Title: Simulations of Black Holes and Neutron Stars

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Abstract:


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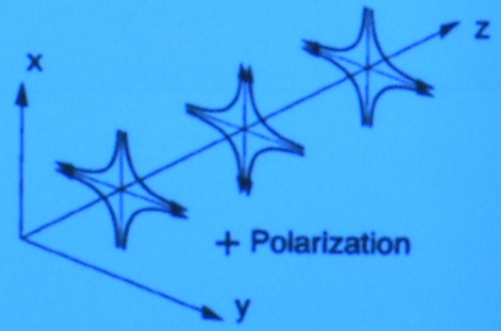
Warped Space and Time

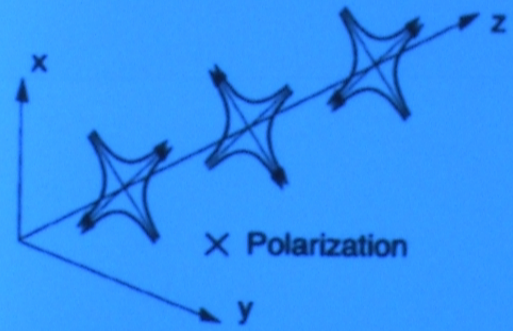
Albert Einstein 1915

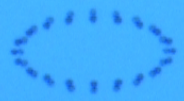
General Relativity:

- Space and time are warped by matter and energy
- Einstein's equations
  - Extremely hard to solve
  - We have glimpsed only a few of their predictions
- Numerical Relativity (Supercomputer simulations of warped space and time)
  - Will revolutionize our understanding of warped space and time

Gravitational Waves







Effect on detector: $h = \frac{\Delta L}{L}$


Livingston, LA
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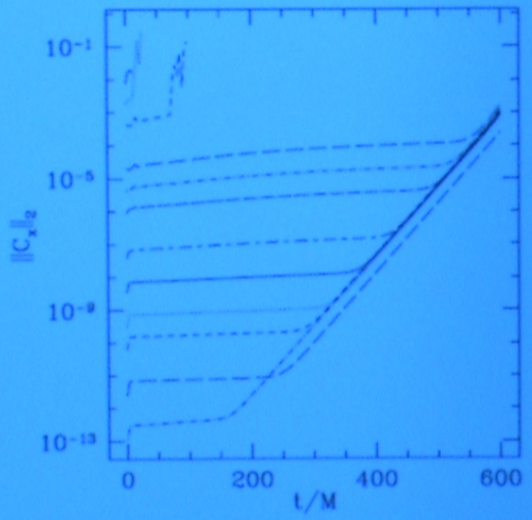
Are these the black holes of Einstein's theory?

- Event horizon = 1-way membrane
- Geometry of spacetime = Kerr metric
- etc.

"It's black, and it looks like a hole. I'd say it's a black hole."

Simulating Black Holes

- Until 2005, all 3-d black hole evolutions unstable
- Key preceding accomplishment: instability comes from constraint violation



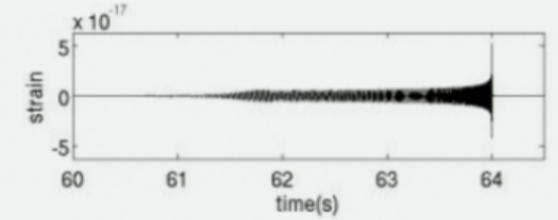
Kidder, Scheel & Teukolsky (2001)

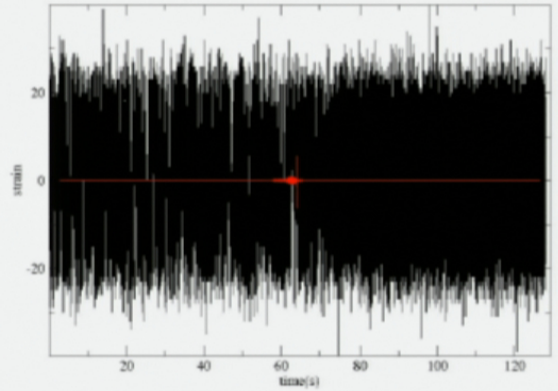
Properties of Einstein's Equations

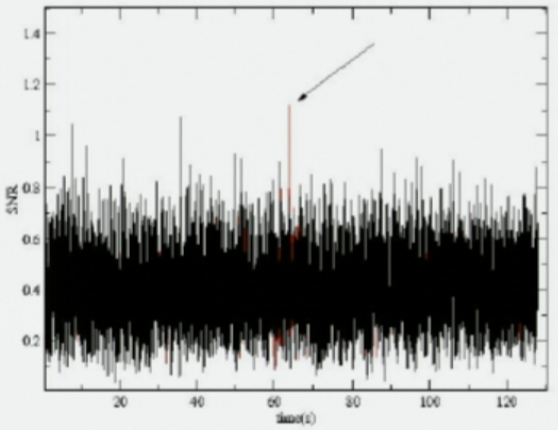
- 10 eqns — 10 components of $g_{\alpha\beta}$

LIGO Template Bank

- Cross-correlate template with data
- 8-d $(M_1/M_2, \mathbf{S}_1, \mathbf{S}_2, e)$
- Need semi-analytic waveforms (calibrate with simulations)







(Figures: Cardiff University Grav. Physics)

Required Accuracy

- Subtle (Lindblom 2009)

  f vs. t, calibration error, ...

- Advanced LIGO:

  $\delta\Phi \lesssim 0.05$ detectability

  $\lesssim 0.005$ parameter estimation

  Number of orbits important!

- Current status:
  - Detectability: Simulations OK for equal mass, no spin
  - Perhaps OK for low spins
  - Not good for high spins (precession)
  - Not good for parameter estimation
- LISA: much smaller errors!

Dual Frames

1. "Inertial coordinates"
   - asymptotically cartesian
   - black holes orbit, distort, merge
   - vector and tensor fields defined
2. "Grid coordinates"
   - excision boundaries spherical, stationary
   - comoving

Spectral in grid coords ⇔ Mapping ⇔ Inertial coords

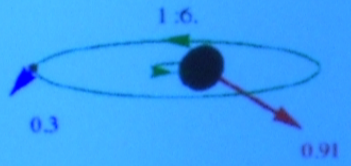
PN Expansion

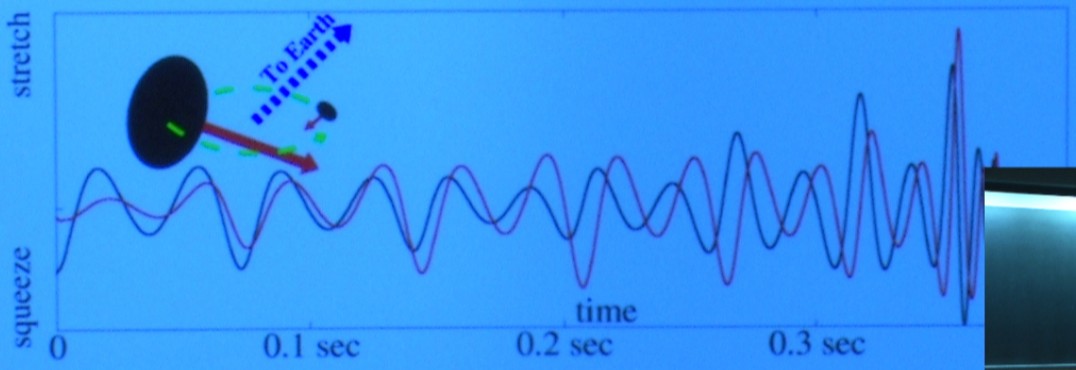
$$\Phi = \Phi_0 - \frac{1}{8}x^{-5/2}\left\{1 + \frac{2435}{504}x - 10\pi x^{3/2} + \frac{11747195}{508032}x^2 + \frac{1165}{42}\pi x^{5/2}\ln x + \left[\frac{15738127248 19}{4694215680} - \frac{7985}{192}\pi^2 - \frac{1712}{21}\gamma - \frac{856}{21}\ln(16x)\right]x^3 + \frac{357185}{7938}\pi x^{7/2}\right\}$$

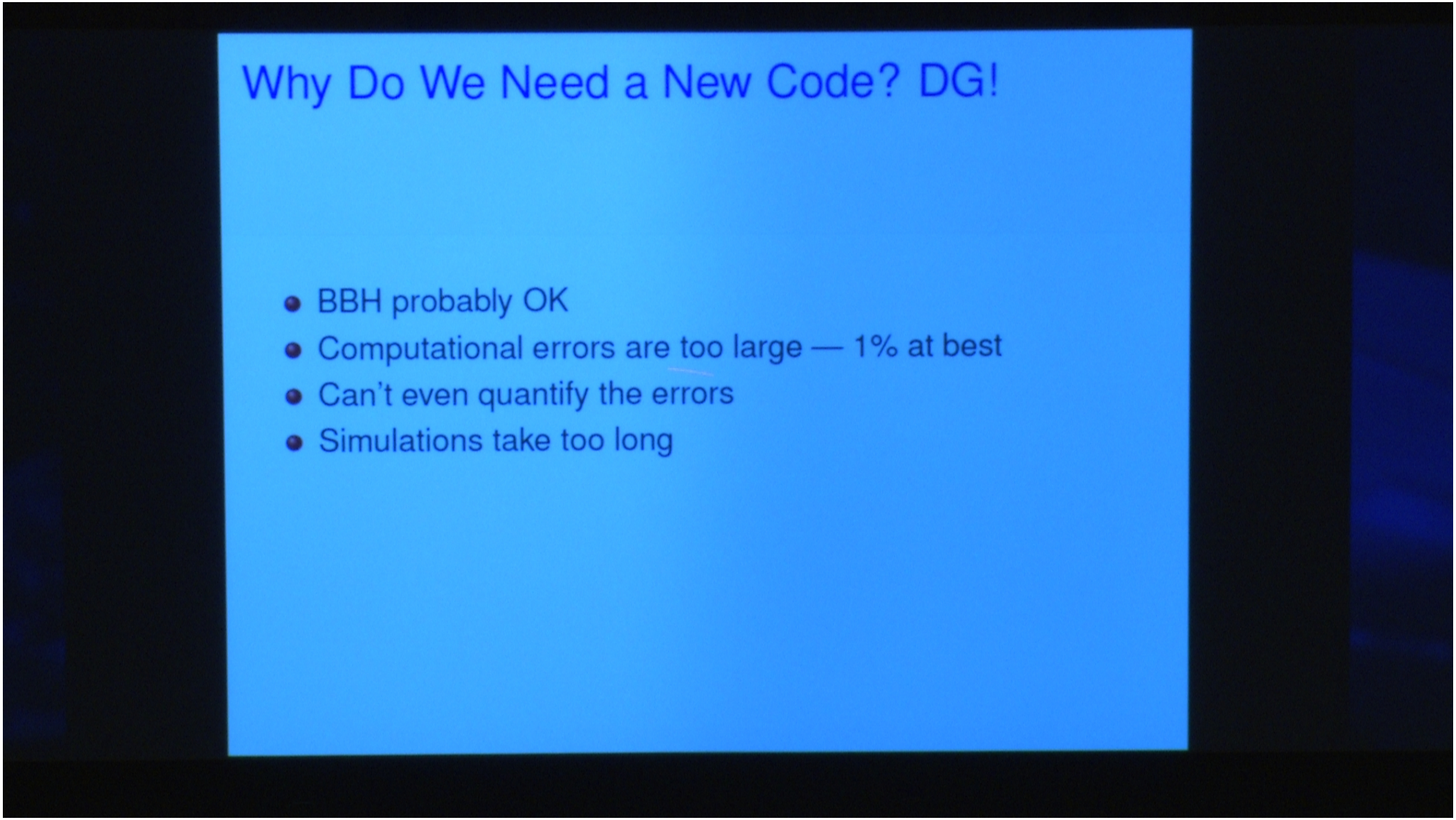
$$x \equiv \left(\frac{Gm\Omega}{c^3}\right)^{2/3} = O\left(\frac{v}{c}\right)^2$$

Calibrating Templates for Realistic Cases

- Current LIGO templates: small spins, aligned
- Need simulations with large spins, precession






Why Do We Need a New Code? DG!
BBH probably OK
Computational errors are too large — 1% at best
Can't even quantify the errors
Simulations take too long

What's So Hard?

- NS surface + shocks $\Longrightarrow$ solution not smooth
- Multiple time scales
- Multiple spatial scales (adaptivity)
- Geometry changes (disruption, merger, black hole formation)
- Multiphysics (GR, hydro, MHD, neutrinos, photons, nuclear reactions,. . .)