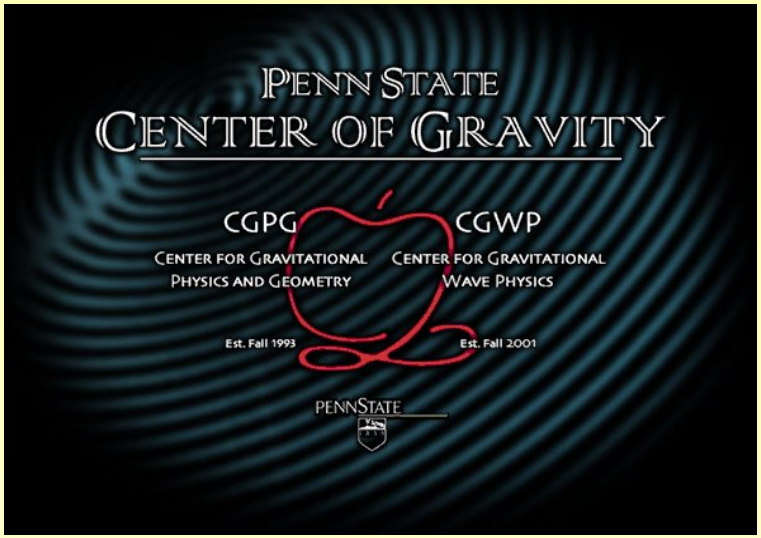
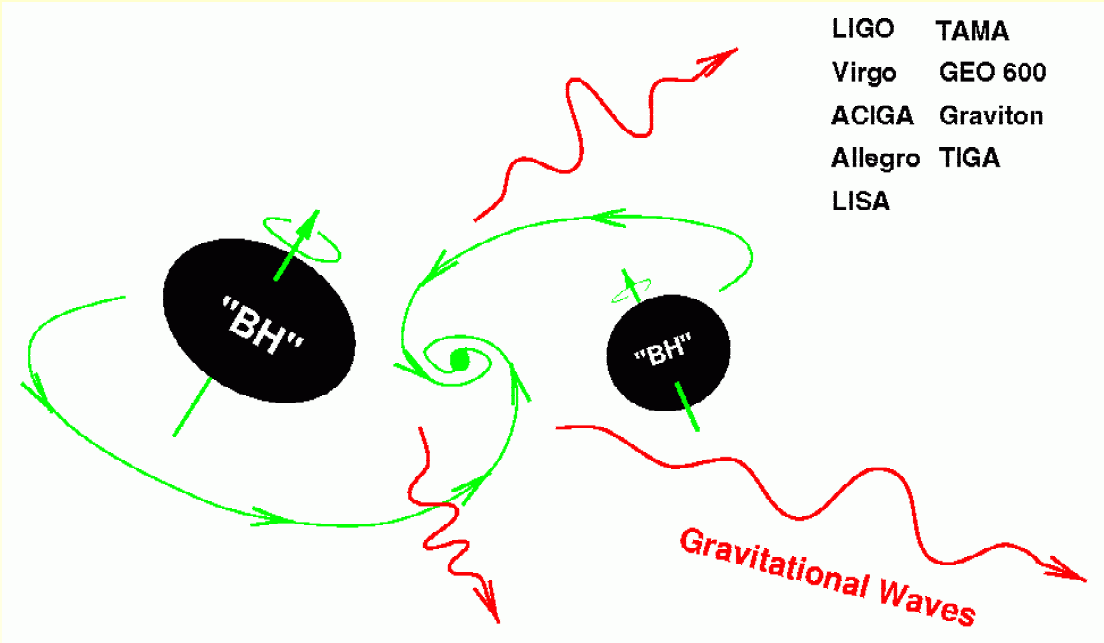
Bernd Brügmann
Penn State, 1/29/2004



Numerical Simulation of Orbiting Black Holes

BB, Wolfgang Tichy, Nina Jansen
(gr-qc/0312112)

New:
+ evolutions last for one orbital time scale for close but still separate black holes (based on apparent horizon)
+ comoving coordinates
+ fixed mesh refinement



Brief history of brief 3d binary black hole evolutions

Schwarzschild: Anninos, Camarda, Massó, Seidel, Suen, Towns 95; Daues 96 (shift)
Brügmann 96 (FMR, excision); Alcubierre, Brügmann 00 (stable 3+1 evolution)
Kidder, Scheel, Teukolsky 01 (spectral)

single black hole: Allen, Camarda, Seidel 98 (3d dist)
Cook, Huq, Klasky, Scheel, Grand Challenge 98 (Cauchy evolution, excision)
Gomez, Marsa, Lehner, Winicour, Grand Challenge 98 (stable characteristic evolution)
e.g. Duez, Shapiro, Yo 04 (matter collapse)

axisymmetric collision: Baker, Brügmann, Campanelli, Lousto 00 (**Lazarus**); AEI 03

non-axisym. black hole binary, grazing collision:
Brügmann 97, 99 (**BAM**, punctures); AEI 00-03 (**Cactus**, waves)
Pitt-PSU-Texas 00-03 (**Maya**, excision)

plunge, "pre-ISCO" through ring-down
Baker, BB, Campanelli, Lousto, Takahashi 01; Baker, Campanelli, Lousto, … (Lazarus)
AEI 01, 04 (merger, corotation)

The first "orbit" simulation of BH Binaries

BB, Wolfgang Tichy,
Nina Jansen, 12/2003

Evolve for one orbital period (defined by initial data) for separated AH.

Initial data		quasi-circular puncture data (Tichy, BB, Laguna 03), equal mass, no spin r_0 = 3.0M, T = 114M (ISCO: Cook 1.1, 37; PN: 1.9, 65)
Evolution		
	System	modified BSSN, ICN
	Gauge	1+log, Gamma freezing; commoving coordinates
	Outer B.	radiative
	Inner B.	simple excision
Analysis		
	Horizon	apparent horizon
	Waves	no wave extraction yet (S invariant is noisy but not hopeless)
Infrastructure		BAM (new code based on BB 96,97,99, Cactus for analysis) finite differencing, multigrid elliptic solver, unigrid parallel fixed mesh refinement (FMR)

BAM ('bifunctional adaptive mesh', BB 96, 97, 99, 03, Jansen, Tichy 03)

Light-weight, small group code

- Explicit finite difference schemes on 3d Cartesian grids
- Programmed in C
- Tensor equations are compiled into C using Mathematica (and MathTensor)
- Basic cell based adaptive mesh refinement
- MPI parallelization by domain decomposition
- Plug-and-play modularity

Status 9/03:
- BBH initial data
- stable single black hole
- BBH to 20M
- unigrid scaling on 64 processors
- basic FMR for wave eqn

New:
- fixed mesh refinement

for Schwarzschild and BBH orbits (single processor)
(BB 96, 99; Lanfermann 99; Schnetter, Hawley, Hawke 03; Centrella et al 04)

```
~/bam/exe> bam
Welcome to bam. BAM or poof, that is the question.
Usage:  bam name.par
Thank you for running b a m.
~/bam/exe>
```

Dynamic gauge for stable single black holes

1+log lapse, hyperbolic Gamma-driver
(Alcubierre, BB, Diener, Koppitz, Pollney, Seidel, Takahashi 01, 01, 03)

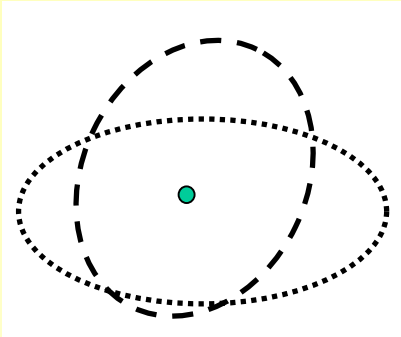
$$\partial_t \alpha = -2\alpha K \psi^m,$$
$$\partial_t \beta^i = \frac{3}{4}\alpha^p \psi^{-n} B^i, \quad \partial_t B^i = \partial_t \tilde{\Gamma}^i - \eta B^i$$

- can approximately freeze evolution of single black hole (3000M and more)

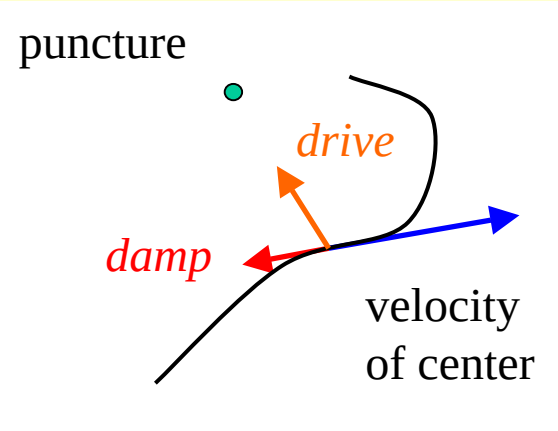
- *knows nothing about rotation, spirals, or other global coordinate effects !!*

Dynamically adjusted comoving coordinates

Cancel "bulk motion" of two black holes by adding shift based on asymmetry in lapse.



$$\beta^i_{com} = \psi^{-q}(A_1\omega(-y,x,0)^i - A_2\dot{r}(x,y,0)^i)$$
$$\Delta\bar{\beta}^i/\Delta t = -\gamma_{damp}\partial_t a^i(t) - k_{drive}(a^i(t) - a^i_0)$$

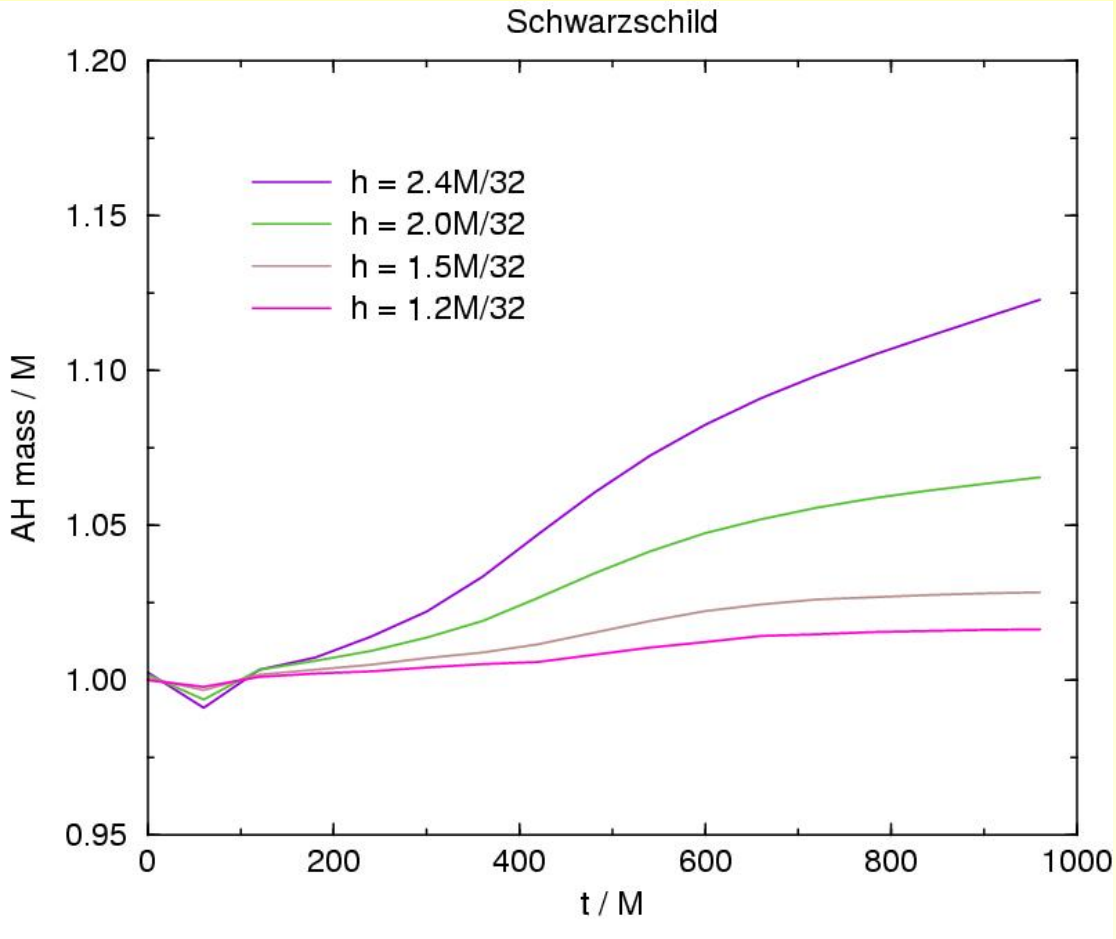


a^i: "center of lapse"; A_n: attenuation

- minimize dynamics in metric (cmp. moving excision region)
- not very dynamic if $T_{orbit} << T_{spiral}$
- (differential) rotation + radial motion
- "servo loop": damped harmonic oscillator
- in principle perfect for two point particles
- can latch on to apparent horizon, lapse, …, but cannot cancel all 3d effects

Compare: AEI, Hawley, Diener, Guzman 01, 03 (corotation, "drift correction")
neutron stars: Duez, Marronetti, Shapiro, Baumgarte 03; Swesty; Tohline; …

Convergence for FMR Schwarzschild evolutions

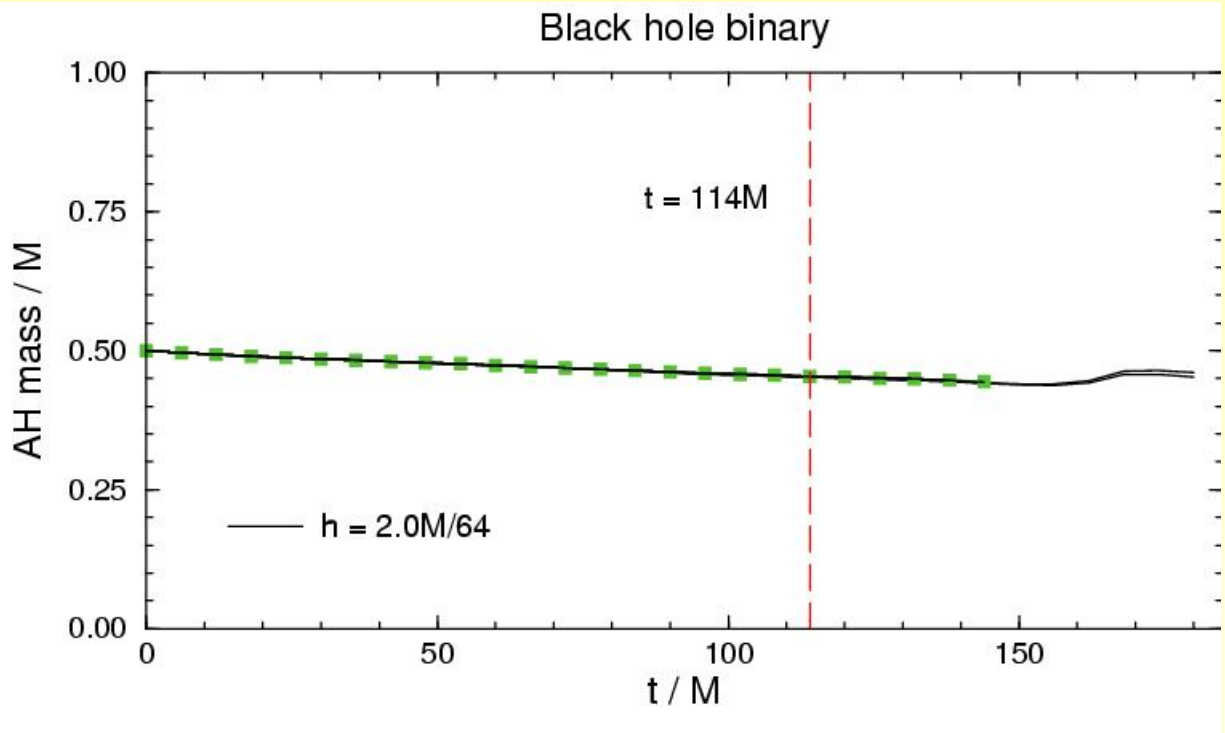


- octant runs
- runs on

full grid to > 1000M
on quadrant > 3000M

BH binary, equal mass, no spin, starting at $r_0 = 3M$: evolutions last beyond one orbital time scale

no common apparent horizon found

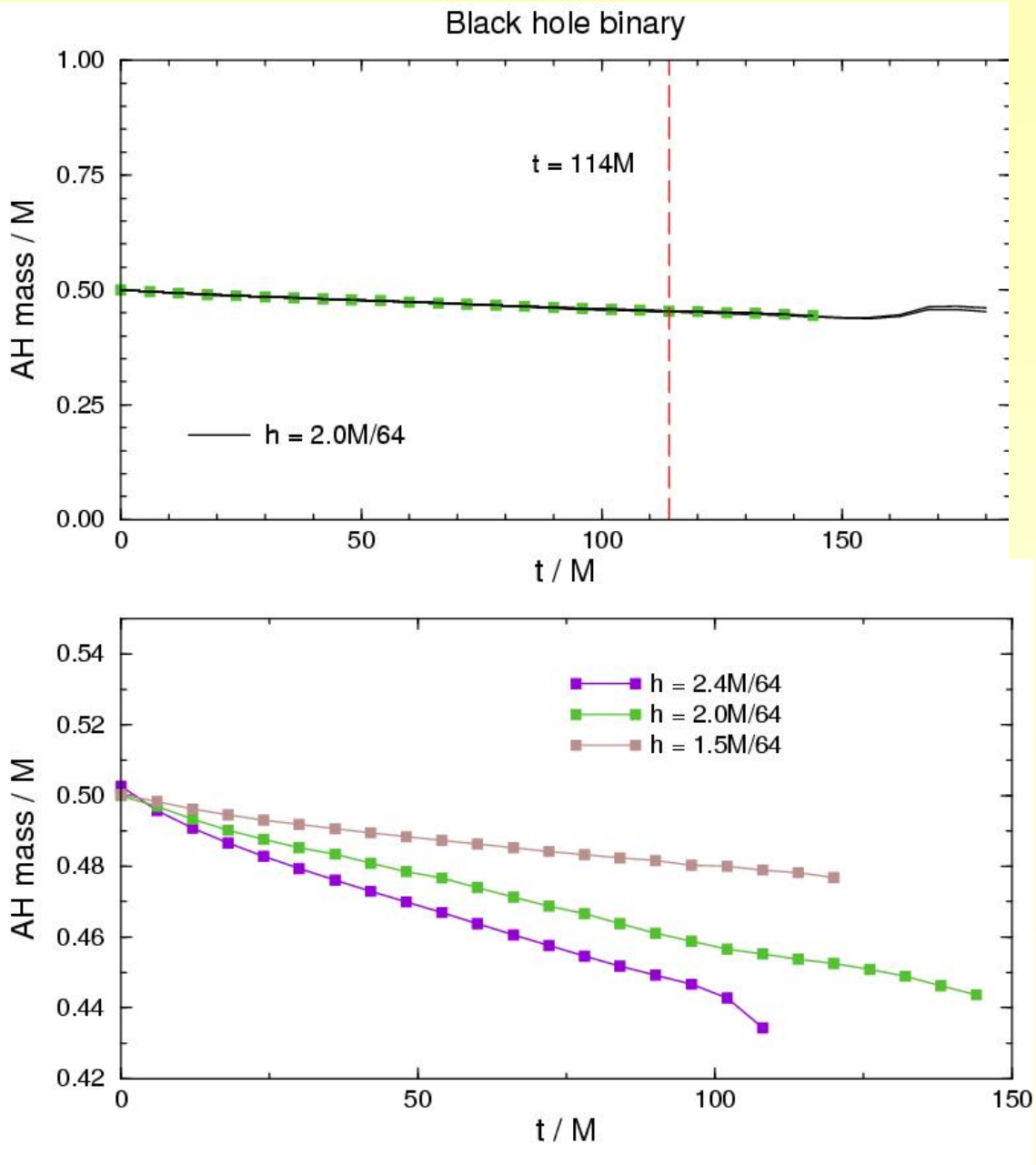


BH binary, $r_0 = 3M$

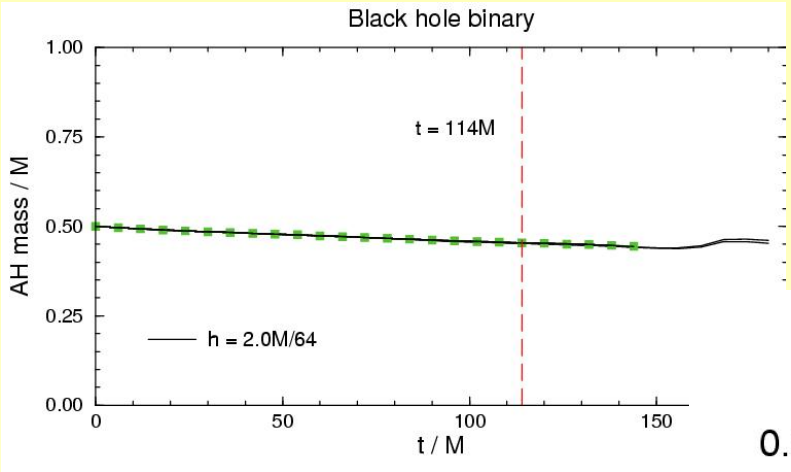
- squares: 7 nested levels
  h = 2M, …, 0.03125M, spherical outer boundary at 48M

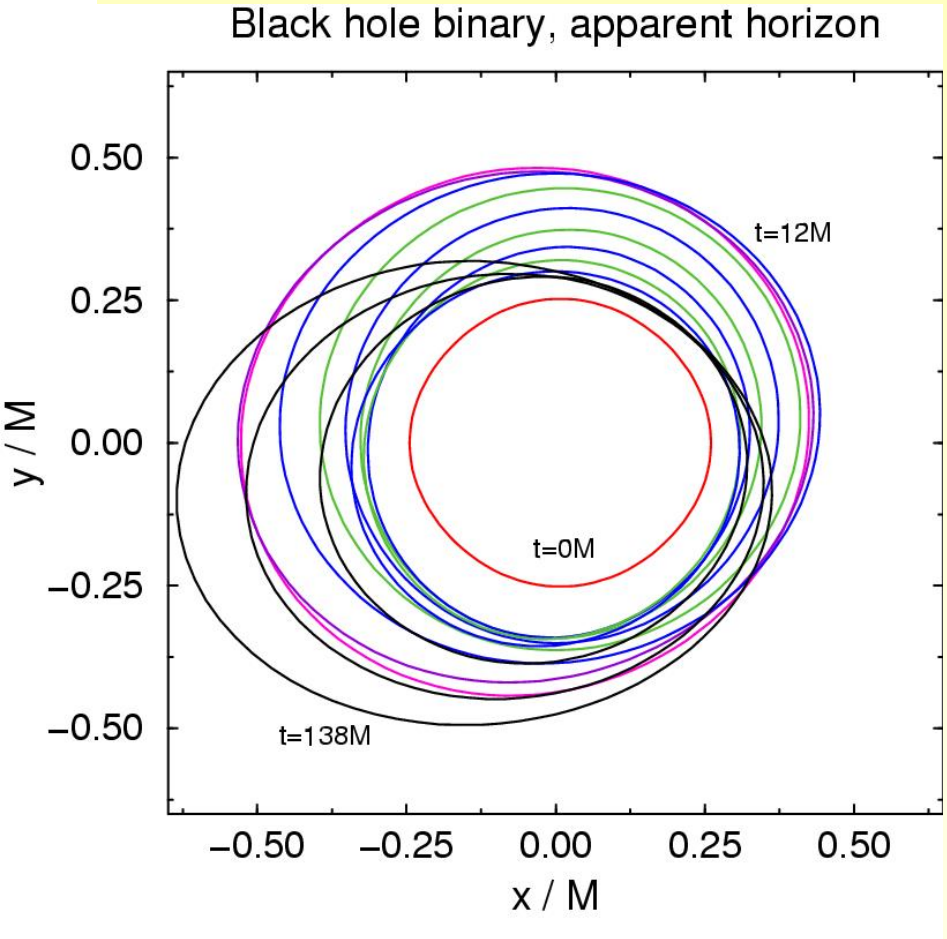
also shown are seven control runs:
- spherical or cubical outer bound.
- outer boundary at 24, 48, 96M
- AH finding on coarser grid

- convergence in limited regime (due to computational resources)
- linear drift
- drift decreases with resolution
- similar but shorter lived with punctures (excision seems ok)



BH binary, $r_0 = 3M$: coordinate location of apparent horizon

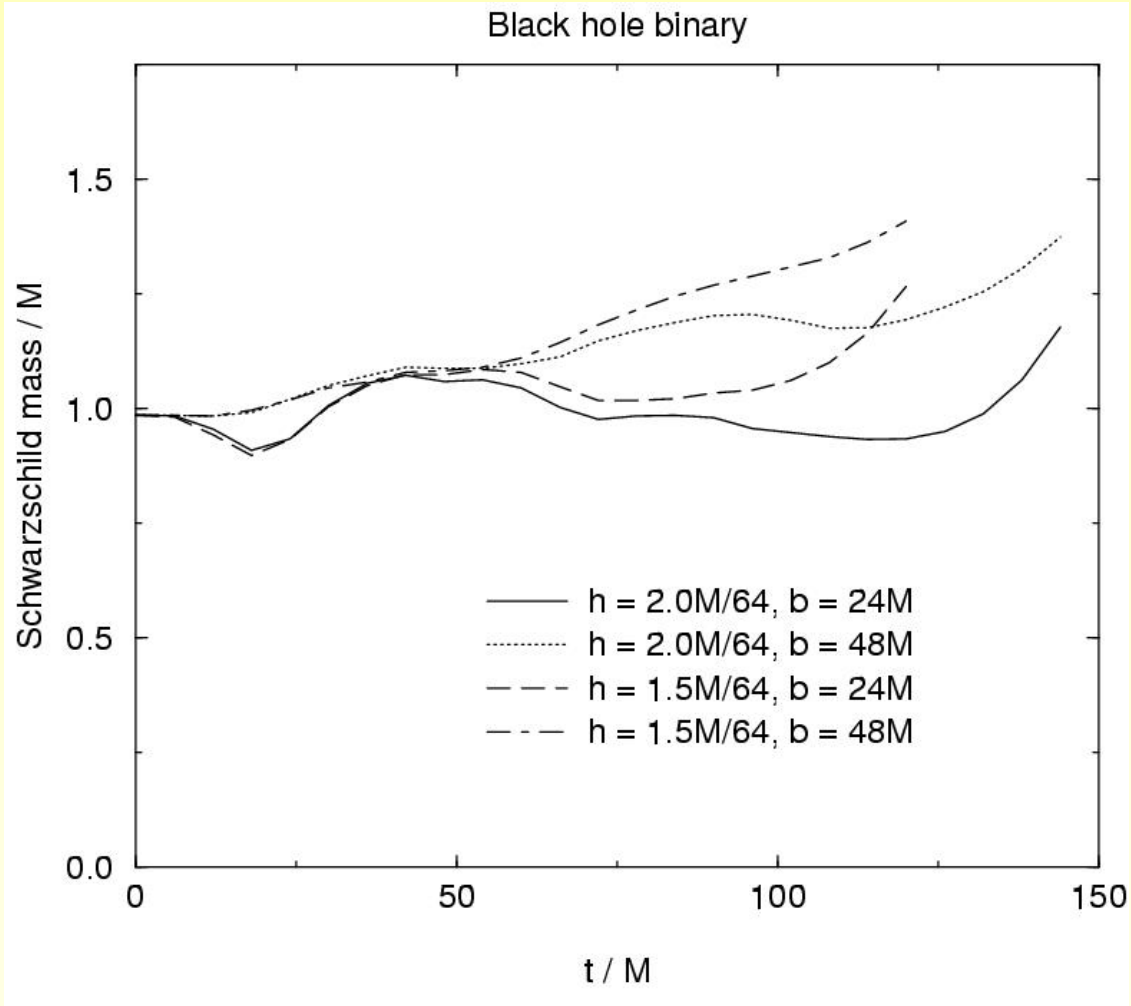




Runs for $r_0 = 3, 4, 5, ...12M$ fail after roughly 150M with motion in AH.

Suggests that better control of radial drift will help, but note that this is just one of many non-local coordinate effects.

BH binary, $r_0 = 3M$: estimate for ADM mass



- up to 30% error
- non-flat coordinates, e.g. differential coord. rotation
- improvements are possible

but still a long way to go for wave extraction

Summary

Binary black hole evolutions are moving into the orbital regime.

Dynamic, ‘non-local’ coordinate condition was needed.
(As opposed to better evolution system, excision, boundary, …)

Next:
- Improved dynamic gauge
- Event horizon finding, better masses, waves?
- Merger regime (cmp. AEI runs, $r_0 < 2.7M$, $t_{merger} < 40M$)
- Larger separations
- Spins, unequal mass, intermediate mass ratios (FMR)
- Parallel FMR

Refinement of existing technology should allow several orbits.