Detection of Gravitational Waves with the Laser Interferometer Gravitational-Wave Observatory (LIGO)...

California State University at Northridge

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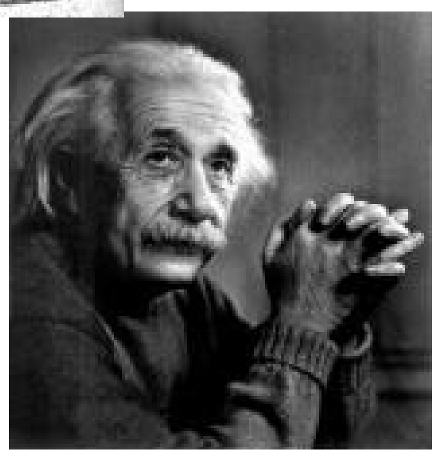
LIGO-G010210-00-E

Outline of this talk

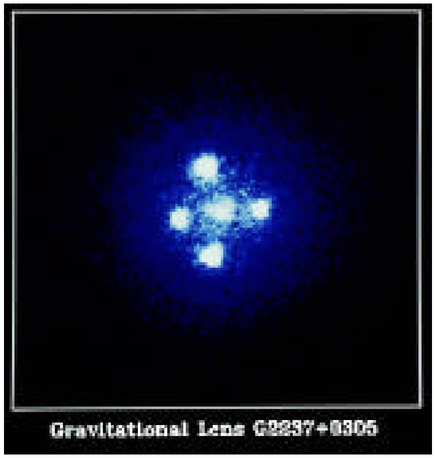
- Gravitational waves and relativity
- Past surprises in astronomy
- Sources of gravitational waves
- Interferometers as detectors of gravitational waves
- Signal analysis

Albert Einstein

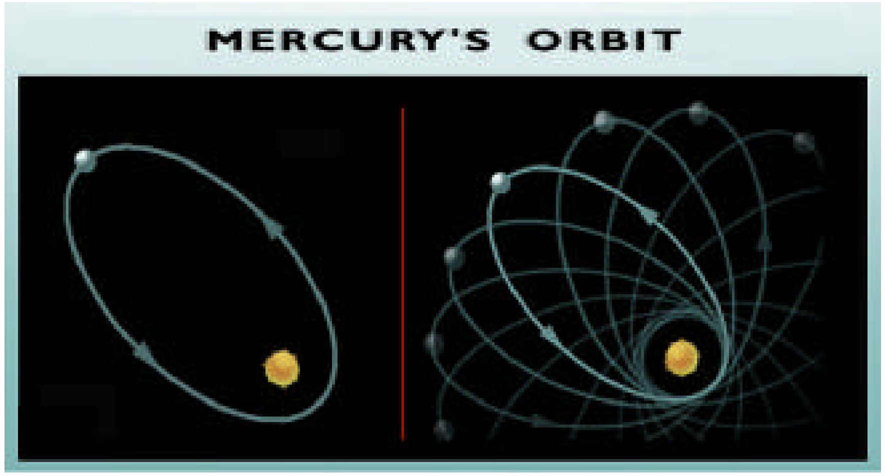


- The Special Theory of Relativity (1905) overthrew commonsense assumptions about space and time. Relative to an observer, near the speed of light, both are altered
  - *distances appear to stretch*
  - *clocks tick more slowly*
  - *Space+time == spacetime*
- The General Theory of Relativity and theory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

“Einstein Cross”
The bending of light rays
gravitational lensing

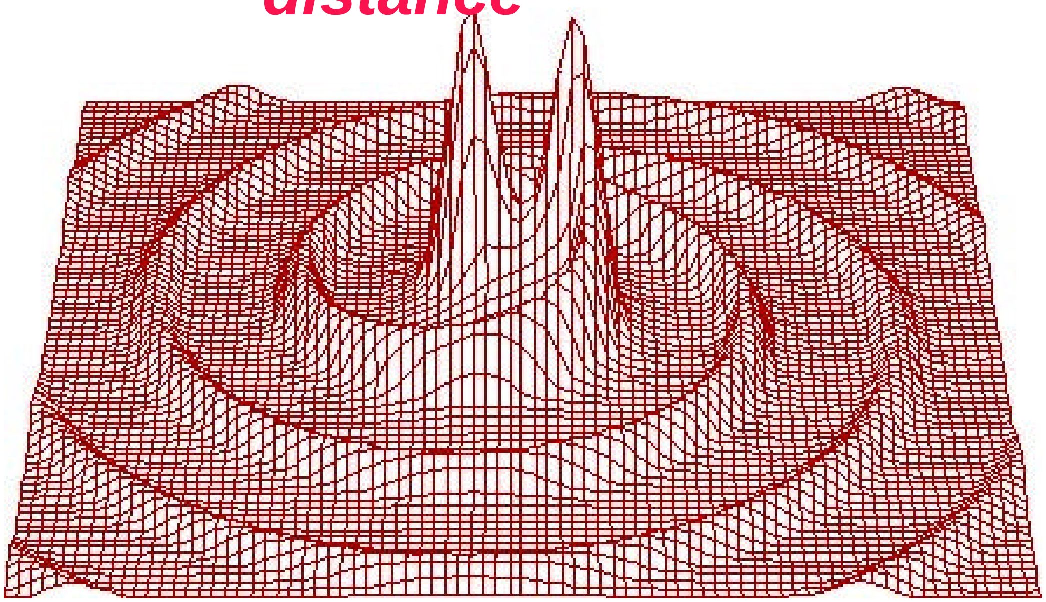


Mercury’s orbit
perihelion shifts forward
twice Newton’s theory



Newton's Theory

"instantaneous action at a distance"



Einstein's Theory

information carried by gravitational radiation at the speed of light

Strength: TINY!!!

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

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

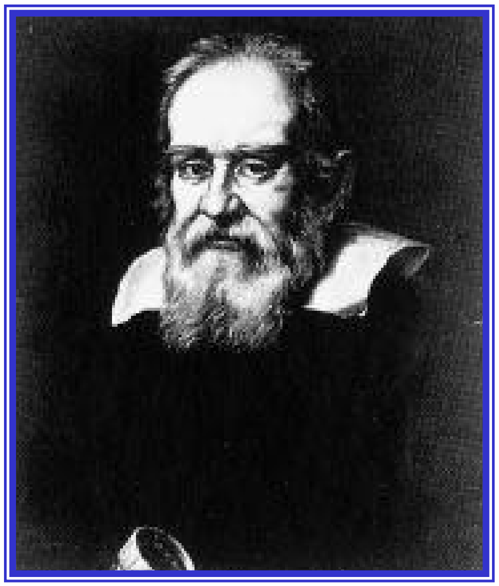
For NS+NS in binary orbit at Virgo Cluster distance: ~10^{-21}

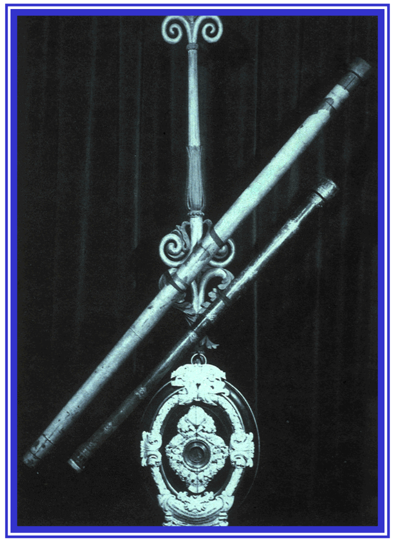
Ultimate Goals for the Detection of Gravitational Waves

- 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)*
- Gravitational Wave Astronomy
  - *Compact binary inspirals*
  - *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*

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***



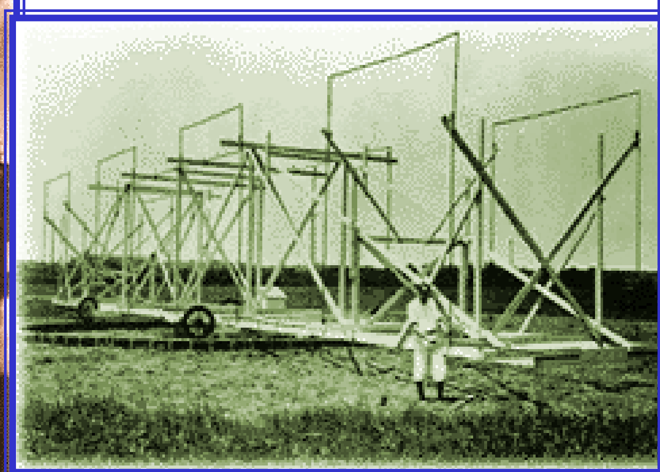


http://es.rice.edu:80/ES/humsoc/Galileo//

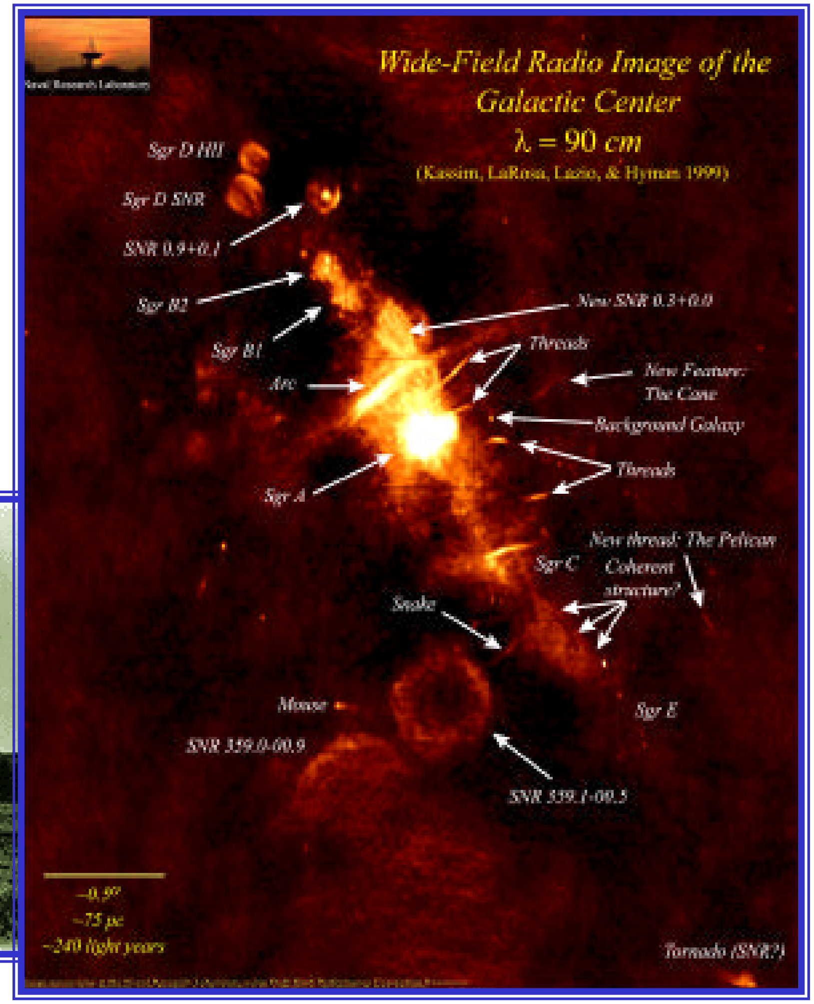
http://photojournal.jpl.nasa.gov

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***



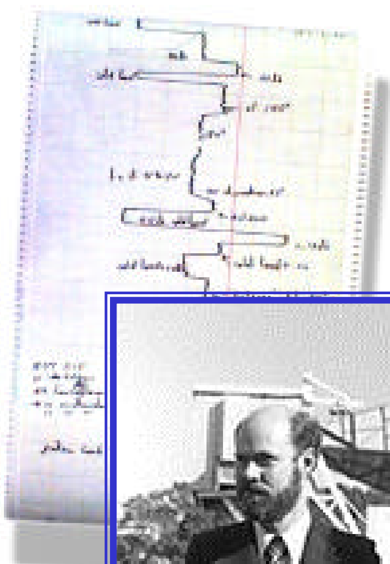
http://www.lucent.com/museum/1933rt.html

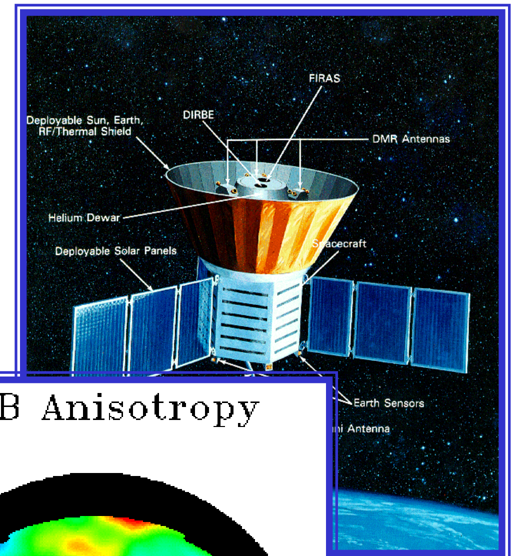


//http://rsd-www.nrl.navy.mil/7213/lazio/GC/

The Opening of a New Observational Window on the Universe

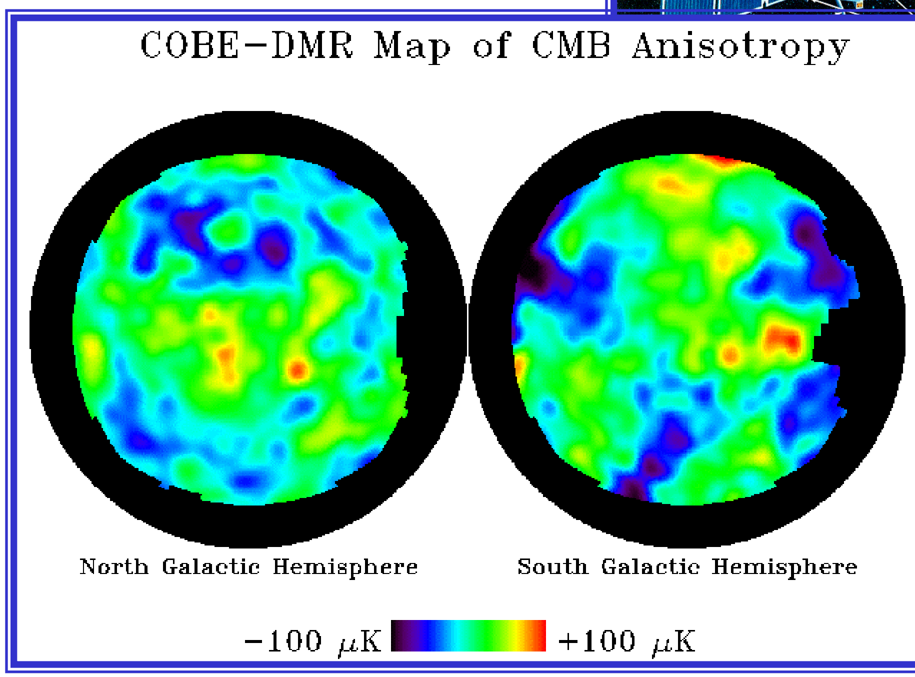
- Penzias & Wilson,1963
  - *Track down excess antenna noise*
    - ! ***Discover the cosmic microwave background radiation (CMBR)***





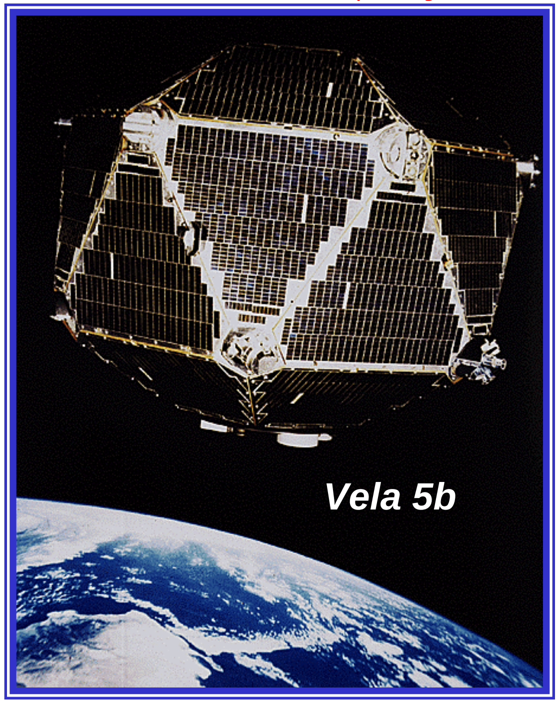
http://www.gsfc.nasa.gov/astro/cobe/cobe_home.html

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

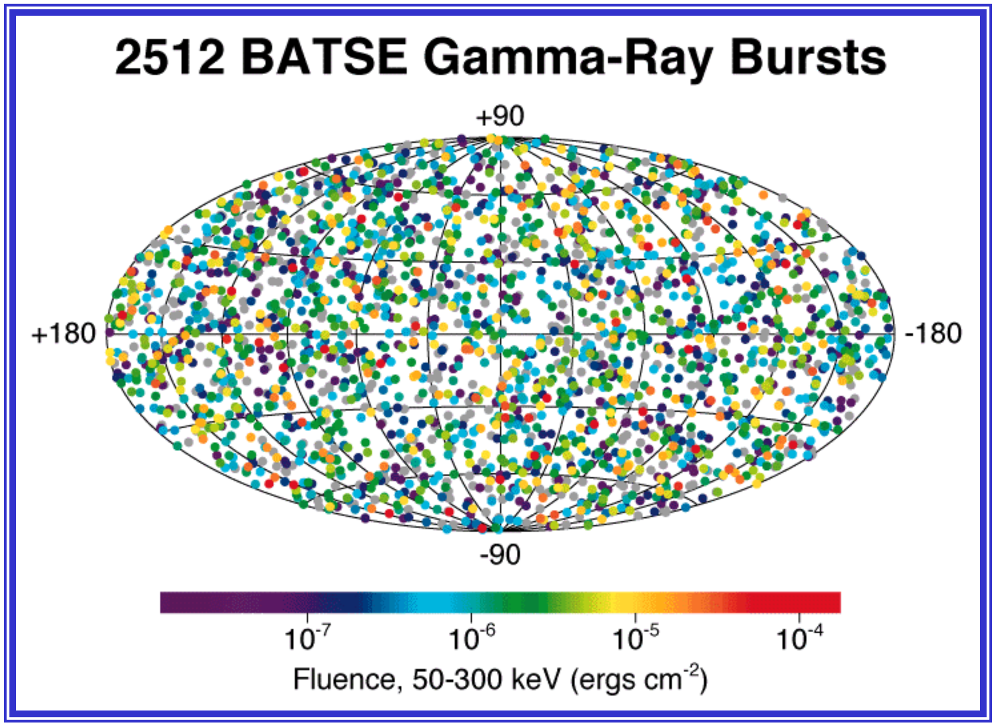


The Opening of a New Observational Window on the Universe

- 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/

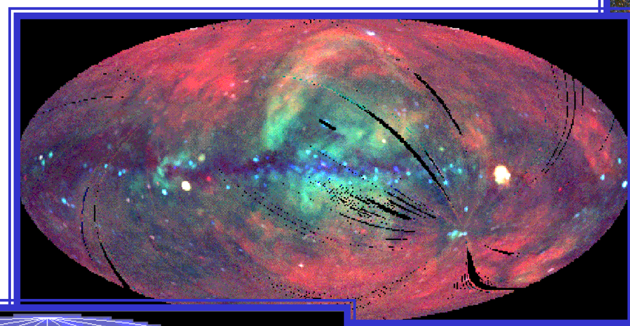
Observing the Galaxy with Different Electromagnetic Wavelengths

http://antwrp.gsfc.nasa.gov/apod/image/SagSumMW_dp_big.gif

$\lambda = 5 \times 10^{-7}$ m

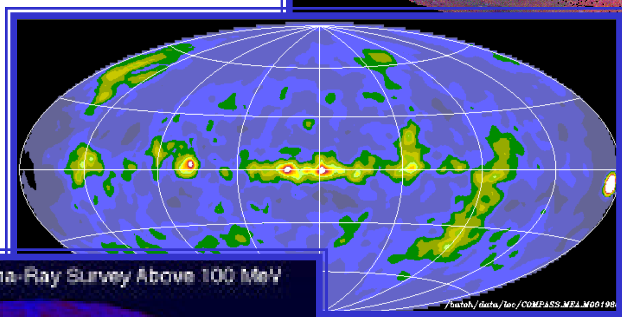
http://antwrp.gsfc.nasa.gov/apod/image/xallsky_rosat_big.gif

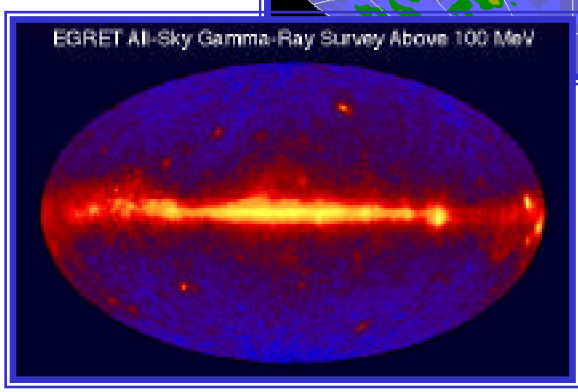
$\lambda = 5 \times 10^{-10}$ m



http://antwrp.gsfc.nasa.gov/apod/image/comptel_allsky_1to3_big.gif

$\lambda = 6 \times 10^{-13}$ m



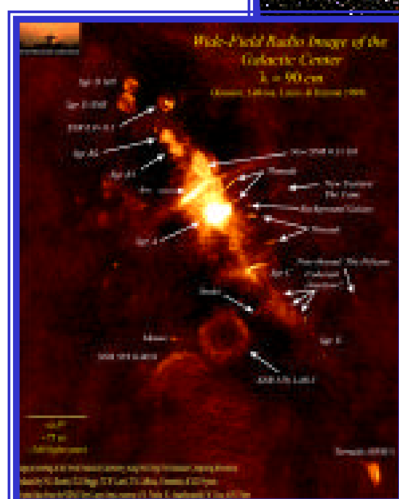


http://cossc.gsfc.nasa.gov/cossc/egret/

$\lambda = 1 \times 10^{-14}$ m

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

$\lambda = 2 \times 10^{-6}$ m

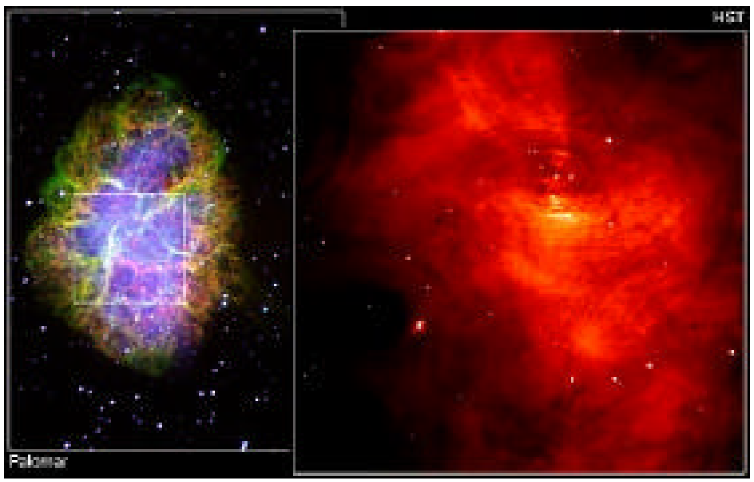


//rsd-www.nrl.navy.mil/7213/lazio/GC/

$\lambda = 9 \times 10^{-1}$ m

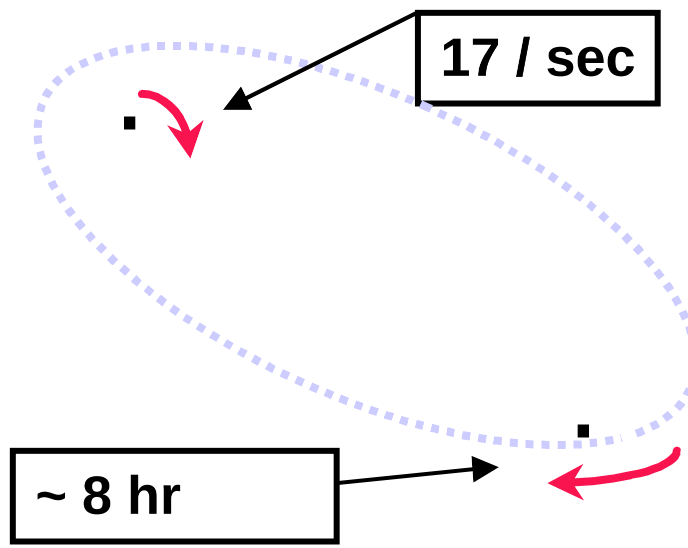
Gravitational Waves

the evidence



Neutron Binary System

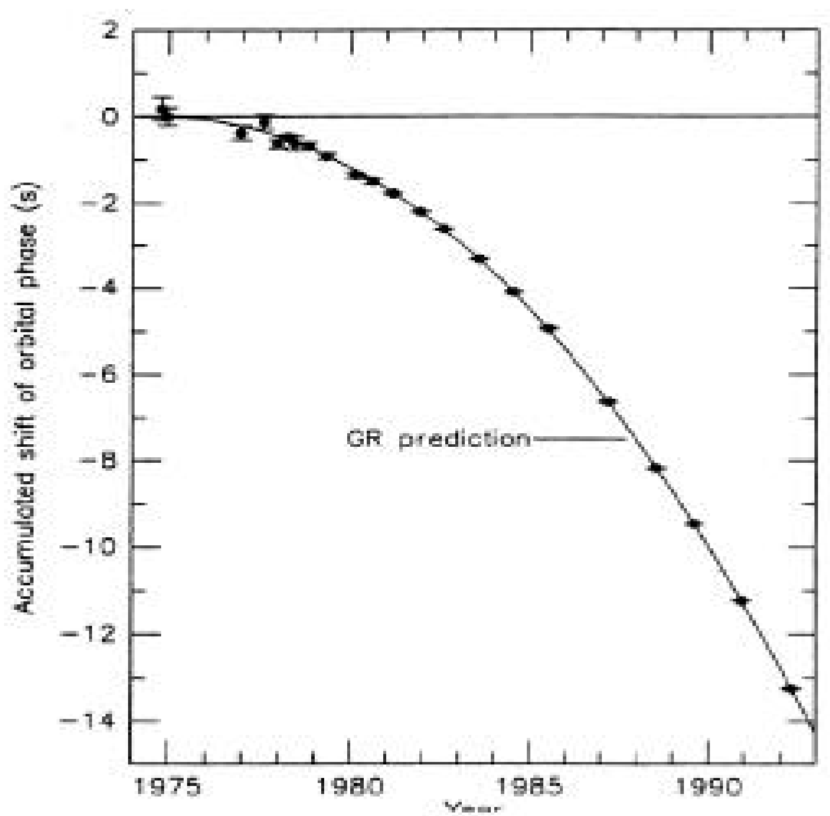
PSR 1913 + 16 -- Timing of pulsars



Hulse and Taylor *results*

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



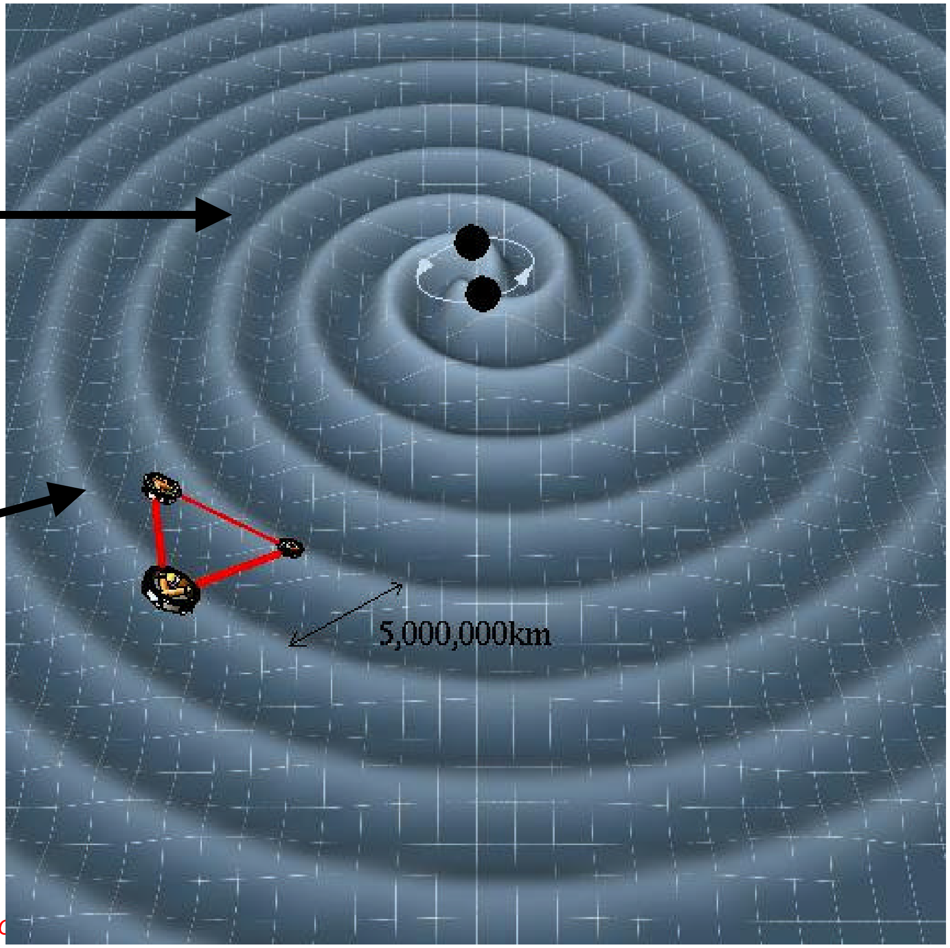
Science in LIGO I
data analysis plan of the Collaboration

- Compact binary inspiral: ***"chirps"***
  - ***NS-NS waveforms are well described***
  - ***BH-BH need better waveforms***
  - ***search technique: matched templates***
- Supernovae / GRBs: ***"bursts"***
  - ***burst search algorithms – excess power; time-freq patterns***
  - ***burst signals - coincidence with signals in E&M radiation***
  - ***prompt alarm (~ 1 hr) with ν detectors [SNEWS]***
- Cosmological Signals ***"stochastic background"***
- Pulsars in our galaxy: ***"periodic"***
  - ***search for observed neutron stars (freq., doppler shift)***
  - ***all sky search (computing challenge)***
  - ***r-modes***

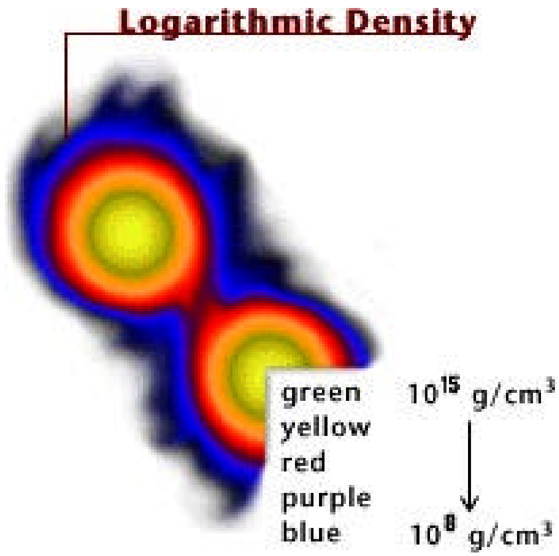
Einstein's *Songlines*

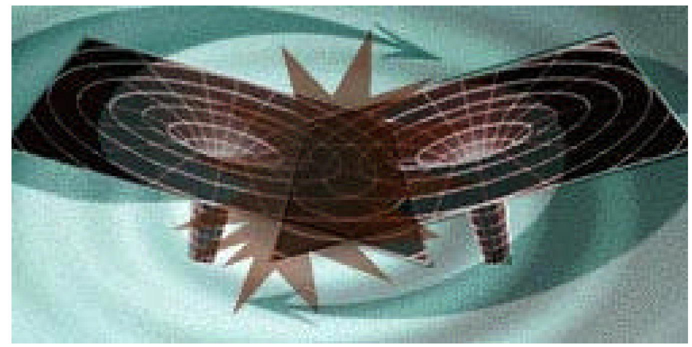
Radiation of Gravitational Waves from binary inspiral system

LISA
(Space-based version of LIGO)

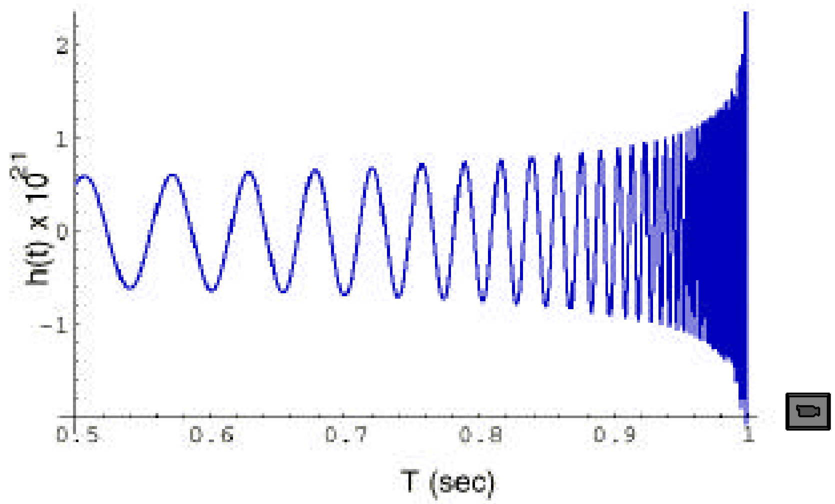


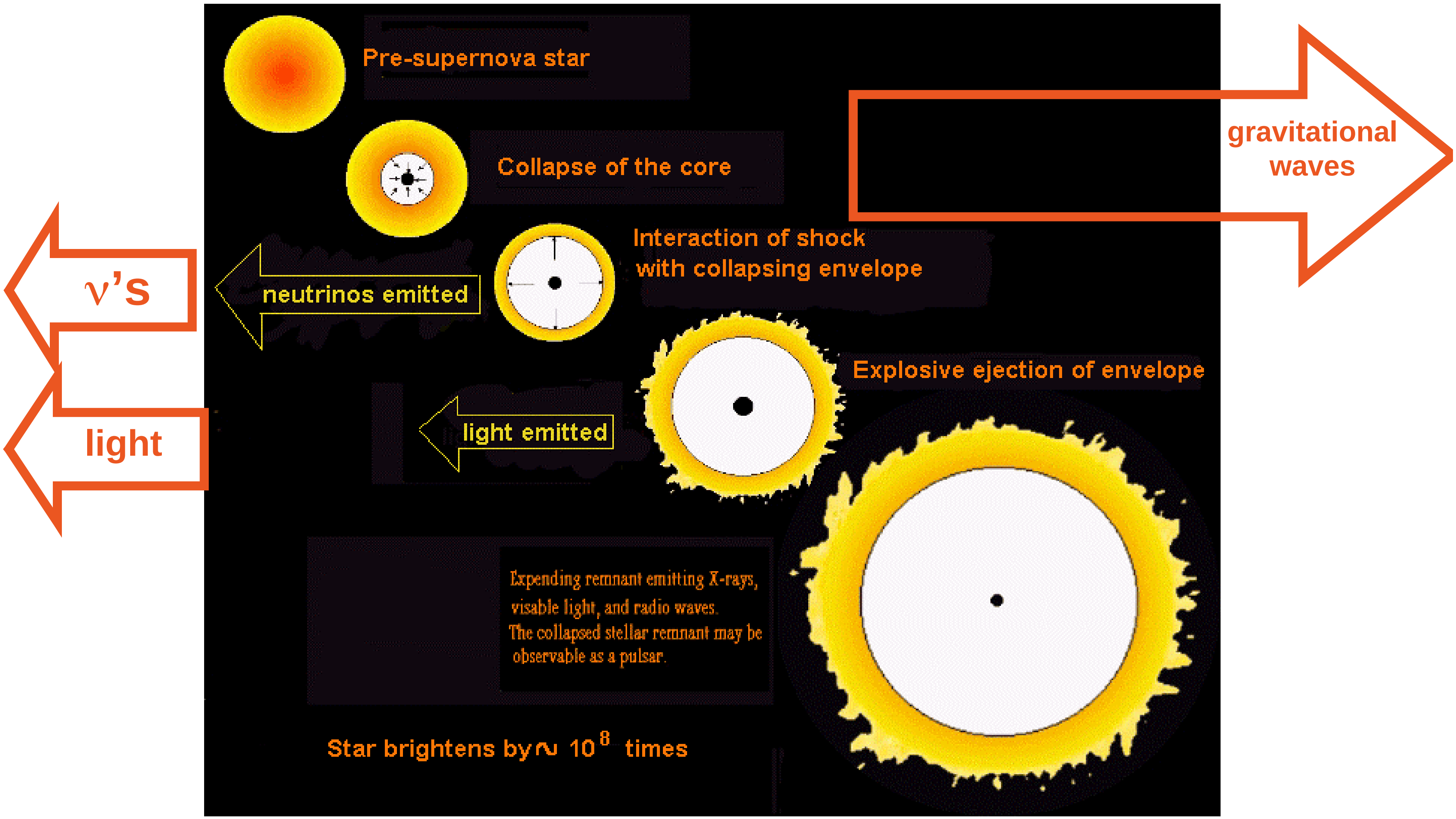
Inspiral of Neutron Stars





"Chirp Signal"

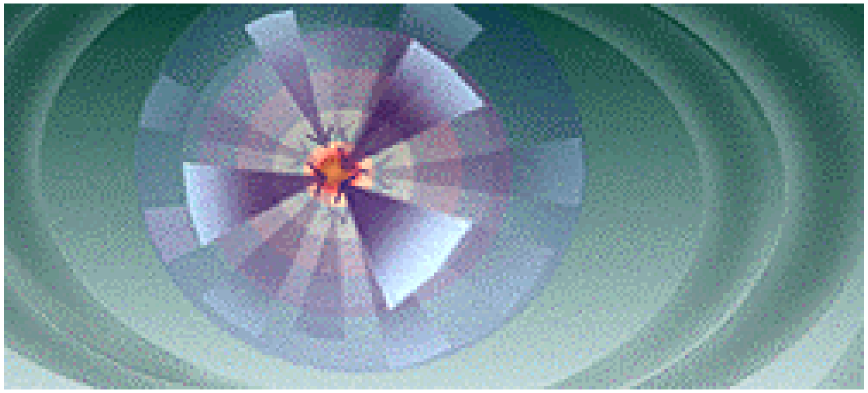




ν's
light
Pre-supernova star
Collapse of the core
Interaction of shock
with collapsing envelope
neutrinos emitted
Explosive ejection of envelope
light emitted
Expending remnant emitting X-rays,
visable light, and radio waves.
The collapsed stellar remnant may be
observable as a pulsar.
Star brightens by ~ 10^8 times
gravitational
waves

Supernovae
Gravitational Waves

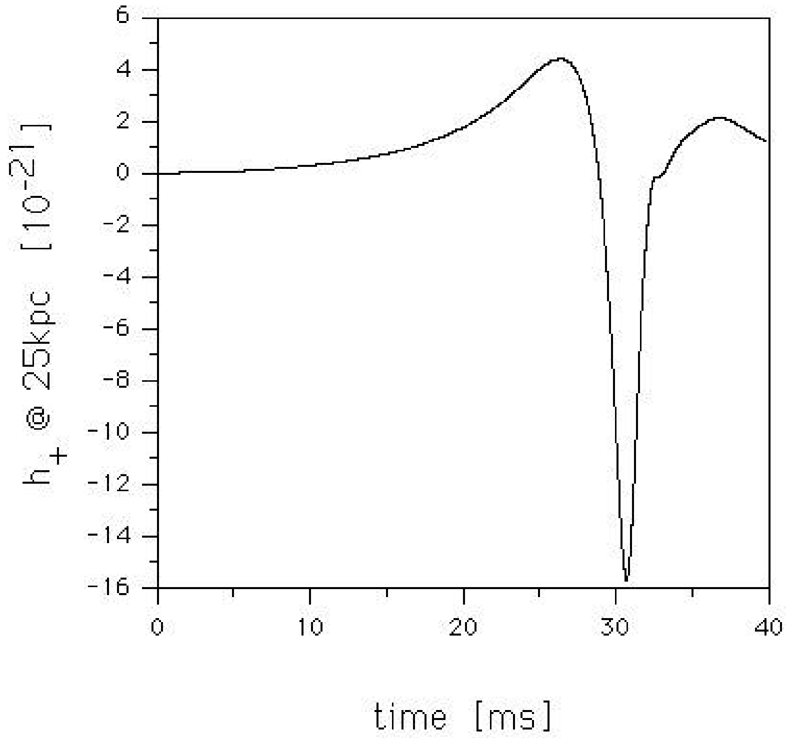
Non axisymmetric collapse



Rate

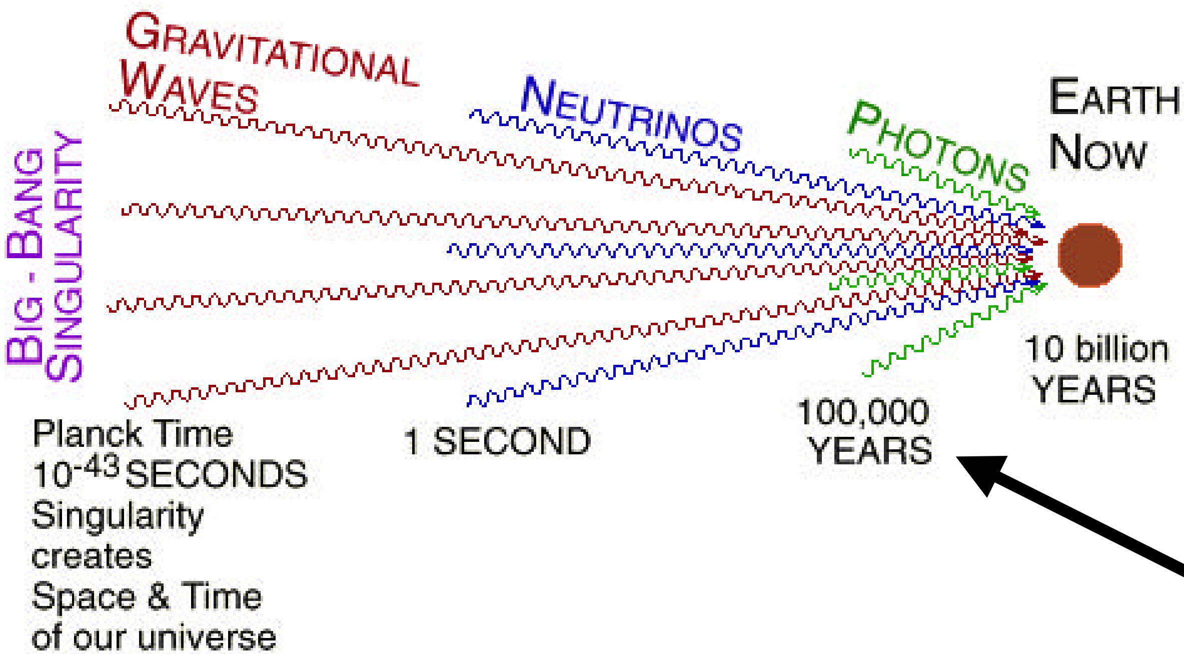
1/50 yr - our galaxy
3/yr - Virgo cluster

'burst' signal

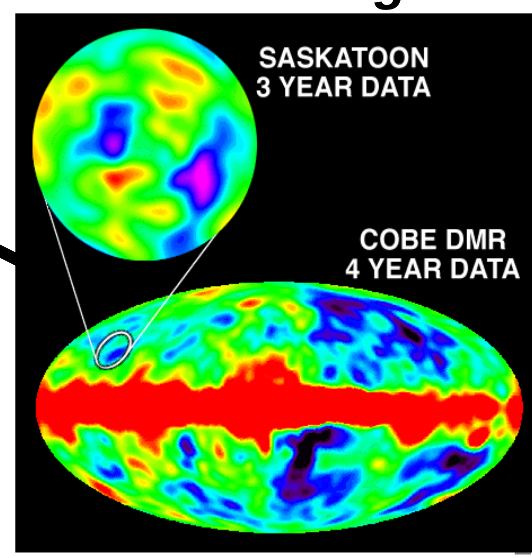


‘Murmurs’ from the Big Bang

signals from the early universe



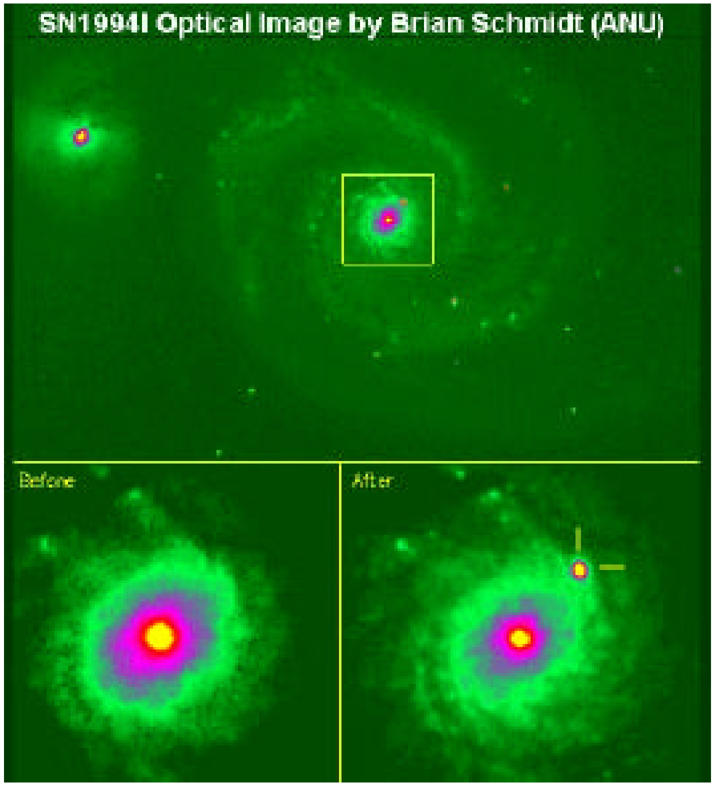
Cosmic microwave background



Pulsars
Continuous waves

Crab Nebula 1054 AD

Supernovae
optical observations

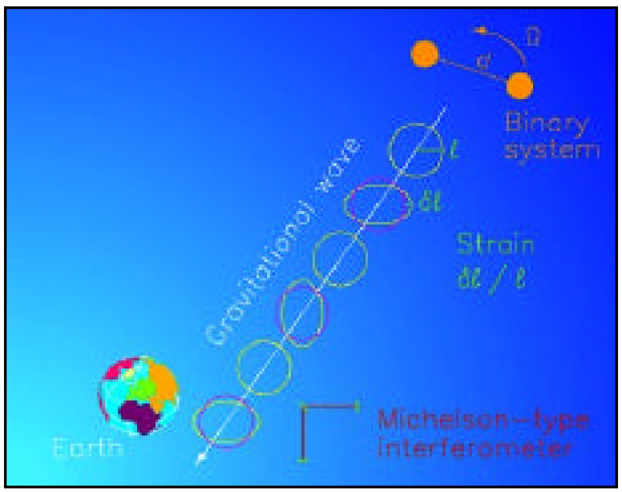


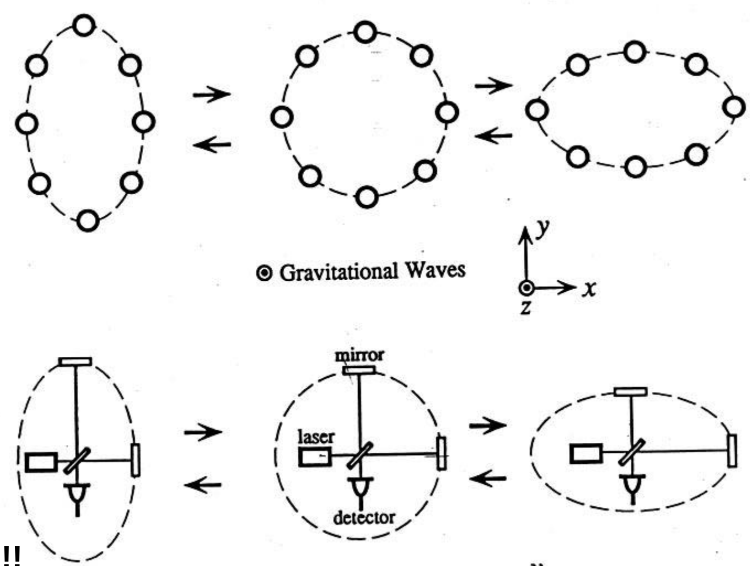
Supernovae - SN1994I

Interferometry for Detection

Suspended mass Michelson-type interferometers on earth's surface detect distant astrophysical sources

International network (LIGO, Virgo, GEO, TAMA) enable locating sources and decomposing polarization of gravitational waves.



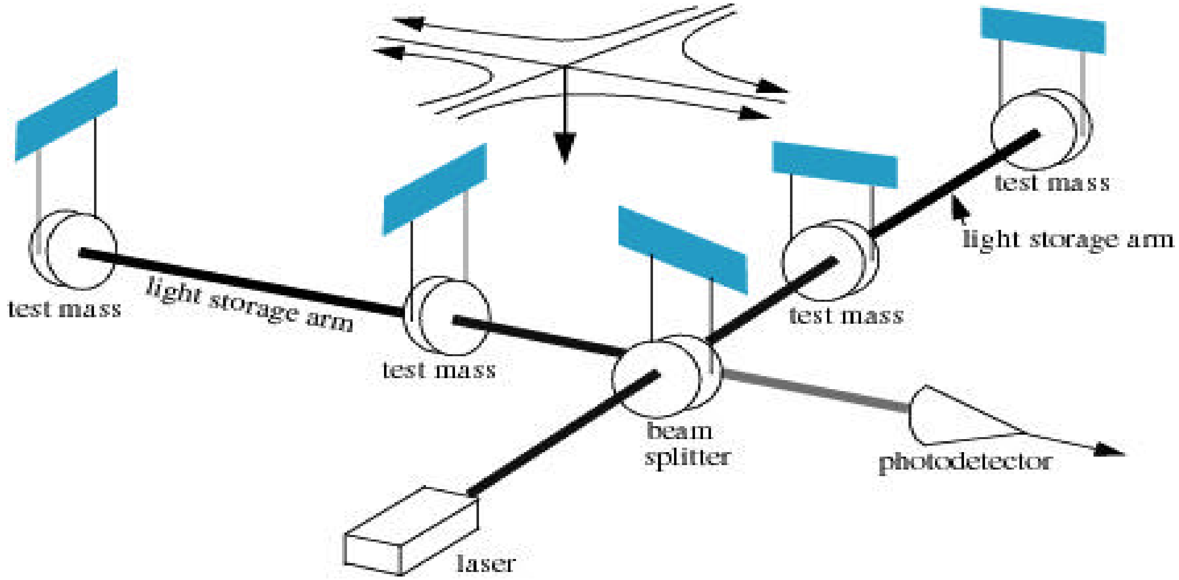


The effect is greatly exaggerated!!

If the ring were 4.5 light years in diameter, it would change by only a 'hairs width'
LIGO (4 km), stretch (squash) = 10^{-18} m will be detected at frequencies of 10 Hz to 10^4 Hz. It can detect gravitational waves from a distance of 600 10^6 light years

LIGO

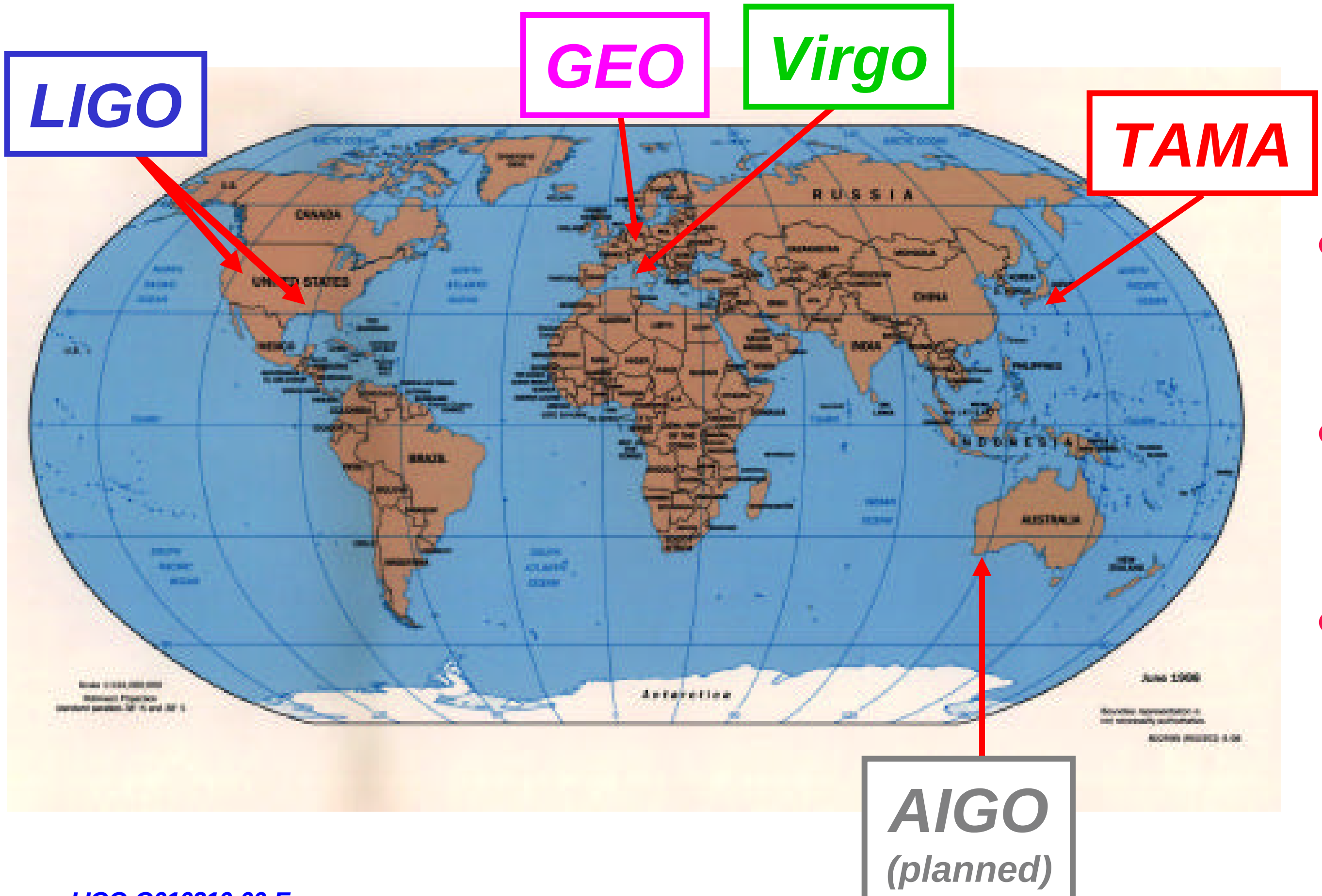
Detector ***concept***



- 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.

International Network of Detectors

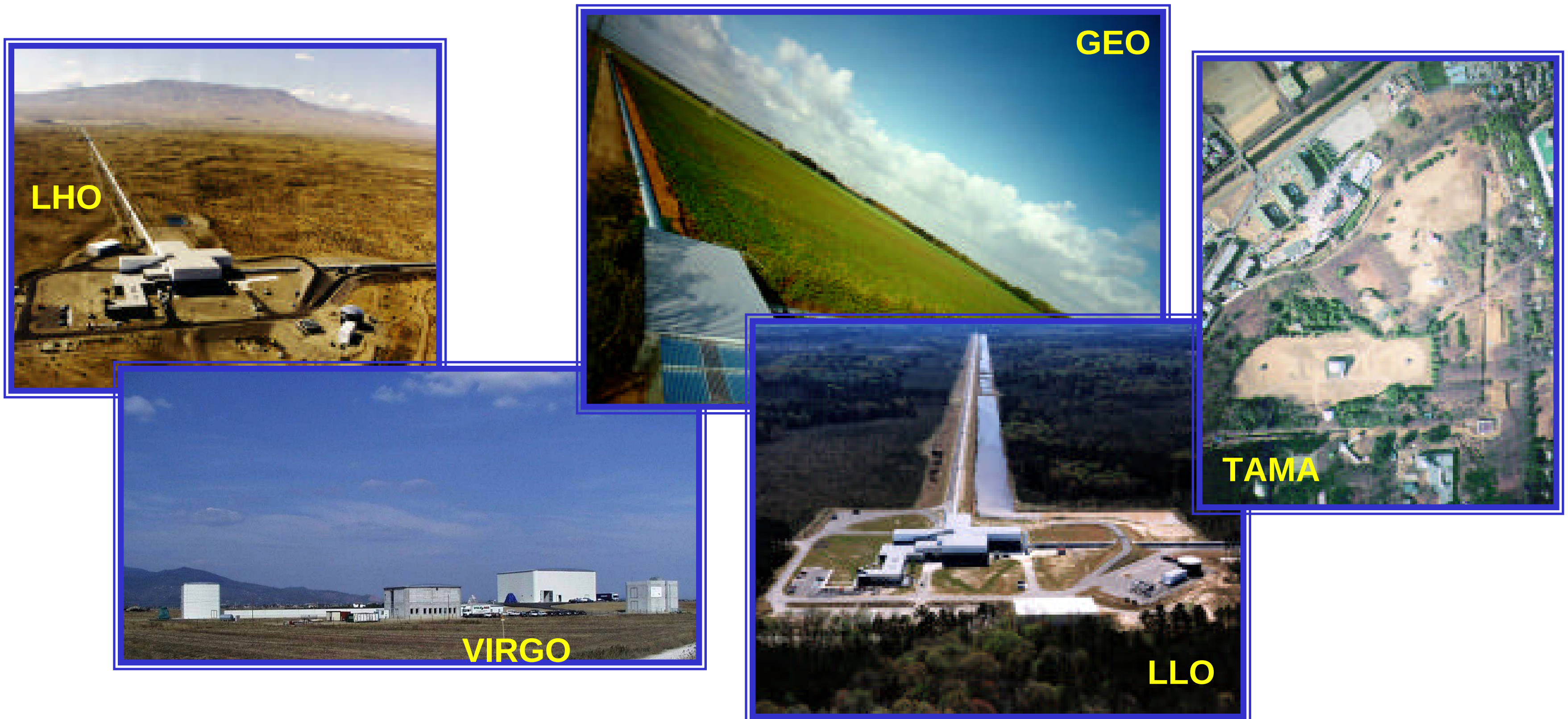
Simultaneously detect signal (within milliseconds)



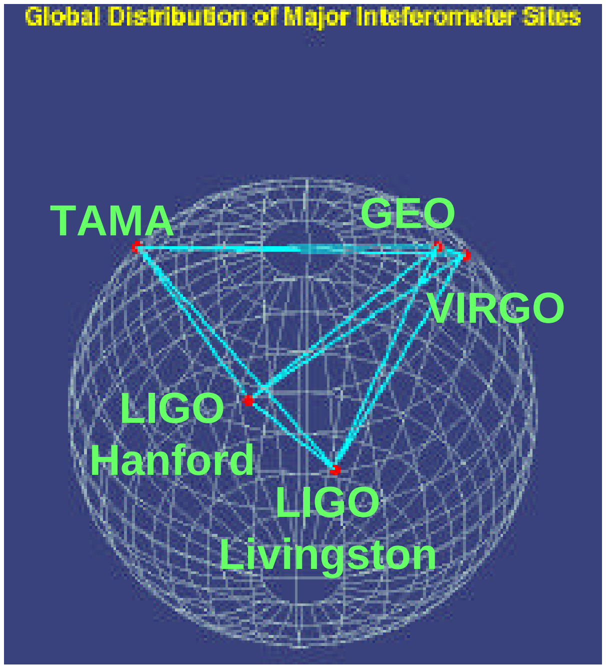
- **detection confidence**
- **locate the sources**
- **decompose the polarization of gravitational waves**

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*

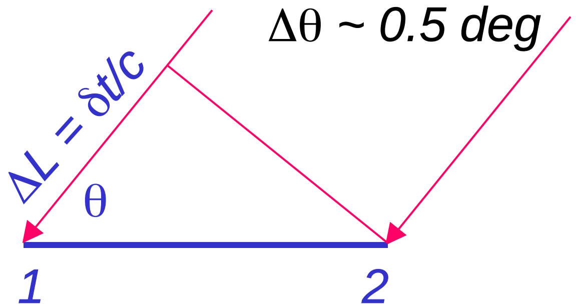


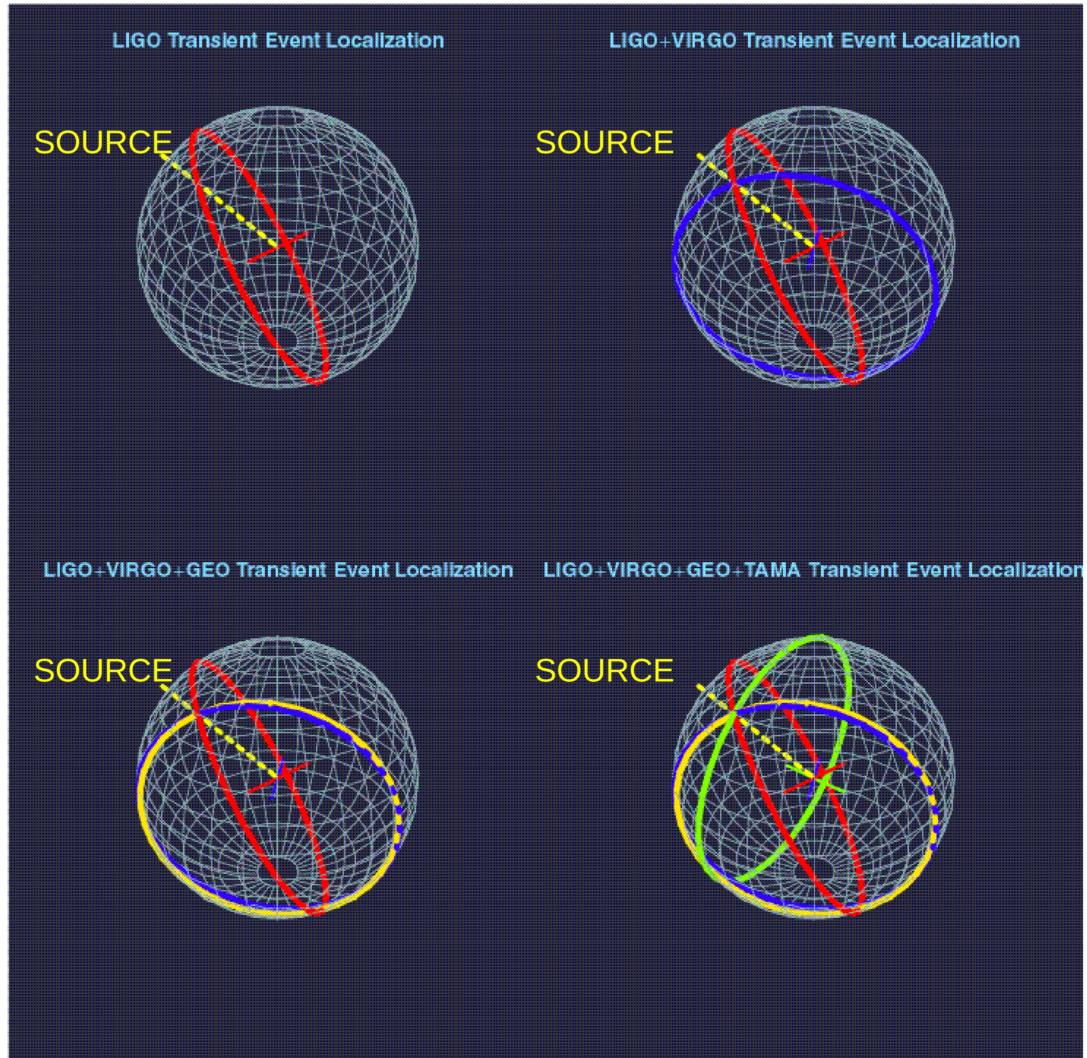
Event Localization With An Array of GW Interferometers



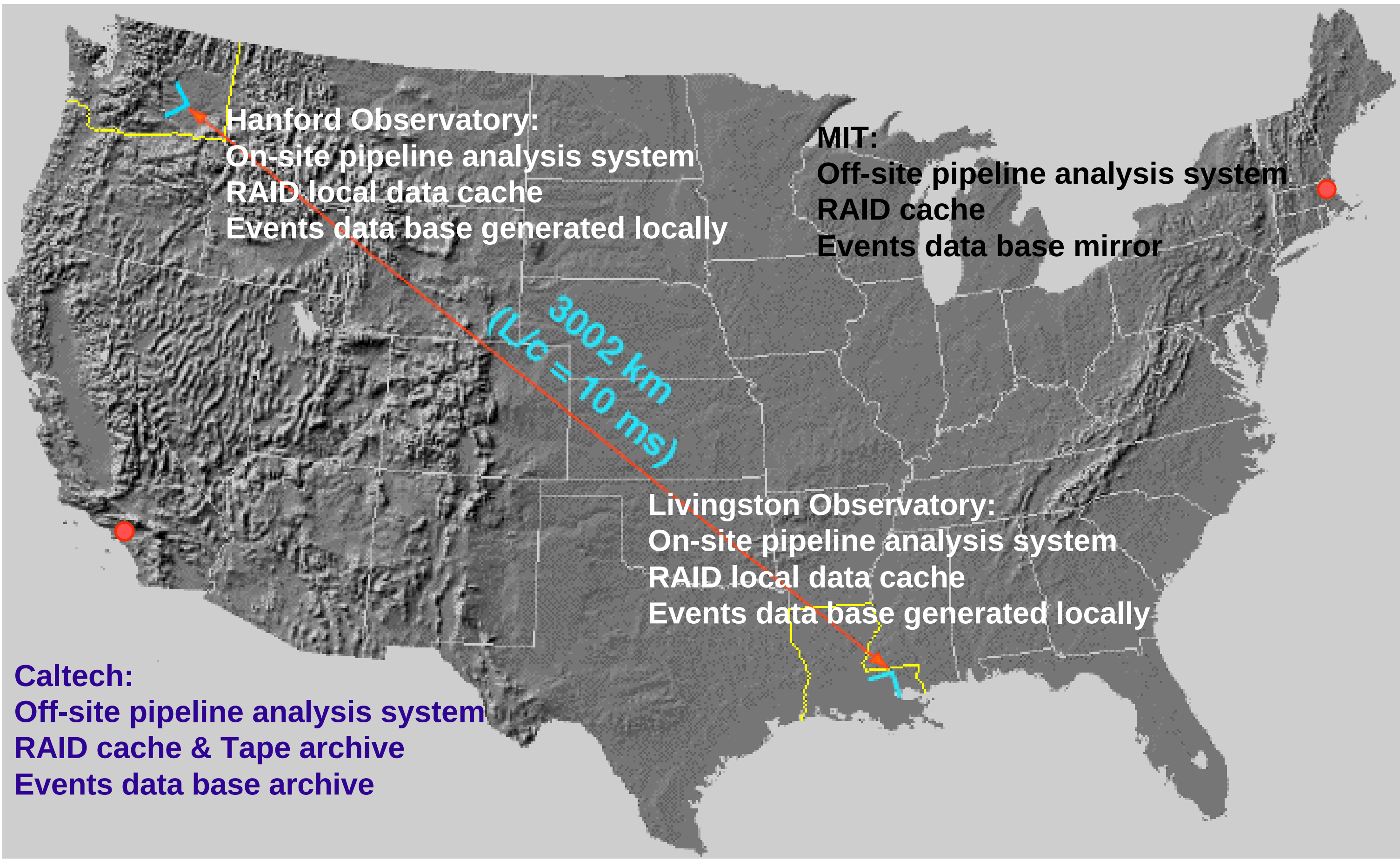
$$\cos\theta = \delta t / (c\, D_{12})$$

$$\Delta\theta \sim 0.5 \text{ deg}$$





The LIGO Laboratory Sites



Detection Strategy
Coincidences

Two Sites - Three Interferometers

– *Single Interferometer*	*non-gaussian level*	*~50/hr*
– *Hanford (Doubles)*	*correlated rate (x1000)*	*~1/day*
– *Hanford + Livingston*	*uncorrelated (x5000)*	*<0.1/yr*

- Data Recording (time series)
  - *gravitational wave signal (0.2 MB/sec)*
  - *total data (9 MB/s => 280 TB/yr)*
  - *on-line filters, diagnostics, data compression*
  - *off line data analysis, archive etc*
- Signal Extraction
  - *signal from noise (vetoes, noise analysis)*
  - *templates, wavelets, etc*

Time vs Frequency Analysis

- Gravitational Strain signal is an (audio) time series
  - *Signal processing techniques are applied in the frequency domain*
  - *Fourier transformation:* s(t) <->**s**(ω): $\omega = 2\pi f$

$$\hat{\boldsymbol{s}}(\omega) = \int_{-\infty}^{\infty} dt\ \ s(t)\ \ e^{i\omega t}$$

  - Discretized version for digital signal processing: DFT
    $t_p = p\ \delta\tau$; $f_k=2\pi\, k\delta f$; $\delta f\ \delta\tau = 1/N$

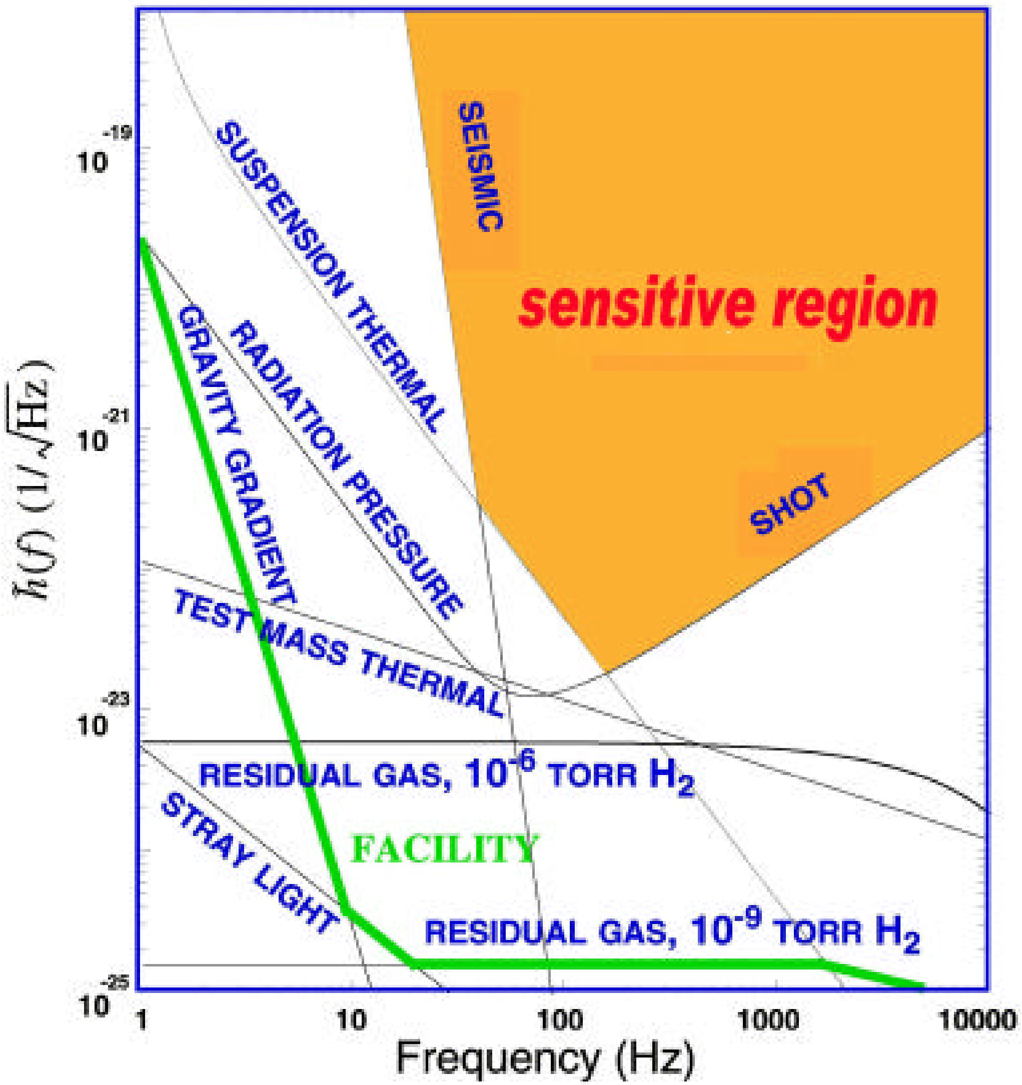
$$\hat{\boldsymbol{s}}(k) = \sum_{p=0}^{N-1} s(p)\ \ e^{i\frac{2\pi pk}{N}}$$

  - Optimized for computation: Fast Fourier Transform (FFT)
    - Computations per FFT: ~ 5 N $\log_2$[N];
    - 1 hr of data @ 16kHz: N~$5.7\text{x}10^7$ points => 7.5 GFLOP

LIGO I

the noise floor

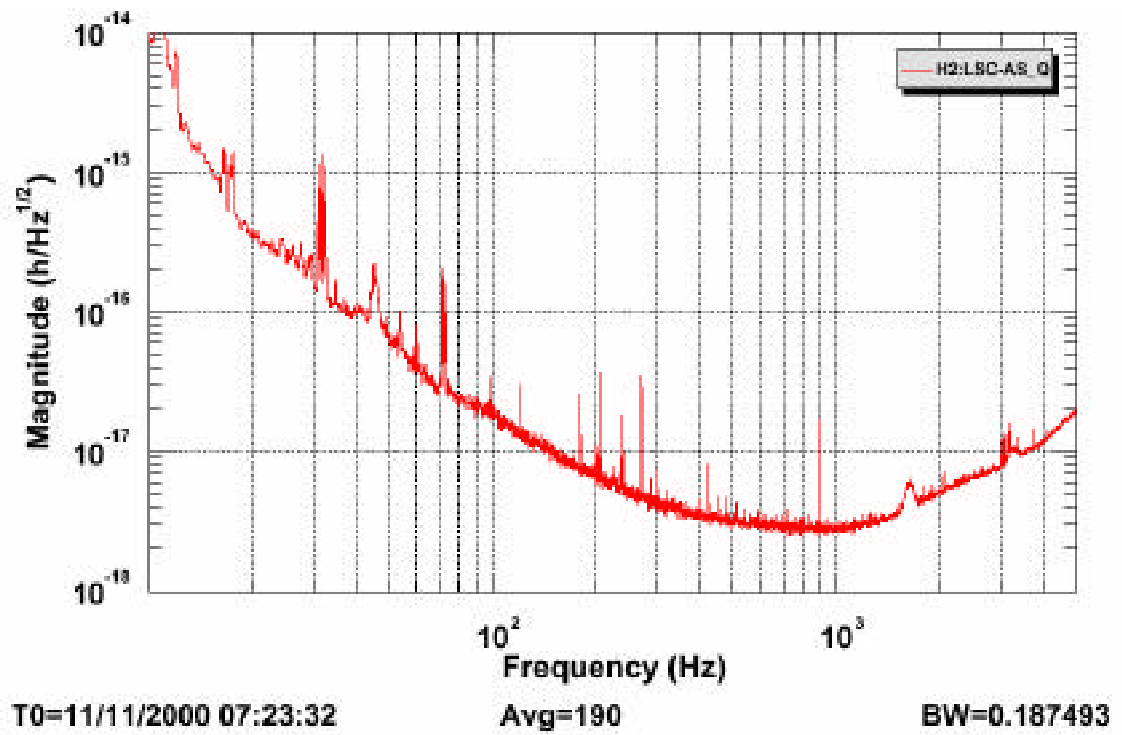
- Interferometry is limited by three fundamental noise sources
  - seismic noise at the lowest frequencies
  - thermal noise at intermediate frequencies
  - shot noise at high frequencies
- Many other noise sources lurk underneath and must be controlled as the instrument is improved



Strain Sensitivity

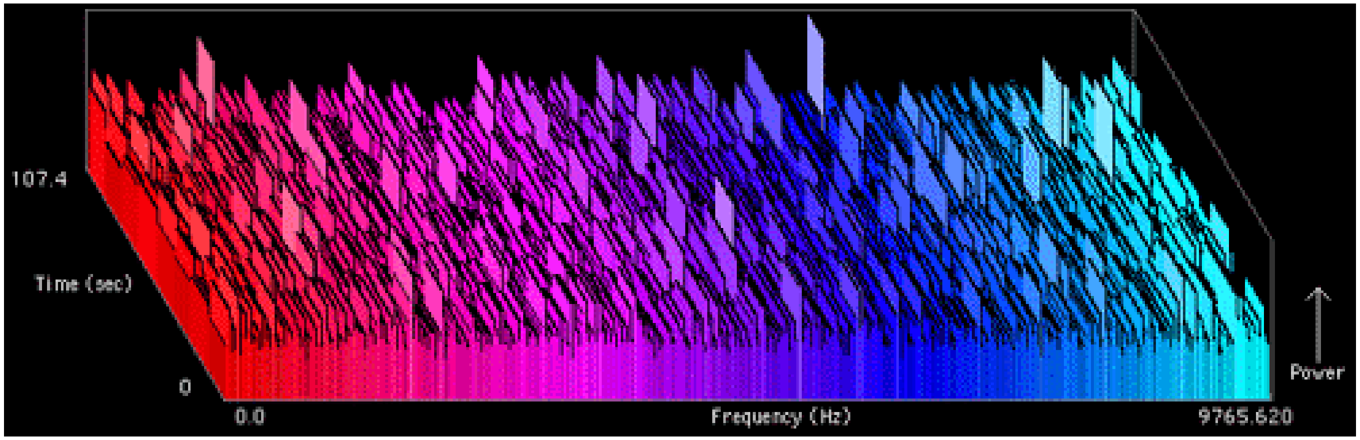
Nov 2000

2-km Hanford Interferometer



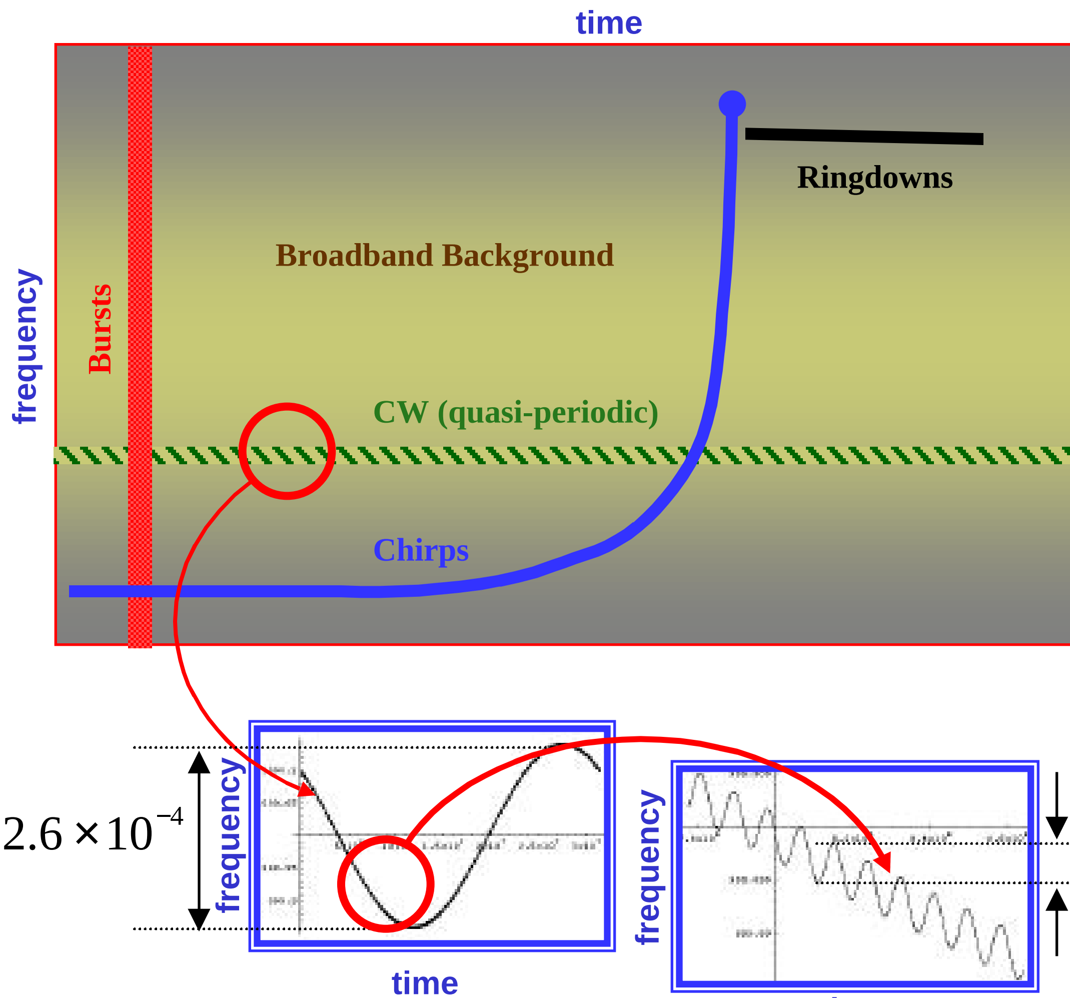
- **operating as a Michelson with Fabry-Perot arms**
- **reduced input laser power on the beam splitter (about 3 mW)**
- **without recycling**
- **noise level is a factor of 10^4-10^5 above the final specification**
- **sources of excess noise are under investigation**

Frequency-Time Maps ("Images")



SETI@home **uses frequency-time analysis methods to detect *unexpected* or *novel* features in otherwise *featureless "hiss"***

Frequency-Time Characteristics of GW Sources



$$\frac{\delta f}{f} \approx 2.6 \times 10^{-4}$$

$$\frac{\delta f}{f} \approx 4 \times 10^{-6}$$

- **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**

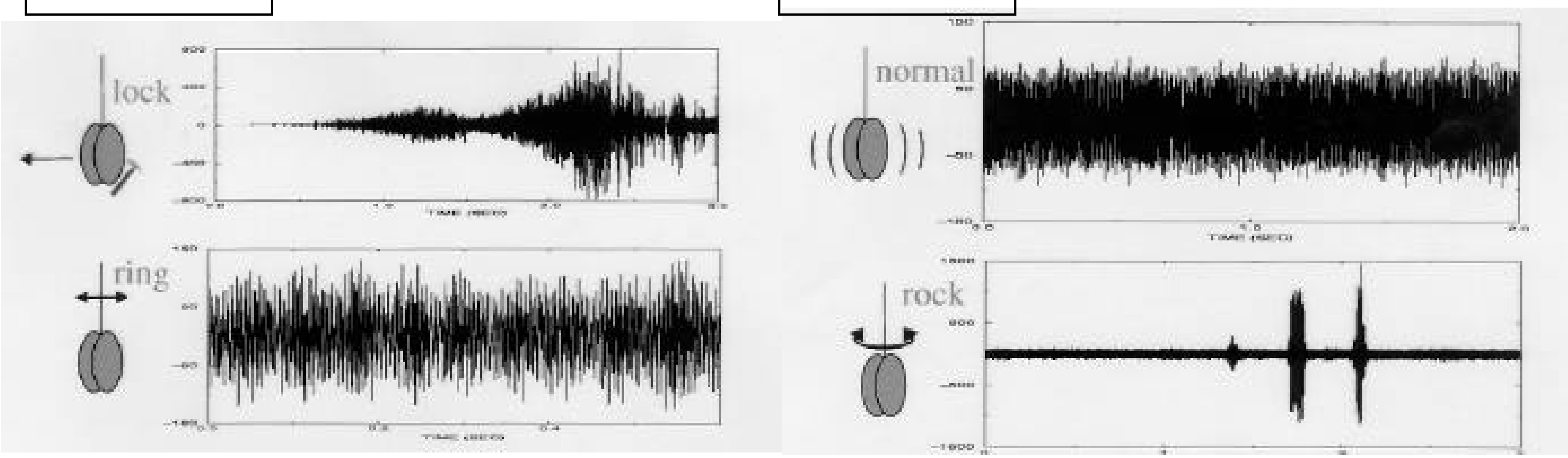
- **For each source, the optimal signal to noise ratio is obtained by integrating signal *along* the trajectory**
  - **If SNR >> 1, kernel ∝ |signal|^2**
  - **If SNR < 1, kernel ∝ |template* signal| or $|signal_j{*}\ signal_k|$**
  - **Optimal filter: kernel ∝ 1/(noise power)**

Interferometer Data
40 m

Real interferometer data is UGLY!!!

(Gliches - known and unknown)

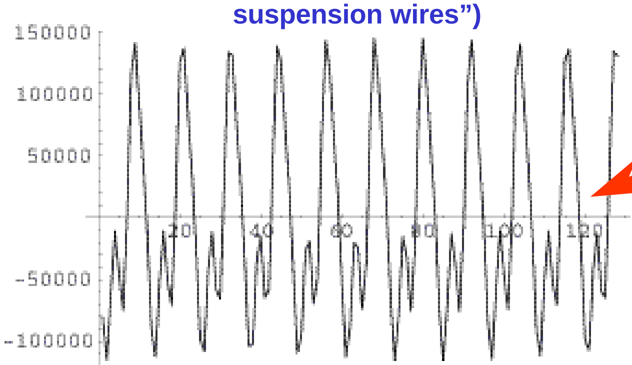
LOCKING **NORMAL**



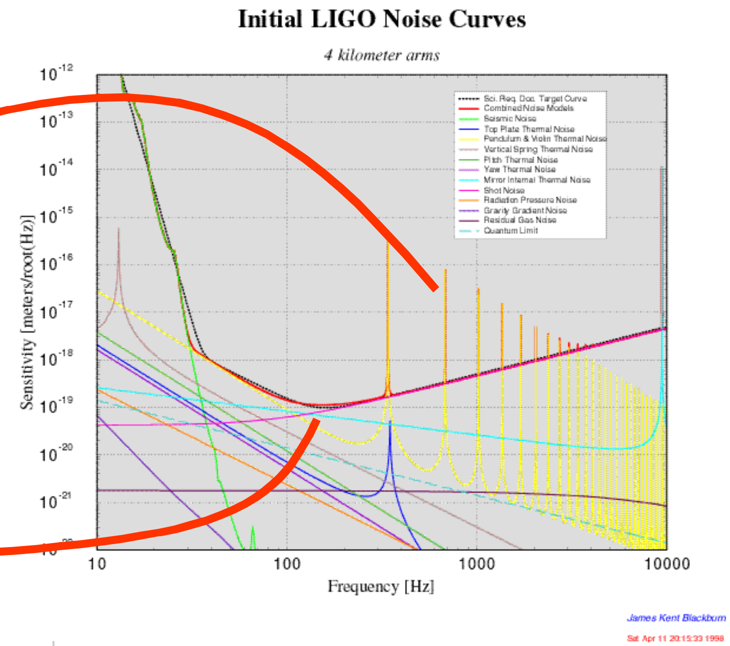
RINGING **ROCKING**

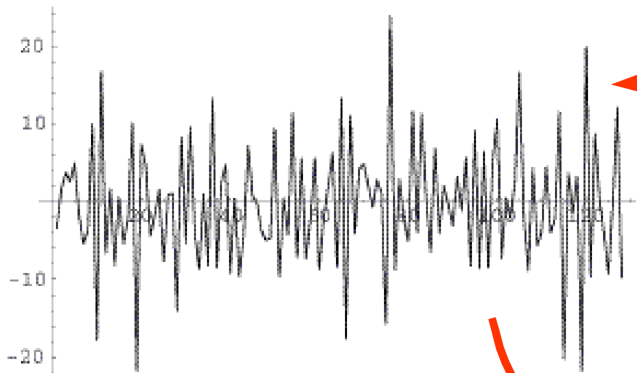
Interferometer Strain Signal (Simulated)

Dominated by narrowband features in spectrum ("violin resonances" of suspension wires")

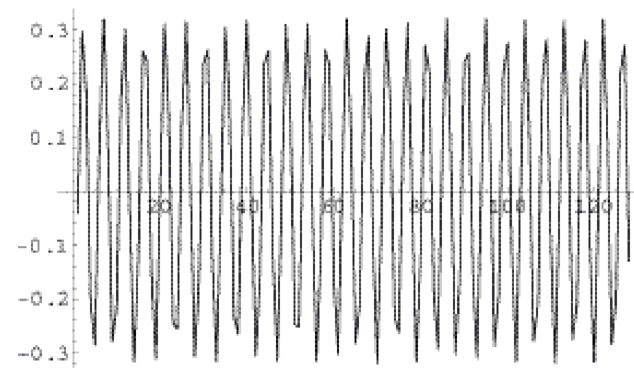


Design LIGO I limiting strain sensitivity



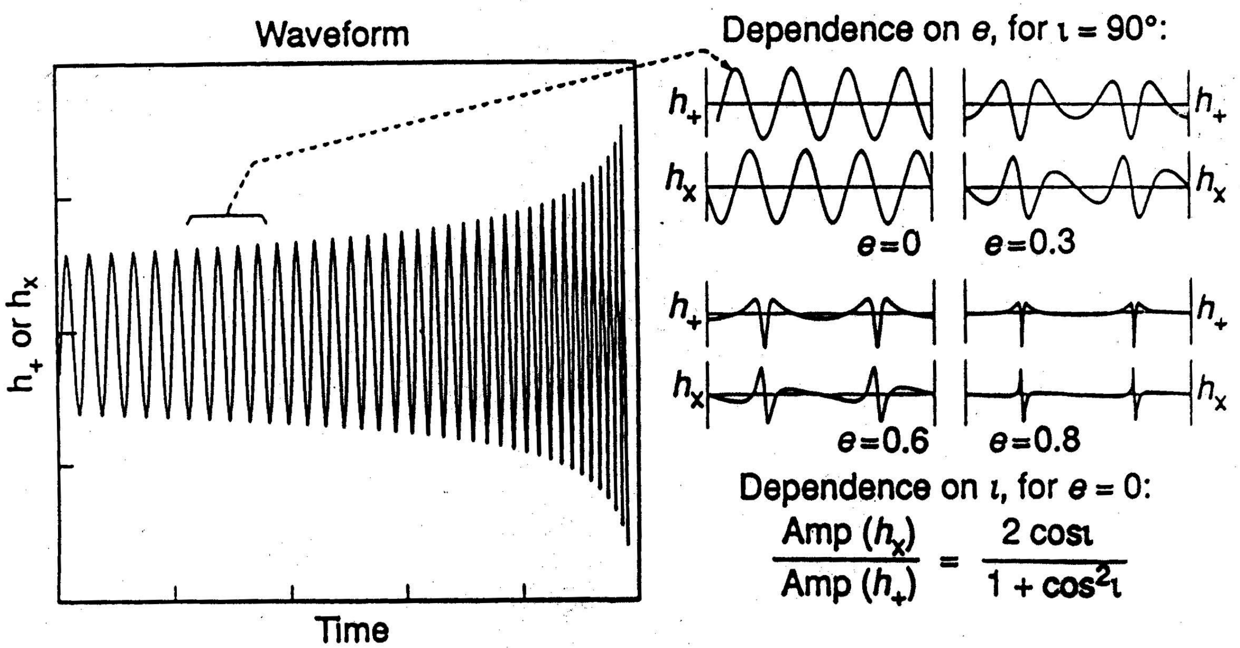


Broadband noise spectrum



Chirped waveform

“Chirp Signal”
binary inspiral



determine

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

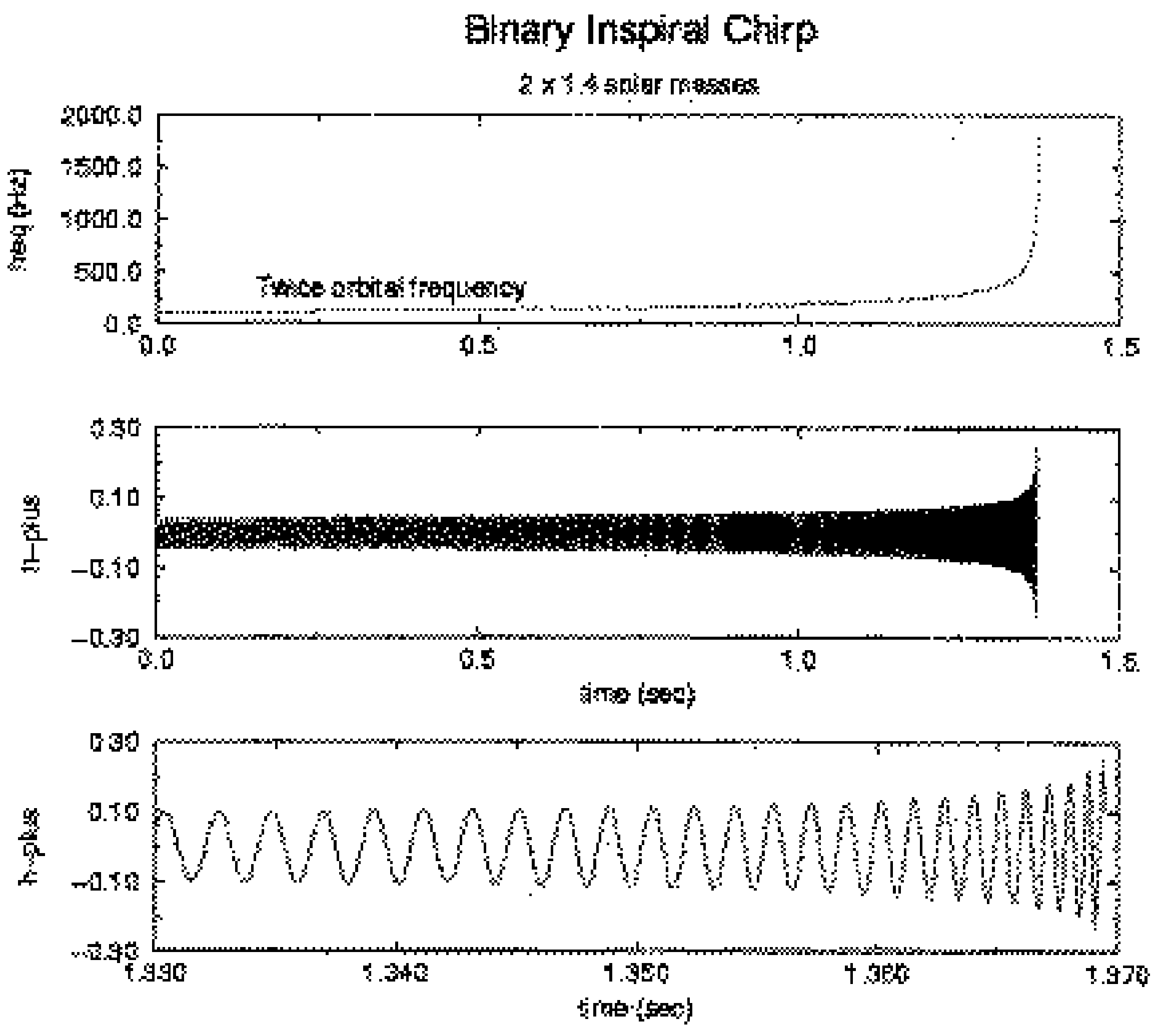
Inspiral 'Chirp' Signal

Template Waveforms

"matched filtering"
687 filters

44.8 hrs of data
39.9 hrs arms locked
25.0 hrs good data

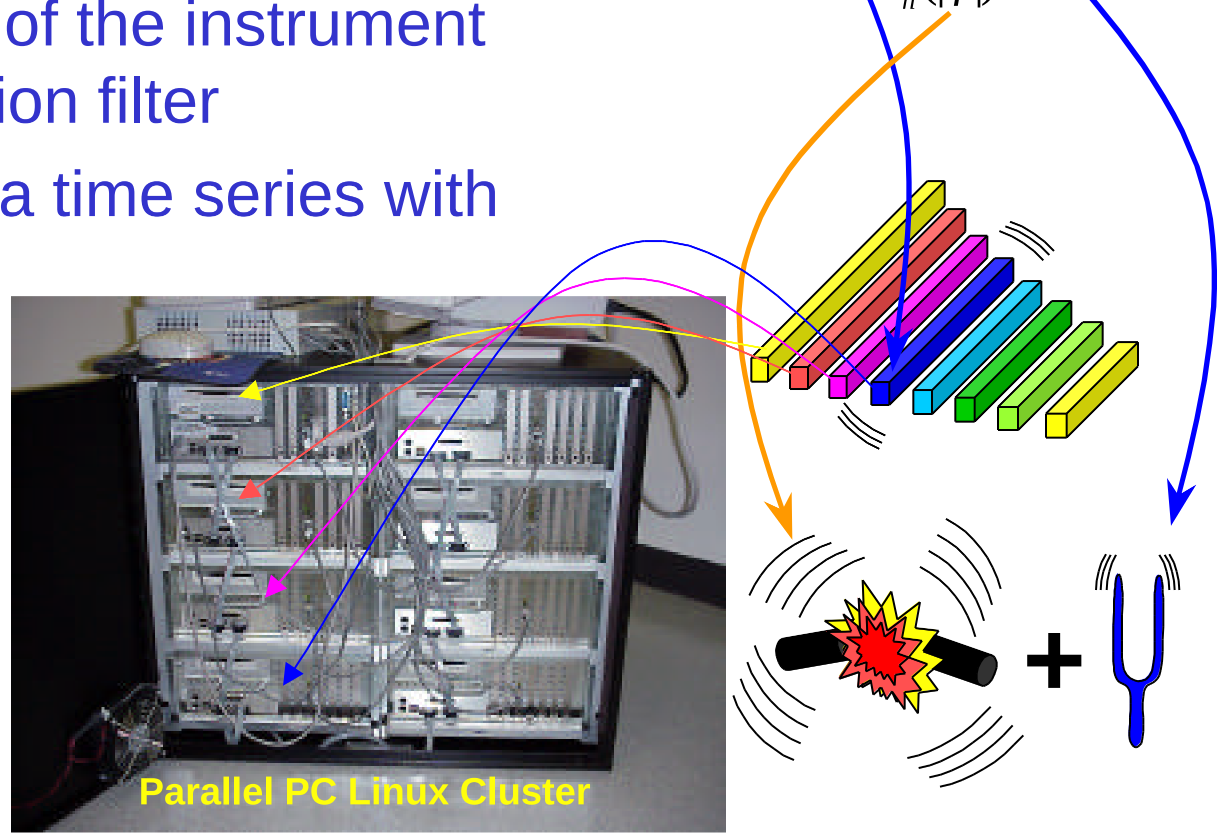
sensitivity to our galaxy
h ~ 3.5 10^{-19} $mHz^{-1/2}$
expected rate ~10^{-6}/yr



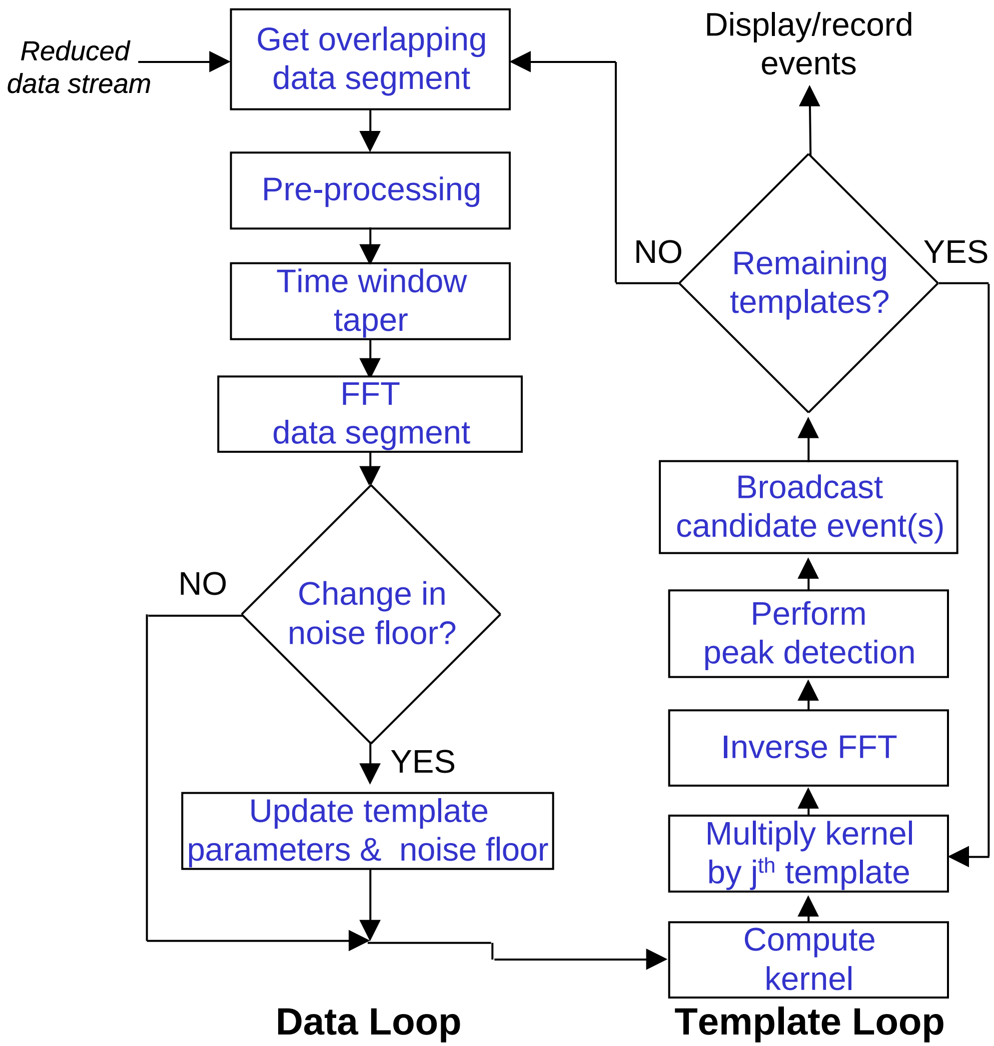
Optimal Wiener Filtering

- 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

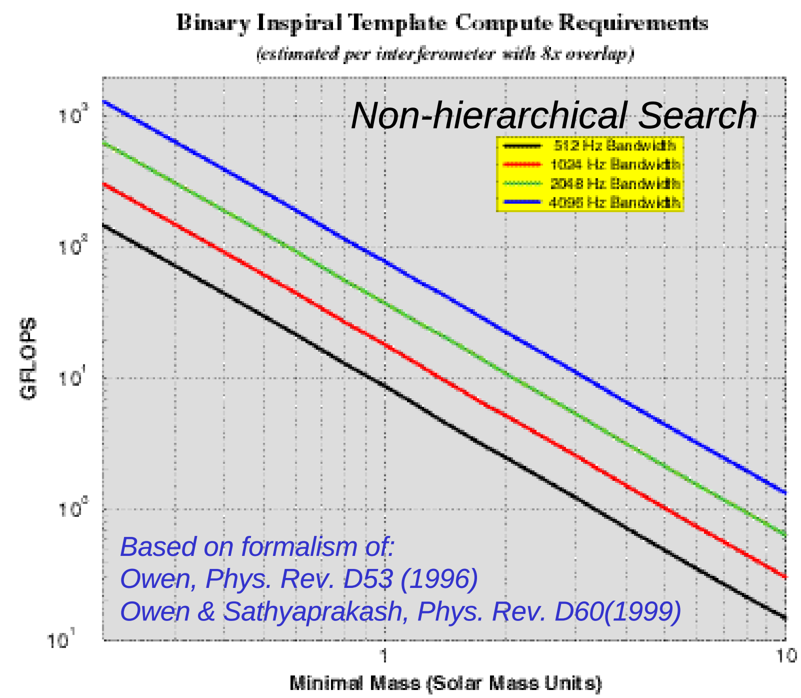
$$\xi_p[t_c] = \int \frac{\hat{T}_p^*(f)\ \hat{s}(f)}{\hat{S}_n(|f|)} e^{-2\pi i f t_c} df$$



Compact Binary Inspirals
Data Analysis Flow



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

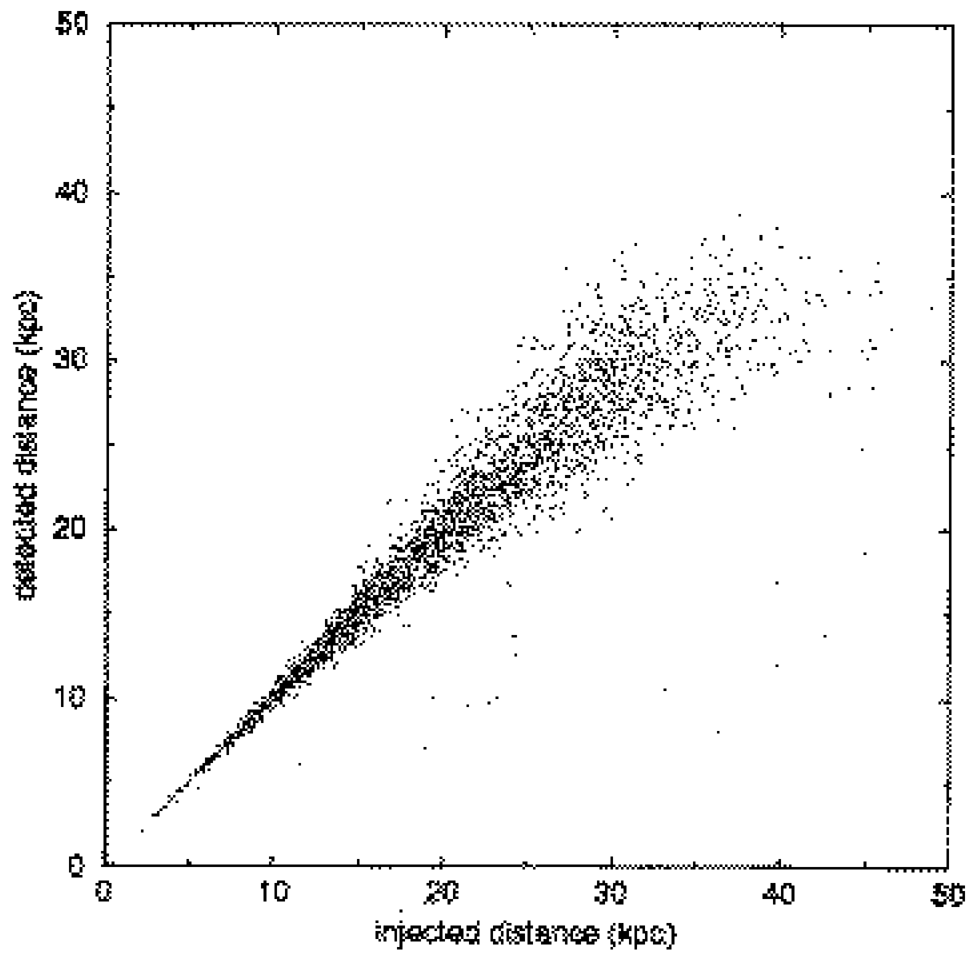


- **Process data at real time rate**
- **Improvements:**
  - ***Hierarchical searches being developed***
  - ***Phase coherent analysis of multiple detectors (Finn, in progress)***

Detection Efficiency

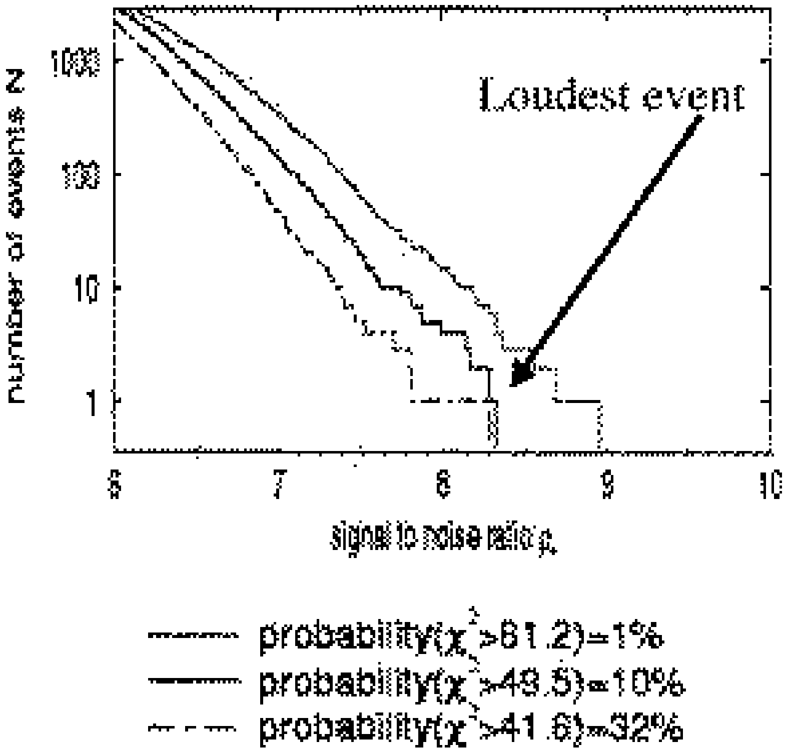
Monte Carlo (Statistical) techniques are needed to characterize complex detection probabilities

- **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

Quantitative Science: making a probabilistics 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

ε = 0.33 = detection efficiency

An ideal detector would set a limit:

R < 0.16/hour

Conclusion: Astrophysics and Cosmology

- 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 will be taking data 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***