Gravitational Wave Astronomy using LIGO

Stan Whitcomb (for the LIGO Scientific Collaboration)

Annual General Meeting (AGM) of the

Astronomical Society of Australia

8 July 2008

LIGO-G080402-00-D

LIGO Scientific Collaboration

LIGO

LSC

University of Maryland 18 56

Michigan

University of Strathclyde

Loyola University New Orleans

Leland Stanford Junior University 1891

ACIGA

Montana State University

University of Washington

Syracuse University Founded AD 1870 Suos cultores scientia coronat

University of Glasgow

Università degli Studi del Sannio

Trinity University

San José State University

University of Wisconsin UW Milwaukee

ANU The Australian National University

LSU

UTB TSC

The University of Western Australia

1754

NASA Goddard Space Flight Center

California Institute of Technology 1891

Northwestern University

Rochester Institute of Technology R·I·T 1829

Andrews University

Massachusetts Institute of Technology 1861

Southeastern Louisiana University

The University of Texas at Austin

Moscow State University

The University of Adelaide Australia

PAN

GEO 600

Embry-Riddle Aeronautical University

University of Massachusetts Amherst 1863

University of Southampton

PennState 1855

Sigill. Coll. Carleton Northfield, Minn. A.D. 1866

Cardiff University

Universitat de les Illes Balears

Washington State University

UF University of Florida

The University of Mississippi 1848

Charles Sturt University

University of Rochester

NAOJ

Southern University Agricultural & Mechanical College

Hobart and William Smith Colleges

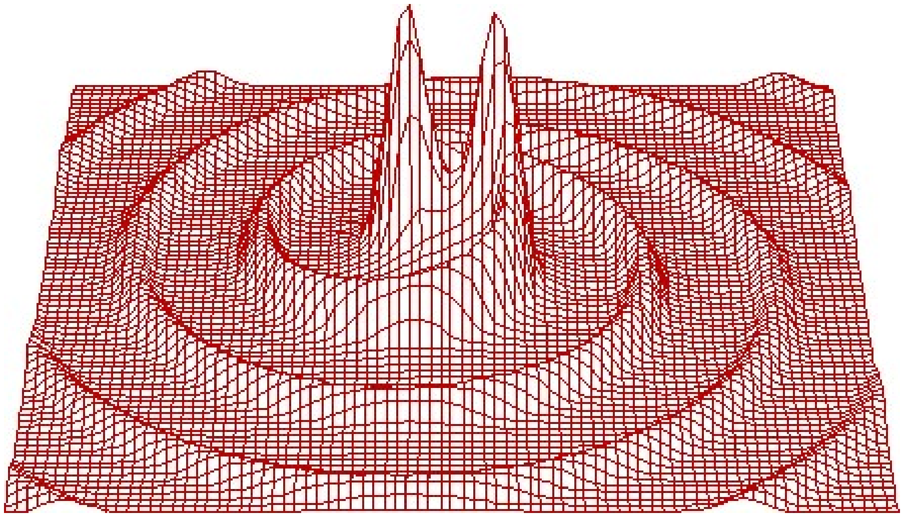
University of Minnesota

Science & Technology Facilities Council Rutherford Appleton Laboratory

Universität Hannover

Outline of Talk

- Quick Review of GW Physics and Astrophysics
- LIGO Overview
- Recent Results
- The Future
  - » More sensitive detectors
  - » Global network

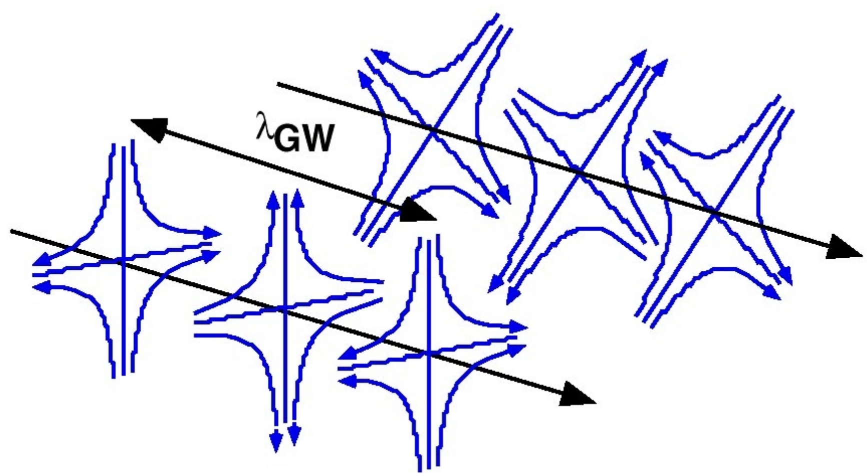


gravitational radiation
binary inspiral of compact objects
(blackholes or neutron stars)

Gravitational Wave Physics

- **Einstein (in 1916 and 1918) recognized gravitational waves in his theory of General Relativity**
  - » **Necessary consequence of Special Relativity with its finite speed for information transfer**
  - » **Most distinctive departure from Newtonian theory**
- **Time-dependent distortions of space-time created by the acceleration of masses**
  - » **Propagate away from the sources at the speed of light**
  - » **Pure transverse waves**
  - » **Two orthogonal polarizations**

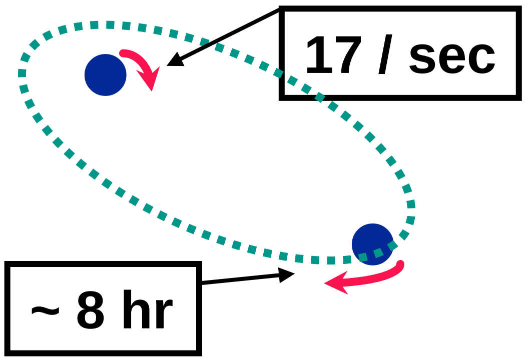
$$h = \Delta L / L$$



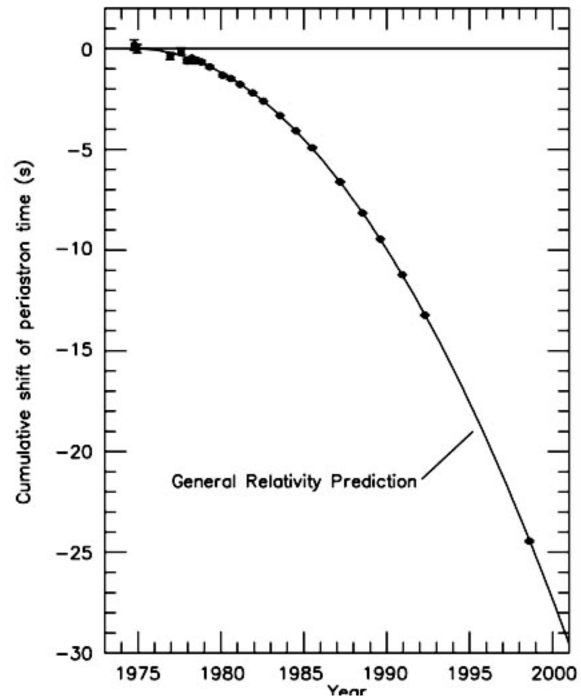
Astrophysics Differences
Electromagnetic vs. Gravitational waves

	Electromagnetic waves	Gravitational waves
Sources	Accelerations of individual charged particles	Coherent acceleration of very large masses
Examples	Atomic and nuclear transitions, plasmas, synchrotron radiation	Binary black holes, supernova core collapse, big bang
Propagation	Strong absorption Strong scattering Dispersion	Essentially, no absorption or scattering

Evidence for Gravitational Waves: Binary Pulsar PSR1913+16



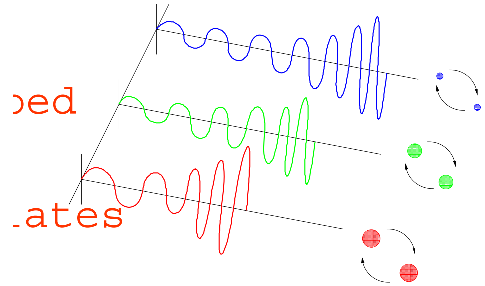
- Discovered by Hulse and Taylor in 1975
- Unprecedented laboratory for studying gravity
  » Extremely stable spin rate
- Possible to repeat classical tests of relativity (bending of "starlight", advance of "perihelion", etc.



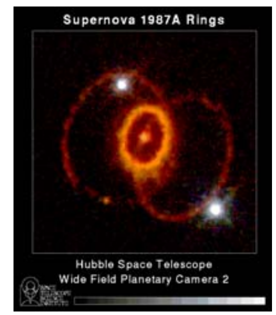
- After correcting for all known relativistic effects, observe loss of orbital energy
  => Emission of GWs

Astrophysical Sources for Terrestrial GW Detectors

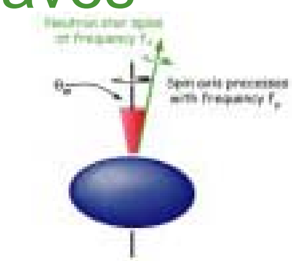
- Compact binary inspiral: "chirps"
  - » **NS-NS, NS-BH, BH-BH**



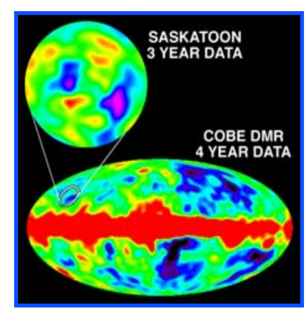
- Supernovas or GRBs: "bursts"
  - » **GW signals observed in coincidence with EM or neutrino detectors**



- Pulsars in our galaxy: "periodic waves"
  - » **Rapidly rotating neutron stars**
  - » **Modes of NS vibration**



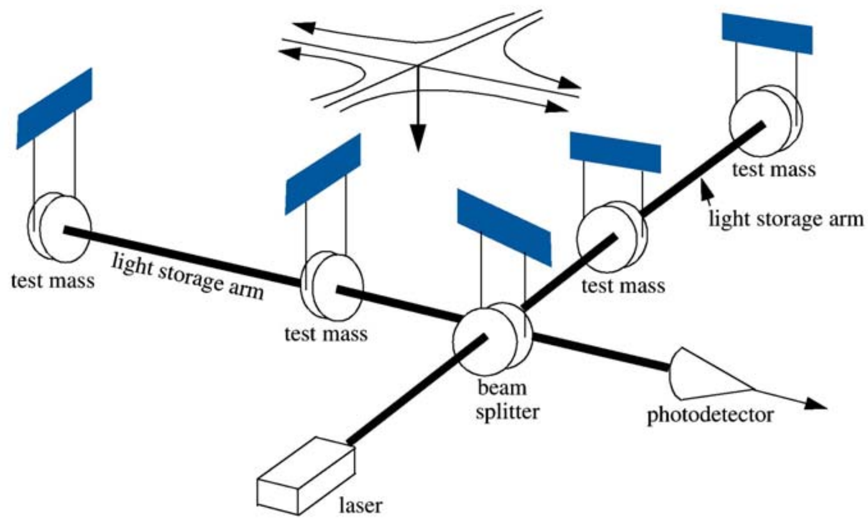
- Cosmological: "stochastic background"
  - » **Probe back to the Planck time (10^{-43} s)**



Detecting GWs with Interferometry

Suspended mirrors act as "freely-falling" test masses (in horizontal plane) for frequencies f >> f_{pend}

$$h = \Delta L / L$$



Terrestrial detector

For $h \sim 10^{-22} - 10^{-21}$

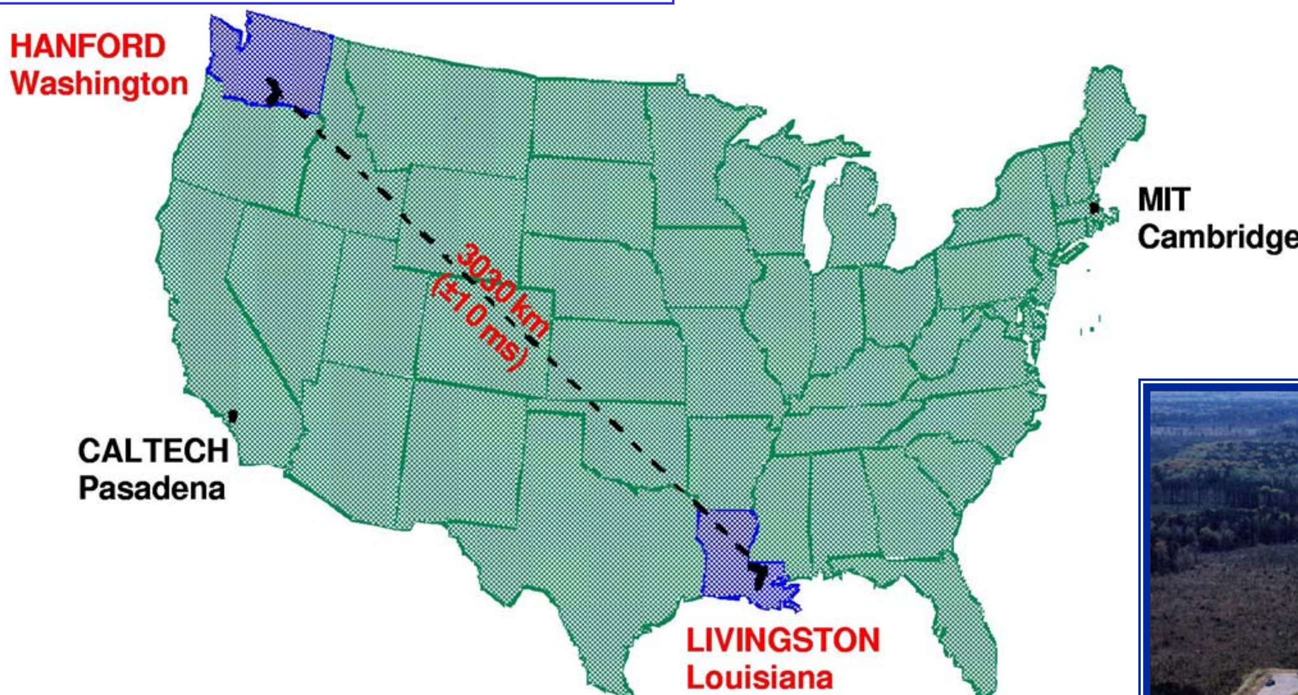
L ~ 4 km (LIGO)

$\Delta L \sim 10^{-18}$ m

LIGO

(Laser Interferometer Gravitational-wave Observatory)

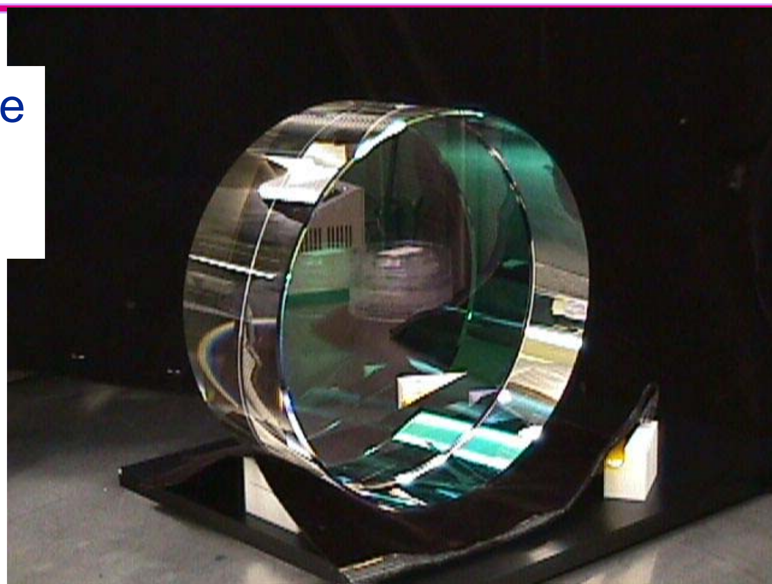
One interferometer with 4 km Arms, One with 2 km Arms

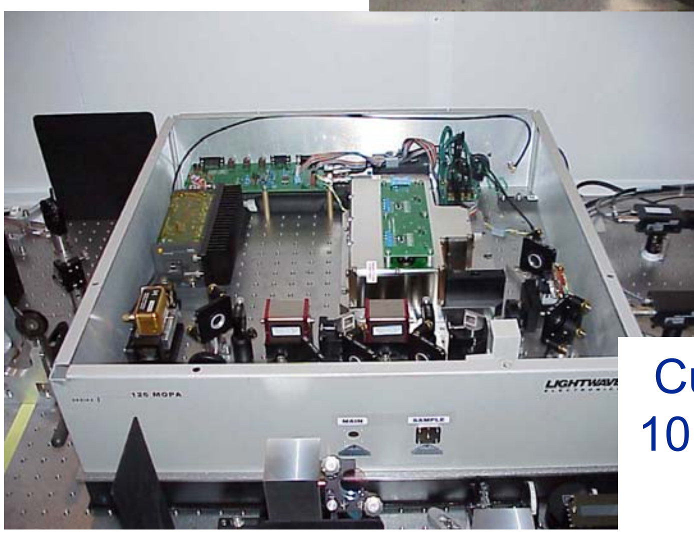


One interferometer with 4 km Arms

LIGO Interferometers

Ultra-precise
$\lambda/1000$
optics

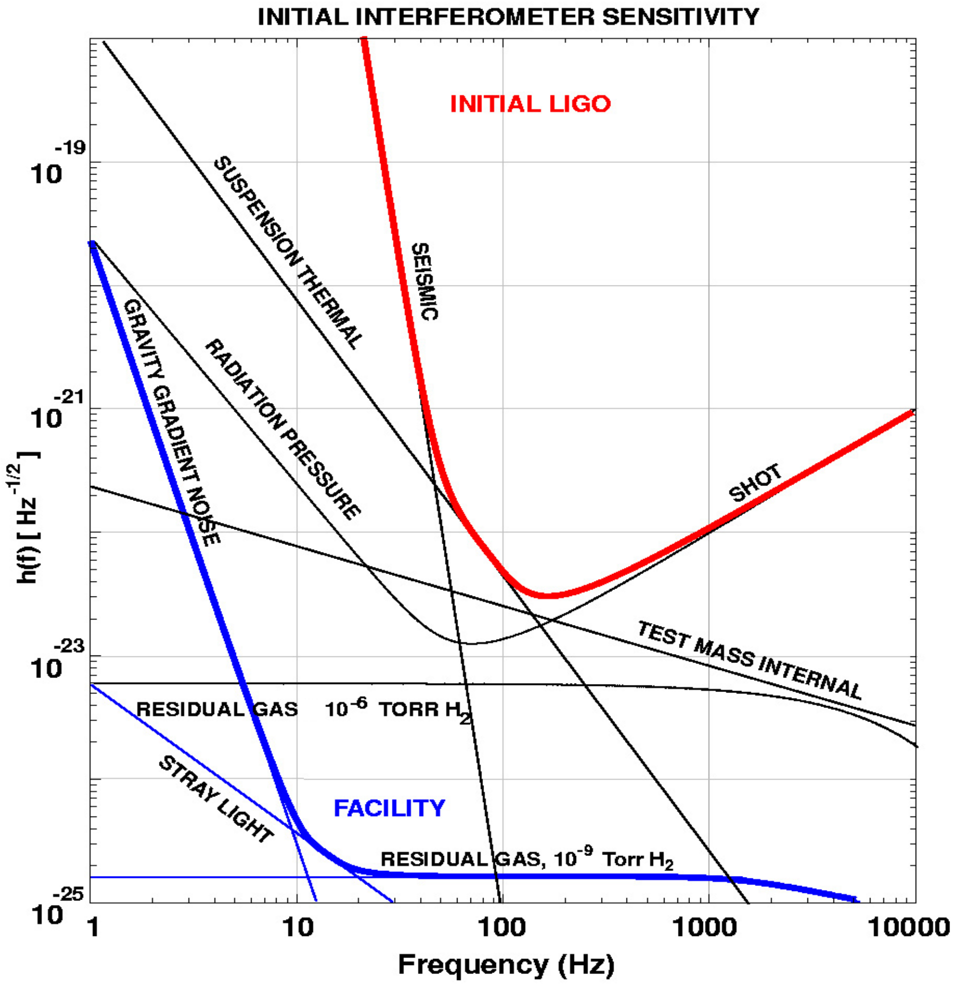




Custom-built
10 W Nd:YAG
Laser

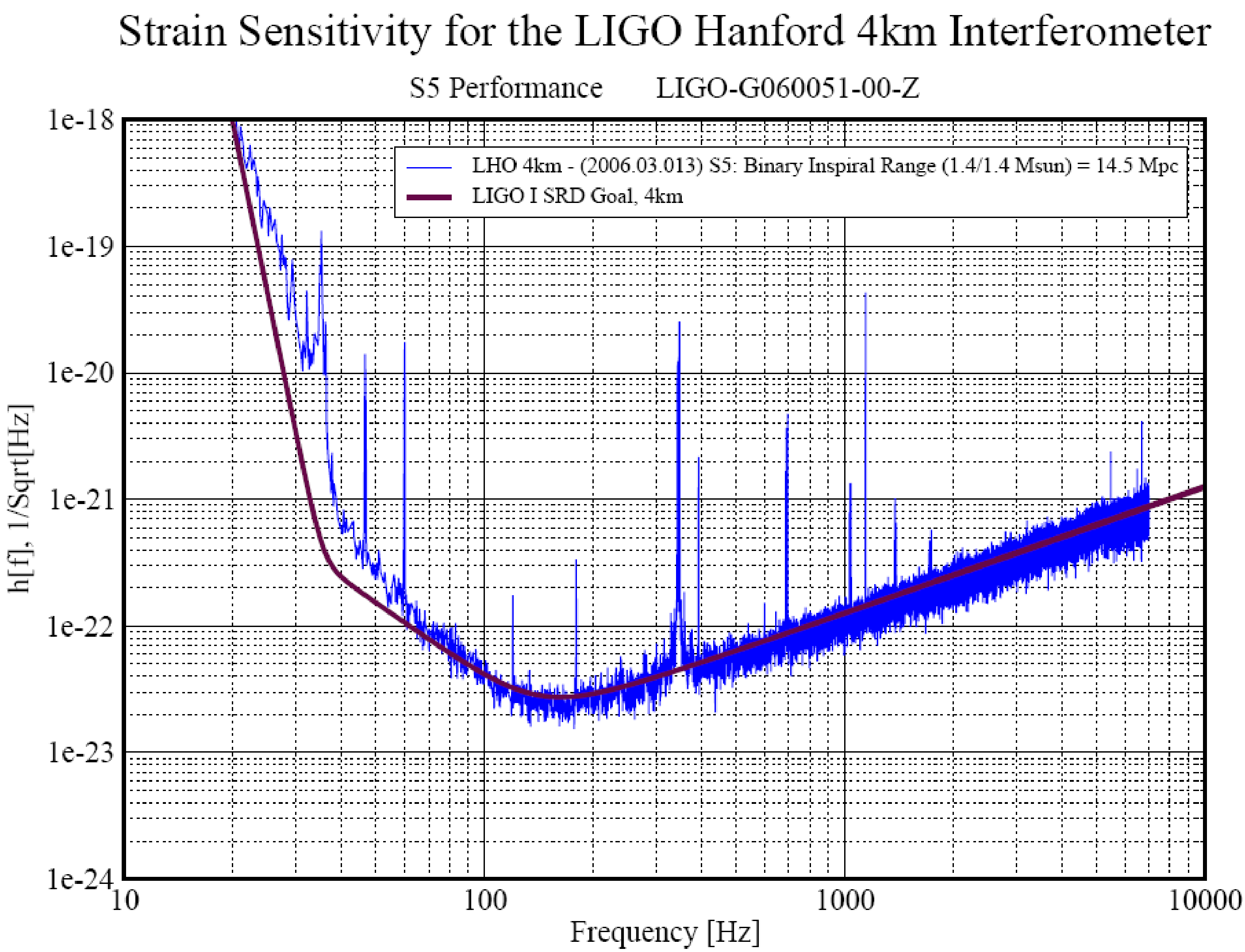
Low-noise
Suspensions

Initial LIGO Sensitivity Goal



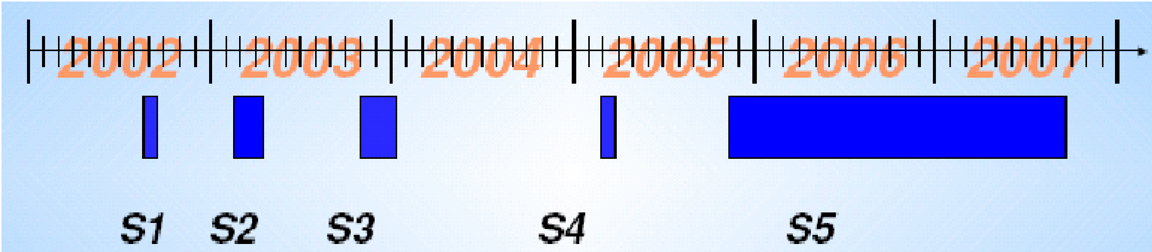
- Strain sensitivity $<3\times10^{-23}$ $1/Hz^{1/2}$ at 200 Hz
- Sensing Noise
  - » Photon Shot Noise
  - » Residual Gas
- Displacement Noise
  - » Seismic motion
  - » Thermal Noise
  - » Radiation Pressure

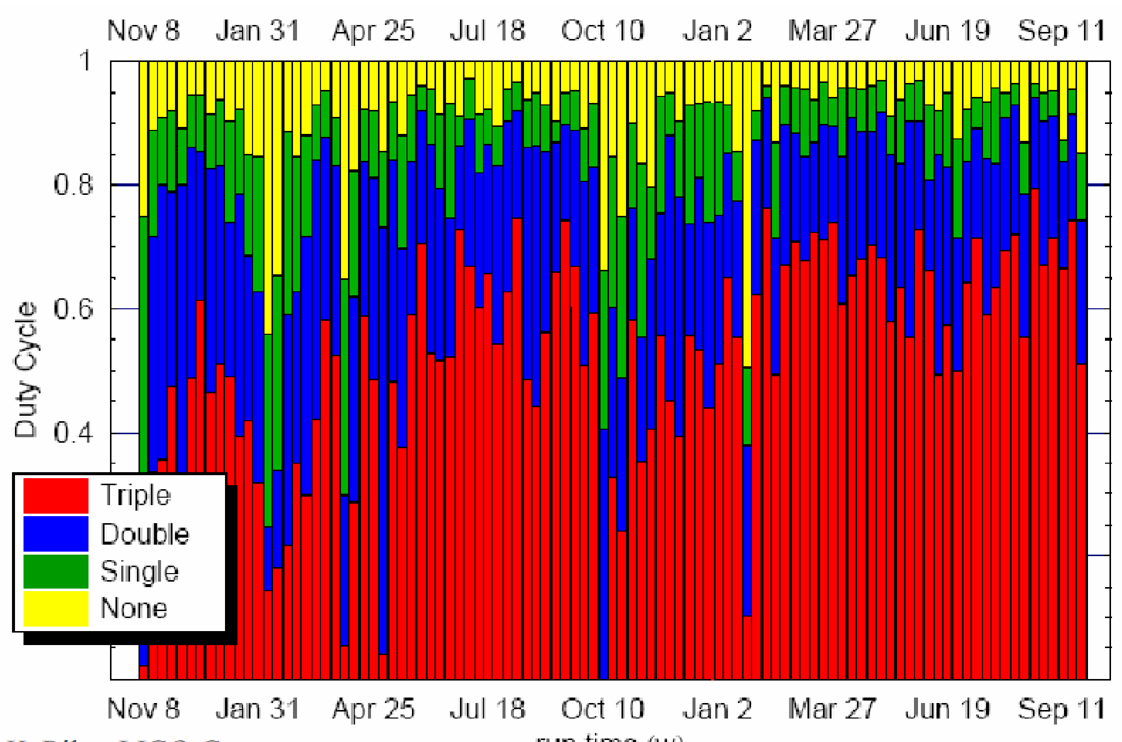
LIGO Sensitivity



LIGO Science Run ("S5")

- Nov 2005 – Oct 2007 (23 months)
- One year of triple coincident data
- Virgo (Italian-French-Dutch collaboration) joined in June 2007 for last 7 months

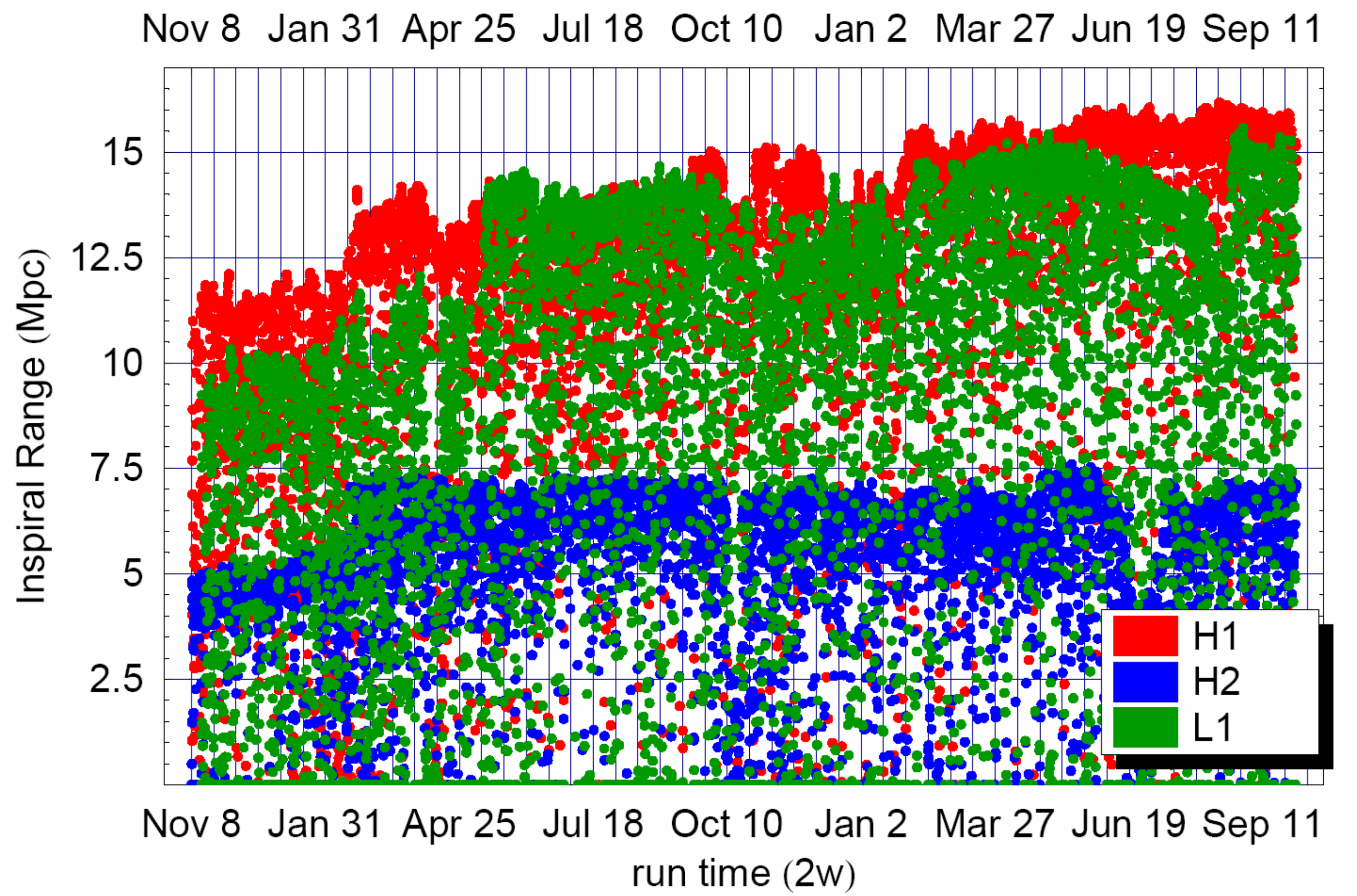




K. Riles, LIGO-G070793

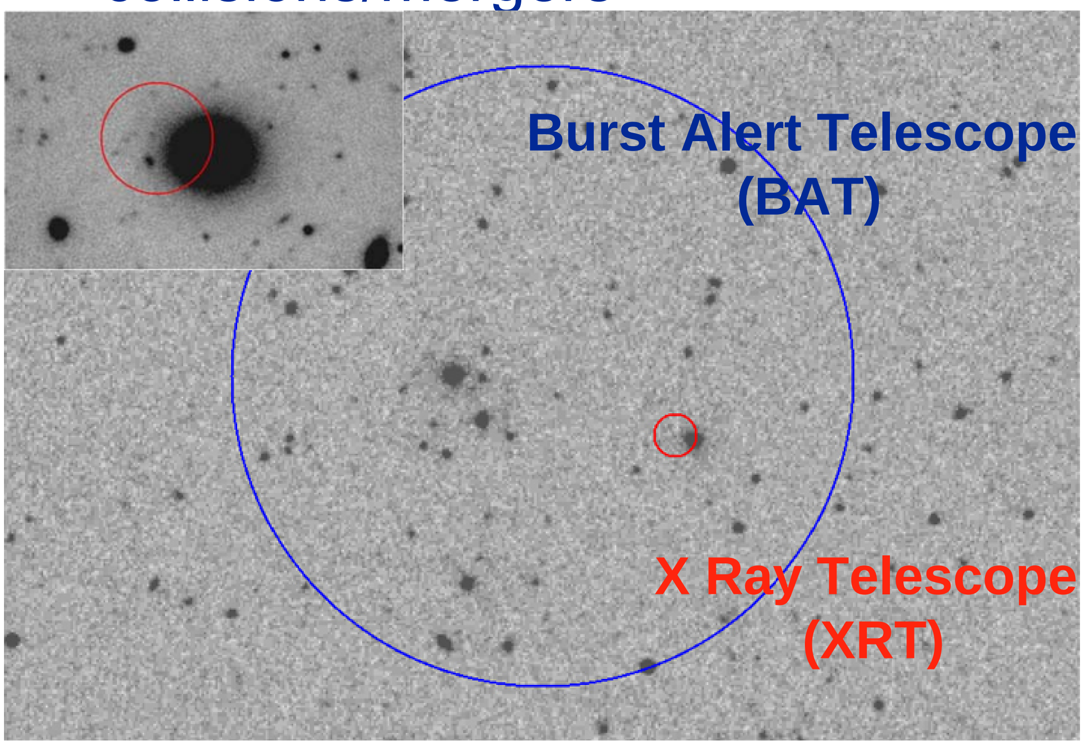
S5 Sensitivity

Average range for a 1.4 - 1.4 solar mass Binary Neutron Star at SNR = 8



Short Gamma Ray Bursts (GRBs)

- "Long" GRBs identified with type II (or Ic) supernovae in 1998
- "Short" GRBs hypothesized as NS-NS or NS-BH collisions/mergers



GRB050509b

First Identification from SWIFT

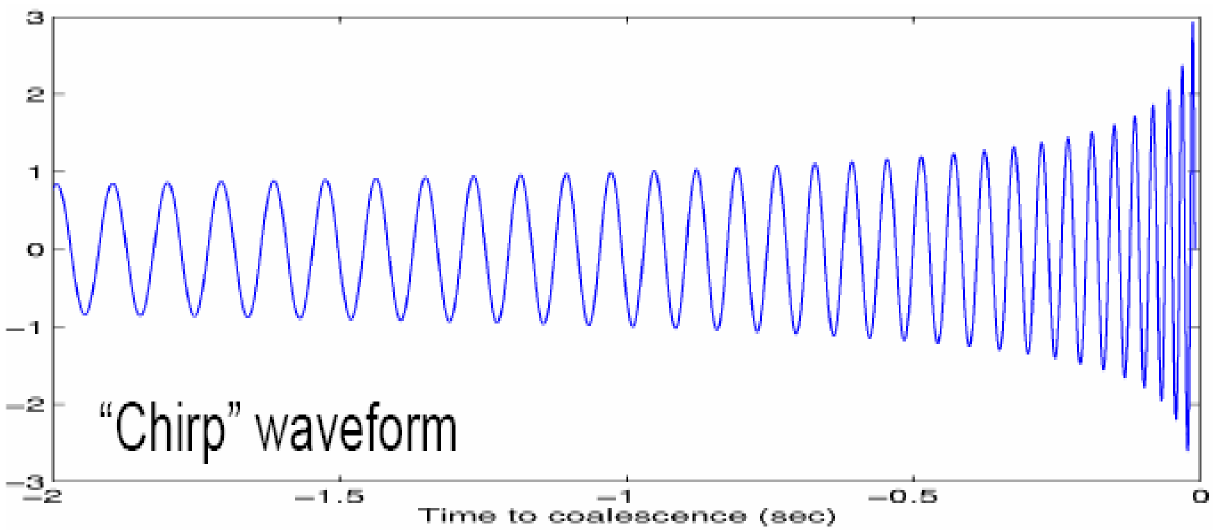
- Observation supports NS-NS or NS-BH hypothesis

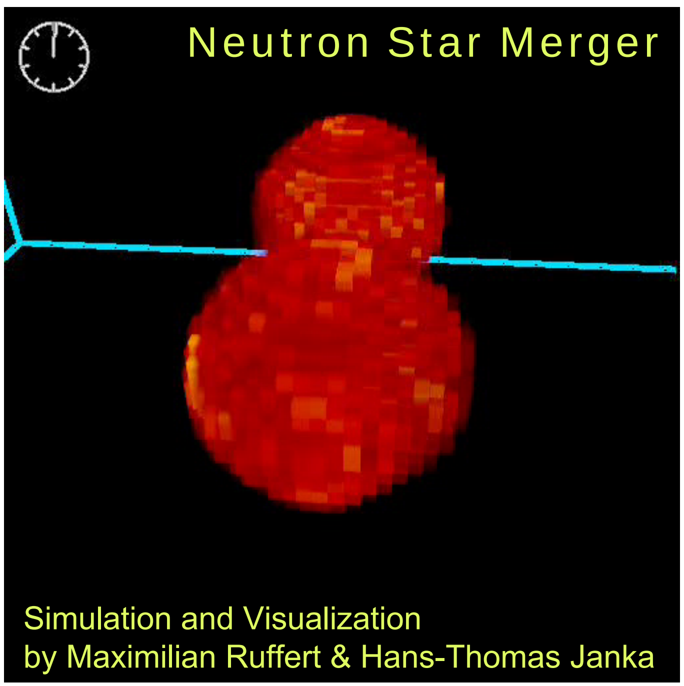
Gehrels et al., *Nature*, **437**, 851 (2005)

Using Gravitational Waves to Learn about Short GRBs

Chirp Signal

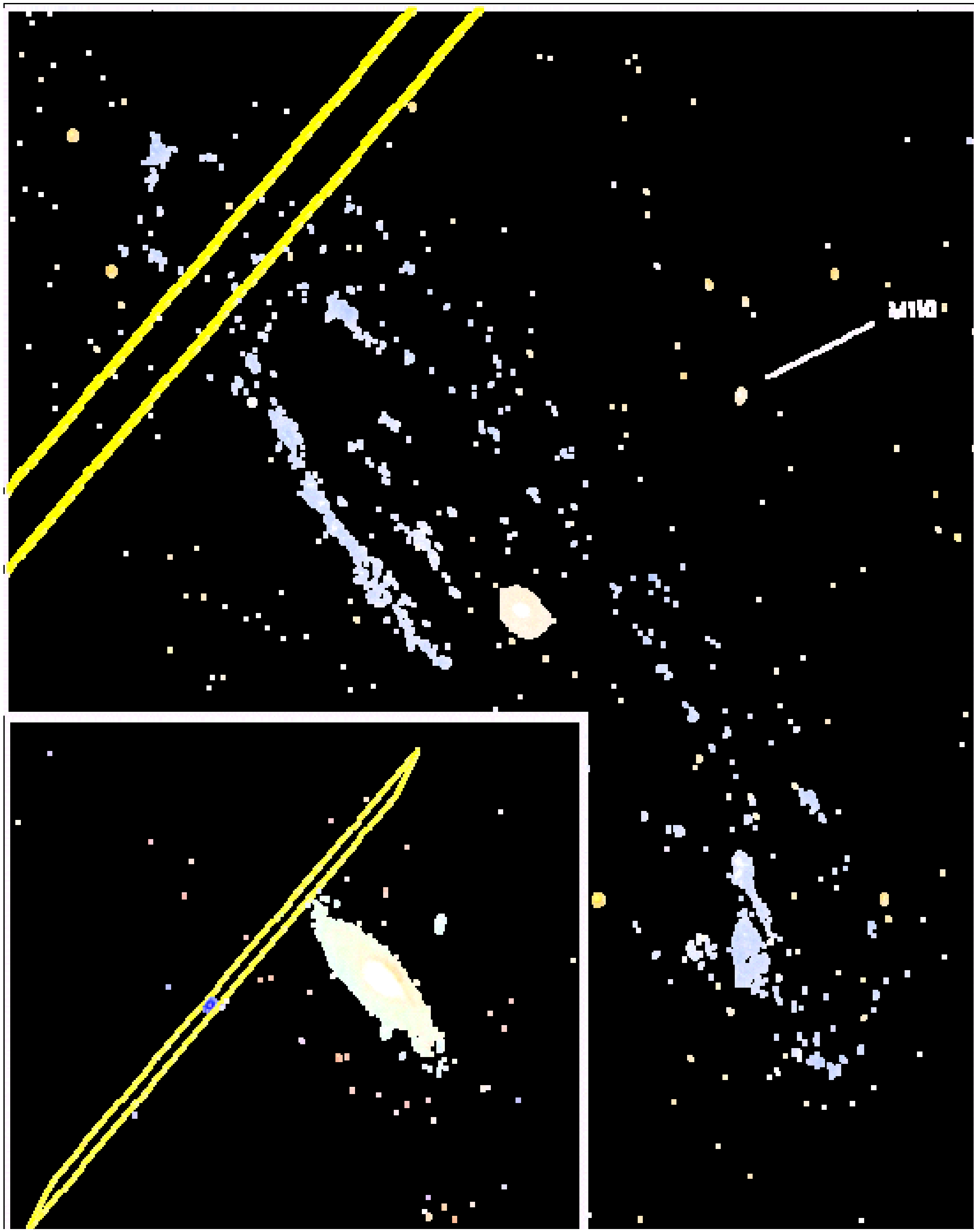
binary inspiral





Chirp waveform gives:

- **Masses and spins of the two bodies (NS, BH)**
- **Distance**
- **Orientation of orbit**
  - ➢ **Determine beaming of gamma rays (with enough observations)**



GRB 070201

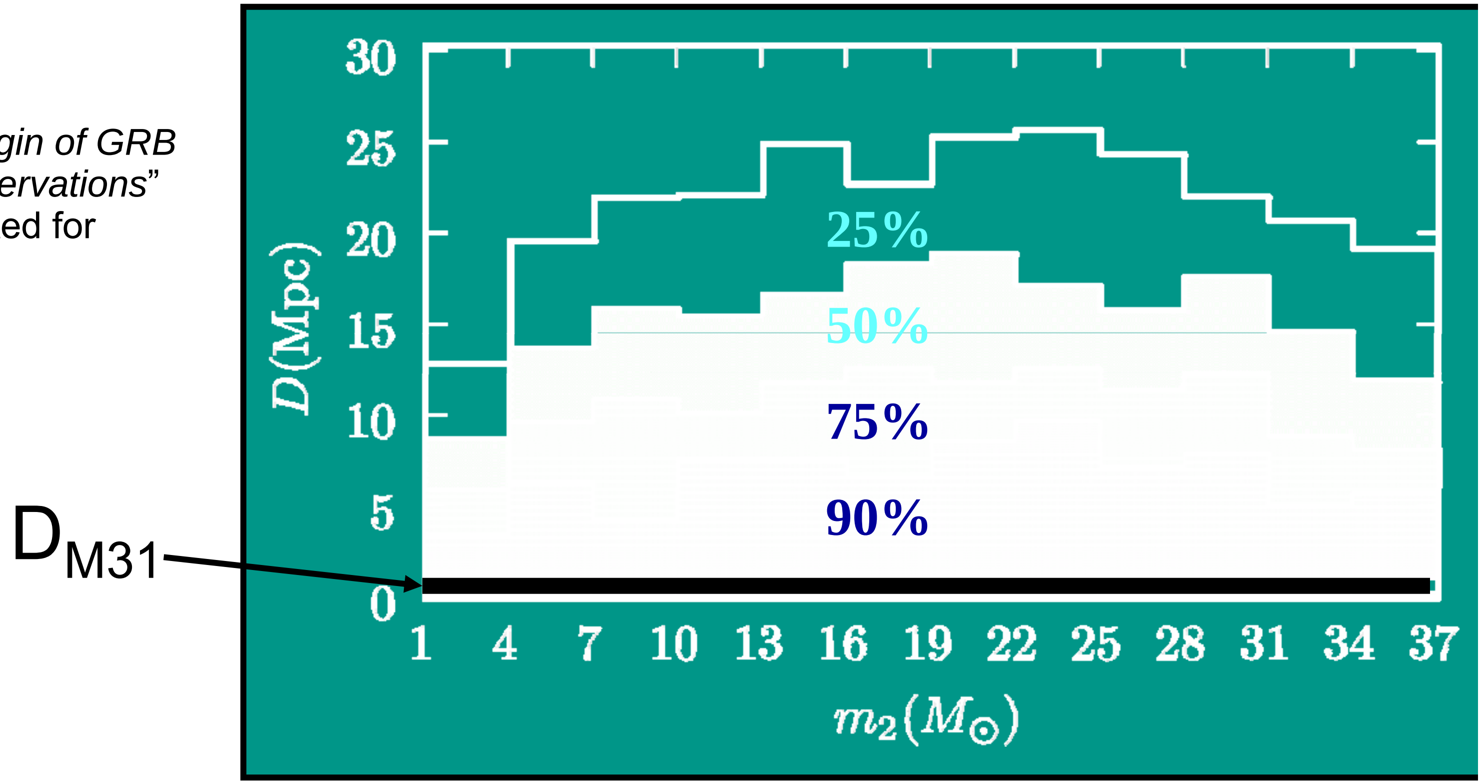
- Detected by Konus-Wind, INTEGRAL, Swift, MESSENGER
- Duration ~0.15 s, followed by a weaker, softer pulse with duration ~0.08 s
- Location error box overlaps Andromeda galaxy
- $D_{M31} \approx 770$ kpc
- Two LIGO detectors operating (Hanford)

ng

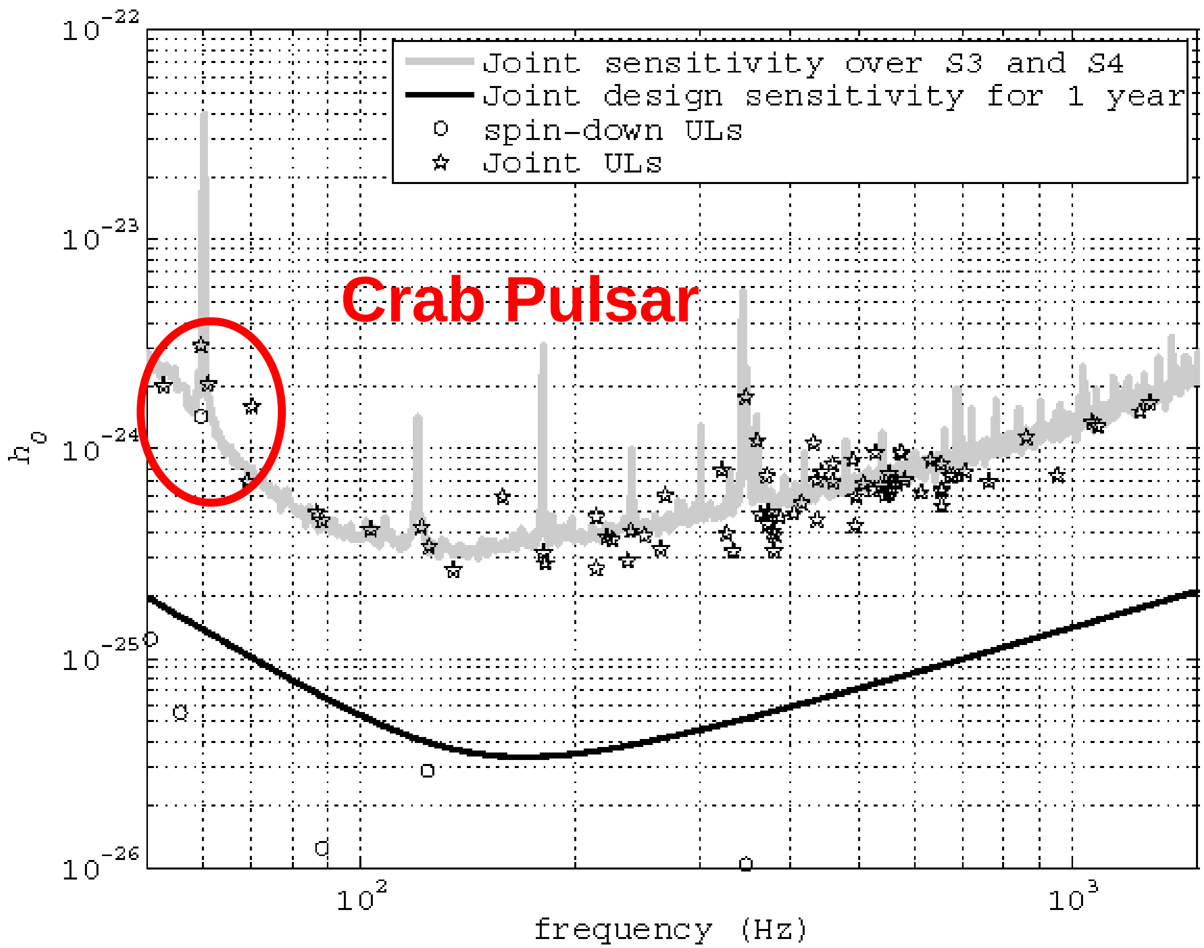
LIGO Observations

- Searched for compact binary inspiral signal, over the range $1\ M_\odot < m_1 < 3\ M_\odot$ and $1\ M_\odot < m_2 < 40\ M_\odot$,
- Location in M31 excluded at > 99% confidence

"*Implications for the Origin of GRB 070201 from LIGO Observations*" arXiv:0711.1163 accepted for publication in ApJ



Gravitational Waves from Rotating Neutron Stars

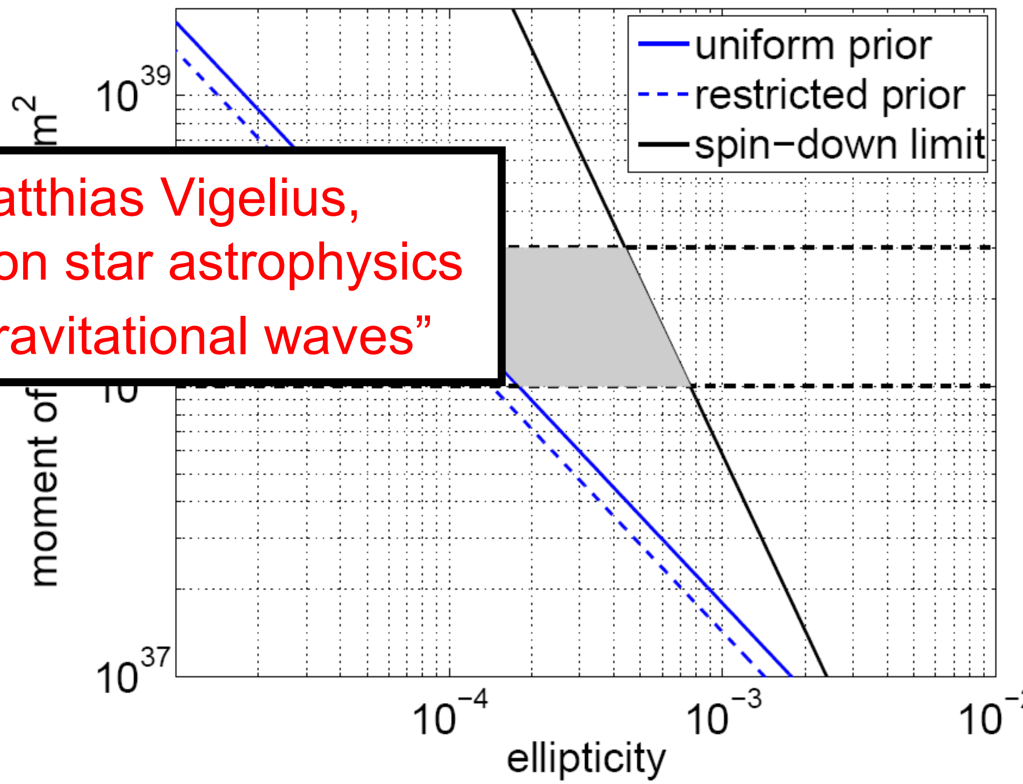


S3 and S4 data

- Rapidly rotating neutron stars can radiate GWs due to deviations from axi-symmetry
- Known pulsars allow long integrations
- Measured spin down rates set upper limits on GW strength (emitted power in GWs)

LIGO Limits on Gravitational Wave Contribution to Spin-Down

- Highest spin-down limit of all pulsars in the LIGO frequency range
- Crab pulsar glitch in Aug 2006 makes for convenient break-point in the analysis
- First 9 month
  gives upper li
  $h^{95\%}$ < 3.5x10
- GW emission accounts for <6% of spin-down power

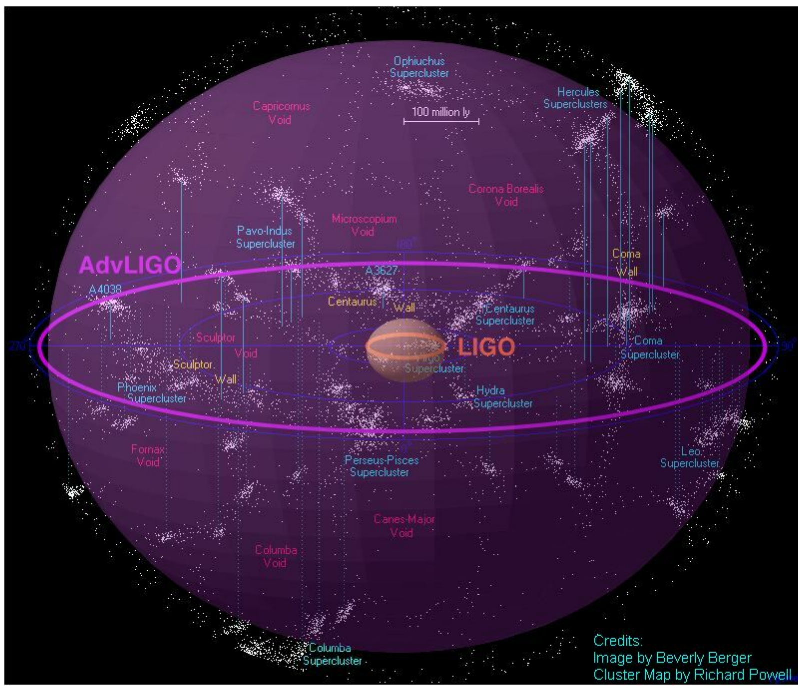


Matthias Vigelius,
"Neutron star astrophysics with gravitational waves"

"*Beating the spin-down limit on gravitational wave emission from the Crab pulsar*", arXiv:0805.4758, accepted by *ApJ Letters*

What's Next?
Advanced LIGO

- Take advantage of new technologies and on-going R&D
  - » Active anti-seismic system operating to lower frequencies
  - » Lower thermal noise suspensions and optics
  - » Higher laser power
  - » More sensitive and more flexible optical configuration



x10 better amplitude sensitivity

$\Rightarrow$ x1000 rate=(reach)^3

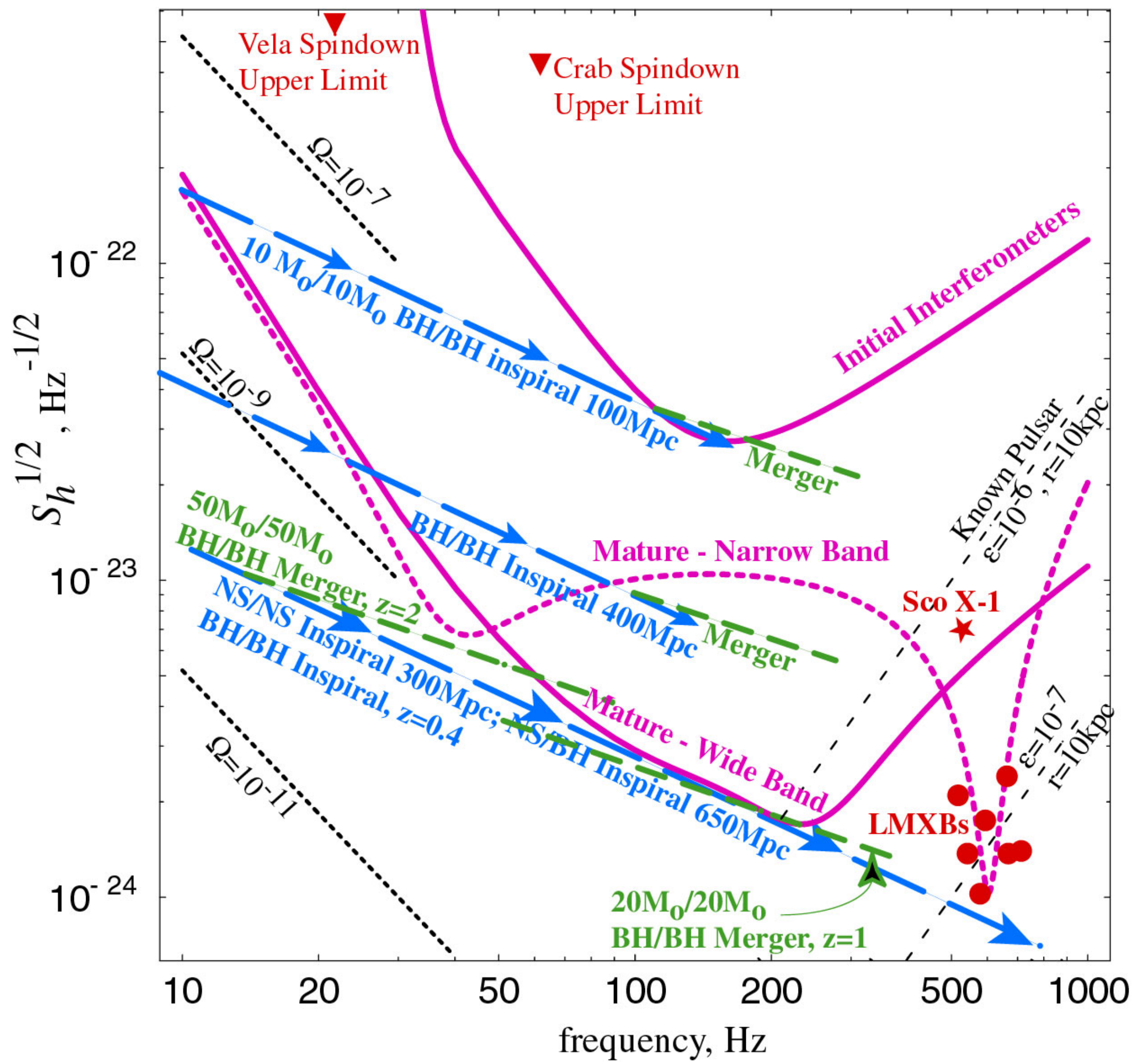
$\Rightarrow$ 1 day of Advanced LIGO

» 1 year of Initial LIGO !

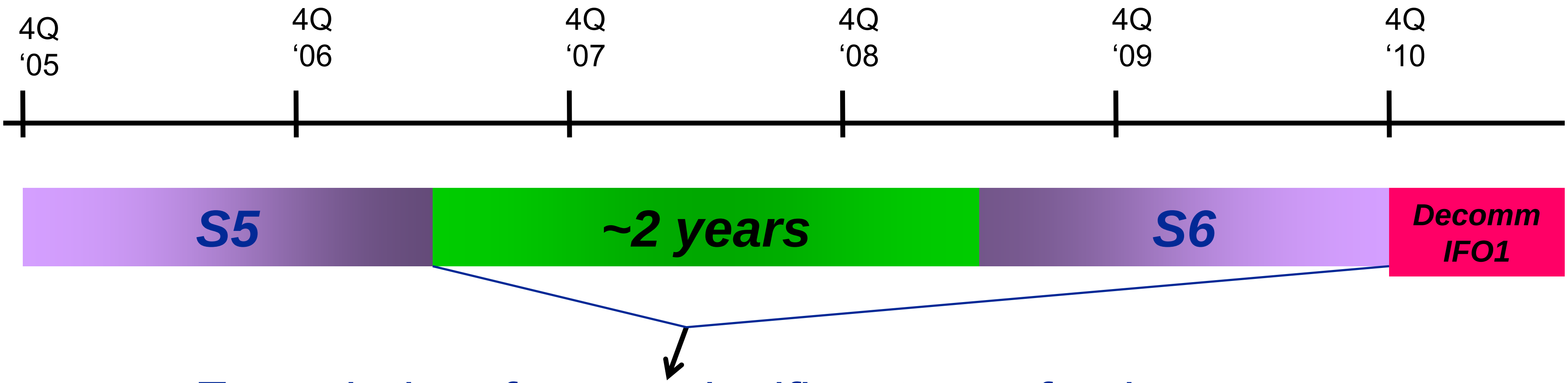
2008 start
Installation to begin 2011

What's next for LIGO? Targets for Advanced LIGO

- Neutron star & black hole binaries
  - » inspiral
  - » merger
- Spinning neutron stars
  - » LMXBs
  - » known pulsars
  - » previously unknown
- Supernovae
- Stochastic background
  - » Cosmological
  - » Early universe

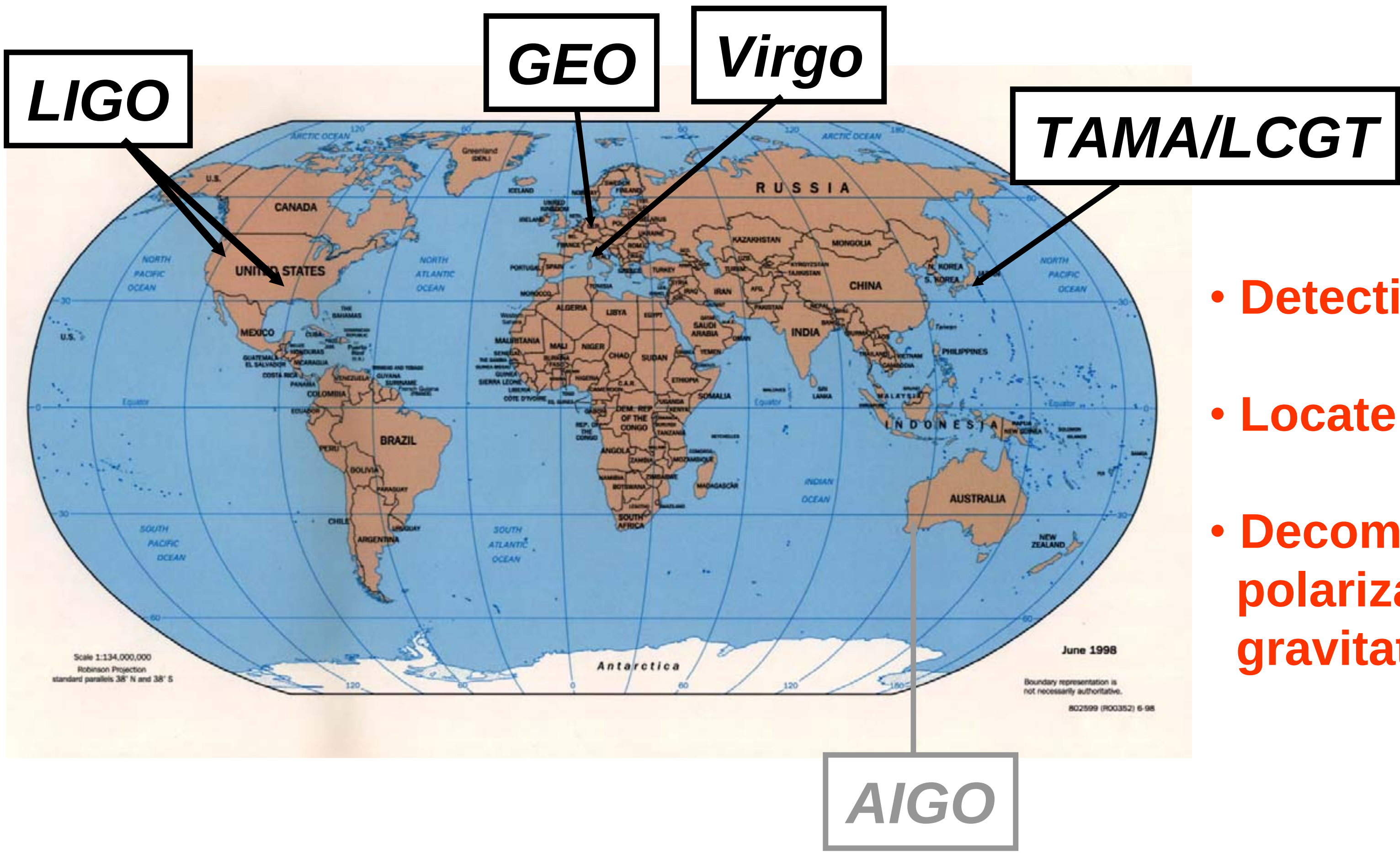


Enhanced LIGO



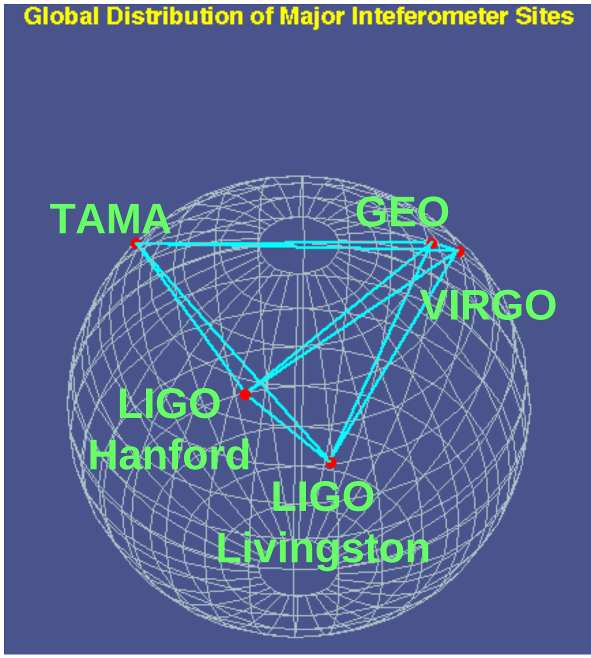
- Enough time for one significant set of enhancements
- Aim for a factor of 2 improvement in sensitivity (factor of 8 in event rate)
- Early tests of Advanced LIGO hardware and techniques

What else is Coming?
A Global Network of GW Detectors



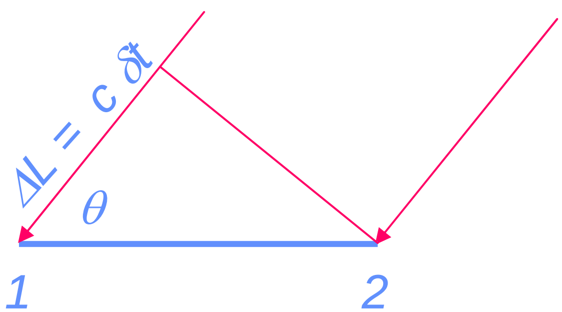
- **Detection confidence**
- **Locate sources**
- **Decompose the polarization of gravitational waves**

Why a Global Network?



Virgo
Italy

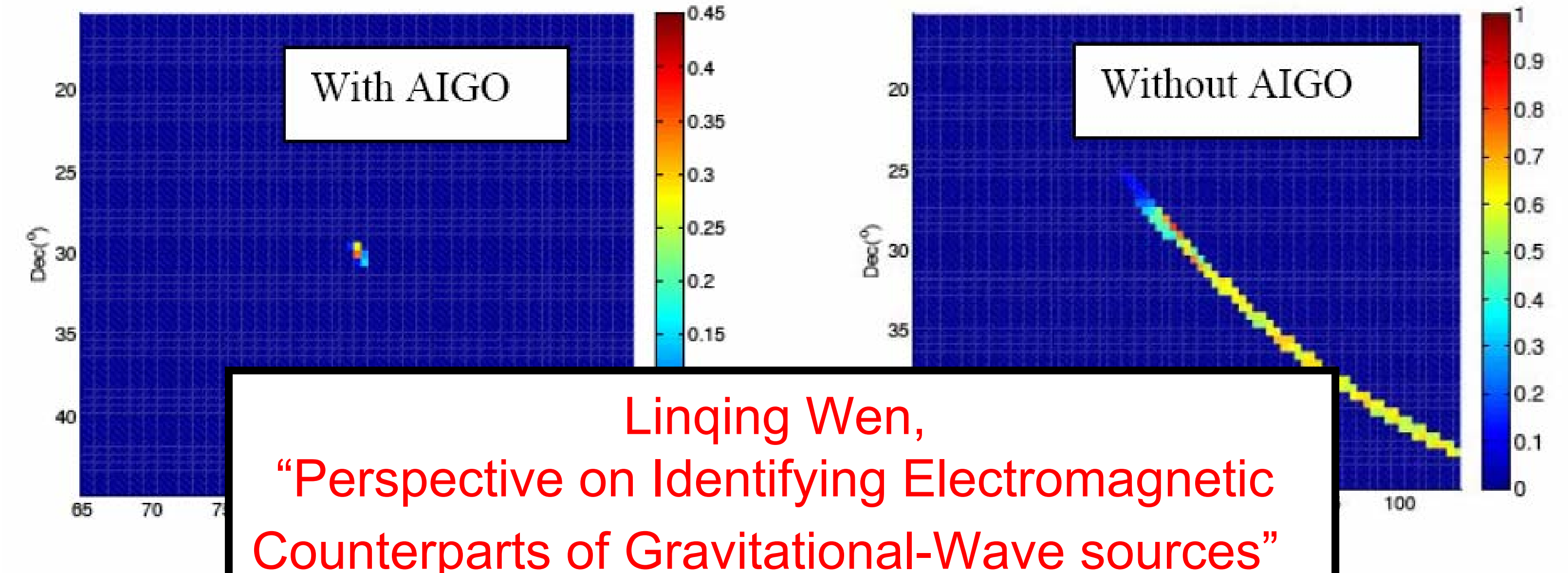
GEO 600
Germany



AIGO (Australian International Gravitational-wave Observatory)

- 8km x 8km AIGO site 70km north of Perth granted 1998.
- Site development begun 1999
- Currently operating 80m High Optical Power test facility in collaboration with LIGO

Importance of AIGO



Linqing Wen,
"Perspective on Identifying Electromagnetic Counterparts of Gravitational-Wave sources"

- AIGO provides strong science benefits e.g. host galaxy localization
- Comparable sensitivity to Advanced LIGO
- Australian Consortium seeking partners and funding

Final Thoughts

- We are on the threshold of a new era in GW detection
  - » LIGO has reached design sensitivity and is taking data
- First results are yielding interesting new results
  - » First detection could come at any time…
- Second generation detector (Advanced LIGO) has started
  - » Will expand the "Science" (astrophysics) by factor of 1000
- A worldwide network is starting to come on line
  - » Groundwork has been laid for operation as a integrated system
  - » Australia could play a key role