Gravitational recoil in the coalescence of astrophysical black-hole binaries

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Overview

- Black holes
- The recoil effect
- Black holes in astrophysics
  - MBH formation history
  - BH populations
  - Structure of galaxies
- Results on gravitational recoil
  - Analytic predictions
  - Numerical results: non-spinning binaries
  - Numerical results: spins
- Discussion…

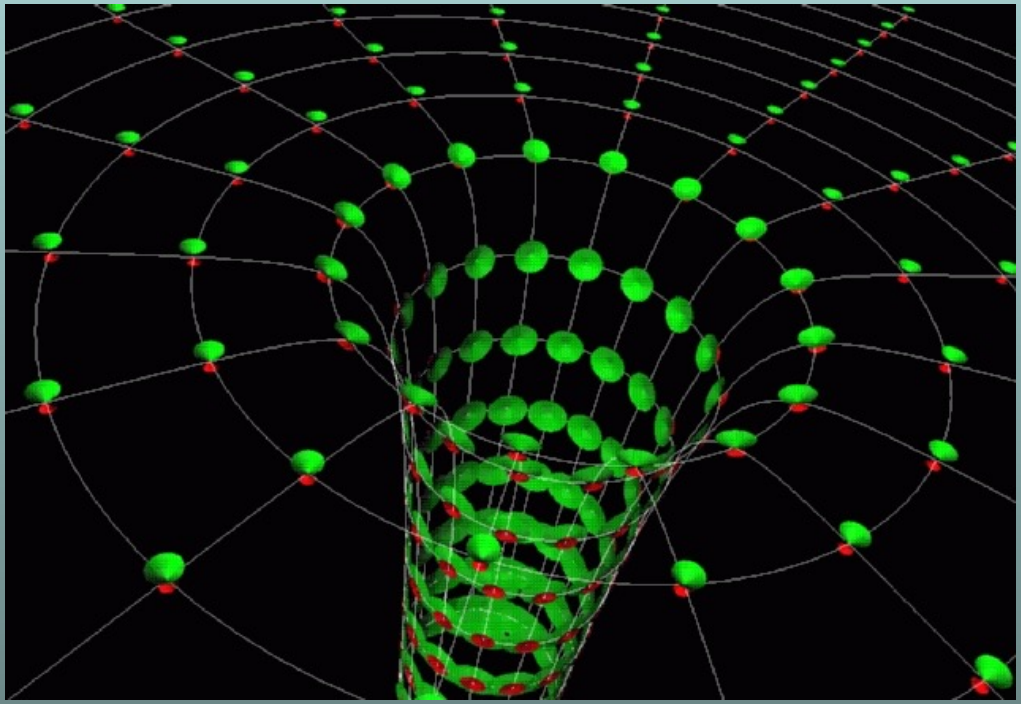
1. Black Holes

What are black holes?

- General Relativity

  $\Rightarrow$ Gravitation via spacetime curvature, no force!

- Regions of extreme curvature $\Rightarrow$ black hole



- Mathematical: Event horizon, apparent horizon

Black hole solutions

- Mathematical solutions of Einstein's equations

$$ds^2 = -\left(1 - \frac{2M}{r}\right)dt^2 + \left(1 - \frac{2M}{r}\right)^{-1} dr^2 + r^2\left(d\theta^2 + \sin^2\theta \, d\phi^2\right)$$

Schwarzschild 1916

- With charge and/or spin

Reissner & Nordström 1916
Kerr 1963
Kerr-Newman 1965

- Just a mathematical curiosity or physically real?

- Renaissance in the last 20-30 years!

What about black-hole binaries?

- Numerical Relativity necessary to simulate BBHs!!
- Pioneers: Hahn, Lindquist ’60s, Eppley, Smarr et.al. ‘70s

  Expected problem to be solved with bigger computers
- Instabilities for several decades

  Problems not common in other computational physics

  (gauge, formulation of equations,…)
- Breakthrough

  Pretorius ‘05,
  Brownsville ‘05, Goddard ‘05

BBH inspiral now routinely performed by about 10 groups

Pretorius, RIT, Goddard, Penn State, **U.S. (Lean), Jena (BAM),**
Potsdam-Louisiana, Caltech-Cornell, Urbana-Champaign

Black-hole binaries

- Black holes orbiting each other emit GWs

  ⇒ The orbit shrinks

  Indirect proof of GR via Neutron Star inspiral

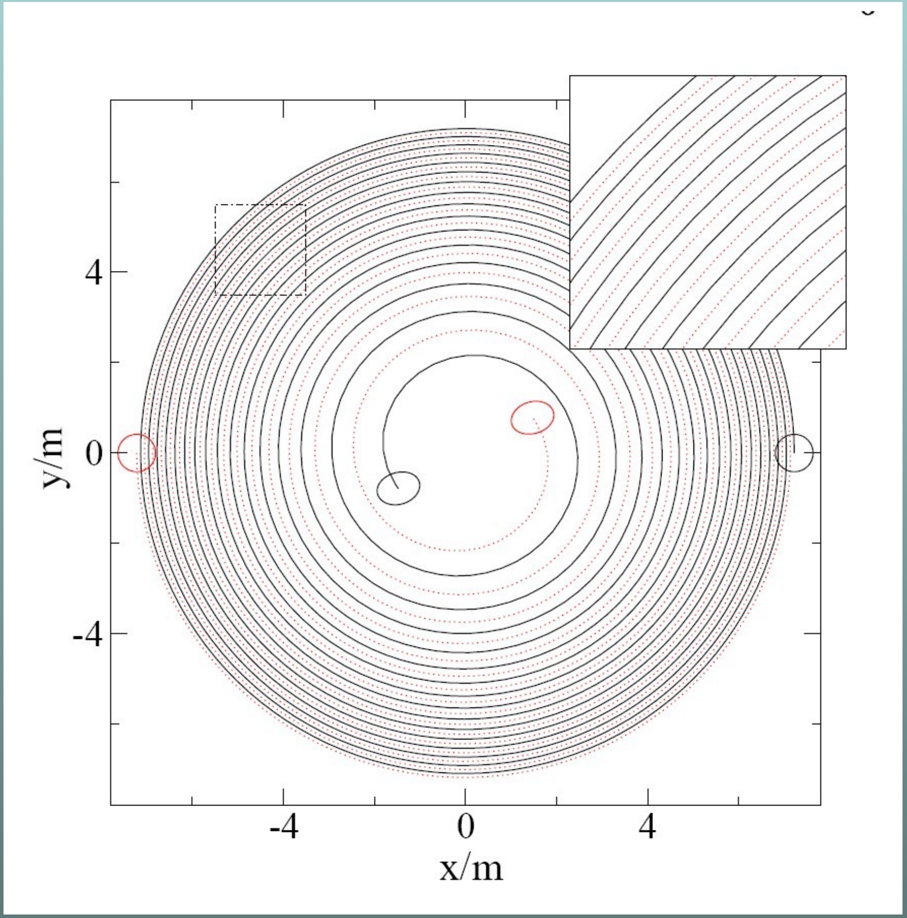
  Hulse & Taylor

  Nobel Prize 1993

- Requires solution of Einstein equations

  Most complex system of Eqs. In physics

  ⇒ Numerics!

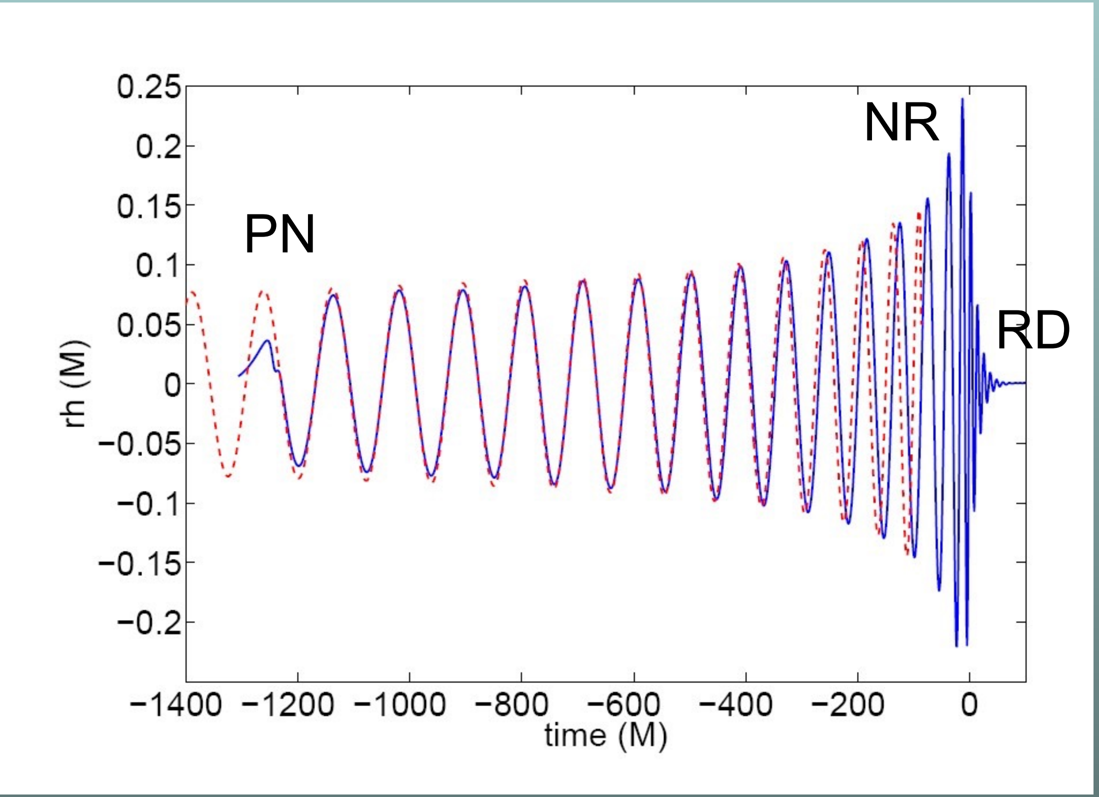


Caltech-Cornell

The anatomy of a BBH inspiral

- Two black holes from a bound system
- Orbit shrinks due to three-body-interactions, gas,…
- Eventually, GW emission dominates energy loss
- Still many orbits (thousands, millions) $\Rightarrow$ circularization
- Merger into one hole
- Ringdown

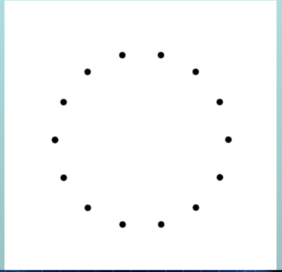
Three stages
of a BBH inspiral

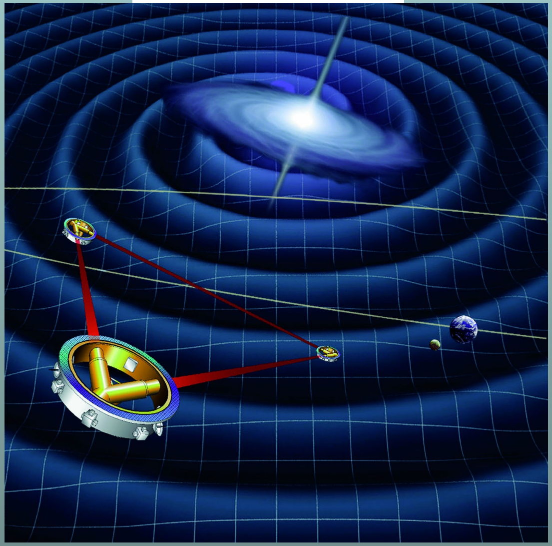


Gravitational Wave (GW) Physics

- Einstein $\Rightarrow$ GWs; Analog of electromagn. waves
- Strongest sources merging black holes
- GWs $\Rightarrow$ Change of distances

  < Atomic nucleus in 1 km

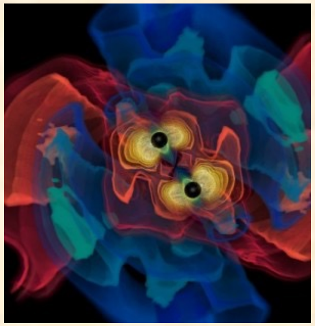




- Latest laser technology: Geo600, LIGO, TAMA, VIRGO
- Space mission: LISA

The big picture

Physical system



observe

Detectors

describes

test

Help detection

Provide info

Model

- GR (NR)
- PN
- Perturbation theory
- Alternative Theories?

External Physics

- Astrophysics
- Fundamental Physics
- Cosmology

2. The recoil effect

Gravitational recoil

- Anisotropic emission of GW carries away linear momentum
  $\Longrightarrow$ recoil of remaining system

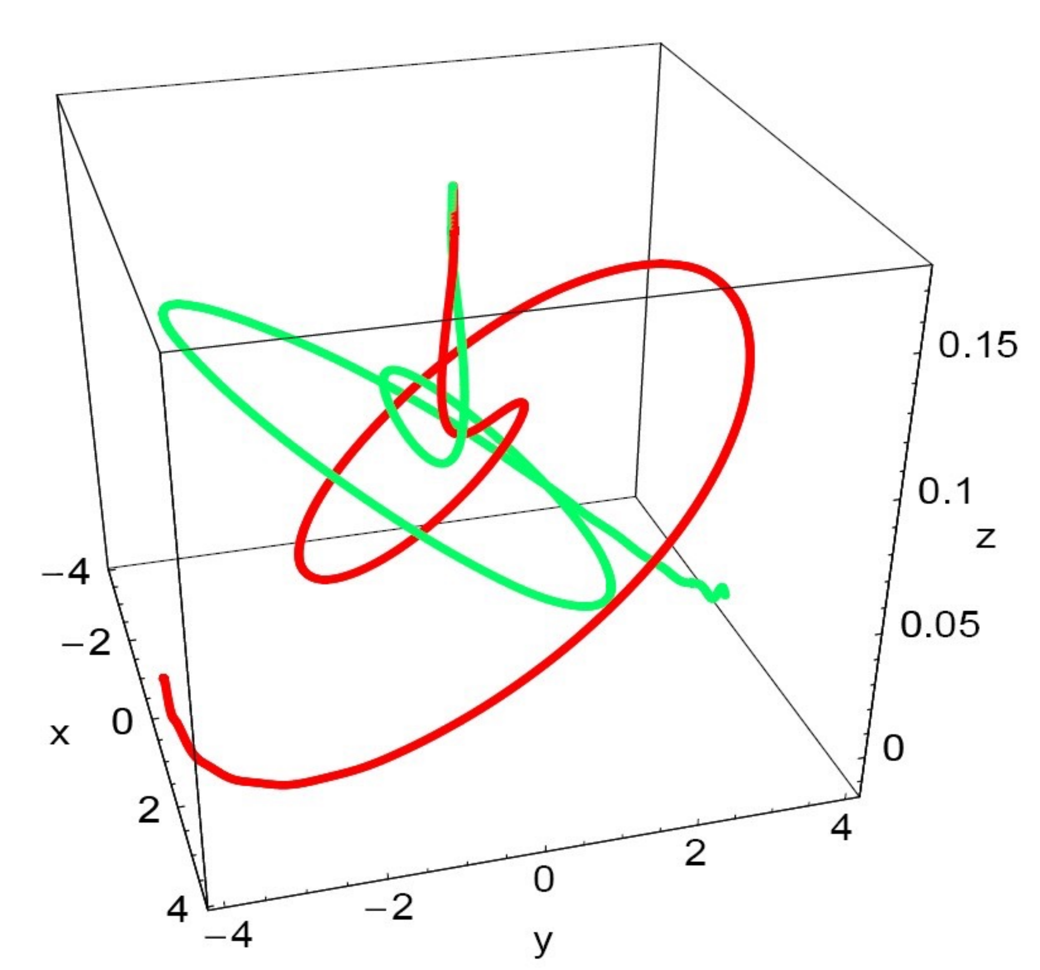
- Lowest order: overlap of mass-quadrupole with mass octupole and/or flow quadrupole
  Bonnor & Rotenburg ’61, Peres ’62, Bekenstein ‘73

- Observations: QSO
  Komossa et al. ‘08
  BH kicked out of galaxy?

  Blueshift of Narrow Line Region
  Relative to Broad Line Region

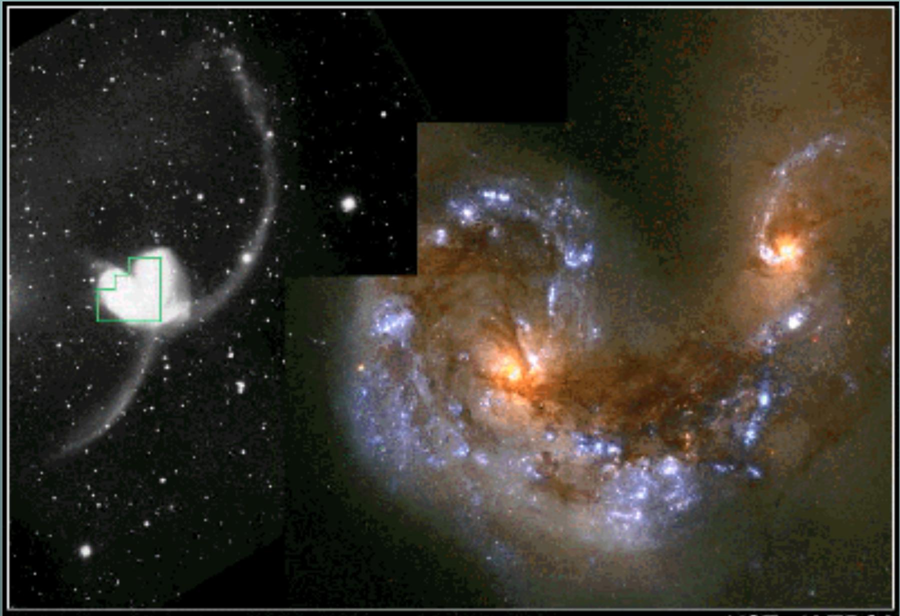
Black hole recoil

- Initial COM frame is not the final COM frame!!!



BBH-inspiral

- SMBH inspiral: Galaxies merge $\Rightarrow$ BHs merge?
  - Early stages: three-body interaction
    Boylan-Kolchin et al.'04
  - Final parsec problem: Does inspiral stop? Probably not!
  - Late stages: GW $\Rightarrow$ kick
  - Possible ejection/displacement from host
- Efficiency depends on
  - Magnitude of kick
  - Depth of potential well



Colliding Galaxies NGC 4038 and NGC 4039 HST • WFPC2
PRC97-34a • ST ScI OPO • October 21, 1997 • B. Whitmore (ST ScI) and NASA

BBH-inspiral

- Escape velocities: globular clusters $30\,\mathrm{km/s}$
  dSph $20-100\,\mathrm{km/s}$
  dE $100-300\,\mathrm{km/s}$
  large galaxies $\approx 1000\,\mathrm{km/s}$

  Merritt et al.'04

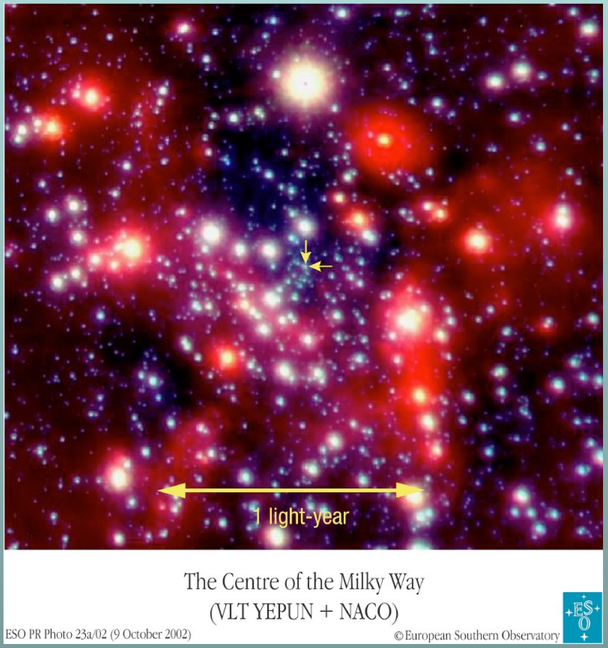
- Higher redshift $\Rightarrow$ DM halos smaller $\Rightarrow$ smaller v_{esc}
- Consequences
  - BH growth via mergers stops
  - Population of intergalactic BHs
  - Event rates for LISA
  - Structure of galactic cores

3. Black Holes in Astrophysics

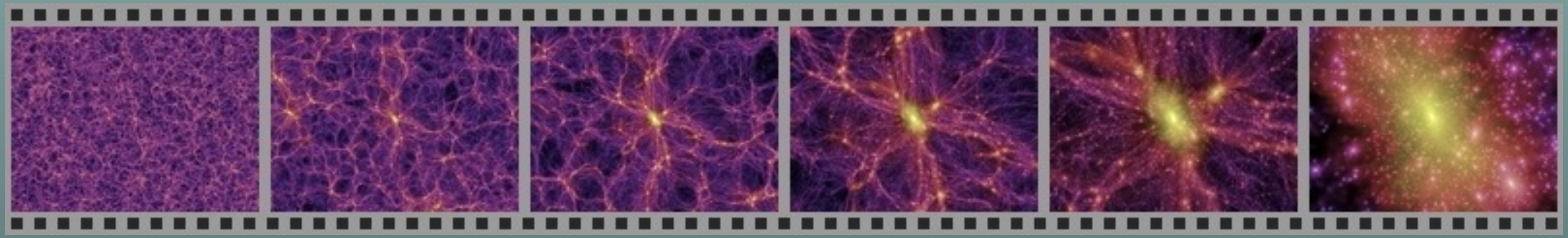
Black holes in astrophysics

- End product of stellar evolution
- Massive black holes in centres of (almost) all galaxies
  - Structure formation
  - Structure of galaxies

    $M_{BH} - \sigma$ Relation
  - Gamma-ray bursts?
  - AGNs
  - BH-formation, populations



The Centre of the Milky Way
(VLT YEPUN + NACO)



MBH formation history

- $z \geq 10$ Seed BHs form in low mass DM halos

  $z \approx 10...6$ Evolution into bright QSOs via halo merger,

  $z \approx 6...0$ Growth into SMBH remnants we observe today

  (e.g. Madau & Quataert '04)

- Problem: Large kicks eject BHs in DM halo mergers at high z

  $\Longrightarrow$ Not enough time for MBHs to grow hierarchically

  Kicks constrain growth models for MBHs; gas accretion?

  Merrit et al. '04, Haiman '04

MBH formation history

- Sloan Digital Sky Survey

  $\Rightarrow$ Quasars with MBHs $> 10^9 M_{\text{sol}}$ exist at $z \approx 6$

- Questions

  When does hierarchical BH-formation start?

  What is the mass of seed BHs?

  Do all progenitor halos have seed BHs?

  Alternative BH growth processes (gas accretion)?

BH populations

- Kicks might deplete globular clusters, galaxies of their BHs

  $\Rightarrow$ Population of interstellar and intergalactic BHs

  e.g. Madau & Quataert ’04, Merritt et al.’04

- Larger kicks allow for larger masses of wandering BHs

- Kicks also affect population of BHs in the galaxies
  - M_{BH} and M_{Bulge} are related linearly
  - Kick leads to deviations from this relation
  - BHs get ejected but regrow $\Rightarrow$ IMBHs?

  Libeskind et al.’06

- Merger event rates, GW detector design?

Structure of galaxies

- Recoil has impact on structure of host stellar bulges
- Density profile of the bulge steep (powerlaw)
- Recoil makes density profile evolve: flattening near centre
- Effect strongest for kicks just below v_{esc}
  - BHs get displaced but fall back
  - Stars follow BH, heating via dynamic friction
- Kicks $100-500\ \mathrm{km/s}$ may cause cores in bright ell. galaxies

  Boylan-Kolchin et al.'04
- Density profiles of early type galaxies show 2 categories: steep profiles and cores
- How can galaxies with steep profiles exist?

  No BHs in small galaxies?

4. Calculation of recoil

4.1. Analytic results

(Semi-)Analytic predictions

- Focus on non-spinning binaries with $q \equiv \frac{M_1}{M_2} \neq 1$
- First efforts: perturbation theory

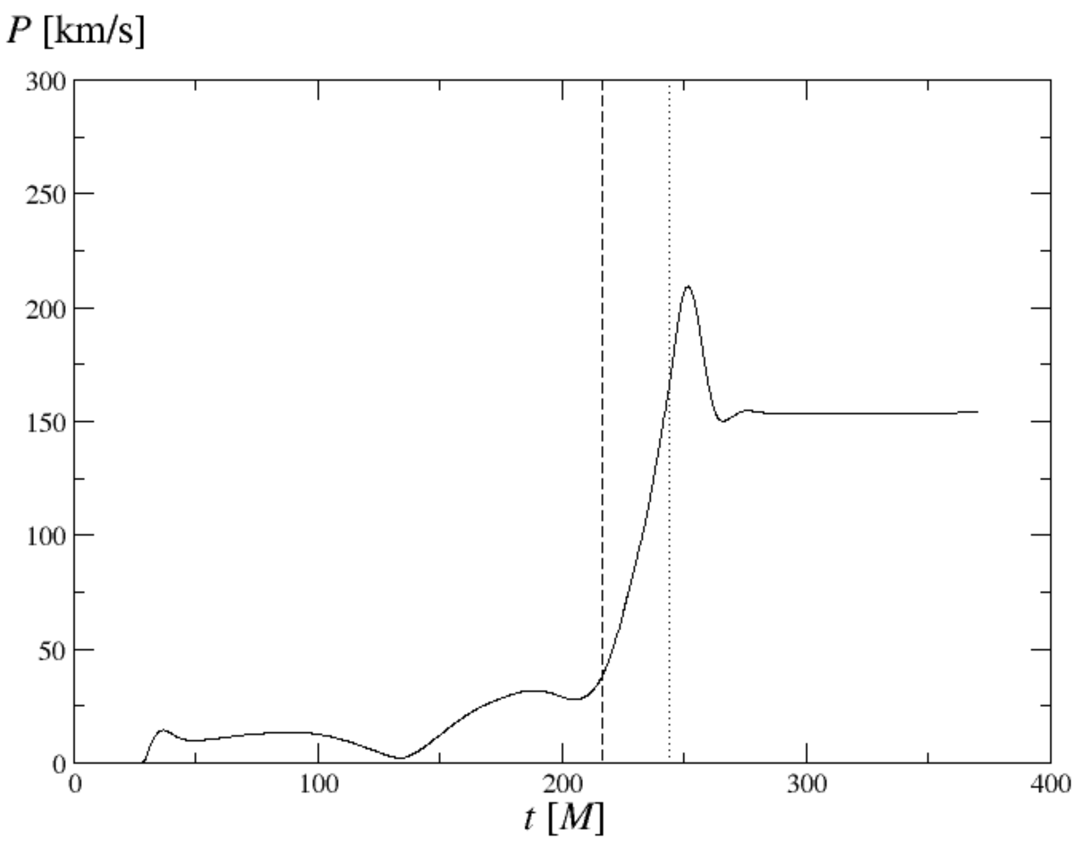
  Moncrief ’79, Nakamura & Haugan ‘82
- First study of binary inspiral Fitchett ’83

  Newtonian analysis of 2 particles using quadrupole formula
- Ensuing studies:
  - Particle approximation
  - Post-Newtonian
  - Close-limit
- Emerging picture: Kicks unlikely to exceed a few $100\,\mathrm{km/s}$
- Impact of spins???

4.2. Numerical results: no spin, unequal masses

Radiated linear momentum

- Typical P_{rad} extracted at large radius



Recoil I: Unequal masses

- Expected mass ratios

$$M_1 / M_2 = 1 \;\; \ldots \;\; 10^6 \qquad \eta := \frac{M_1 M_2}{(M_1 + M_2)^2} = 0.25 \;\; \ldots \;\; 10^{-6}$$

- Numerical study: González, US, Brügmann, Hannam & Husa '07

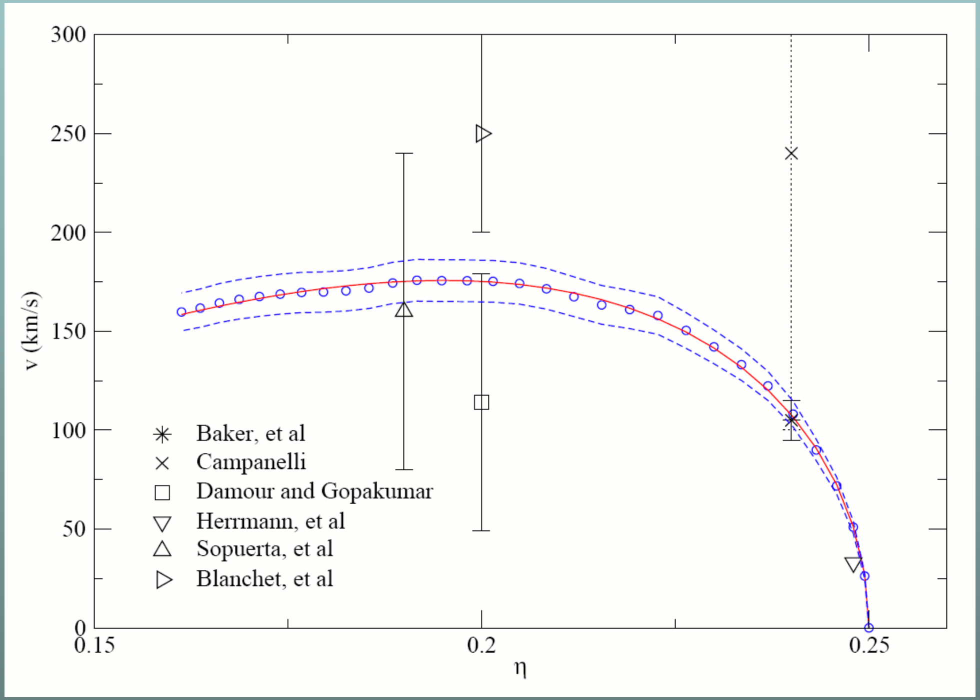
$$M_1 / M_2 = 1 \;\; \ldots \;\; 4$$

- Fit: Fitchett '83

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

- Maximal kick 178 km/s

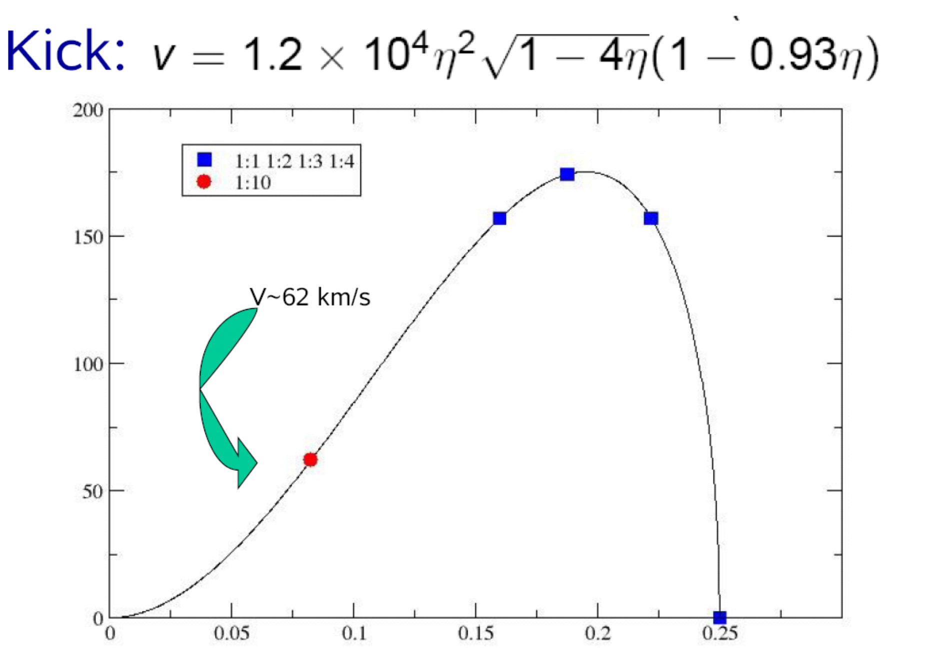
für $M_1 / M_2 \approx 3$



Recoil I: Unequal masses

- What about more extreme mass ratios?

González, US & Brügmann '08 $M_1 / M_2 = 10$



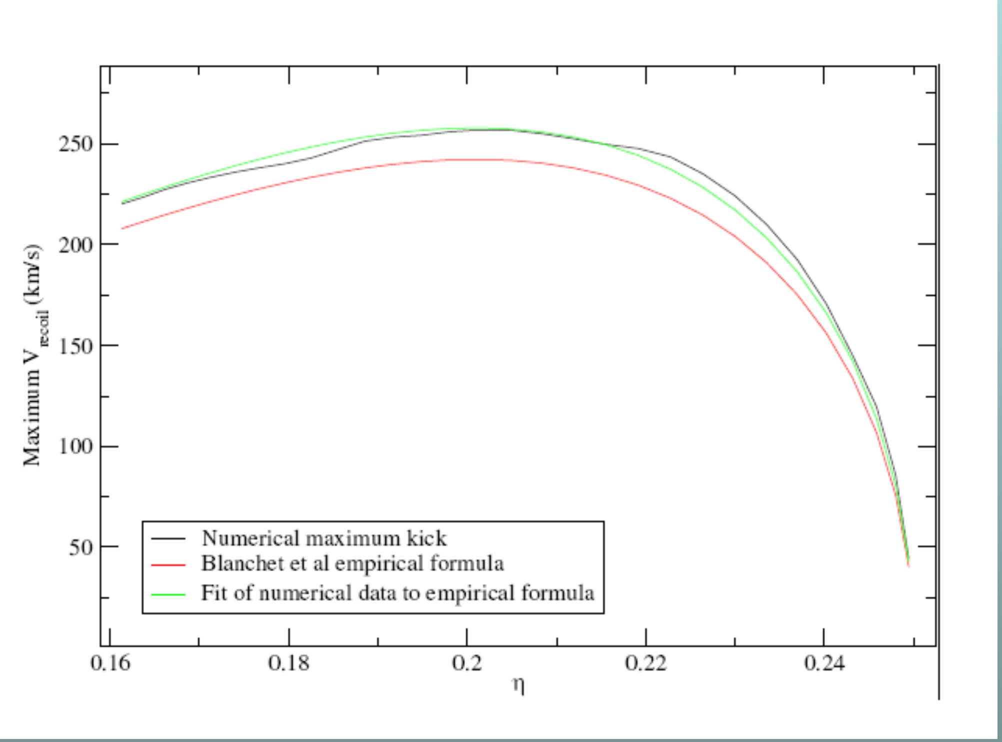
Fitchett (MNRAS **203** 1049,1983)
Gonzalez et al. (PRL **98** 091101, 2007)

- What about eccentricity? Close limit: $v_{\rm kick} \propto (1+e)$

Sopuerta et al. '06a, b

Comparison with Post-Newtonian results

- Excellent agreement between velocity maximum and Blanchet et al.'05



- Ring-down omitted in PN calculations

  ⇒Ring-down breaking?

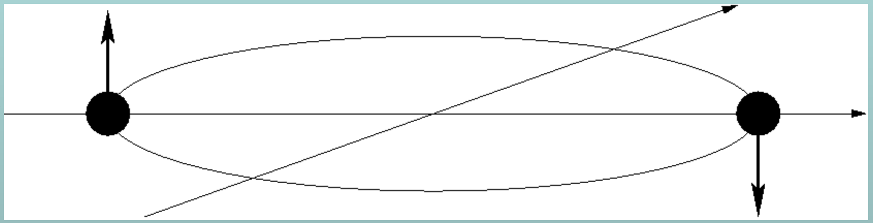
4.3. Numerical results `II`: Spins

Recoil of spinning holes

- Kidder ’95: PN study with Spins

$$\frac{d\mathbf{P}}{dt} = \dot{\mathbf{P}}_{\mathrm{N}} + \dot{\mathbf{P}}_{\mathrm{SO}},$$ = “unequal mass” + “spin(-orbit)”

- Penn State ‘07: SO-term larger

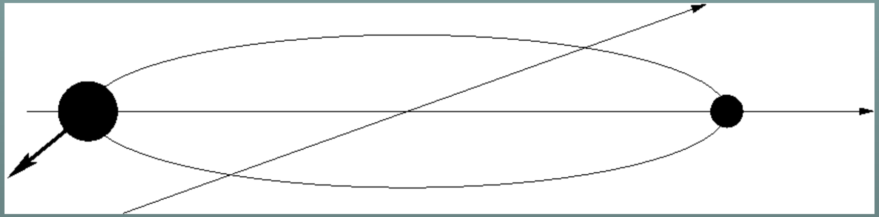


$$\frac{a}{m} = 0.2,...,0.8$$

extrapolated: $v = 475\,\mathrm{km/s}$

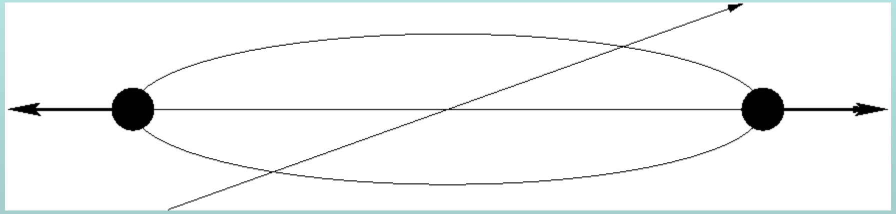
- AEI ’07 : One spinning hole, extrapolated: $v = 440\,\mathrm{km/s}$

- UTB-Rochester: $v = 454\,\mathrm{km/s}$



Super Kicks

- Side result RIT '07, Kidder '95: maximal kick predicted for



$$v \approx 1300\,\mathrm{km/s}$$

- Test hypothesis

  González, Hannam, US, Brügmann & Husa '07

  Use two codes: Lean, BAM

- Generates kick $v = 2500\,\mathrm{km/s}$ for spin $a \approx 0.75$

Super Kicks

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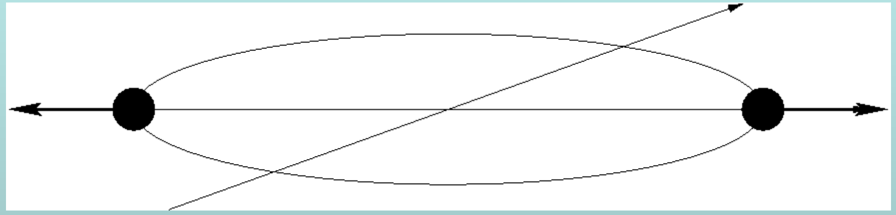

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- Test hypothesis

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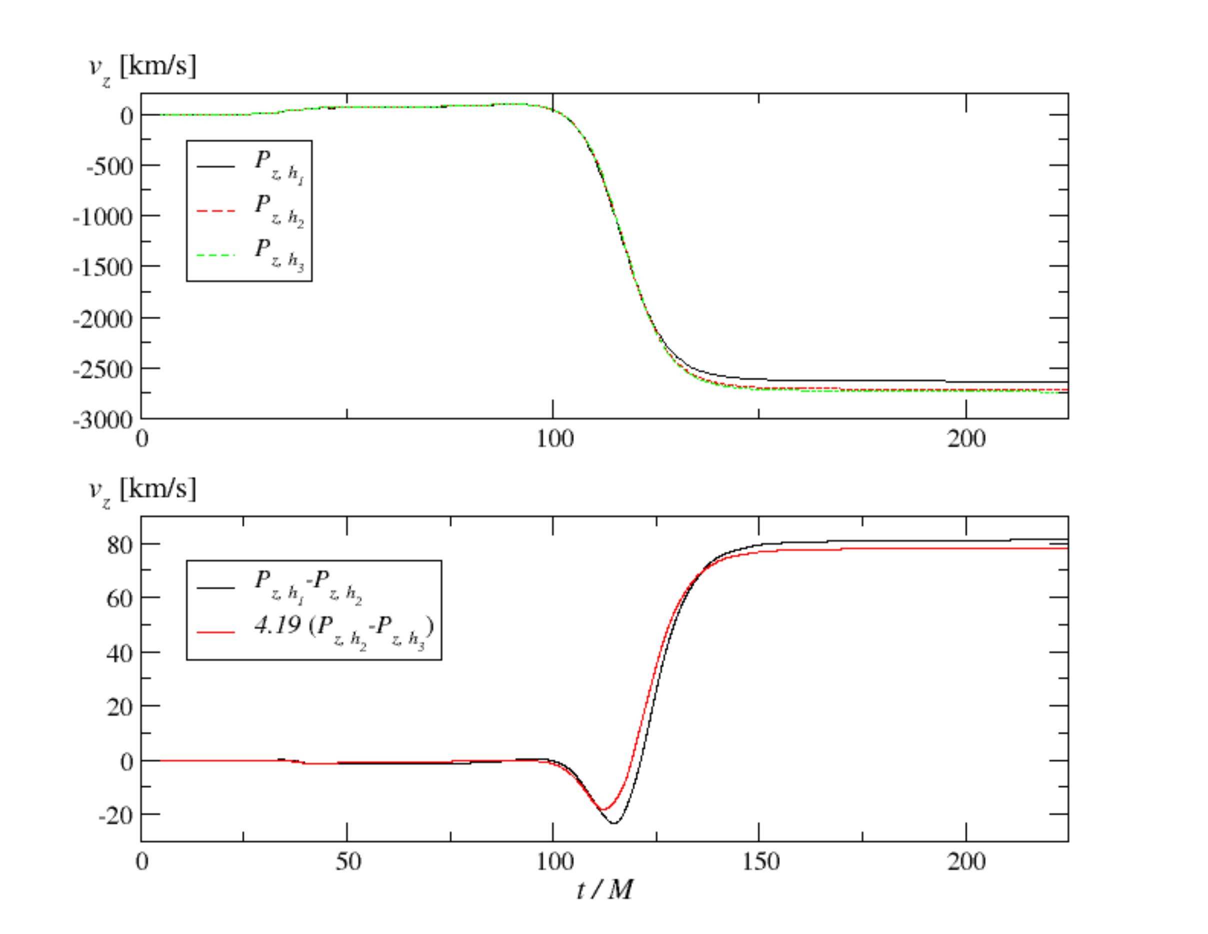
  Use two codes: Lean, BAM

- Generates kick $v = 2500\,\mathrm{km/s}$ for spin $a \approx 0.75$
- Extrapolated to maximal spin $v = 4000\,\mathrm{km/s}$
  RIT ‘07
- Highly eccentric orbits $v = 10000\,\mathrm{km/s}$
  PSU ‘08

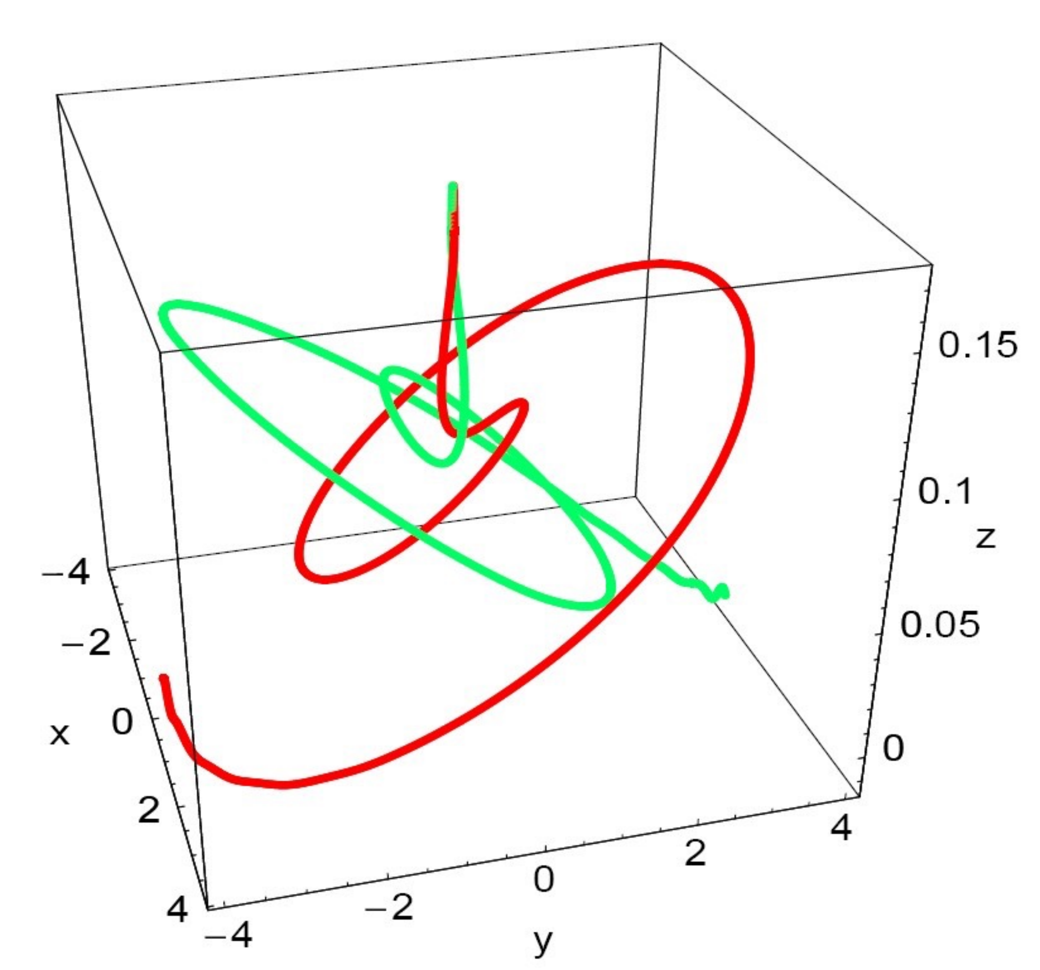
Convergence



- Discretization error: $\Delta v = 43\,\mathrm{km/s}$
- Confirmed by various studies PSU, RIT, FAU

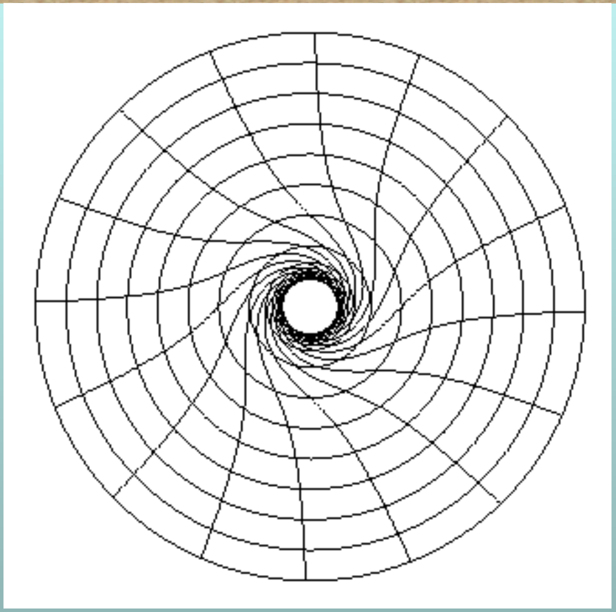
What’s happening physically?

- Black holes “move up and down”



A closer look at super kicks

- Physical explanation:
  “Frame dragging”
- Recall: rotating BH drags objects along with its rotation



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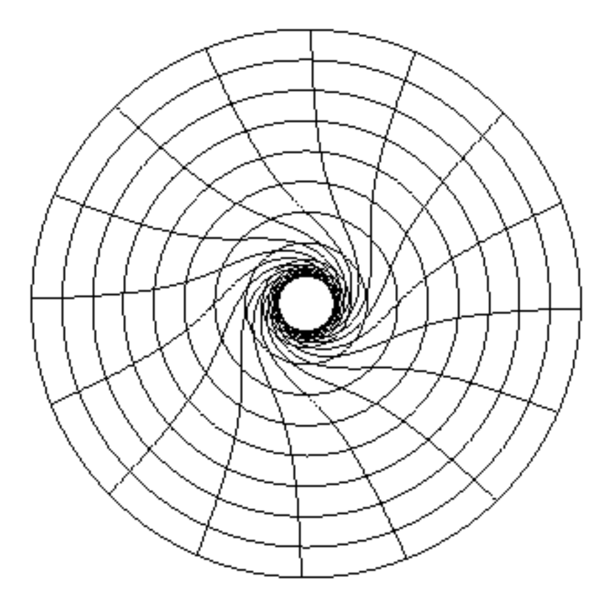
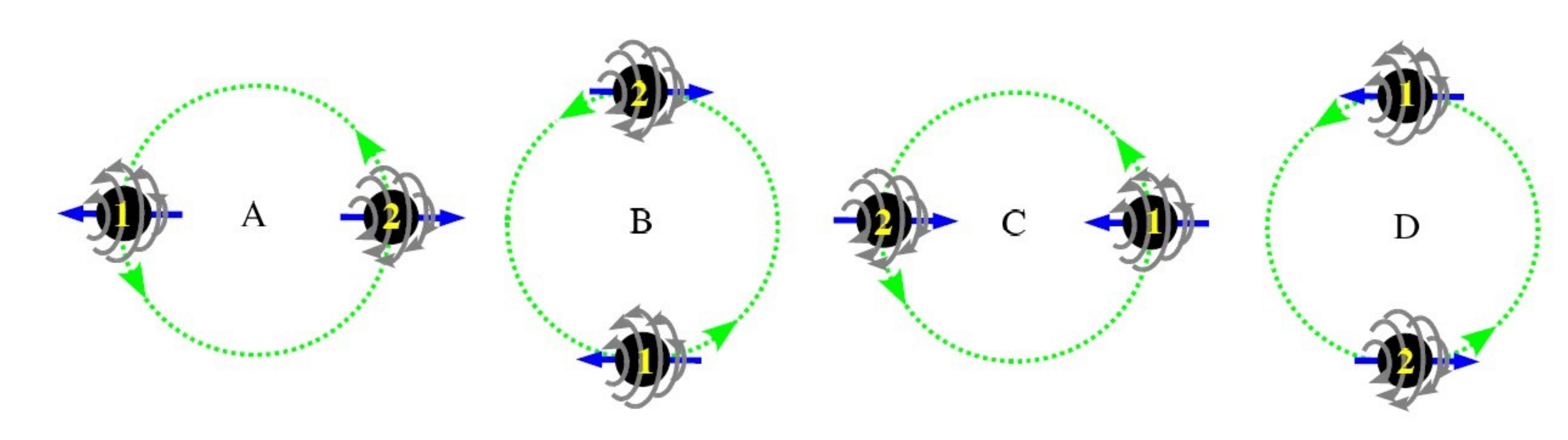
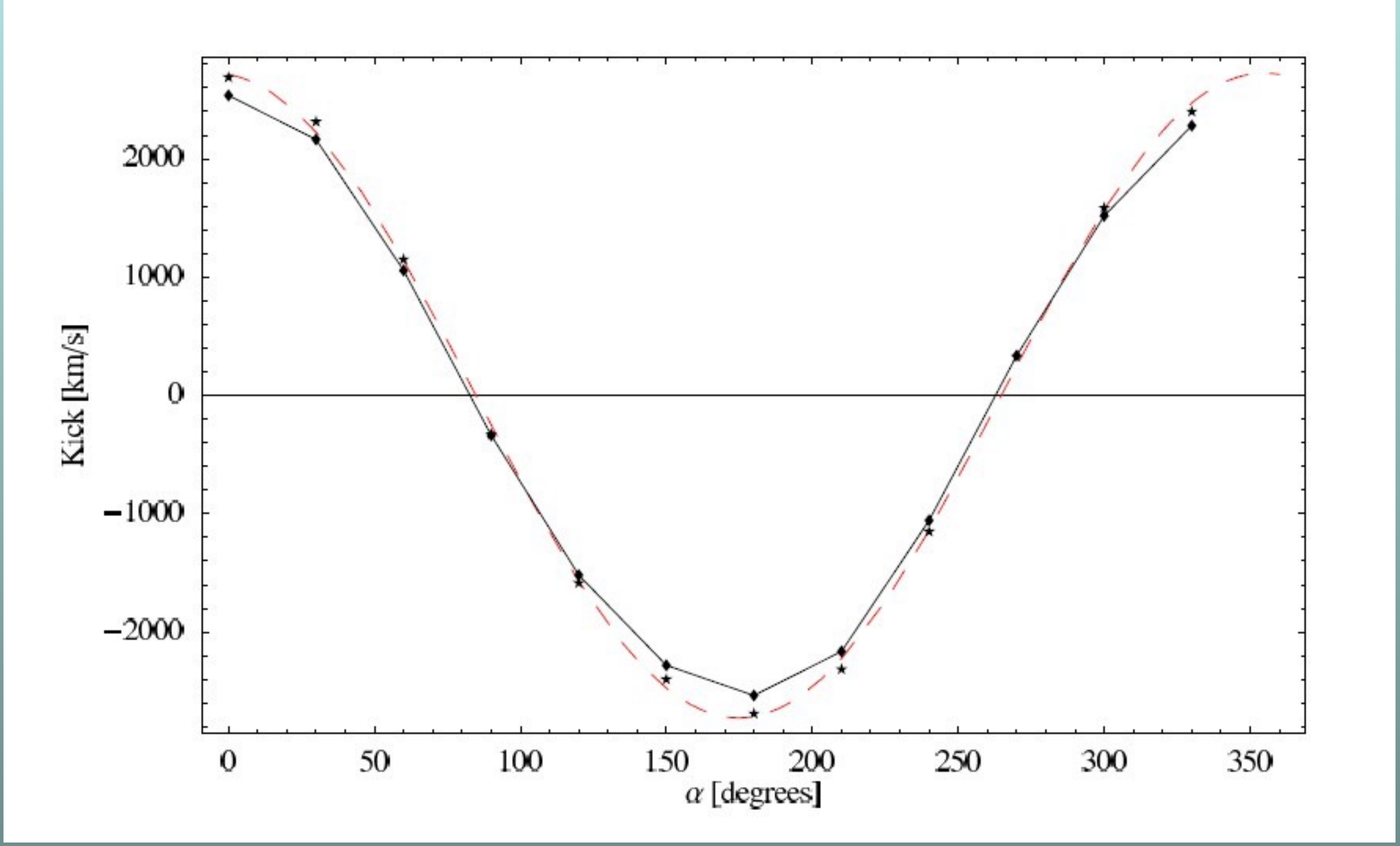




Thanks to F. Pretorius

A closer look at super kicks

- Final kick depends on angle between $\vec{S}$ and $\vec{P}$



UTB-Rochester ‘07, Jena ‘07

How realistic are superkicks?

- Observations $\Rightarrow$ BHs are not generically ejected!
- Are superkicks real?
- Gas accretion may align spins with orbit Bogdanovic et al.
- Kick distribution function: $v_{\text{kick}} = v_{\text{kick}}(\vec{S}_1,\ \vec{S}_2,\ M_1/M_2)$
- Analytic models and fits: Boyle, Kesden & Nissanke, AEI, RIT, Tichy & Marronetti,…
- Use numerical results to determine free parameters
- 7-dim. Parameter space: Messy! Not yet conclusive…
- EOB study $\Rightarrow$ only 12% of all mergers have $v > 500\ \text{km/s}$ Schnittman & Buonanno '08

Conclusions

- BHs important in many areas of astrophysics
- Numerical relativity has solved the BBH problem
- Maximum kick from non-spinning binaries

  $178\,\mathrm{km/s}$ for $M_1 / M_2 \approx 3$
- Spins generate much larger kicks
- Superkicks $2500\,\mathrm{km/s}$; maybe observed
- Observations $\Rightarrow$ superkicks most likely not generic
- Kick distribution function? Not yet clear…

Astrophysical implications

- Important note: $v = 2500\,\mathrm{km/s}$ is possible.
  We do not know whether it is generic or even likely!!
- $v = 2500\,\mathrm{km/s}$ larger than escape velocities from giant elliptic galaxies
- Giant elliptic galaxies do harbor SMBHs **`Magorrian et al.'98`**
  $\Rightarrow$ constraints kicks; massive kicks not realized?
- Further astrophysical constraints
  - **`Libeskind et al.'06`**: Deviations of relation $m_{\mathrm{BH}} \propto m_{\mathrm{bulge}}$

    $\Rightarrow v \leq 500\,\mathrm{km/s}$
  - **`Merritt et al.'06:`** Narrow emission lines in quasar spectra

    $\Rightarrow v \leq 500\,\mathrm{km/s}$
- It appears unlikely, kicks as large as thousands of $\mathrm{km/s}$ are generic
- Why? Eccentricity?, Spin alignment? Parameter study needed!!!

Black holes in astrophysics

- Many galaxies have MBHs at their centers
- CDM cosmogony:
  - Structure forms via hierarchical growth of small objects
  - Galaxies form from mergers of smaller progenitors
  - Dark matter resides as DM halos in galaxies, progenitors
  - These DM halos undergo frequent merger!
- Galaxy mergers imply

  BH merger

  if BHs are present!