Gravitational Recoil and Astrophysical impact

U. Sperhake

DAMTP, University of Cambridge

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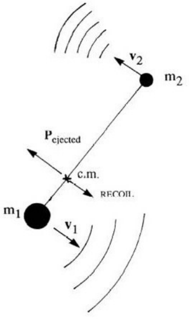
Overview

- Introduction and motivation
- Calculation of the recoil
- Suppression of superkicks
- Unknown
- Unknown
- Conclusions

1. Introduction, motivation

Gravitational recoil

- Recoil = move abruptly backward as a reaction on firing a bullet, shell, or other missile



- Anisotropic GW emission
  $\Rightarrow$ Gravitational recoil
- Here: Black-hole binary kicks
  Also relevant for supernovae

Gravitational recoil

- Anisotropic GW emission $\Rightarrow$ recoil of remnant BH

  Bonnor & Rotenburg 1961,   Peres 1962,   Bekenstein 1973

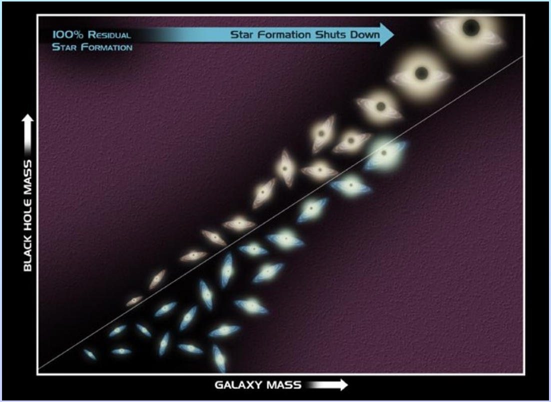
- Escape velocities:

Globular clusters	30 $\mathrm{km/s}$
dSph	20 – 100 $\mathrm{km/s}$
dE	100 – 300 $\mathrm{km/s}$
Giant galaxies	$\sim$ 1000 $\mathrm{km/s}$

- Ejection / displacement of BH

Motivation: Galaxies harbor BHs

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



Motivation: Formation history of SMBHs

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

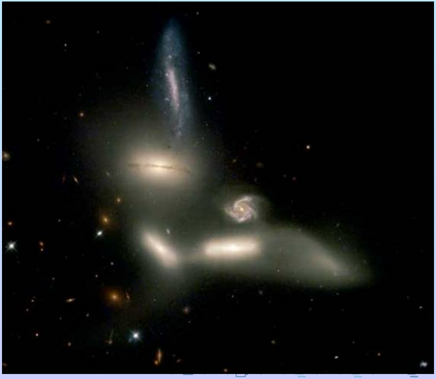
large kicks

$\Rightarrow$ ejection of BHs

$\Rightarrow$ BH assembly possible?

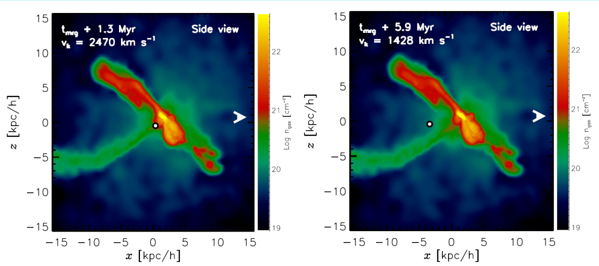
Higher accretion needed?

E.g. Merrit et al 2004



Motivation: Ejection of SMBHs

recoil AGN (Blecha et al) double AGN



- Doppler shifts of BLR vs. NLR: 2 650 $\mathrm{km/s}$; Komossa *et al.* 2008
- Galaxy CID-42: Double AGN or recoiling AGN? Blecha *et al.* 2012
- BH wandering from NGC 1275 to NGC 1277? Shields & Bonning 2013
- Review: Komossa 2012

Motivation: BH ejection, BH populations

- Hierarchical growth $\Rightarrow$ BH mergers
- Most massive dark matter halos at $z \geq 11$:

  BHs not retained if $v_{\rm kick} \gtrsim 150~{\rm km/s}$

  $\Rightarrow$ Even modest kicks suppress SMHB growth from seed BHs

  $\Rightarrow$ $>$Eddington accretion needed to assemble SMBHs by $z \approx 6$?

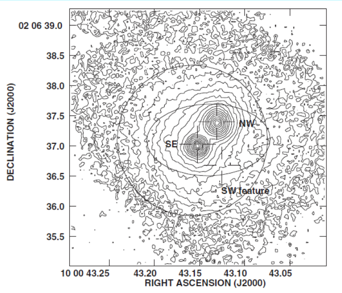
  e.g. Merrit et al 2004 , Micic et al 2006
- Ejection affects BH populations

  e.g. Holley-Bockelmann et al 2008 , Miller & Lauburg 2009
- BH depeleted globular clusters? e.g. Mandel et al 2008
- Kicks impact event rates for GW observatories

Motivation: Displacement of SMBHs, Elm signature

- Quasars kinematically or spatially offset from host galaxy
- E.g. COSMOSJ1000+0206: 2 optical nuclei, 2 kpc apart

  Wrobel 2014



- Moving BH ⇒ tidal disruption of star ⇒ X ray flares

  Komossa & Bade 1999 , Bloom et al 2011 , Komossa & Merrit 2008a ,

- BHs oscillating on scale of accretion torus ⇒ repeated flares

  Komossa & Merrit 2008b

- BH velocity relative to accreted gas Lora-Calvijo & Guzman 2013

2. Calculation of kicks

Influential work pre NR

- Non-spinning, equal-mass BH binaries

  $\Rightarrow$ no kick by symmetry

  $\Rightarrow$ Symmetry breaking through mass ratio or spins

- Quasi-Newtonian calculation for unequal masses (no spins)

  Fitchett 1983

  $$v_{\rm kick} = A\eta^2\sqrt{1-4\eta}(1+B\eta)\,, \quad \eta = \frac{q}{(1+q)^2}\,, \quad q = \frac{m_2}{m_1}$$

  But: Amplitude unclear.

- PN calculations including spin-orbit coupling

  Kidder 1995

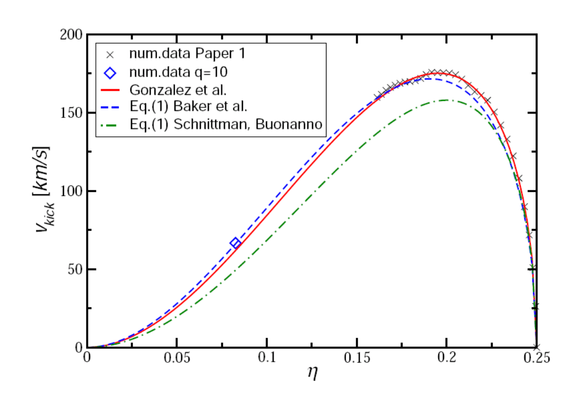
  $$\frac{d\boldsymbol{P}}{dt} = \frac{d\boldsymbol{P}_{\rm F}}{dt} + \frac{d\boldsymbol{P}_{SO}}{dt}\,, \quad \frac{d\boldsymbol{P}_{\rm F}}{dt} = \text{Fitchett}\,, \quad \frac{d\boldsymbol{P}_{SO}}{dt} = \text{spin-orbit contr.}$$

Kicks from non-spinning BHs

- NR simulations for BH binaries with $q \in [0.1, 1]$

  $\Rightarrow$ Max. kick: $\sim 175\ km/s$ for $q = 0.36$

  González et al 2007a, 2009



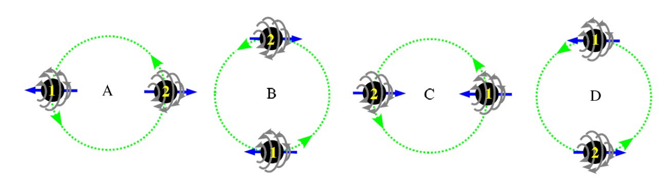
Kicks from spinning BHs

- Spins $\boldsymbol{S}||\boldsymbol{L}$ but $\boldsymbol{S}_1 \neq \boldsymbol{S}_2$

  $\Rightarrow$ kicks up to $v_{\rm kick} \lesssim 500~\rm km/s$

  Herrmann *et al* 2007 , Koppitz *et al* 2007

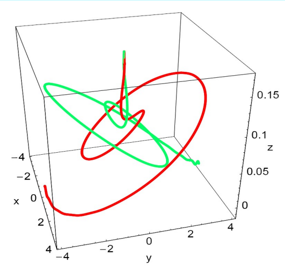
- Kidder 1995, Campanelli et al 2007a: maximum kick expected for



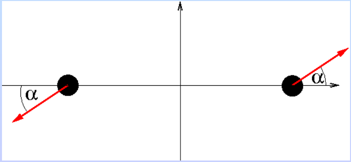
"Superkicks": $\boldsymbol{S}_1 = -\boldsymbol{S}_2$ in orbital plane

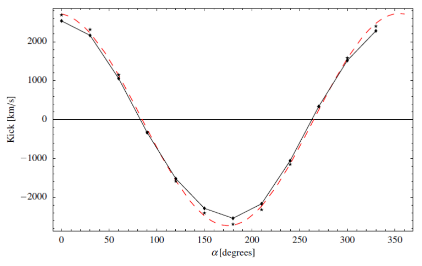
Superkicks

- Measured: $v_{\text{kick}} \approx 2\,500\ \text{km}/\text{s}$
  Extrapolated maximum: $\sim 4\,000\ \text{km}/\text{s}$
  González et al 2007b , Campanelli et al 2007b



- Sinusoidal dependency on spin orientation α

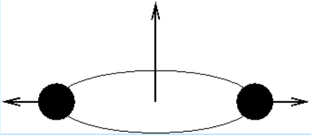




Even larger kicks: superkick and hang-up

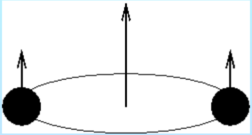
Lousto & Zlochower, PRL **107** 231102

Superkicks

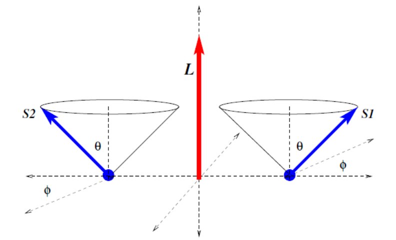


- Moderate GW generation
- Large kicks

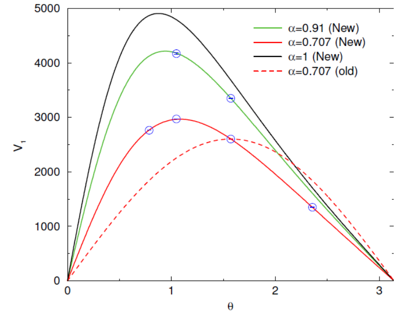
Hangup



- Strong GW generation
- No kicks



Superkicks and orbital hang-up



- Maximum kick about 25 % larger: $v_{\rm max} \approx 5\,000$ km/s
- Distribution asymmetric in θ; v_{max} for partial alignment
- Higher order corrections to hang-up kick

  $\Rightarrow$ Further 10 % increase "Cross-kick"

  Lousto & Zlochower 2013

Fitting formulae for the kick

- Goal: Machine, in: BH parameters, out: v_{kick}
- Campanelli 2007b

$$\vec{V}_{\text{kick}}(q,\vec{\alpha}_i) = v_m \boldsymbol{e}_1 + v_\perp \left[\cos\xi\, \boldsymbol{e}_1 + \sin\xi\, \boldsymbol{e}_2\right] + v_{||}\boldsymbol{e}_{||}\,,$$

$$v_m = A\frac{q^2(1-q)}{(1+q)^5}\left[1 + B\frac{q}{(1+q)^2}\right]\,,$$

$$v_\perp = H\frac{q^2}{(1+q)^5}\left(\alpha_2^{||} - q\alpha_1^{||}\right)\,,$$

$$v_{||} = K\cos(\Theta - \Theta_0)\frac{q^2}{(1+q)^5}|\vec{\alpha}_2^{\perp} - q\vec{\alpha}_1^{\perp}|$$

- $A = 1.2\times 10^4~\mathrm{km/s}\,,~ B = -0.93\,,~ H = 7.3\times 10^3~\mathrm{km/s}\,,~ \xi \sim 145^\circ$
  $\vec{\alpha}_i = \boldsymbol{S}_i/m_i^2\,,~ \Theta =$ infall angle

Fitting formulae for the kick

Extensions of the fitting formula

- Systematic spin expansion,

  exploit symmetry conditions to reduce terms Boyle, Kesden & Nissanke 2007, 2007a

- Calibration of higher-order spin terms,

  $\sim$ 100 NR simulations ($q = 1$) Lousto & Zlochower 2013

- Ongoing work; more simulations required

3. Open questions

Open problems with current kick predictions

- Mass ratio q
  - Current calibration through $q = 1$ runs
  - Predictions for $q < 1$ uncertain; too large?
  - Solution: More runs
- BH parameters
  - Fitting formulae apply to parameters shortly before merger
  - Astrophysical BH parameters apply to large separations
  - What happens to the statistical spin distribution during inspiral?
- Almost all galaxies harbor BHs
  - Superkicks easily eject BHs from giant hosts
  - Why are BHs still there?

- Superkicks easily eject BHs from their host galaxies
- But: Almost all observed galaxies host BHs
- How probable are superkicks?
  - EOB study of $q \in [0.1, 1]$, $\alpha_i = 0.9$

    $\Rightarrow \sim 3\,\%$ with $v_{\rm kick} > 500\ {\rm km/s}$, $\sim 12\,\%$ with $v_{\rm kick} > 1\,000\ {\rm km/s}$

    Schnittman & Buonanno 2007
  - Gas-rich mergers tend to align $\boldsymbol{S}_{1,2}$ with $\boldsymbol{L}$

    10 (30)$^\circ$ residual misalignment for cold (hot) gas

    $\Rightarrow$ superkick suppression

    Bogdanović et al 2010, Dotti et al 2009
  - PN inspiral of isotropic BH ensemble remains isotropic

    Bogdanović et al 2010

    But: How about non-isotropic ensembles?

4. Spin orbit resonances

Parameters of a black-hole binary

10 intrinsic parameters for quasi-circular orbits

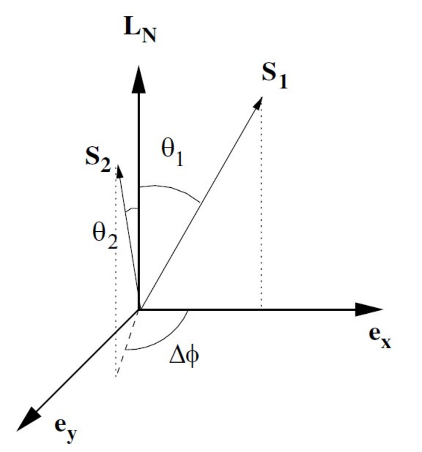
- 2 masses m_1, m_2
- 6 for two spins $\mathbf{S}_1$, $\mathbf{S}_2$
- 2 for the direction of the orbital ang. mom. $\hat{\mathbf{L}}$.

Elimination of parameters in PN inspiral

- 1 mass; scale invariance
- 2 for $\hat{\mathbf{L}}$; fix z axis
- 2 spin magnitudes, 1 mass ratio q; conserved
- 1 spin direction; fix x axis

Evolution variables

⇒ Three variables: θ_1, θ_2, $\Delta\phi$



Evolution equations

$$\frac{d\mathbf{S}_1}{dt} = \boldsymbol{\Omega}_1 \times \mathbf{S}_1, \qquad M\boldsymbol{\Omega}_1 = \eta v^5 \left(2 + \frac{3q}{2}\right)\hat{\mathbf{L}} + \frac{v^6}{2M^2}\left[\mathbf{S}_2 - 3\left(\hat{\mathbf{L}}\cdot\mathbf{S}_2\right)\hat{\mathbf{L}} - 3q\left(\hat{\mathbf{L}}\cdot\mathbf{S}_1\right)\hat{\mathbf{L}}\right];$$

$$\frac{d\mathbf{S}_2}{dt} = \boldsymbol{\Omega}_2 \times \mathbf{S}_2, \qquad M\boldsymbol{\Omega}_2 = \eta v^5 \left(2 + \frac{3}{2q}\right)\hat{\mathbf{L}} + \frac{v^6}{2M^2}\left[\mathbf{S}_1 - 3\left(\hat{\mathbf{L}}\cdot\mathbf{S}_1\right)\hat{\mathbf{L}} - \frac{3}{q}\left(\hat{\mathbf{L}}\cdot\mathbf{S}_2\right)\hat{\mathbf{L}}\right];$$

$$\frac{d\hat{\mathbf{L}}}{dt} = -\frac{v}{\eta M^2}\frac{d}{dt}(\mathbf{S}_1 + \mathbf{S}_2);$$

$$\begin{aligned}
\frac{dv}{dt} = \frac{32}{5}\frac{\eta}{M}v^9\Bigg\{ & 1 - v^2\frac{743 + 924\eta}{336} + v^3\left[4\pi - \sum_{i=1,2}\chi_i(\hat{\mathbf{S}}_i\cdot\hat{\mathbf{L}})\left(\frac{113}{12}\frac{m_i^2}{M^2} + \frac{25}{4}\eta\right)\right] \\
& + v^4\left[\frac{34103}{18144} + \frac{13661}{2016}\eta + \frac{59}{18}\eta^2 + \frac{\eta\chi_1\chi_2}{48}\left(721(\hat{\mathbf{S}}_1\cdot\hat{\mathbf{L}})(\hat{\mathbf{S}}_2\cdot\hat{\mathbf{L}}) - 247(\hat{\mathbf{S}}_1\cdot\hat{\mathbf{S}}_2)\right)\right. \\
& \left. + \frac{1}{96}\sum_{i=1,2}\left(\frac{m_i\chi_i}{M}\right)^2\left(719(\hat{\mathbf{S}}_i\cdot\hat{\mathbf{L}})^2 - 233\right)\right] - v^5\pi\frac{4159 + 15876\eta}{672} \\
& + v^6\left[\frac{16447322263}{139708800} + \frac{16}{3}\pi^2 - \frac{1712}{105}(\gamma_E + \ln 4v) + \left(\frac{451}{48}\pi^2 - \frac{56198689}{217728}\right)\eta + \frac{541}{896}\eta^2 - \frac{5605}{2592}\eta^3\right] \\
& + v^7\pi\left[-\frac{4415}{4032} + \frac{358675}{6048}\eta + \frac{91495}{1512}\eta^2\right] + O(v^8)\Bigg\};
\end{aligned}$$

- 2.5 PN: precessional motion about $\hat{\mathbf{L}}$
- 3 PN: spin-orbit coupling

Schnittman's resonances

Schnittman '04

For a given separation r of the binary, resonances are

- $\mathbf{S}_1,\ \mathbf{S}_2,\ \hat{\mathbf{L}}_N$ lie in a plane $\Rightarrow \Delta\phi = 0^\circ, \pm 180^\circ$
- Resonance condition: $\ddot{\theta}_{12} = \dot{\theta}_{12} = 0$ Apostolatos '96, Schnittman '04
- $\Delta\phi = 0^\circ$ resonances: always $\theta_1 < \theta_2$

  $\Delta\phi = \pm 180^\circ$ resonances: always $\theta_1 > \theta_2$
- The resonance $\theta_1,\ \theta_2$ vary with r or $\mathbf{L}_N$

  $\Rightarrow$ Resonances sweep through parameter plane
- Time scales: $t_{\rm orb} \ll t_{\rm pr} \ll t_{\rm GW}$

  $\Rightarrow$ "Free" binaries can get caught by resonance

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

$\theta_i := \angle(\vec{S}_i, \vec{L}_N)$

$\theta_1 = \theta_2$

$\mathbf{S} \cdot \mathbf{L}_N = \text{const}$

$\mathbf{S}_0 \cdot \mathbf{L}_N = \text{const}$

evolution

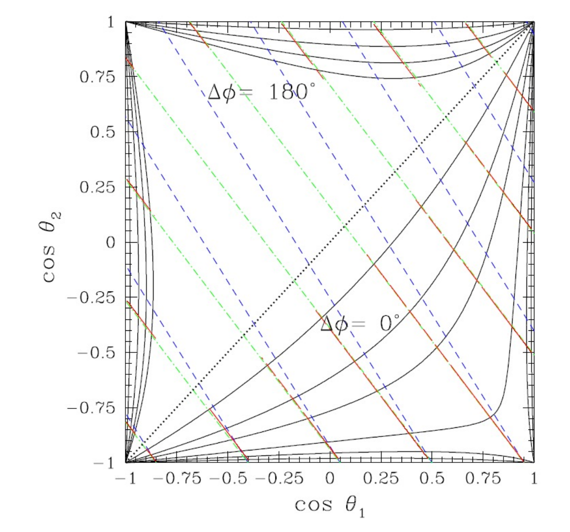
$\Rightarrow$ BHs approach

$\theta_1 = \theta_2$

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

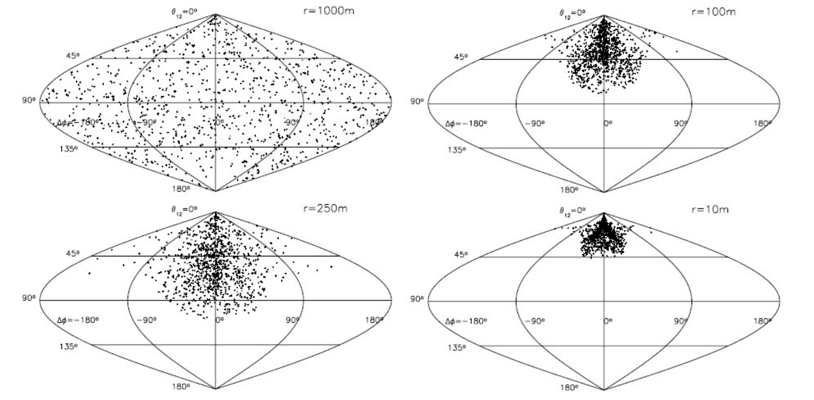
if θ_1 small

Kesden, US & Berti ’10



Resonance capture: $\Delta\phi = 0^\circ$

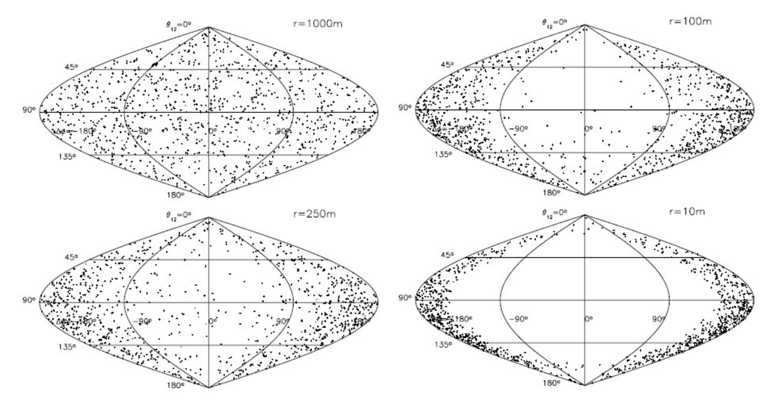
$q = 9/11$, $\chi_i = 1$, $\theta_1(t_0) = 10^\circ$, rest random



Schnittman '04

Resonance capture: $\Delta\phi = 180^\circ$

$q = 9/11$, $\chi_i = 1$, $\theta_1(t_0) = 170^\circ$, rest random



Schnittman '04

Consequences of resonances

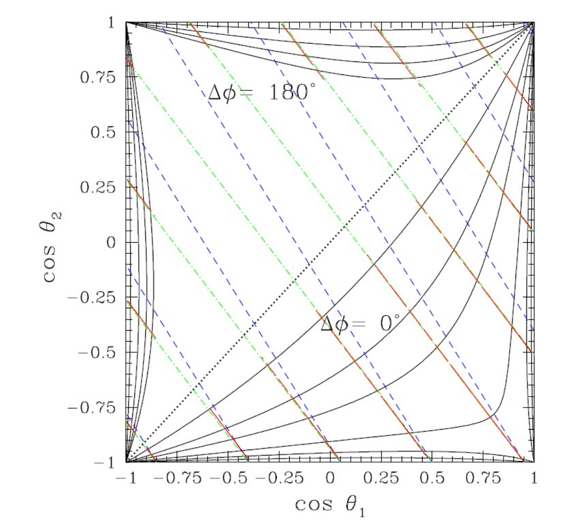
EOB spin

$\mathbf{S_0} = \frac{M}{m_1}\mathbf{S}_1 + \frac{M}{m_2}\mathbf{S}_2$

$\mathbf{S_0} \cdot \mathbf{L_N} = \mathrm{const}$

evolution

$\Rightarrow \mathbf{S}_0 \ \sim$conserved



Consequences of resonances

Total spin

$\mathbf{S} = \mathbf{S}_1 + \mathbf{S}_2$

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

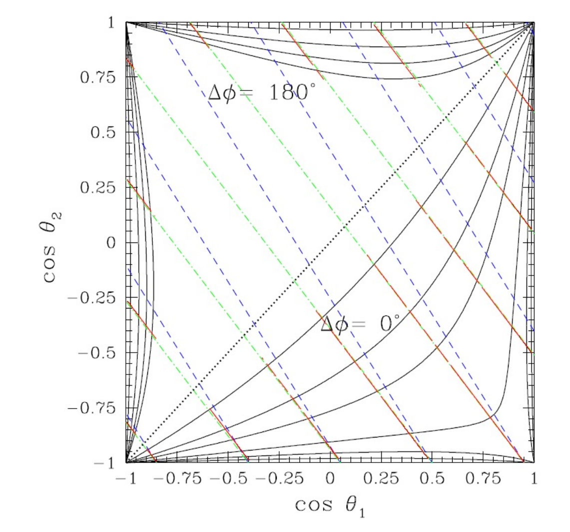
evolution

blue steeper red

$\Rightarrow$ **S**, $\mathbf{L}_N$ become

antialigned; $\Delta\phi = 0^\circ$

aligned; $\Delta\phi = 180^\circ$



Consequences of resonances

r decreases

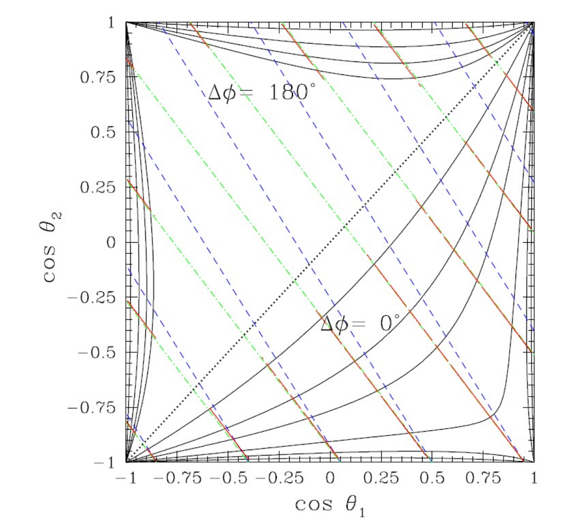
$\Rightarrow\ \theta_1, \theta_2 \rightarrow$ diagonal

i.e. $\theta_1 = \theta_2$

$\Rightarrow$ $\mathbf{S}_1,\ \mathbf{S}_2$ become

aligned; $\Delta\phi = 0^\circ$

$\theta_{12} = \theta_1 + \theta_2;\ \ \Delta\phi = 180^\circ$



Summary: Resonances

- $\mathbf{S}_1$, $\mathbf{S}_2$, $\mathbf{L}_N$ precess in plane
- 2 types: I) $\Delta\phi = 0°$, II) $\Delta\phi = 180°$
- Free binaries can get caught by resonances
- Consequences for $\Delta\phi = 0°$
  - $\mathbf{S}_1$, $\mathbf{S}_2$ aligned
  - $\mathbf{S}$, $\mathbf{L}_N$ antialigned
- Consequences for $\Delta\phi = 180°$
  - $\mathbf{S}_1$, $\mathbf{S}_2$ approach $\theta_{12} = \theta_1 + \theta_2$
  - $\mathbf{S}$, $\mathbf{L}_N$ aligned

5. Suppression of superkicks

Setup

- BBHs inspiral from 1000 M to 10 M
- Ensemble 1: $10 \times 10 \times 10$ isotropic
- Ensemble 2: 30×30 isotropic in θ_2, $\Delta\phi$

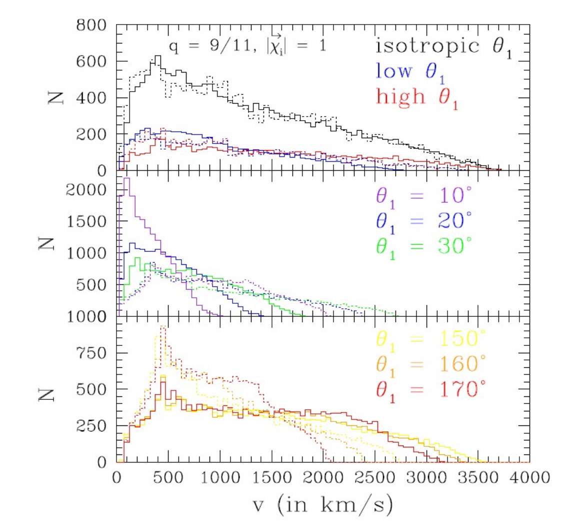
  fix $\theta_1(t_0) = 170°, 160°, 150°, 30°, 20°, 10°$
- Map $\mathbf{S}_1$, $\mathbf{S}_2$, q to v_{kick}

  $\vec{v}(q, \chi_1, \chi_2) = v_m \hat{\mathbf{e}}_1 + v_\perp(\cos\xi \hat{\mathbf{e}}_1 + \sin\xi \hat{\mathbf{e}}_2) + v_{||}\hat{\mathbf{e}}_z$

  $v_{||} \sim |\mathbf{\Delta}^\perp|, \qquad \mathbf{\Delta} = \frac{q\chi_2 - \chi_1}{1+q}$

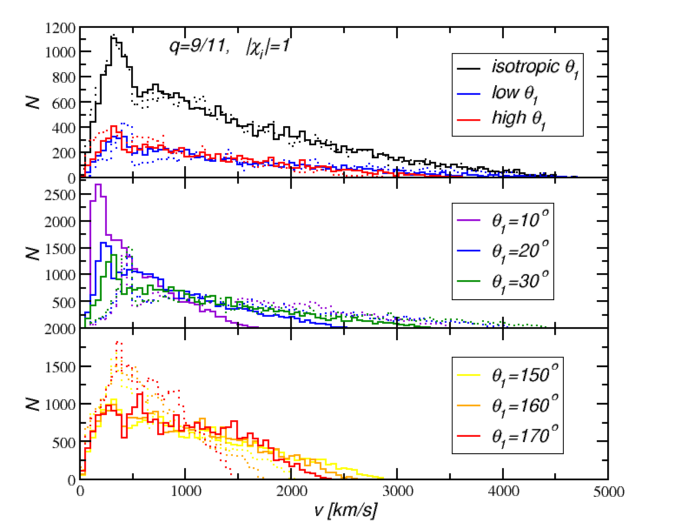
  Campanelli, Lousto, Zlochower & Merritt '07

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



Kesden, US & Berti 2010

Same game for hang-up kicks: $q = \frac{9}{11}$



Berti, Kesden & US 2012

Summary: Kick suppression

- Resonances attract aligned (anti aligned) configurations towards $\Delta\phi = 0^\circ$ (180°)
- Superkicks suppressed (enhanced) for $\Delta\phi = 0^\circ$ $(\Delta\phi = 180^\circ)$ resonances
- If accretion torque partially aligns $\vec{S}_1$ with $\vec{L}_N$ $\Rightarrow \Delta\phi = 0^\circ$ resonances dominate and suppress kicks
- Kick suppression still effective for hang-up kicks
- Why? Because the key angle is $\Delta\phi$

6. Conclusions

Conlcusions

- Kicks important for many astrophysical scenarios

  BH ejection, BH populations, SMBH assembly, galaxy struxture
- Kicks generate through asymmetry: mass ratio, spins
- Superkicks: $v_{\rm kick}$ up to $4\,000~{\rm km/s}$, Hangup kicks: $5\,000~{\rm km/s}$
- Kick formulae: apply to late inspiral
- Gas disks $\Rightarrow$ spin alignment
- Spin-orbit resonances

  $\Rightarrow$ change spin distribution

  $\Rightarrow$ can suppress superkicks
- Open questions: q dependence, spin distribution