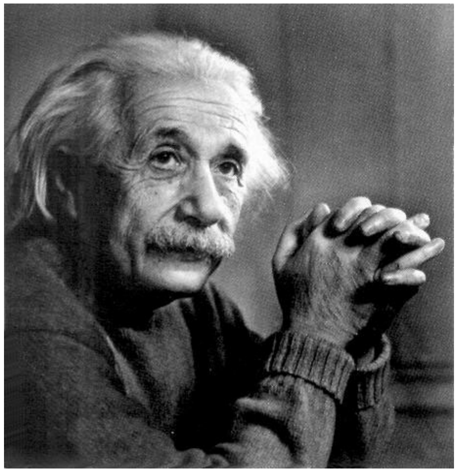
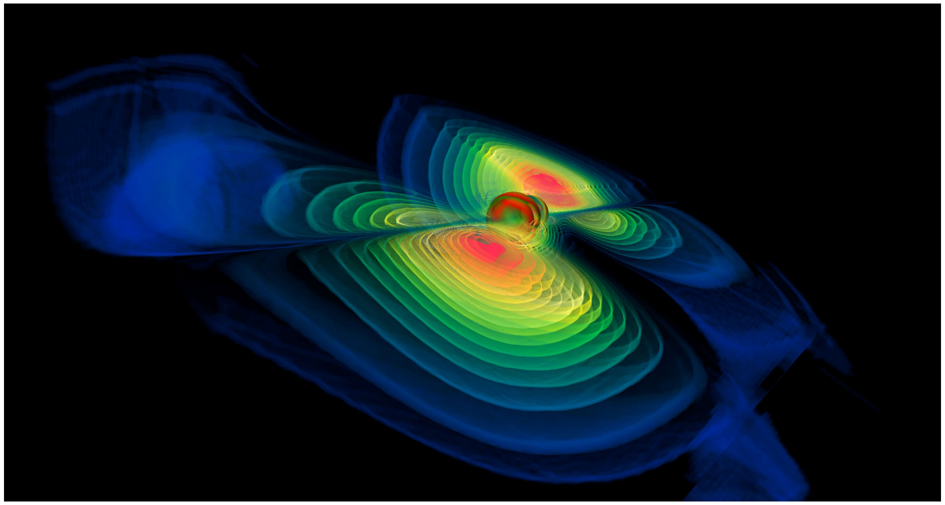
LIGO:
on the threshold of first observations





"Colliding Black Holes"
Credit: National Center for
Supercomputing Applications (NCSA)

Stan Whitcomb
for the LIGO Scientific Collaboration

UBC Physics Colloquium
27 March 2003

Outline of Talk

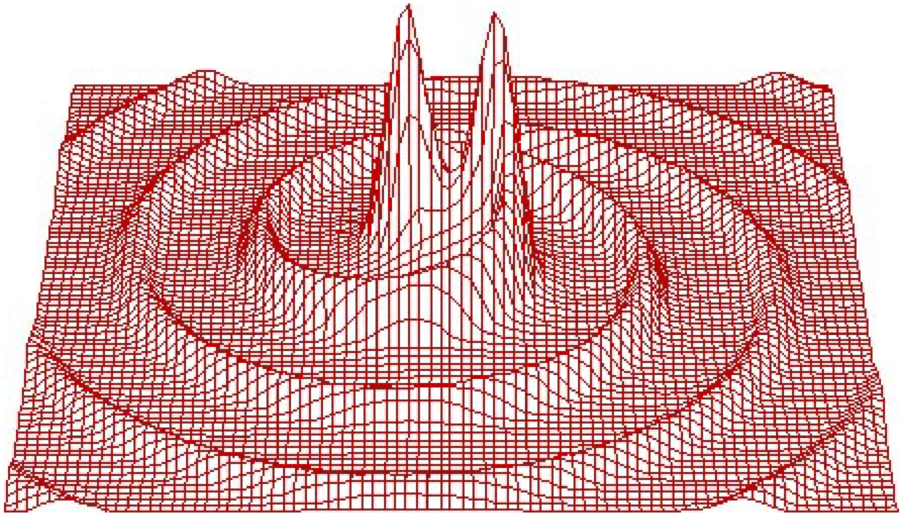
- Quick Review of GW Physics
- LIGO Detector Overview
  - » Performance Goals
  - » How do they work?
  - » What do the parts look like?
- LIGO's First Science Run
  - » Hints at first results
  - » Next steps
- Global Network
- Advanced LIGO Detectors

Gravitational Waves

- 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

- Time-dependent distortion of space-time created by the acceleration of masses that propagates away from the sources at the speed of light



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

Physics of Gravitational Waves

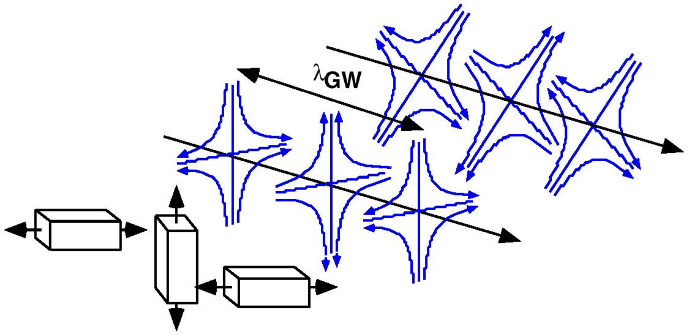
- In the Minkowski metric, space-time curvature is contained in the metric as an added term, $h_{\mu\nu}$

$$(\nabla^2 - \frac{1}{c^2}\frac{\partial^2}{\partial t^2})h_{\mu\nu} = 0$$

- In the weak field limit and the *transverse traceless gauge,* the formulation becomes a familiar wave equation

- Strain $h_{\mu\nu}$ takes the form of a transverse plane wave propagating with the speed of light (like EM)

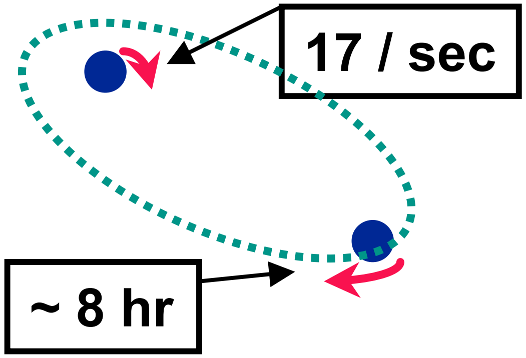
$$h = \Delta L / L$$



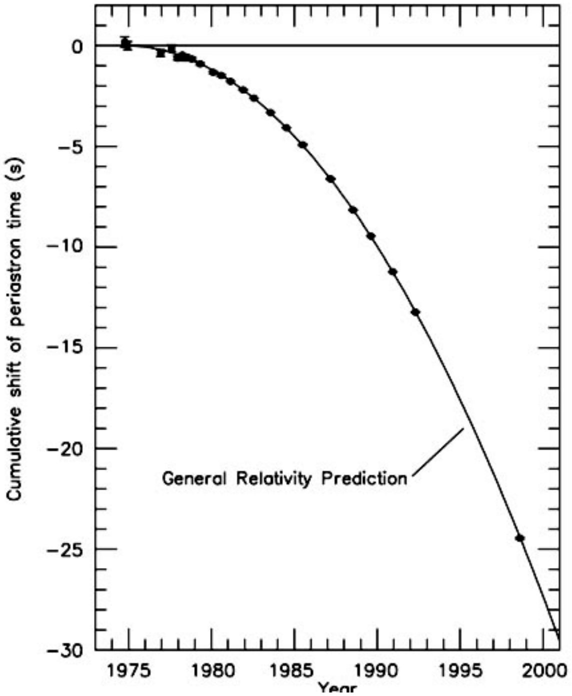
- Since gravity is described by a tensor field (EM is a vector field),
  - » gravitons have spin 2 (cf. spin 1 for photons)
  - » the waves have two polarization components, but rotated by 45^0 instead of 90^0 from each other (as in EM)

Evidence for Gravitational Waves:

Neutron Star Binary 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.**

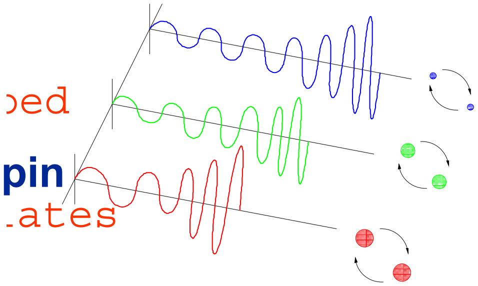


- **After correcting for all known relativistic effects, observe loss of orbital energy**

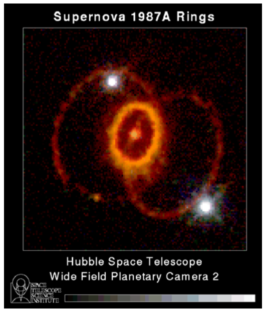
=> Emission of GWs

Astrophysical Sources of GWs

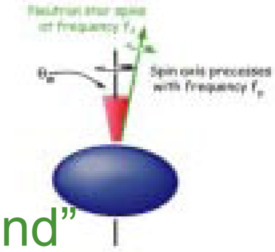
- Compact binary inspiral: “chirps”
  - » **NS-NS binaries well understood**
  - » **BH-BH binaries need further calculation, spin**
  - » **Search technique: matched templates**



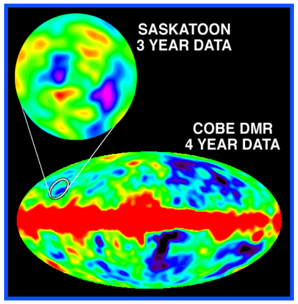
- Supernovas or GRBs: “bursts”
  - » **GW signals observed in coincidence with EM or neutrino detectors**
  - » **Prompt alarm for supernova? (~1 hour?)**



- Pulsars in our galaxy: “periodic waves”
  - » **Search for observed neutron stars (frequency, doppler shift known)**
  - » **All sky search (unknown sources) computationally challenging**
  - » **Bumps? r-modes? superfluid hyperons?**



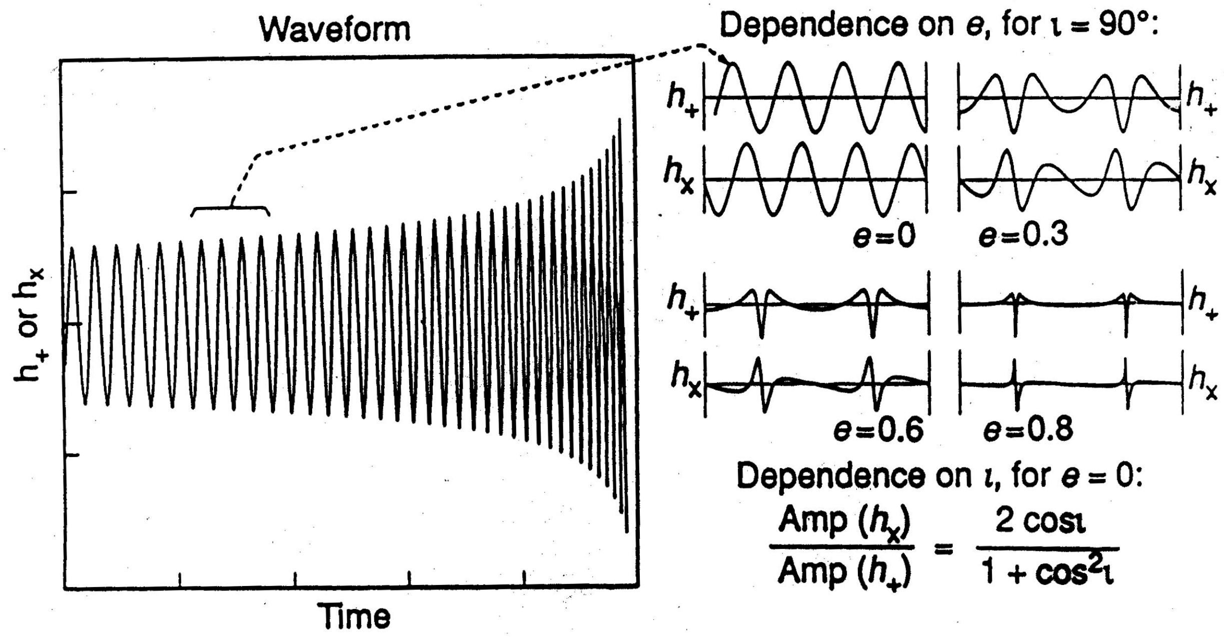
- Cosmological: “stochastic background”
  - » **Probing the universe back to the Planck time (10^{-43} s)**



Using GWs to Learn about the Sources: an Example

Chirp Signal

binary inspiral



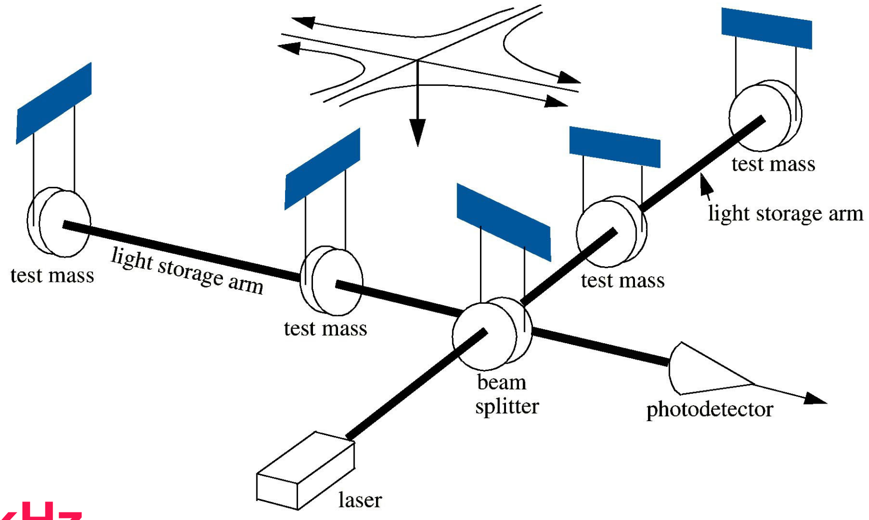
Can determine

- **Distance from the earth r**
- **Masses of the two bodies**
- **Orbital eccentricity e and orbital inclination *i***

Detecting GWs with Interferometry

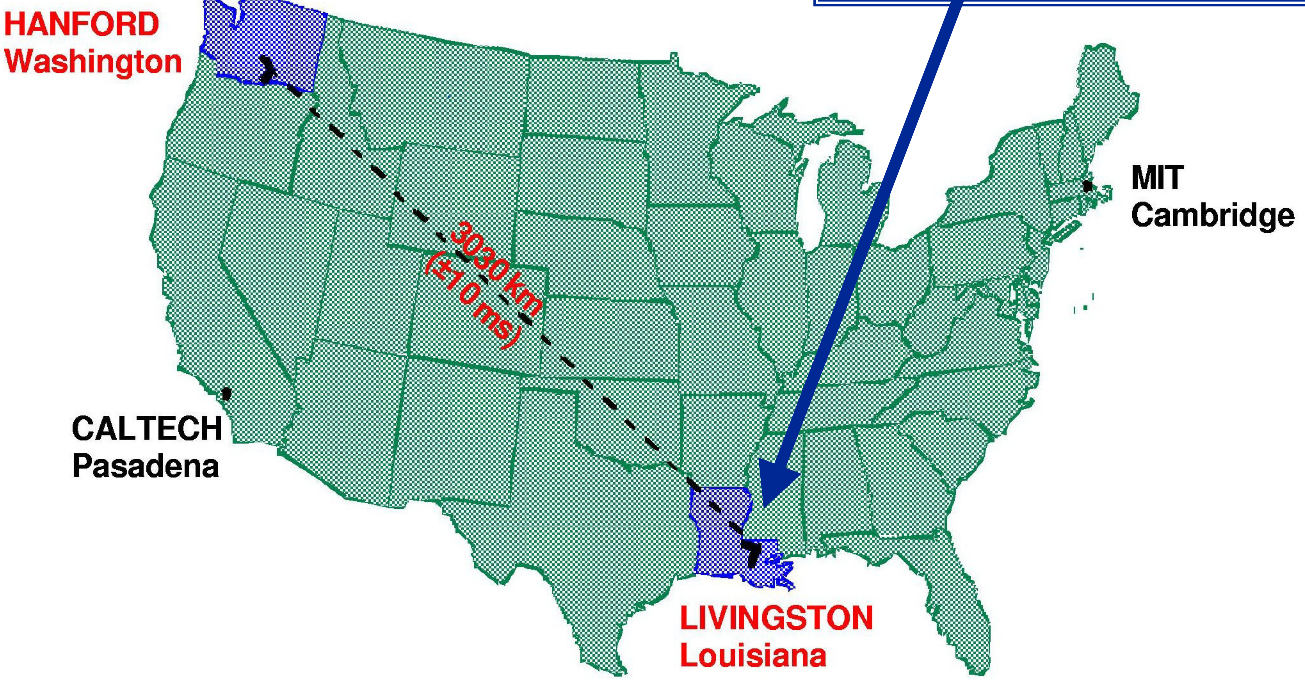
Suspended mirrors act as "freely-falling" test masses in horizontal plane for frequencies $f \gg f_{pend}$

$$h = \Delta L / L$$

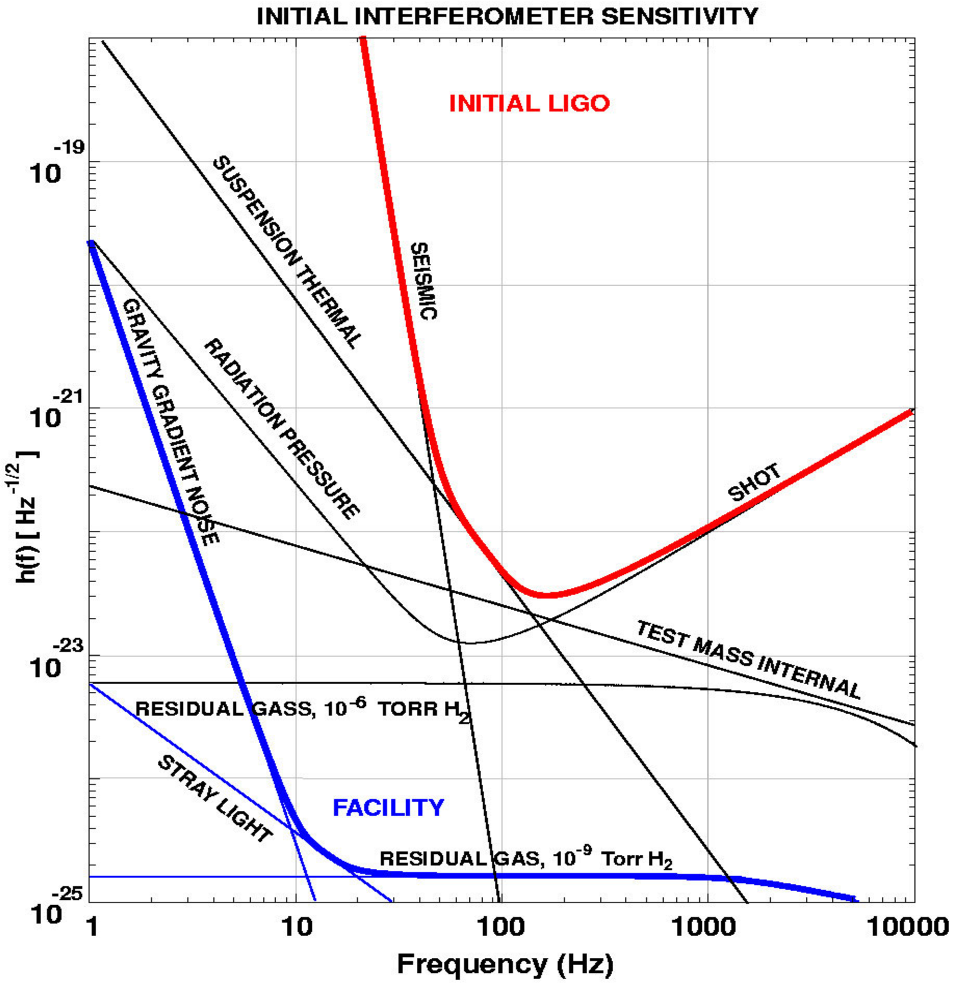


Terrestrial detector,
L ~ 4 km (LIGO)
For $h \sim 10^{-22} - 10^{-21}$
$\Delta L \sim 10^{-18}$ m
Useful bandwidth 10 Hz to 10 kHz, determined by "unavoidable" noise (at low frequencies) and expected maximum source frequencies (high frequencies)

LIGO Observatories



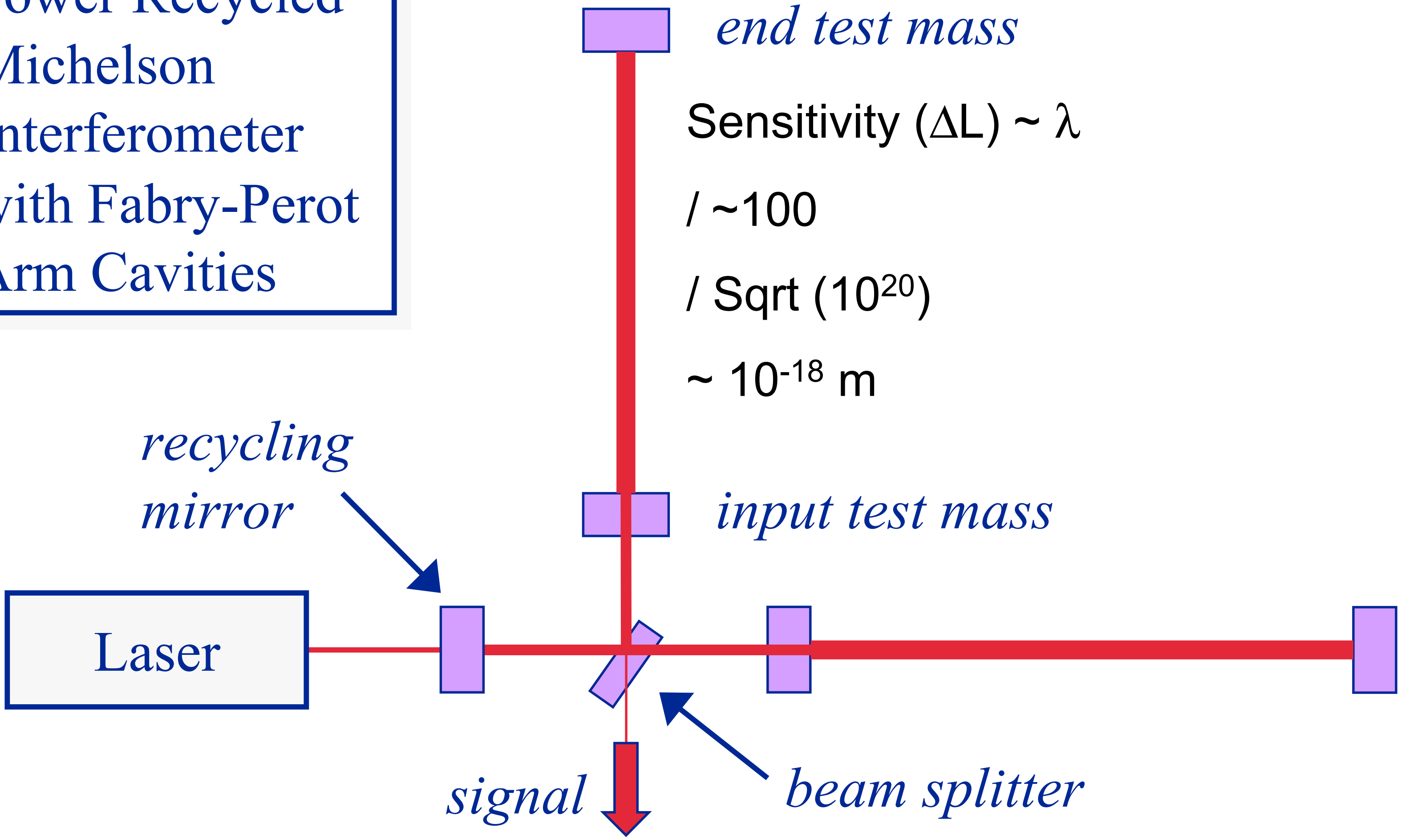
Initial LIGO Sensitivity Goal



- 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

Optical Configuration

Power Recycled Michelson Interferometer with Fabry-Perot Arm Cavities



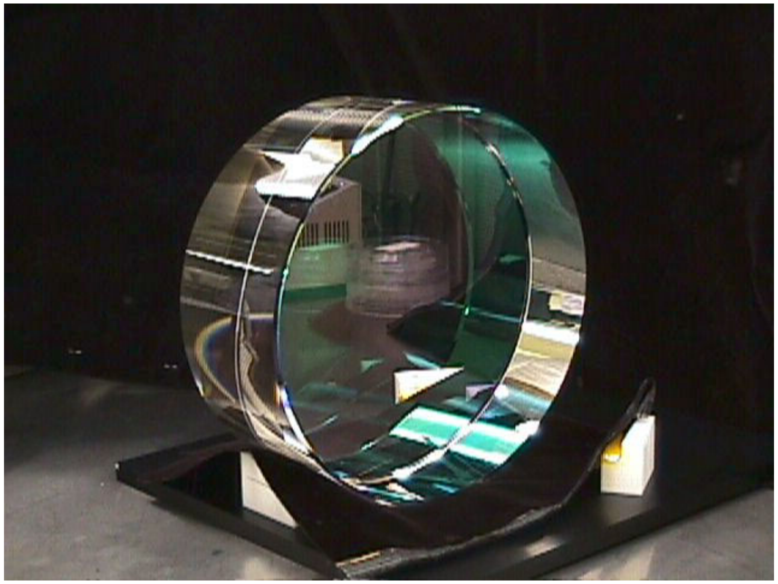
Sensitivity (ΔL) ~ λ

/ ~100

/ Sqrt (10^{20})

~ 10^{-18} m

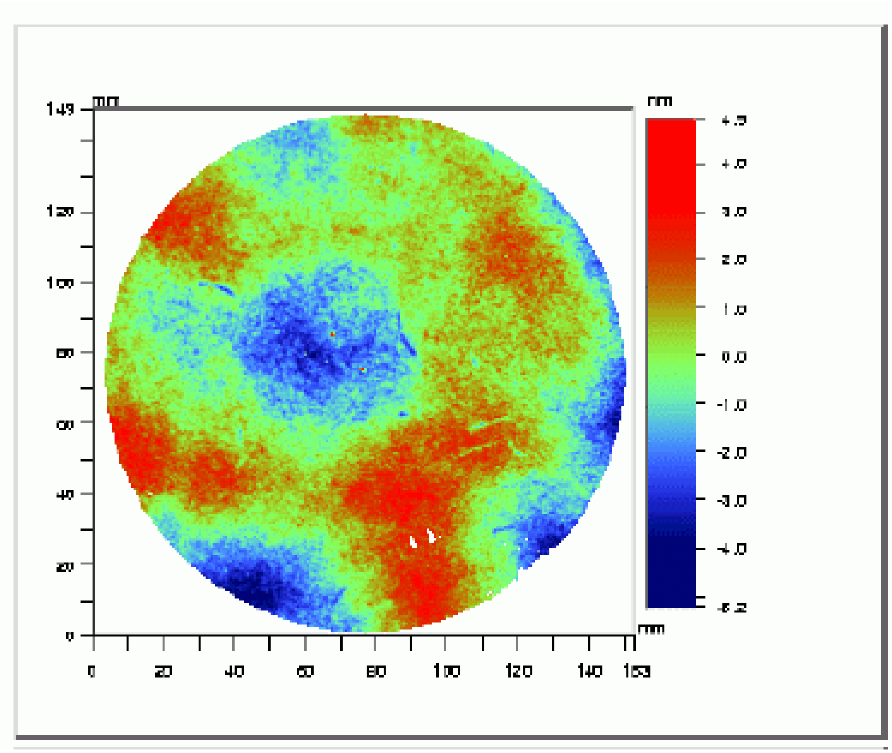
Test Mass/Mirrors



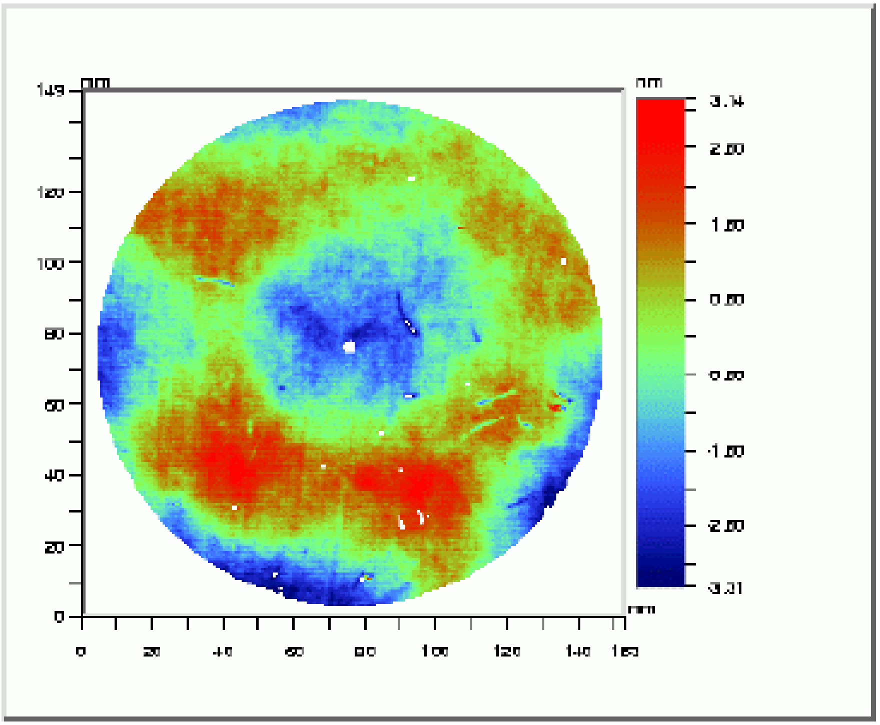
- Substrates: SiO_2
  - 25 cm Diameter, 10 cm thick
  - Homogeneity $< 5 \times 10^{-7}$
  - Internal mode Q's $> 2 \times 10^{6}$
- Polishing
  - Surface uniformity < 1 nm rms (λ / 1000)
  - Radii of curvature matched < 3%
- Coating
  - Scatter < 50 ppm
  - Absorption < 2 ppm
  - Uniformity $<10^{-3}$
- Production involved 6 companies, NIST, and LIGO

λ / 1000 Optics?

- State of the art metrology: 0.2 nm repeatability

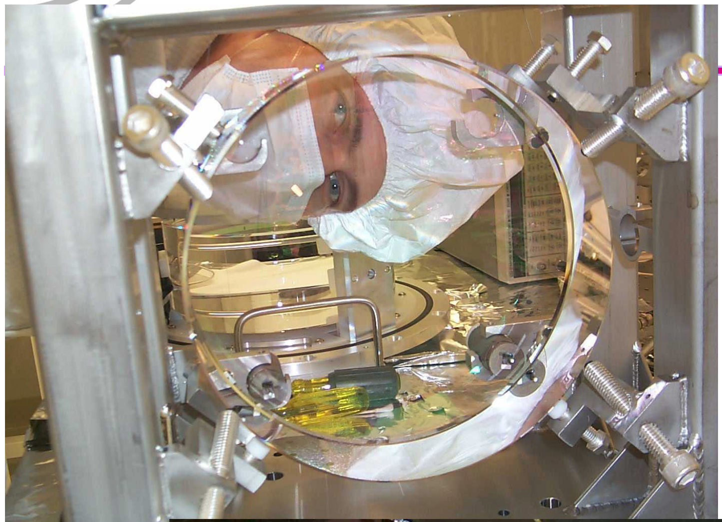


LIGO data (1.2 nm rms)



CSIRO data (1.1 nm rms)

Test Mass Suspension and Control

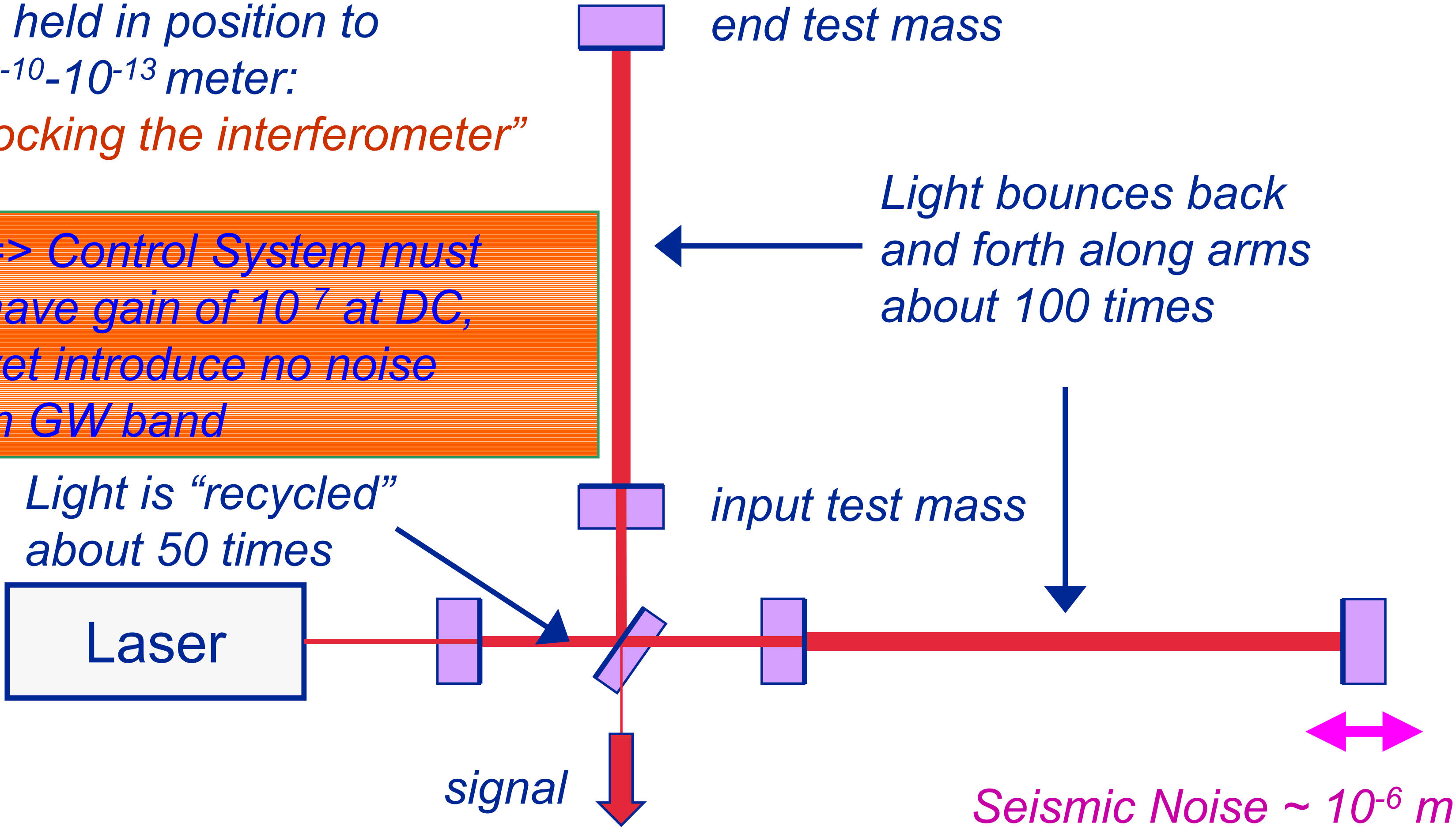


Control Systems

Test masses must be held in position to 10^{-10}-10^{-13} meter:

"Locking the interferometer"

=> Control System must have gain of 10^{7} at DC, yet introduce no noise in GW band



end test mass

Light bounces back and forth along arms about 100 times

Light is "recycled" about 50 times

input test mass

Laser

signal

Seismic Noise ~ 10^{-6} m

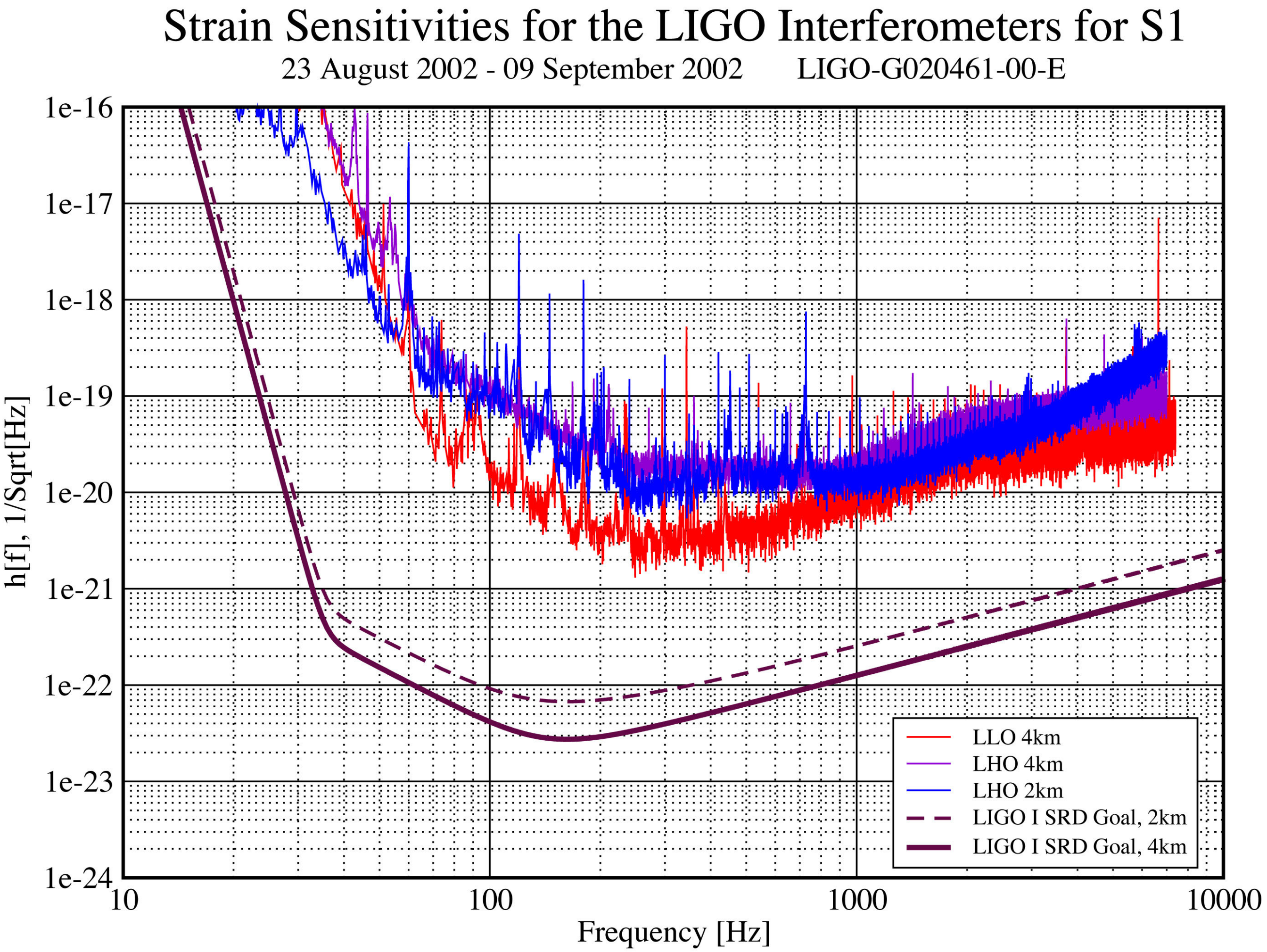
First Science Run (S1)

LIGO
S1 Run

"First Upper Limit Run"

- **Aug – Sept 2002**
- **17 days**

Also GEO And TAMA



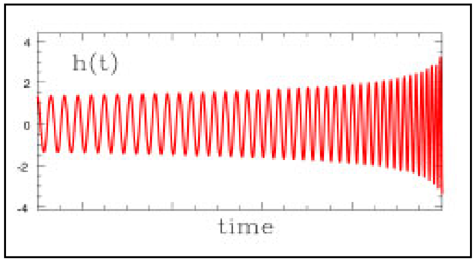
S1 Duty Cycle

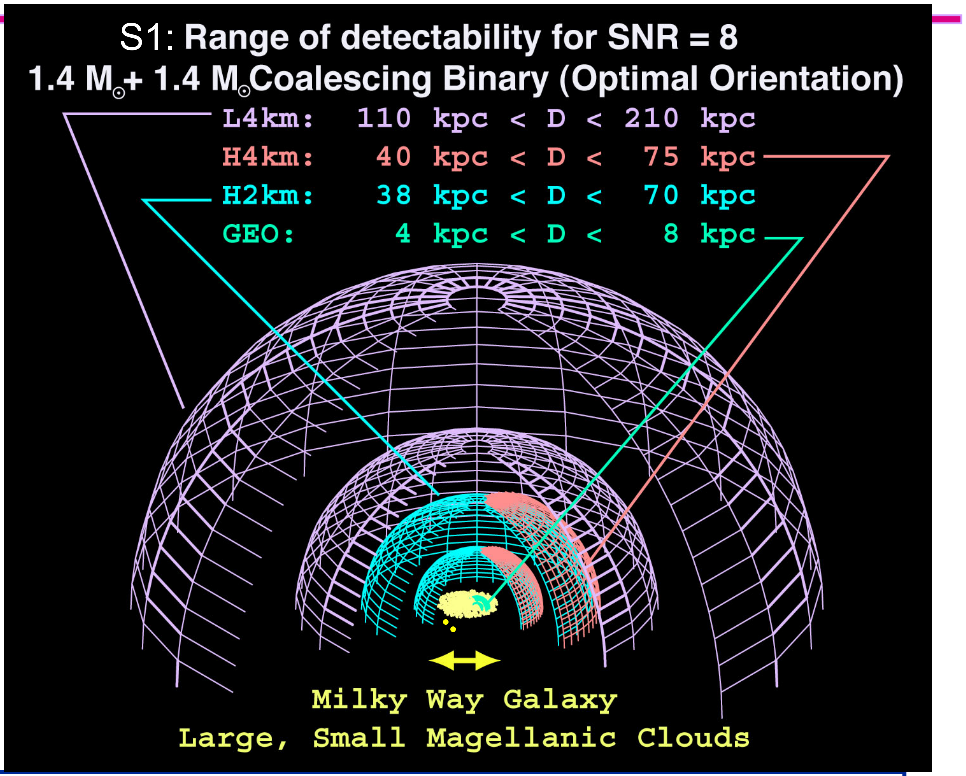
	LLO-4K	LHO-4K	LHO-2K	All three together
Integrated lock time (>300 sec per segment)	169 hours	232 hours	288 hours	96 hours
Duty cycle (cf. 400 hour run time)	43%	59%	73%	24%

- Longest locked section for individual interferometer: 21 hrs (11 in “Science mode”)
- Need to improve low frequency seismic isolation – protection from local anthropogenic noise

Coalescing Binaries

- Three source targets:
  - » Neutron star binaries (1-3 M_{sun})
    - ✓ Neutron star search complete
  - » Black hole binaries (> 3 M_{sun})
  - » MACHO binaries (0.5-1 M_{sun})
- Search method
  - » Template based matched filtering




S1: Range of detectability for SNR = 8

$1.4\,M_\odot + 1.4\,M_\odot$ Coalescing Binary (Optimal Orientation)

L4km: 110 kpc < D < 210 kpc

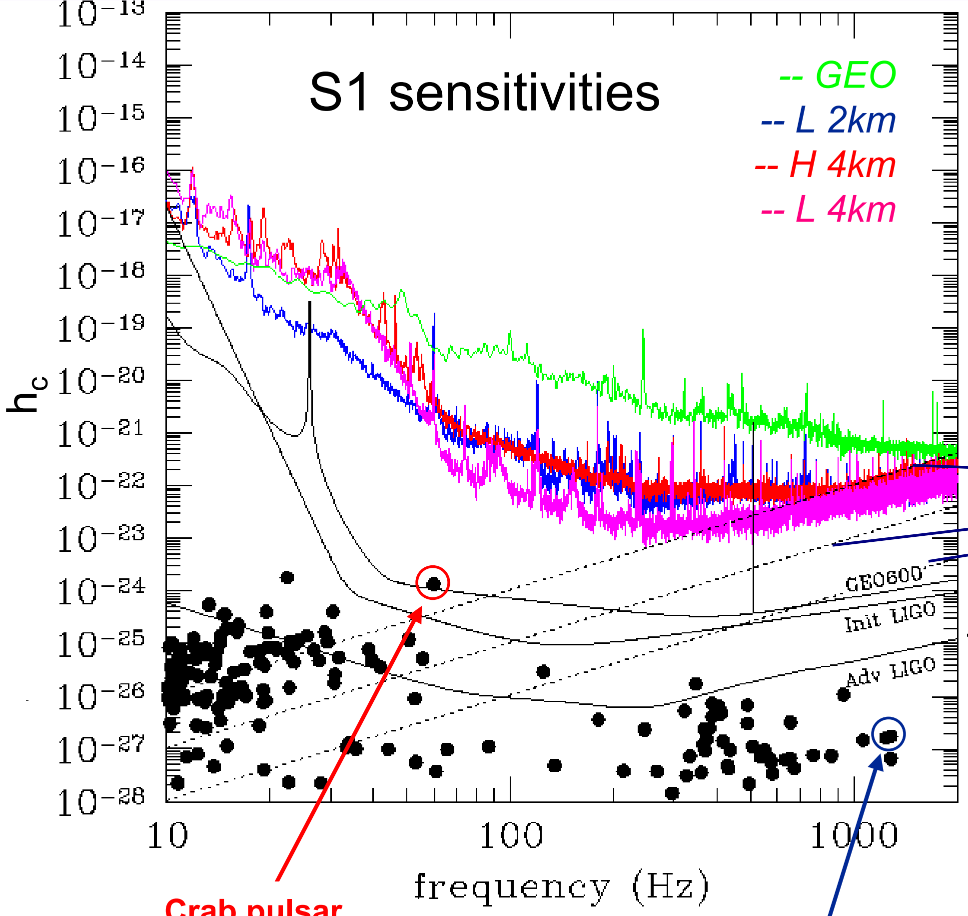
H4km: 40 kpc < D < 75 kpc

H2km: 38 kpc < D < 70 kpc

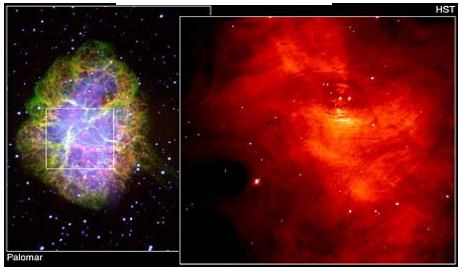
GEO: 4 kpc < D < 8 kpc

- Use data from H 4km and L 4km interferometers: *T ~ 300 hours*
  - » Monte Carlo simulation to get efficiency: *ε ~ 35% for Milky Way Population*
  - » 90% confidence limit = *2.3 / (ε T)*
- Limit on binary neutron star coalescence rate:
  - » *$R_{90\%}$ < 2xx / yr / Milky Way Equivalent Galaxy*

Establishing limits on gravitational waves radiated by periodic sources



Crab pulsar



PSR J1939+2134
P = 0.00155781 s
f_{GW} = *1283.86 Hz*
$\dot{P}$ = 1.0519 10^{-19} s/s
D = 3.6 kpc

- h_c: Amplitude detectable with 99% confidence during observation time T:

$$h_c = 4.2\,[S_h(f)/T]^{1/2}$$

- *Limit of detectability for rotating NS with equatorial ellipticity, $\varepsilon = \delta I/I$:*

10^{-3} , 10^{-4} , 10^{-5} @ 10 kpc

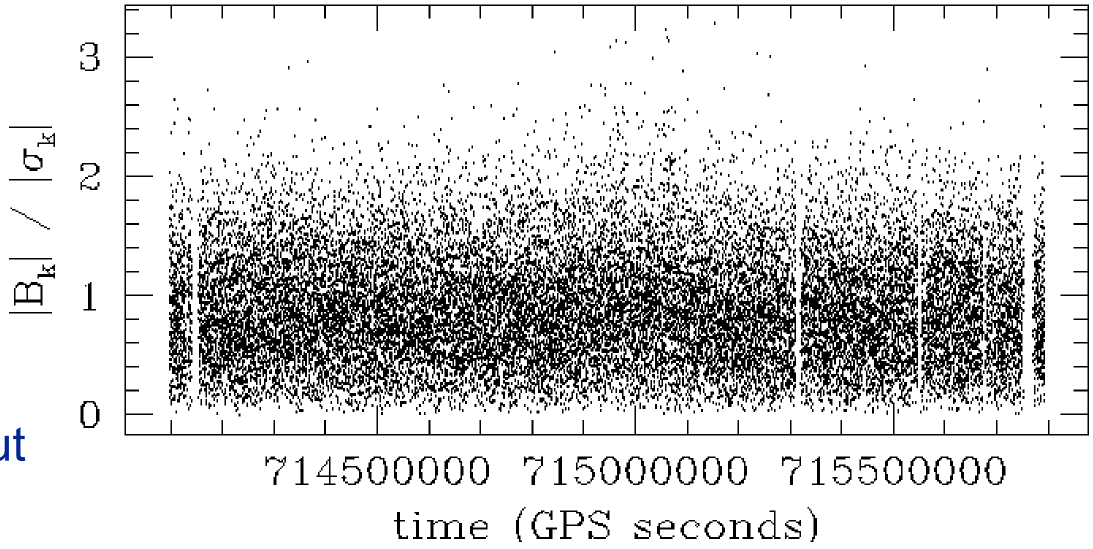
- ***Known** EM pulsars*
  - *Values of h_c derived from measured spin-down*
    - *IF spin-down were entirely attributable to GW emissions*
    - *Rigorous astrophysical upper limit from energy conservation arguments*

Graphic by R. Dupuis, Glasgow

Two complementary analysis approaches

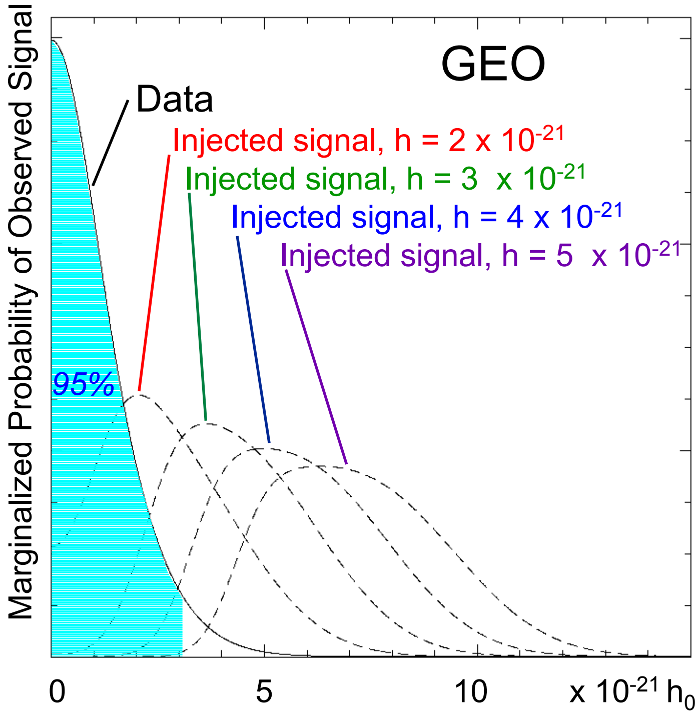
- Time-domain search -- process signal to remove frequency variations due to Earth's motion around Sun
  - »Targeted searches
  - »Handles missing data
  - »Adaptable to complicated phase evolutions.
  - »Upper limit interpretation straightforward
    - –Compare result to what would be expected from noise without signal

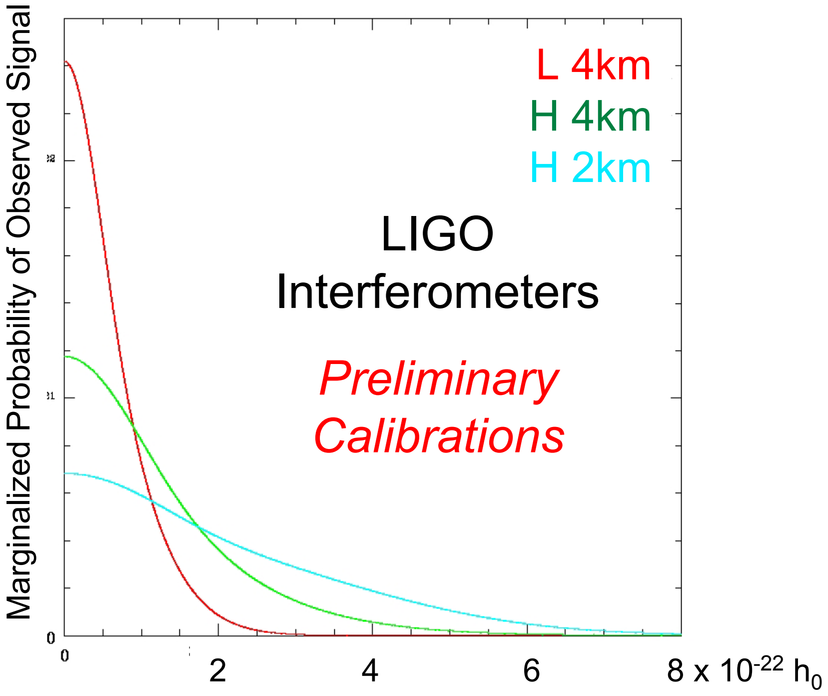
GEO -- Time series of amplitude near 1283 Hz (PSR J1939)



- Frequency-time domain search
  - »Standard matched filtering technique
    - –Cross-correlation of signal with template, look for correlated power
  - »Analysis gives comparable result, but more easily extrapolated to unknown target

Preliminary results: EM pulsar PSR J1939



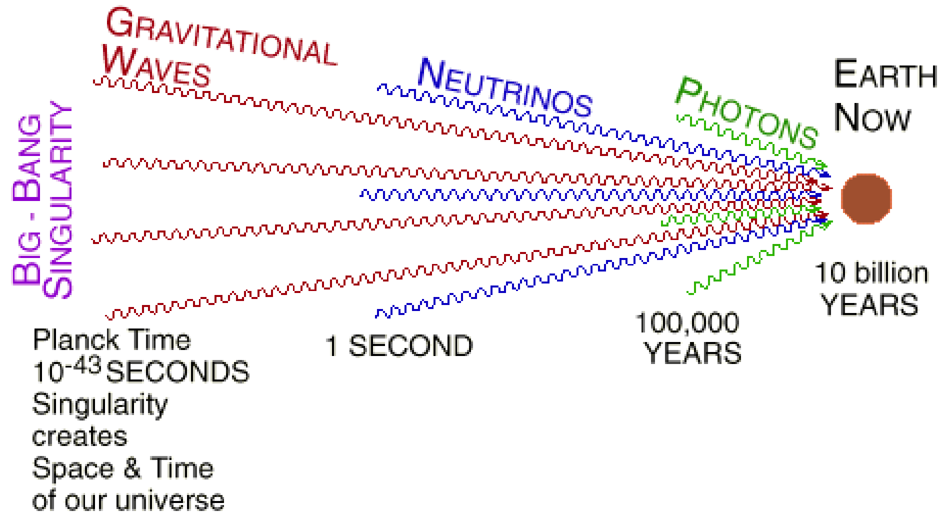


- ***Time domain analysis: No evidence of signal from PSR J1939 at f = 1283.86 Hz***
- 95% of the probability lies below:
  - GEO: $h_{max} < 3 \times 10^{-21}$
  - H 2km: $h_{max} < 5 \times 10^{-22}$
  - H 4km: $h_{max} < 3 \times 10^{-22}$
  - ***L 4km:*** $\boldsymbol{h_{max} < 2 \times 10^{-22}}$ **(**$\boldsymbol{\varepsilon < 7 \times 10^{-5}}$ **@ 3.6 kpc)**

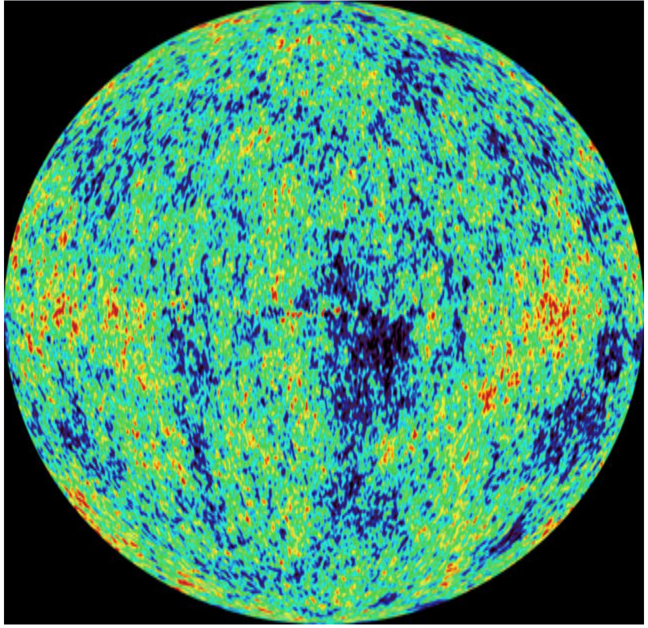
Ref. -- $h_{max} < 3 \times 10^{-20}$ *for PSR J1939 -- Hough, J. et al., Nature,* ***303*** *(1983) 216*

$h_{max} < 3 \times 10^{-24}$ at f =921.35 (+/- 0.03) Hz - Astone, *Phys.Rev. D65 (2002) 022001 (untargeted search)*

Stochastic Background Sources



- Detect by cross-correlating interferometer outputs in pairs
  - Hanford - Livingston, Hanford - Hanford
- Good sensitivity requires:
  - $\lambda_{GW} \geq$ **2D** (detector baseline)
  - f $\leq$ 40 Hz for L - H pair
- Initial LIGO limiting sensitivity: $\Omega <$ **10^{-5}**



Analog from cosmic microwave background -- WMAP 2003

$$\int_0^\infty d(\ln f)\ \ \Omega_{GW}(f) = \frac{\rho_{GW}}{\rho_{critical}}$$

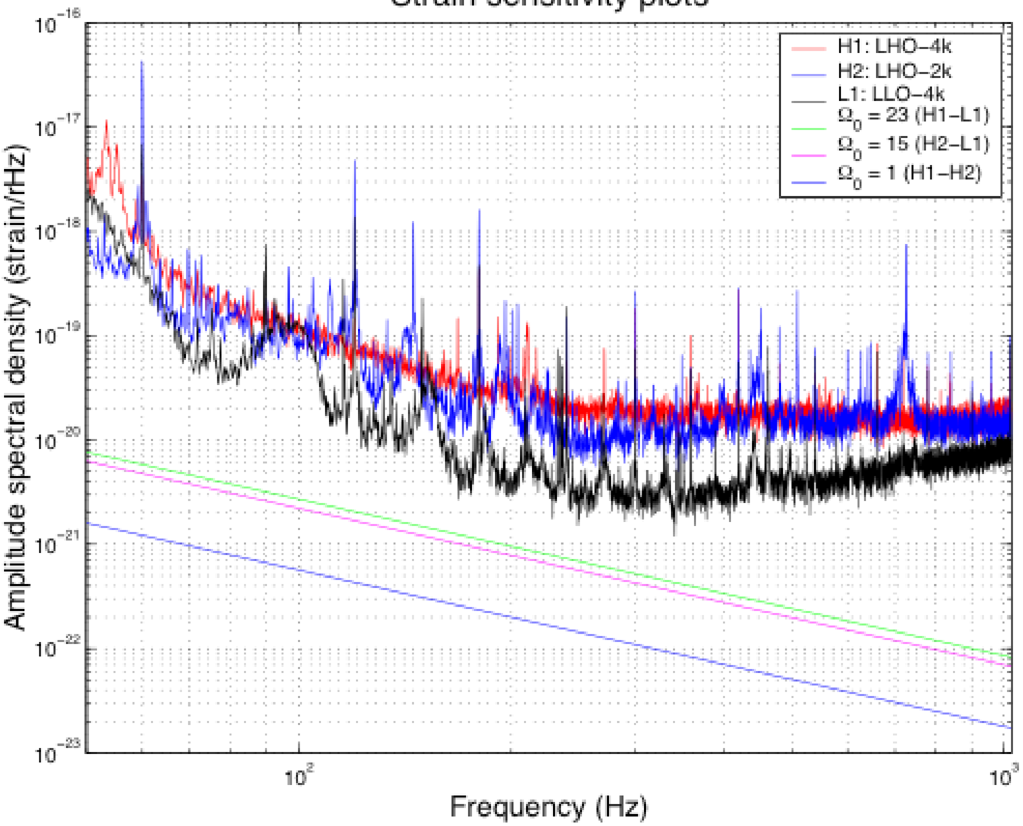
The integral of [Ω_{GW}(f) / f] over all frequencies corresponds to the fractional energy density in gravitational waves in the Universe

Stochastic Gravitational Wave Background

- Current best upper limits:
  - » Inferred: From Big Bang nucleosynthesis: (Kolb et al., 1990) $\int \Omega_{GW}(f)\ d\ln f < 1\times10^{-5}$
  - » Measured: Garching-Glasgow interferometers (Compton et al. 1994): $\Omega_{GW}(f) < 3\times10^{5}$
  - » Measured: EXPLORER-NAUTILUS (cryogenic bars -- Astone et al., 1999): $\Omega_{GW}(907Hz) < 60$

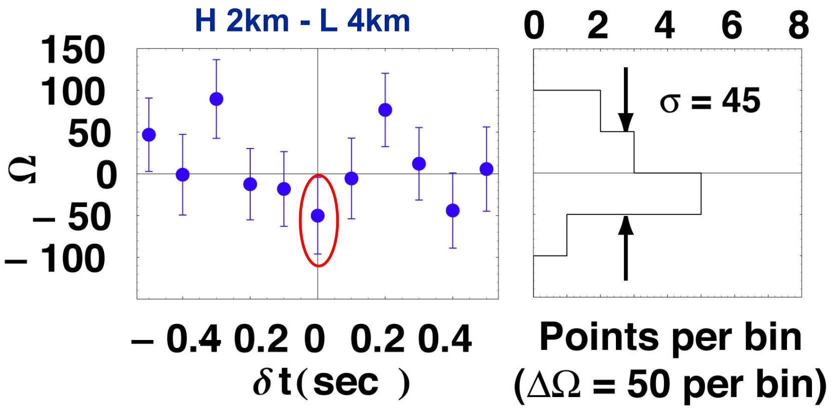
Cross-correlation technique enables one to "dig" signal below individual interferometer noise floors

Strain sensitivity plots



Stochastic Gravitational Wave Background Result

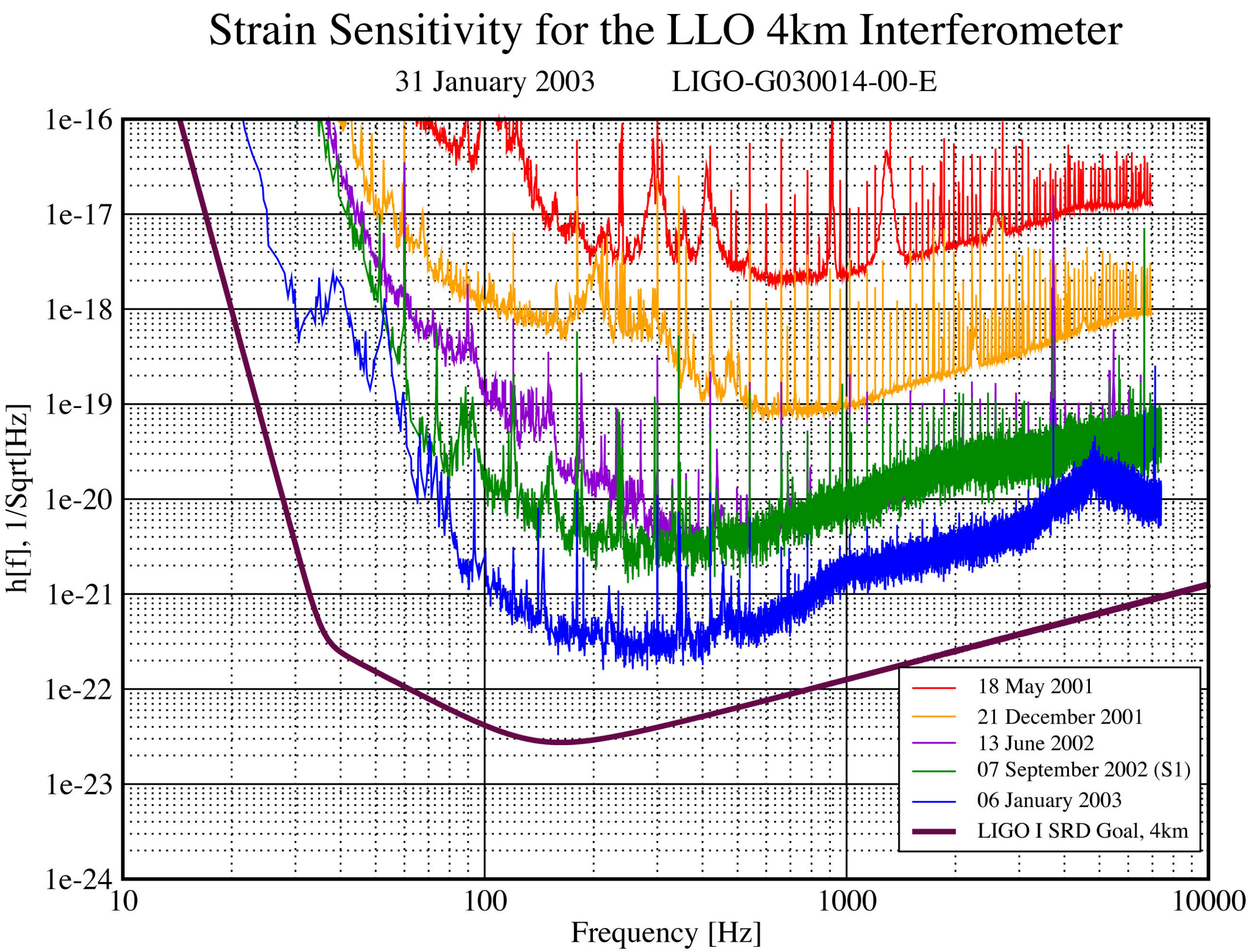
- Preliminary results from 7.5 hr of data -



- Introduce non-astrophysical time lags (>20ms) to determine backgrounds
  - *Δ t = 0 sec* measurements consistent with *off-source* backgrounds

Interferometer Pair	Extrapolated Upper Limit for S1 (by scaling 7.5 hrs to 150 or 100 hrs)	T_{obs}
H 2km - L 4km	Ω_{GW} (40Hz - 314 Hz) < 50 (90% C.L.)	100 hr
H 4km - L 4km	Ω_{GW} (40Hz - 314 Hz) < 70 (90% C.L.)	100 hr

Progress toward Design Sensitivity

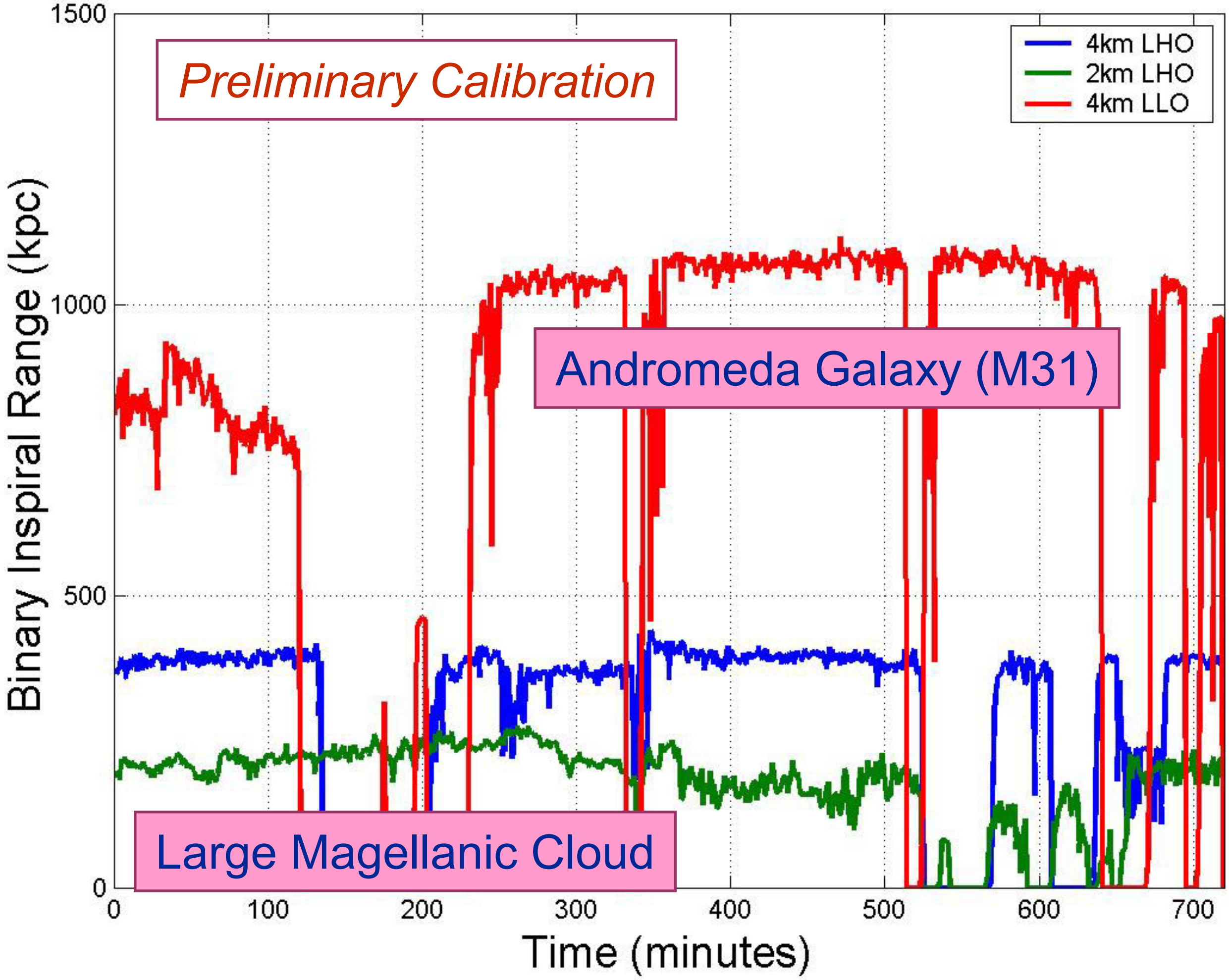


Second Science Run (S2)

- Currently underway
  - » 14 February – 14 April 2003 (~4 times S1)
- Three LIGO interferometers, plus TAMA (Japan)
  - » GEO attempting to get on-line in time to participate
- Dramatic improvement in sensitivity
  - » Range for binary neutron star inspiral up to ~1 Mpc
- Duty cycle approximately the same as S1,
  - » but new record for longest locked stretch – 66 hours
- Analysis results expected by fall 2003
  - » Probably upper limits again, but detection not impossible

Virgo Cluster

Greatly Increased Range

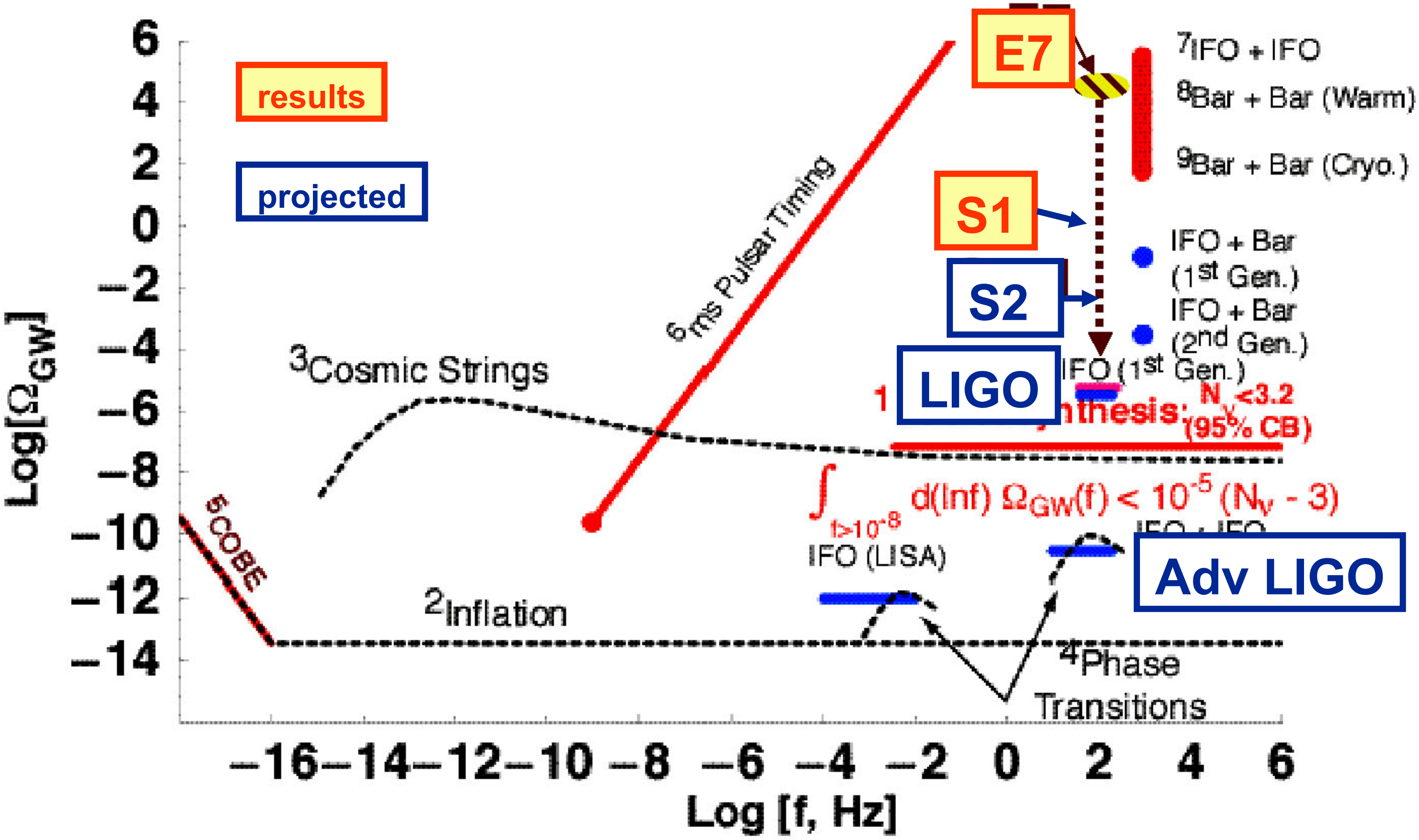


Preliminary Calibration

Andromeda Galaxy (M31)

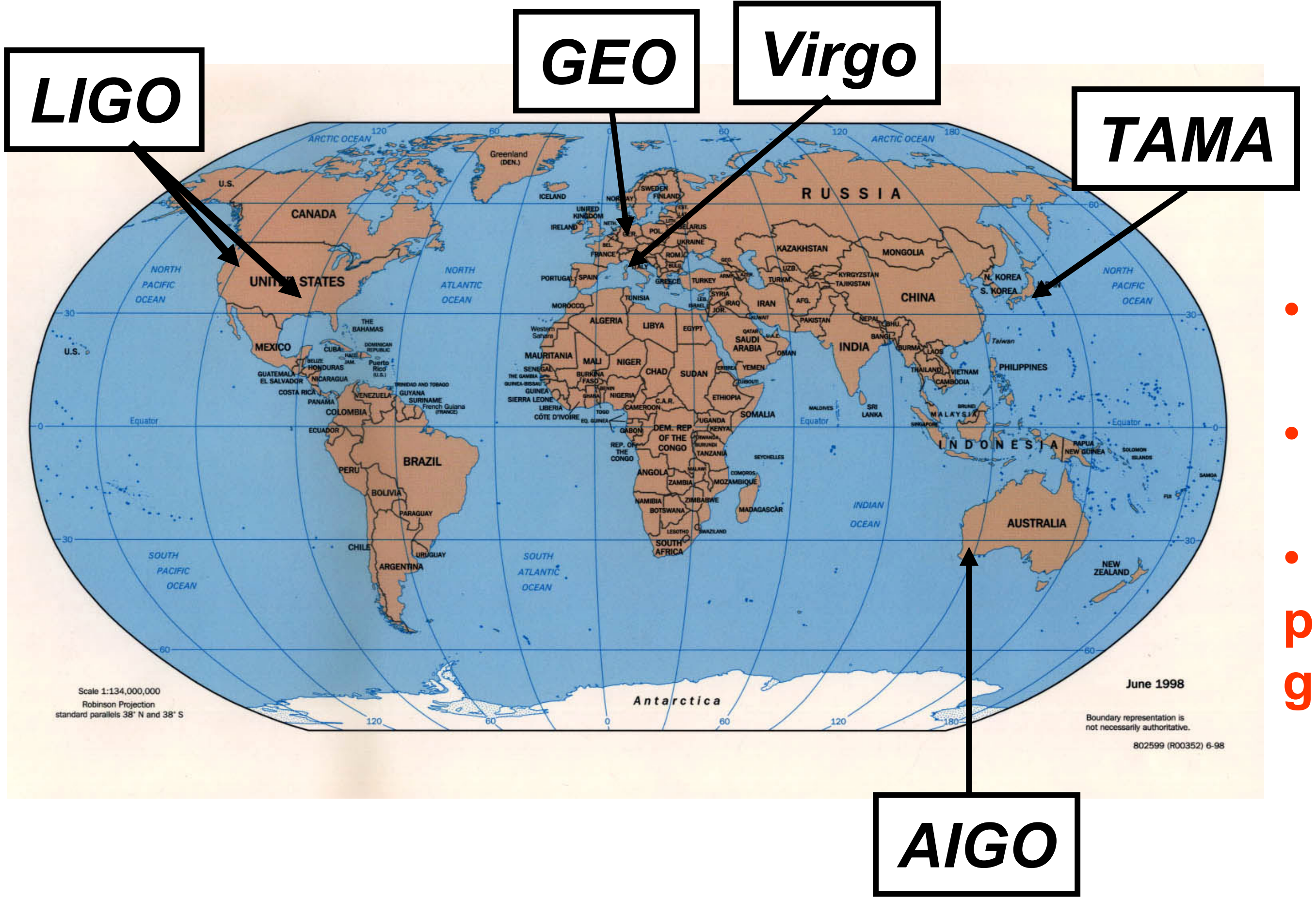
Large Magellanic Cloud

Stochastic Background
sensitivities and theory



Toward a Global Network of GW Detectors

Simultaneously detect signal (within msec)



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

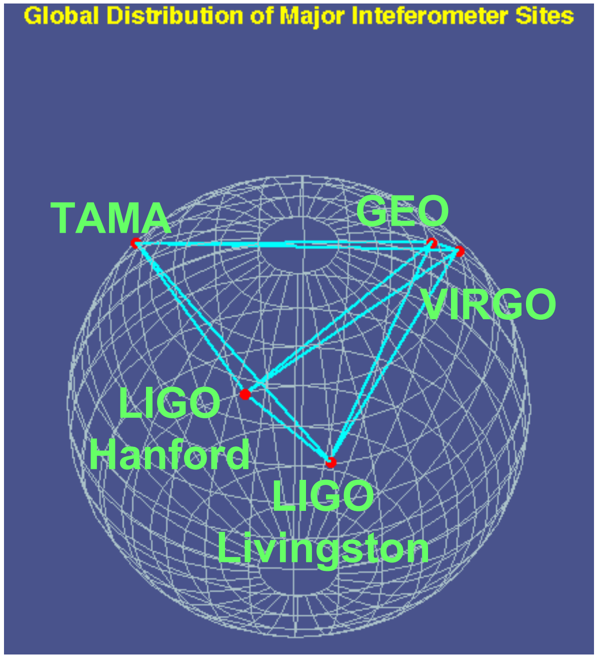
GW Detectors around the World

AIGO
Australia

Virgo
Italy

GEO 600
Germany

Event Localization with Detector Array (“Imaging with GWs”)



SOURCE

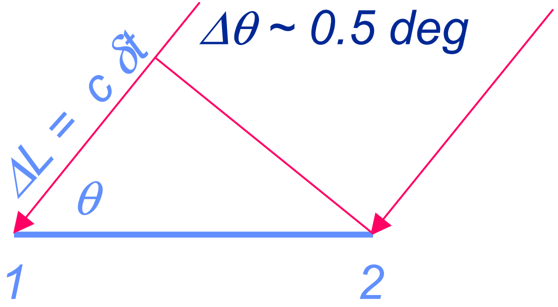
SOURCE

SOURCE

SOURCE

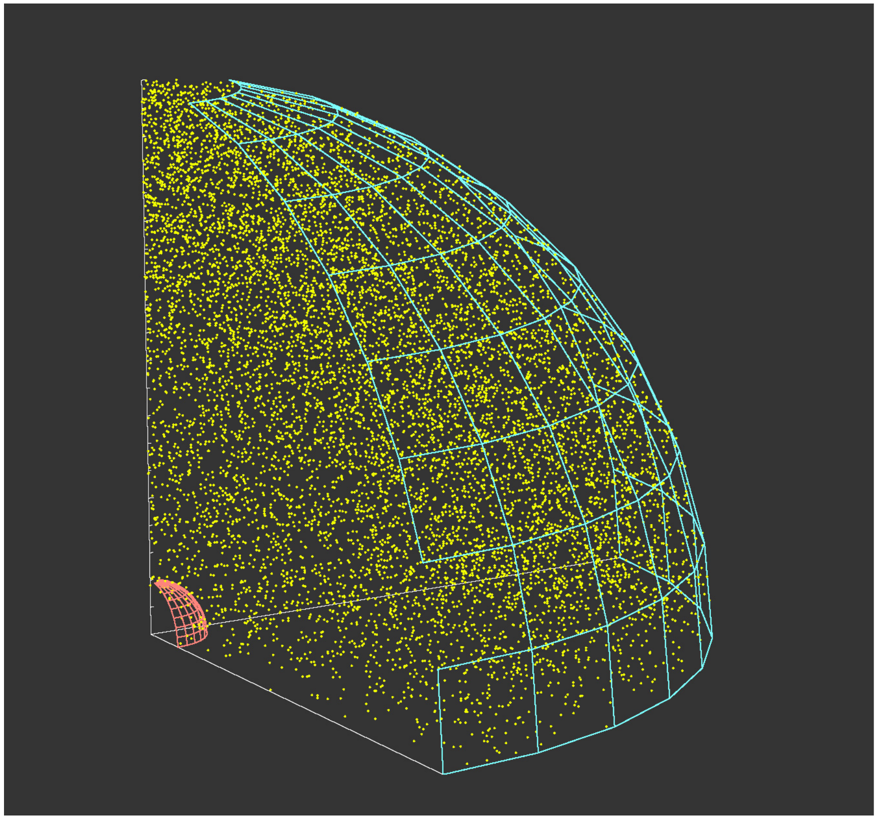
$$\Delta\theta \sim c\,\delta t\ / D_{12}$$

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



Advanced LIGO

- Next detector
  - » Must be of significance for astrophysics
  - » Should be at the limits of reasonable extrapolations of detector physics and technologies
  - » Should lead to a realizable, practical, reliable instrument
  - » Should come into existence neither too early nor too late
- Advanced LIGO: ~2.5 hours = 1 year of Initial LIGO
  - » Volume of sources grows with cube of sensitivity
  - » >10x in sensitivity; ~ 3000 in rate

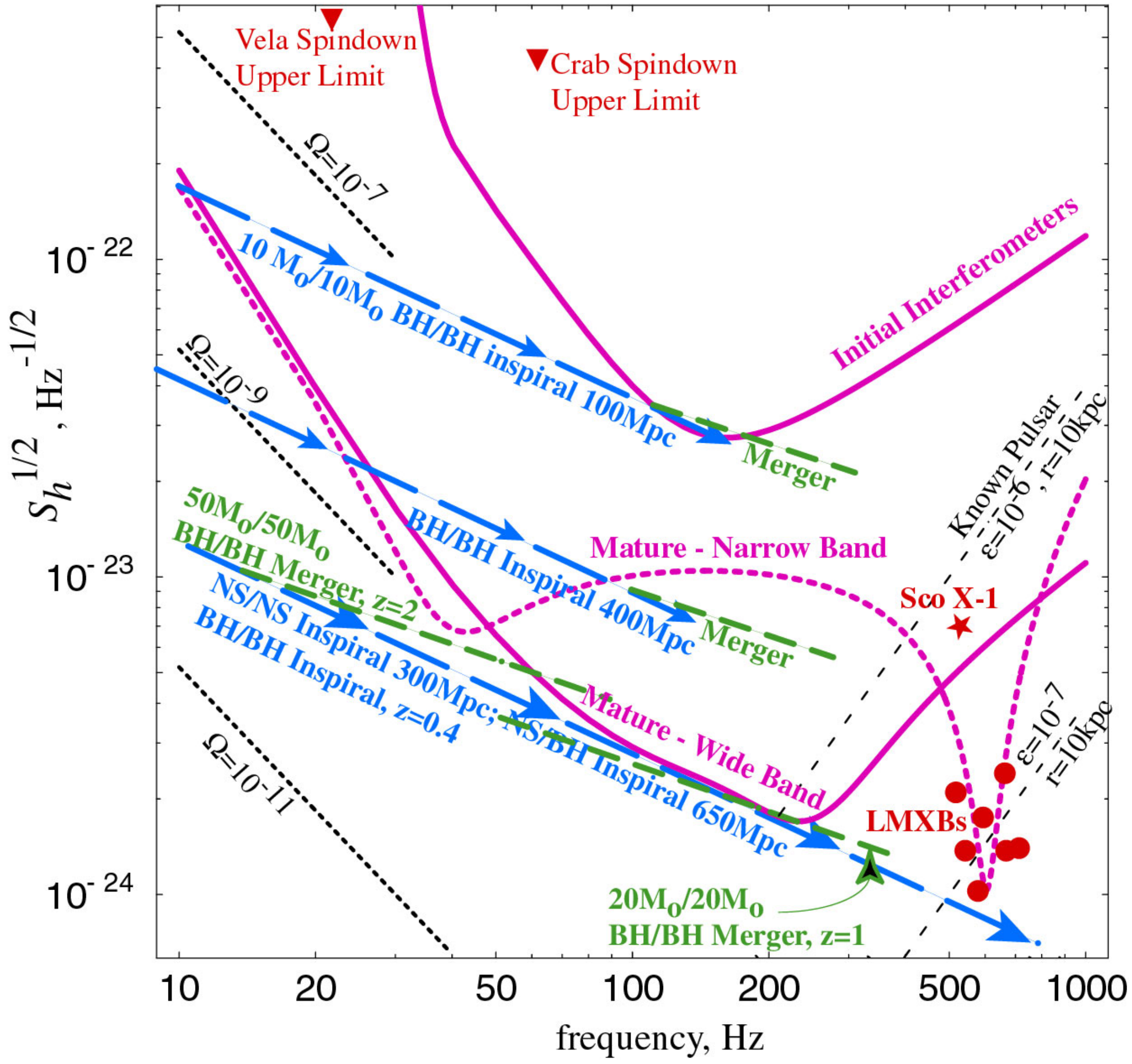


- » Begin installation: 2007
- » Operational: 2008-9

Astrophysical Reach

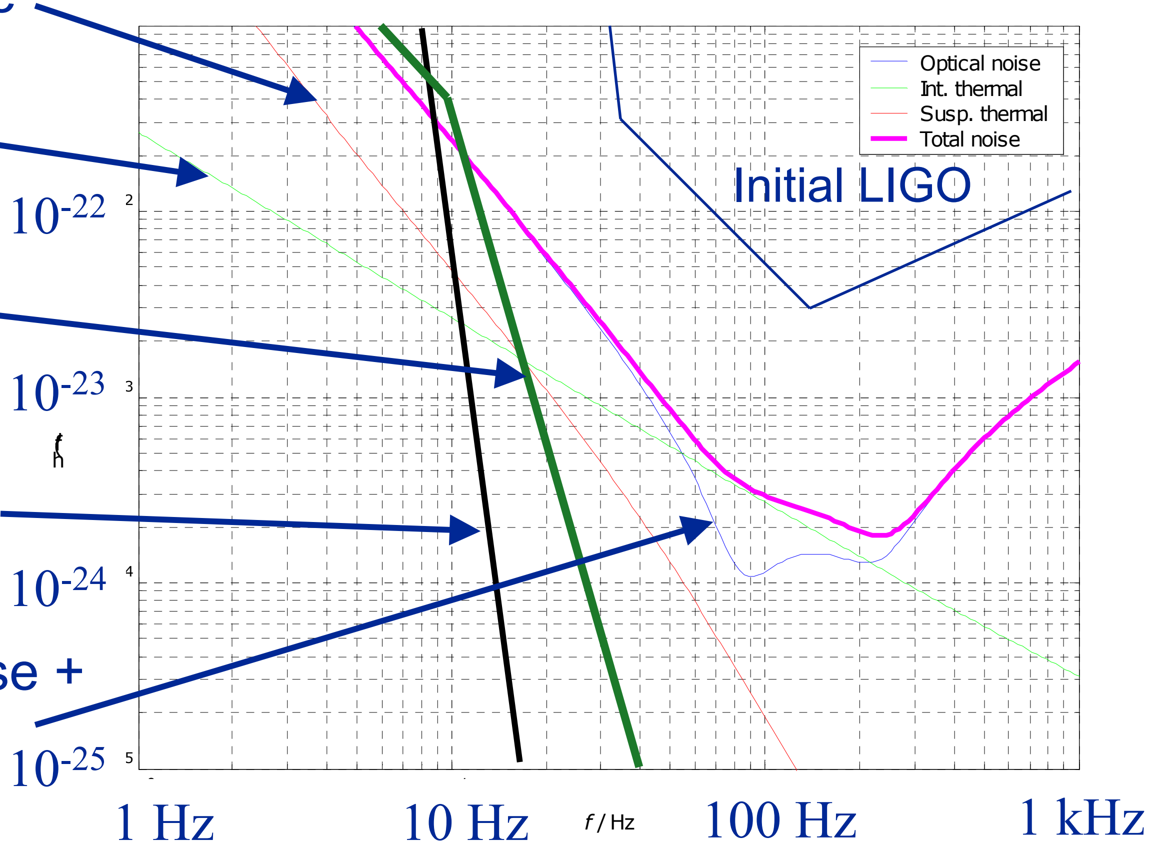
(Kip Thorne)

- Neutron Star & Black Hole Binaries
  - » inspiral
  - » merger
- Spinning NS's
  - » LMXBs
  - » known pulsars
  - » previously unknown
- NS Birth (SN, AIC)
  - » tumbling
  - » convection
- Stochastic background
  - » big bang
  - » early universe



Anatomy of the Projected Adv LIGO Detector Performance

- Suspension thermal noise
- Internal thermal noise
- Newtonian background, estimate for LIGO sites
- Seismic ‘cutoff’ at 10 Hz
- Quantum noise (shot noise + radiation pressure noise) dominates at most frequencies



Beyond Advanced LIGO?

- Third generation GW interferometers will have to confront (and beat) the uncertainty principle
- Standard Quantum Limit (early 1980's)
  - » Manifestation of the "Heisenberg microscope"
  - » Shot noise ~ $P^{-1/2}$
  - » Radiation pressure noise ~ $P^{1/2}$
  - » Together define an optimal power and a maximum sensitivity for a "conventional" interferometer
- Resurgent effort around the world to develop sub-SQL measurements ("quantum non-demolition")
  - » Require non-classical states of light, special interferometer configurations, …
- But that's a story for another time….

Final Thoughts

- We are on the threshold of a new era in GW detection
- First results from LIGO will be released within a few weeks
  - Upper limits -- nothing unexpected -- but improving rapidly
- A worldwide network is starting to come on line
  - Program underway for future generations of detectors required to fully exploit the “gravitational wave window”