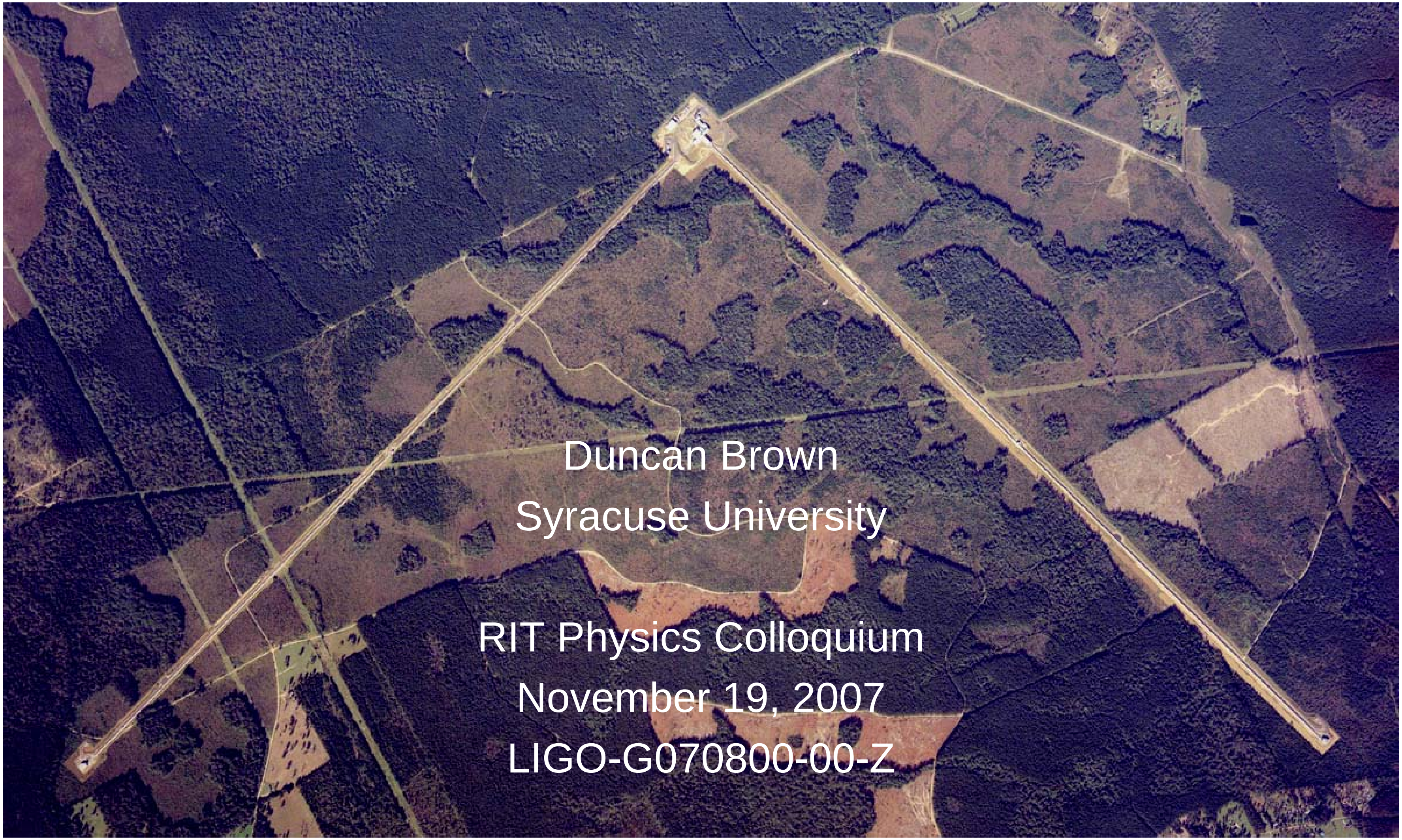
Searching for Gravitational Waves with LIGO: A New Window on The Universe



Duncan Brown
Syracuse University

RIT Physics Colloquium
November 19, 2007
LIGO-G070800-00-Z

Overview

- So far, our knowledge of the universe comes from observing electromagnetic radiation, neutrinos and cosmic rays
- Einstein’s theory of General Relativity predicts **gravitational waves**
- So far there has been no direct detection of gravitational waves
- Their detection would open a new window on the universe
- One of the most promising sources are **binary inspirals**
- What are gravitational waves? What are binary inspirals? How do we search for inspirals and what might we learn when we see them?

Electromagnetic Waves

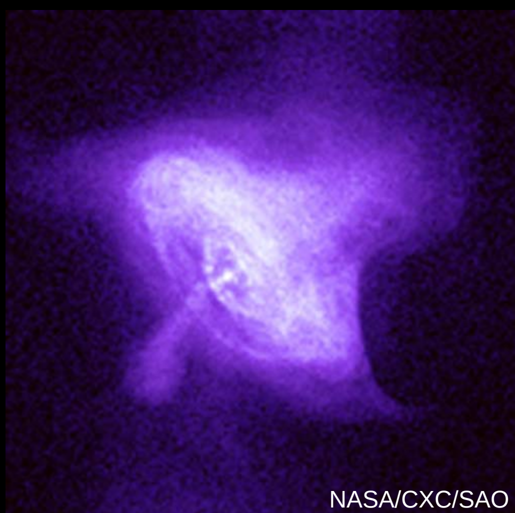
- From Maxwell's equations in empty space, we can derive wave equations for the Electric and Magnetic fields

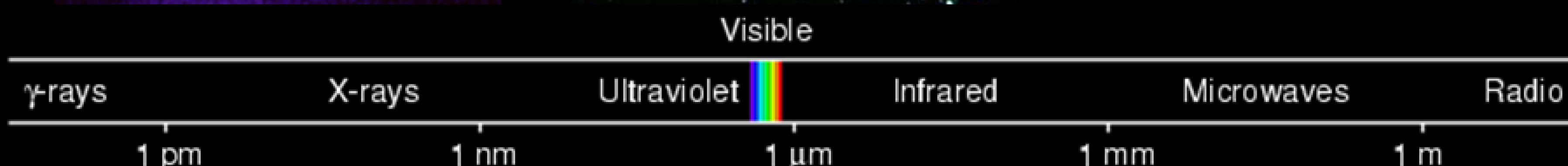
- Oscillating charges generate electromagnetic waves

- Different wavelengths make up electromagnetic spectrum

Electromagnetic Astronomy

- Observing electromagnetic waves at different frequencies gives us different views of the universe





Gravitational Wave Astronomy

- Gravitational waves are not just a different wavelength: they are a different spectrum!
- What will we see when we observe the universe with gravitational waves?

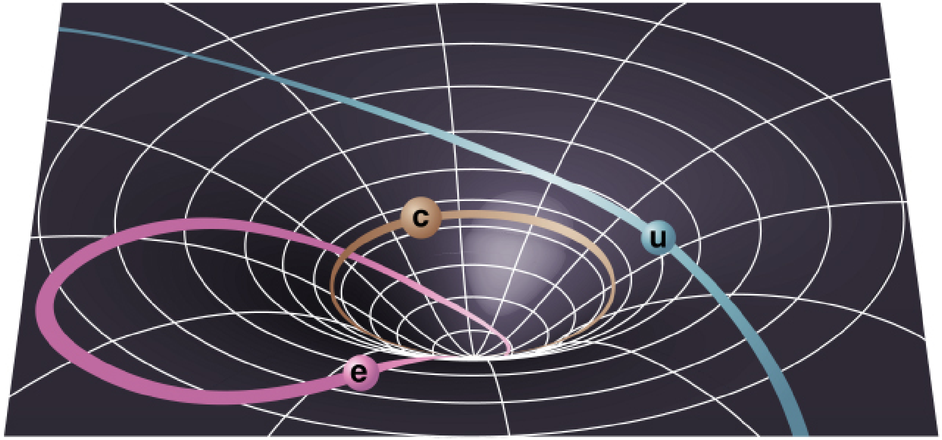
?

Gravitational Wave Astronomy

- Gravitational waves interact very weakly with matter
- We will see deep into regions inaccessible to electromagnetic observations
- See far back in to the early universe, beyond the cosmic microwave background
- Detection of gravitational waves would give us **astronomy** and **physics**!

General Relativity

- Einstein's theory of general relativity describes gravity as curvature of spacetime

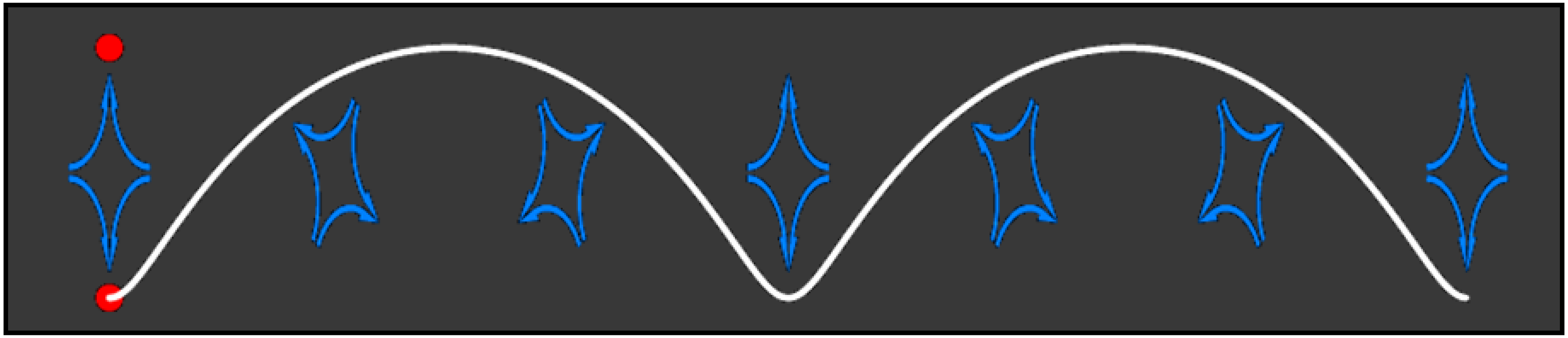


- Gravitational fields are described by Einstein's equation's

$$G_{\mu\nu} = 8\pi T_{\mu\nu}$$

- Matter tells space how to curve and space tells matter how to move

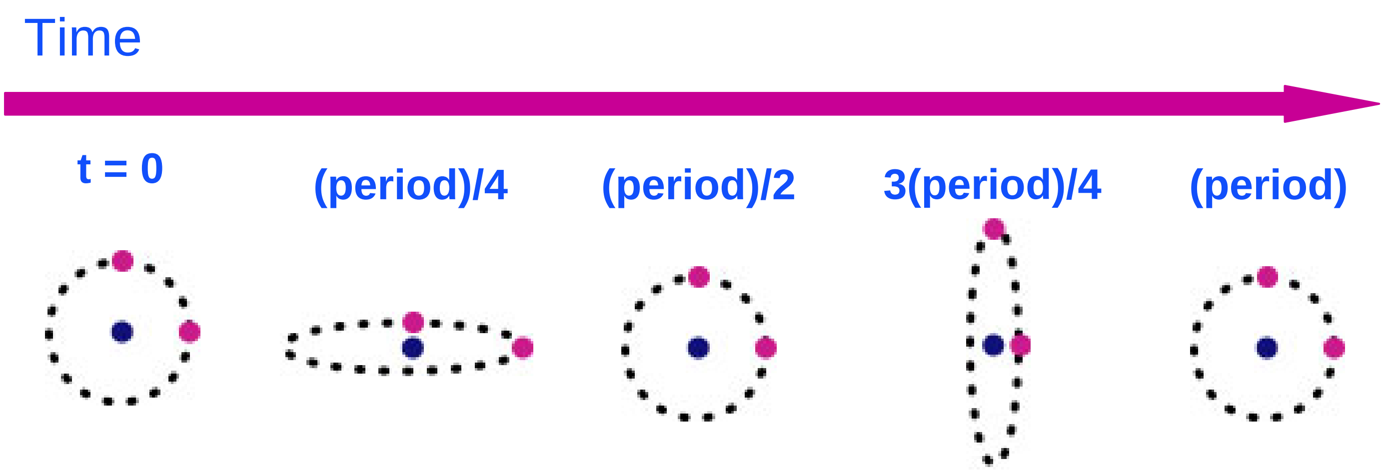
Gravitational Waves



- Oscillating masses will produce gravitational waves
- But unlike electric charge, mass only has one sign
- Need oscillating quadrupoles: spinning dumbbell shape

Effect of a Gravitational Wave

- As gravitational waves pass, they change the distance between neighboring bodies



- Strength of a gravitational wave is given by the *strain* h(t) = change in length / length

Generation of Gravitational Waves

- Problem: it's hard to make gravitational waves…

- Power radiated

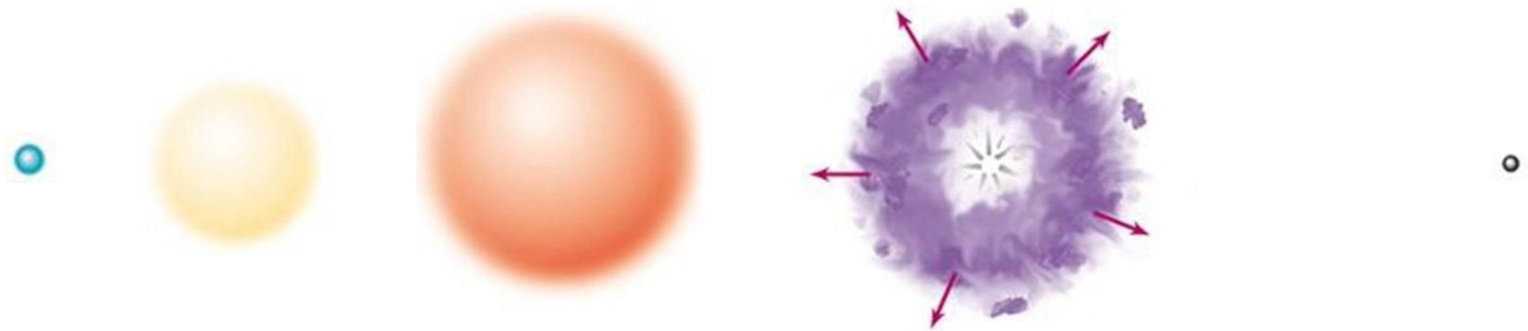
$$P_{\mathrm{EM}} \sim c^2 = 10^{17} \qquad P_{\mathrm{GW}} \sim \frac{G}{c^5} = 10^{-53}$$

- Need a lot of mass in a small space…

- Need the matter to be moving very fast…

How Does the Universe Make Gravitational Waves?

matter



Massive Star

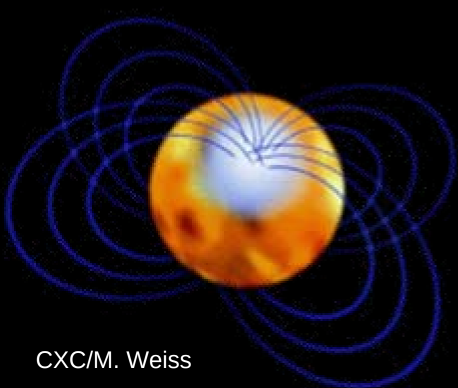
Giant Phases

Supernova Explosion

Neutron star or black hole

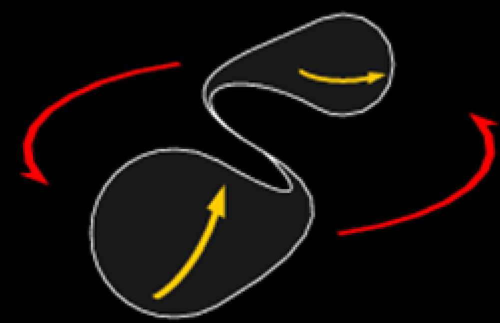
Compress into small space

Sources of Gravitational Waves

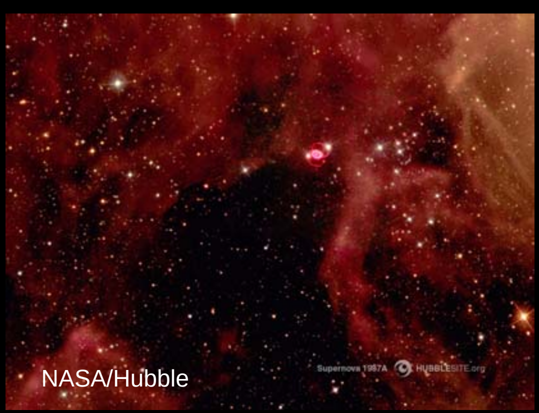


CXC/M. Weiss

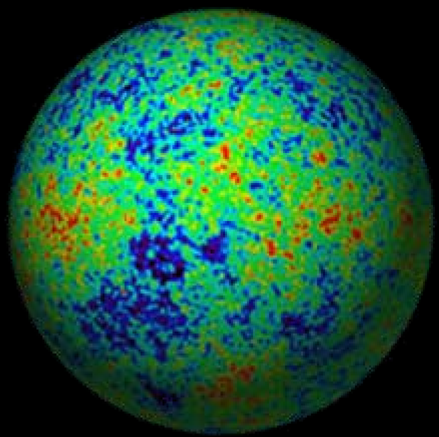
Continuous sources: Spinning neutron stars



Binary inspirals: “long bursts” of gravitational waves as stars inspiral and merge



“Short bursts:” Supernovae, transient sources, ???

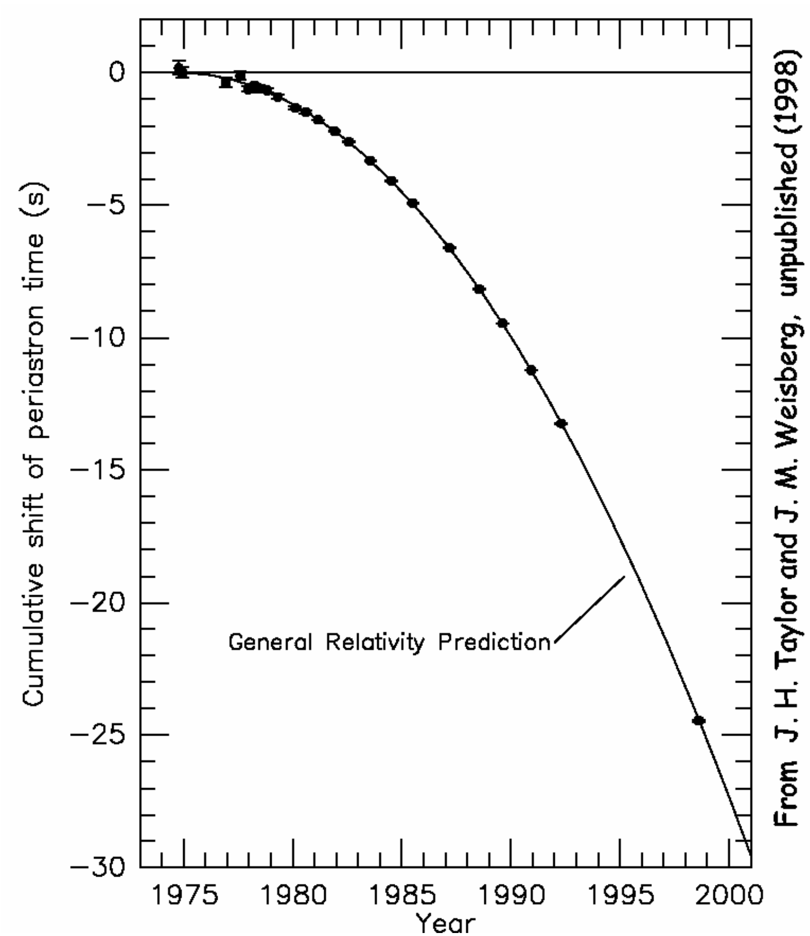


Gravitational wave backgrounds: relic radiation from the big bang

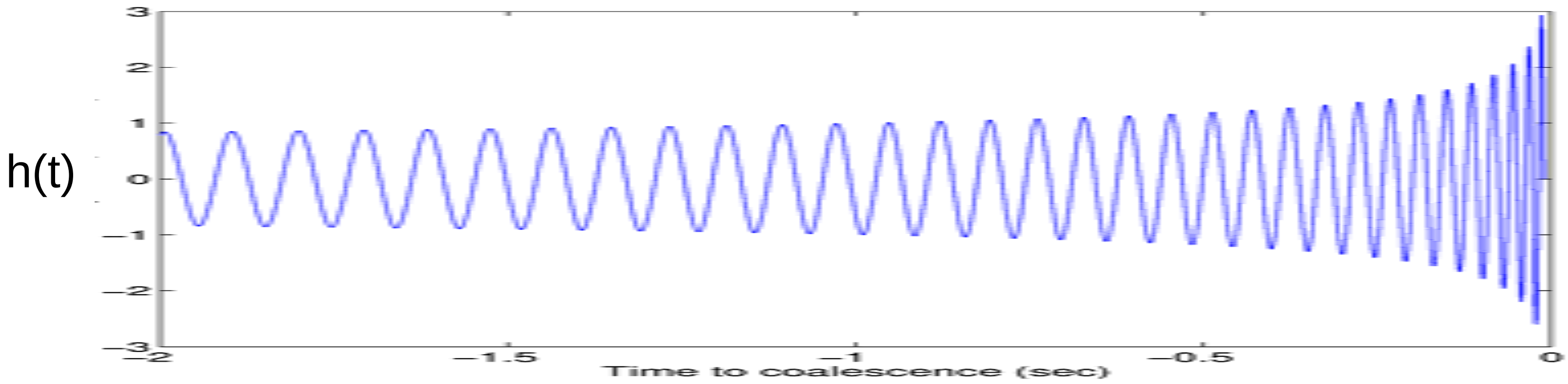
Observation of Inspirals

- No direct detection of gravitational waves yet…
- But we have observed binary neutron stars through their radio emissions!

QuickTime™ and a
YUV420 codec decompressor
are needed to see this picture.

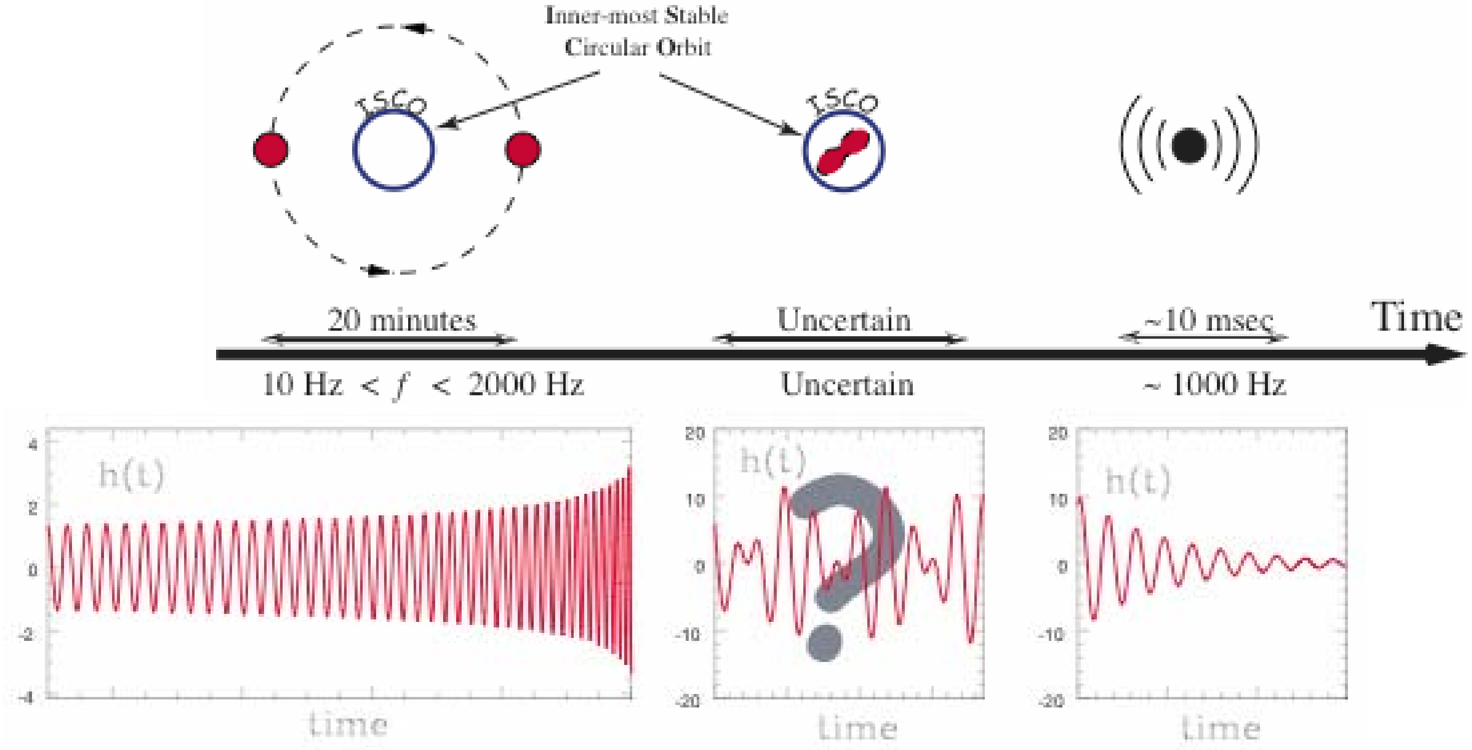


Gravitational Waves from Inspirals



- The frequency of gravitational waves is twice the orbital frequency
- The amplitude increases as the separation decreases
- Putting this all together… the gravitational wave is a **chirp**

Evolution of Binary System



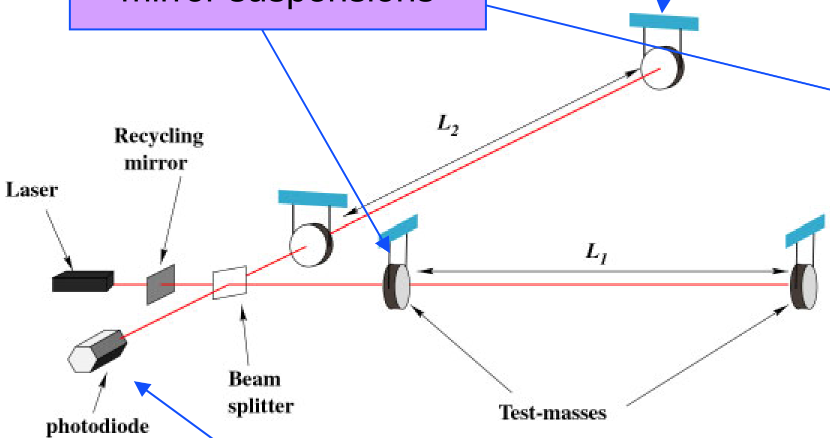
- Gravitational wave strains on earth are h(t) ~ 10^{-21}
- How do we look for them?

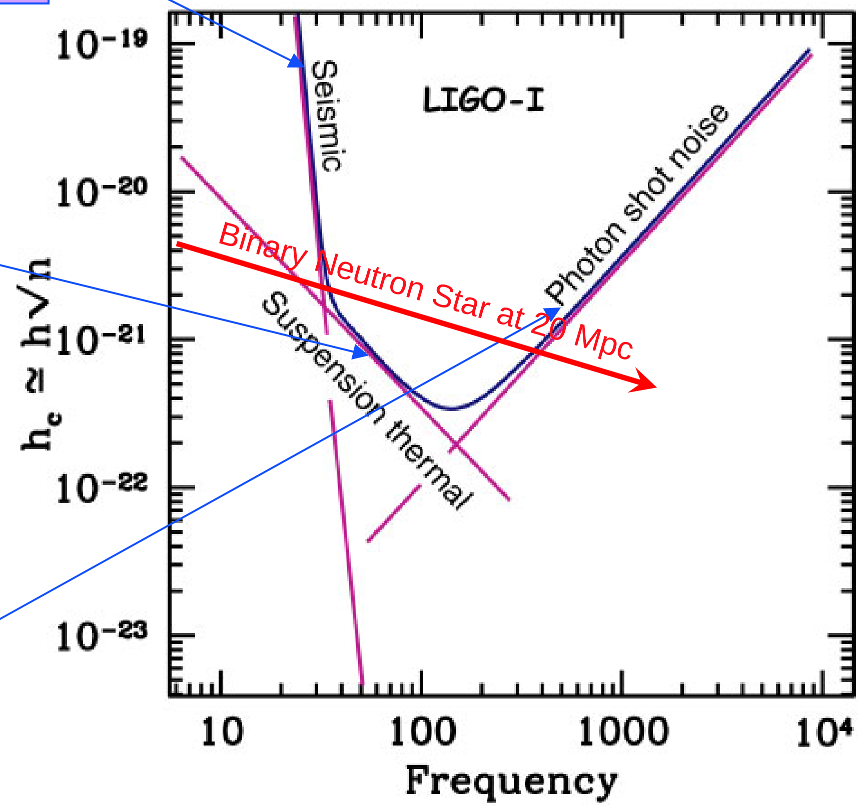
Detection of Gravitational Waves

- Interferometric d... laser light to measure the change in the le... ms produced by GWs

Ground motion couples into motion of mirrors

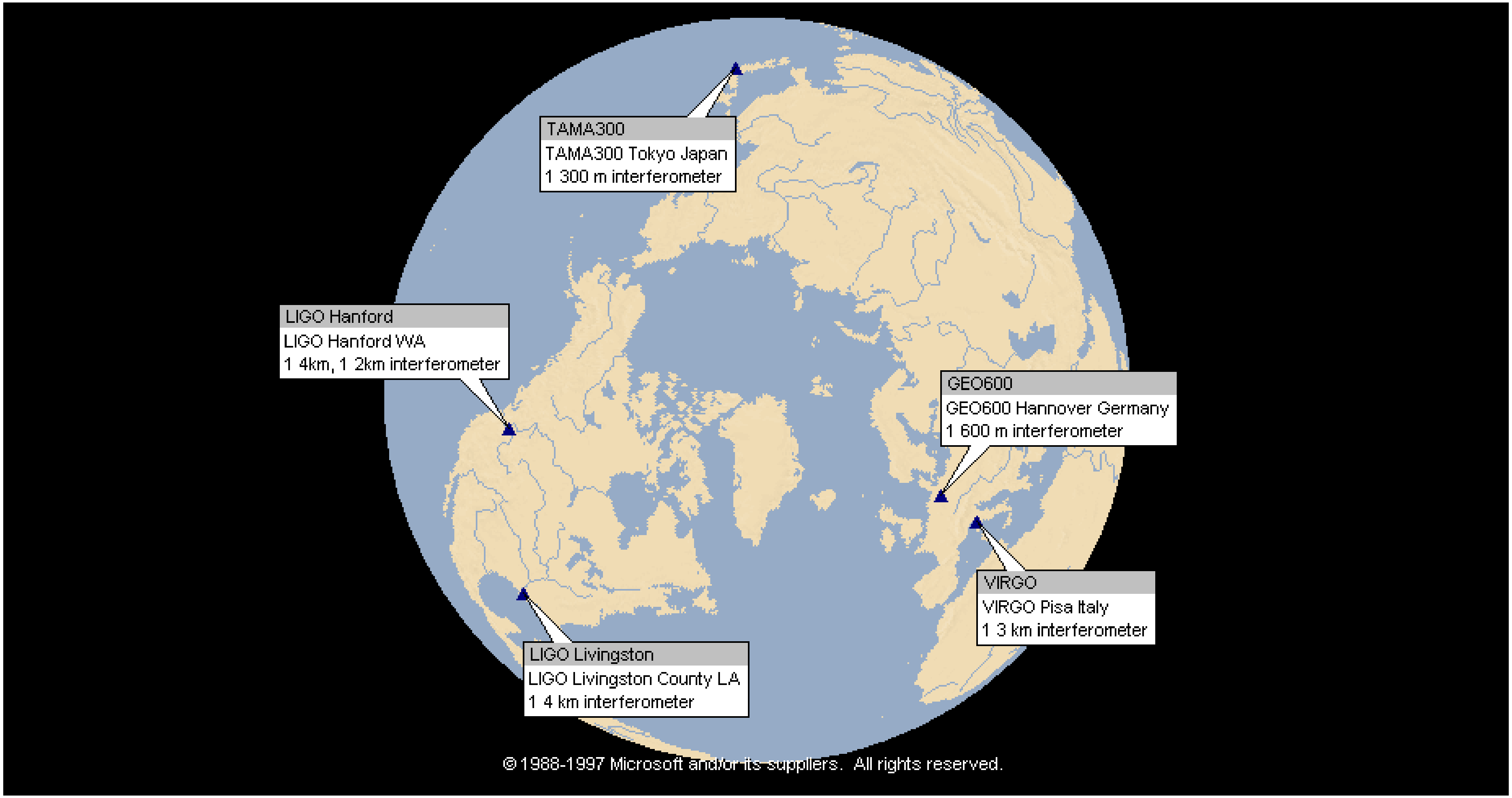
Thermal excitations of mirror suspensions





Counting statistics of photons at photodiode

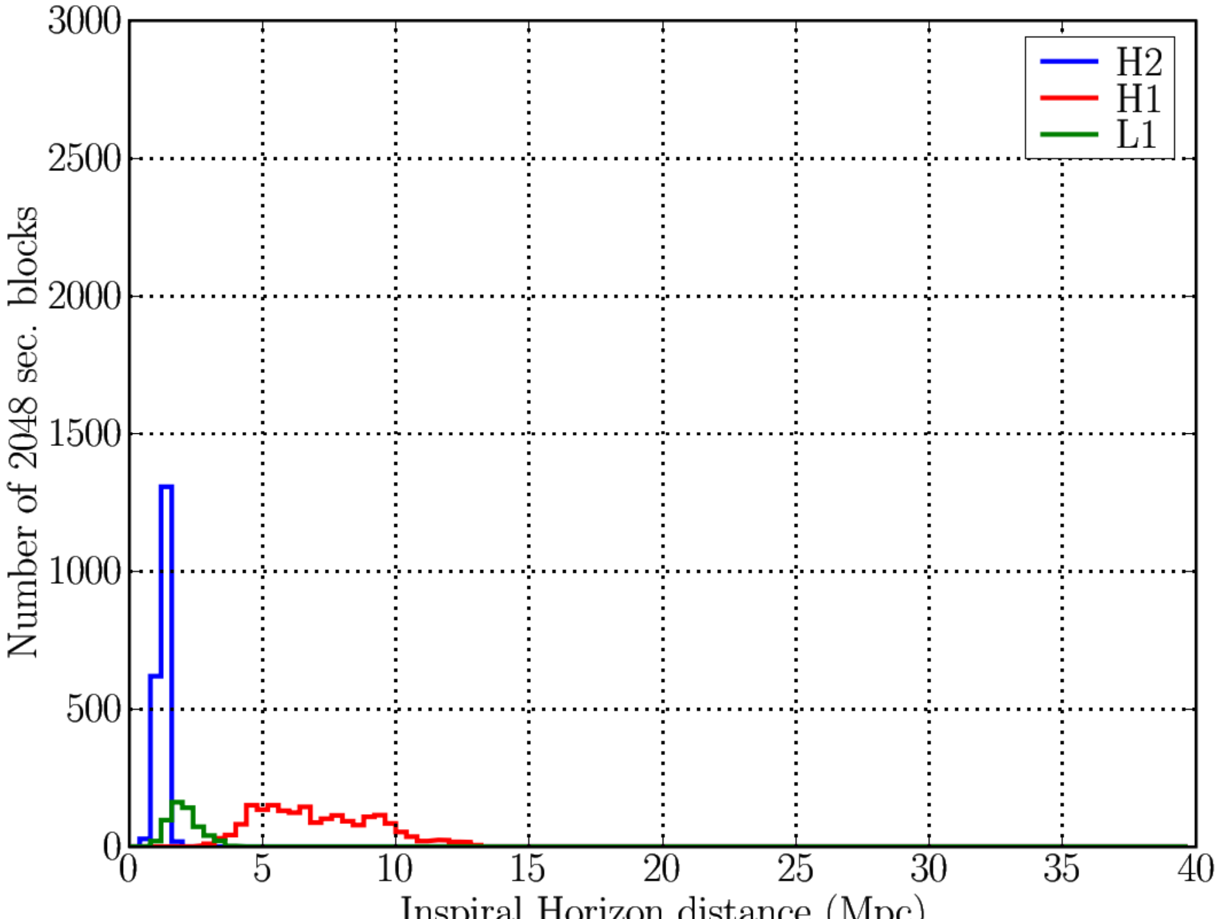
A World Wide Network



The LIGO Detectors

Sensitivity Improvement

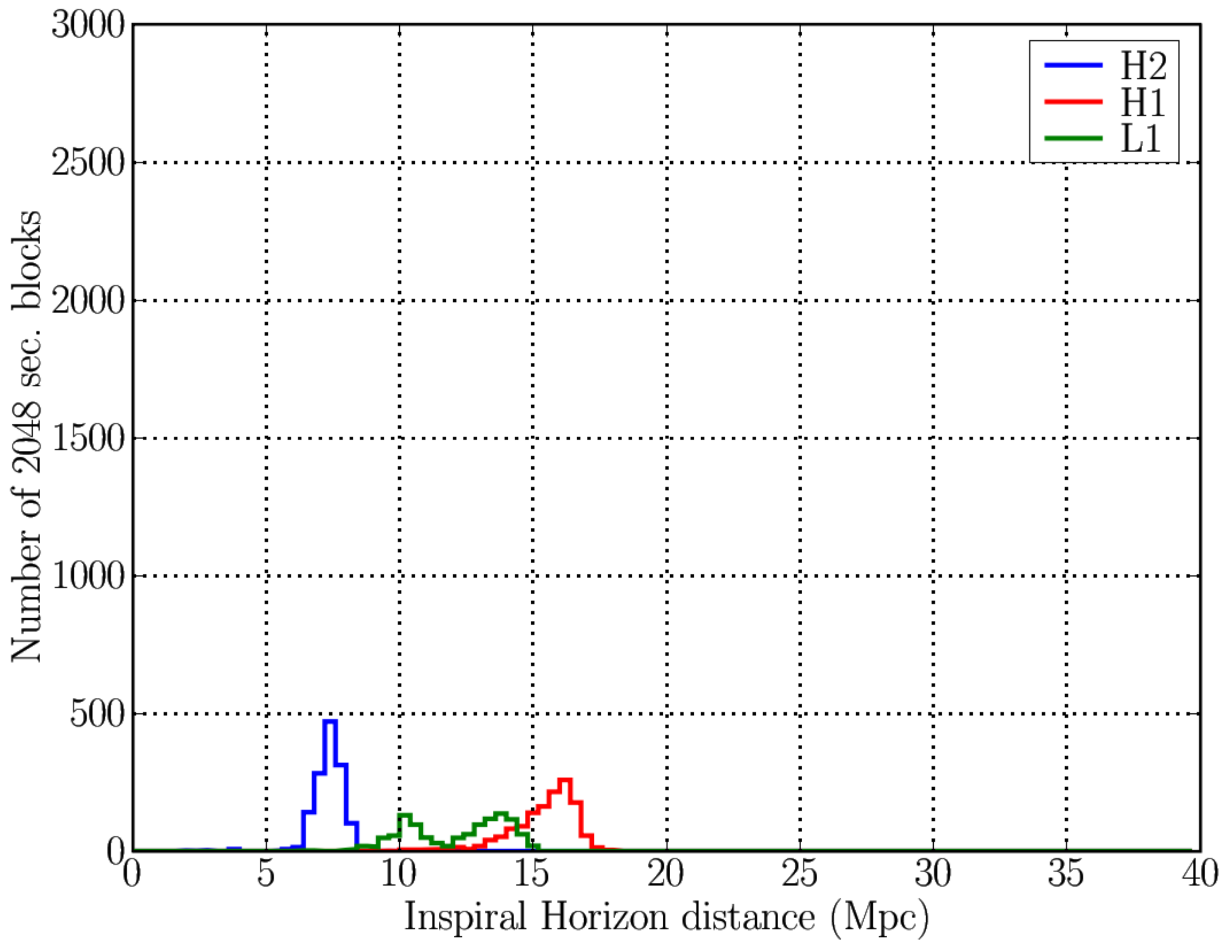
Distance to optimally oriented 1.4,1.4 solar mass BNS at SNR = 8



S3 Science Run
Oct 31, 2003 -
Jan 9, 2004

Sensitivity Improvement

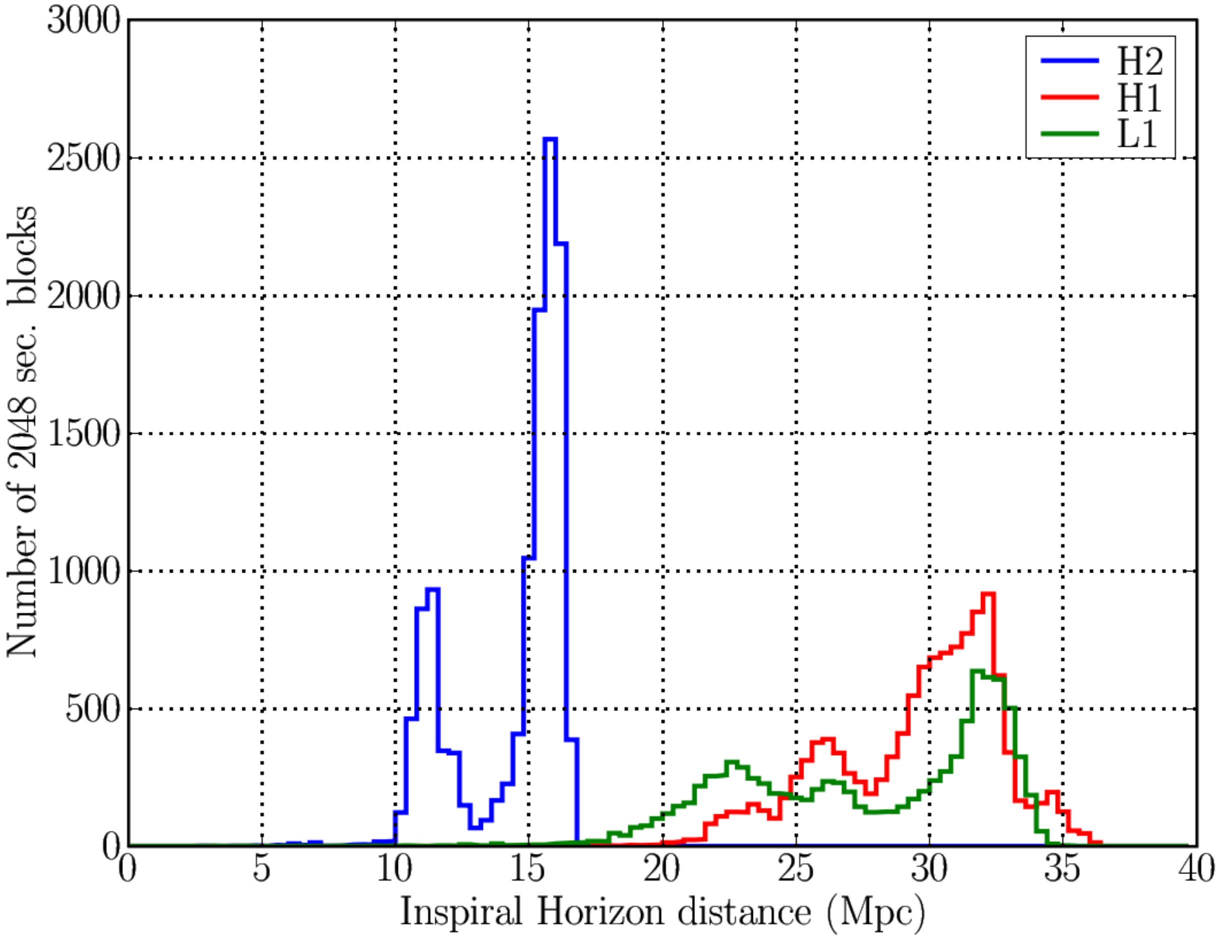
Distance to optimally oriented 1.4,1.4 solar mass BNS at SNR = 8



S4 Science Run
Feb 22, 2005 -
March 23, 2005

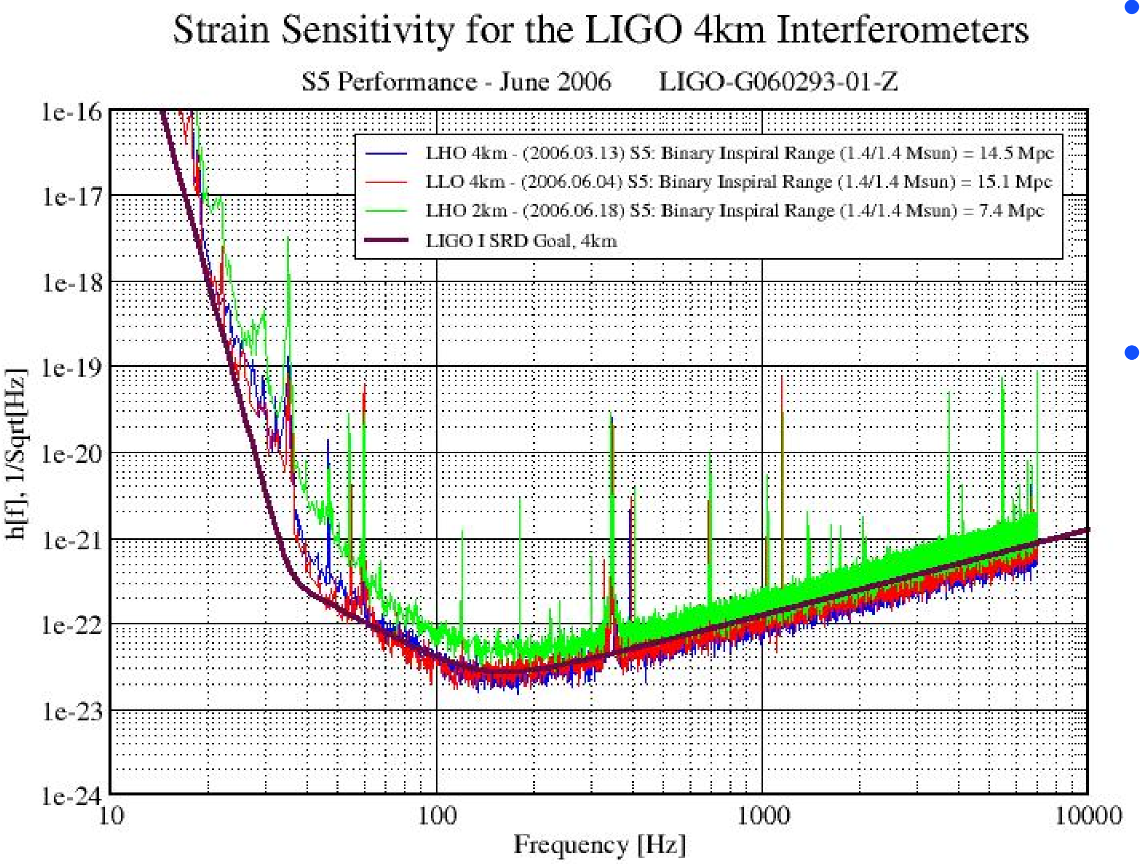
Sensitivity Improvement

Distance to optimally oriented 1.4,1.4 solar mass BNS at SNR = 8



First Year
S5 Science Run
Nov 4, 2005 -
Nov 14, 2006

The Fifth Science Run
Nov 5, 2005 - Oct 1, 2007

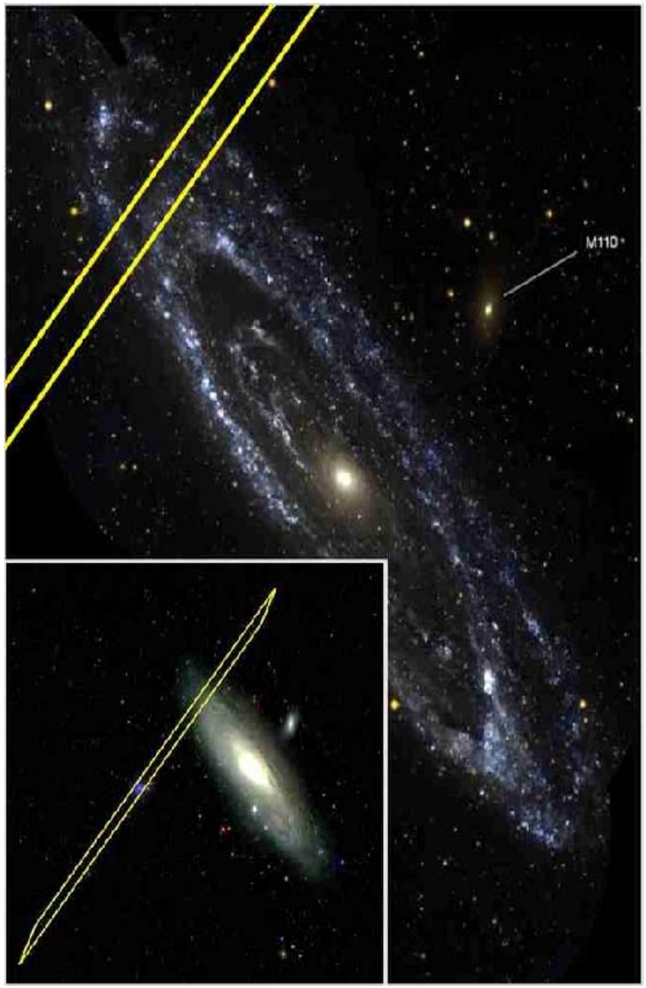


- Recorded **one year of coincident data** from the three LIGO detectors **at design sensitivity**
- LIGO is sensitive to binaries consisting of neutron stars and black holes with

$$M_{\rm total} \lesssim 100 M_\odot$$

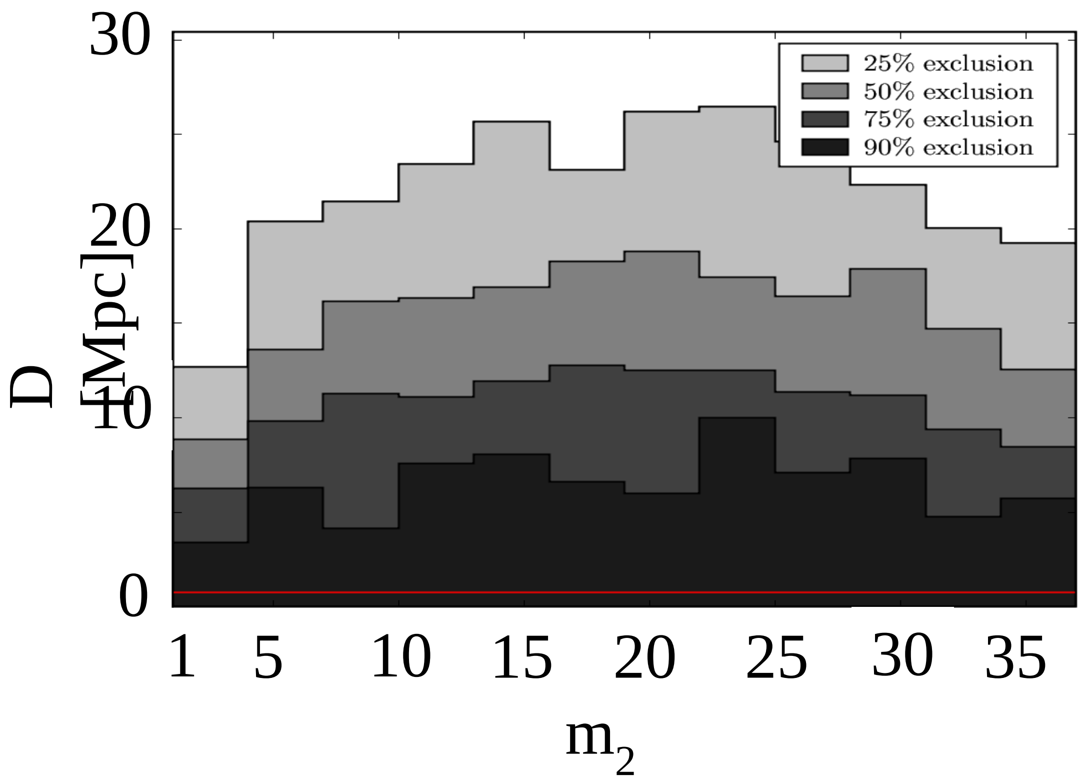
LIGO is already doing astrophysics…

- Gamma Ray Burst 070201
- Short Hard GRB located by five electromagnetic satellites
- SH-GRBs are thought to have inspiral progenitors
- Location error box overlaps the spiral arms of Andromeda (D ~ 770 kpc)
- LIGO Hanford detectors were operating at the time of the GRB

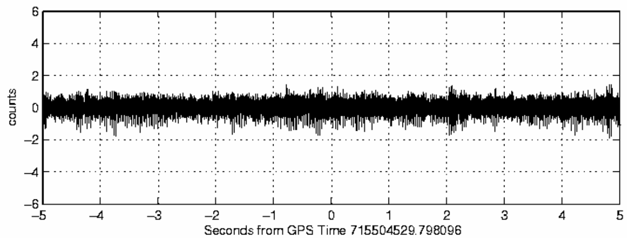


GRB070201

- Inspiral in Andromeda with masses $1.0 < m_1 < 3.0\ M_{sun}$ and $1.0 < m_2 < 40\ M_{sun}$ excluded at > 99% confidence



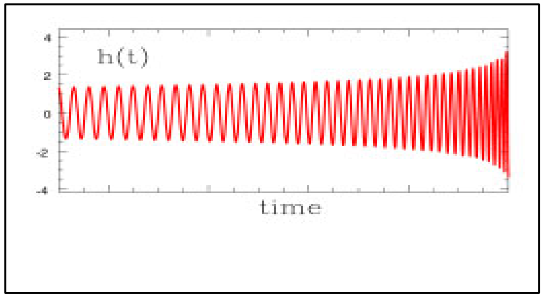
Matched Filtering



☆

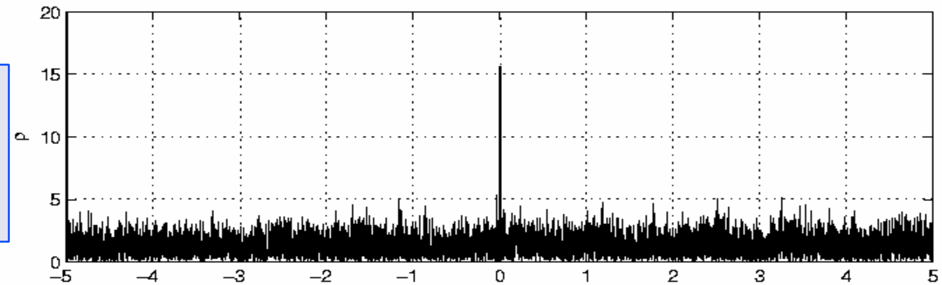
Filter to suppress high/low freq

☆



SNR

$$\rho(t) = \int_{f_{\mathrm{low}}}^{f_{\mathrm{max}}} \frac{\tilde{s}(f)\,\tilde{h}^*(f)}{S_n(f)} e^{2\pi i f t}\, df$$



Coalescence Time

Allen, Anderson, DAB, Brady, Creighton
gr-qc/0509116

Mismatch

- What if the template is incorrect?
- Loss in signal to noise ratio is given by the mismatch

$$\text{mismatch} = 1 - \text{match}$$

$$\text{match} = \max_{t_0,\phi_0,\mathcal{M},\eta,\ldots} \frac{\langle h | h_{\text{true}} \rangle}{\sqrt{\langle h|h\rangle \langle h_{\text{true}} | h_{\text{true}} \rangle}}$$

$$\langle a|b\rangle = \int_{f_{\text{low}}}^{f_{\text{max}}} \frac{\tilde{a}(f)\tilde{b}^*(f)}{S_n(f)}\, df$$

Mismatch and Event Rate

- Any mismatch between signal and template reduces the distance to which we can detect inspiral signals
- Loss in signal-to-noise ratio is loss in detector range
- Loss in event rate = $(\text{Loss in range})^3$
- Initial LIGO binary neutron star rate ~ 1/3 years
- We must be careful that the mismatch between the signal and our templates does not unacceptably reduce our rate

Current Inspiral Waveforms

- Current LIGO inspiral searches use "post-Newtonian" waveforms
- These augment a simple "Newtonian" analysis of inspiralling binaries with relativistic corrections

$$\mathcal{F} = \frac{32}{5}\frac{G^4}{c^5}\frac{M^3\mu}{r^5}\left\{1 + \left(-\frac{2927}{336} - \frac{5}{4}\eta\right)\frac{GM}{rc^2} + 4\pi\left(\frac{GM}{rc^2}\right)^{\frac{3}{2}} + \left(\frac{293383}{9072} + \frac{380}{9}\eta\right)\left(\frac{GM}{rc^2}\right)^2 + \left(-\frac{25663}{672} - \frac{125}{8}\eta\right)\left(\frac{GM}{rc^2}\right)^{\frac{5}{2}} + \cdots\right\}$$

Blanchet, Iyer, Will, Wiseman
CQG **13** 575 (1996)

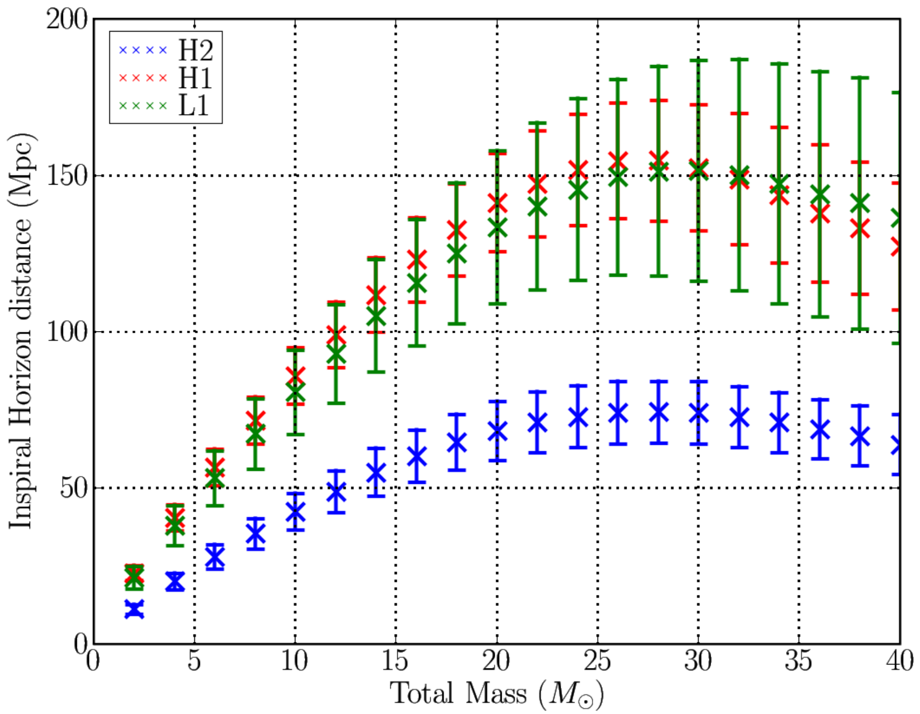
How Good are these Waveforms?

- PN waveforms are great for neutron star binaries where v/c is small while gravitational waves are in the LIGO band

- But the post-Newtonian expansion may fail if v/c is large as in the case of binary black holes in the LIGO band

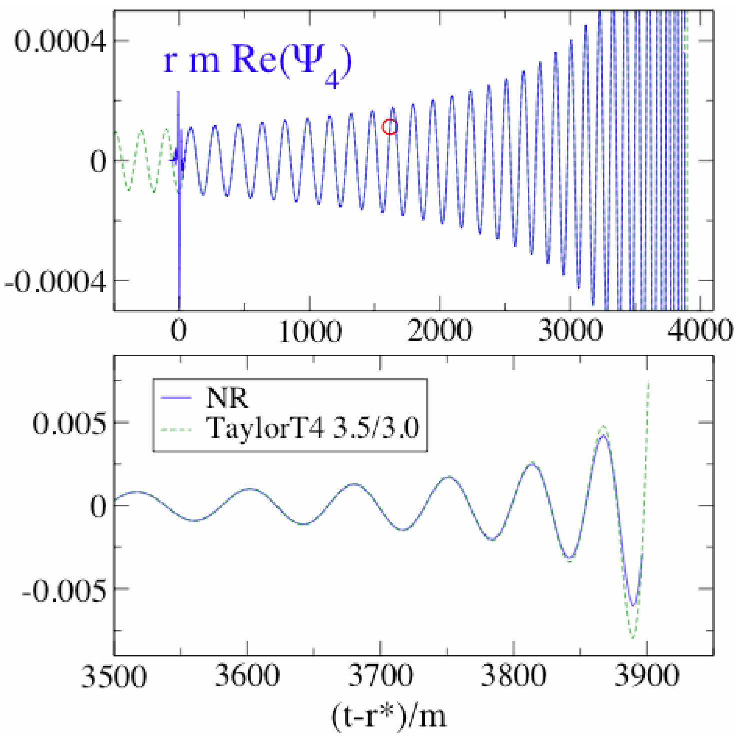
- Signal strength increases with mass!

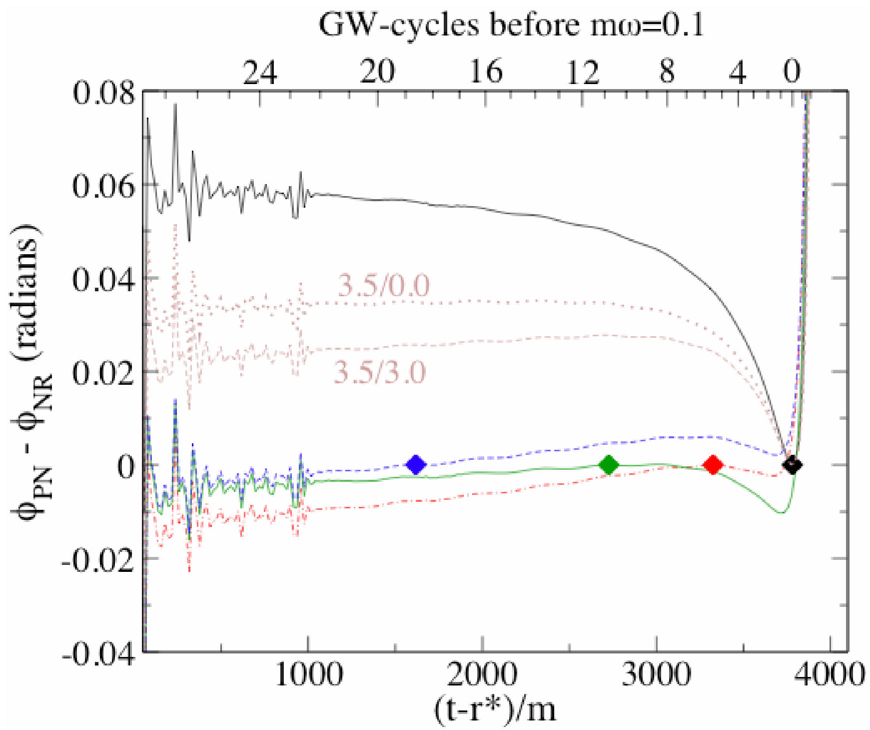
- Need numerical relativity…



What can LIGO learn from NR?

- Compare theoretical waveforms with numerical “signals”
- PN looks good for **all** equal mass inspiral signals

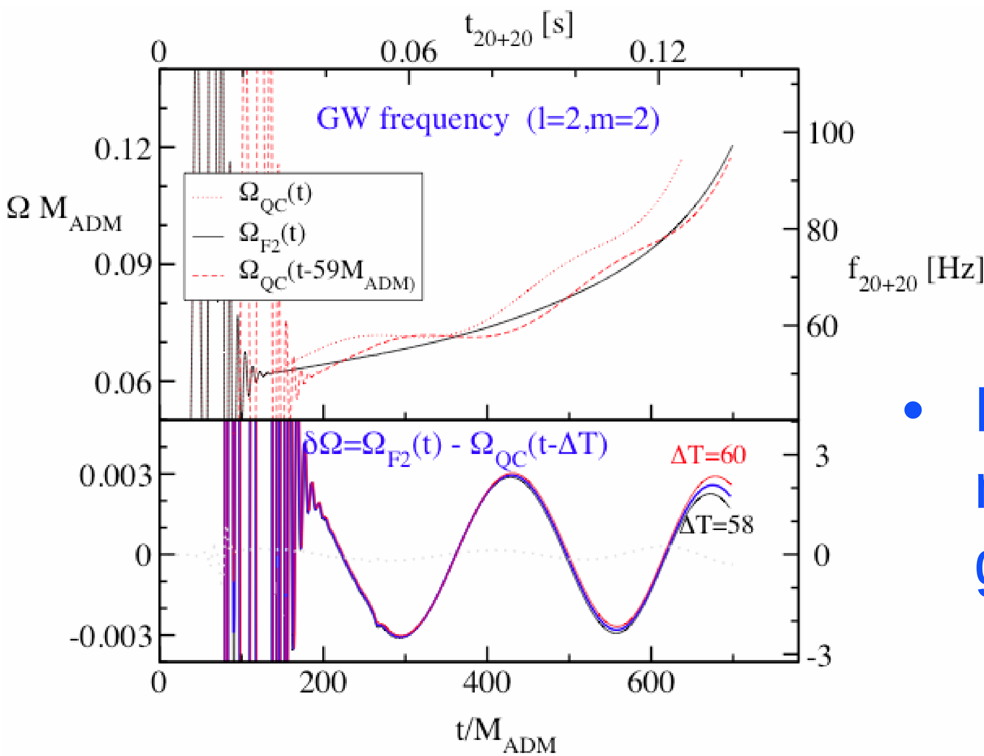


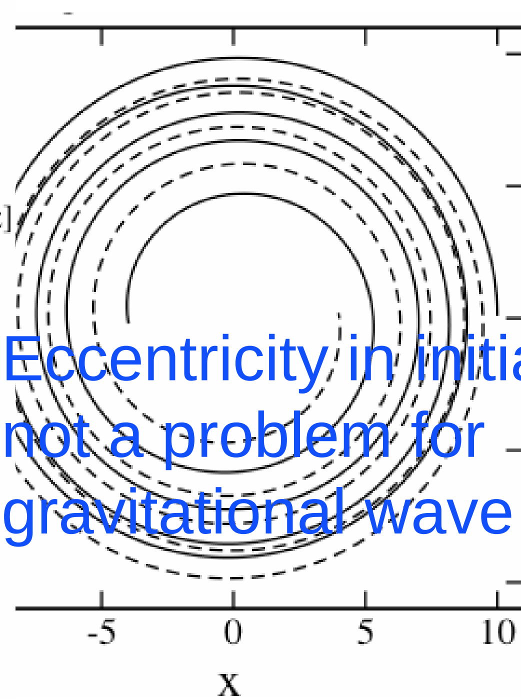


Boyle, DAB, Kidder, Mroue, Pfeiffer, Scheel Cook Teukolsky (arxiv:0710.0158, to appear in PRD)

What Can NR Learn From LIGO?

- Numerical initial data is not quite inspiralling:
  no initial radial velocity… not the case for real inspirals!



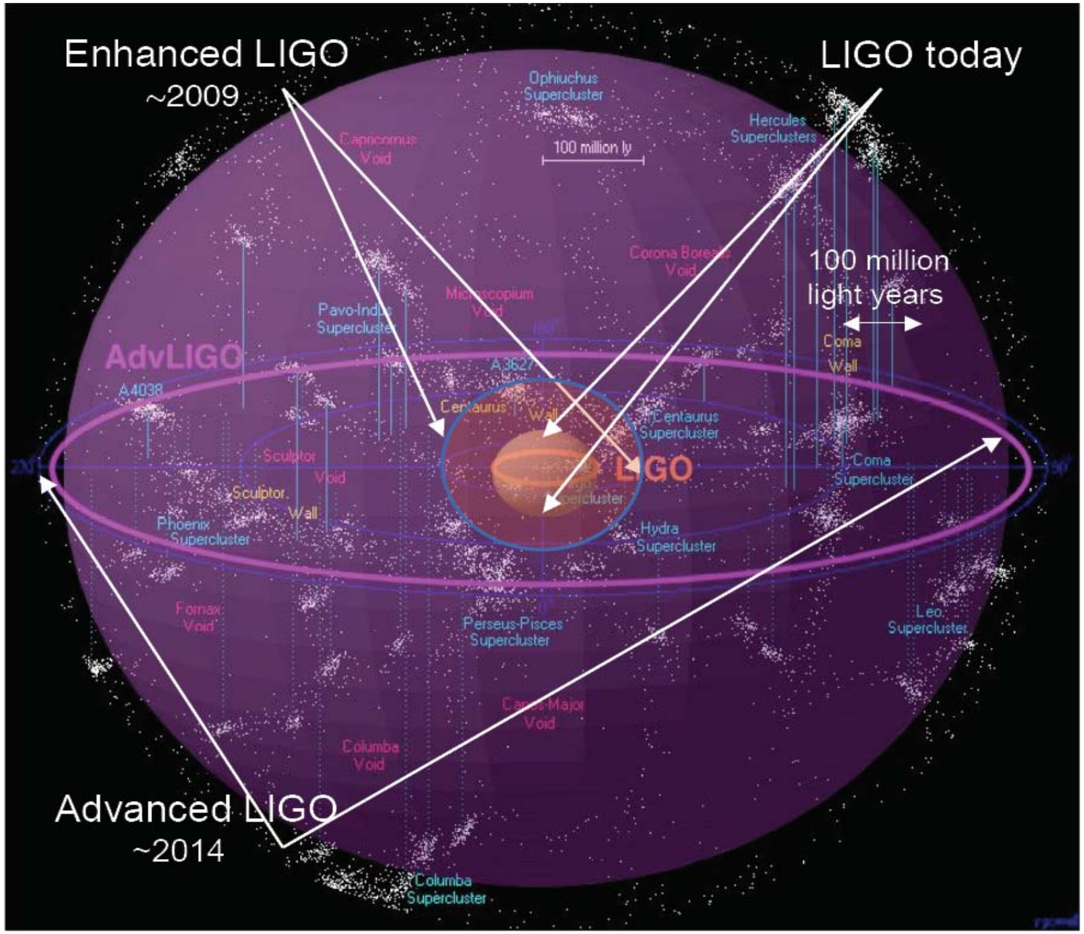


$\leq 1\%$

- Eccentricity in initial data is not a problem for gravitational wave detection

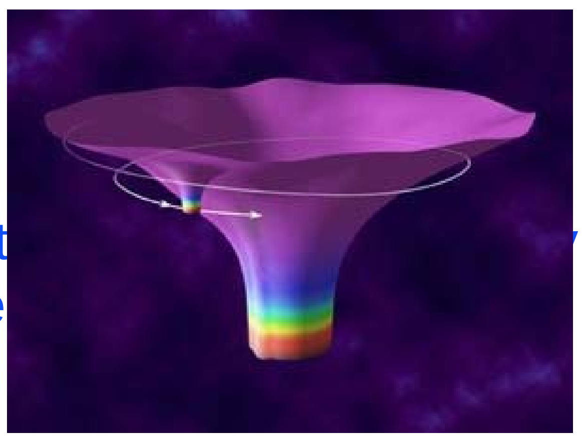
Pfeiffer, DAB, Kidder, Lindblom, Lovelace, Scheel (gr-qc/0702106)

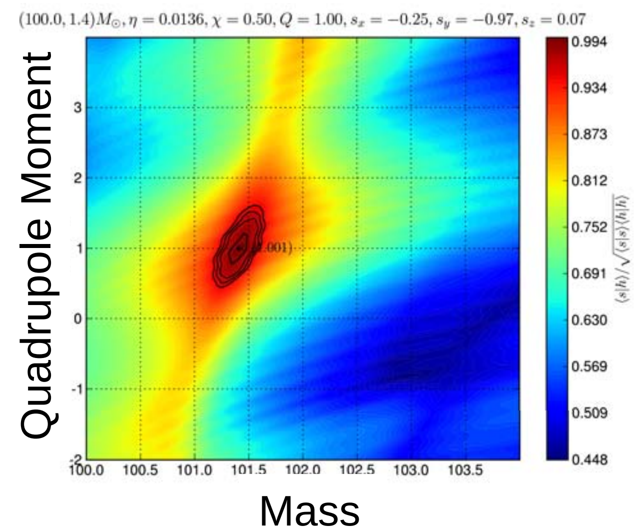
What's next for LIGO?



What happens when we see something?

- Goal is to extract as much physics from the gravitational waves as possible!
- Compare ***observations*** with post-Newtonian and numerical simulations: test GR in the strong field regime…
- With Advanced LIGO detectors, we may be able to map the spacetimes around massive black holes…





- Int… , data ana… ve…

DAB, Fang, Gair, Li, Lovelace, Mandel, Thorne (PRL **99** 201102)

Conclusion

- The fifth science run is complete and analysis of data is underway
  - » We may see something!
- Enhancements to the initial detectors are scheduled for ~ 2009
  - » Factor of ~ 2 increase in sensitivity
- Funding for Advanced LIGO is scheduled to begin in 2008
  - » Factor of ~ 10 increase in sensitivity
- Numerical relativity is making great progress
  - » Interaction between the two communities is very important
- These are exciting time for gravitational-wave astrophysics!