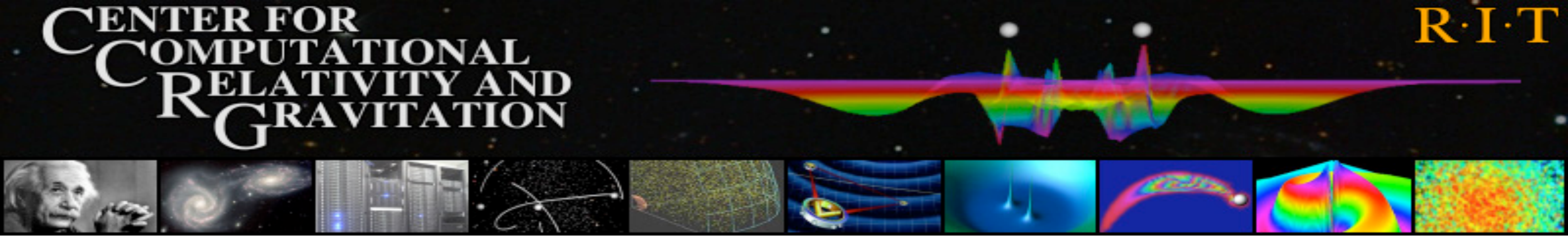

Gravitational Recoil from Merging Black Hole Binaries

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Yukawa Symposium, Kyoto, JP, December 5th, 2012

Introduction

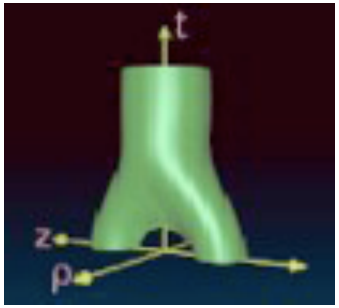
Contribution to Perturbation theory of BHs as well as Cosmology
(Sasaki-Nakamura Eq)

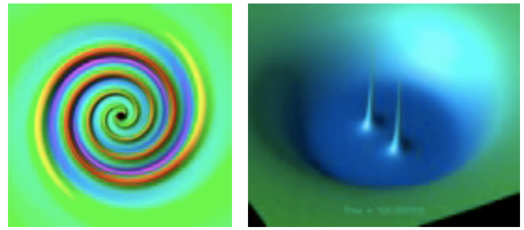
9th Yukawa International Seminar
On Black Holes And Gravitational Waves:
New Eyes In The 21st Century (YKIS 99)
28 Jun - 2 Jul 1999, Kyoto, Japan

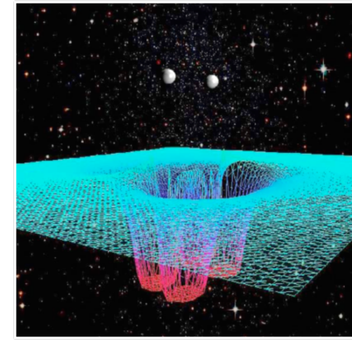
Lazarus=NR+BH Perturbations

BHB with NR tough 7-dimemsional physical parameters problem

A Brief Historical Overview







40+years of hard labor:

1964 First Simulation (Hahn & Lindquist)

… then LIGO …

1990s Grand Challenge

- BSSN-NOK evolution system
- Puncture Initial Data (Brandt-Bruegman)
- Gauge: Fixed Punctures (Alcubierre et al.)
- Lazarus (Campanelli et al)

2004 One Orbit (Buegman et al.)

Breakthrough:

2005 Binary Inspiral and Merger
Pretorius, PRL 95 (2005)

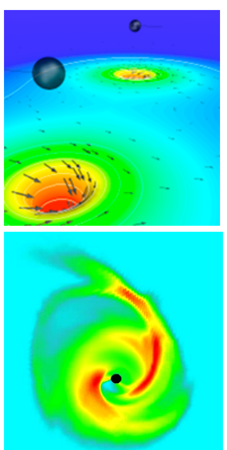
2005 Moving Punctures (RIT & NASA)
Campanelli et al PRL 96 (2006)
Baker et al PRL 96, (2006)

Numerical Relativity today:

2006+ GW Waveforms & Orbits,
Spin dynamics, Mass ratios,
GW Recoils, BH remnants,
BHs multiplets

2009+ Community Collaborations

2010+ Extreme BH Binaries
BH Binaries in a gaseous environment



Spectral Einstein Code (SpEC):

Generalized Harmonic, but 1st order

Physical BCs

Highly-accurate, but less flexible (care needed to get BH-BH merger)

Extended to GRMHD (BH-NS, Duez)

F1

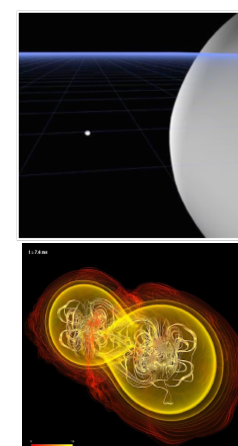
Moving Puncture Codes:

BSSN + Punctures, AMR

Less-accurate, but more flexible and robust (NBBH -BH/NS mergers)

Community Codes, including GRMHD (http://einsteintoolkit.org)

Rally



Merger of Spinning Black Holes: Hang-Up Orbits

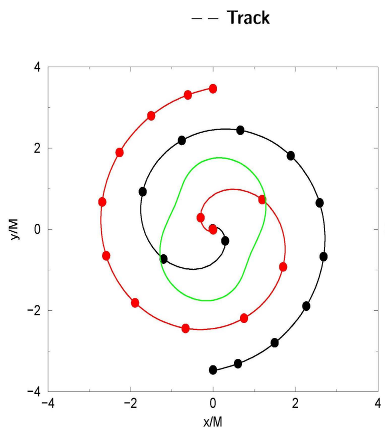


Figure 4: Puncture tracks for the – – configuration.

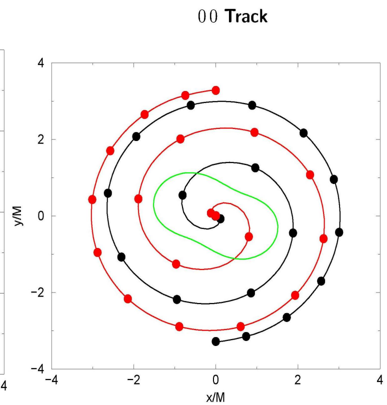


Figure 5: Puncture tracks for the 0 0 configuration.

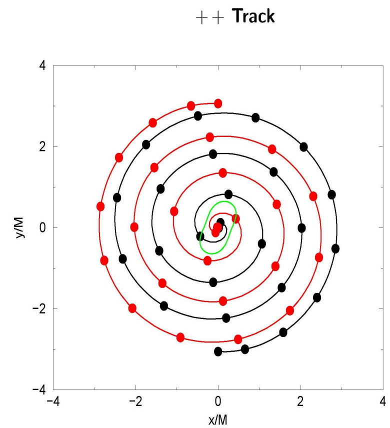
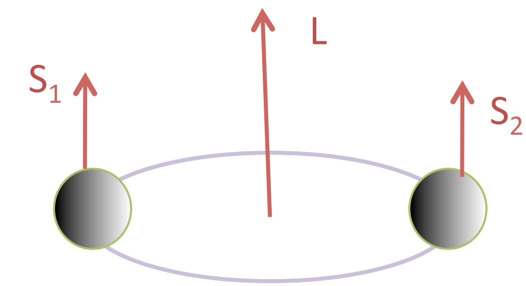
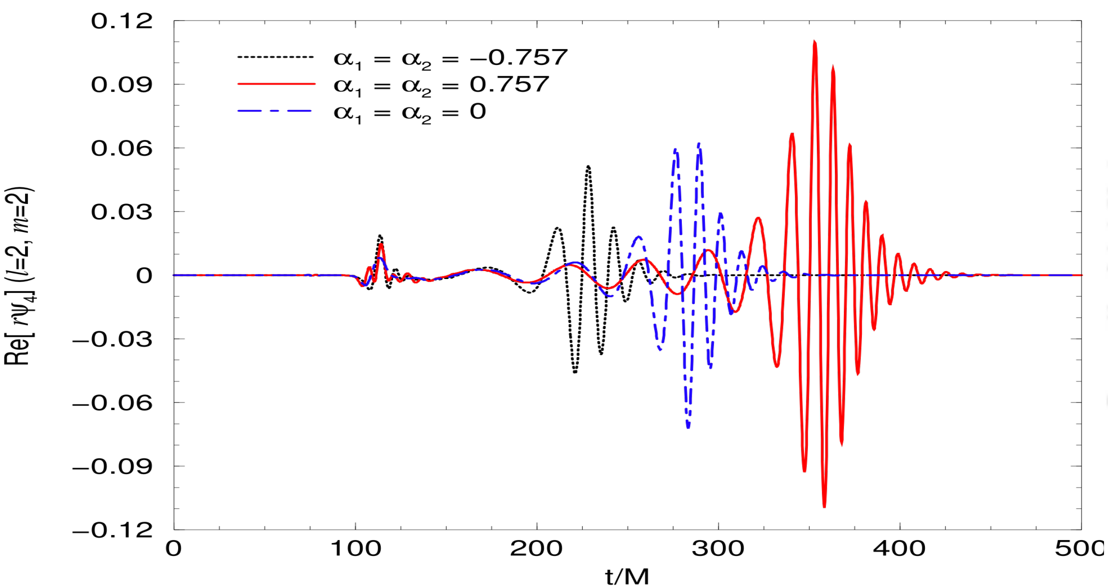


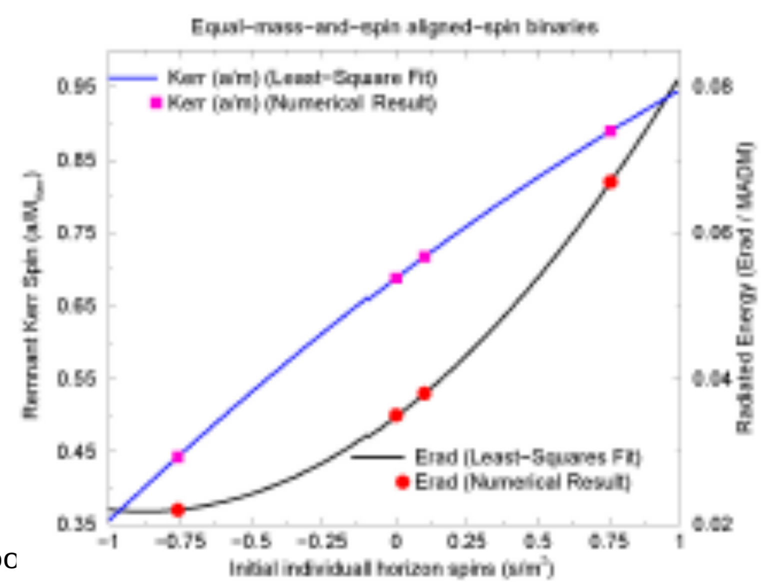
Figure 6: Puncture tracks for the + + configuration.



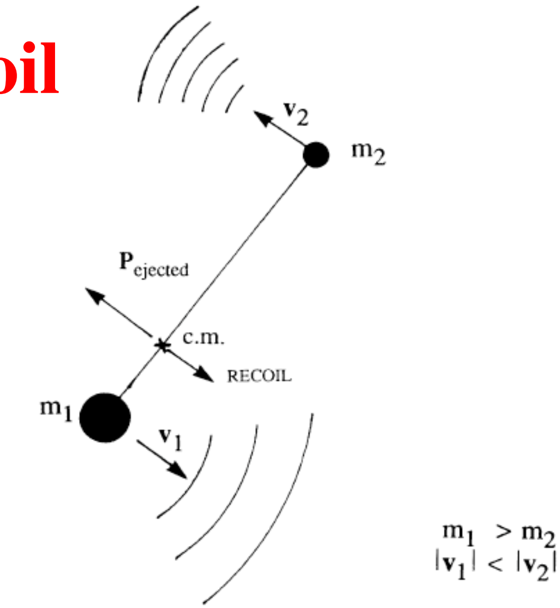
- Equal-mass BHBs
- $S_{1,2}/m^2 = \{-0.75, 0, 0.75\}$
- $M\Omega = 0.05$ (Starting "radius" the same).

• Hang-up effect due to repulsive spin-orbit interaction leaving behind a remnant with sub-maximal spin <0.96) [Campanelli, Lousto, Zlochower, PRD 2006]: cosmic censorship respected!





Gravitational Radiation Recoil



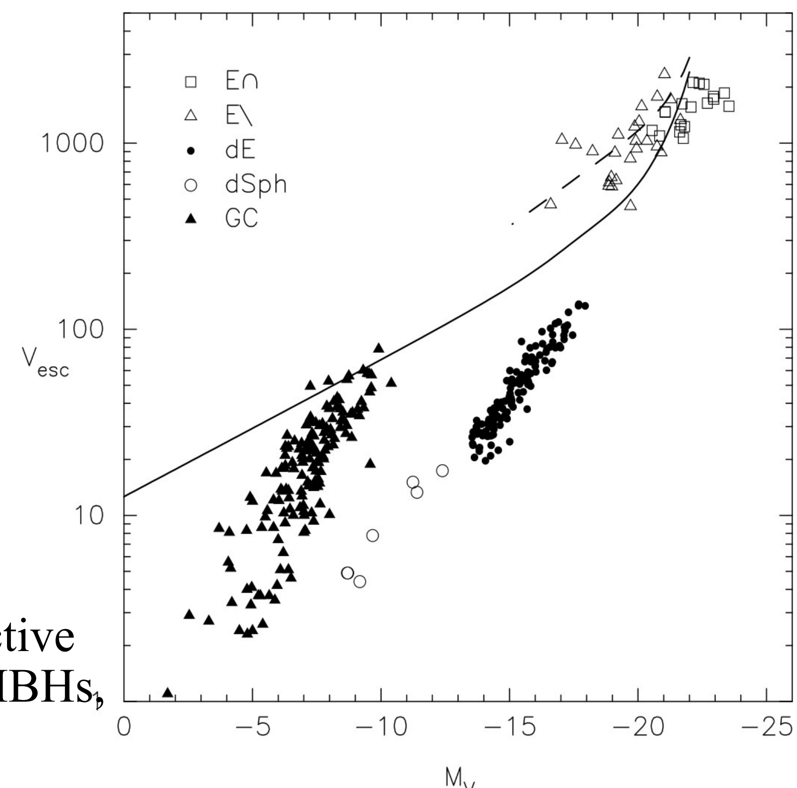
- In binary black-hole (BH) coalescences, asymmetrical gravitational radiation carries a net linear momentum, causing center-of-mass recoil. To conserve momentum the merged BH is given a kick in the opposite direction.

- 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, etc.



Kicks: non-spinning black-hole binaries

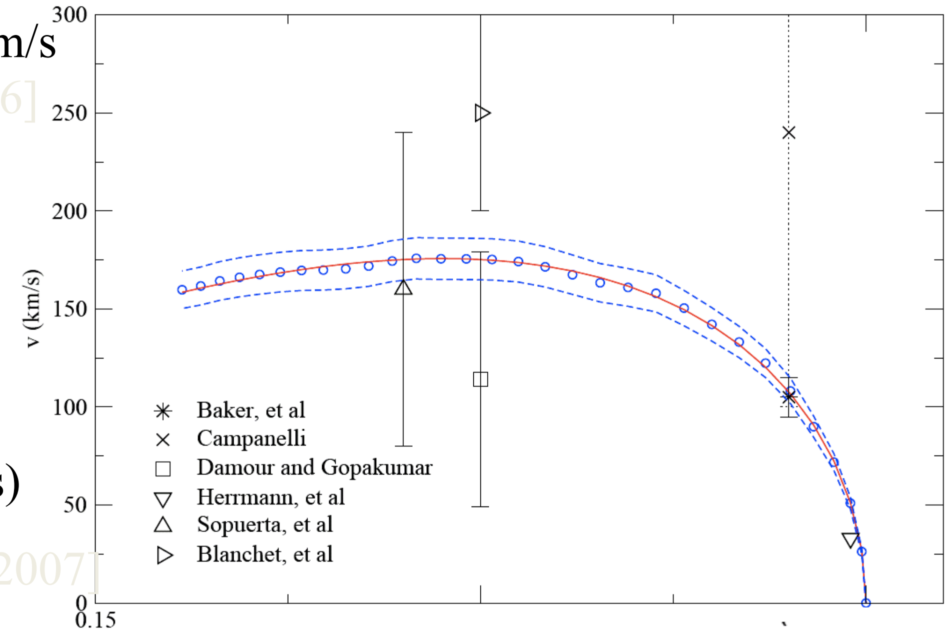
- Maximum non-spinning binary kick ~178 km/s for mass ratio $q \approx 0.36$ [Gonzalez et al, 2006]

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

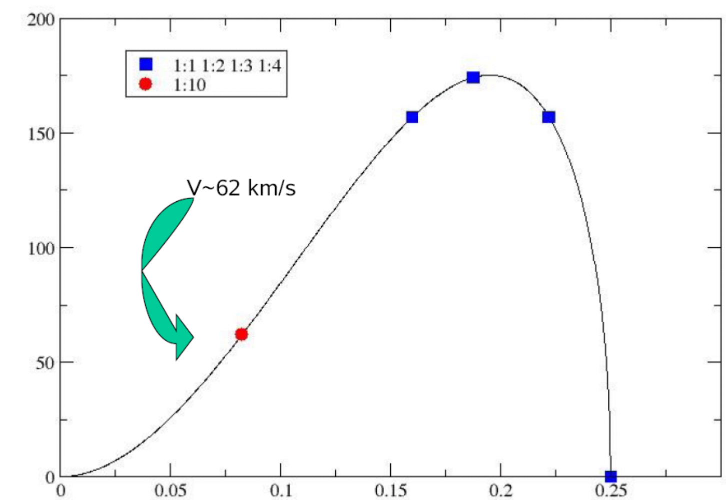
$$v_F \simeq 1480\,\mathrm{km/sec}\,\frac{f(q)}{f_{\max}}\left(\frac{2G(m_1+m_2)/c^2}{R_{\mathrm{term}}}\right)^4$$

(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)

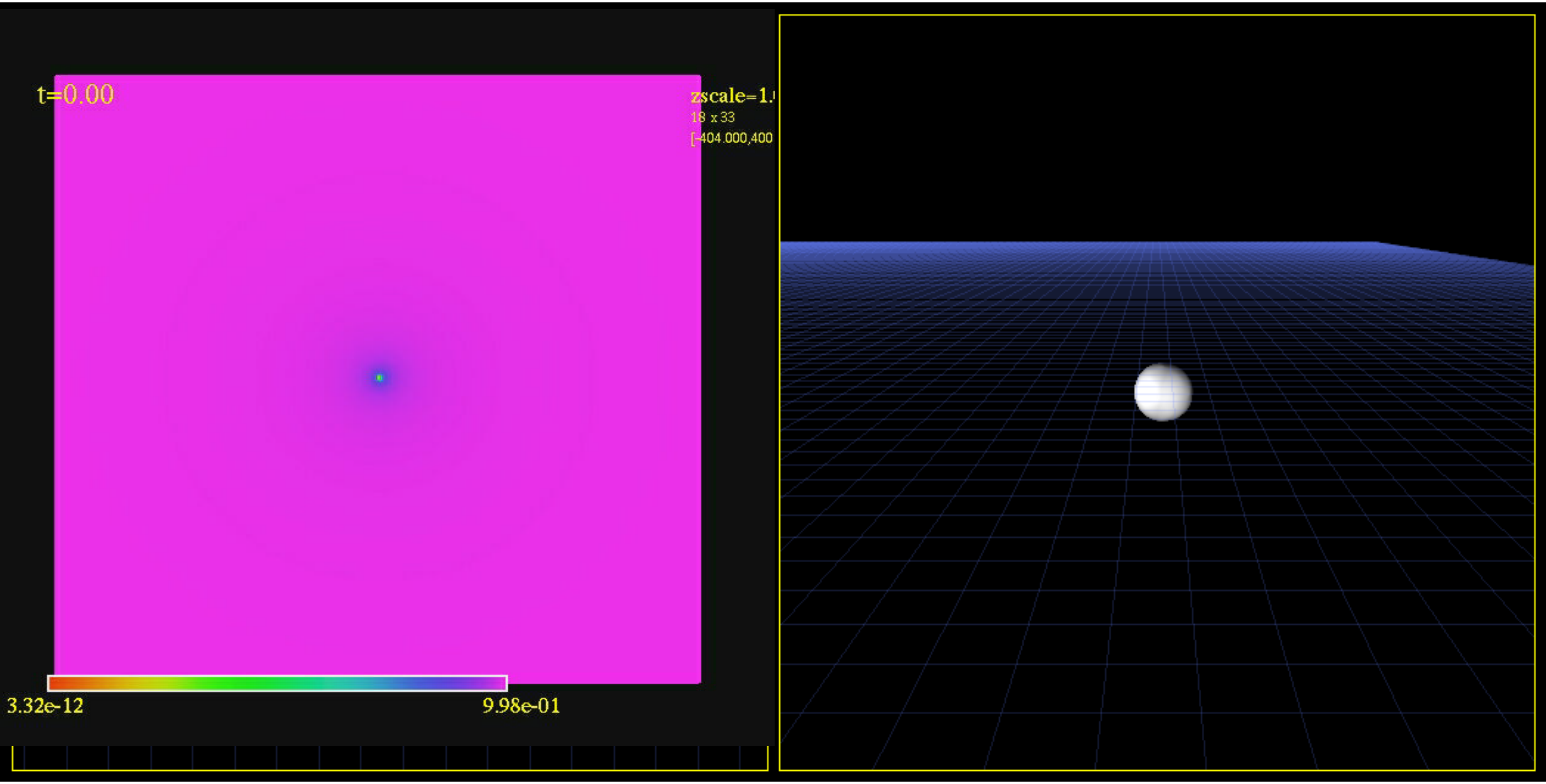
- NR calculation of radiated linear momentum [Campanelli & Lousto, 1999]:

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

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

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

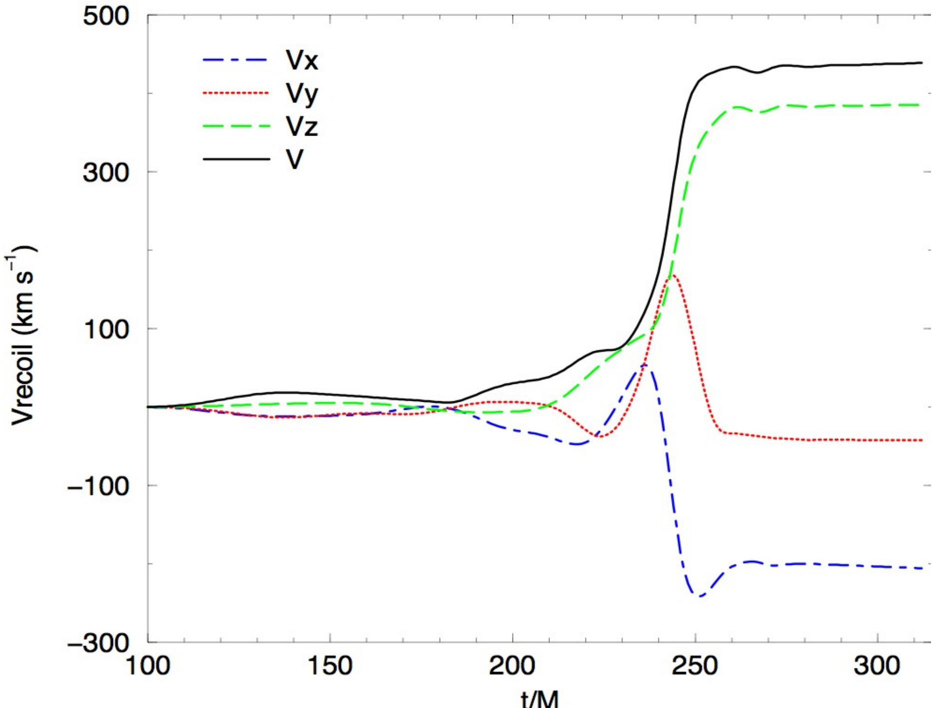
Large mass-ratio BBH: 100:1

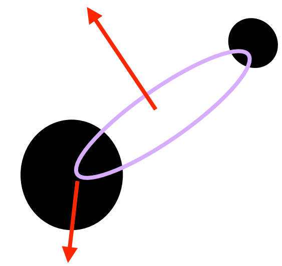


q=1/100 mass ratio BBH, with 15 levels of refinements in AMR [Lousto & Zlochower 11].
Perturbative realm!

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 ..."

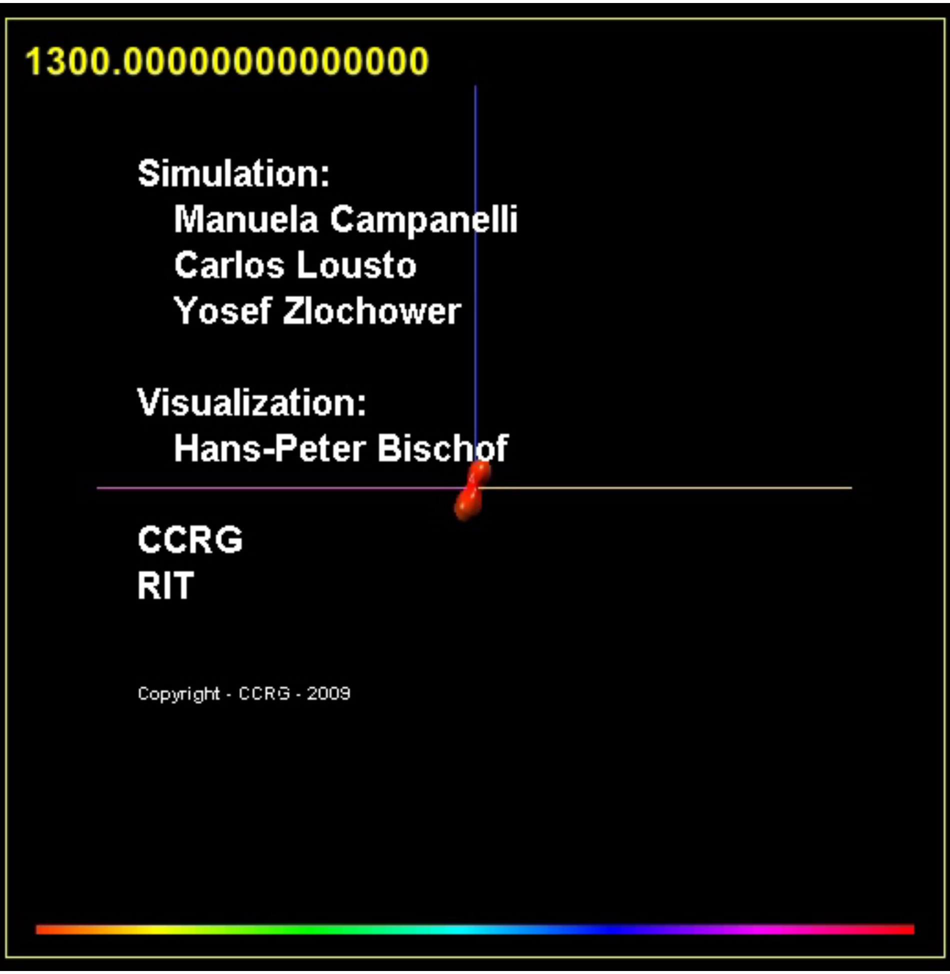
Maximum kick configuration: equal-mass circular binaries with opposite in-plane spins produce large out-of-plane kicks

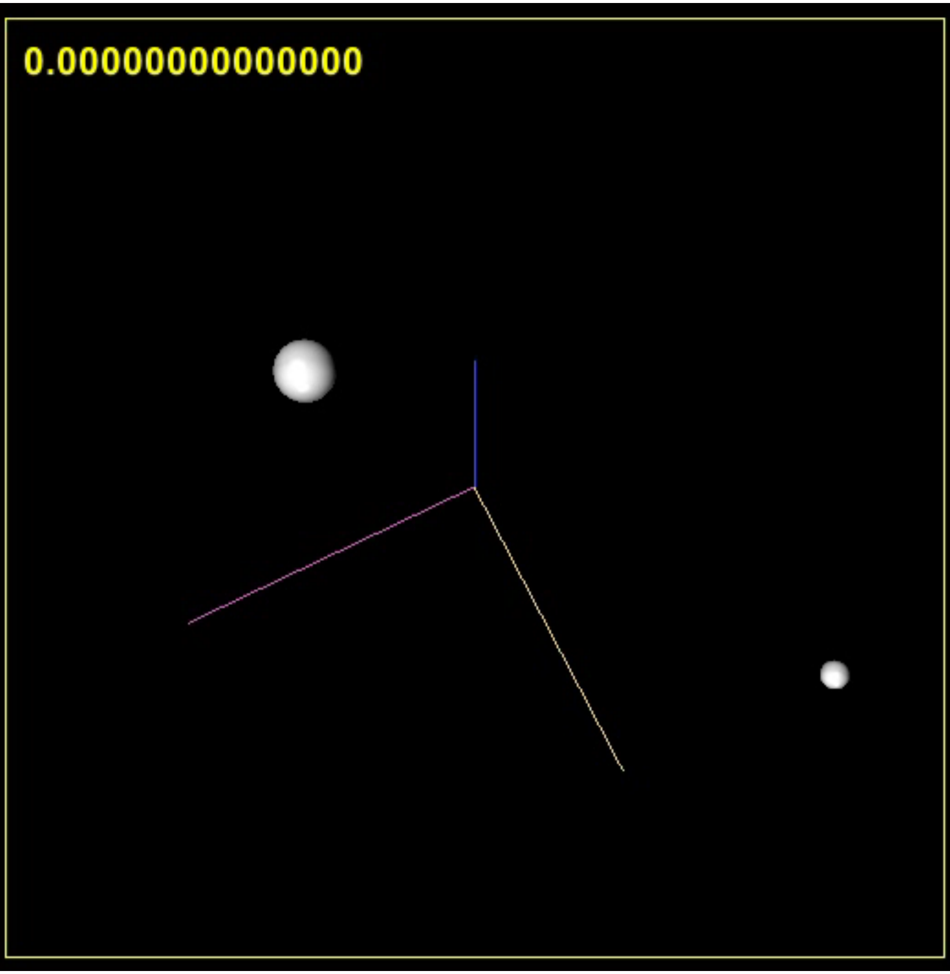
- Following:

  [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

Kick from a Generic Astrophysical BH binary

- In astrophysical, quasi-circular, spinning BH binaries mergers, such kicks can be as large as 3,680 km/s





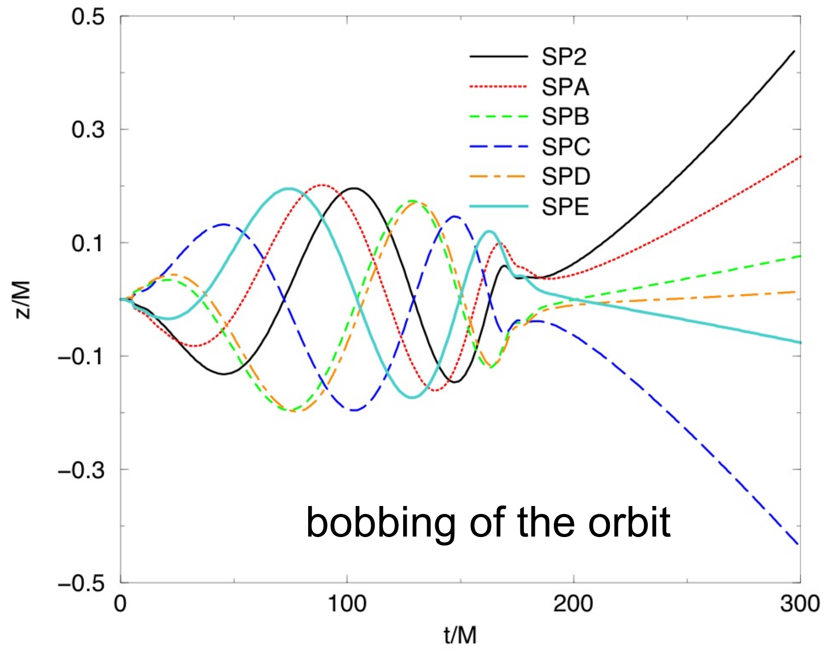
Radiated power (Left), Orbit and Kick (Right)

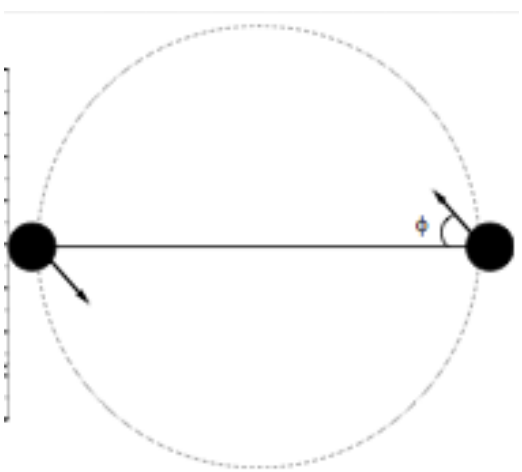
The Superkick Configurations

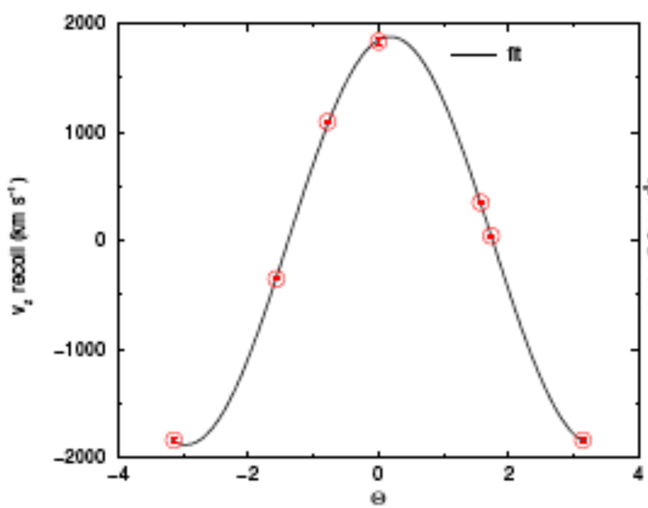
- Spin-orbit coupling effects can lead to very large kick velocities (superkicks) for equal-mass BBH, in-plane BH spins [Campanelli+07a,b,]

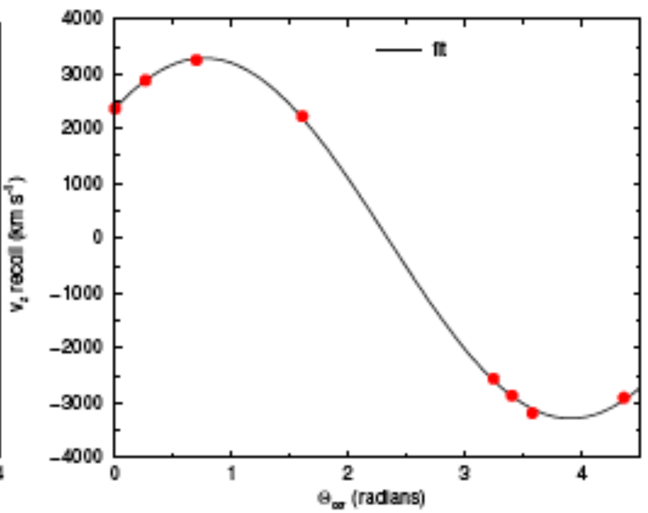
- Recoil velocity depends sinusoidally on the initial phase of the binary, and linearly (at leading order) on the spin magnitude :

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









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]

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

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

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

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

Life was good…

- NR predicted Large recoils (up to 3800 km/s)
- Modeling to do statistics predicts plenty of them
- Astronomers got very interested,
- But (astrophysicists),
- Bogdanovic et al '07, Dotti&Volonteri'10:
  Accretion aligns spins and reduce recoils,
  SMBHs are safe in Galaxy cores.
- So, the ball is back to NR field. Back to the drawing board

Hang up configurations

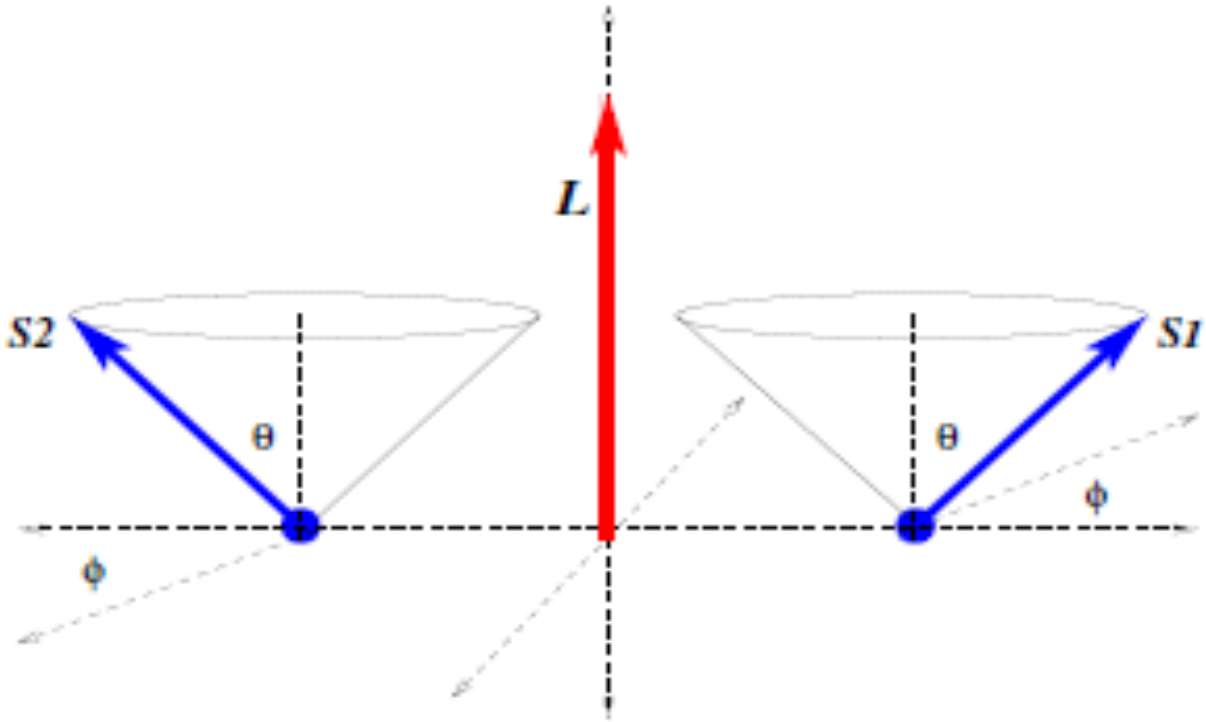
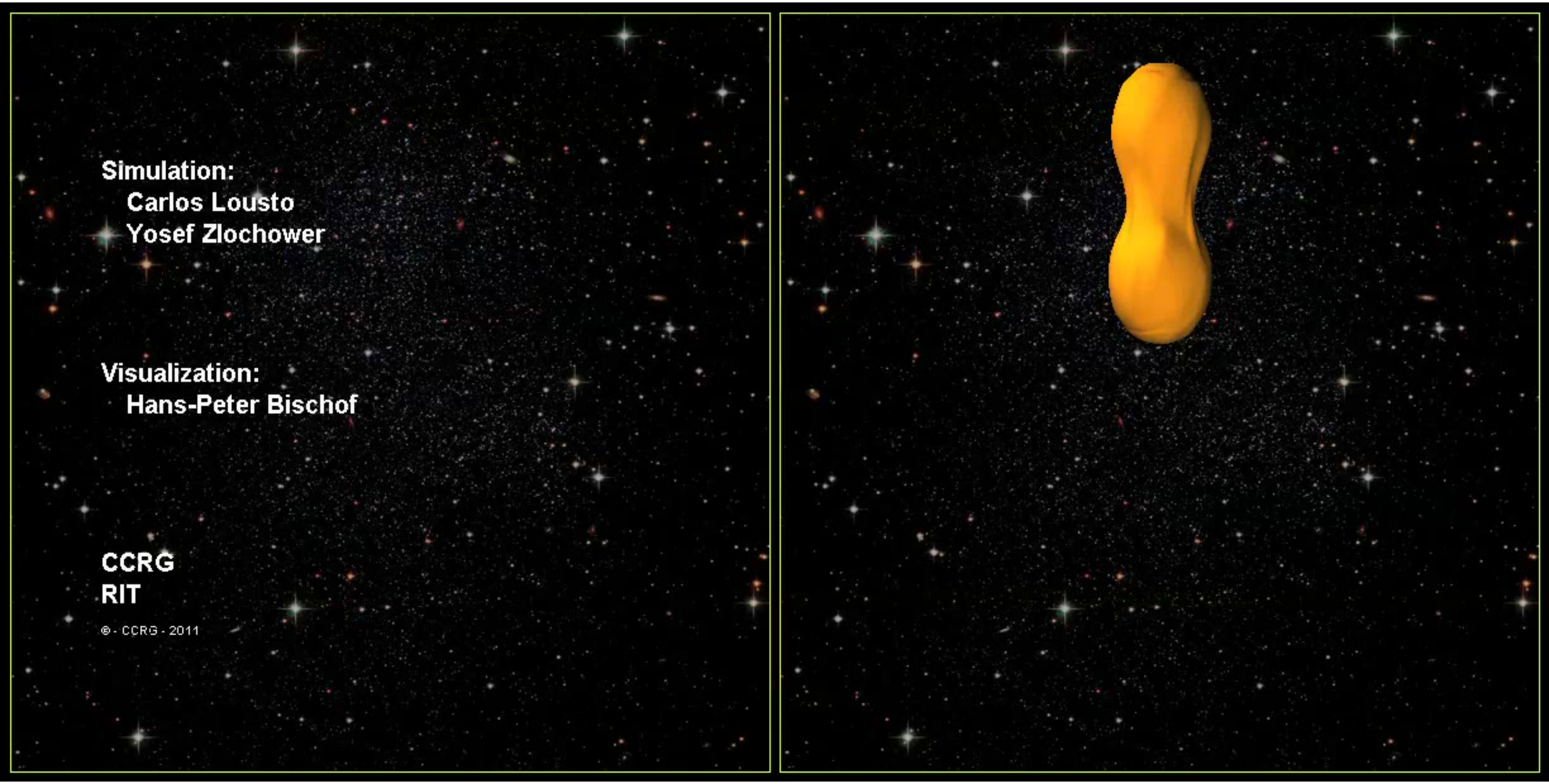


FIG. 1: Black-hole-binary configuration for hangup recoils.

Lousto & Zlochower (PRL, 2011)

Hangup Kicks: The Movie



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

Hangup recoils

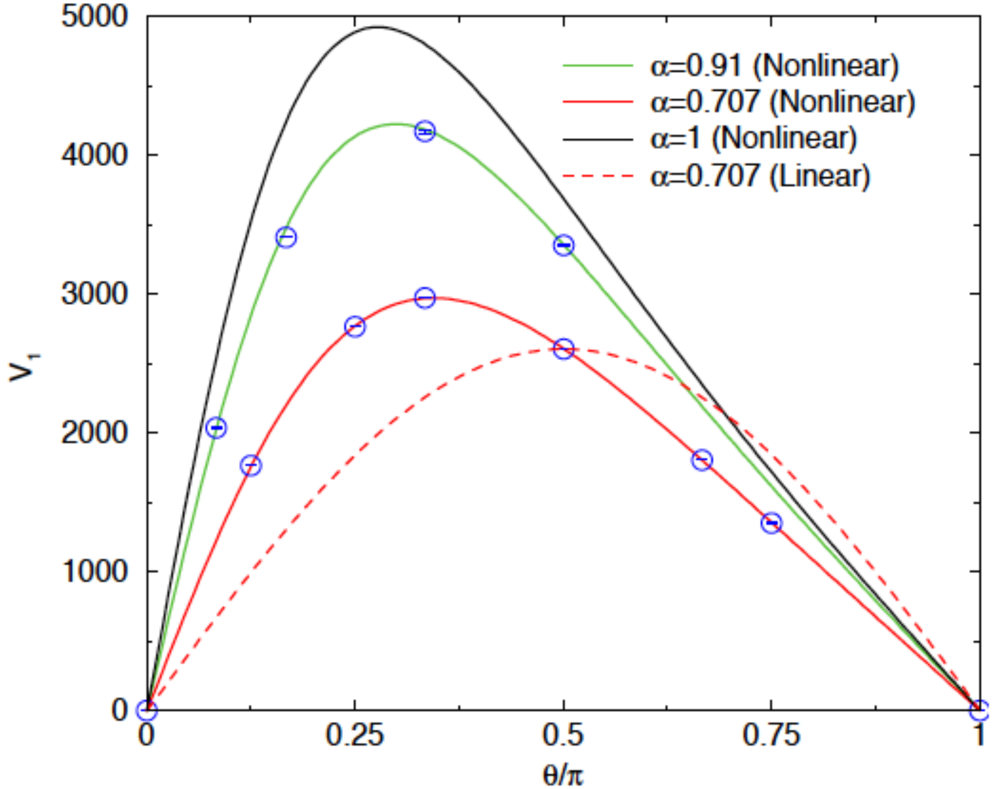


FIG. 6: fit of the recoil (V_1) to the form Eq. (8) for the $\alpha = 1/\sqrt{2}$ configurations, and predictions (based on this fitting) for the $\alpha = 0.91$ recoils. Note how well the $\alpha = 0.91$ curve matches the four measured values. For reference, curves corresponding to the original empirical formula prediction (which only had terms linear in Δ) for $\alpha = 1/\sqrt{2}$ and the new formula for $\alpha = 1$ are also included. Note the skew in the velocity profile compared to the linear predictions.

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.

5000 km/s matters, but more importantly is the angle it gets: ~ 50^0

Hangup Recoil Velocity Formula

GR simulations of BH recoil (e.g. Campanelli+07a,b; Lousto+12) show that the best-fit recoil velocity is given:

- Superkick maximum ~ 4000 km/s occurs when the spins are exactly anti-aligned and q=1.
- Hang-up kick maximum ~ 5000 km/s occurs for nearly aligned and q=1.

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

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

Unequal mass non-spinning binaries produces in-plane kicks < 175 km/s

$$v_\perp = H \frac{\eta^2}{(1+q)}\left[(\alpha_2^\| - q\alpha_1^\|)\right],$$

The perp. term to L produce in-plane kicks < 500 km/s

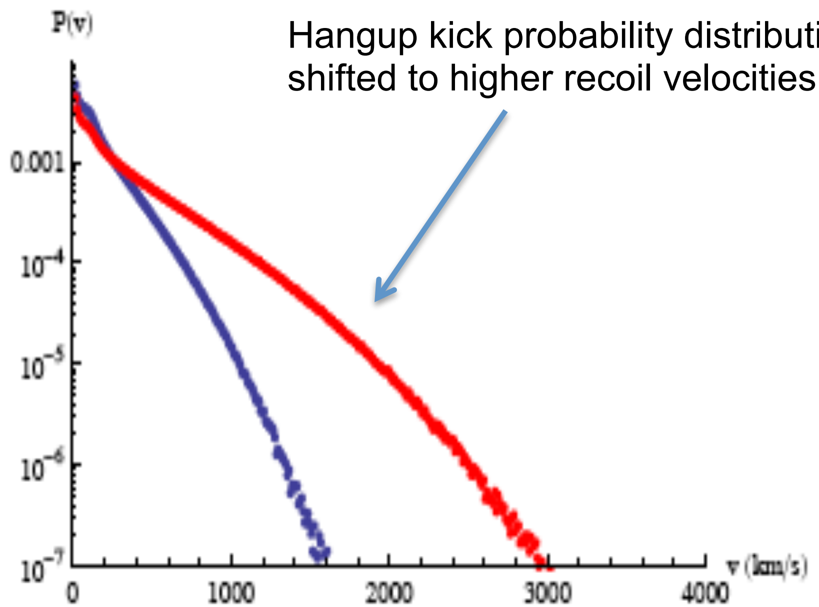
$$\begin{aligned} v_\| \;=\; & 16\frac{\eta^2}{(1+q)}\left|\alpha_2^\perp - q\alpha_1^\perp\right| \times \\ & \left[V_{1,1} + A\left(\frac{2[\alpha_2^z + q^2\alpha_1^z]}{(1+q)^2}\right) + B\left(\frac{2[\alpha_2^z + q^2\alpha_1^z]}{(1+q)^2}\right)^2 \right. \\ & \left. + C\left(\frac{2[\alpha_2^z + q^2\alpha_1^z]}{(1+q)^2}\right)^3\right]\cos(\phi_\Delta - \phi_1), \end{aligned} \tag{4}$$

The parallel term to L, that is responsible for the superkicks (linear spins) and hang-up kick (quadratic spins)

where η = q/(q+1) and q =m1/m2 < 1. A,B,H,K, ξ, and Φi are constants.

Probabilities to Observe Large Recoils

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



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.%

Precessing BHB

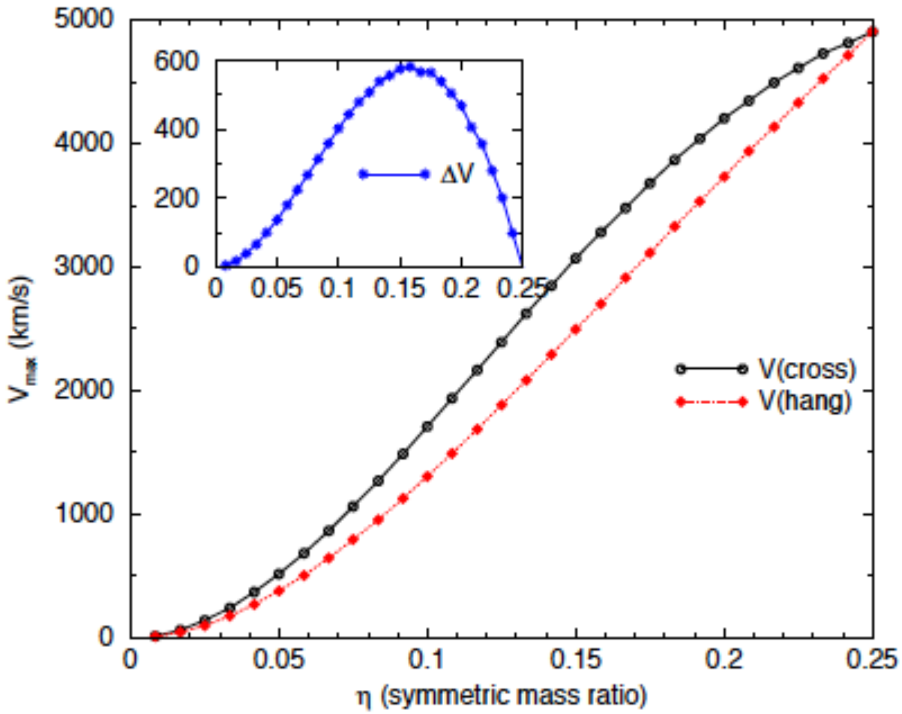


TABLE IX: Comparison between the predicted probabilities for a recoil in a given range as from the *hangup kick* and *cross kick* formulas for hot (top) and cold (bottom) accretion.

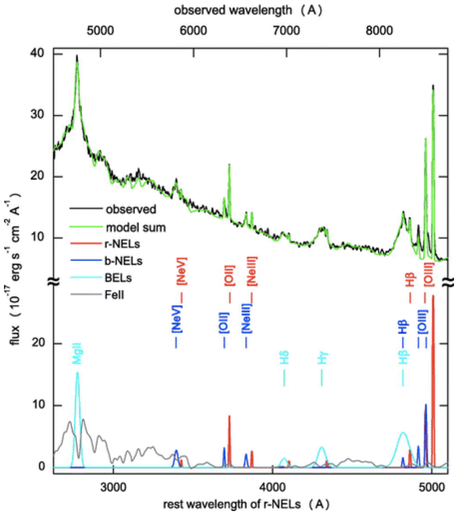
Range	P(cross)	P(cross obs)	P(hang)	P(hang obs)
0-500	77.000%	91.301%	80.871%	93.210%
500-100	15.564%	6.903%	13.843%	5.623%
1000-2000	6.930%	1.741%	5.046%	1.143%
2000-3000	0.498%	0.055%	0.237%	0.025%
3000-4000	0.007%	$3.5 \cdot 10^{-4}\%$	0.003%	$10^{-4}\%$
0-500	91.193%	97.765%	93.657%	98.522%
500-100	7.974%	2.114%	5.919%	1.423%
1000-2000	0.832%	0.120%	0.423%	0.055%
2000-3000	0.002%	$1.3 \cdot 10^{-4}$	$4.7 \cdot 10^{-4}\%$	0 %
3000-4000	0%	0%	0%	0%

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

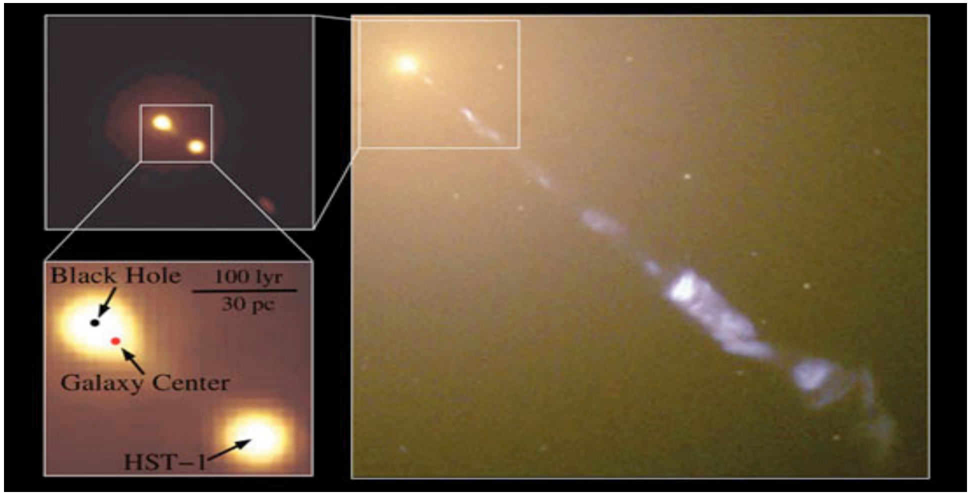
Lousto & Zlochower (2012): 83-New precessing BHB runs add a cross-kick term

BH Kicks as Post-Merger Signatures

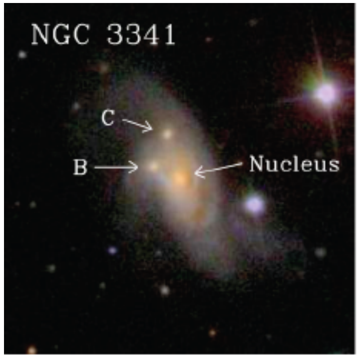
- Recoiling BHs can retain a massive accretion disk. The disk will fuel a lasting QSO phase while the BH wanders far from the galactic nucleus.
- There are relatively few observations of kick candidates:



- 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

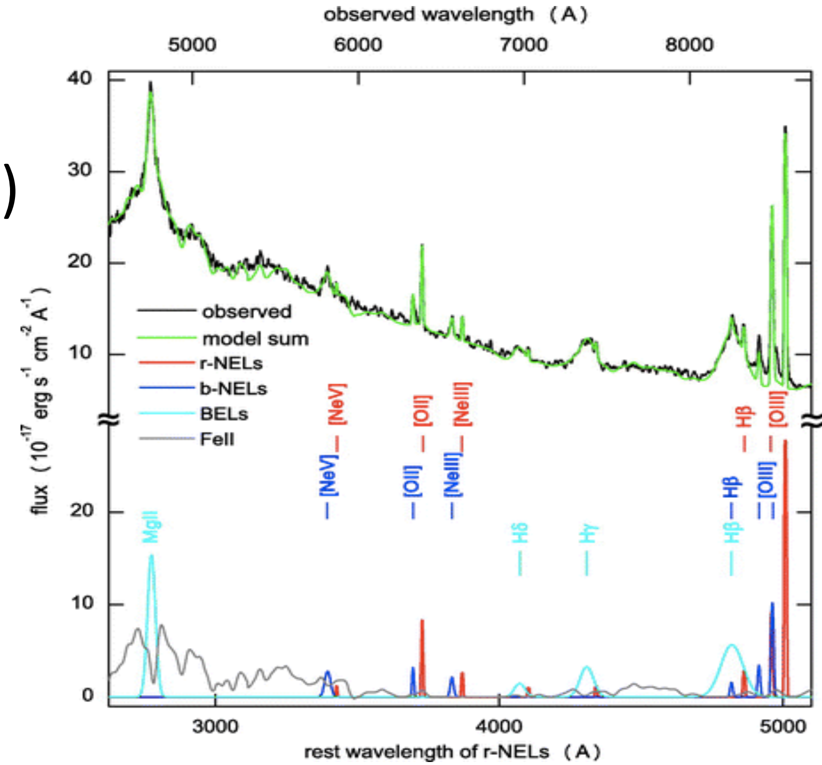


- HST image of a displaced SMBH in M87 [Batchelor et al, ApJL 2010]; Kick due postmerger ot jet?
- More off-set nuclei [Barth et al. 2008]



Observational evidence

- Komossa et al (2008),
- Shield et al (2009), Civano et al (2010)
- Surveys
  - Eracleous et al (2011)
    - DV>1000km/s. 88 objects,
    - 68 spectra -14 binaries
  - Tsalmantza et al (2011)
    - SDSS, 32 objects -9 binaries



- Komossa (2012) compact review of observations of recoil

This observations could well be the first confirmation of highly dynamic, nonlinear (strong field), predictions of GR (NR)!

Happy young 60th Birthday!