LIGO: Opening a New Window on the Universe
The Laser Interferometer Gravitational-Wave Observatory

Wayne State University

28 March 2002

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Pasadena, California 91125

LIGO-G020140-00-E

LIGO Scientific Collaboration

LIGO I Development Group: 21 Institutions, 26 Groups, 281 Members

http://www.ligo.caltech.edu/LIGO_web/lsc/lsc.html

US Universities:

- Caltech LIGO/CaRT/CEGG/CACR
- Carleton
- Cornell
- Cal State University Dominguez Hills
- Florida
- Louisiana State
- Louisiana Tech
- Michigan
- MIT LIGO
- Oregon
- Penn State
- Southern
- Syracuse
- Texas-Brownsville
- Wisconsin-Milwaukee

International Members:

- ACIGA (Australia)
- GEO 600 (UK/Germany)
- IUCAA (Pune, India)

US Agencies & Institutions

- FNAL (DOE)
- Goddard-GGWAG (NASA)
- Harvard-Smithsonian

International partners (have MOUs with LIGO Laboratory):

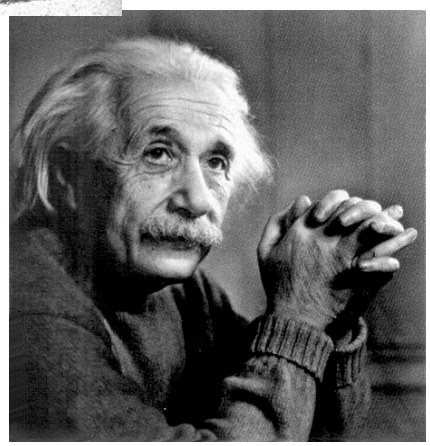
- *TAMA (Japan)*
- *Virgo (France/Italy)*

LIGO

Outline of this talk

- Gravitational waves and relativity
- Past surprises in astronomy
- Interferometers as detectors of gravitational waves
- Sources of gravitational waves
- Data analysis

Albert Einstein



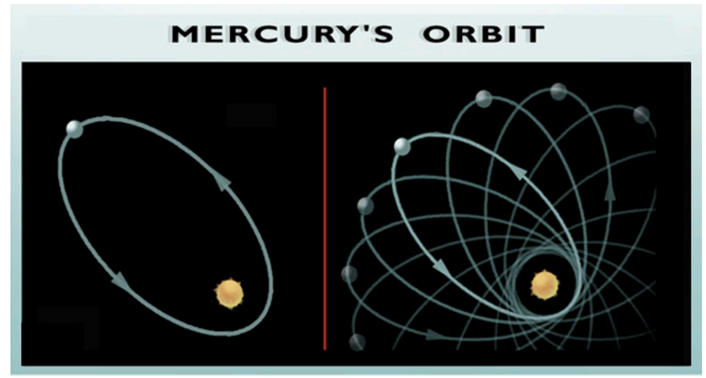
- 1905 - The Special Theory of Relativity overthrew commonsense assumptions about space and time. Relative to an observer, near the speed of light, both are altered
  - *distances appear to contract*
  - *clocks tick more slowly*
  - *Space+time => spacetime*
- 1916 - The General Theory of Relativity and theory of Gravity
  - *gravity described as a warpage of spacetime, not a force acting at a distance*

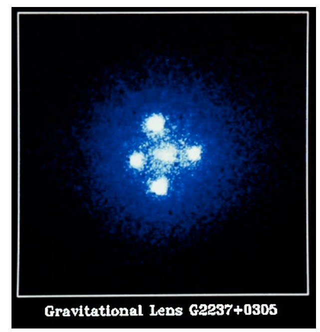
Einstein's Theory of Relativistic Gravity

experimental manifestations

Mercury's orbit

perihelion shifts an extra 43"/century that cannot be explained by Newton's theory





"Einstein Cross"

The bending of light rays

gravitational lensing

GPS timing

clocks run more slowly in a gravitational field

|*GR* *blueshift*| > |*SR* *redshift*|

$$\left.\frac{\Delta\tau}{\tau}\right|_{GR} \approx -6 \left.\frac{\Delta\tau}{\tau}\right|_{SR} \approx 5\times10^{-10}$$

$$\left.\delta X\right|_{1day} \approx 11\ km;\ \delta X\ \text{exceeds reqmts. in less than 2 min!}$$

LIGO *Motivation for Gravitational Wave Astrophysics*

- Enormous difference between EM and GW wave emission mechanisms
  - *Incoherent atomic processes vs. coherent mass motions*
    - *Individual atoms vs. 10^{57} nucleons!*
  - *Interaction with matter*
    - *photons interact readily with charged particles;*
    - *gravitons interact hardly at all - mean free path ~Hubble distance*
  - *Gravitational sources likely to have weak electromagnetic signatures and vice versa*
    - *Potential for great surprises*
  - *Strongest sources are extragalactic ... near cosmological distance scales*
  - *Challenge: detection without imaging*

Ultimate Goals for the Detection of Gravitational Waves

http://www.ligo.caltech.edu/

- Fundamental physics, tests of relativity
  - *Black holes & strong-field gravity (ringdown of excited BH)*
  - *Spin character of the radiation field (polarization of radiation from CW sources)*
  - *Wave propagation speed (delays in arrival time of bursts), particle masses*

$$\frac{c - v_{GW}}{c} \approx \frac{c\Delta t}{R} \approx few \times 10^{-11} \quad for \;\; R_{Virgo\ Cluster},\ \Delta t \approx 1 \;\; day$$

$$\Rightarrow \;\; m_{GW} \approx 10^{-5}\, \hbar\omega_{GW} \approx 10^{-16} eV \;\; @ \;\; 1kHz$$

$$\frac{m_{\nu}}{T_{\nu}} \approx \sqrt{\frac{2c\;\Delta t}{R}} \approx 10^{-5} \quad for \;\; R_{Galaxy},\ \Delta t \approx 60s$$

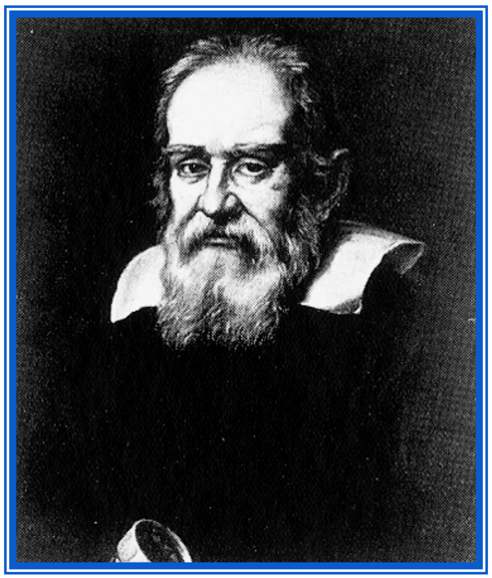
  - *Nuclear equation of state (e.g., waveform details after merger yield NS radius)*

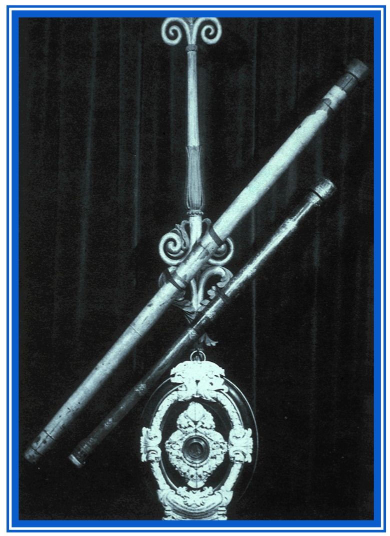
- Gravitational wave astronomy
  - *Compact binary systems*
  - *Gravitational waves and gamma ray burst associations*
  - *Black hole formation*
  - *Supernovae in our galaxy*
  - *Newly formed neutron stars - spin down in the first year*
  - *Pulsars and rapidly rotating neutron stars*
  - *Low-Mass X-Ray Binaries (LMXBs)*
  - *Stochastic GW background - 10^{-43} s vs. 10^{12}s for EM vs. 1 s for ν*

Past surprises in astronomy

The Opening of a New Observational Window on the Universe

- Galileo Galilei, 1610
  - *Improves on an invention by Hans Lipperhey to build a 9X telescope*
    - *Discovers the "Gallilean" moons of Jupiter*



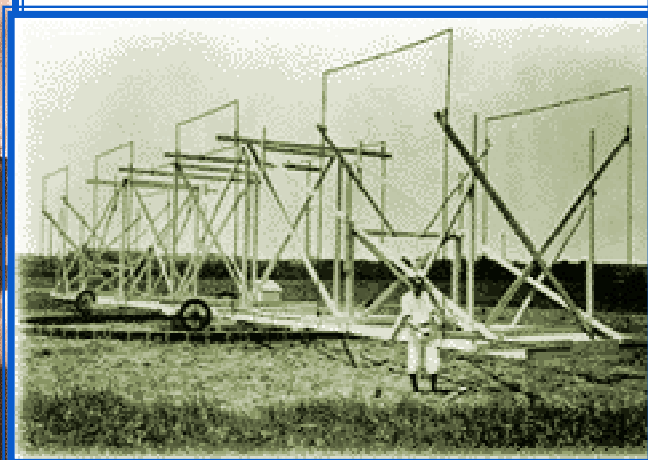


http://es.rice.edu:80/ES/humsoc/Galileo//

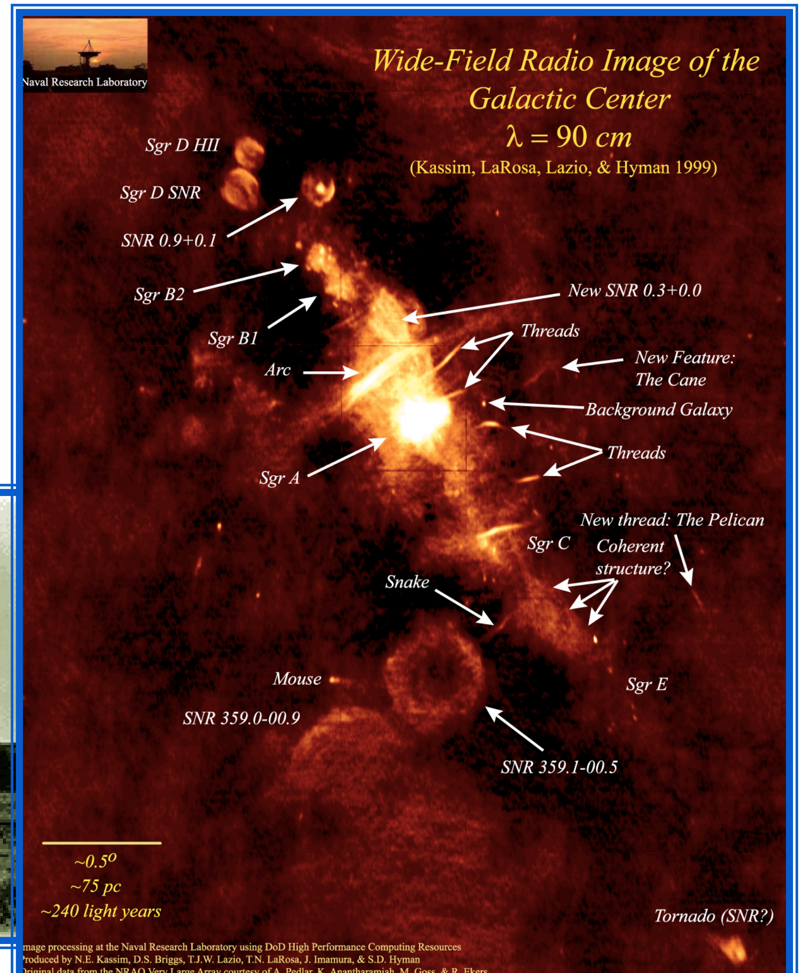
http://photojournal.jpl.nasa.gov

The Opening of a New Observational Window on the Universe

- Karl Janksy, 1933
  - *Builds a radio antenna array to study interference in transatlantic telecommunications*
    - ! *Discovers radio emissions from the galactic center*



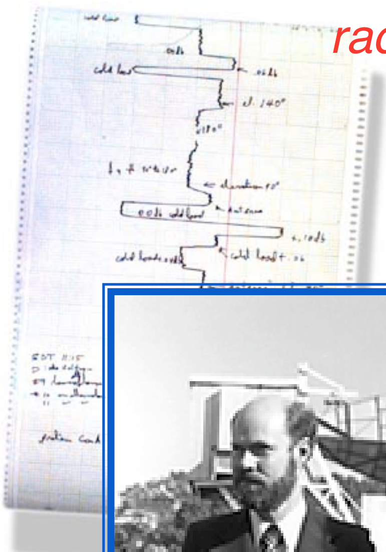
http://www.lucent.com/museum/1933rt.html

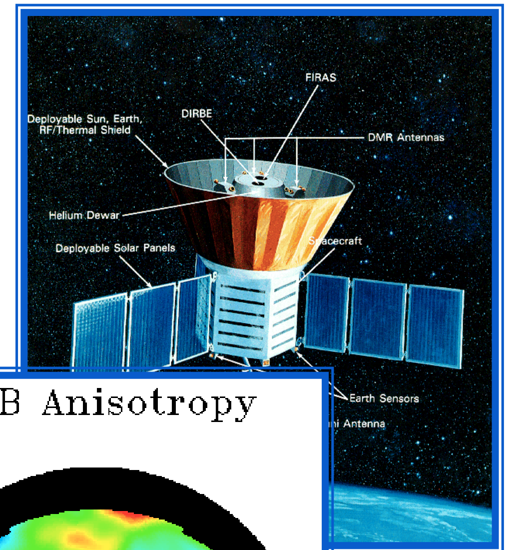


//http://rsd-www.nrl.navy.mil/7213/lazio/GC/

The Opening of a New Observational Window on the Universe

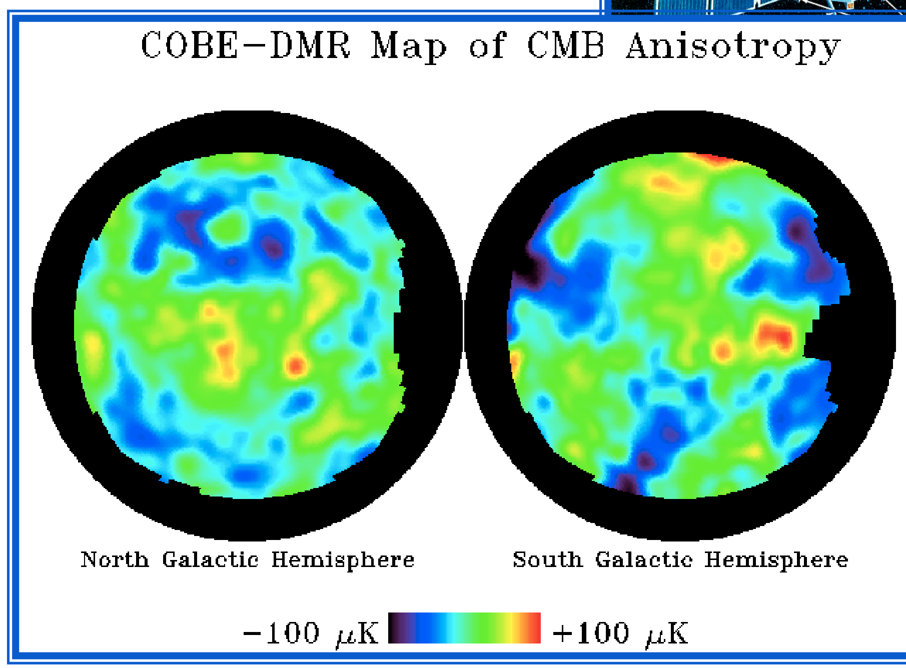
- Penzias & Wilson, 1963
  - *Track down excess antenna noise*
    - ! *Discover the cosmic microwave background radiation (CMBR)*





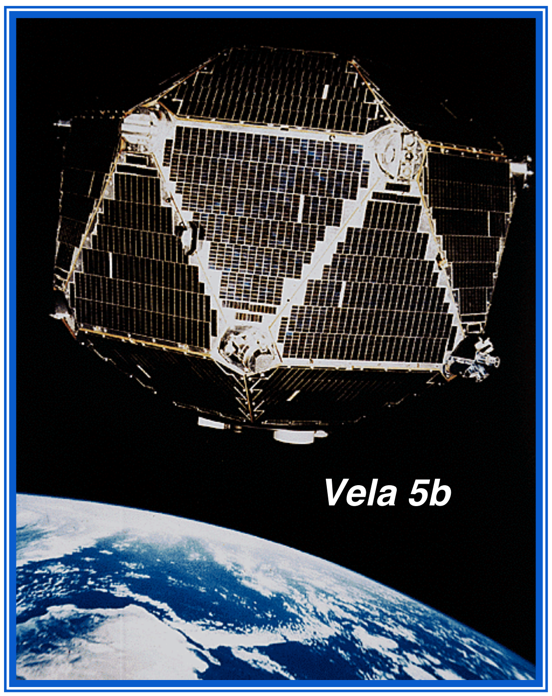
http://www.gsfc.nasa.gov/astro/cobe/cobe_home.html

http://www.lucent.com/museum/1964bang.html

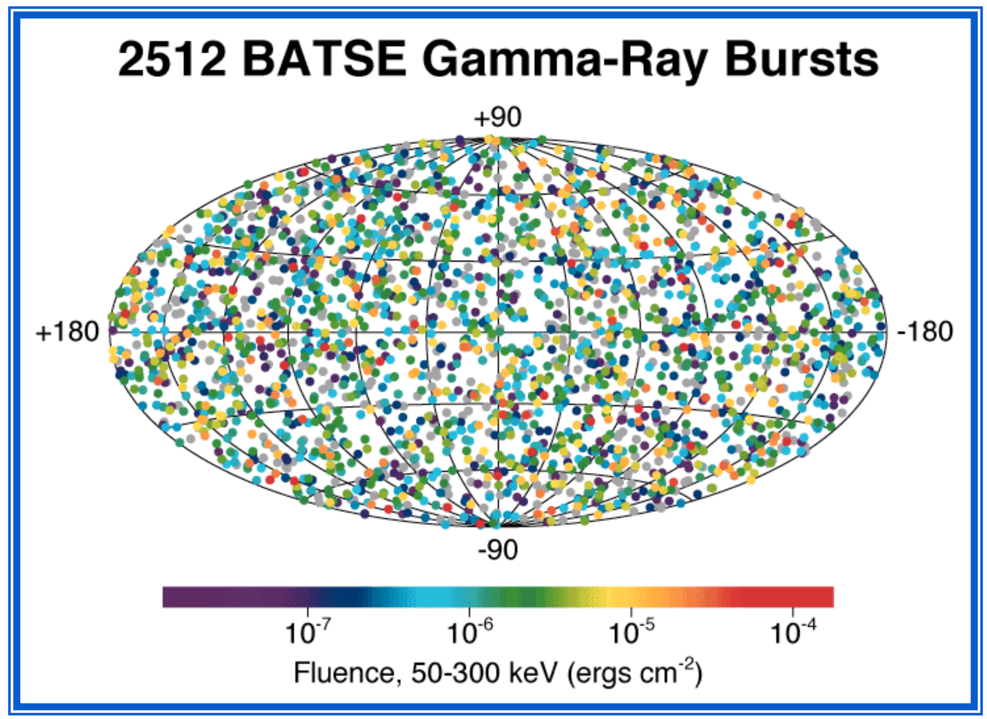


The Opening of a New Observational Window on the Universe

- Klebesadel, Strong & Olsen (LANL), 1969
  - Review of Vela 5 satellite data from 1967.07.02 shows a γ event of non-terrestrial origin
    - ! Discover γ-ray bursts (GRBs), X-ray sources



http://science.msfc.nasa.gov/newhome/headlines/ast19sep97_2.htm

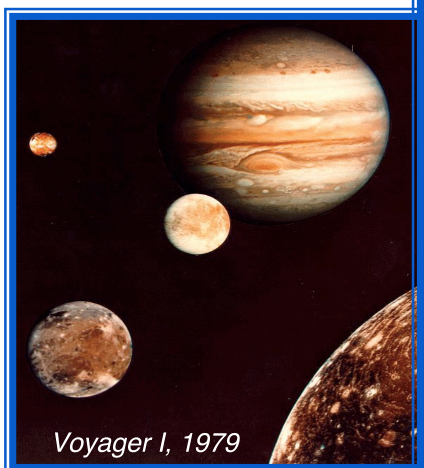


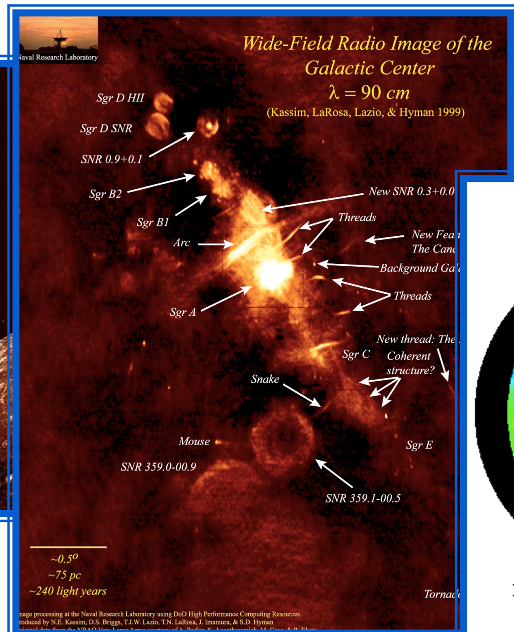
http://www.batse.com/

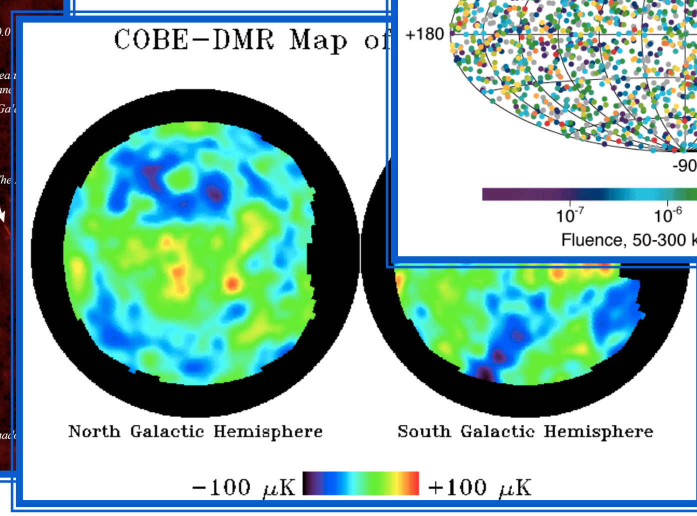
Search & Discovery

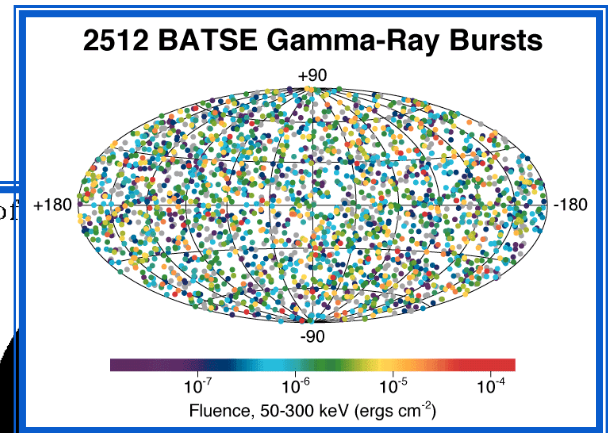
"There are more things in heaven and earth, Horatio,
Than are dreamt of in your philosophy."

- *Common theme: looking for something else; saw the unexpected; follow-up to understand, explain; made an important new discovery*
- *Physics from the instrument outwards (unexpected) vs. physics from the Cosmos inwards (predicted)…*
  - *LIGO will look for both the expected and unexpected*







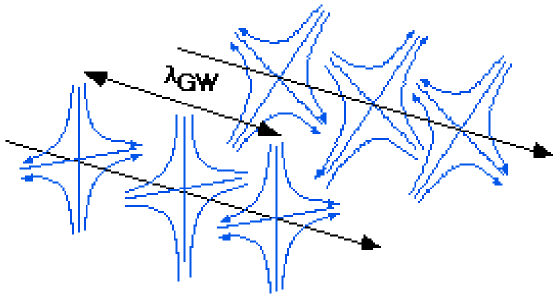


Interferometers as detectors of gravitational waves

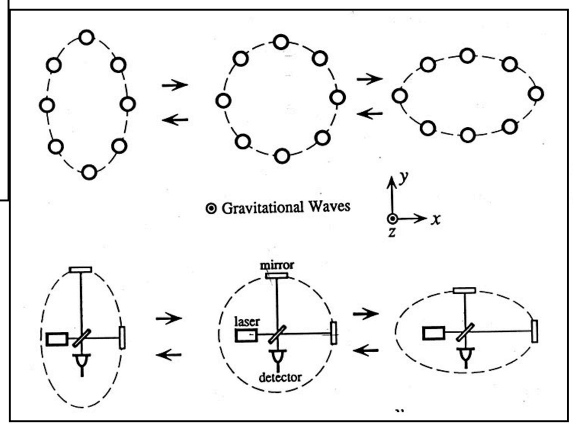
History of laser interferometer GW detectors

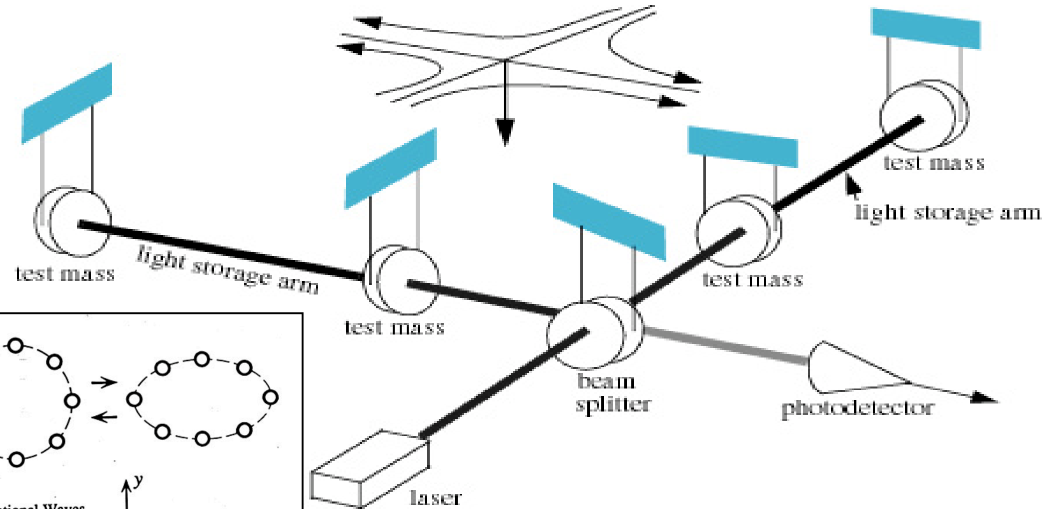
- 1956 Germ of the idea is born (Pirani, Imperial College)
- 1962 Gertsenshtein & Pustovit provide an explicit suggestion
- Mid-60s J. Weber independently discovers idea but does not publish/pursue it
- 1970 R. Weiss independently (re)discovers idea, carries out detailed design & feasibility study (1971, 1972)
  - *1970-1972 R. Forward (Hughes) indirectly motivated by Weiss, constructs first working prototype (achieves h~2 x 10^{-16} 1/√Hz). Work languishes due to lack of funding.*
- Mid-70s Munich (MPI Garching) pursues Weiss design (Michelson interferometer with arm delay lines)
- Mid-70s Glascow (R. Drever) invents resonant arm (Fabry-Perot) cavity interferometer (LIGO design)
  - *1979 Drever moves to Caltech to pursue large-scale prototype research*
- 1983 French (A. Brillet) initiate interferometer design at Orsay
- 1985-1989 CIT/MIT collaboration fostered by NSF
- 1992 LIGO Project funded in U.S.

Interferometer as a Detector of Gravitational Waves *"Strain Gauge"*



$$g_{\Box\Box} = \Box_{\Box\Box} + h_{\Box\Box}(\vec{r},t)$$
$$h_{+} = \Box_{+} \; h \; e^{i(\vec{k}\cdot\vec{r}\Box\Box t)}$$
$$h_{\Box} = \Box_{\Box} \; h \; e^{i(\vec{k}\cdot\vec{r}\Box\Box t)}$$

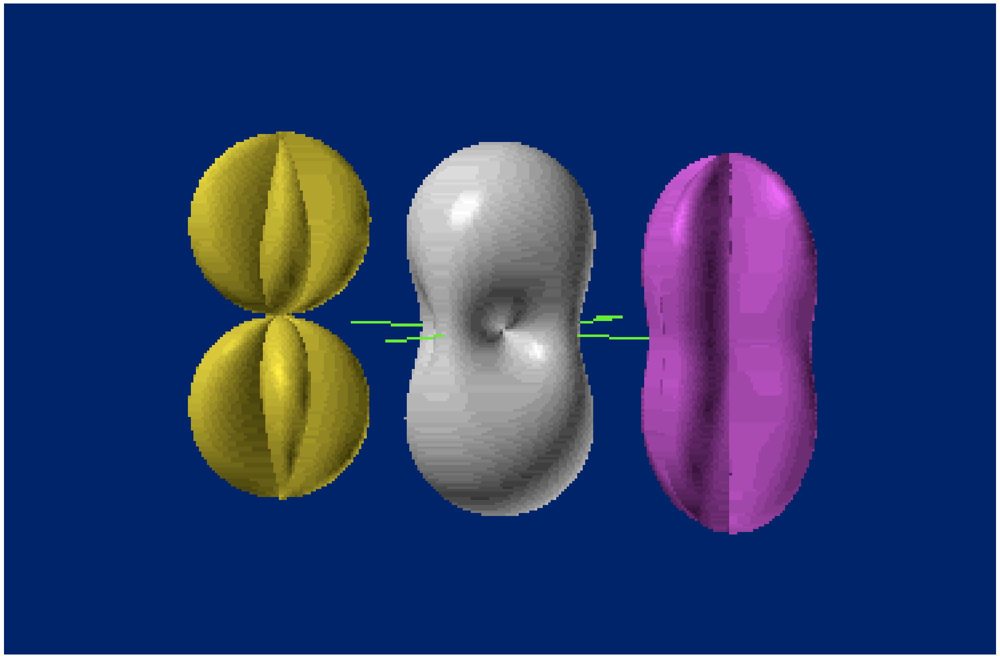




- The concept is to compare the time it takes light to travel in two orthogonal directions transverse to the gravitational waves.
- The gravitational wave causes the time difference to vary by stretching one arm and compressing the other.
- The interference pattern is measured (or the fringe is split) to one part in 10^{10}, in order to obtain the required sensitivity.

Interferometer Antenna Response Pattern

Polarization Dependence

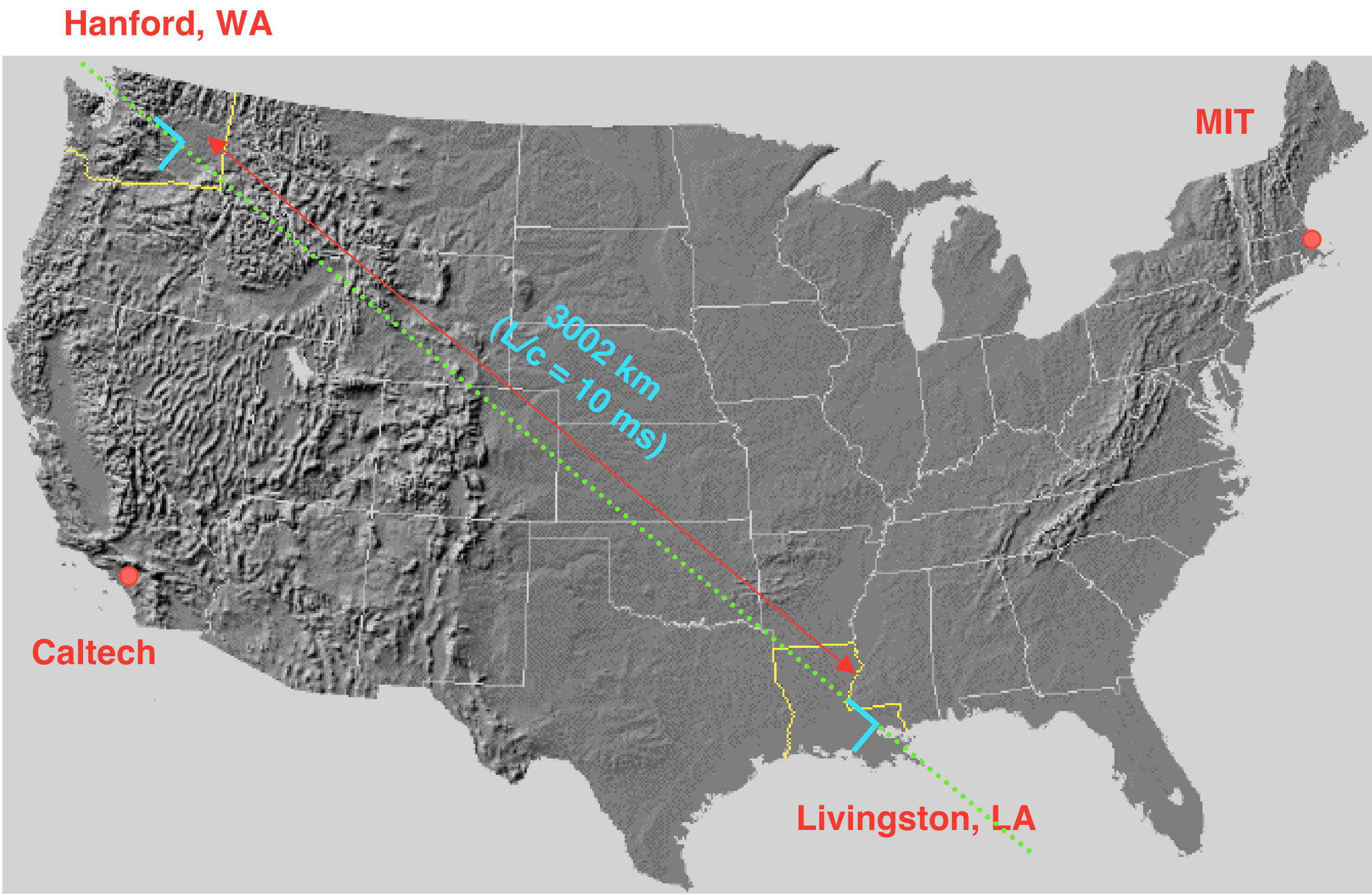


h_x $(h_+^2 + h_x^2)^{1/2}$ h_+

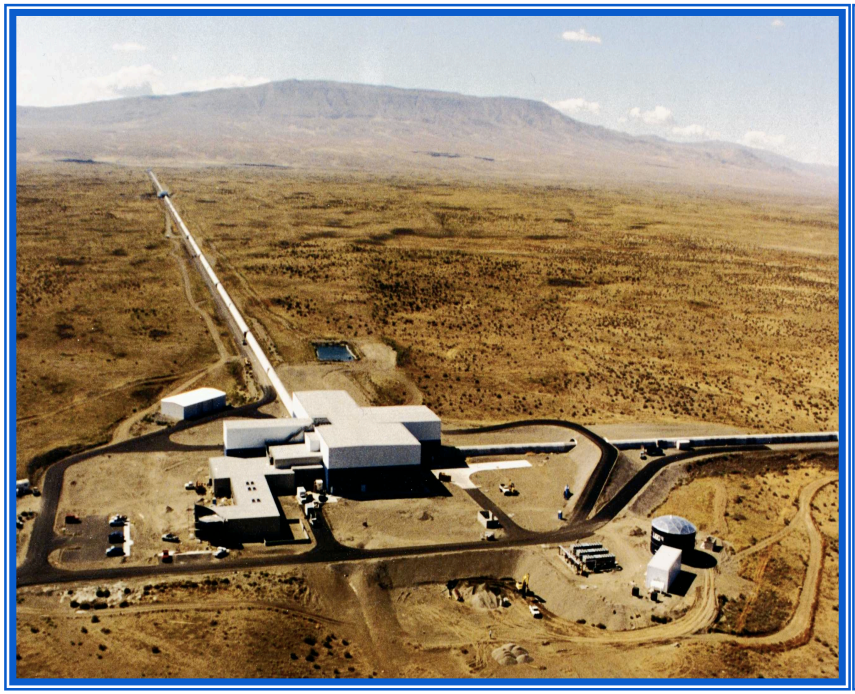
Implementation

The LIGO Laboratory Sites

Interferometers are aligned along the great circle connecting the sites



The LIGO Observatories
4 km armlengths



LIGO Hanford Observatory [LHO]

26 km north of Richland, WA

DOE Hanford Nuclear Reservation

2 km + 4 km interferometers in same vacuum envelope

LIGO Livingston Observatory [LLO]

42 km east of Baton Rouge, LA

LSU fiducial owner of site

Single 4 km interferometer

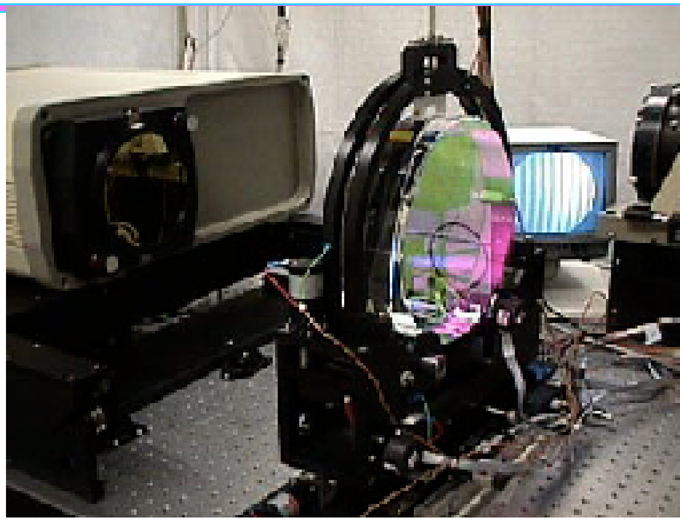
LIGO Beam Tubes

- *20 m spiral welded sections*
  - *girth welded in portable clean room in the field*
  - *1.2 m diameter - 3mm stainless*
  - *50 km of weld -- NO LEAKS!*
- Aligned using GPS - straight to an rms error < 5mm, all four arms (both sites)
- *Final vacuum does not limit sensitivity (even future detectors)*

LIGO Vacuum Equipment

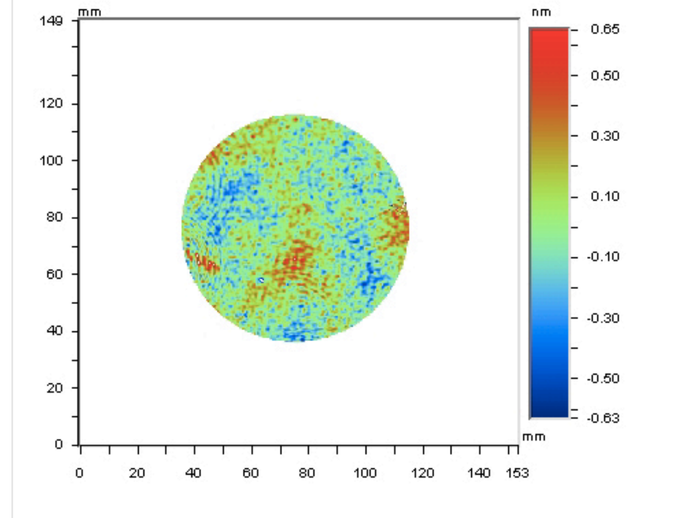
Fused Silica Optics

Corning Glass, Polished by CSIRO (Australia)



LIGO requirements

- Surface uniformity < 1 nm rms
- Scatter < 50 ppm
- Absorption < 2 ppm
- ROC matched < 3%
- Internal mode Q's > 2 x 10^6



Date: 10/17/2000
Time: 09:26:37
Wavelength: 1.064 um
Pupil: 100.0 %
PV: 1.2818 nm
RMS: 0.1620 nm
Rad of curv: 14.053 km

X Center: 283.00
Y Center: 244.00
Radius: 150.00 pix
Terms: Tilt Power Astig
Filters: None
Masks: Analysis 4.0 Sigma Masks
Ref Sub:
Averages:

LIGO measurements

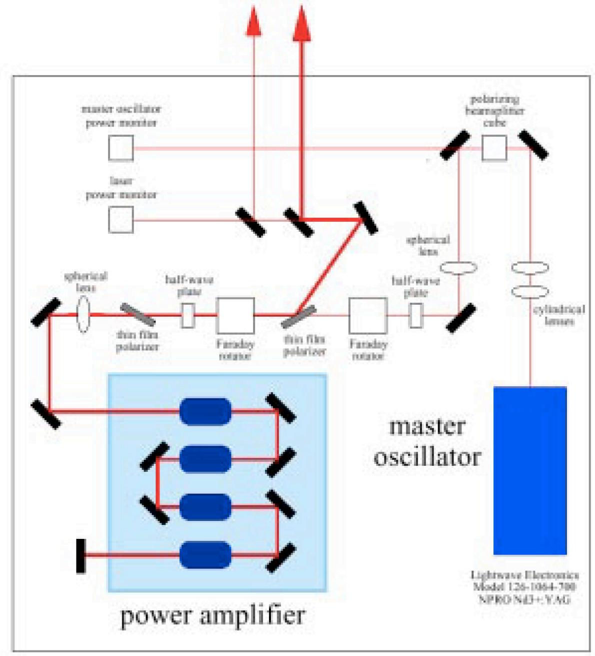
- central 80 mm of 4ITM06 (Hanford 4K)
  - rms = 0.16 nm
  - optic far exceeds specification.

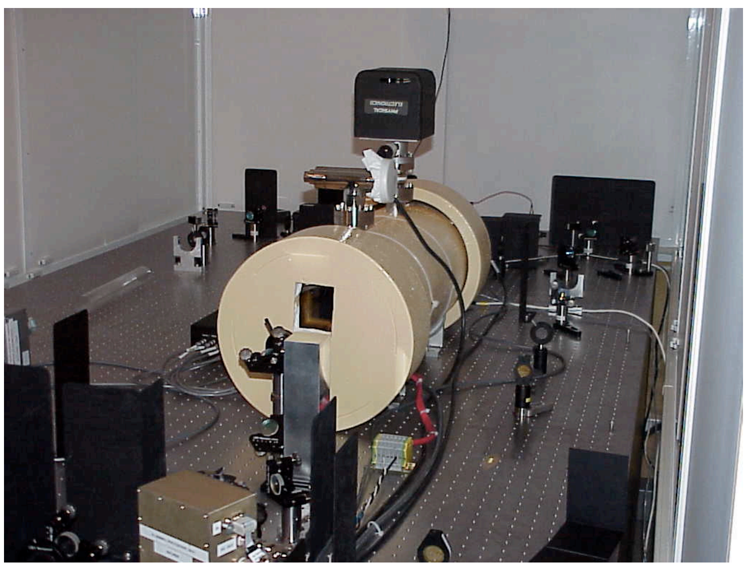
Surface figure = λ/ 6000

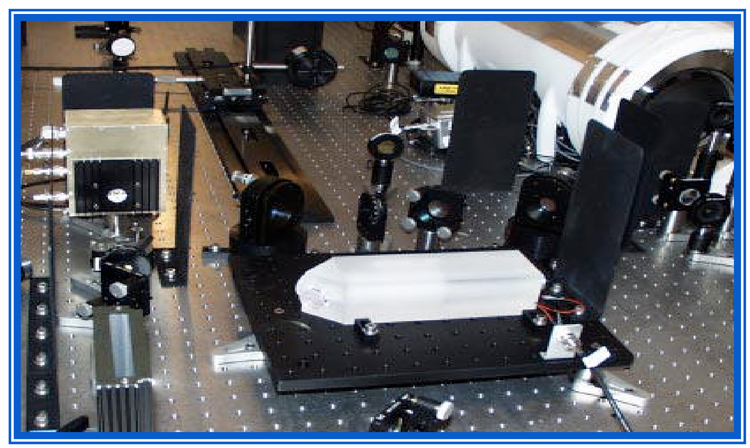
Core Optics installation and alignment

LIGO Laser Subsystem

- Nd:YAG; 1.064 μm
  - *Output power > 8W in TEM_{00} mode*
  - *Frequency noise: $\delta\nu(f) < 10^{-2}$ Hz/Hz$^{1/2}$, 40Hz<f<10kHz*
  - *Intensity noise: $\delta I(f)/I < 10^{-6}$/ Hz$^{1/2}$, 40 Hz<f<10 kHz*





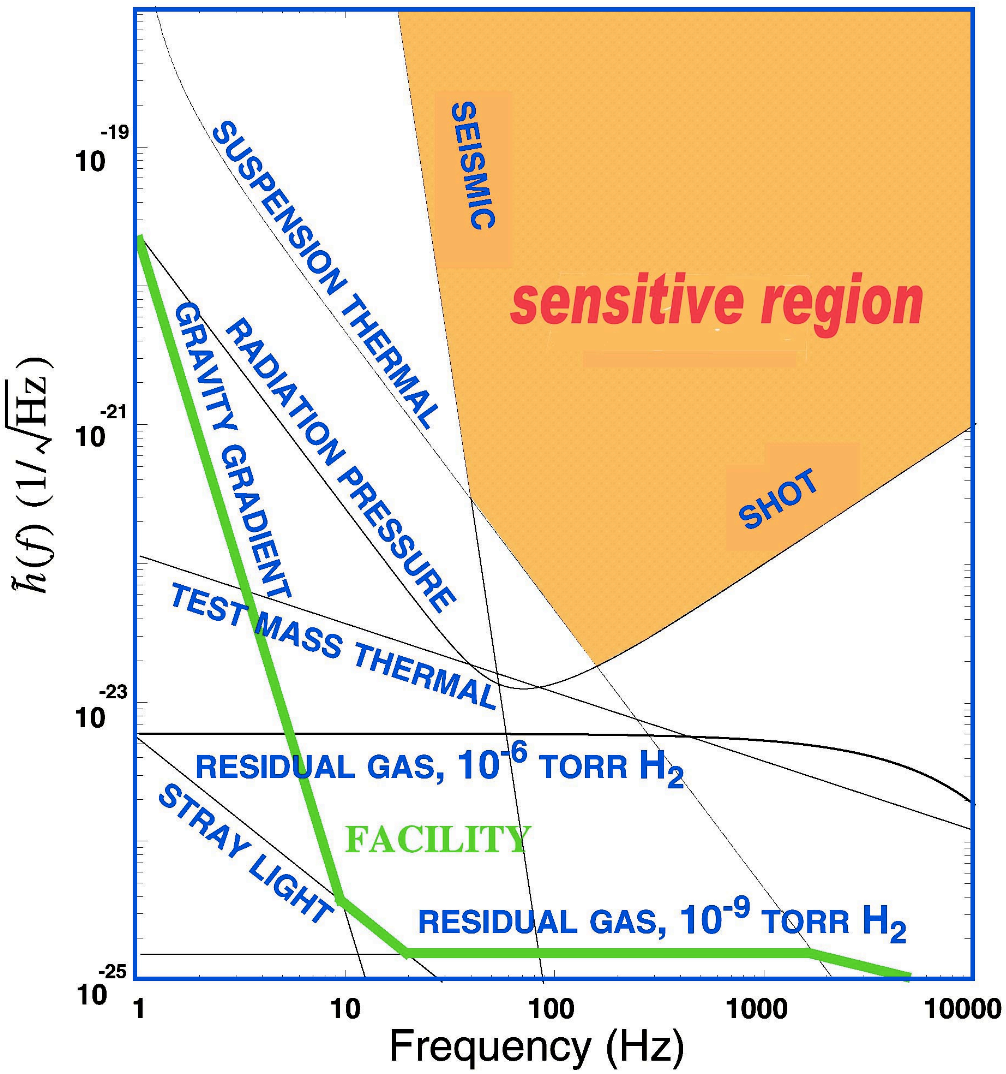


LIGO First Generation Detector

Limiting noise floor

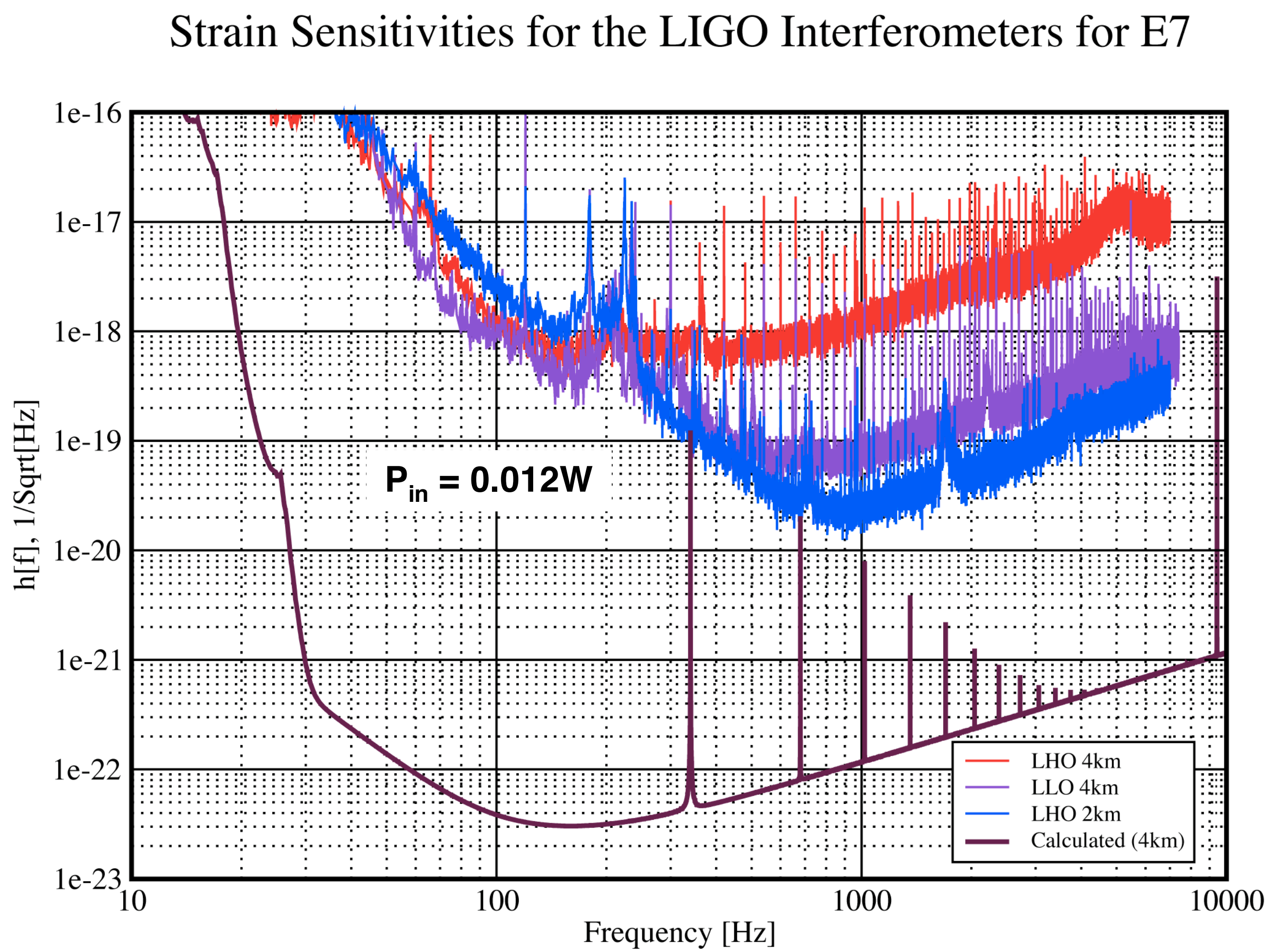
- **Interferometry is limited by three fundamental noise sources**
  - ➢ seismic noise at the lowest frequencies
  - ➢ thermal noise (Brownian motion of mirror materials, suspensions) at intermediate frequencies
  - ➢ shot noise at high frequencies

- **Many other noise sources lie beneath and must be controlled as the instrument is improved**



E7 sensitivities for LIGO Interferometers

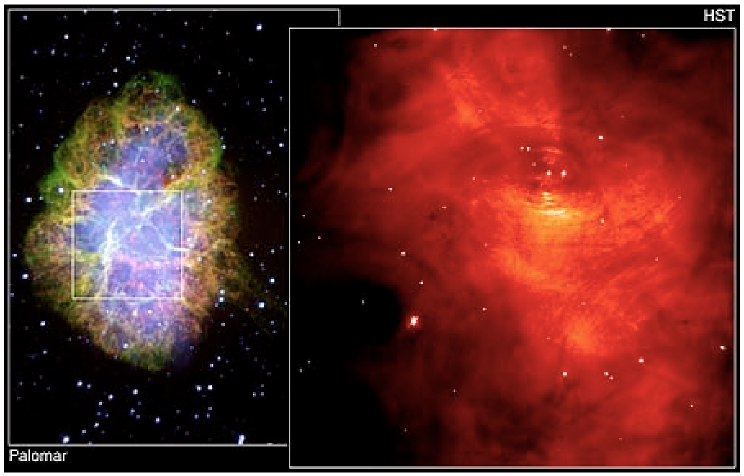
28 December 2001 - 14 January 2002

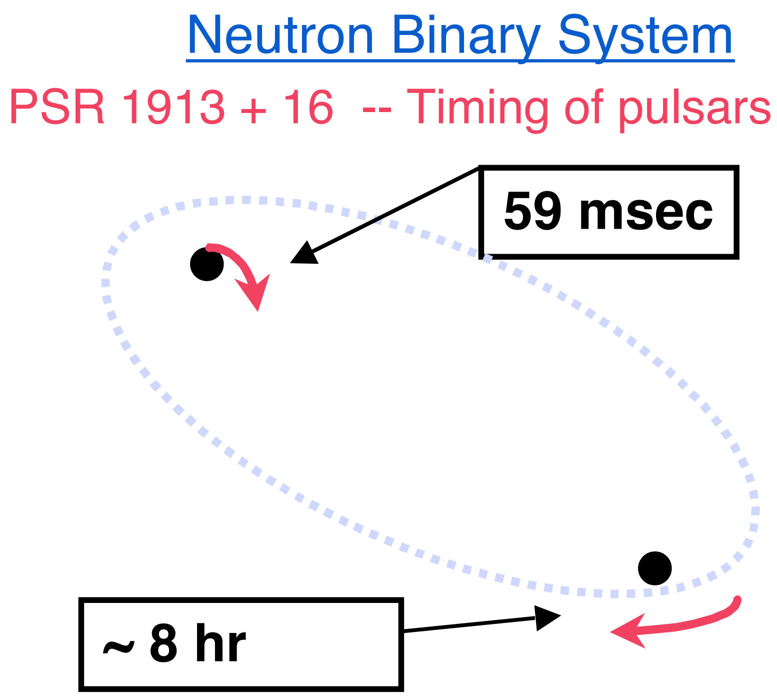


LIGO

Sources of gravitational waves

Gravitational Waves
The evidence





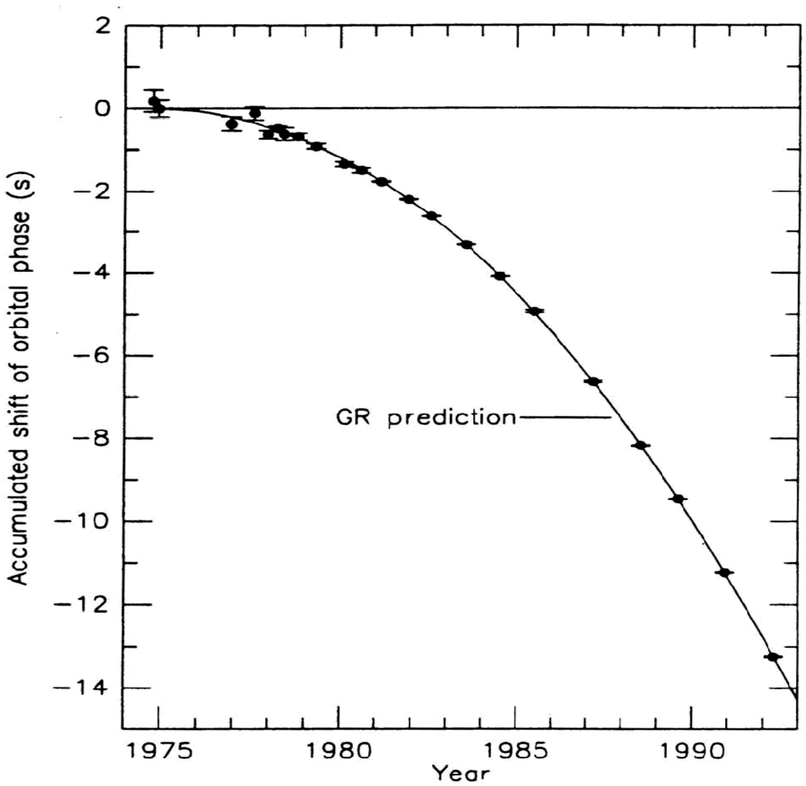
Taylor, J.H., Fowler, L.A. and Weisberg, J.M. 1979, *Nature* 277, 437
Weisberg, J.M., Taylor, J.H. and Fowler, L.A., 1981, *Scientific American* **Oct**, 74

Gravitational Waves

Hulse & Taylor Results

Energy loss through the emission of gravitational waves

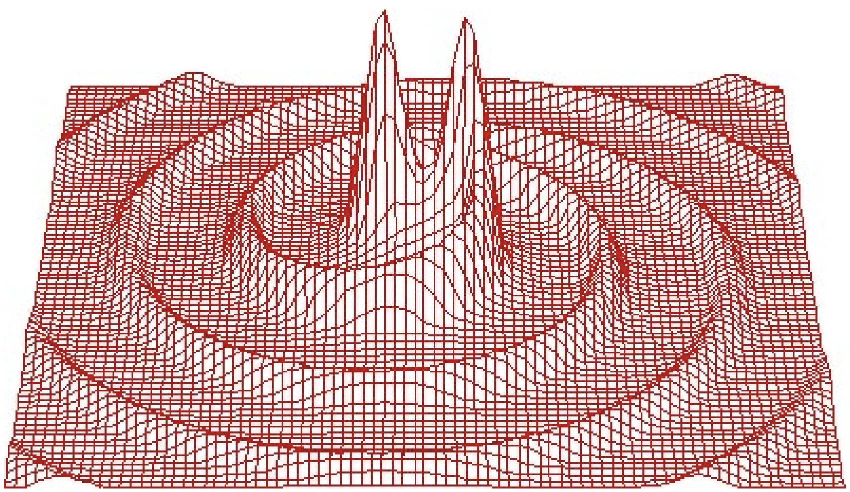
- *due to loss of orbital energy*
- *period speeds up 14 sec from 1975-94*
- *measured to ~50 msec accuracy*
- *deviation grows quadratically with time*
- *will enter LIGO band in ~ 10^8 yr!*



http://www.nobel.se/physics/laureates/1993/taylor-lecture.html

Einstein's Theory of Relativistic Gravity
Gravitational Radiation

Newton's Theory
"instantaneous action at a distance"



Einstein's Theory
information carried by gravitational radiation at the speed of light

$$h \sim \frac{2G}{3c^4 r}\ddot{Q} \quad \textit{amplitude of wave}$$

$$\left|\dot{E}\right| \sim \frac{G}{45c^5}\dddot{Q}^2 \quad \textit{radiated power}$$

$$\boldsymbol{R}_{separation} = 100\ km;\ M = 1.4\,M_{sun}$$

$$f_{orbit} \sim 100\ Hz;\ f_{GW} \sim 200\ Hz$$

$$t_{coalesence} \sim 0.4\,s$$

$$\frac{v}{c} \sim 0.2$$

$$\mathcal{L}_{GW} \sim 2 \times 10^{45}\ W$$

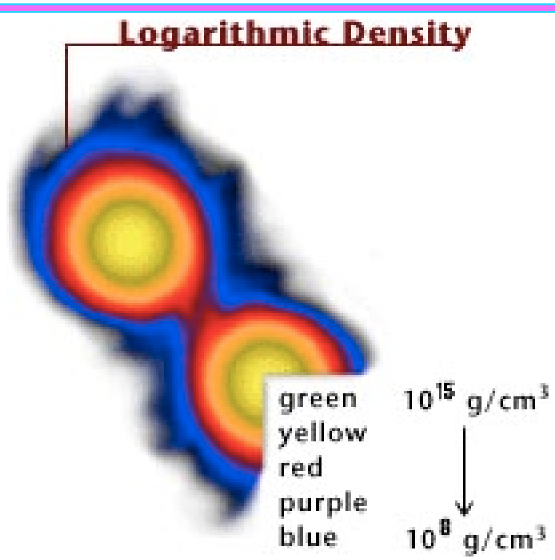
$$d_{Virgo\ Cluster} \sim 16\ Mpc \sim 5 \times 10^{20}\ km$$

$$\mathcal{F}_{GW}\big|_{d_{Virgo}} \sim 0.008\ \frac{W}{m^2}$$

$$h \sim 10^{-22}$$ ***TINY effect!!!***

Sources of Gravitational Waves

Closely orbiting compact stars

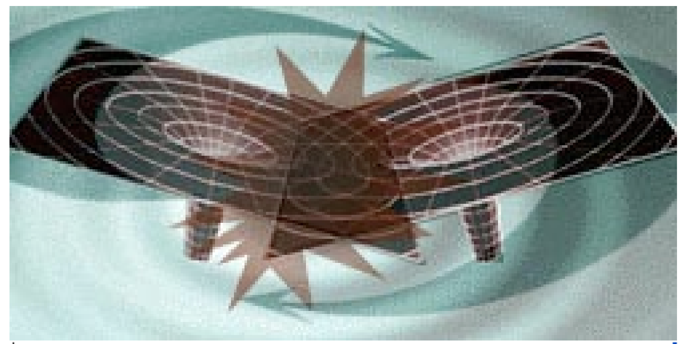


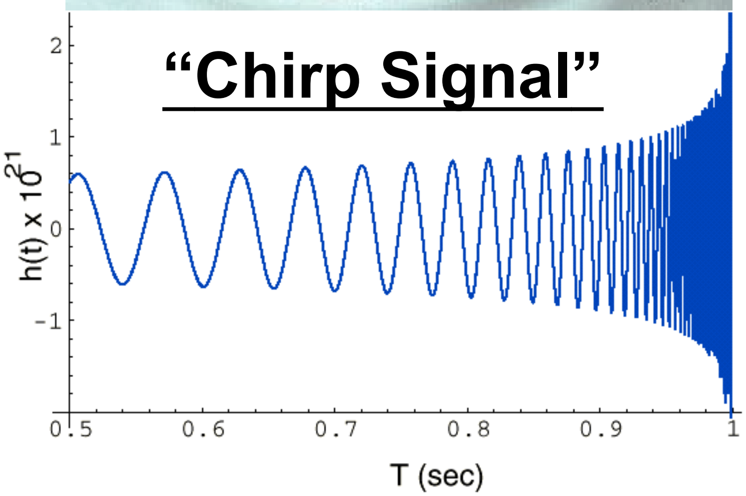
Rate

10^{-6} - 10^{-4} yr^{-1} - per galaxy
1/1000 - 1/ 10 yr^{-1} - to Virgo cluster
2 - 100 yr^{-1} 350 Mpc

Based on statistics of 3 observed systems

Inspiral of Neutron Stars



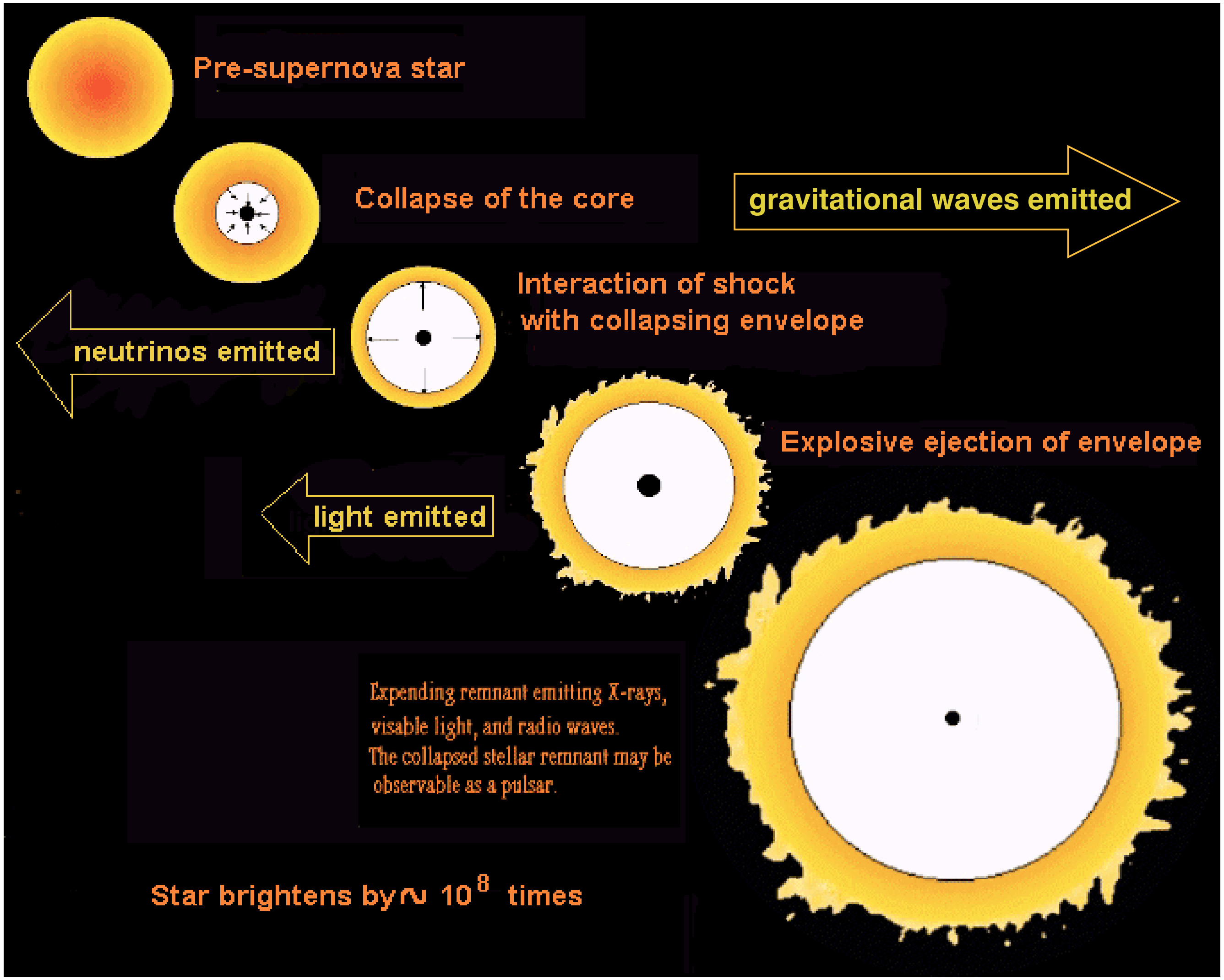


Thorne, gr-qc/9506084
Owen & Sathyaprakash, gr-qc/9808076

$$h_c \approx 4 \times 10^{-22} \left(\frac{\mu}{M_{sun}}\right)^{\frac{1}{2}} \left(\frac{M}{M_{sun}}\right)^{\frac{1}{3}} \left(\frac{100\ \ Mpc}{r}\right) \left(\frac{100\ \ Hz}{f_c}\right)^{\frac{1}{6}}$$

Sources of Gravitational Waves

Supernovae



□GW

□

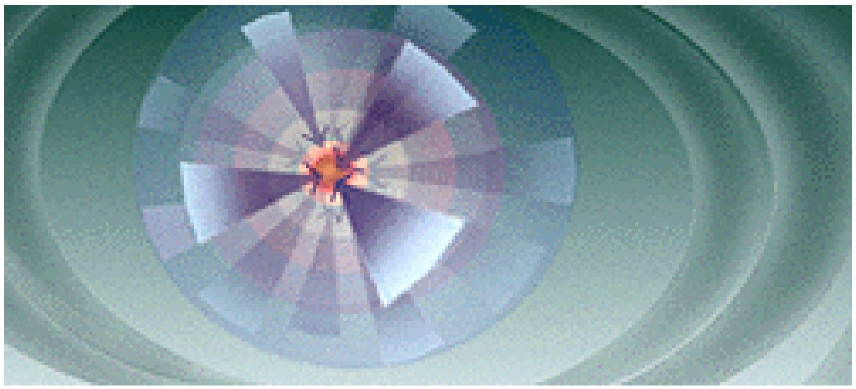
□EM

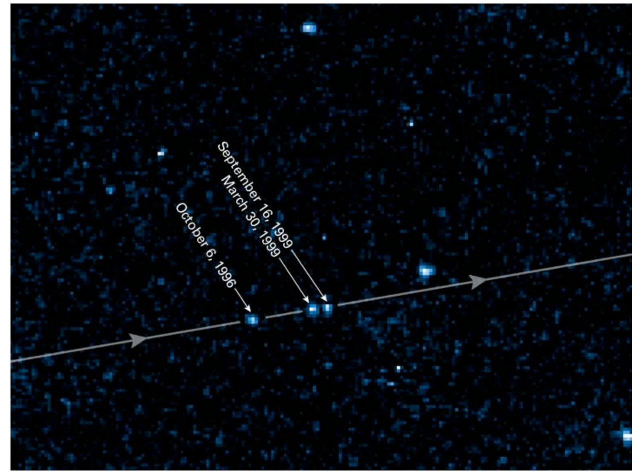
Sources of Gravitational Waves

Supernovae

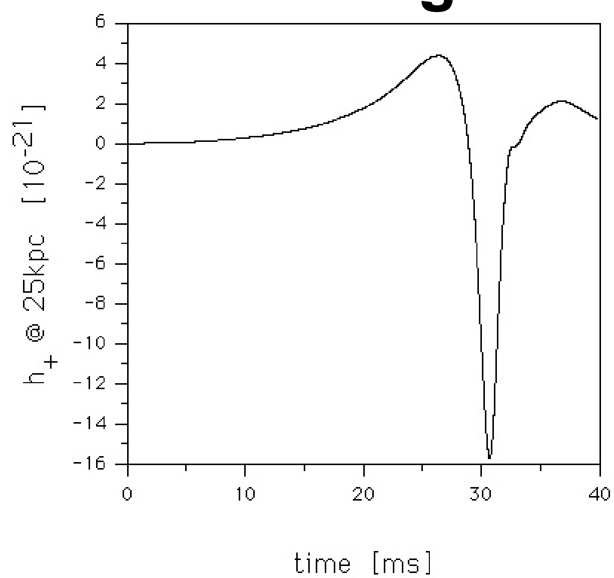
Non axisymmetric collapse

✓*Recoiling NS with v~several 100s km/s*





'burst' signal



Rate

1/50 yr^{-1} - our galaxy

3 yr^{-1} - Virgo cluster

$$h_c \approx 3\times10^{-20}\left(\frac{E_{GW}}{M_{sun}c^2}\right)^{\frac{1}{2}}\left(\frac{1\ kHz}{f_c}\right)^{\frac{1}{2}}\left(\frac{10\ Mpc}{r}\right)$$

Zwerger & Mueller, Astron. Astrophys. 320, 209 (1997)
Dimmelmeier, Font & Mueller, Astrophys.J. 560 (2001) L163-L166

Sources of Gravitational Waves

The Rotating Deformed Neutron Stars (Pulsars)

Pulsars

Continuous waves

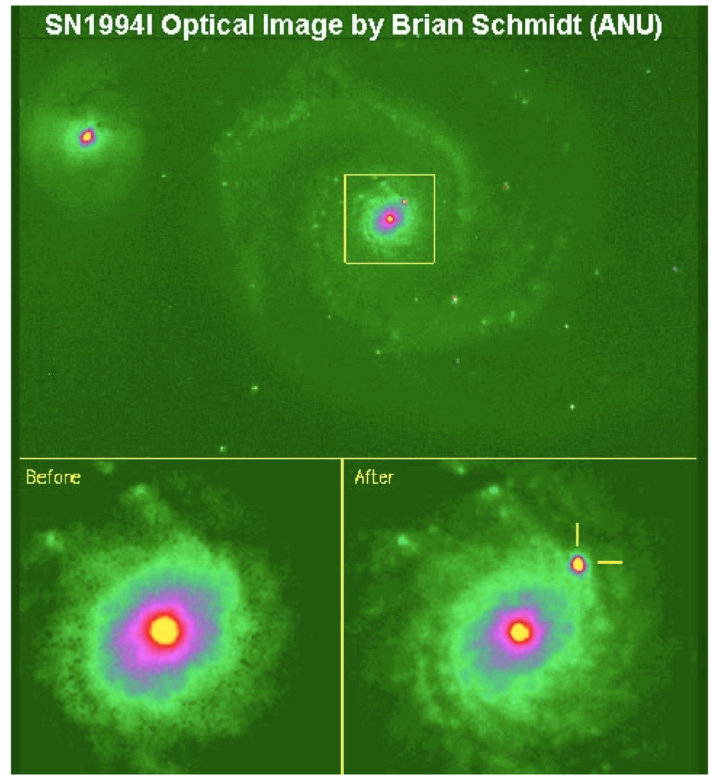
Crab Nebula 1054 AD

$$h_c \approx 8\times10^{-25}\,\frac{\varepsilon}{10^{-5}}\,\frac{I_{zz}}{10^{45}\,g\;cm^2}\,\frac{10\;kpc}{r}\left(\frac{f}{1\;kHz}\right)^2$$

Brady & Creighton, gr-qc/9812014

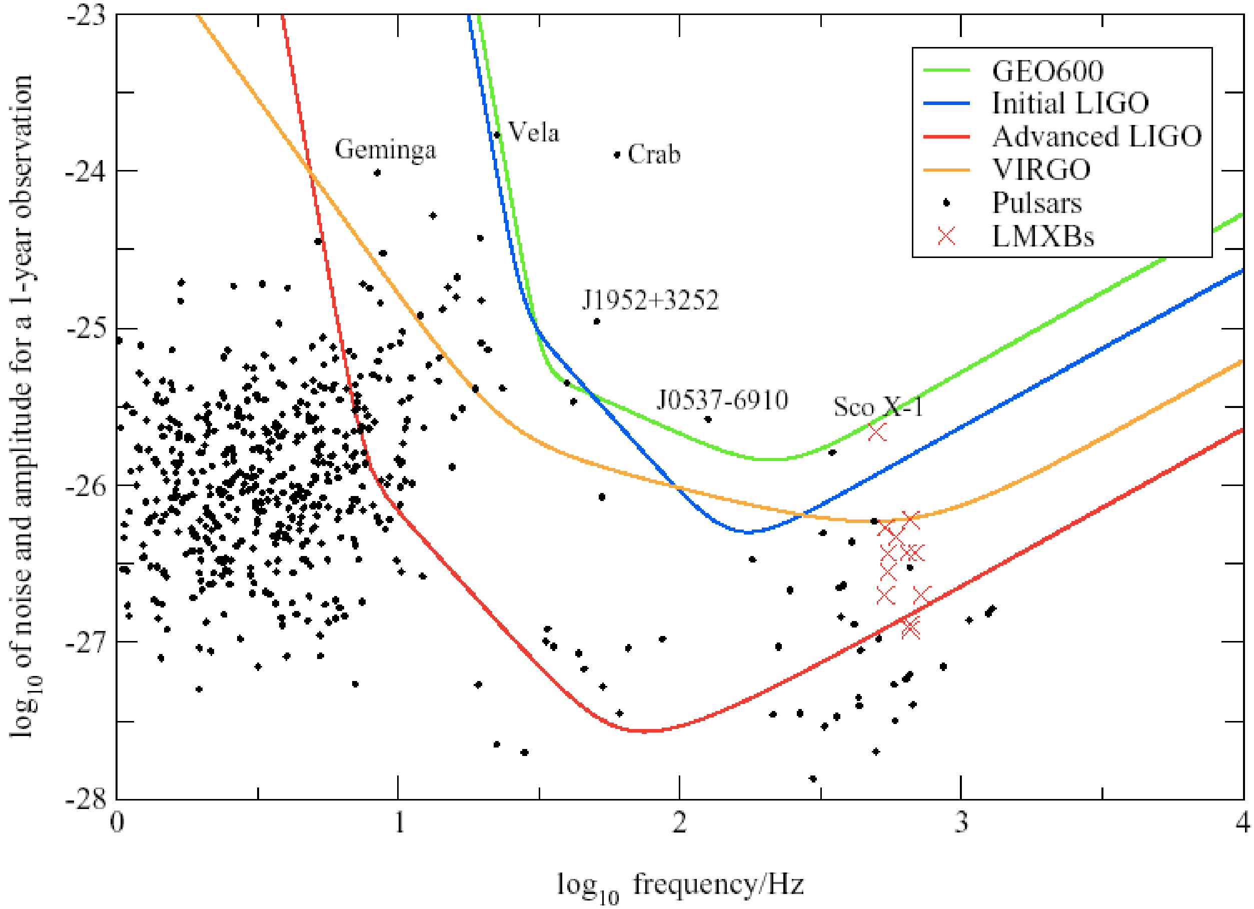
Supernovae

optical observations



Supernovae - SN1994I

Maximum GW luminosity of known pulsars

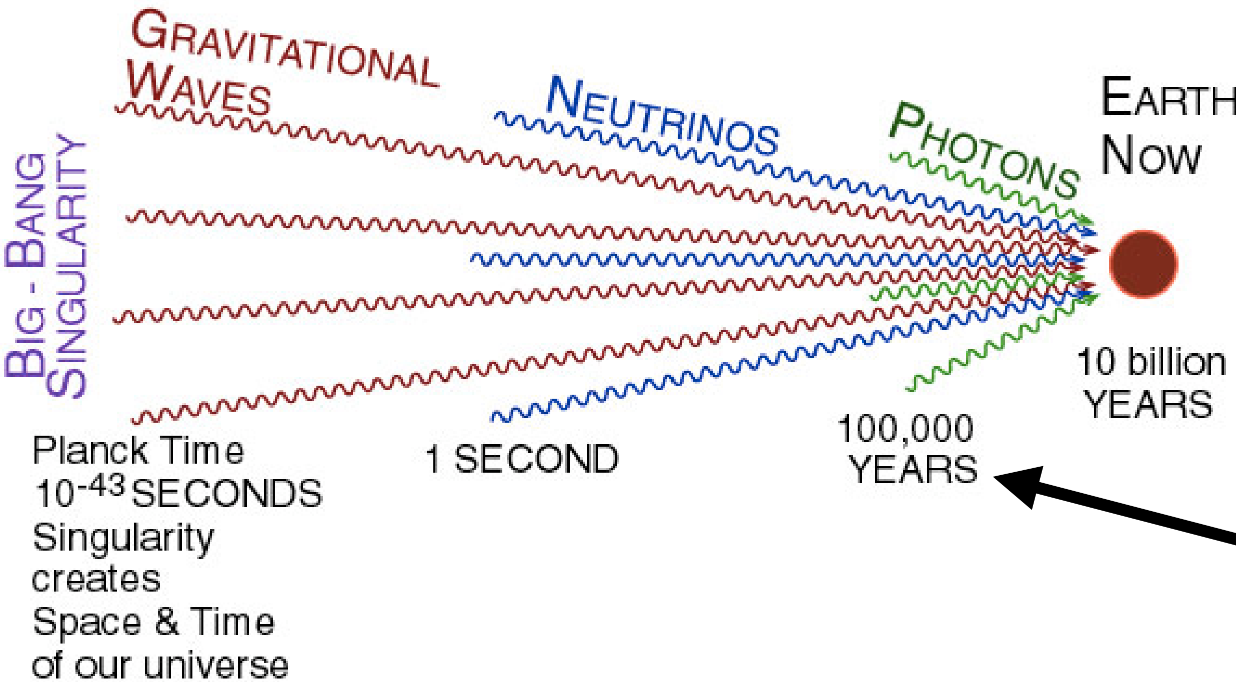


Jones, gr-qc/0111007

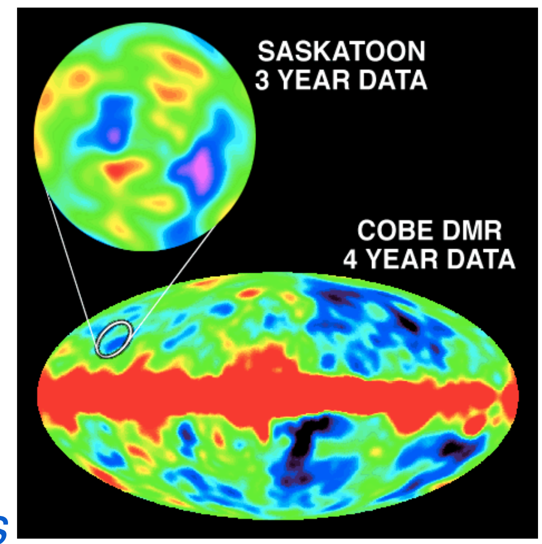
Sources of Gravitational Waves

Stochastic Background from the Early Universe

- GWs are the ideal tool for probing the very early universe



Cosmic microwave background

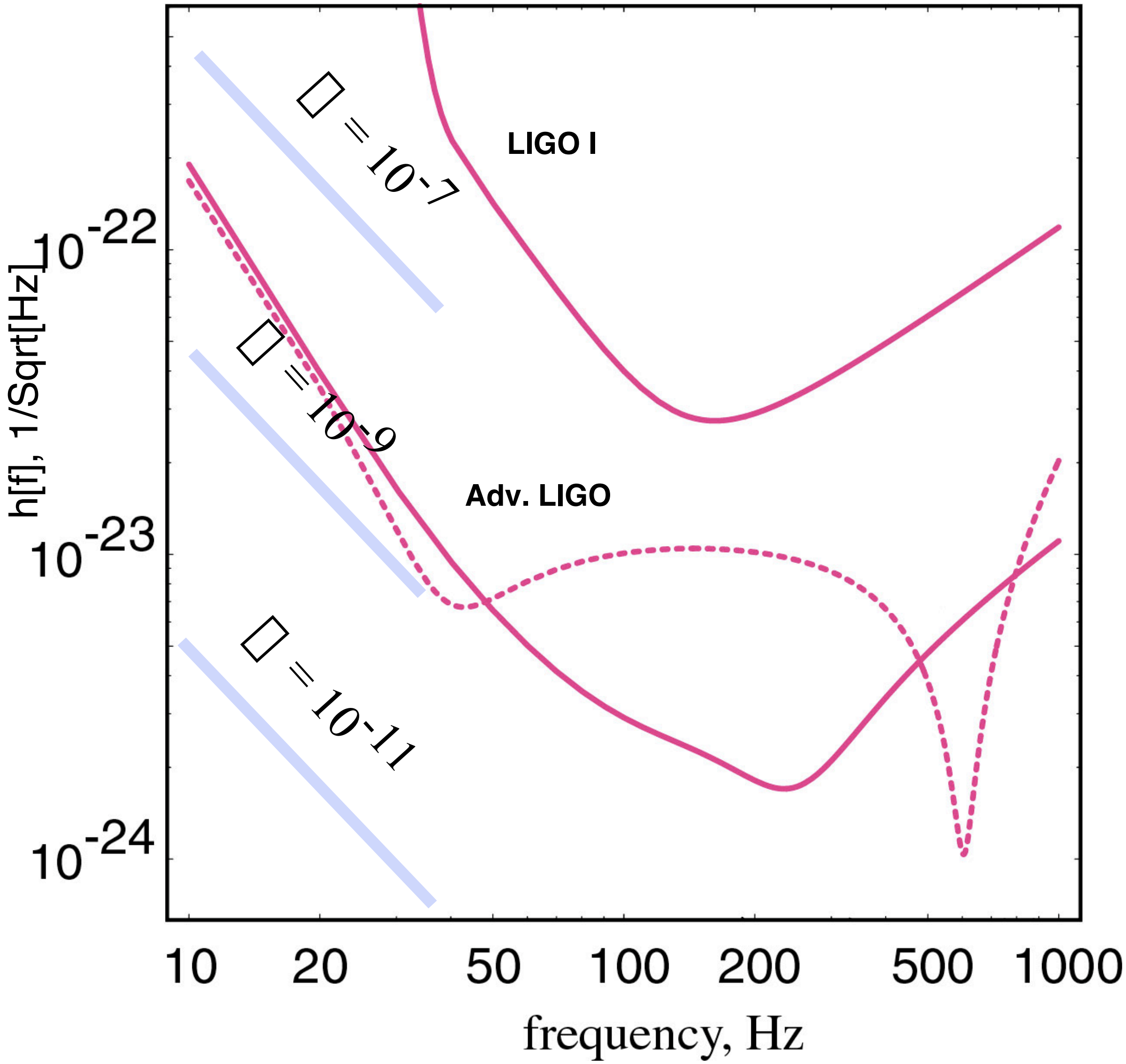


- Present limit on GWs
  - *From effect on primordial nucleosynthesis*
  - ***Ω = (GW energy density)/(closure density) $< 10^{-5}$***

Allen & Romano, gr-qc/9710117
Maggiore, gr-qc/9909001

Stochastic Gravitational Wave Background

- Detect by
  - *cross correlating output of Hanford + Livingston 4km IFOs*
- Good sensitivity requires:
  - *$\lambda_{GW} \geq 2\ L_{baseline}$*
  - *$f_{GW} \leq 40$ Hz*
- Initial LIGO sensitivity:
  - *$\Omega_{GW} \geq 10^{-5}$*
- Advanced LIGO sensitivity:
  - *$\Omega_{GW} \geq 5x10^{-9}$*



Data Analysis for Detection

Detection Strategy

Coincidences

- Data Recording (time series sampled @ 16384 sample/s)
  - *gravitational wave signal (0.2 MB/sec)*
  - *total data (9 MB/s => 280 TB/yr)*
  - *on-site filters, diagnostics, data compression, real-time searches*
  - *off-site data analysis, archive and data distribution*

- Signal Extraction
  - *Signal from noise (environmental & instrumental vetoes, noise analysis)*
  - *Matched optimal filters in frequency domain: templates, wavelets, …*

- Two Sites - Three Interferometers
  - *Single Interferometer - limited by non-gaussian noise* — *~50/hr*
  - *Hanford -- 2x coincidence requirement (**x1000 reduction**)* — *~1/day*
  - *Hanford + Livingston -- 3x coincidence (another **x5000 reduction**)* — ***<0.1/yr***

E7 Run Summary

LIGO + GEO Interferometers

Courtesy G. Gonzalez & M. Hewiston

28 Dec 2001 - 14 Jan 2002 (402 hr)

LIGO

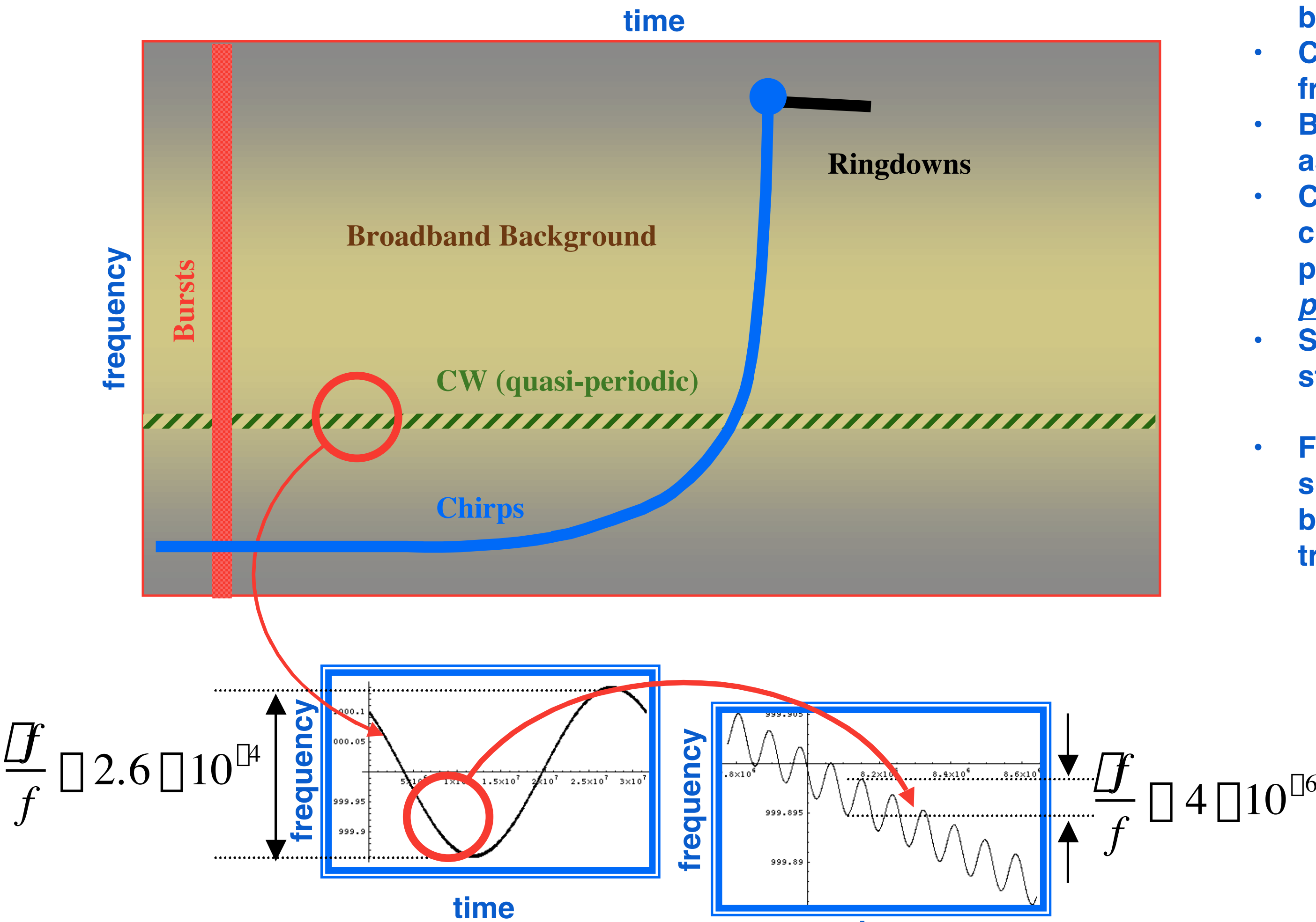
Singles data

	All segments	Segments >15min
L1 locked	284hrs (71%)	249hrs (62%)
L1 clean	265hrs (61%)	231hrs (53%)
L1 longest clean segment: 3:58		
H1 locked	294hrs (72%)	231hrs (57%)
H1 clean	267hrs (62%)	206hrs (48%)
H1 longest clean segment: 4:04		
H2 locked	214hrs (53%)	157hrs (39%)
H2 clean	162hrs (38%)	125hrs (28%)
H2 longest clean segment: 7:24		

Coincidence Data

	All segments	Segments >15min
2X: H2, L1		
locked	160hrs (39%)	99hrs (24%)
clean	113hrs (26%)	70hrs (16%)
H2,L1 longest clean segment: 1:50		
3X : L1+H1+ H2		
locked	140hrs (35%)	72hrs (18%)
clean	93hrs (21%)	46hrs (11%)
L1+H1+ H2 : longest clean segment: 1:18		
4X: L1+H1+ H2 +GEO:	77 hrs (23 %)	26.1 hrs (7.81 %)

Frequency-Time Characteristics of GW Sources



- Bursts are short duration, broadband events
- Chirps explore the greatest time-frequency area
- BH Ringdowns expected to be associated with chirps
- CW sources have FM characteristics which depend on position on the sky (***and source parameters***)
- Stochastic background is stationary and broadband

- For each source, the optimal signal to noise ratio is obtained by integrating signal ***along*** the trajectory
  - •If SNR >> 1, kernel µ |signal|^2
  - •If SNR < 1, kernel µ |template* signal| or |signal$_j$* signal$_k$|
  - •Optimal filter: kernel µ 1/(noise power)

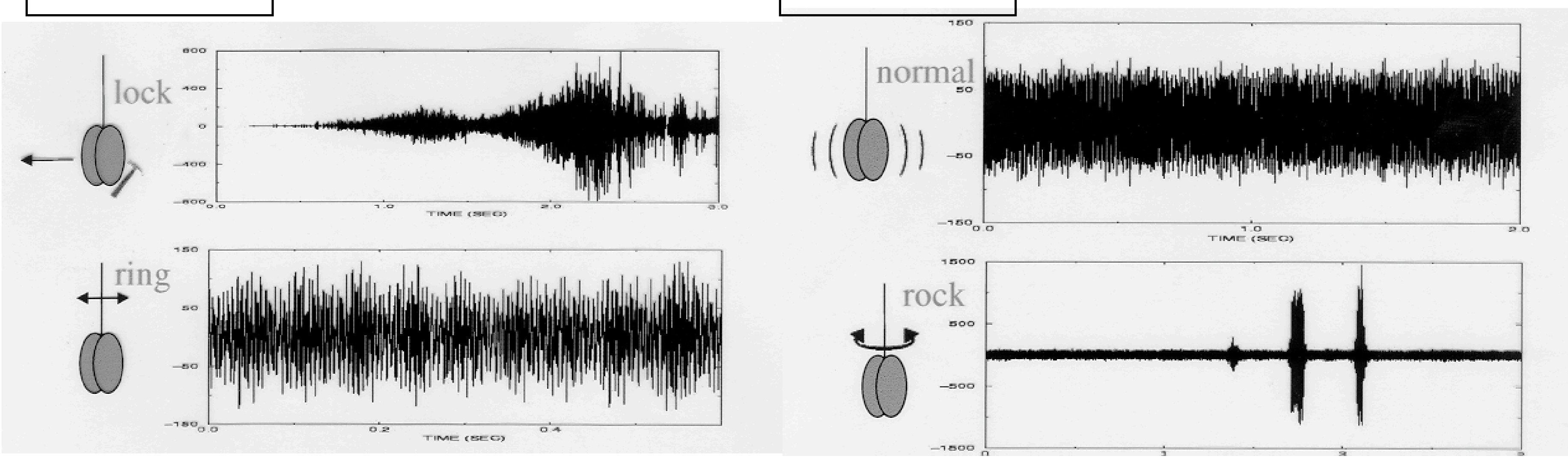
Interferometer Data

Instrumental transients from Caltech 40 m prototype

Real interferometer data are UGLY!!!

(Gliches - known and unknown)

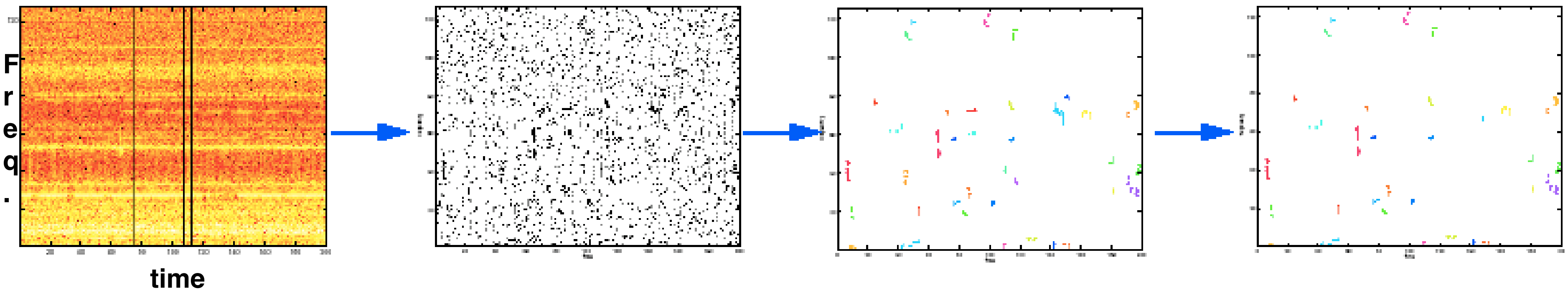
LOCKING **NORMAL**



RINGING **ROCKING**

t-f clusters algorithm

May be used to detect transients when only $\Delta f \Delta t$ product is known about the signal

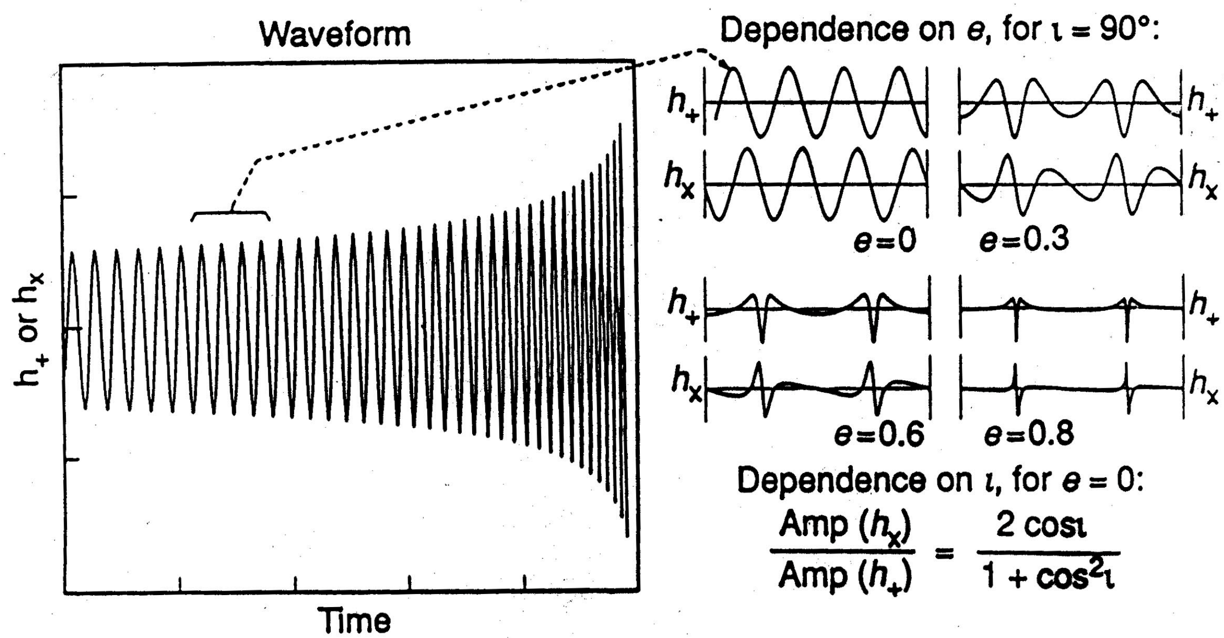


construct spectrogram → first power threshold → clustering analysis → threshold on integrated power

construct spectrogram	first power threshold	clustering analysis	threshold on integrated power
time domain whitening filter	black pixel probability noise model	minimum cluster size distance thresholds	threshold type

Chirp Signal

Binary inspiral chirp at high SNR



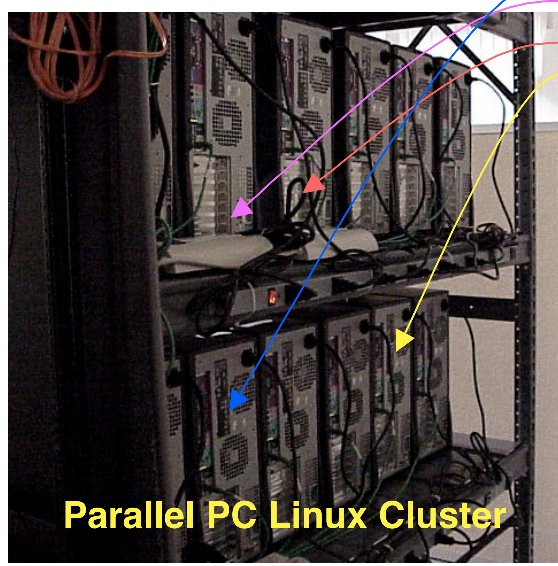
determine

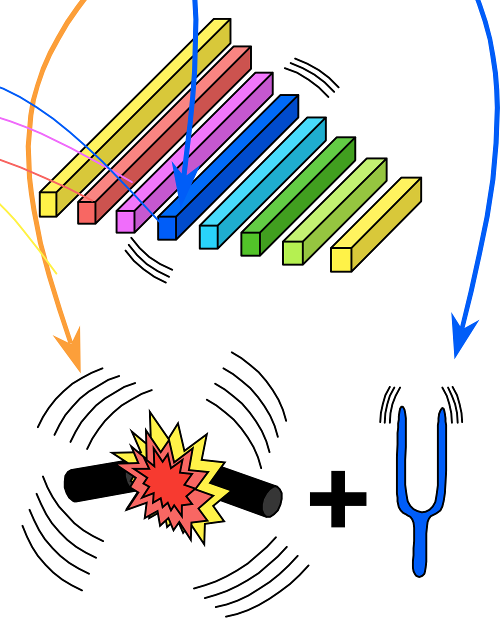
- distance from the earth r
- masses of the two bodies
- orbital eccentricity e and orbital inclination *i*

Optimal Wiener Filtering

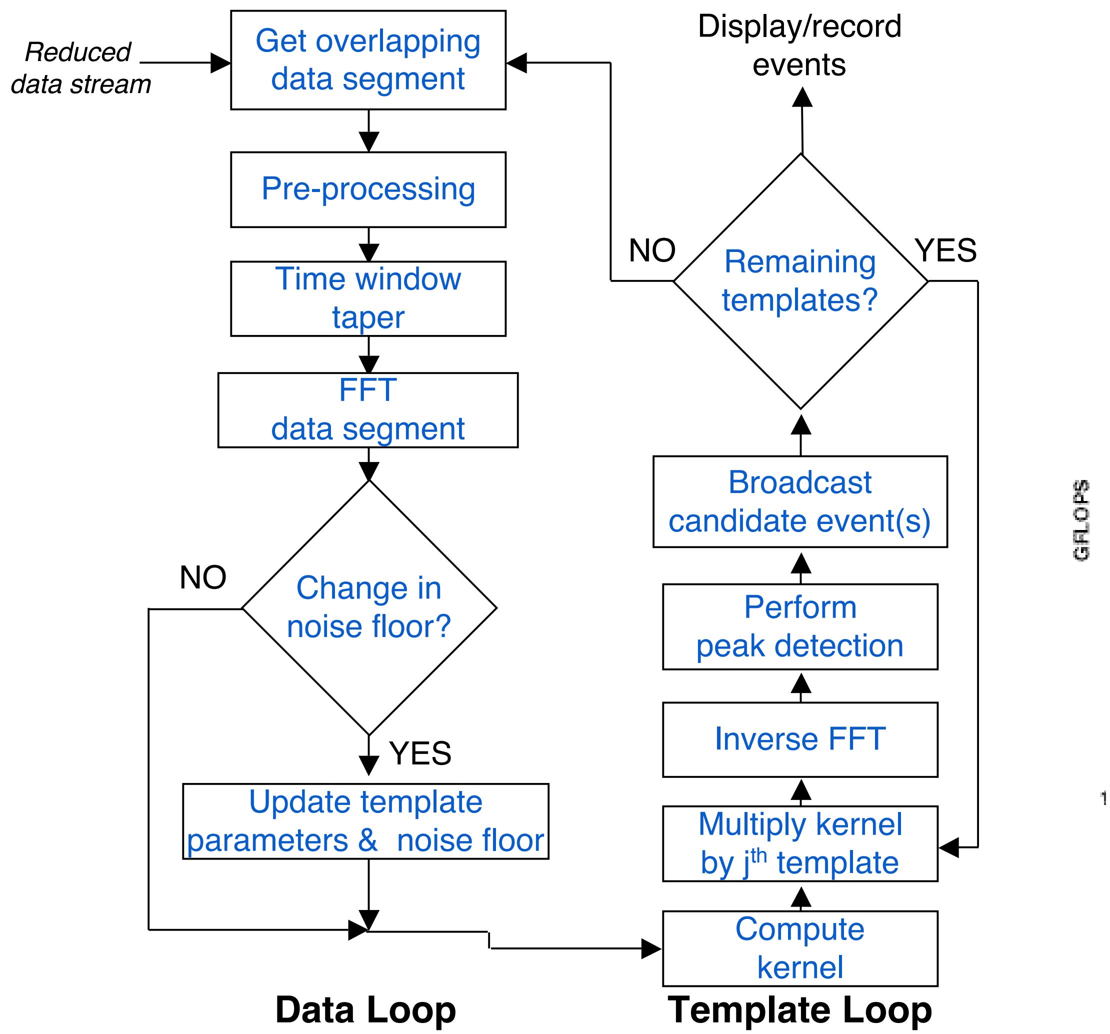
- Matched filtering (optimal) looks for best overlap between a signal and a set of expected (template) signals in the presence of the instrument noise -- correlation filter
- Replace the data time series with an SNR time series
- Look for excess SNR to flag possible detection

$$\rho_p[t_c] = \int \frac{\hat{T}_p^*(f)\ \hat{s}(f)}{\hat{S}_n(|f|)} e^{-2\pi i f t_c} df$$

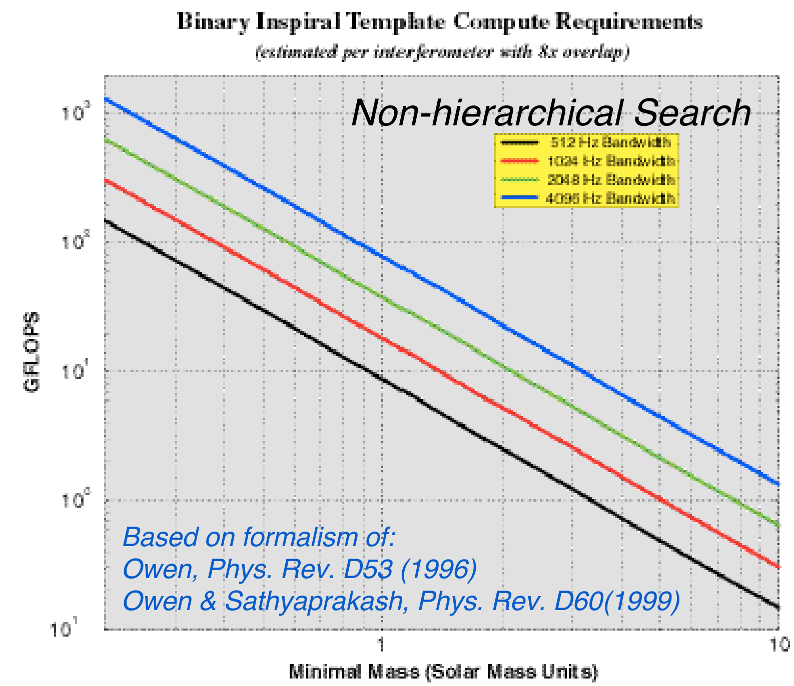




Compact Binary Inspirals
Data Analysis Flow



$$\rho_p[t_c] = 2\int \frac{\hat{T}_p^*(f)\ \hat{s}(f)}{\hat{S}_n(|f|)} e^{-2\pi i f t_c}\, df$$



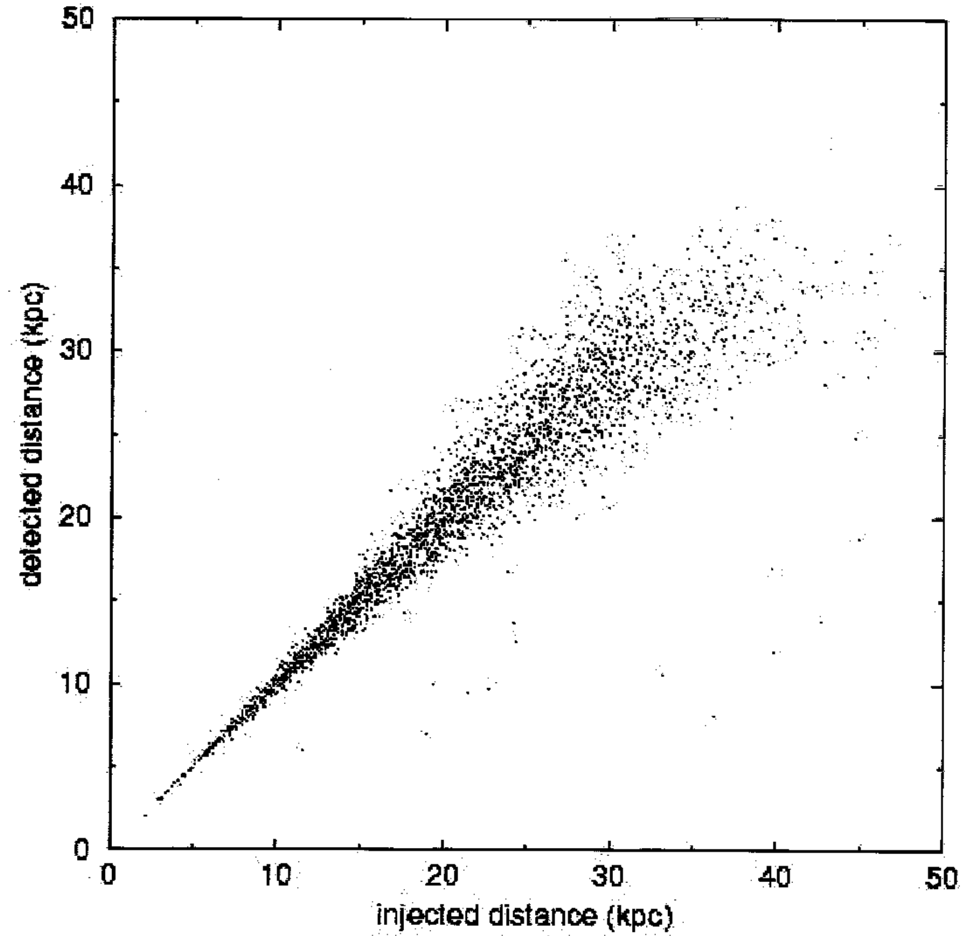
- **Process data at real time rate**
- **Improvements:**
  - ***Hierarchical searches being developed***
  - ***Phase coherent analysis of multiple detectors (Finn, in progress)***

Detection Efficiency

Monte Carlo (Statistical) techniques are needed to characterize complex detection probabilities

- **Simulated inspiral events provide end to end test of analysis and simulation code for reconstruction efficiency**

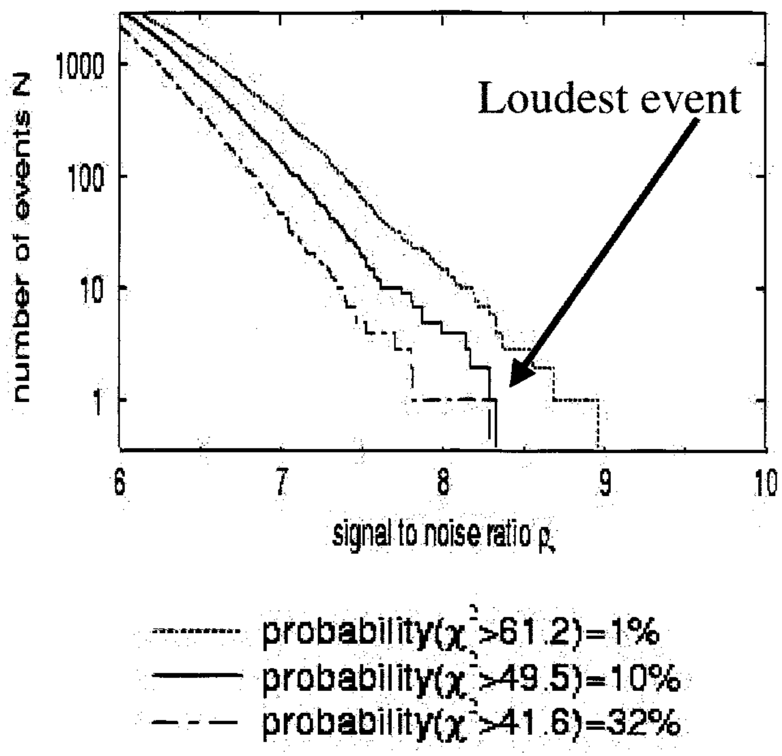
- **Errors in distance measurements from presence of noise are consistent with SNR fluctuations**



Setting a limit on inspiral coalescence rate within the galaxy

(1994 40m prototype data)

Quantitative Science: making a probabilistic statement about the likelihood of an observation (or lack thereof)



Upper limit on event rate can be determined from SNR of 'loudest' event

Limit on rate:

R < 0.5/hour with 90% CL

□= 0.33 = detection efficiency

An ideal detector would set a limit:

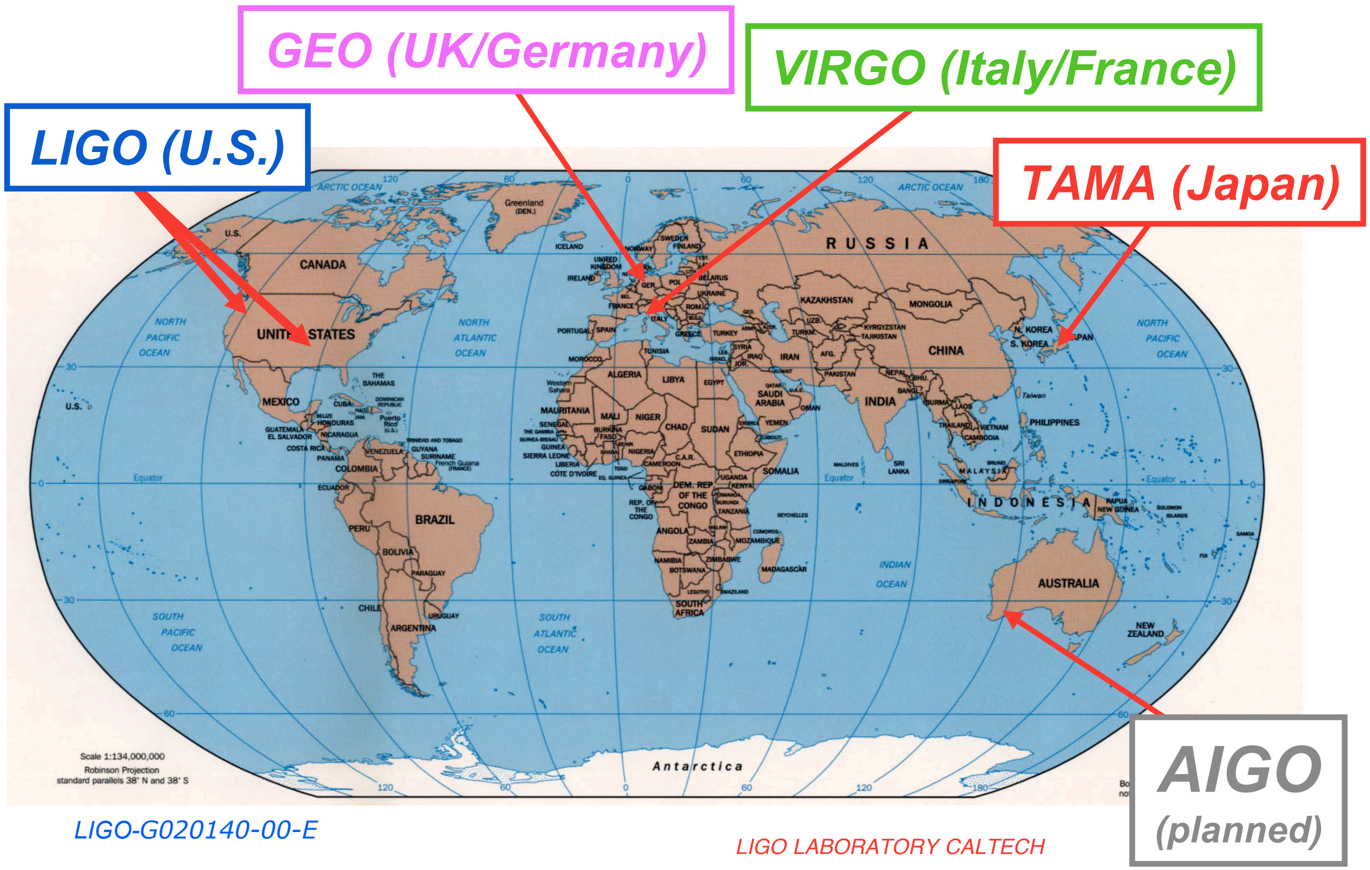
R < 0.16/hour

B. Allen et al., gr-qc/9903108

Towards a Global Network of Detectors

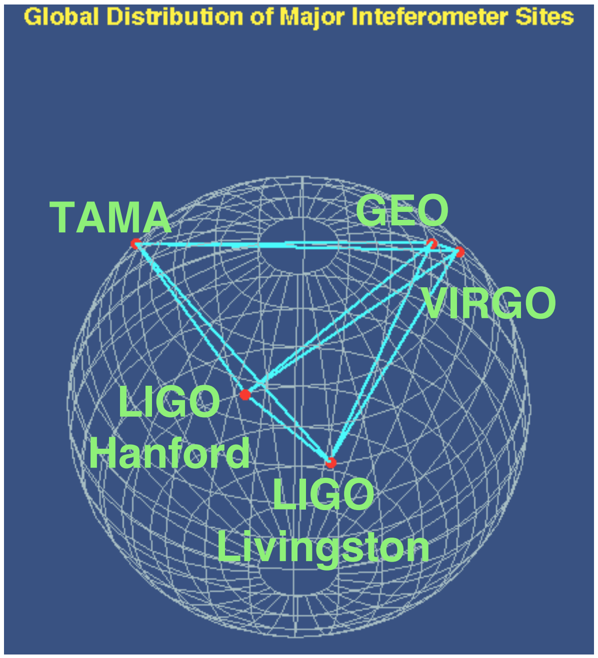
International Network of Detectors

- A number of projects are bringing detectors on line during the next few years
- Operated as a phased array, they will augment the chances for detection by excluding backgrounds and localizing sources
- *True coincidences will be within milliseconds of each other*



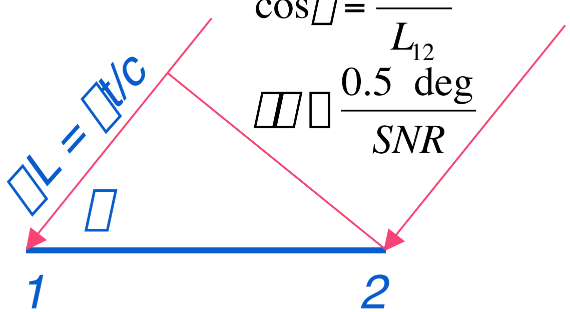
- **detection confidence**
- **locate the sources**
- **decompose the polarization of gravitational waves**

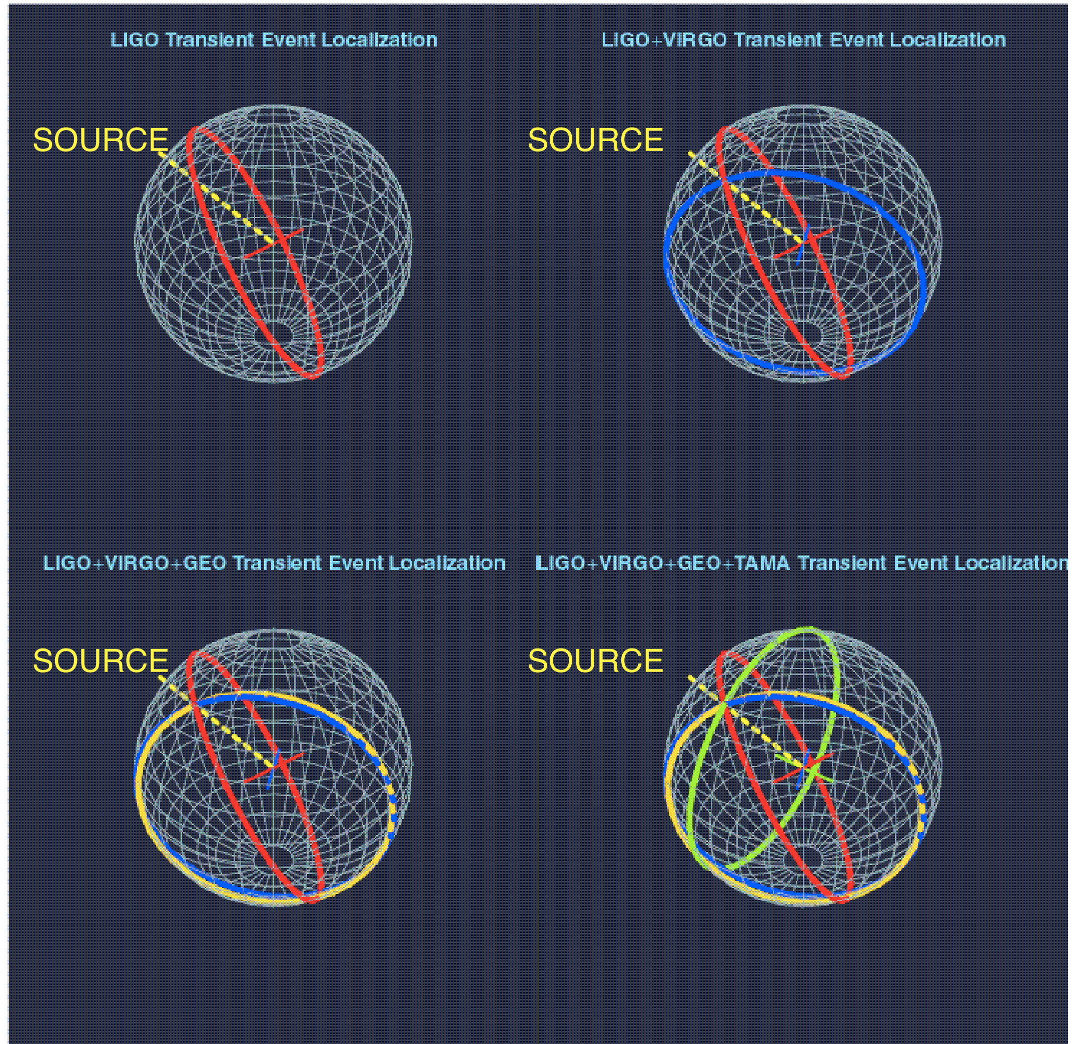
Event Localization With An Array of GW Interferometers



$$\cos\theta = \frac{\delta t / c}{L_{12}}$$

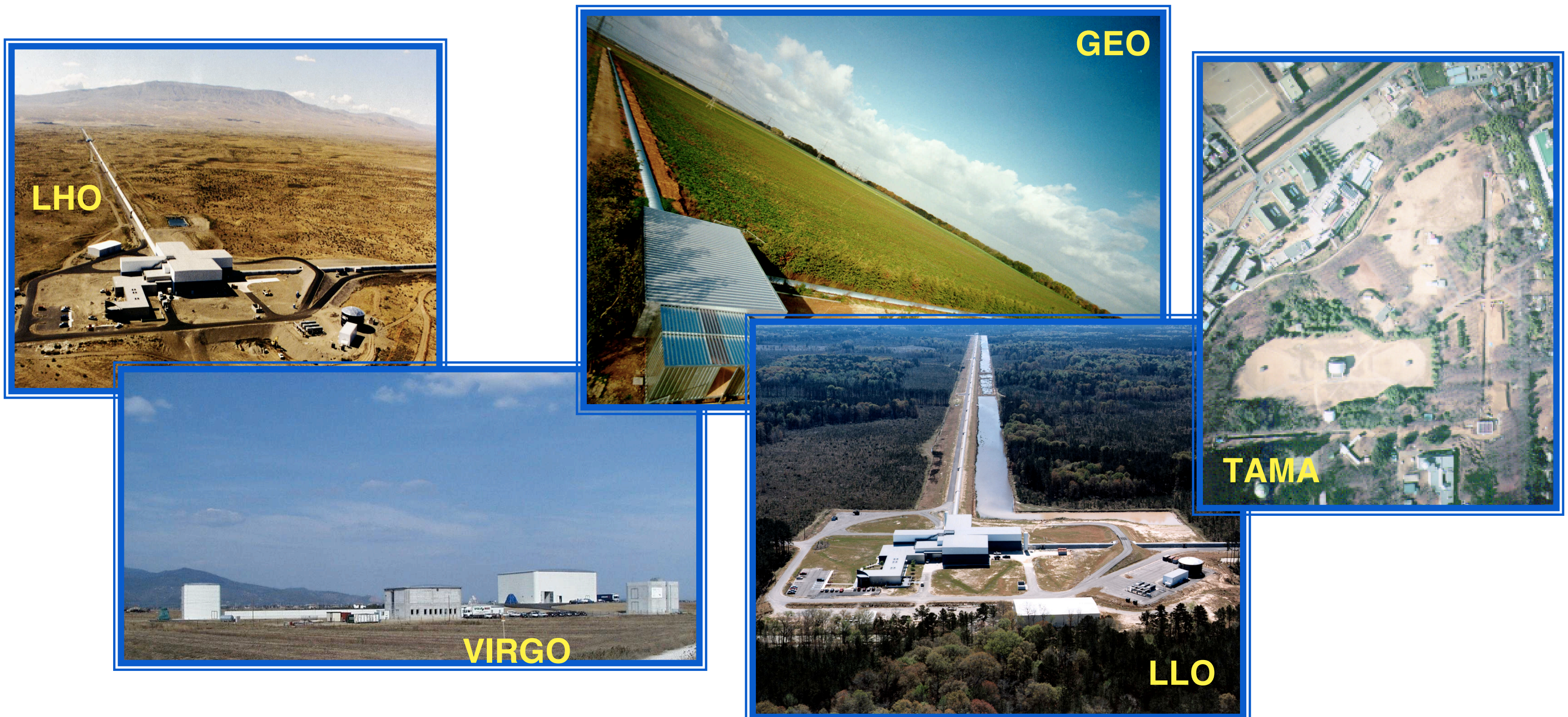
$$\delta\theta \approx \frac{0.5 \ \deg}{SNR}$$





Gravitational Wave Astronomy at the Beginning of the 21st Century

- LIGO, VIRGO, GEO, TAMA
  - *4000m, 3000m, 2000m, 600m, 300m interferometers built to detect gravitational waves from compact objects*



Conclusion
Gravitational Wave Astrophysics

- Gravitational waves will open up an entirely new window on the Universe
  - *More than 95% of the Universe is non luminous matter (dark matter)*
- LIGO is taking data in this year
  - *Two planned science runs in 2002*
  - *The first searches will look for expected and unexpected sources of gravitational radiation*
- The challenge is to sieve through many terabytes of data (10^{12} bytes) looking for rare events --
  - *Few per decade for the initial interferometers*
  - *~3000X greater event rate for the next generation instruments*