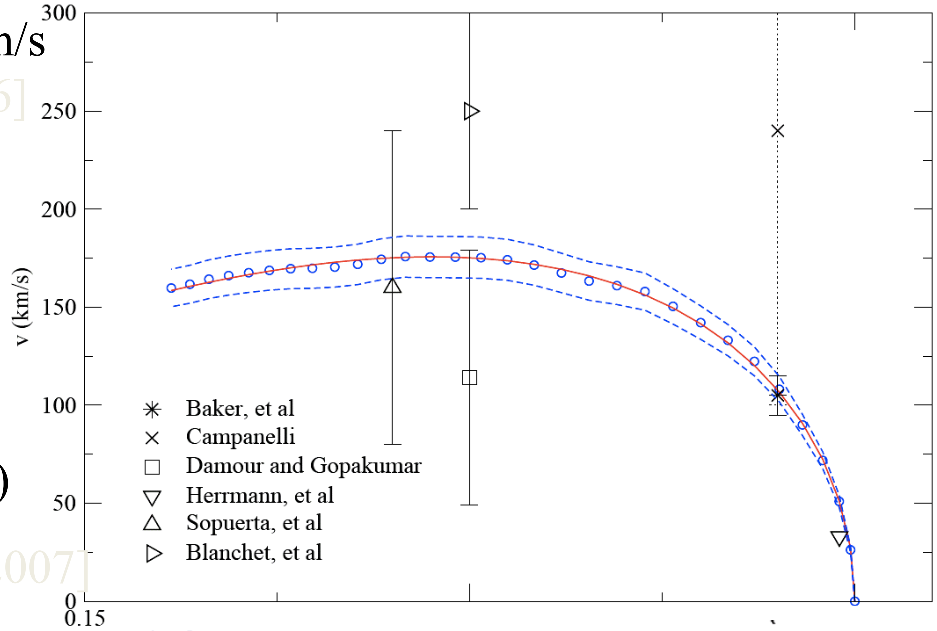
- Maximum non-spinning binary kick ~178 km/s for mass ratio $q \approx 0.36$ [Gonzalez et al, 2006]

- Good agreement with Fitchett's formula [Fitchett 1983, Fitchett & Detweiler 1984]:

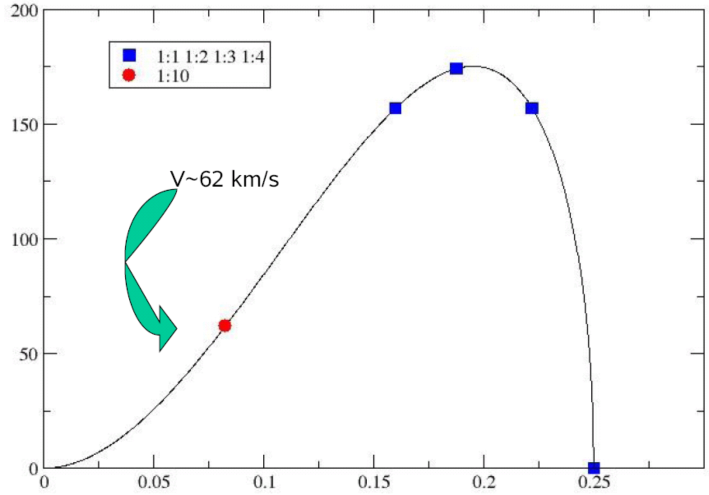
$$v_{\mathrm{F}} \simeq 1480\,\mathrm{km/sec}\,\frac{f(q)}{f_{\max}}\left(\frac{2G(m_1+m_2)/c^2}{R_{\mathrm{term}}}\right)^4$$

(Newtonian physics plus dissipation by GWs)

- Now, up to mass ratio 1:10 [Gonzalez et al, 2007]



Kick: $v = 1.2 \times 10^4 \eta^2 \sqrt{1-4\eta}(1-0.93\eta)$



Fitchett (MNRAS **203** 1049,1983)
Gonzalez et al. (PRL **98** 091101, 2007)

- NR calculation of radiated linear momentum [Campanelli & Lousto, 1999]:

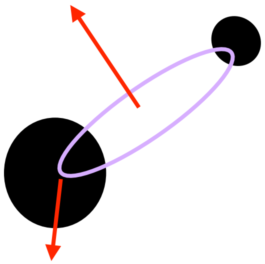
$$\frac{dP_i}{dt} = \lim_{r\to\infty}\left[\frac{r^2}{16\pi}\int_\Omega \ell_i \left|\int_{-\infty}^{t}\Psi_4 d\tilde{t}\right|^2 d\Omega\right]$$

$$\Psi_4 = \ddot{h}_+ - i\ddot{h}_\times$$

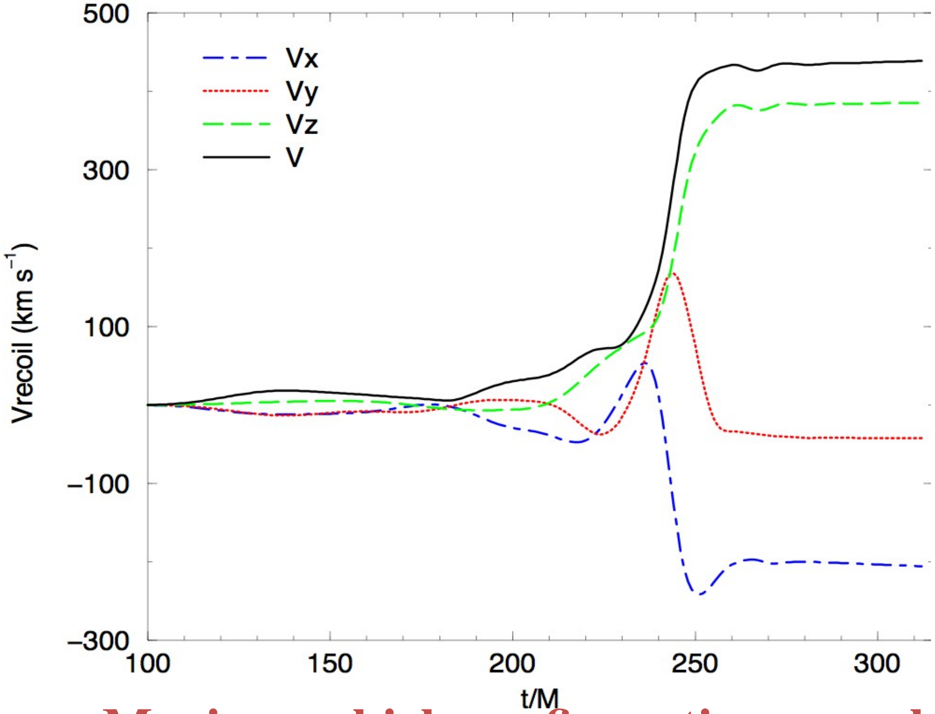
$$h(t) = \sum_{lm} A^{-2}_{lm} Y_{lm}(\theta,\phi) e^{im\omega t}$$

Large merger recoils from precessing quasi-circular binaries

Generic binary displaying significant precession of spin axis is observed to produce a large recoil kick at merger [Campanelli et al, APJ Lett 2007]



SP6: q = 0.5, a_1= 0.885, a_2 = 0



> *"... the spin component to the recoil velocity may produce the leading contribution. This is suggested by the fact that the z-component of the recoil, which is not present for non-spinning binaries, is the dominant component ..."*

Maximum kick configuration: equal-mass circular binaries with opposite in-plane spins produce large out-of-plane kicks

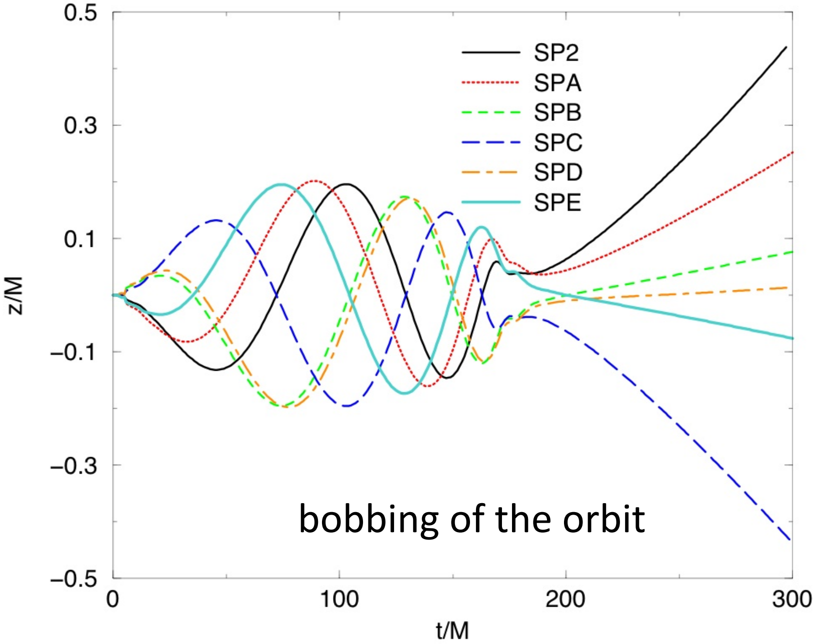
- Following:
  [Gonzalez et al, Phys. Rev. Lett, 2007] calculate kick of 2500 km/s
  [Campanelli et al, Phys. Rev. Lett, 2007] predicts kicks up to 4000 km/s
  [Dain, et al, Phys. Rev. D 2008] calculate 3300 km/s for nearly maximal spins

The Superkick Configurations

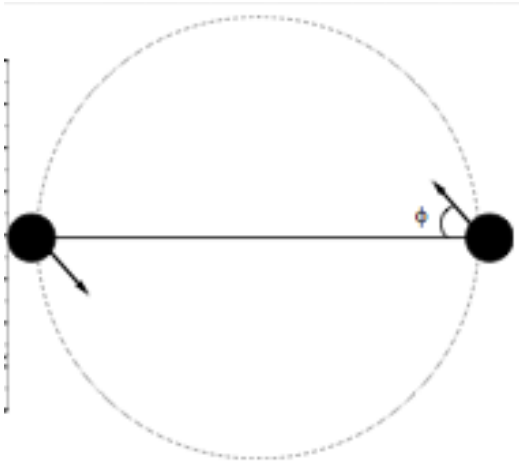
- Spin-orbit coupling effects can lead to very large kick velocities (superkicks) for equal-mass BBH, in-plane BH spins [Campanelli+07a,b,]

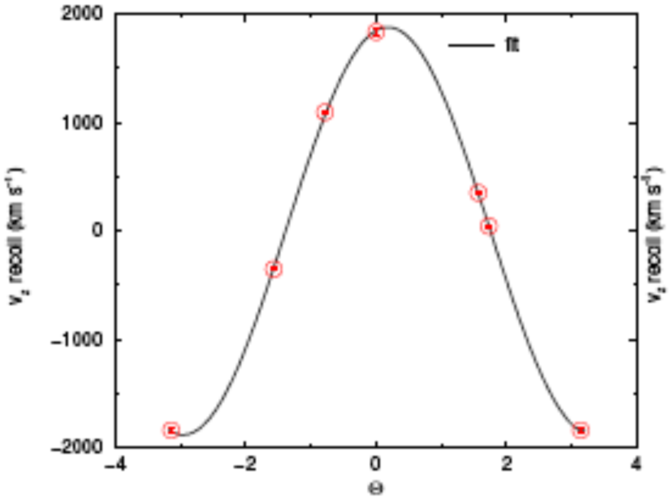
- Recoil velocity depends sinusoidally on the initial phase of the binary, and linearly (at leading order) on the spin magnitude :

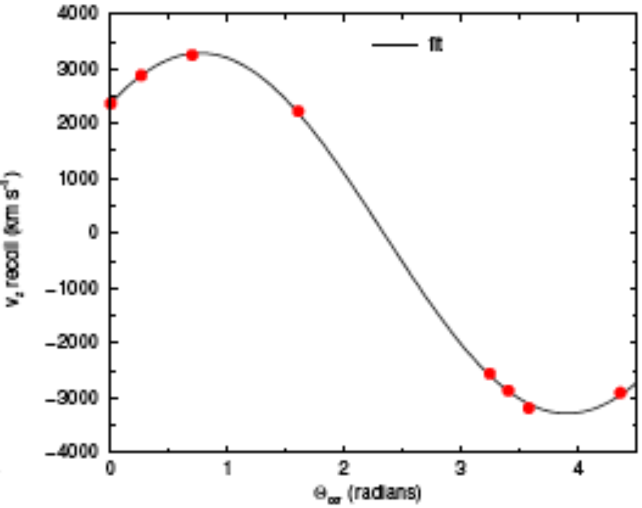
$$\begin{aligned} V &= V_1 \cos(\phi - \phi_1) + V_3 \cos(3\phi - 3\phi_3), \\ V_1 &= V_{1,1}\alpha + V_{1,3}\alpha^3, \\ V_3 &= V_{3,1}\alpha + V_{3,3}\alpha^3, \end{aligned}$$



bobbing of the orbit







An empirical Formula for the merger kick

Empirical formula [Campanelli et al '07] for the radiation recoil of generic binary black-hole mergers originally motivated by PN instantaneous radiated momentum dependence [Kidder 1995]

$$\vec{V}_{\text{recoil}}(q, \vec{a}_i) = v_m\, \hat{e}_1 + v_\perp(\cos(\xi)\, \hat{e}_1 + \sin(\xi)\, \hat{e}_2) + v_\|\, \hat{e}_z,$$

$$q = m_1/m_2, \quad \eta = q/(1+q)^2, \quad \vec{a}_i = \vec{S}_i/m_i^2$$

$$v_m = A\eta^2\sqrt{1-4\eta}(1+B\eta)$$

in-plane kick < 175 km/s [Fitchett '83, Gonzalez et al 07]

$$v_\perp = H\frac{\eta^2}{(1+q)}\left(a_2^\| - q a_1^\|\right)$$

in-plane kick < 500 km/s [Baker et al 07, Hermann et al '07, Koppitz et al '07]. See [Pollney et al 2007] for quadratic corrections in the spins. Also, work in progress by RIT …

$$v_\| = K\frac{\eta^2}{(1+q)}\cos(\Theta - \Theta_0)\left|\vec{a}_2^\perp - q\vec{a}_1^\perp\right|$$

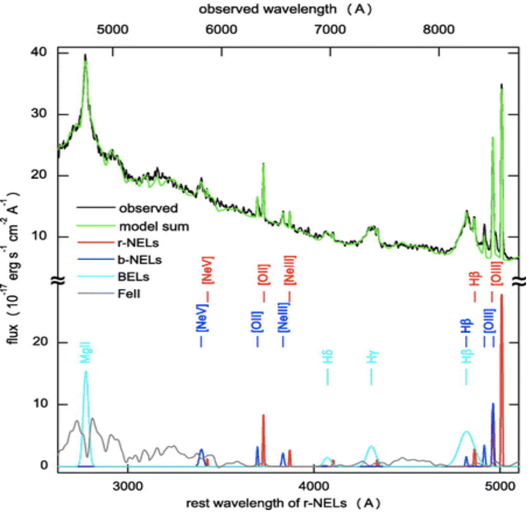
out-of-plane kick < 4,000 km/s [Campanelli et al 07, Lousto et al '08].

- ξ angle between unequal-mass and spin contributions to recoil in the orbital plane
- Θ angle between in-plane $\vec{\Delta} \equiv (m_1+m_2)(\vec{S}_2/m_2 - \vec{S}_1/m_1)$ and infall direction at merger

BH Kicks as Post-Merger Signatures

- Recoiling BHs can retain a massive accretion disk. The disk will fuel a lasting QSO phase while the BH wanders far from the galactic nucleus.

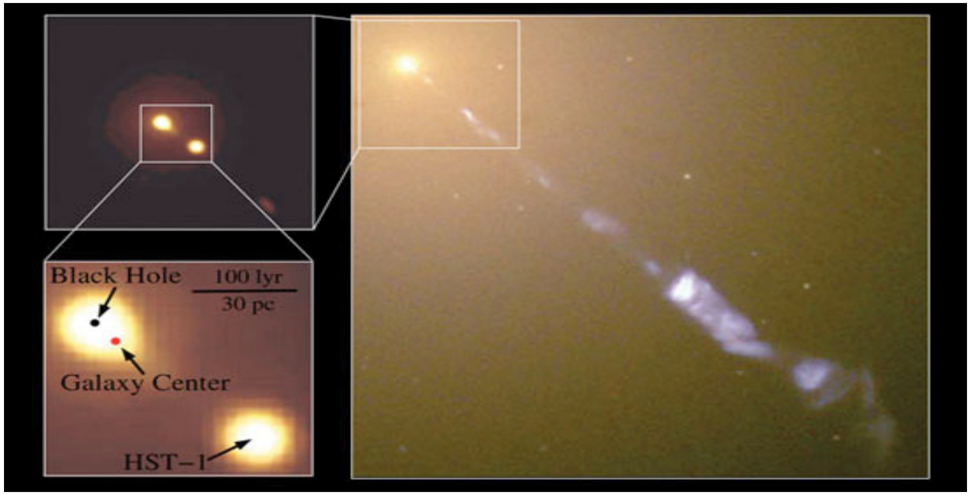
- There are relatively few observations of kick candidates:



- SDSS J0927 + 2943 [Komossa et al. 2008]
  - BLR (one set) shifted 2600 km/s; double picked NLR
  - Kick interpretation: blue system is kicked hole, with blue NLR due to expanding gas from edge of bound disk. Red NLR is in host galaxy ionized by kicked AGN.

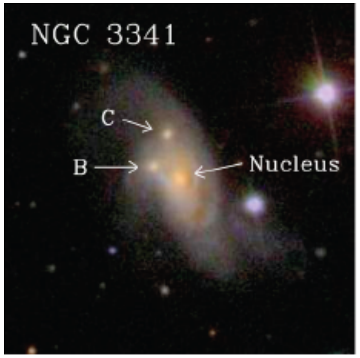
- More double-peaked emitters [Bonning et al, 2007; SDSSJ1050 Shields et al, 2009; Civano et al, 2010]

- Alternative interpretations: binary BHs, unusual NLR properties



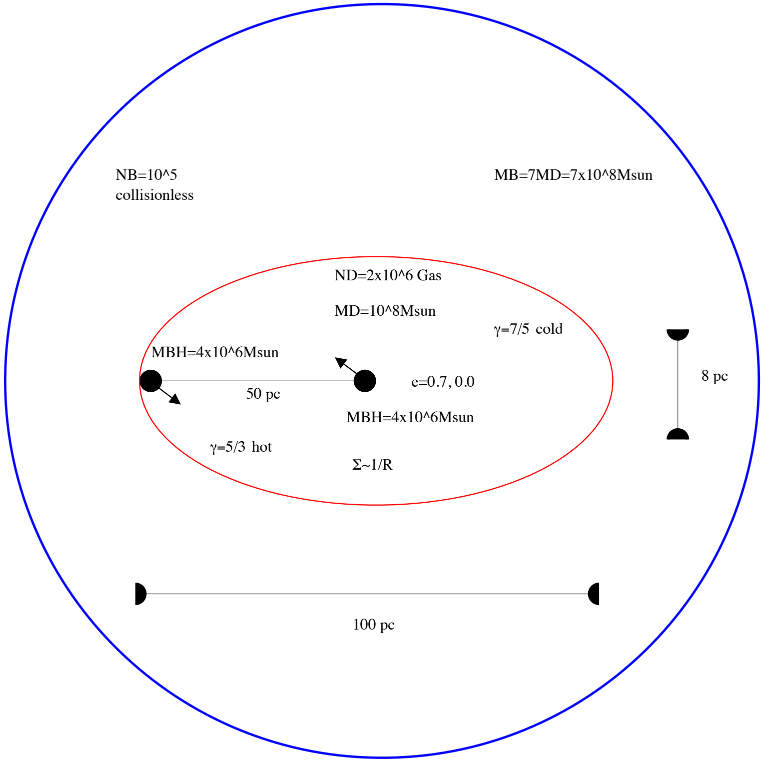
- HST image of a displaced SMBH in M87 [Batchelor et al, ApJL 2010]; Kick due postmerger ot jet?

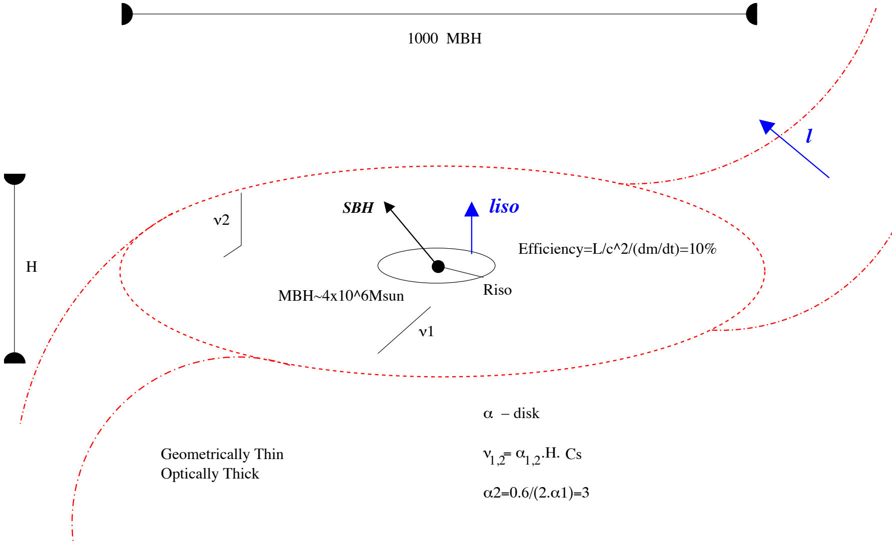
- More off-set nuclei [Barth et al. 2008]



N-body/SPH simulations

The two BHs are placed in the plane of a massive circumnuclear gaseous disk, embedded in a larger stellar spheroid. The disk is modeled with $\approx 2 \times 10^6$ gas particles, has a total mass $M_{\rm Disk} = 10^8 {\rm M}_\odot$, and follows a Mestel surface density profile $\Sigma(R) \propto R^{-1}$, where R is the radial distance projected into the disk plane. Dotti et al. truncated the disk at an outer radius of 100 pc. The massive disk is rotationally supported in R and has a vertical thickness of 8 pc. Gas is evolved assuming a polytropic equation of state with index $\gamma = 5/3$ or $\gamma = 7/5$. In the former case, the disk is termed "hot" as the temperature is proportional to a higher power of density than in the latter class of models ("cold" cases). The spheroidal component (bulge) is modeled with 10^5 collisionless particles, initially distributed as a Plummer sphere with a total mass $M_{\rm Bulge} (= 6.98 \times M_{\rm Disk})$. The mass of the bulge within 100 pc is five times the mass of the disk, as suggested by [58]. The BHs are equal in mass ($m_{\rm BH} = 4 \times 10^6 {\rm M}_\odot$), and their initial separation is 50 pc. A BH is placed at rest at the center of the circumnuclear disk, while the other is moving on an initially eccentric ($e_0 \simeq 0.7$) counter-rotating (retrograde BH) or corotating (prograde BH) orbit with respect to the circumnuclear disk.





Dotti & Volonteri '11

Spin distributions for hot & cold accretion disks

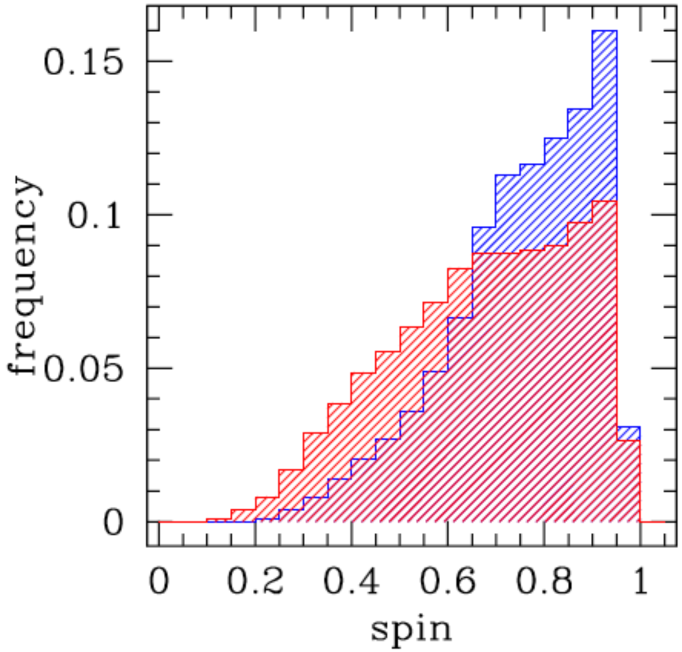


FIG. 5: Distributions of BH spin magnitudes after the formation of a BH binary. The blue and red histograms refer to BHs embedded in cold and hot discs, respectively. Fits to the two distributions are shown as dashed lines.

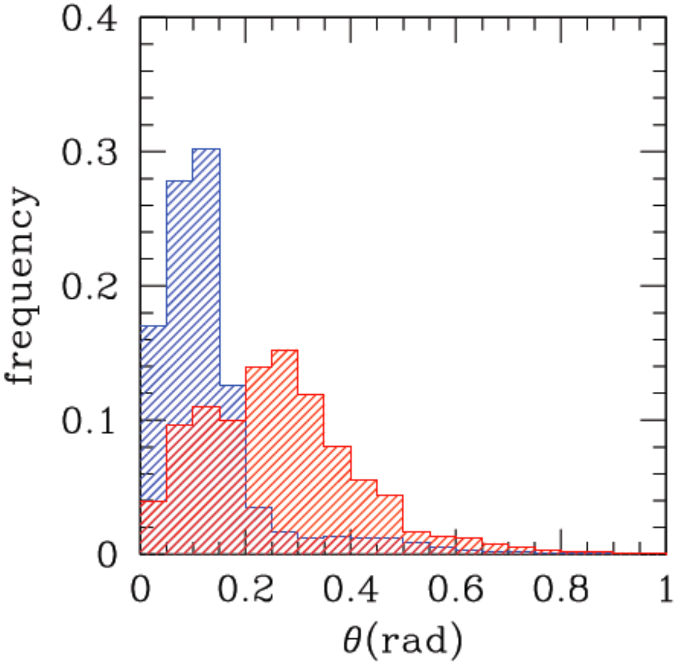


FIG. 6: The same as Fig. 5 for the relative angle between the BH spins and the BH binary angular momentum.

Hangup Recoils

- When spins are aligned with L, repulsive spin-orbit coupling delays the merger (orbital-hangup effect), maximizing the amplitude of gravitational radiation (up to 10%) [Campanelli+ 06].
- Combined with the superkick effect (which maximizes the asymmetry of momentum radiated), this leads to very large recoils [Lousto & Zlochower 11].

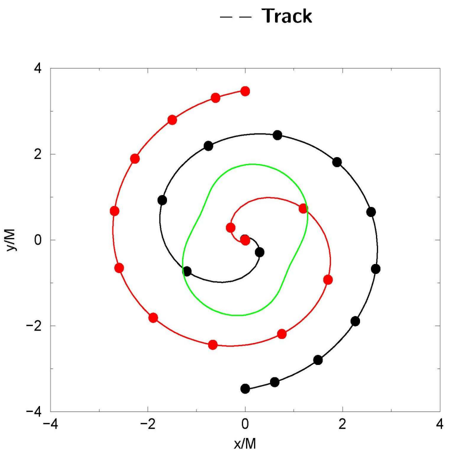


Figure 4: Puncture tracks for the − − configuration.

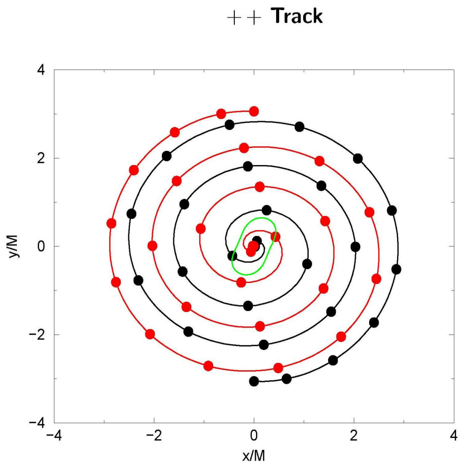
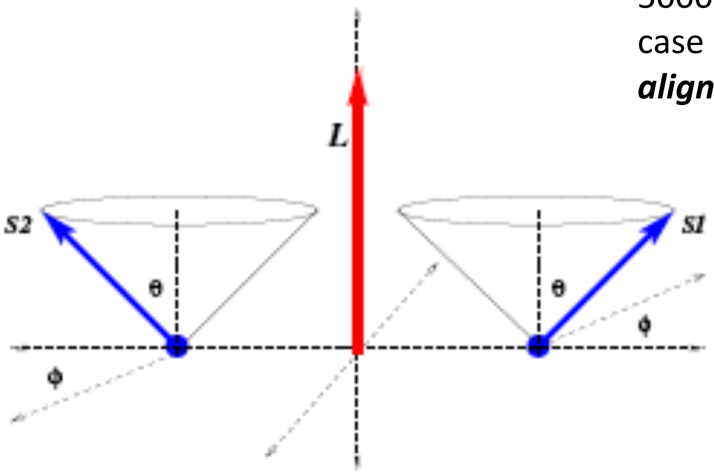
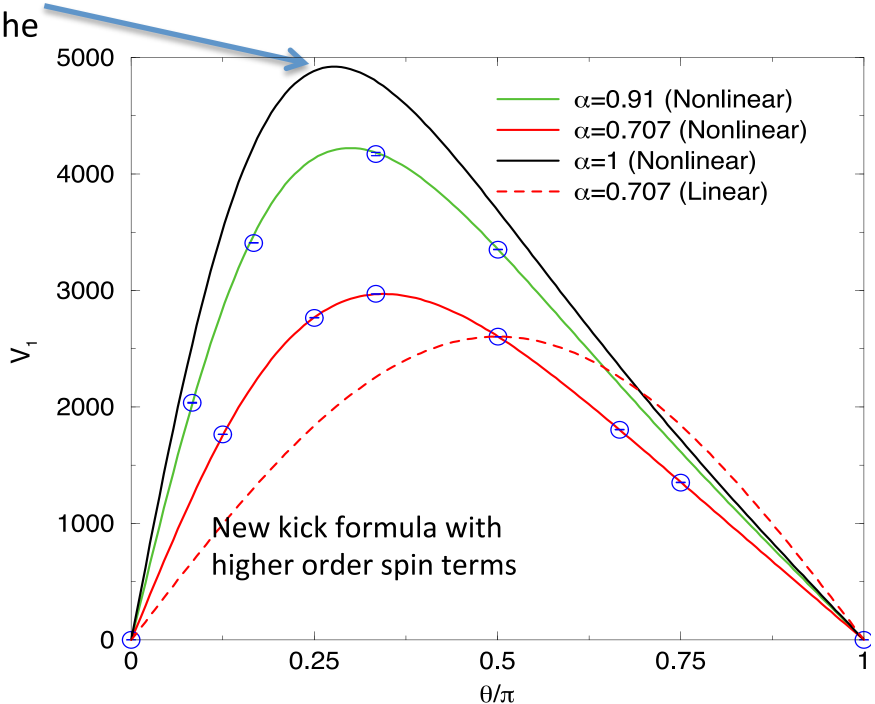


Figure 6: Puncture tracks for the + + configuration.



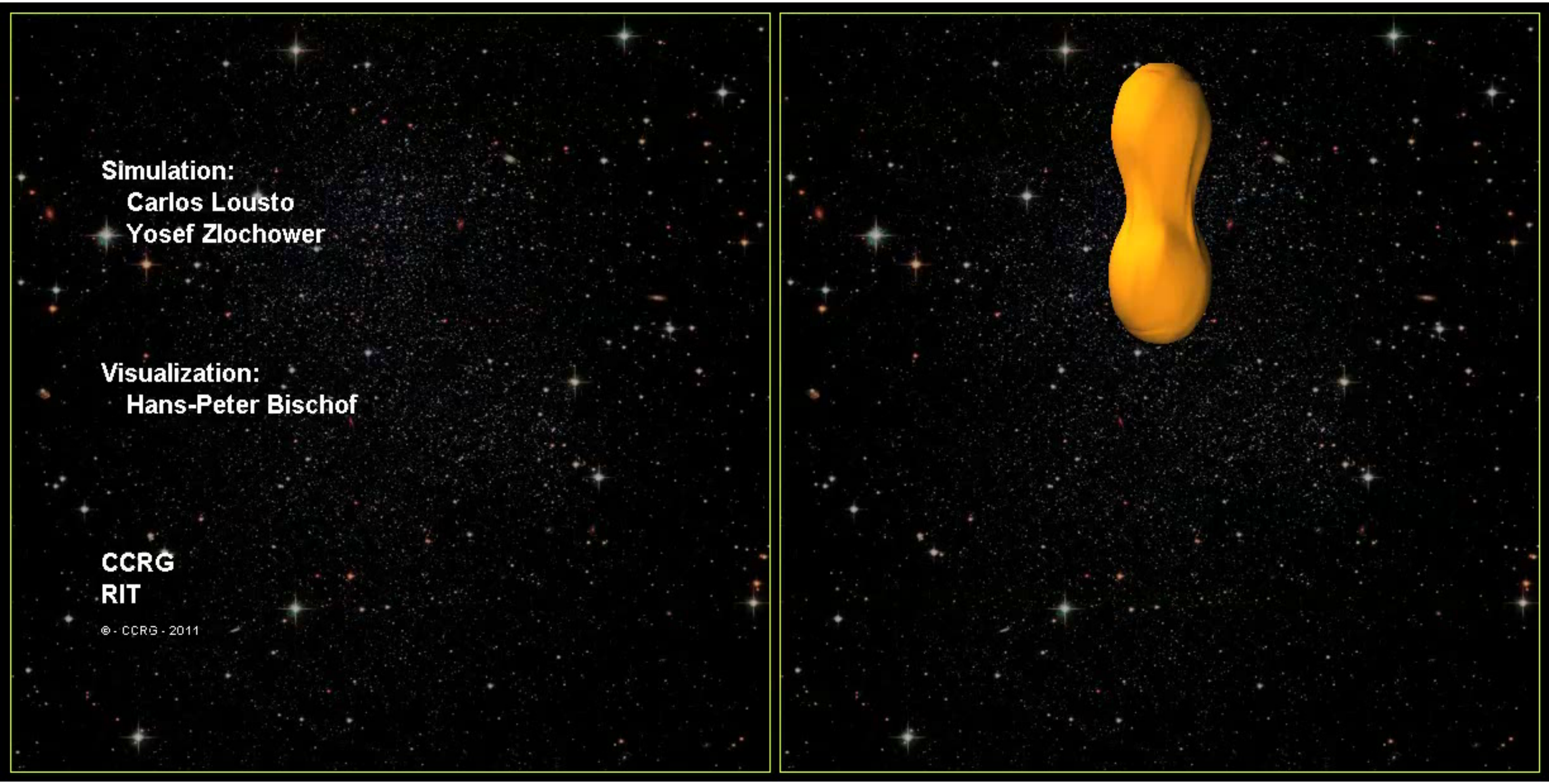
Three parameters family of initial configurations depending of φ, θ, and spin magnitude, a. Each dot in the plot are 6- runs to span the φ dependence. 48 new runs.

Peak occurs at 5000 km/s in the case of ***nearly aligned spins***



New kick formula with higher order spin terms

Hangup Kicks: The Movie



Simulation:
Carlos Lousto
Yosef Zlochower

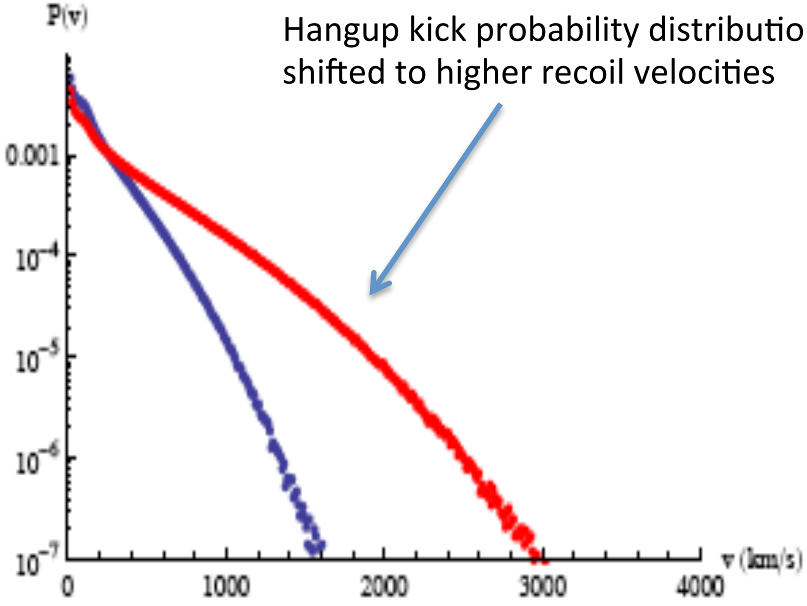
Visualization:
Hans-Peter Bischof

CCRG
RIT

Hangup Kick (Left) and Radiated Power (Right)
[Lousto & Zlochower PRL,2011, visualization by H.P. Bischof]

Probabilities to Observe Large Recoils

Partial alignment of the spins by gas accretion cannot inhibit large recoils as conjectured in [Bogdanovic+07), Dotti +10)]



Hangup kick probability distribution shifted to higher recoil velocities

Spin distribution: $P(x) \propto (1-x)^{(b-1)}x^{(a-1)}$

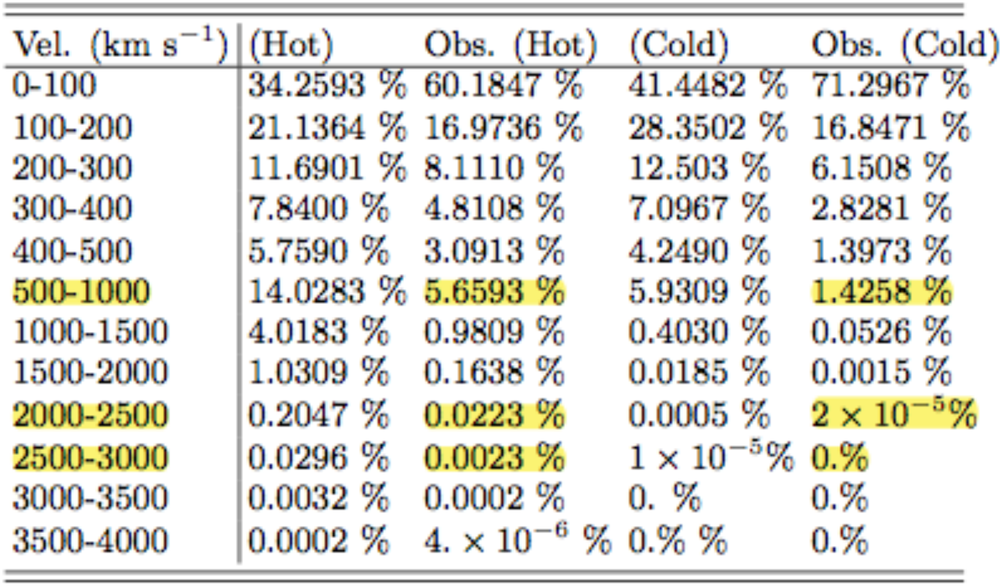
Mass distribution: $P(q) \propto q^{-0.3}(1-q)$

Feed this to recoil velocity formula and calculate the recoil distribution (table).

Probabilities that remnant BH recoils in any direction from host structure (spins from SPH simulations of hot and cold accretion models) [Lousto+12]:

- 0.02% for galaxies with v_{esc} ~ 2500 km/s
- 5% for galaxies with v_{esc} ~1000 km/s
- 20% for galaxies with v_{esc} ~500 km/s

For the hot case, there is a nontrivial probability of observing a recoil larger than 2000 km/s, but for cold disks, such recoils are suppressed.



Vel. (km s^{-1})	(Hot)	Obs. (Hot)	(Cold)	Obs. (Cold)
0-100	34.2593 %	60.1847 %	41.4482 %	71.2967 %
100-200	21.1364 %	16.9736 %	28.3502 %	16.8471 %
200-300	11.6901 %	8.1110 %	12.503 %	6.1508 %
300-400	7.8400 %	4.8108 %	7.0967 %	2.8281 %
400-500	5.7590 %	3.0913 %	4.2490 %	1.3973 %
500-1000	14.0283 %	5.6593 %	5.9309 %	1.4258 %
1000-1500	4.0183 %	0.9809 %	0.4030 %	0.0526 %
1500-2000	1.0309 %	0.1638 %	0.0185 %	0.0015 %
2000-2500	0.2047 %	0.0223 %	0.0005 %	2×10^{-5}%
2500-3000	0.0296 %	0.0023 %	1×10^{-5}%	0.%
3000-3500	0.0032 %	0.0002 %	0. %	0.%
3500-4000	0.0002 %	$4. \times 10^{-6}$ %	0.% %	0.%

Angular distribution of recoils

TABLE X: Maximum recoil angle θ (angle with respect to the orbital angular momentum axis) for given recoil velocity ranges. Note here that $\theta_{\max} < \delta$ means that θ must smaller than δ or larger than $180^\circ - \delta$.

Range	$\theta_{\max}$ (Hot)	$\theta_{\max}$ (Cold)
$0 - 100$ km s^{-1}	90°	90°
$100 - 200$ km s^{-1}	90°	90°
$200 - 300$ km s^{-1}	$< 80^\circ$	$< 70^\circ$
$300 - 400$ km s^{-1}	$< 45^\circ$	$< 40^\circ$
$400 - 500$ km s^{-1}	$< 33^\circ$	$< 30^\circ$
$500 - 600$ km s^{-1}	$< 25^\circ$	$< 21^\circ$
$500 - 1000$ km s^{-1}	$< 25^\circ$	$< 21^\circ$
$1000 - 1500$ km s^{-1}	$< 11^\circ$	$< 8^\circ$
$1500 - 2000$ km s^{-1}	$< 7^\circ$	$< 5^\circ$
$2000 - 2500$ km s^{-1}	$< 5^\circ$	$< 4^\circ$
$2500 - 3000$ km s^{-1}	$< 4^\circ$	$< 2^\circ$
$3000 - 3500$ km s^{-1}	$< 3^\circ$	***

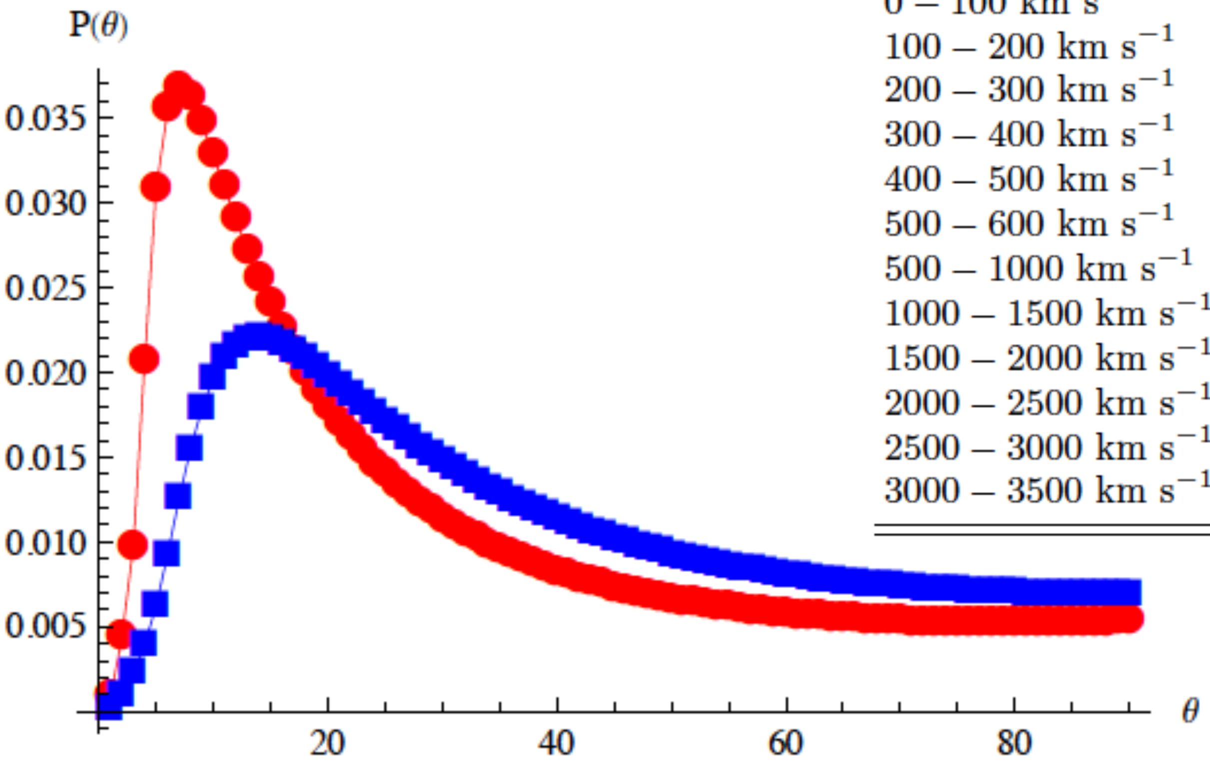


FIG. 11: The probability distribution of the inclination angle θ of the recoil (measured with respect to the axis of the angular momentum) for hot (narrower distribution, red circles) and cold environments (blue squares). Angles are measured in degrees. Note that $P(180^\circ - \theta) = P(\theta)$. These distributions were created by mapping $\theta \to 180^\circ - \theta$ for $\theta > 90^\circ$.

New precessing configurations

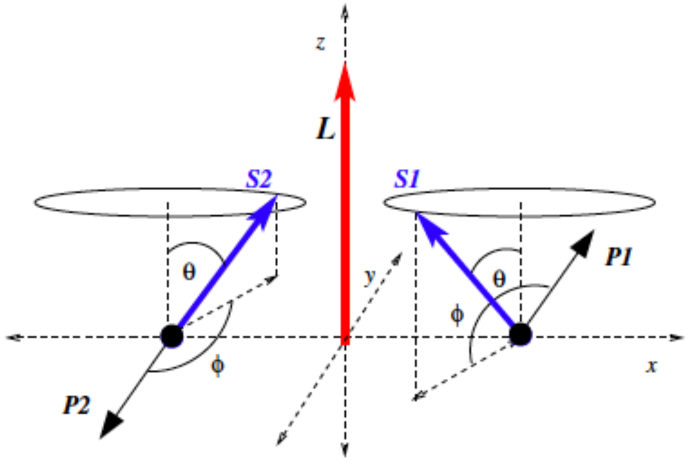


FIG. 1 (color online). The *hangup kick* configuration. Here $S_{1z}=S_{2z}$, while $S_{1x} = -S_{2x}$ and $S_{1y} = -S_{2y}$. The *hangup kick* configurations are preserved exactly by numerical evolutions.

52 hangup runs

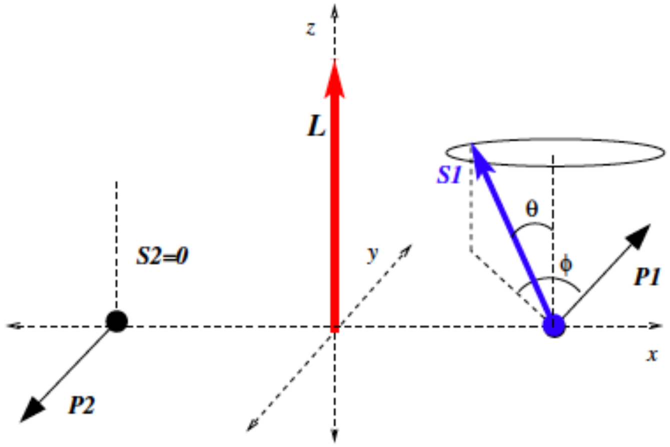


FIG. 5 (color online). The *N* configuration. These configurations differ from the *hangup kick* configurations in that BH2 is nonspinning. Numerical evolutions preserve the *N* configurations only approximately.

58 New runs to model
The cross-kick term

NEW: Precessing BH Binaries

$$\vec{V}_{\rm recoil}(q,\vec{\alpha}) = V_m\hat{e}_1 + V_\perp(\cos\xi\,\hat{e}_1 + \sin\xi\,\hat{e}_2) + V_\|\hat{L},$$

$$V_m = A_m\frac{\eta^2(1-q)}{(1+q)}[1 + B_m\eta],$$

$$V_\perp = H\frac{\eta^2}{(1+q)}\left[(1 + B_H\eta)(\alpha_2^\| - q\alpha_1^\|)\right.$$

Largest component (by factor 10) is along **L**

$$\begin{aligned} V_\|^{\cos\varphi} &= \Delta_\perp.(1 + \Delta_\|^2 + \cdots).(1 + S_\| + S_\|^2 + S_\|^3 + \cdots) && \text{< - hangup} \\ &\quad + S_\perp.\Delta_\|.(1 + \Delta_\|^2 + \cdots).(1 + S_\| + S_\|^2 + \cdots). && \text{< - cross} \end{aligned}$$

New precessing configurations

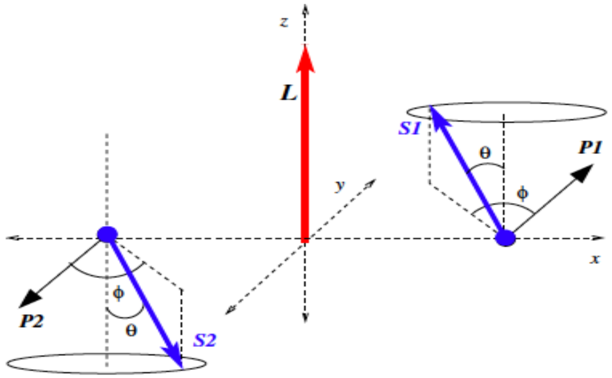


FIG. 6 (color online). The *S* configuration. These configuration differ from the *hangup kick* configuration in that $S_{1z} = -S_{2z}$ (and hence $\vec{S}_1 = -\vec{S}_2$) initially. Numerical evolutions preserve the *S* configurations only approximately.

Runs to verify the cross-kick fit
6 S-runs
12 K-runs
6 L-runs
6-higher spin N runs

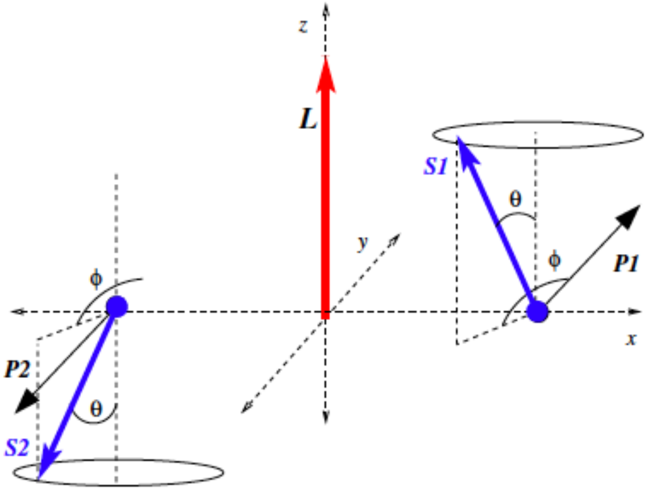


FIG. 7 (color online). The *K* configuration. These can be thought of as a modification of the *S* configurations. Here $S_{1z} = -S_{2z}$, while $S_{1x} = S_{2x}$ and $S_{1y} = S_{2y}$, initially.

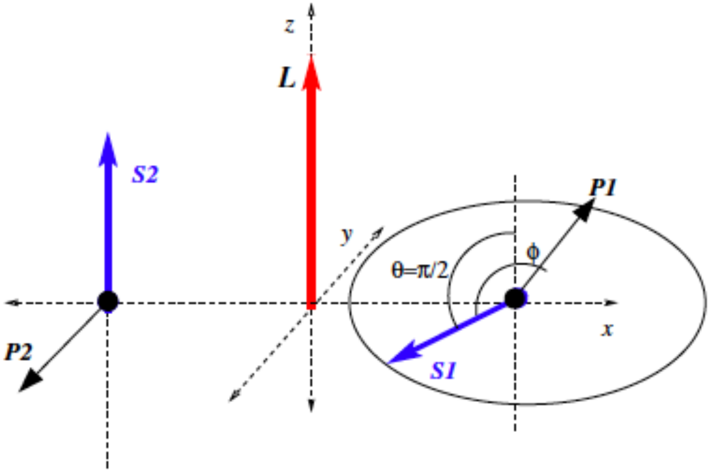


FIG. 8 (color online). The *L* configuration. The *L* configuration is a modification of the *N* configuration, where S_1 is aligned with the orbital angular momentum $\hat{z}$, and rather than having $S_2 = 0$, $\vec{S}_2$ is varied initially in the orbital plane.

Predicted vs computed

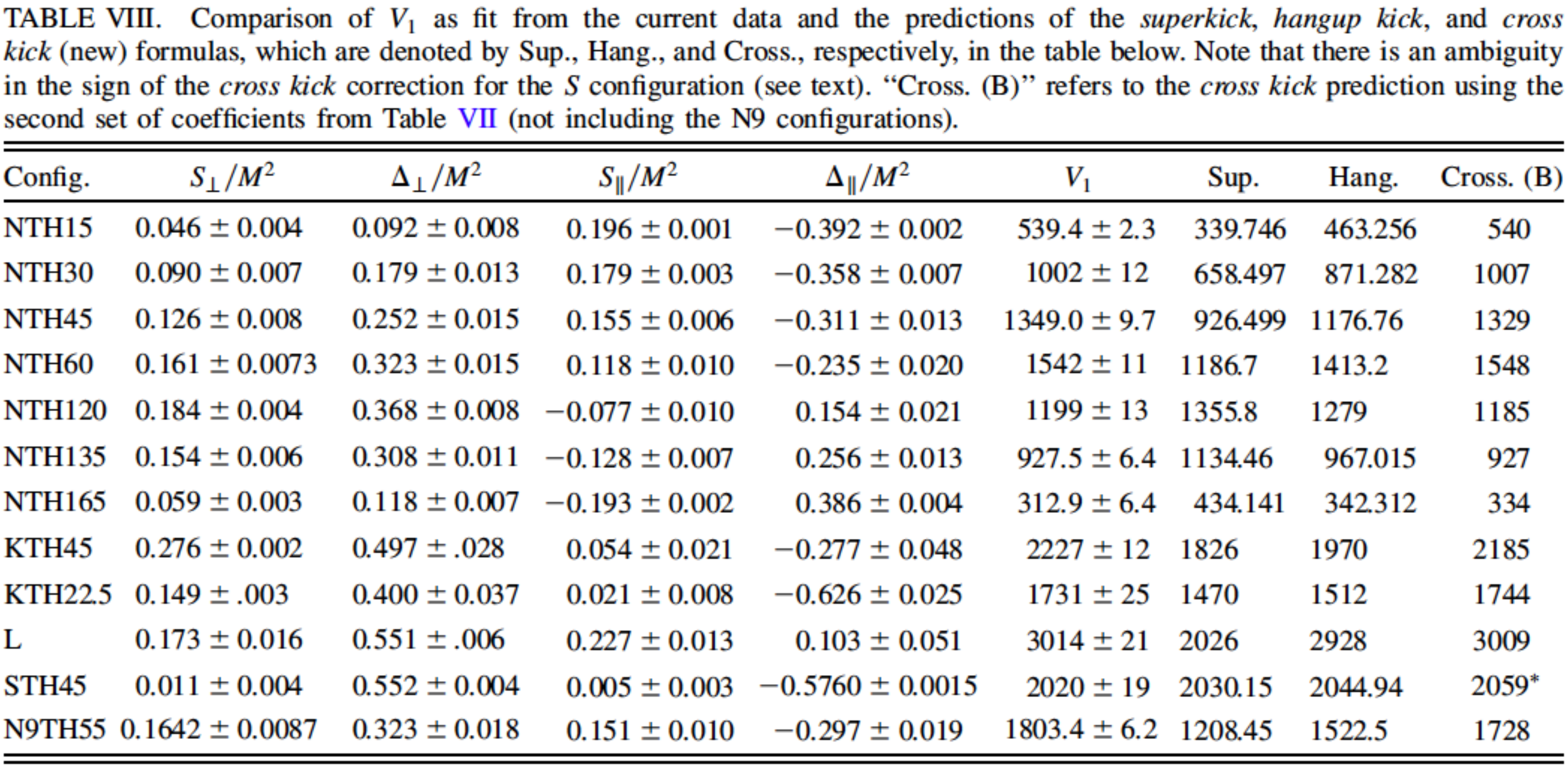
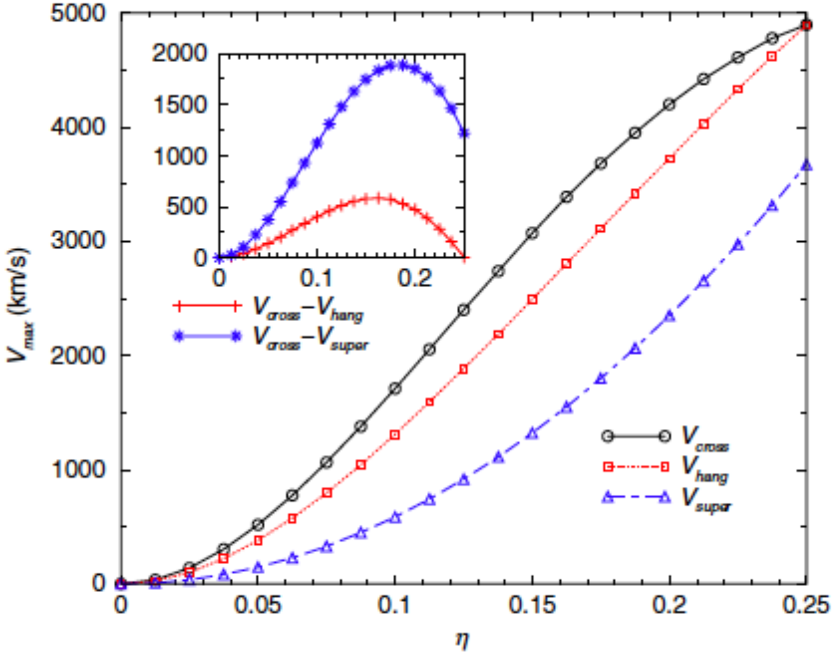


TABLE VIII. Comparison of V_1 as fit from the current data and the predictions of the *superkick*, *hangup kick*, and *cross kick* (new) formulas, which are denoted by Sup., Hang., and Cross., respectively, in the table below. Note that there is an ambiguity in the sign of the *cross kick* correction for the S configuration (see text). "Cross. (B)" refers to the *cross kick* prediction using the second set of coefficients from Table VII (not including the N9 configurations).

Config.	$S_\perp/M^2$	$\Delta_\perp/M^2$	$S_\parallel/M^2$	$\Delta_\parallel/M^2$	V_1	Sup.	Hang.	Cross. (B)
NTH15	0.046 ± 0.004	0.092 ± 0.008	0.196 ± 0.001	-0.392 ± 0.002	539.4 ± 2.3	339.746	463.256	540
NTH30	0.090 ± 0.007	0.179 ± 0.013	0.179 ± 0.003	-0.358 ± 0.007	1002 ± 12	658.497	871.282	1007
NTH45	0.126 ± 0.008	0.252 ± 0.015	0.155 ± 0.006	-0.311 ± 0.013	1349.0 ± 9.7	926.499	1176.76	1329
NTH60	0.161 ± 0.0073	0.323 ± 0.015	0.118 ± 0.010	-0.235 ± 0.020	1542 ± 11	1186.7	1413.2	1548
NTH120	0.184 ± 0.004	0.368 ± 0.008	-0.077 ± 0.010	0.154 ± 0.021	1199 ± 13	1355.8	1279	1185
NTH135	0.154 ± 0.006	0.308 ± 0.011	-0.128 ± 0.007	0.256 ± 0.013	927.5 ± 6.4	1134.46	967.015	927
NTH165	0.059 ± 0.003	0.118 ± 0.007	-0.193 ± 0.002	0.386 ± 0.004	312.9 ± 6.4	434.141	342.312	334
KTH45	0.276 ± 0.002	$0.497 \pm .028$	0.054 ± 0.021	-0.277 ± 0.048	2227 ± 12	1826	1970	2185
KTH22.5	$0.149 \pm .003$	0.400 ± 0.037	0.021 ± 0.008	-0.626 ± 0.025	1731 ± 25	1470	1512	1744
L	0.173 ± 0.016	$0.551 \pm .006$	0.227 ± 0.013	0.103 ± 0.051	3014 ± 21	2026	2928	3009
STH45	0.011 ± 0.004	0.552 ± 0.004	0.005 ± 0.003	-0.5760 ± 0.0015	2020 ± 19	2030.15	2044.94	2059*
N9TH55	0.1642 ± 0.0087	0.323 ± 0.018	0.151 ± 0.010	-0.297 ± 0.019	1803.4 ± 6.2	1208.45	1522.5	1728

NEW: Precessing BH Binaries



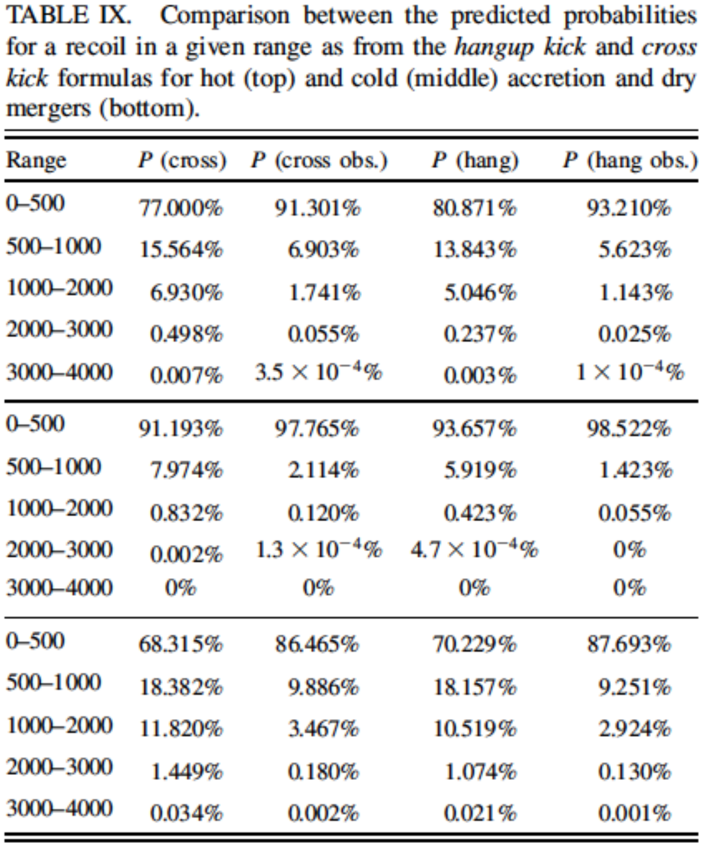


TABLE IX. Comparison between the predicted probabilities for a recoil in a given range as from the *hangup kick* and *cross kick* formulas for hot (top) and cold (middle) accretion and dry mergers (bottom).

Range	P (cross)	P (cross obs.)	P (hang)	P (hang obs.)
0–500	77.000%	91.301%	80.871%	93.210%
500–1000	15.564%	6.903%	13.843%	5.623%
1000–2000	6.930%	1.741%	5.046%	1.143%
2000–3000	0.498%	0.055%	0.237%	0.025%
3000–4000	0.007%	3.5×10^{-4}%	0.003%	1×10^{-4}%
0–500	91.193%	97.765%	93.657%	98.522%
500–1000	7.974%	2.114%	5.919%	1.423%
1000–2000	0.832%	0.120%	0.423%	0.055%
2000–3000	0.002%	1.3×10^{-4}%	4.7×10^{-4}%	0%
3000–4000	0%	0%	0%	0%
0–500	68.315%	86.465%	70.229%	87.693%
500–1000	18.382%	9.886%	18.157%	9.251%
1000–2000	11.820%	3.467%	10.519%	2.924%
2000–3000	1.449%	0.180%	1.074%	0.130%
3000–4000	0.034%	0.002%	0.021%	0.001%

For q~1/4 gives 25% increase in recoil velocity
and a factor 2 in the probability of v > 2000 km/s.

This new effect is also enhanced at higher
Spin alignment with orbital angular momentum.

It also confirms the hangup kick for precessing BHB

$$\begin{aligned} V_{\|}^{\cos\varphi} = {} & \Delta_{\perp}.(1+\Delta_{\|}^2+\cdots).(1+S_{\|}+S_{\|}^2+S_{\|}^3+\cdots) \\ + {} & S_{\perp}.\Delta_{\|}.(1+\Delta_{\|}^2+\cdots).(1+S_{\|}+S_{\|}^2+\cdots) \quad (\end{aligned}$$

Lousto & Zlochower (2012): 88-New precessing BHB runs add a cross-kick term.
Nonlinearities in the spins are very important!

Discussion

- Non-linear dependence on the spin is important.
  Recoils are generated in the highly general relativistic regime with BHs merge.
- The new correcting terms for the recoil formula have been modeled and tested with 52 hangup and 88 precessing new runs = 130 new runs.
- More simulations needed to verify the massratio dependence (surprises here?).
- Recoiling black holes through accretion disks have observational effects are very anysotropic, highly peaked along orbital **L**.
- Other observational effects: Core displacement, star velocity field.
- Blecha's talk!
- Recoil may explain the lack of IMBH in globular clusters and difficulty in growing IMBH
- Relevant for Mseeds and growing of structure in Universe
- Other observational effects like the tidal disruption of an star field by a passing BH
- Contribution to Baryonic DM?
- Spin alignment by accretion leads to hangup configuration that may radiate up to 11% of total mass making the BH merger the most energetic event in the Universe *by far* (by many orders of magnitude!).