The Lazarus Project

Black Hole Mergers: from simulation to observation

MANUELA CAMPANELLI
Center for Gravitational Wave Astronomy
Department Physics & Astronomy
The University of Texas
at Brownsville
Who is Lazarus?

- Built a prototype model for binary black hole mergers which incorporates all best information available …
- Use the results obtained to build bridges among Source Simulation, GW Data Analysis and Astrophysics.

Lousto talk (this meeting)
Coalescing binary black holes

- **Inspiral**
  - FL/PN approx

- **merger/plunge**
  - ~ 40 M
  - FN simulation

- **ring-down**
  - ~ 100 M
  - CL approx

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Decennial Meeting 06/2003
The Lazarus Approach

GR Initial data:
Quasi-Circular (QC)
Initial Data, approaching PN in the Far Limit
Binary black holes in quasi-circular orbits

- **FL** kinematical model based on Quasi-Circular (QC) BY puncture initial data (positions, momenta, spins) (Cook 94; Brandt, Brügmann 97)

- Meet **PN** at large separation $L$, 3PN ISCO close to QC3-QC4 parameters

- Improved **PN** Initial Data (Tichy, Brügmann, Campanelli, Diener, 03) (see Tichy talk)

- **Assess the validity of the initial data dynamically** (Baker, Campanelli, Lousto, Takahashi 02;)

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The Lazarus Approach

Full Nonlinear (FN) evolution: ADM (BSSN) eqs, Maximal slicing (shift), Fisheye (BC) etc.
The Lazarus Approach

CL approx:
Perturbative evolution of a single distorted Kerr hole via the Teukolsky Eq. Waveforms in terms $\psi_4$
The Lazarus Approach

Built-in self-consistency check
Waveforms: A first glimpse on Plunge Radiation

Evolutionary seq. of plunge waveforms which do not depend strongly on the initial separation within this data family.

(Baker, Campanelli, Lousto, Takahashi, Phys Rev D, 2002)
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Final Kerr BH spin parameter $a/M$

- Weak dependence on the QC
- Data (conservative estimates of errors).
- Highly rotating, but not nearly maximally. Need other astrophysical mechanisms to reach $a \sim M$
TRACING BLACK HOLE MERGERS THROUGH RADIO LOBE MORPHOLOGY


NGC 326

BH mergers induce a spin flip of the jet in X-shaped radio morphologies
QC orbits of spinning binary black holes

L=4M

L=7M

P=0.23M
P=0.24M
P=0.25M
P=0.28M
P=0.33M
P=0.35M
P=0.44M

S=-0.50m^2
S=-0.37m^2
S=-0.25m^2
S=-0.12m^2
S=0.0m^2
S=+0.08m^2
S=+0.17m^2
The final plunge of spinning binary black holes

\[(a_f/M_f)_s \approx (a_f/M_f)_{s=0} + 0.32 \left( s_i/m_i^2 \right)\]
Results

• Fast plunge, efficient radiation of angular momentum
• Mass radiated $\sim 2-3\%$. Angular momentum radiated $\sim 12\%$. (polar axis)
• Relatively simple Waveforms (ringup+ringdown)
• Mostly circularly polarized waveforms (polar axis)
• Final holes with $0.7 < a/M < 0.75$ for non-spinning binary black holes
• Spin dependence adds up to final hole (for $s/m \leq 0.25$):
  $$(a_f/M_f)_s \approx 0.72 + 0.32 \left( s_i/m_i^2 \right)$$

An extrapolation of this result suggest that it is hard to form nearly maximally spinning black holes from BH mergers (accretion mechanism needed!)
Next

Improve everything!

**Model:** New human blood/brain power + better codes!

- **FN evolution:** BSSN, better gauge and boundary conditions, 4th order accurate code (**Lazev**) …
- **Initial data:** PN inspired, thin sandwich puncture data …
- **Method (Lazarus II):** Careful biopsy of Lazarus needed to better estimate errors …

**Bridges:** Good Relashionships!

- **Astrophysical Parameters:** Different masses (recoil velocity or kicks …)
- **Kudu:** Identify robust features of the results, Explore connection with GW data analysis (detection strategies … see Lousto talk)
Collaborators:
(Past-Present-Future)

• UTB: Carlos Lousto, Enrique Pazos, Marc Hannam, Yosef Zlockower, Warren Anderson, Charlie Torres, Lior Barack, Mino Yasushi ...

• NASA: John Baker, Joan Centrella ...

• PSU: Bernd Bruegman, Wolfgang Tichy ...

• AEI: Ryoji Takahashi, Peter Diener, Frank Hermann ...
Waveforms: $\psi_4$

Here $q = \omega_{QN}^S / \omega_{QN}^{S=0}$. A similar rescaling was observed for 2PN waveforms: $S \rightarrow M + \delta M$. 
Instantaneous frequency from $\psi_4 = A e^{i\phi}$
PN/QC Comparisons

- **3PN-ISCO, Meudon data ISCO, QC3-QC4**
  parameters are close (few %)
  (Tichy et al, qr-qc 0306020)

- Improve the Initial Data to meet **PN** at earlier times ...
  (Tichy et al, PRD (2003))

- Thin sandwich approach ...

[Graph showing PN/QC Comparisons with various curves marked as Cook, BD, DJS-E1B3, DJS-E1B2, DJS-E1B1, DJS-j3, DJS-j2, DJS-j1, QC4, QC3]
Circular polarization

$Re \psi_4$ and $Im \psi_4$ 90 deg out of phase

$$\psi_4 = A(t) e^{i \phi(t)}$$

(Observer along the polar axis)

- Dynamics dominated by rotational motion.

- ID artifact (not circularized) shrinks with increasing L. Not so bad ...

(Baker, Campanelli, Lousto, Takahashi, 02)