Observing the Universe with Gravitational Waves

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**What are gravitational waves?**

- Gravitational waves are waves in the general relativistic gravitational field
- Gravitational waves are produced by asymmetrical accelerations of matter
- Gravitational waves alternately push apart and pull together matter in transverse directions
What are gravitational waves?

- Gravitational waves are not electromagnetic waves, neutrinos, etc.
- Gravitational waves provide us with a completely new, unique way of observing the Universe.
- Gravitational wave sources include:
  - Collisions among ~solar mass BH's and NS's
  - Supermassive BH/BH mergers
  - Inspiral of ~solar mass BH or NS into supermassive BH
  - Neutron stars
  - Supernovae and collapse of supermassive stars
  - Big bang, phase transitions in the early Universe
  - GRB's?
  - Other?
Overview:

- Ground-based gravitational wave detectors
  --- description and status
- Space-based gravitational wave detector
  --- description and status
- Role of theory/computation
- My work
Ground based gravitational wave detectors
Ground based gravitational wave detectors

General relativity: The strain between test masses is

$$\frac{\Delta L}{L} \sim h$$

where the gravitational wave amplitude $h$ satisfies a wave equation.
Ground based gravitational wave detectors

Collision between two 10 solar mass BH's at 100Mpc: $h \sim 10^{-22}$

LIGO arm lengths: $L \sim 4$ km

Test mass displacement: $\Delta L \sim 10^{-17}$ cm
Ground based gravitational wave detectors

Strain Sensitivity for the LLO 4km Interferometer

31 January 2003  LIGO-G030014-00-E

S1

6 Jan
Ground based gravitational wave detectors

- Expected event rates for initial LIGO (~2004)
  - BH/BH to 100Mpc: 1/300yr to 2/yr
  - NS/NS to 20Mpc: 1/2000yr to 1/3yr

- Expected event rates for advanced LIGO (~2007)
  - BH/BH to $z = 0.4$: 30/yr to 4000/yr
  - NS/NS to 300Mpc: 1/yr to 800/yr
Space based gravitational wave detector: LISA

LISA is a joint NASA/ESA project
Space based gravitational wave detector: LISA
**Space based gravitational wave detector: LISA**

- LISA is the top priority project within NASA's Beyond Einstein initiative

**Schedule**
- Test flight: August 2006
- Launch: 2011
- Observations: 2012

**Sources**
- Galactic binaries (WD/WD, Low mass X-ray, etc)
- Supermassive BH/BH mergers to z = 30 or more
- Small BH or NS inspiral into massive BH (1/yr to 10/yr out to 1Gpc)
- Stochastic background radiation from early Universe
**Role of Theory/Computation**

- *Ground based detectors*: Signals are so weak that theoretical templates are needed to extract data from noise

- *LISA space based detector*: Signals from supermassive BH/BH mergers will be so strong that theoretical templates are needed to remove these signals from data stream and uncover other sources

Without theoretical guidance, LIGO might not detect anything and LISA will be constantly saturated by a few signals
Role of Theory/Computation

Binary black hole problem (LIGO and LISA)
Role of Theory/Computation

Why is it so difficult to simulate BH/BH mergers?
**Einstein Equations:**

- Large set of coupled, highly nonlinear PDE's
- Overdetermined system
- Gauge freedom must be determined dynamically
- Have no definite mathematical type

There is no known stable algorithm for evolving the Einstein equations numerically

Nevertheless, recent advances allow for simulations approaching the duration needed for the merger phase
My work:

- Numerical algorithms
- Black hole/gravitational wave initial data
- Black hole/gravitational wave simulations

Funding: NSF, NASA
**My work:**

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Collaboration with NASA Goddard Numerical Relativity Group

Primary focus: address the problem of scales (AMR) and connect the inspiral-merger-ringdown phases
My work:

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- Black hole/gravitational wave initial data
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DB and Lisa Lowe (NCSU)
Black hole/gravitational wave initial data

\[ R - K_{ij} K^{ij} + K^2 = 2 \rho \]

\[ D_j K^j_i - D_i K = S_i \]

- With suitable assumptions, the constraint equations (a subset of the Einstein equations) can be written as an elliptic system.
- Must be solved to obtain initial data.
**Black hole/gravitational wave initial data**

Our code:

- Nonlinear elliptic equation solver
- Multigrid FAS algorithm
- Uses AMR (adaptive mesh refinement) to construct the grid as part of the solution process
Black hole/gravitational wave initial data

Brill waves:

\[ ds^2 = \Psi^4 \left[ e^{2q} (d \rho^2 + d z^2) + \rho^2 d \phi^2 \right] \]

\[ q = a \rho^2 e^{-r^2} \]

\[ K_{ij} = 0 \]
Black hole/gravitational wave initial data

2 Black Holes:
\[ M = 1, \, R = (0,0,8), \, P_x = 15 \]
\[ M = 1, \, R = (0,0,-8), \, P_x = -15 \]

U = nonsingular part of conformal factor
Distorted black hole initial data

Metric: \[ ds^2 = \Psi^4 \left[ e^{2q} (d \rho^2 + dz^2) + \rho^2 d \phi^2 \right] , \quad \Psi = \frac{m}{2r} + u \]
Distorted black hole initial data

Single distorted BH
(u in the x,y,z planes)
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