Binary Black Hole Simulations

- Working towards the “first last orbit”
  \[ t_{\text{numerical}} = 7M, 30M, 100M, \ldots \]
  '97 '99 '02 \ldots
Black holes are out there

Gas Disk in Nucleus of Active Galaxy M87

Hubble Space Telescope
Wide Field Planetary Camera 2
Livingston Observatory, LA

Center for Gravitational Physics and Geometry, Penn State  http://gravity.psu.edu
GEO600 near Hannover

Center for Gravitational Physics and Geometry, Penn State  http://gravity.psu.edu
## Numerical relativity for binary black holes: cutting edge 2003

| Initial data | QE effective potential: Cook; Baker et al  
|             | QE conformal thin sandwich: GGB, PCT; PN data: TBCD |
| Evolution   | BSSN; Hyperbolic: KST, …; resolving constraints  
| System      | K freezing, Gamma freezing; ell/par/hyp; corotating coords.  
| Gauge       | radiative; AMR; characteristics; constraints  
| Outer B.    | punctures; simple excision; excision in adapted coordinates with charact.; excision for moving black holes  
| Inner B.    | Various AHF; EHF: (GC;) Diener; Matzner et al.  
| Analysis    | Moncrief; Lazarus interface to Teukolsky equation  
| Horizon     | Various AHF; EHF: (GC;) Diener; Matzner et al.  
| Waves       | AEI-Cactus, Maya-Cactus, BAM, Illinois, Texas: finite differencing, MPI  
| Infrastructure | Cornell/Caltech, Meudon: pseudo-spectral  
|             | FMR, AMR: Cactus, NASA, Choptuik et al.; multidomain in p.s. multigrid elliptic solver  
|             | fish-eye; p.s. with radially adapted coordinates |

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Numerical relativity for binary black holes: cutting edge 2003

<table>
<thead>
<tr>
<th>Initial data</th>
<th>Conformal transverse traceless or conformal thin sandwich; quasi-equilibrium by effective potential method, helical Killing vector; post-Newtonian; conformal flatness, maximal slice, boundaries</th>
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<tr>
<td></td>
<td>• Numerical convenience → astrophysical relevance</td>
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<tr>
<td></td>
<td>• Artificial components in initial data? Just let it evolve for 5!</td>
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<td>• Gap between “reliable” data and evolution capabilities?</td>
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<tr>
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<td>• How smooth is the transition to plunge?</td>
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<td>• QE evolutions</td>
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<td>• All waves from puncture data ?!</td>
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<tr>
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<td>• Don’t focus too much on ISCO.</td>
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Numerical relativity for binary black holes: cutting edge 2003

| Initial data | BSSN; Hyperbolic: KST, …; resolving constraints K freezing, Gamma freezing; ell/par/hyp; corotating coords. radiative; AMR; characteristics; constraints punctures; simple excision; excision in adapted coordinates with charact.; excision for moving black holes |
| Evolution | • Intelligently engineered systems (BSSN, …) versus/complementing/being slowly replaced by ?? Hyperbolic systems (KST, …) at least one good reason: boundaries |
| System | Analysis | Horizon | Waves | Infrastructure |
| Gauge | • Dynamic gauges bring break-through for 1BH and head-on. |
Alcubierre, Brügmann, Diener, Koppitz, Pollney, Seidel, Takahashi 03

- puncture evolutions without excision
- shift draws points from inner AF region reducing grid-stretch.
- lapse and shift together essentially freeze the evolution
- not minimal distortion, not elliptic
- no excision
Head-on collision: Waveform to $t=5200M$
maximal slicing, octant (!)

Brill-Lindquist data
equal mass, octant
Cook/Baumgarte ISCO separation
maximal slicing
Gamma freezing shift
outer boundary: 12.3, fish-eye 26.0
no excision, no Lazarus
# Numerical relativity for binary black holes: cutting edge 2003

| Initial data | BSSN; Hyperbolic: KST, …; resolving constraints  
K freezing, Gamma freezing; ell/par/hyp; corotating coords.  
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Gauge  
Outer B.  
Inner B.  |
| Analysis Horizon |  
Waves  
Infrastructure  |
|  
• Intelligently engineered systems (BSSN …)  
  *versus/complementing/being slowly replaced by ??*  
  Hyperbolic systems (KST …)  
  └  
  at least one good reason: boundaries |
|  
• Dynamic gauges bring break-through for 1BH, head-on,  
  but what is needed for orbits?  
  • Corotating coordinates may be essential  
  • Outer boundaries are becoming more of a problem (good!)  
  • Inner boundaries: punctures, excision, or *moving excision*?  
  • Constraint conservation? Too many new constraints? |

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Numerical relativity for binary black holes: cutting edge 2003

Initial data
Various AHF; EHF: (GC; Diener; Matzner et al. Moncrief; Lazarus interface to Teukolsky equation

Evolution
System
Gauge
Outer B.
Inner B.

• Apparent horizon finding “essentially” solved
• Event horizon finding: lost, now back!

Analysis
Horizon
Waves

• Waves – our final product!!
• State of the art is Lazarus

Infrastructure
Head-on collision, 80M, convergence in the waveform, AEI03

Center for Gravitational Physics and Geometry, Penn State
http://gravity.psu.edu
First waveform for the plunge from an ISCO (Lazarus)

Baker, Brügmann, Campanelli, Lousto, Takahashi ’01: ISCO data
Baker, Brügmann, Campanelli, Lousto ’00: head-on (Misner) data
Numerical relativity for binary black holes: cutting edge 2003

Initial data
Various AHF; EHF: (GC;) Diener; Matzner et al. 
Moncrief; Lazarus interface to Teukolsky equation

Evolution
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- Apparent horizon finding “essentially” solved
- Event horizon finding: lost, now back!
- Waves – our final product!!
- State of the art is Lazarus
- There are too few groups focussing on
  - producing waves with current tech.
  - translation to world of data analysis

- Really?! Isn’t there still a huge gap between wish and fact?
  Yes and no.
Summary

- Has there been progress since 1993? YES.
- Will there be progress by 2013? OF COURSE.
- **Think about waves! Fund groups with critical mass!**
  
  See Teukolsky Report

1995: Schwarzschild in 3d
1999: Grazing Collision
2003: 50M for plunge from ISCO
      Psi4 in x-y plane
      lapse based excision mask
      corotating coordinates
      AEI/PSU/UNAM