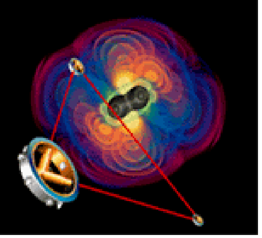

38th ESLAB Symposium
5th International LISA Symposium

# Coalescence remnant of spinning binary black holes

Center for Gravitational Wave Astronomy

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Sponsored by NASA and NSF.



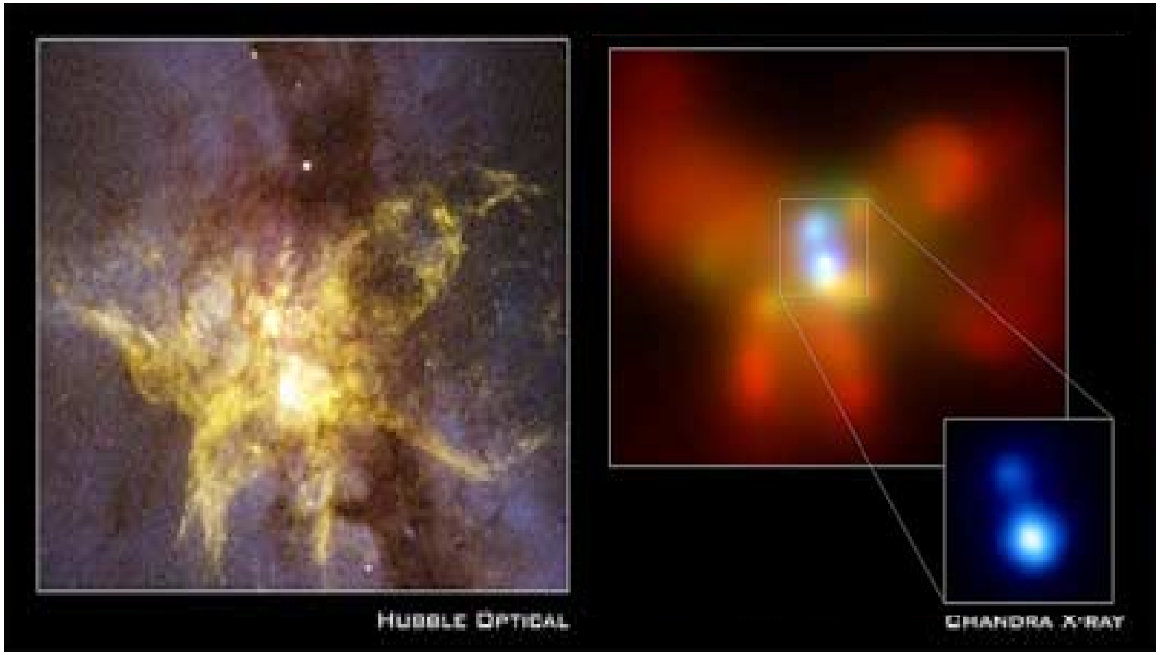
UTB TSC

# Super Massive Black Hole Mergers in galactic cores

- Understanding the fate of merging supermassive black holes (SMBHs) in galactic mergers is one of the LISA science challenges
  - These are expected to provide one the most extreme tests of GR

• SMBHs are believed to reside at the core of all active (and perhaps many normal) galaxies …

• Chandra X-ray Obervatory found a system with binary SMBHs at the core of NGC 6240




*LISA simposium 2004*

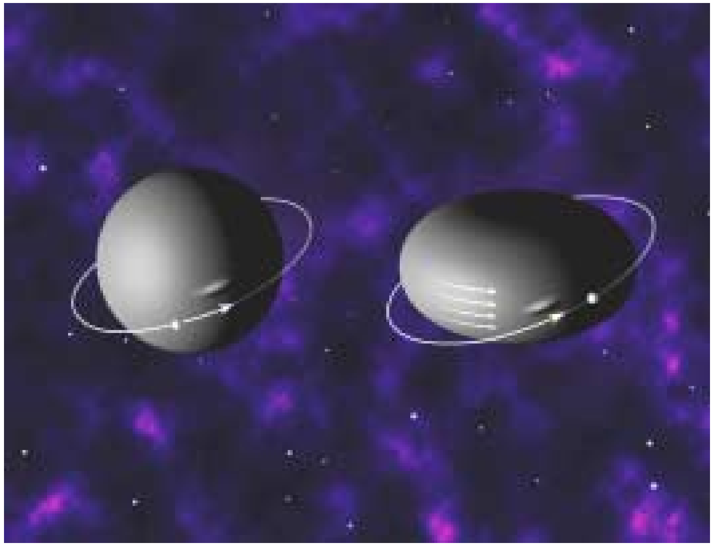
S. Komossa et al, APJ 2003

# Why the spin of the final merged black hole is important?

- Astrophysical black holes are completely characterized by their mass M, spin J=aM parameters (no-hair or uniqueness theorem)

- Some observations suggest that black holes may spin quite rapidly (nearly maximally)
  - $j=J/M^2=a/M\sim0.98$

- Spins may be produced in a variety of scenarios which are related to the growth history of SMBHs
  - Collapse of massive gas clouds → j depends on the initial conditions
  - Relativistic accretion → spin up
  - Capture of smaller objects → spin down
  - BH mergers (comparable mass cases) → generate high, but not near maximal spinning holes



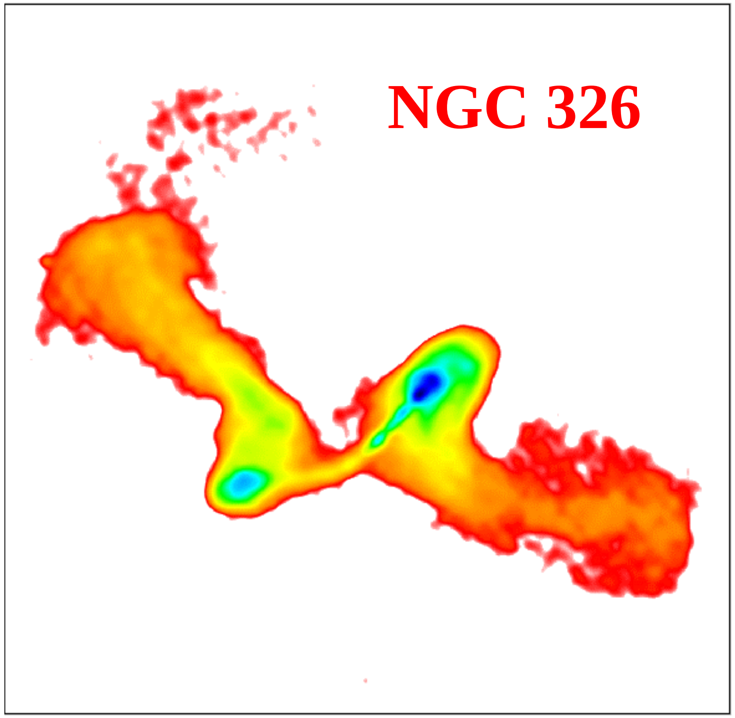
- The final spin may provide an observational probe for SMBH's growth

R. Blandford & S. Hughes, APJ 2003

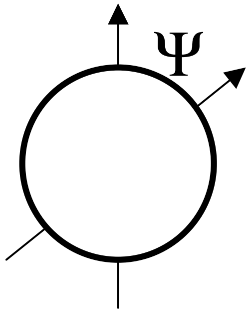
F. Gammie, S. Shapiro & J. McKinney, APJ 2004

# Spin-flip in SMBH Mergers?

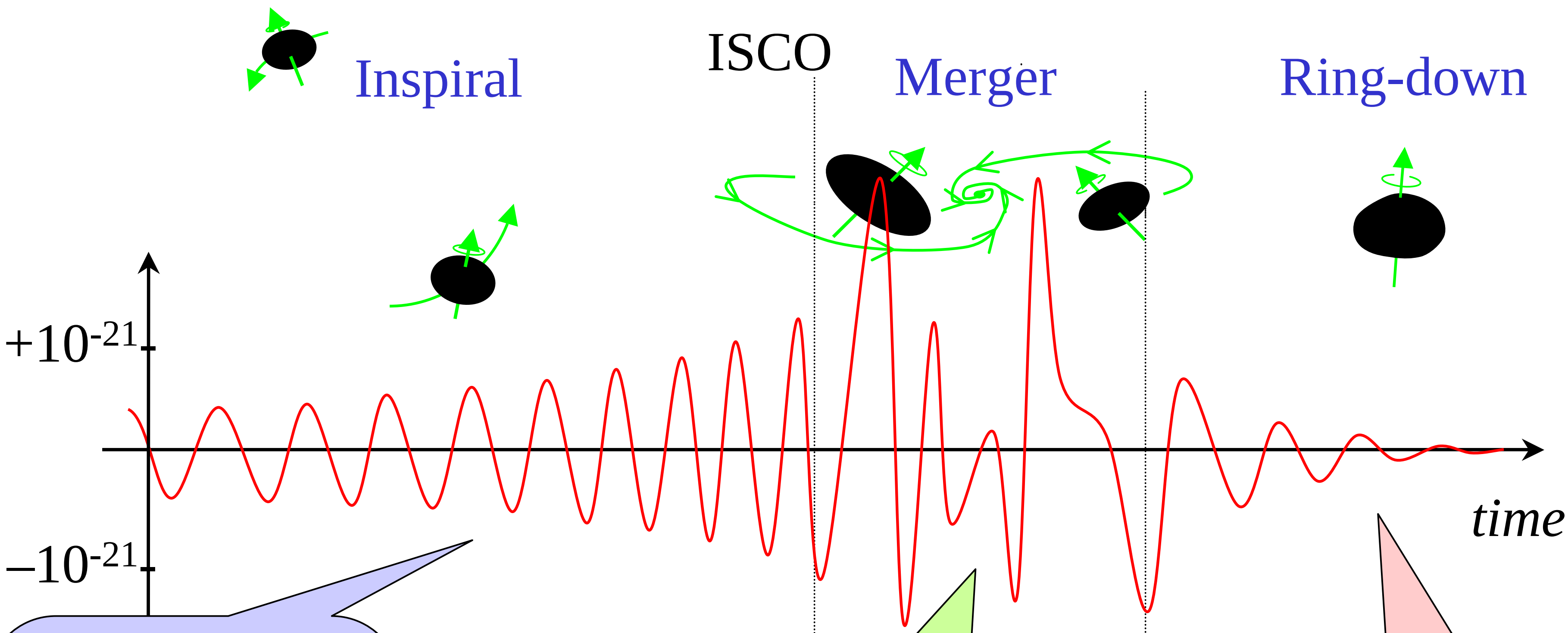
- In the merger scenario spins play an important role
- Spins likely drive the outflows of jets in the core of active galaxies
  - jet directed along the black hole spin (Rees 1978)
- BH mergers may realign the spin of the more massive hole, inducing a spin flip of the jet in X-shaped radio morphologies (Merritt 2002)




D.Merritt & R.D. Eckers, **Science** 297 (2002)



# Modeling the emission from black hole mergers

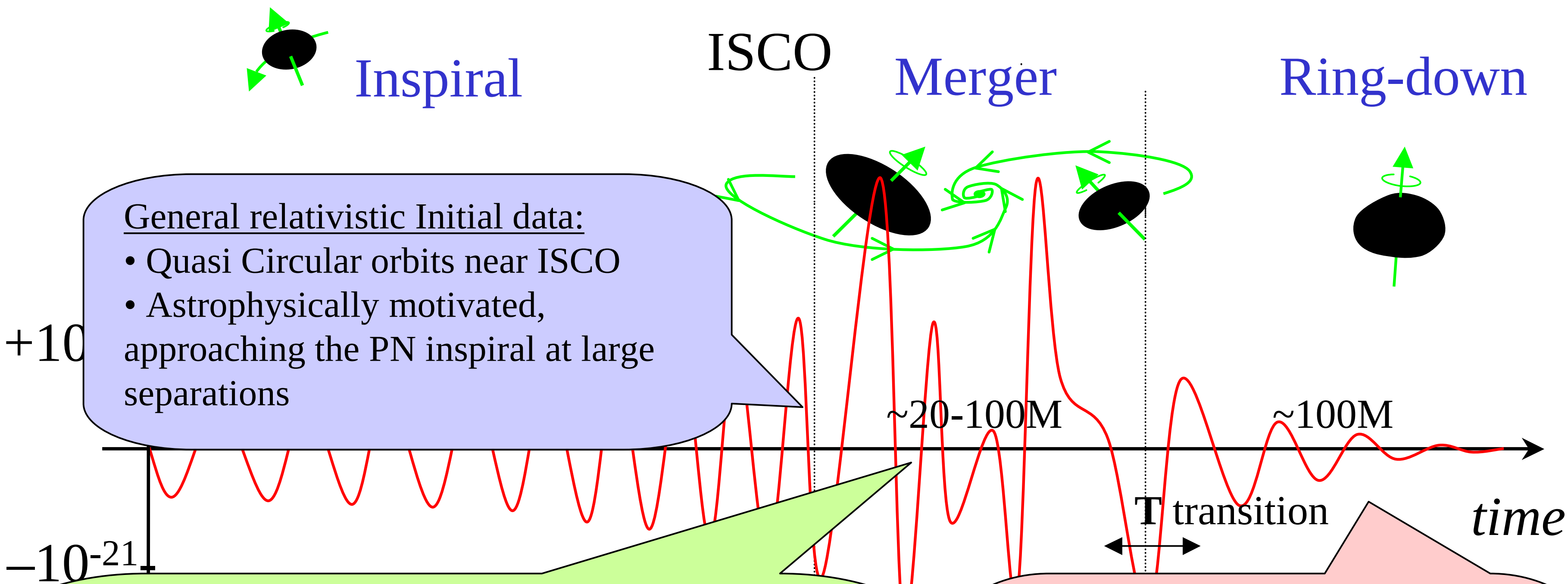



- Weak field slow binary inspiral lasting for a Hubble time until a separation << 1 pc
- Known PN and QS approximations can accurately model this stage

- Strong-field spacetime dynamics, BHs merging in less than 100 M
- Challenging supercomputer simulations solving Einstein's GR eqs are needed to properly model this stage

- Ringdown of the final Kerr BH
- Known BH perturbation theory in the CL approximation can accurately model this final stage

# The Lazarus approach to BH merger modeling




<u>General relativistic Initial data:</u>

- Quasi Circular orbits near ISCO
- Astrophysically motivated, approaching the PN inspiral at large separations

<u>Challenging Numerical Simulations:</u>

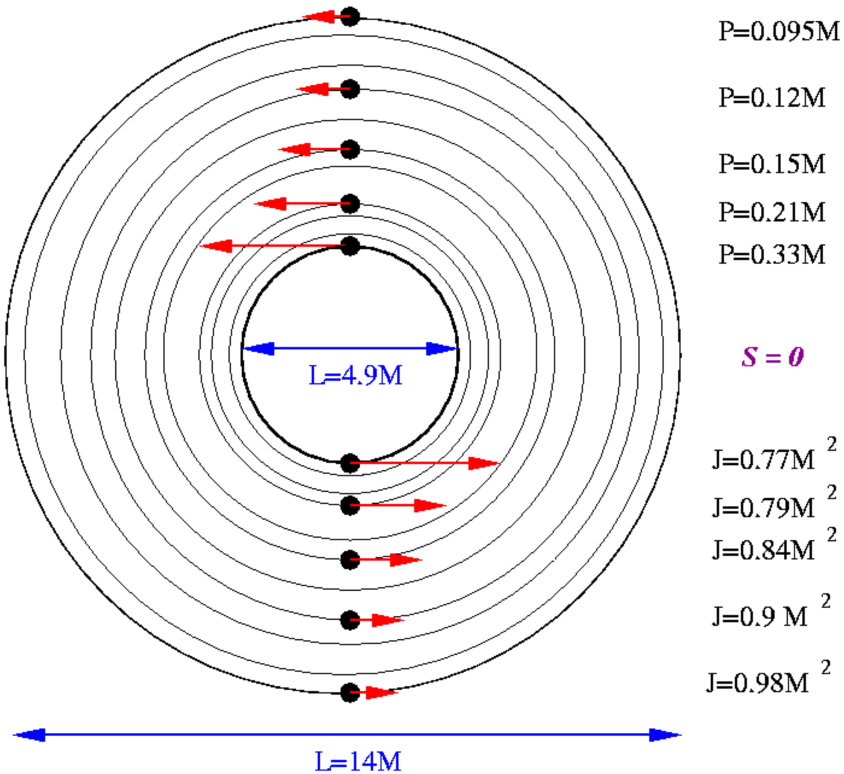
- Need of relatively stable formulations of Einstein's eqs, appropriate gauges choices and boundary conditions, accuracy to extract waveforms
- Need of large massive parallel supercomputers
- The general idea is to make use of all useful full numerical evolution during the BH merger stage rather than using it in the close limit regime

<u>Close Limit approximation:</u>

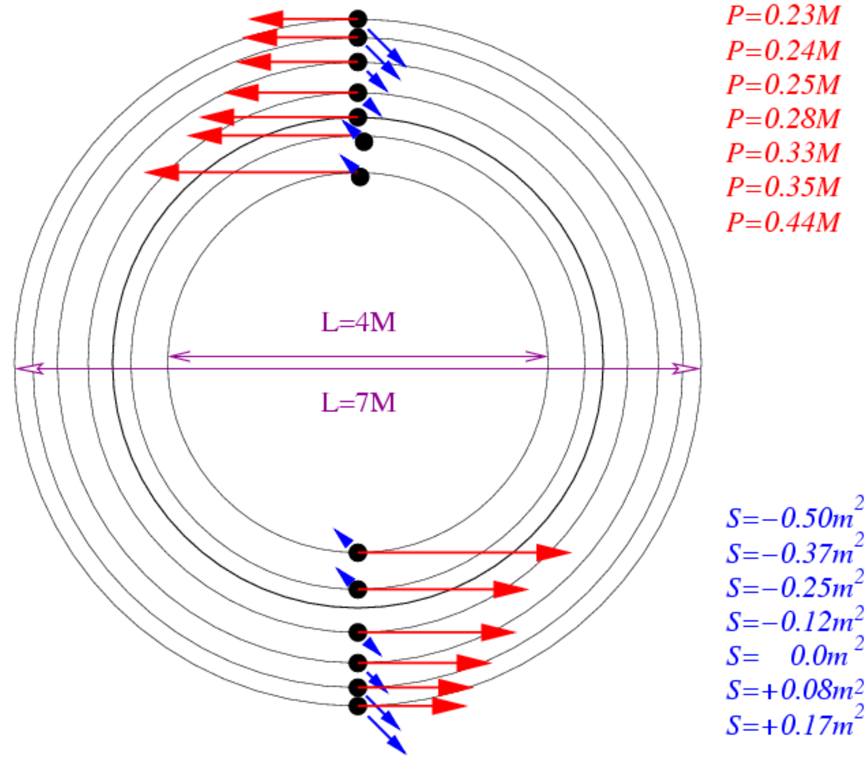
- At late time T extract the cauchy information about the formed single distorted Kerr BH and handle it to perturbative evolution with the Teukolsky equation
- Extract gravitational waveforms in terms $\psi_4$
- Results should be independent of the transition time T

# Initial Black Hole configurations

- Quasi-Circular orbits of Bowen-York BH initial data approaching PN results at large separations
- Assess the validity of initial data dynamically …




Non-spinning BHs




Spinning BHs

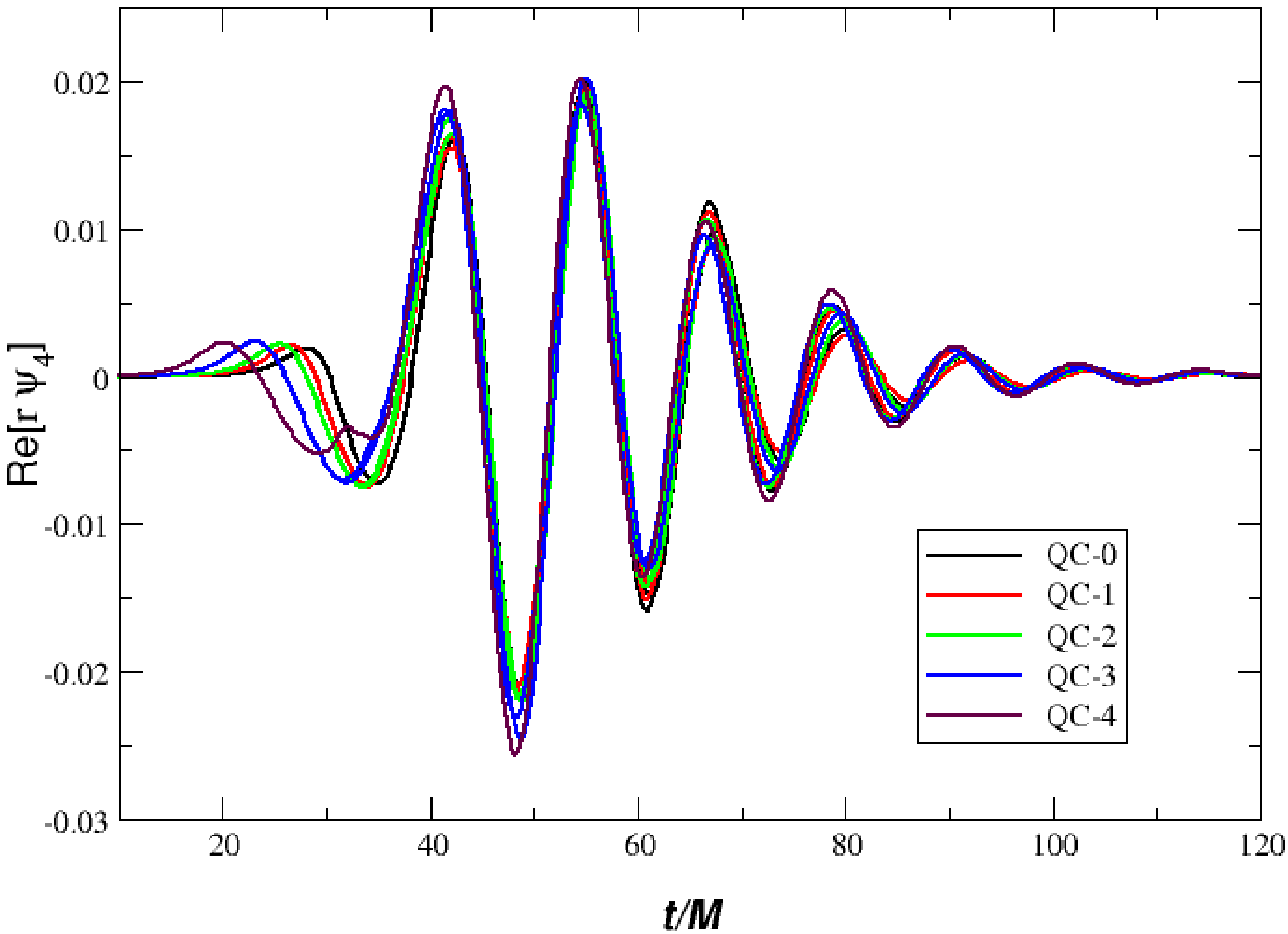
Aligned (ISCO moves inward)

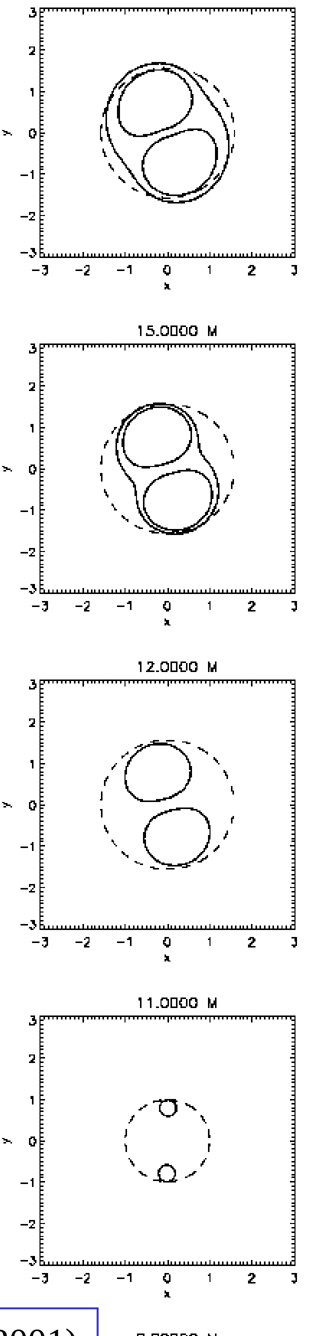
Counter-aligned (ISCO moves outward)



G. Cook, PRD (1994)
H. Pfeiffer, S. Teukolsky & G. Cook, PRD (2000)

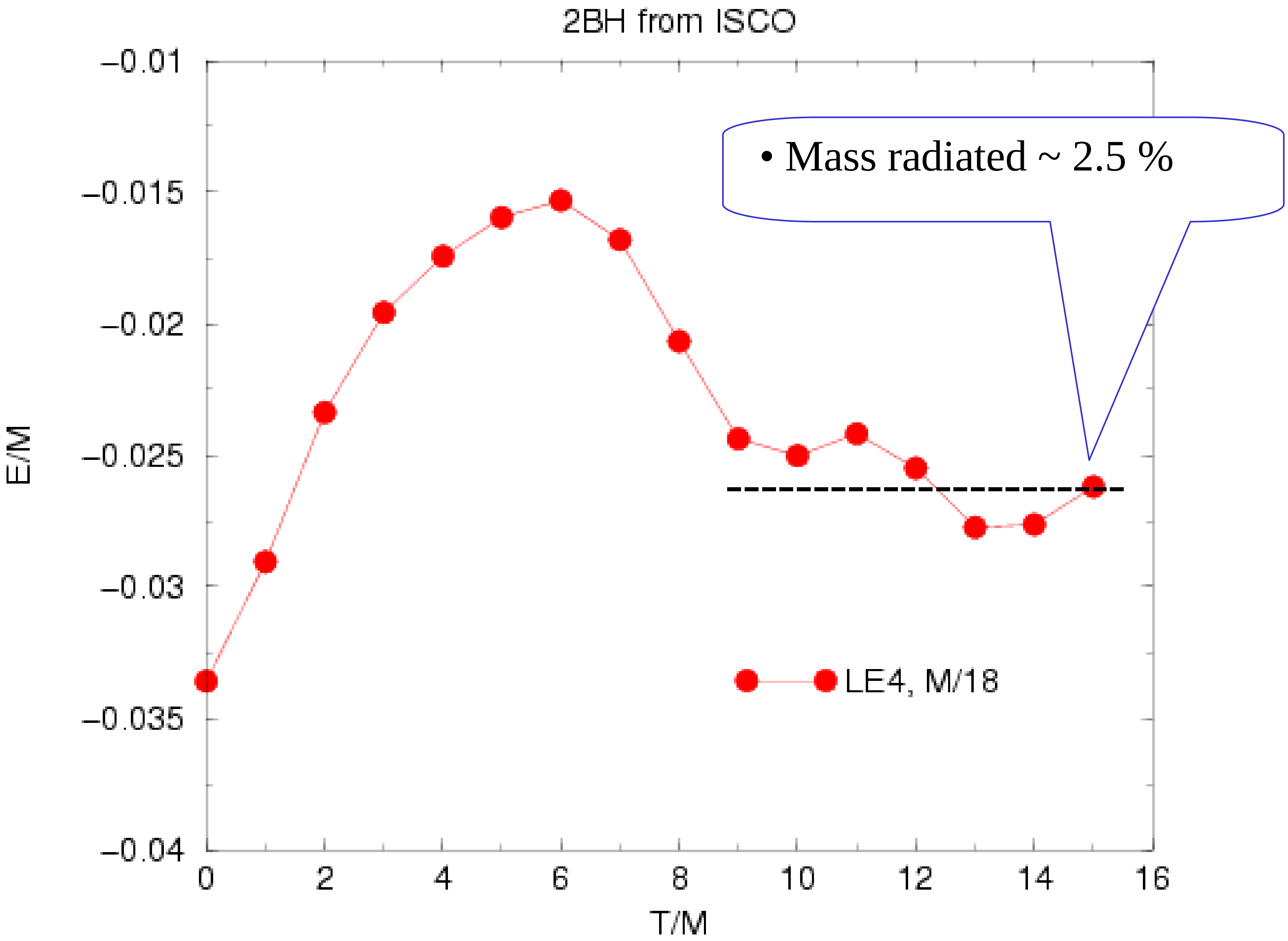
# Waveforms from plunging non-spinning BHS






J. Baker, B. Bruegmann, M. Campanelli, C. Lousto, R. Takahashi, PRL (2001)




J. Baker, B. Bruegmann, M. Campanelli, C. Lousto, R. Takahashi, PRL (2001)
J. Baker, M. Campanelli, C. Lousto, Y. Zlockower, prep (2004)

# On the spin of the final merged hole (I)

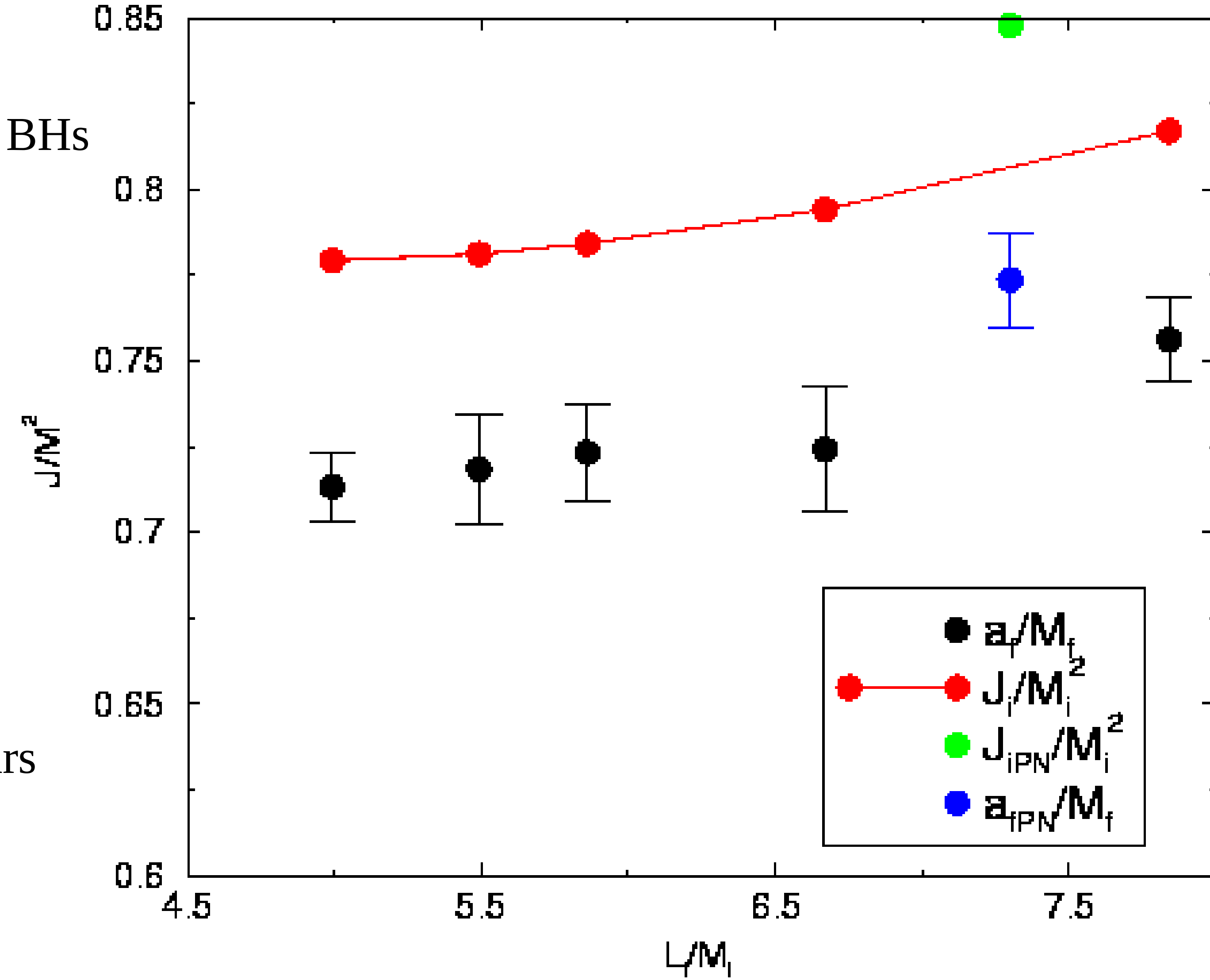
Initially non spinning BHs

Angular momentum radiated ~12%

Final Kerr spin: 0.7 < a/M < 0.75

Results not sensitive to the QC parameters

Conservative errors bars




J. Baker, M. Campanelli, C.Lousto & R. Takahashi, PRD 2004

# On the spin of the final merged hole (II)

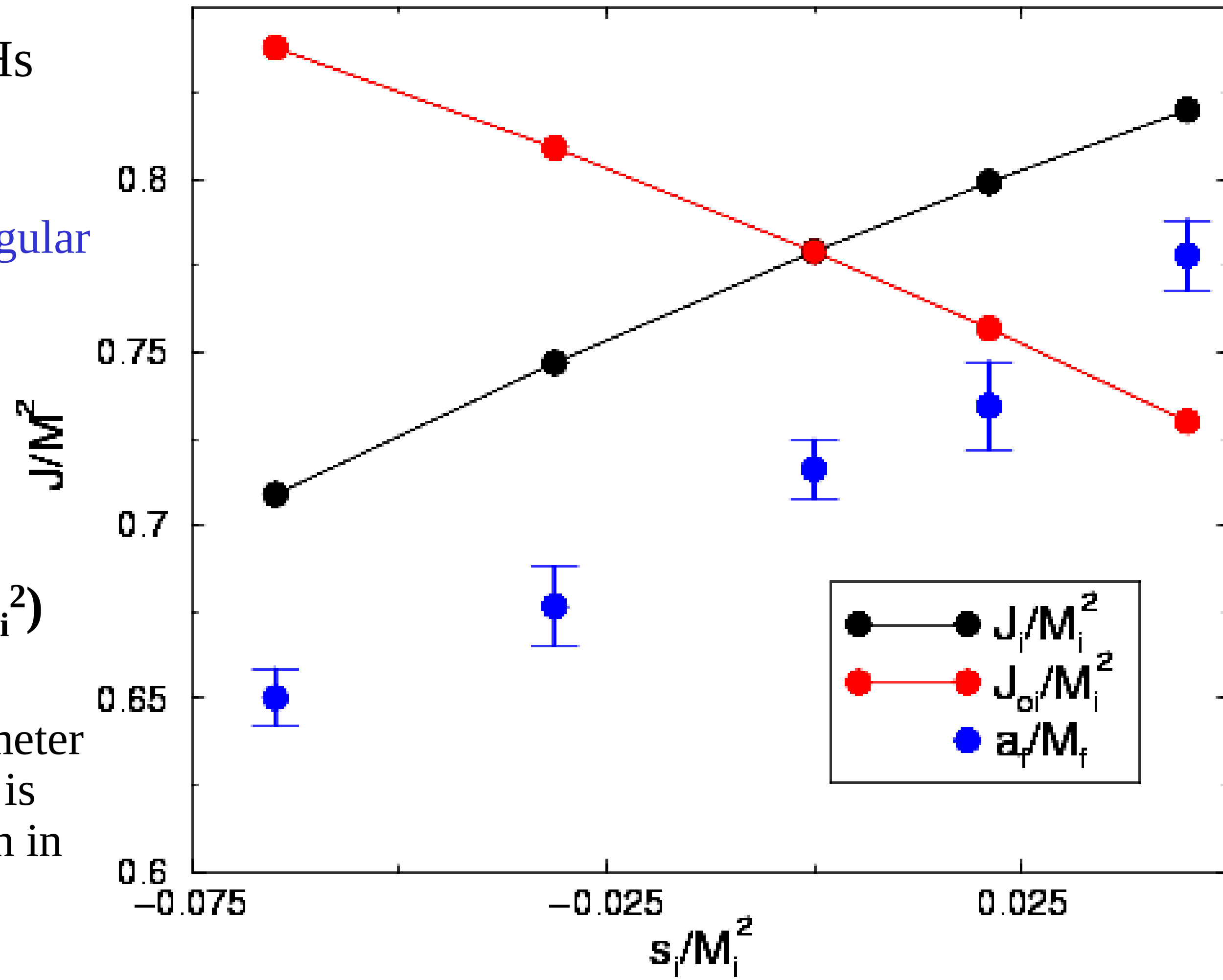
For moderately spinning BHs

- 1.7%-2.5% of the total energy is radiated
- ~0.1M² of the initial angular momentum is lost

Spin dependence adds up to final hole for $s_i/m_i^2 \leq 0.25$:

$$(a_f/M_f)_s \approx 0.72 + 0.32\,(s_i/m_i^2)$$

As expected, the rotation parameter of the final remnant black hole is larger for the aligned cases than in the antialigned cases.




$(s_i/m_i^2)$



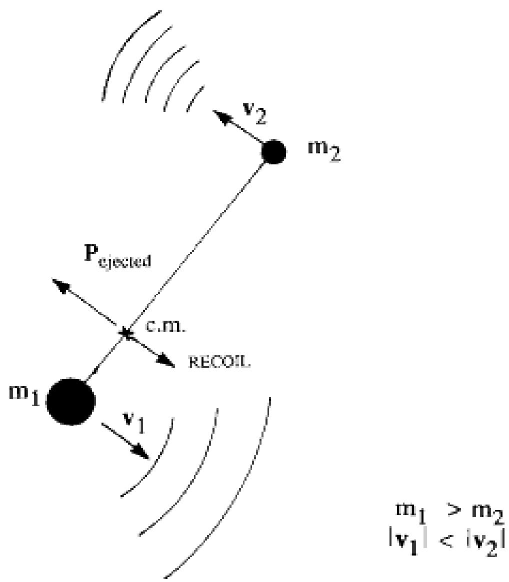
J. Baker, M. Campanelli, C.Lousto & R. Takahashi, PRD 2004

# Conclusions

- BH merger simulations of moderately spinning (equal mass) holes tend to form a final Kerr black hole with j~0.7-075
  - Nearly maximal rotating black holes with spins (parallel to the orbital angular momentum) >0.85 are needed to produce a maximally spinning Kerr remnant
  - More mature numerical relativity simulations are needed to confirm results for nearly equal mass and rapidly spinning holes …
- These results are consistent with the results found in the extreme mass ratio case (Blandford & Hughes 2003)
  - Rapid rotation results only if the massive hole spin quickly and the orbit of the small hole is near prograde.
- This suggest that it is in general difficult (though not excluded) to end up with nearly maximally rotating black hole from merger scenarios
- If, as some observations have suggested, black holes spin rapidly, then this limits the importance of merger scenarios for the growth of  SMBHs in favor of accretion scenarios.

# Radiation Recoil from black hole mergers

Coalescing black holes, with M1≠M2, radiate linear momentum!



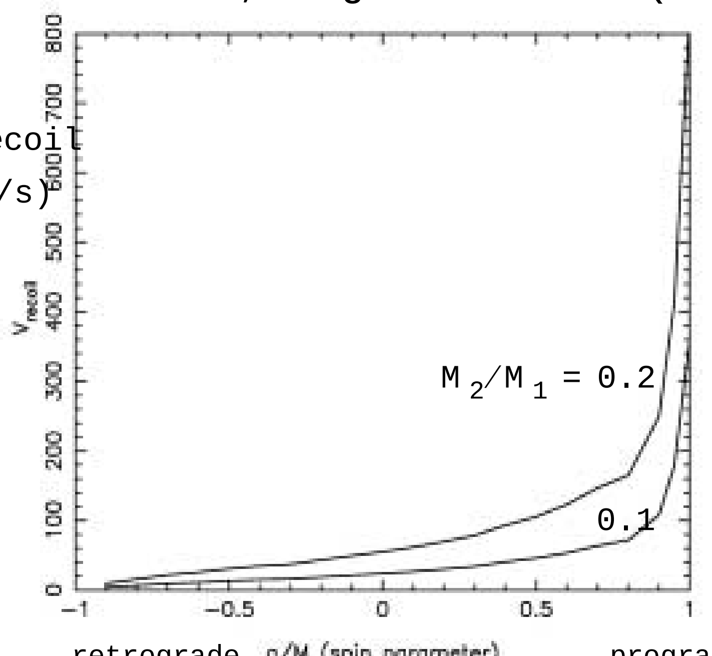

Binary black hole mergers can be ejected, or at least displaced, from a galactic nucleous.

Consequences for the formation of intermediate mass BH in Globular clusters.

# Radiation Recoil from black hole mergers

Favata, Hughes & Holz (in prep.)

$V_{recoil}$ (km/s)




$M_2/M_1 = 0.2$

0.1

retrograde prograde

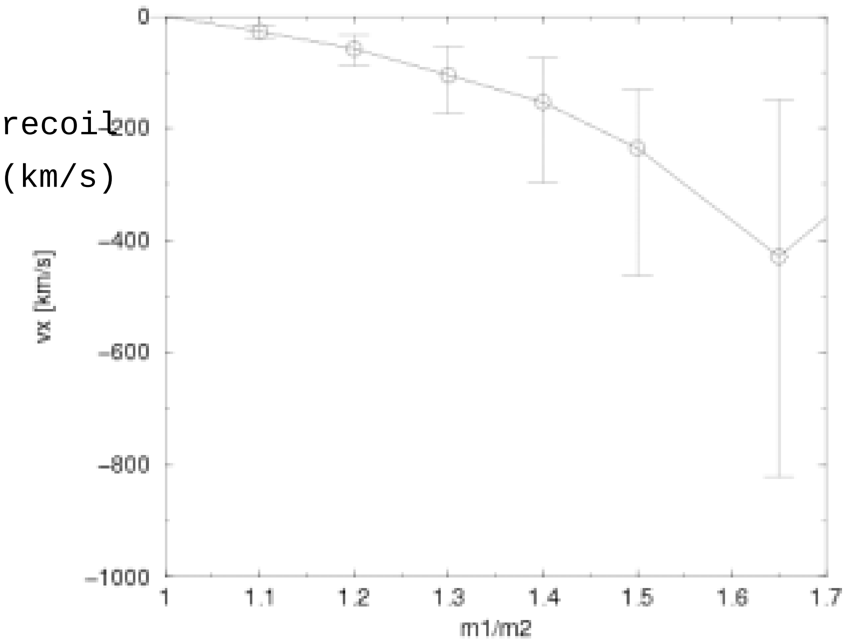
Spin parameter of larger hole

Perturbation treatment

Infall (Teukolsky) + plunge (Ori & Thorne)

Lousto, Baker & Campanelli (in

$V_{recoil}$ (km/s)




$M_1/M_2$

Exact numerical relativity integr

No initial spins

Mesh refinement needed!

$V_{recoil,upper} = 260$ km/s

$V_{recoil,max} \approx 850$ km/s



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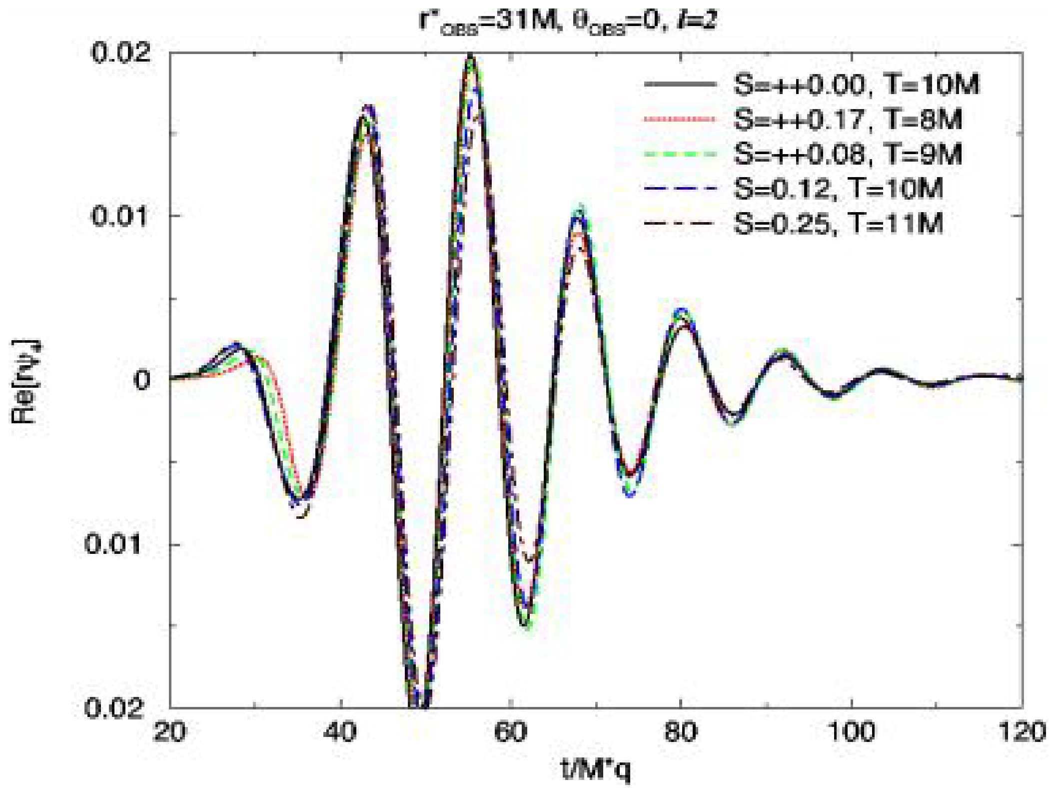

r*OBS=31M, θOBS=0, l=2
0.02
0.01
0
0.01
0.02
Re[rψ4]
20
40
60
80
100
120
t/M*q
S=++0.00, T=10M
S=++0.17, T=8M
S=++0.08, T=9M
S=0.12, T=10M
S=0.25, T=11M