The Detection of Gravitational Waves

Barry Barish
Caltech Board of Trustees

April 8, 1997

LIGO

LIGO-G970121-00-M

LIGO
Introduction

- Laser Interferometer Gravitational Wave Observatory
  - » **DIRECT** Detection of Gravitational Waves

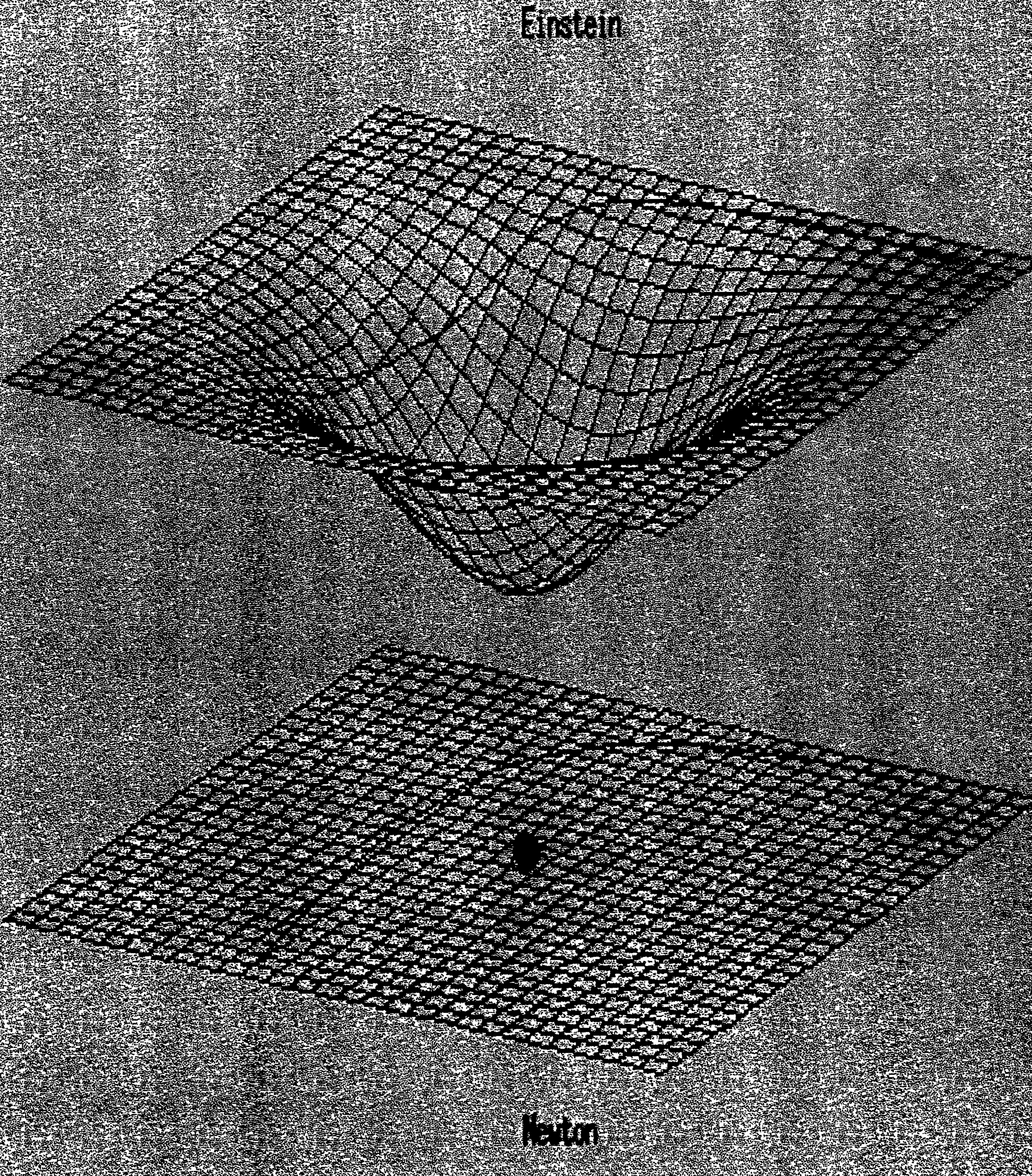
- Joint Caltech/MIT Project funded by the National Science Foundation

- Under Construction
  - » Two Sites -- Louisiana and Washington

The Science

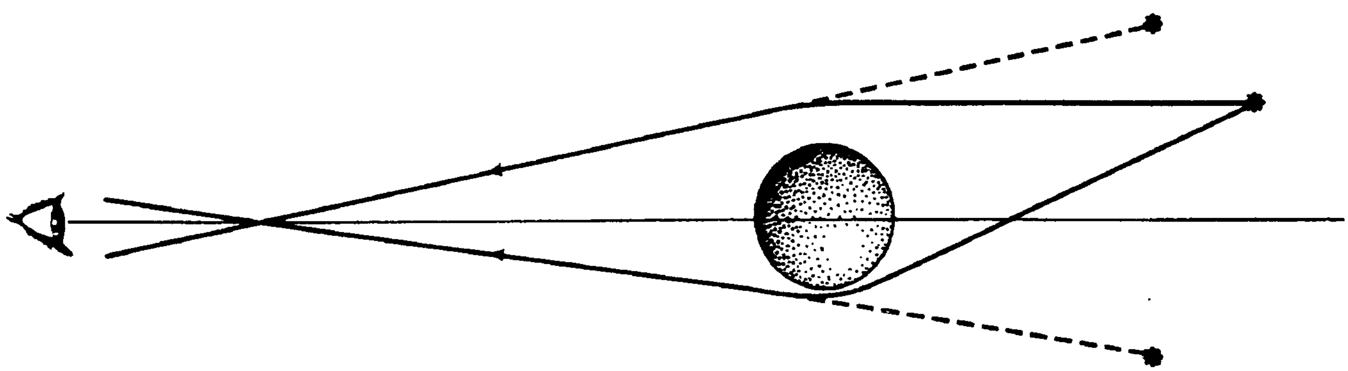
- Newtonian Gravity has instaneous action at a distance
  - » a problem
- Einstein general relativity theory describes gravity as due to curvature of space-time
  - » evidence - bending of light rays; gravitational lensing
- The fluctuating fields give gravitational waves that propogate at speed of light
  - » evidence - Hulse Taylor experiment
- **LIGO**: Laser Interferometer Gravitational Wave Observatory
  - » Direct detection of gravitational waves

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

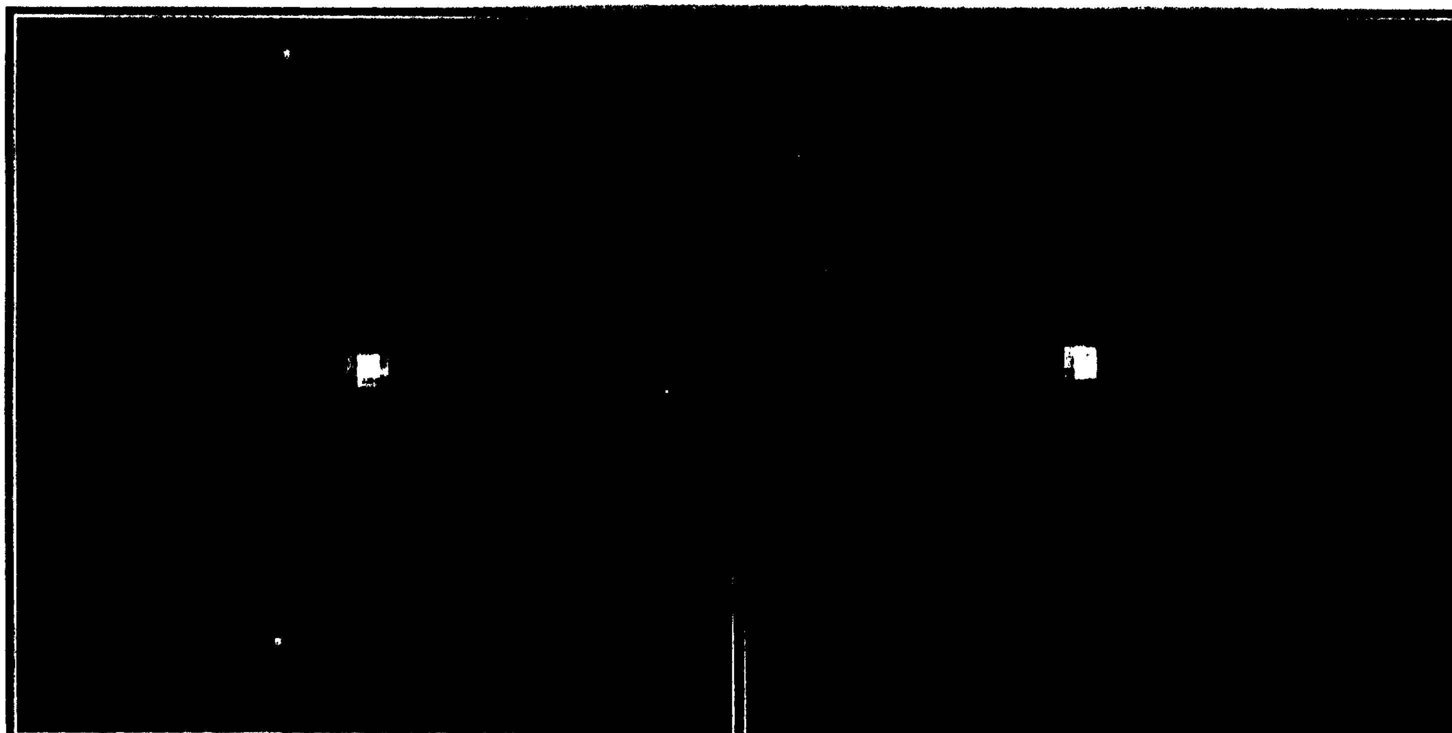


Gravitational Lenses

bending of light rays



- Multiple images from deflection of light rays in gravitational fields
- Stars or galaxies producing such images are called *gravitational lenses*
- Not true lenses, since deflection angle *decreases* with impact parameter, therefore no well-defined focal length
- Can detect *'dark matter'*

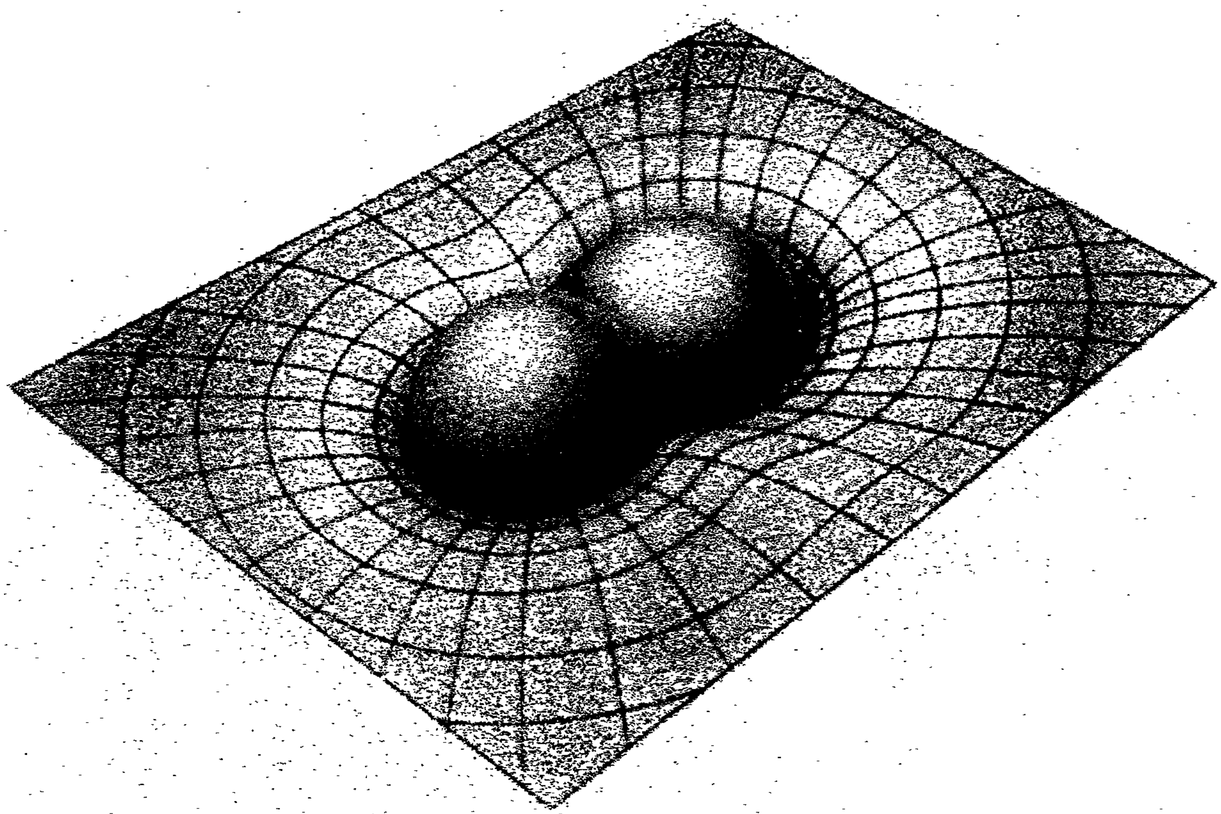


Gravitational Lenses HST • WFPC2

PRC95-43 • ST ScI OPO • October 18, 1995 • K. Ratnatunga (JHU), NASA

Compact Binary Objects

curvature of space-time

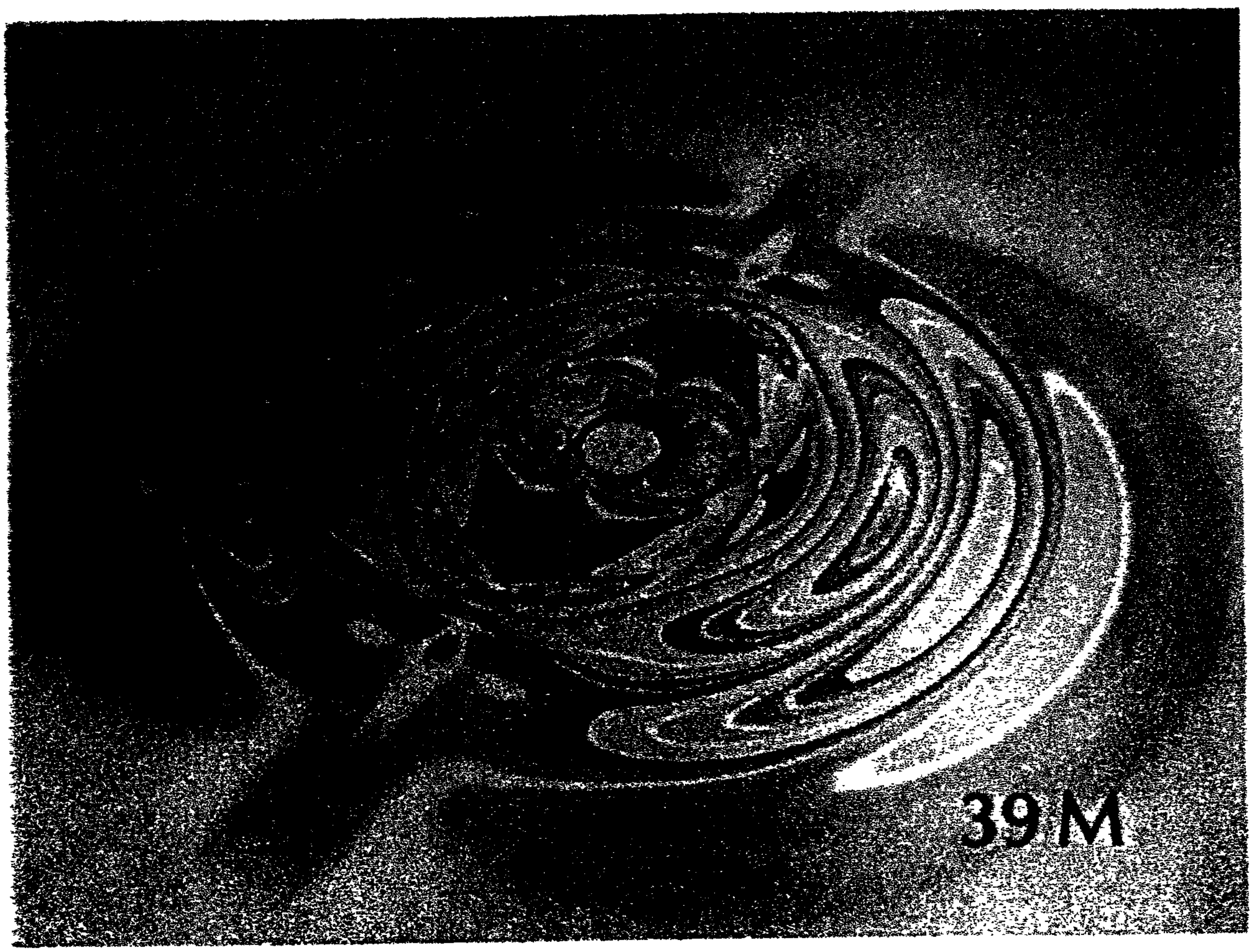


LIGO

LIGO-G960108-00-M

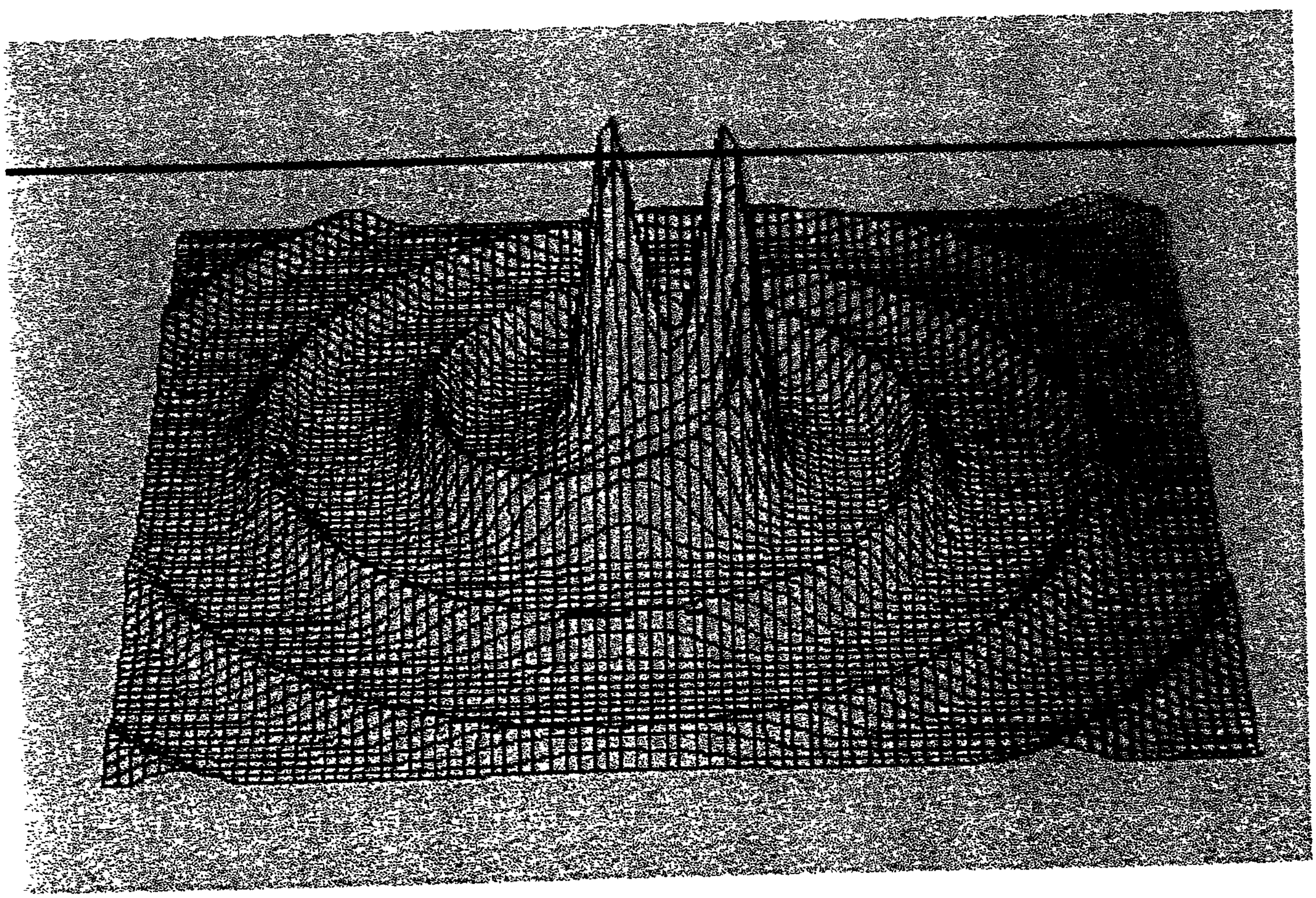
Two Black Holes Collide
gravitational wave emission

- Calculation of direct collision and emission of gravitational waves
  - » NCSA - Anninos, Hobill, Seidel, Smarr, Sven



Gravitational Waves
binary inspiral

- two large masses deform surrounding space-time
- gravitational influence travels at speed of light
- ripples emanate from the bodies
- deformations vary, depending on details

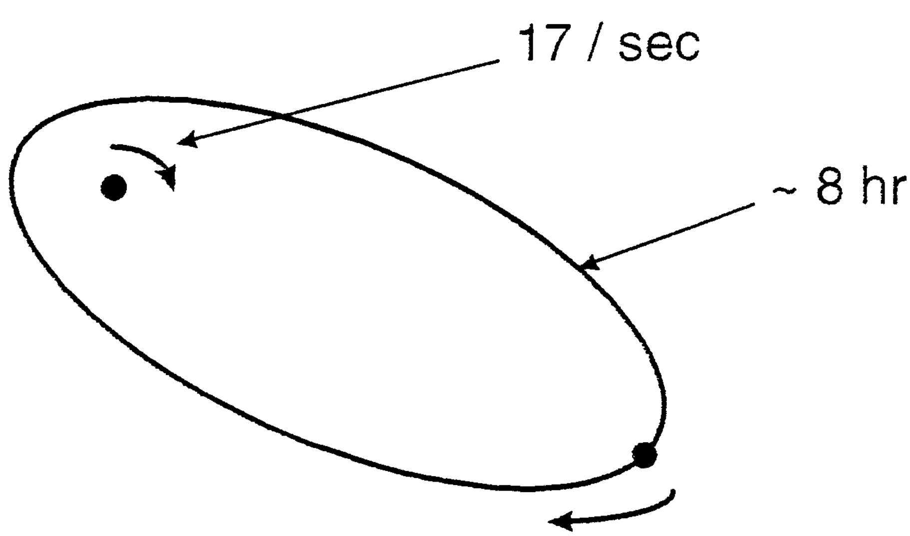


Gravitational Waves
Evidence

- **Russell Hulse and Joseph Taylor**

- Neutron Binary System
  - » PSR 1913 + 16 -- Timing of Pulsars
  - » separated by 10^6 miles
  - » m_1=1.4m_0; m_2=1.36m_o; ε = 0.617

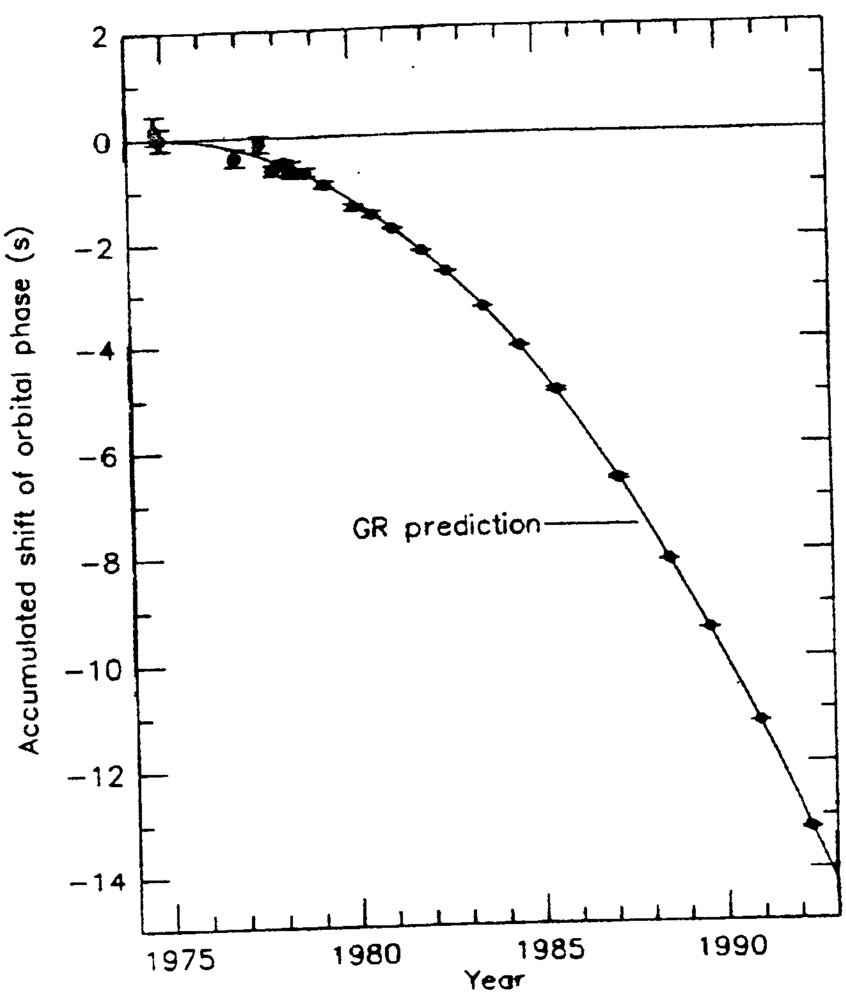
- Predictions from general relativity
  - » spiral in by 3 mm/orbit
  - » rate of change orbital period



Hulse and Taylor

timing of the orbital period

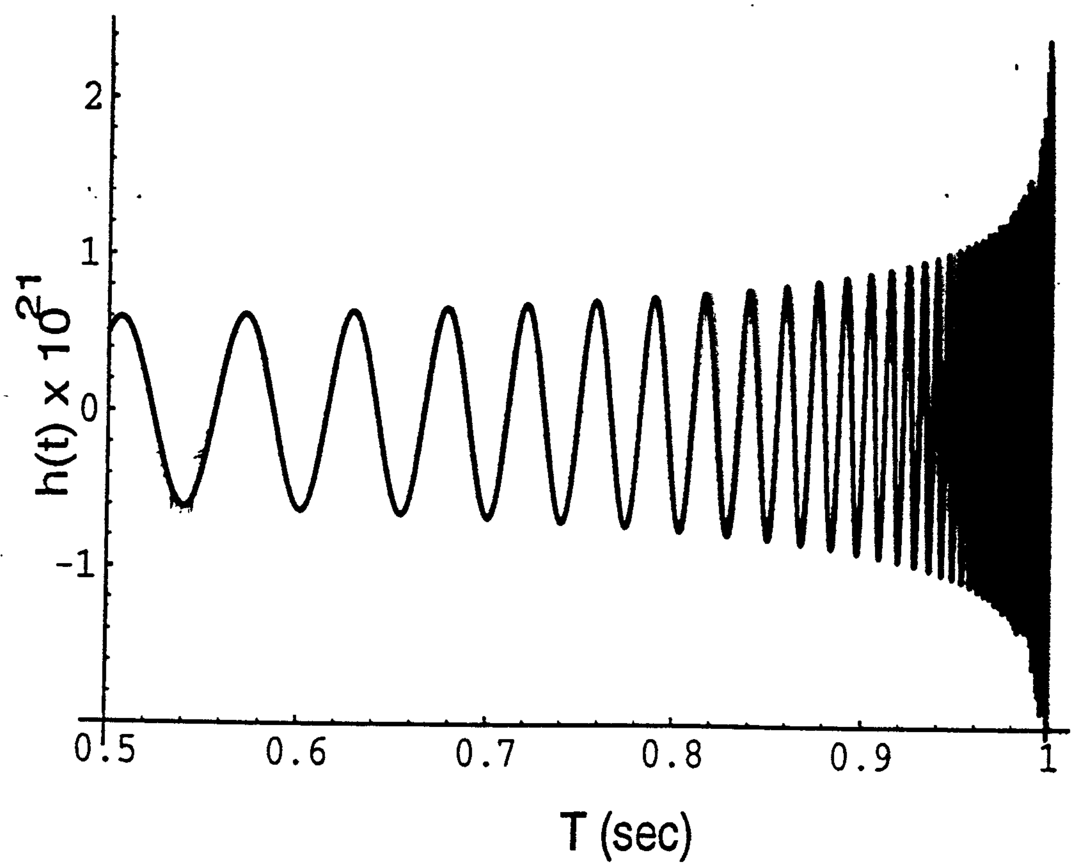
- period speeds up of 14 sec from 1975-94
  - » measured to ~50 μsec accuracy
- deviation grows quadratically with time
- due to loss of orbital energy, from the emission of gravitational waves



Neutron Binary Systems

Inspiral

- LIGO frequency band
  - » last 15 minutes (~10^4 cycles)
- 'Chirp Signal'
- Detailed waveform gives masses, spins, distance, eccentricity of orbit, etc



LIGO
Science Goals

- Final Inspiral of Binary Systems *(chirp)*
  - » Neutron Star/Neutron Star Inspiral
    - – Design Benchmark: last 15 min
      20,000 cycles
      600 MLyr
  - » Black-hole/Black-hole Inspiral and Coalescence
  - » Black-hole/Neutron Star Inspiral
- Supernovae *(burst)*
  - » Axisymmetric in our galaxy
  - » Non-axisymmetric ~300MLyr
- Periodic Sources *(track frequency)*
  - » spinning neutron stars
- Early Universe *(correlations)*
  - » Stochastic Background Radiation
- Unknown Sources

FIGURES

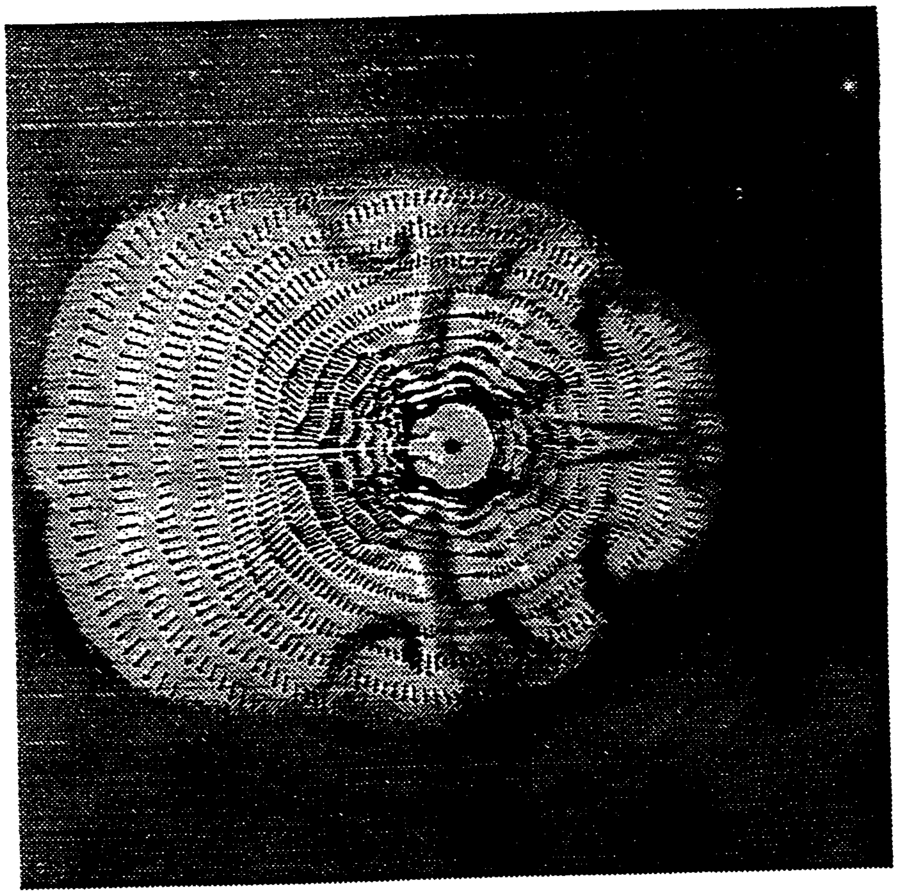


FIG. 1. A grey-scale rendering of the entropy distribution at the end of the simulation, about 50 milliseconds into the explosion. Note the pronounced pole–to–pole asymmetry in the ejecta and the velocity field (as depicted with the velocity vectors). The physical scale is 2000 km from the center to the edge. Darker colcr indicates lower entropy and $\theta = 0$ on the bulge side of the symmetry axis.

Animations from
"The Astronomers: Waves of the Future"
Used with permission of Los Angeles Public
Television station

KCET

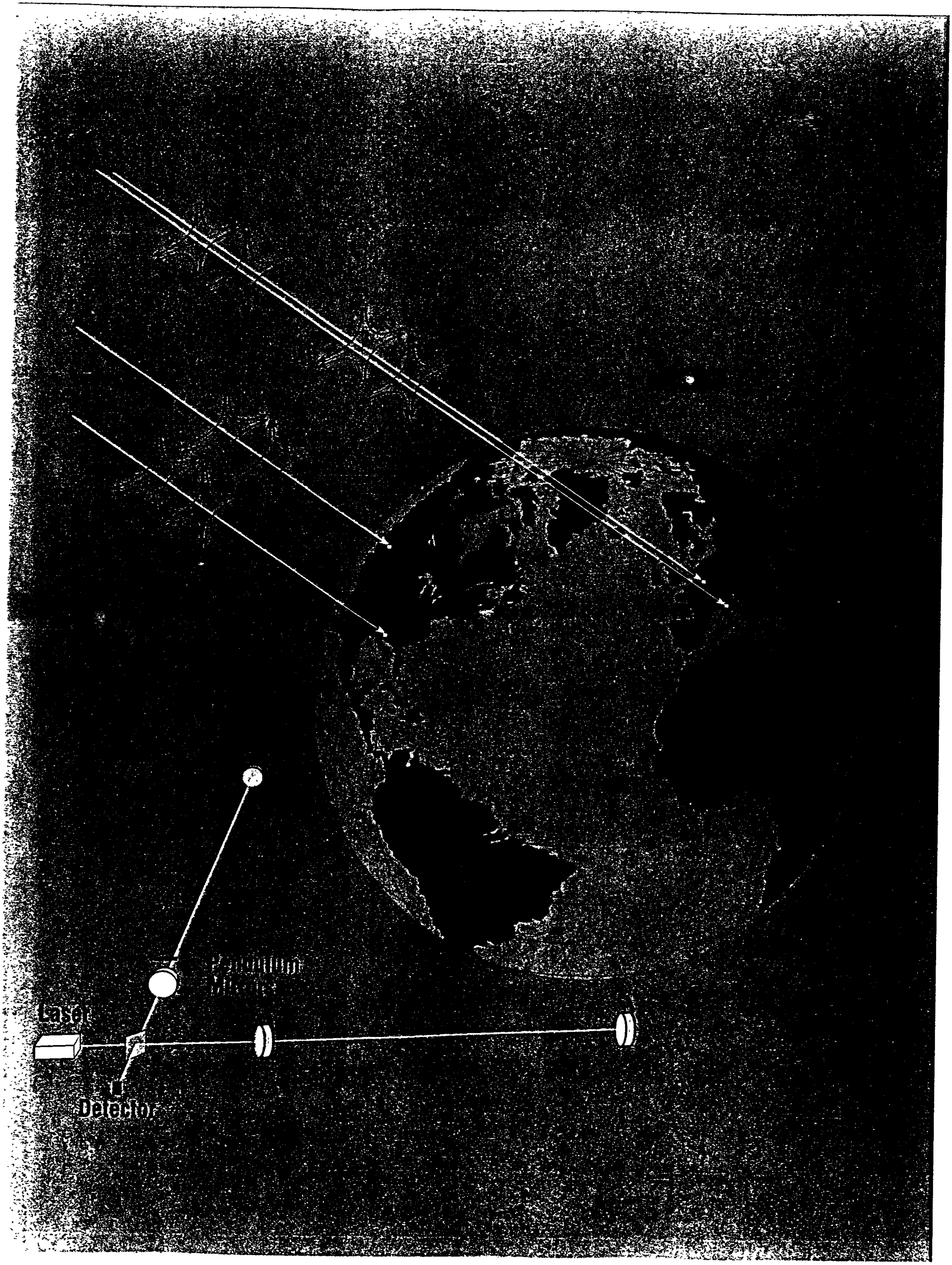
Video

1. Newton apple
2. Earth to ball curvature
3. Earth curvature
4. pass by ball
5. rotating balls →
   fade to waves
6. Info in waveform
   electrocardiogram
7. sine wave continuous
8. bursts
9. chirp
10. burst – supernova GW then light

LIGO
Scientific Mission

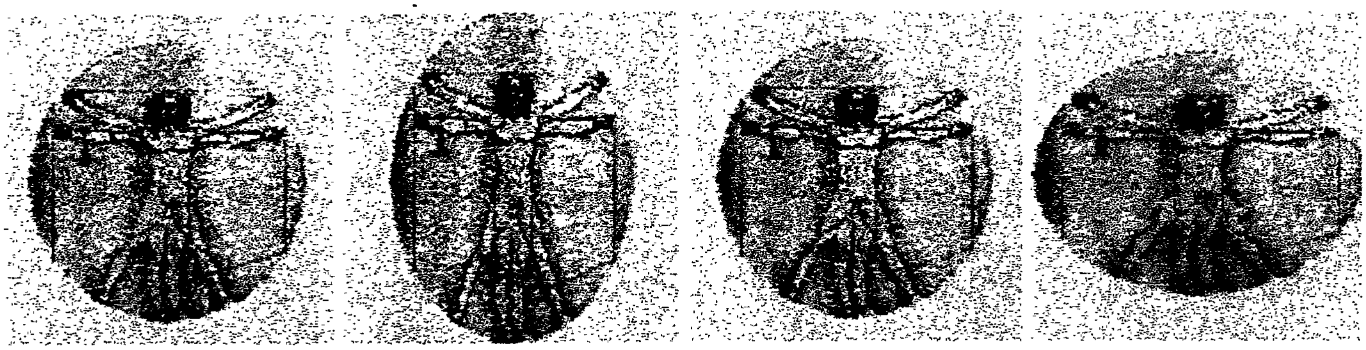
- Direct Detection of Gravitational Waves
  - Benchmark Source: Neutron Binary Coalescence
    - Detect the last 15 minutes of Hulse/Taylor type binary system (eg. 100 million years)
    - Sensitivity -- detection rate >3 year
  - Other Sources

- Fundamental Physics (GR)
  - » Test General Relativity in Strong Field and High Velocity Limit
  - » Measure Polarization and Propagation Speed


Laser
Detector

Gravitational Waves
the effect

Leonardo da Vinci's Vitruvian man

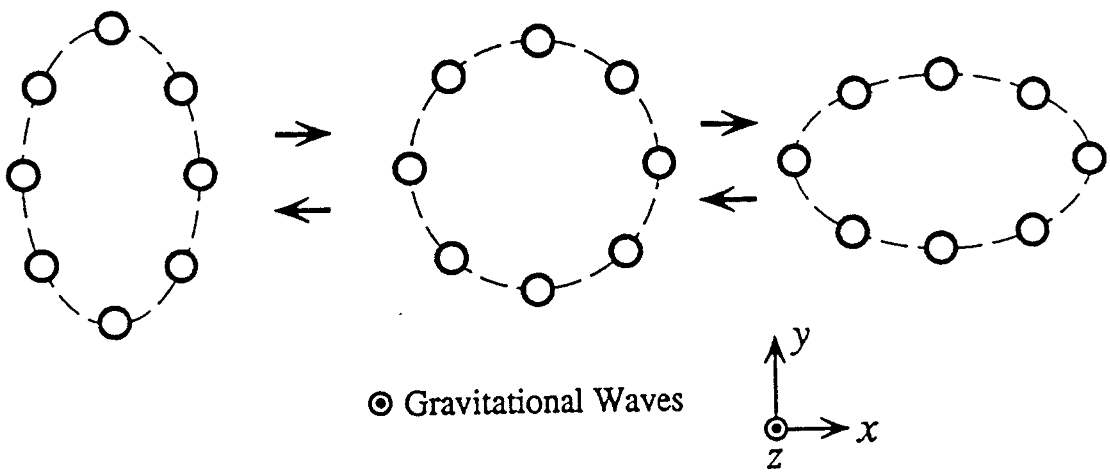


- stretch and squash in perpendicular directions at the frequency of the gravitational waves

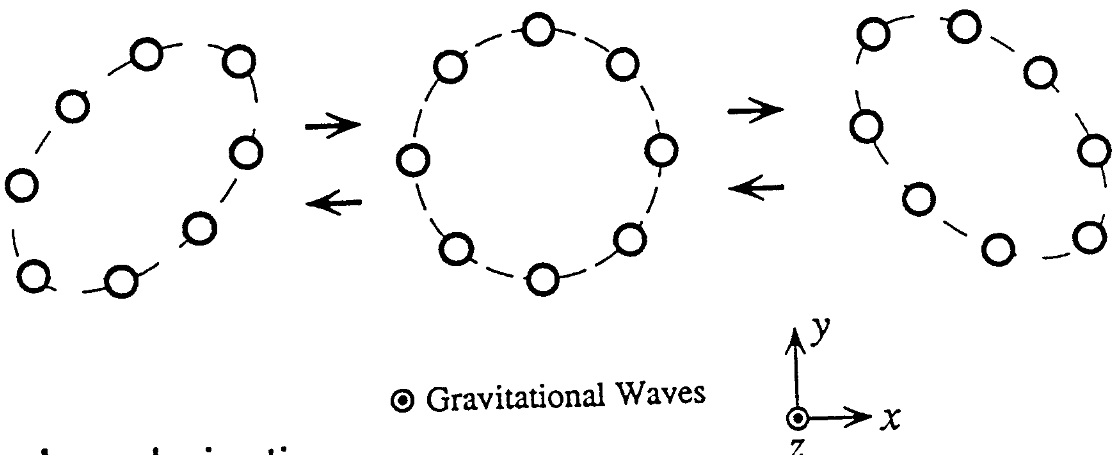
- The effect is greatly exaggerated!!
  - » if the man was 4.5 light years high, he would grow by only a 'hairs width'
  - » for LIGO (4 km), stretch (squash) = 10^{-18} m will be detected at frequencies of 10 Hz to 10^4 Hz. It can detect waves from a distance of 600 10^6 light years

Gravitational Waves
Effects

- Displacement of free particles

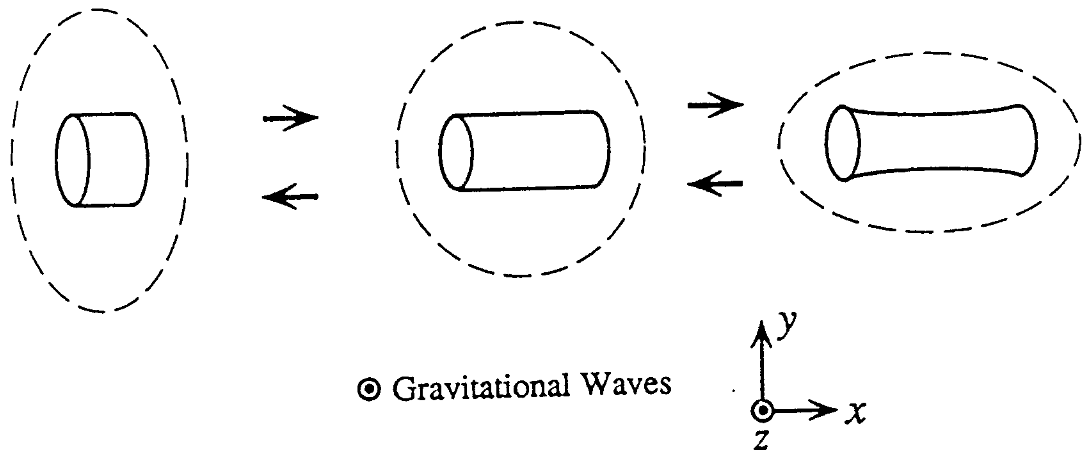


» h_+ polarization

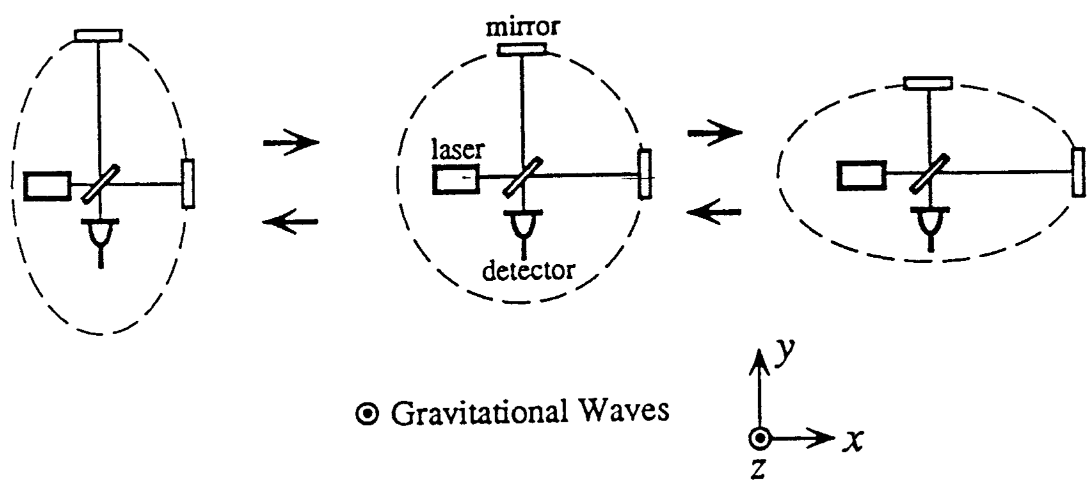


» h_x polarization

Gravitational Waves
Detection

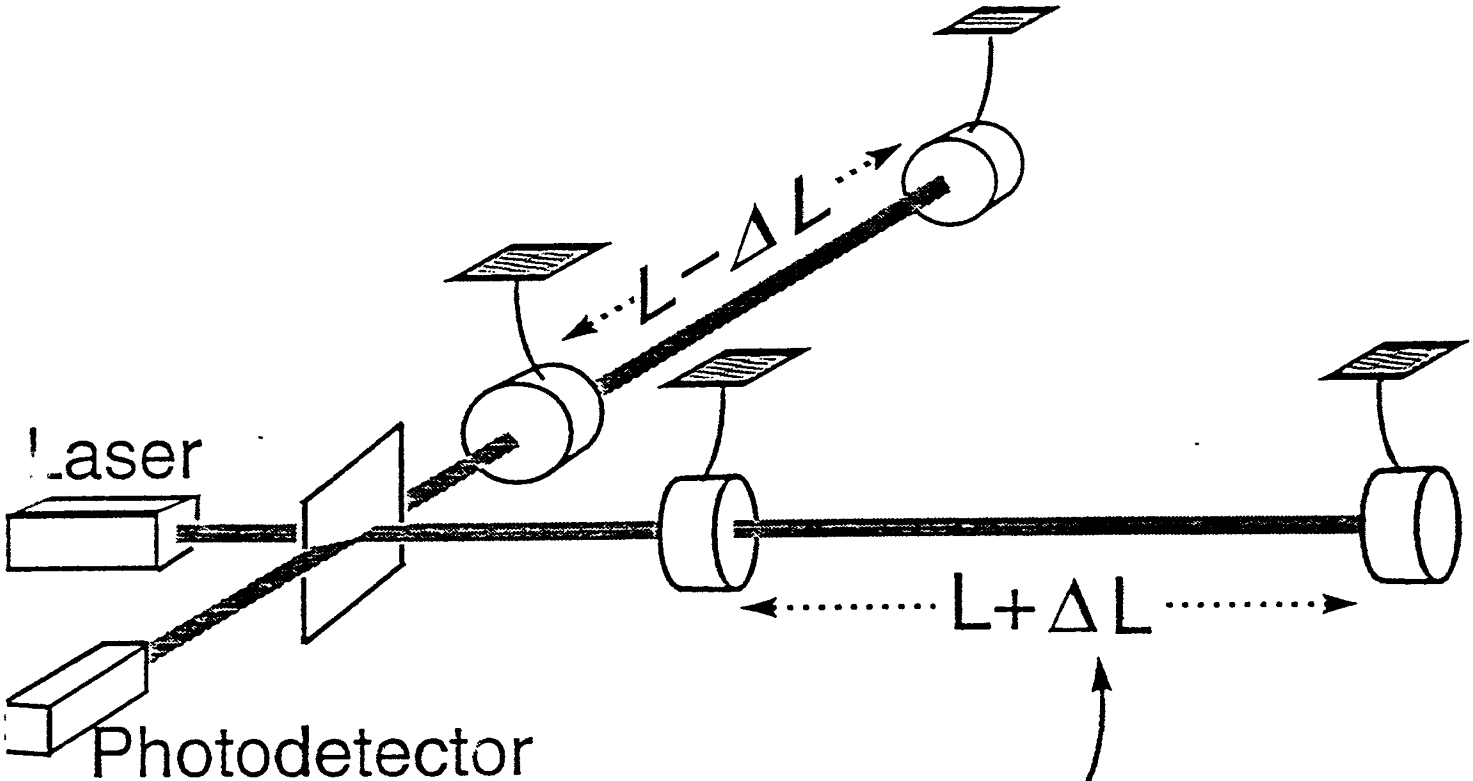


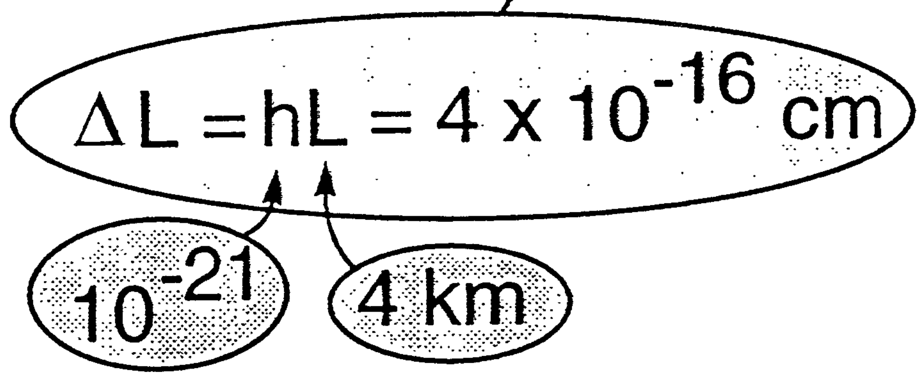
- Bar detector



- Interferometer detector

LIGO INTERFEROMETERS



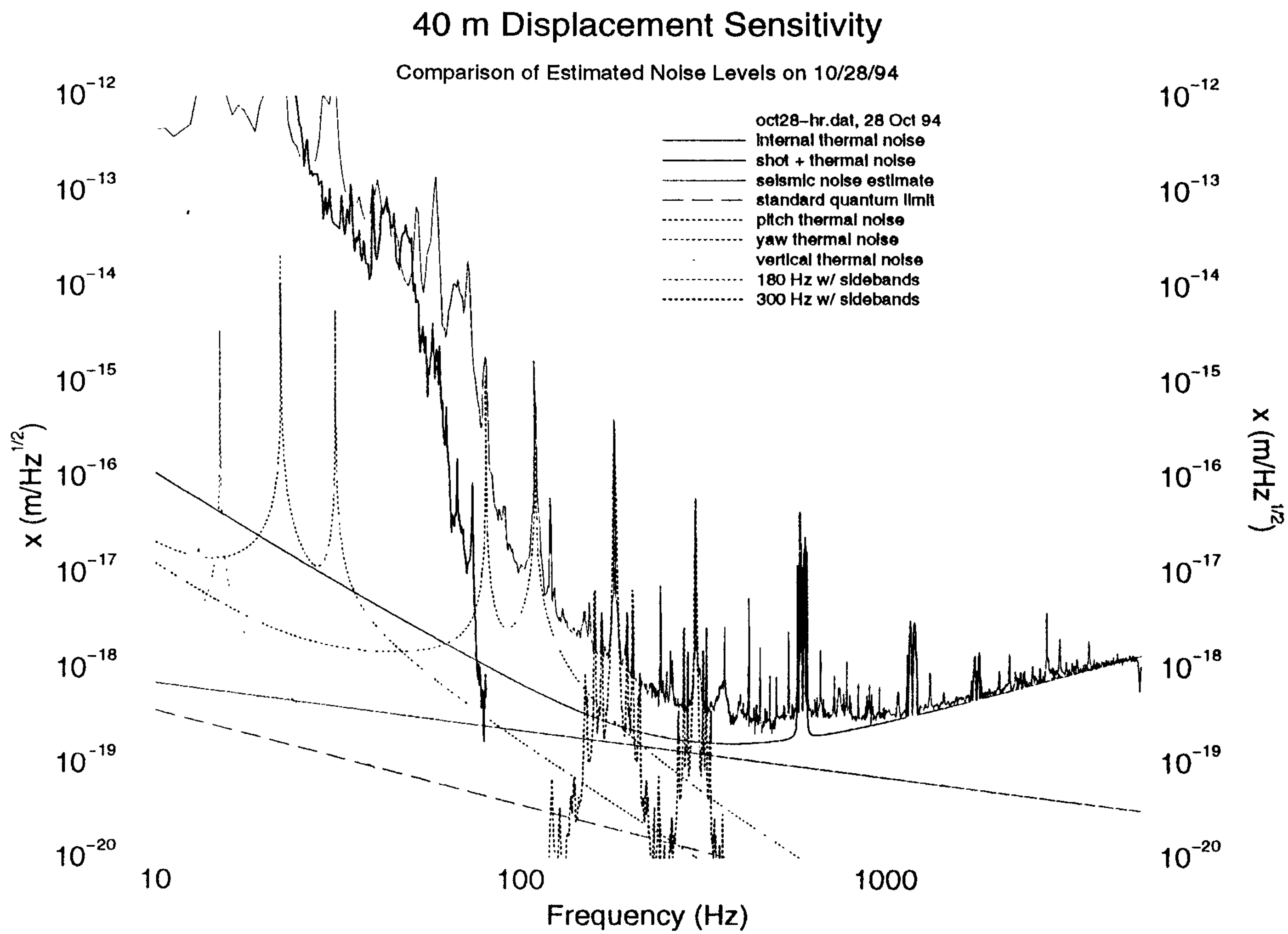


- To make ΔL large enough for detection requires $L \gtrsim 4$ km

- Measured waveform, h(*time*) = ΔL/L, is a linear combination of h_+ and h_x , which depends on interferometer's orientation

LIGO Systems Engineering and Integration

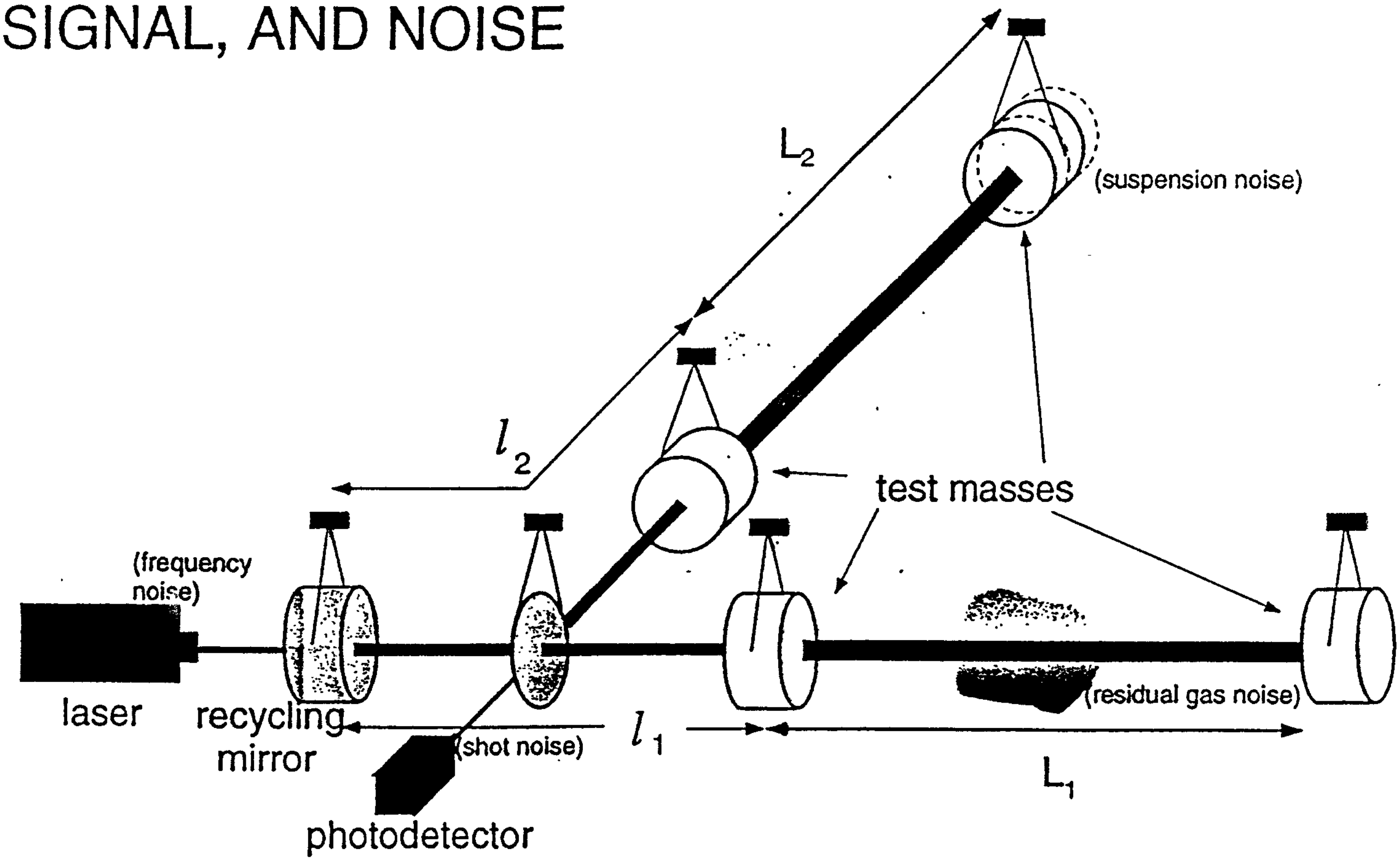
40 m Lab



Interferometer

Noise Limitations

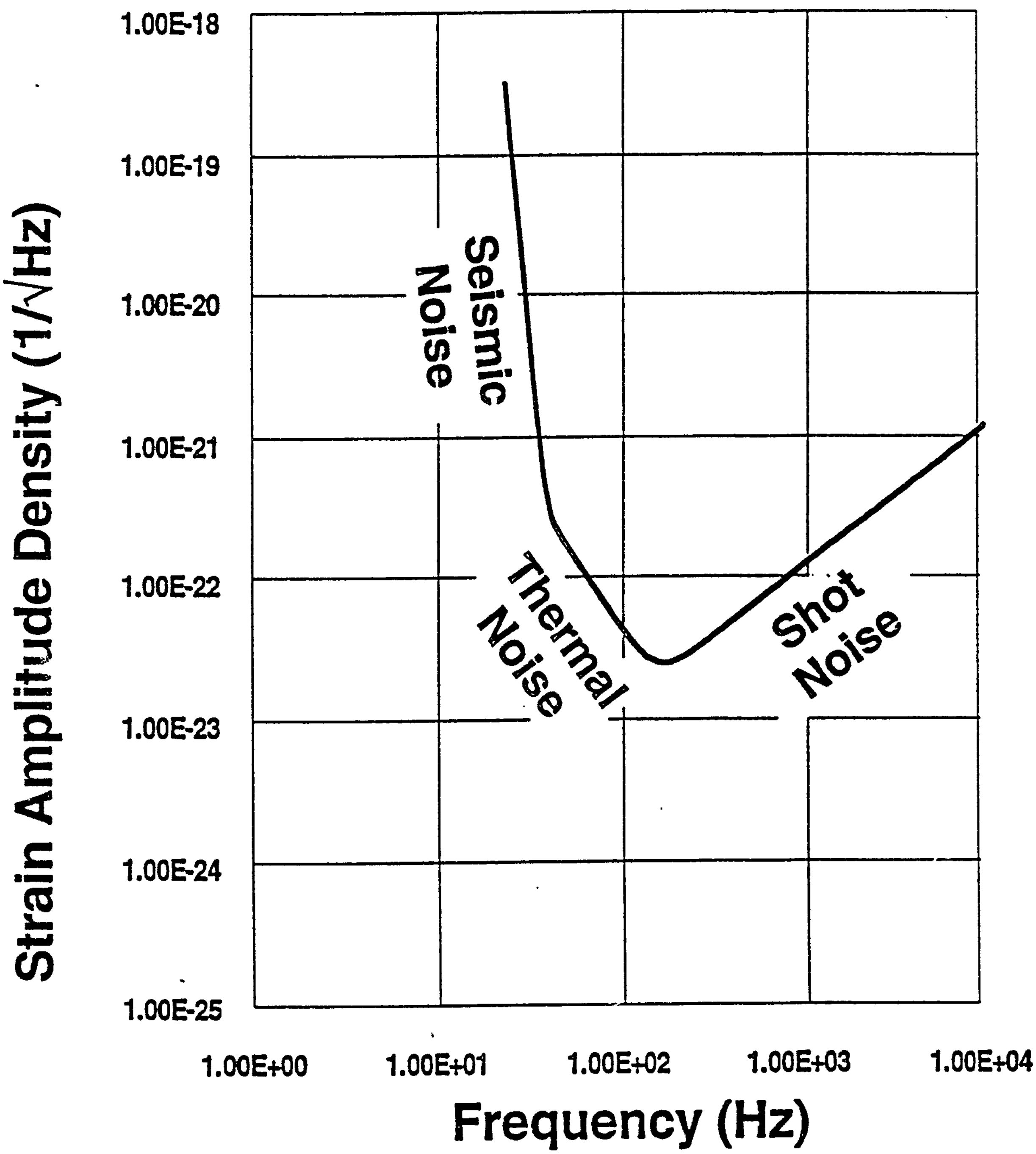
INTERFEROMETER,
SIGNAL, AND NOISE



SIGNAL = $L_1 - L_2$

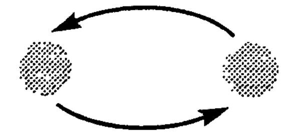
Initial Interferometers

Noise Floor

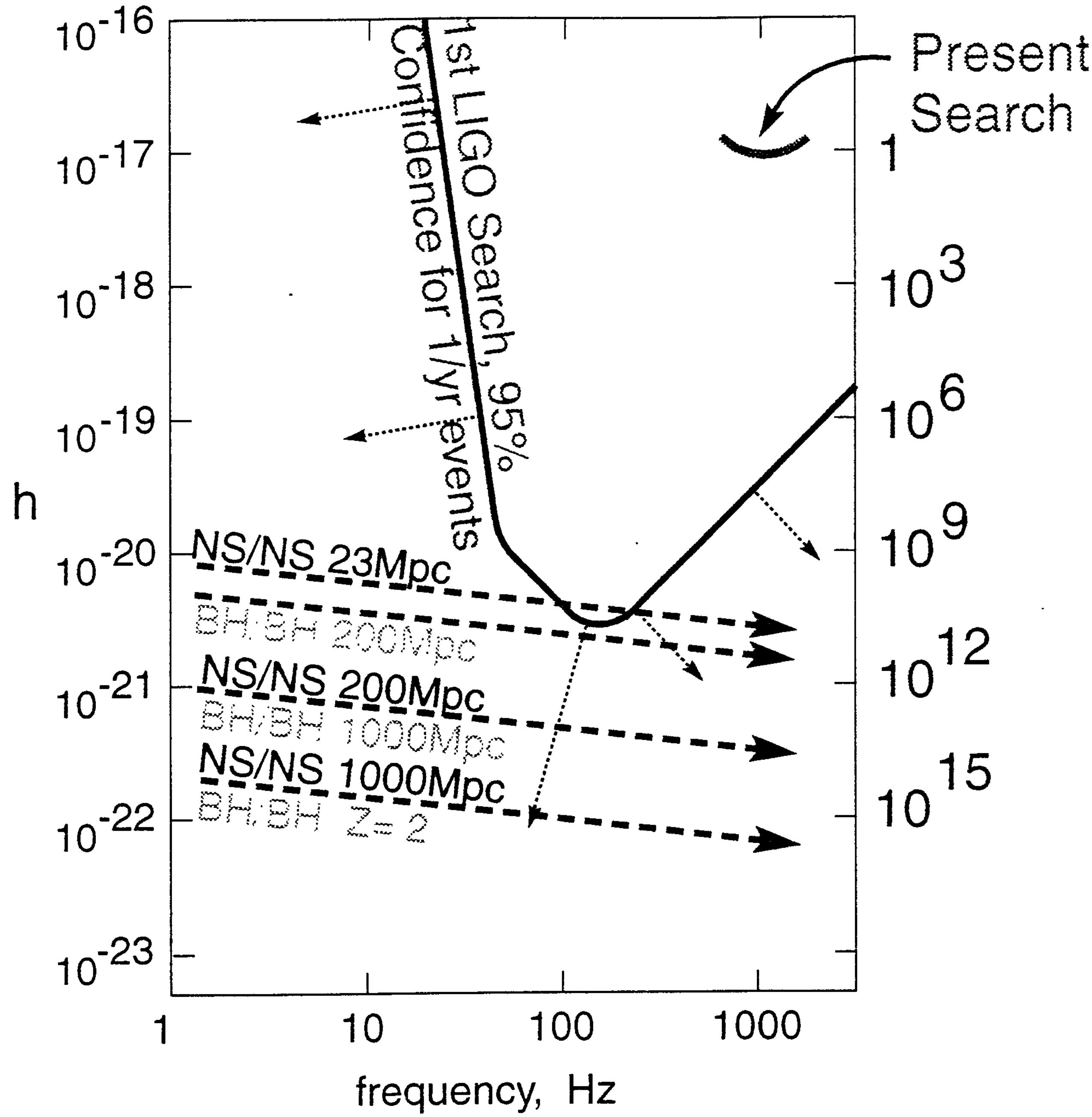


LIGO

NEUTRON STAR BINARIES



["Near-Guaranteed" source]

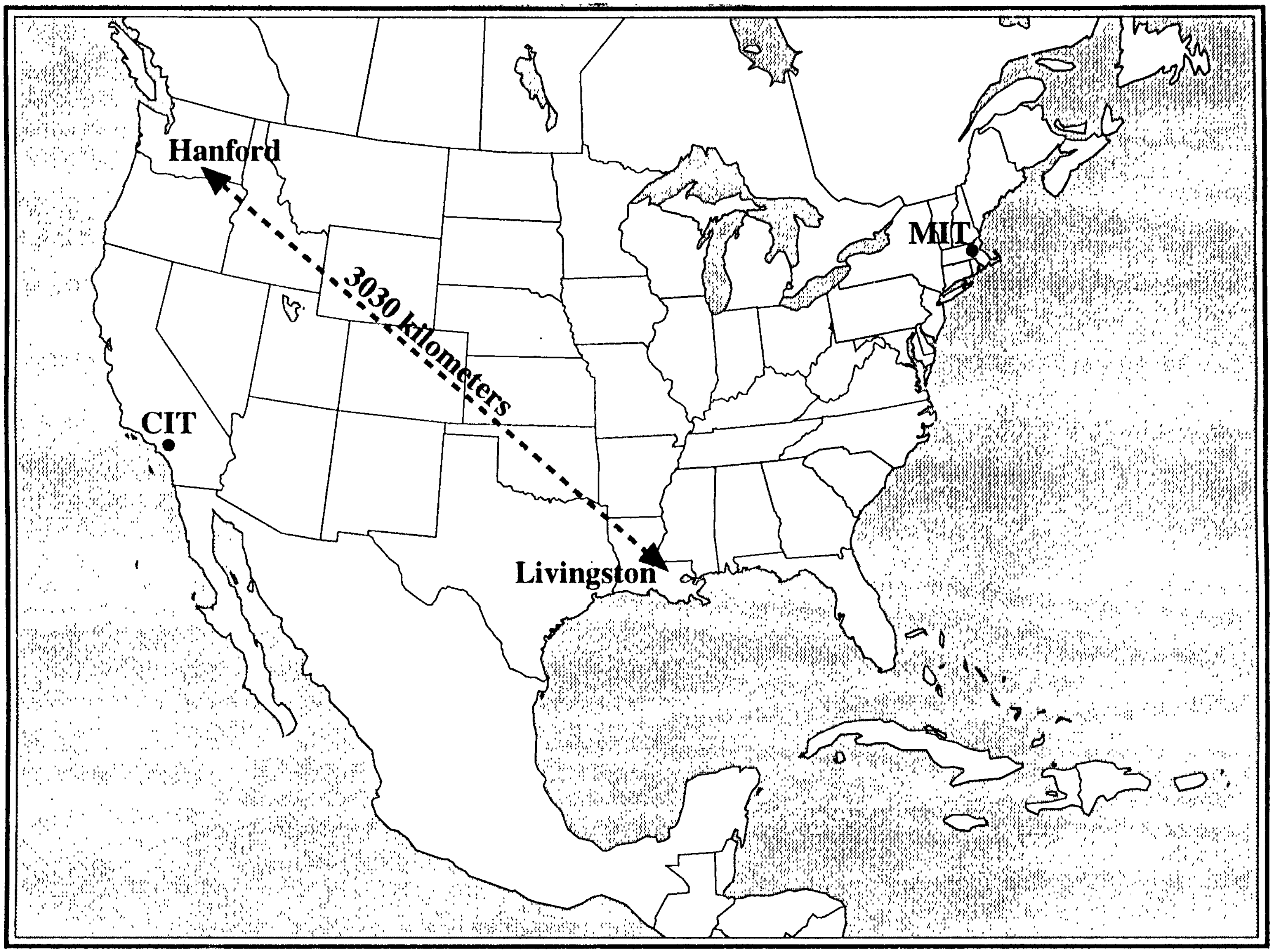


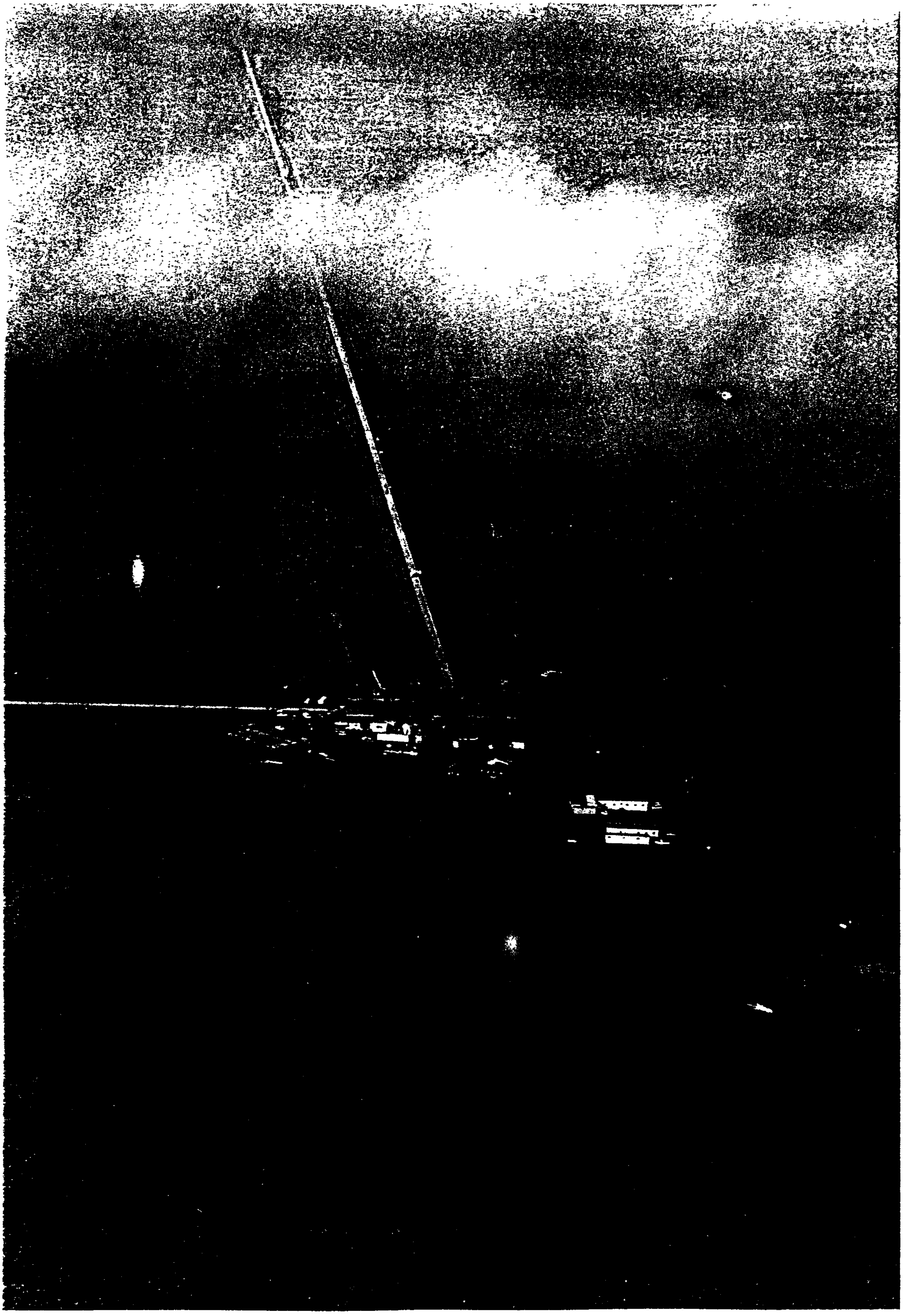
- *15 minutes &10,000 orbits in LIGO band*
- *Rich information in waveforms: masses, spins, distance, direction, nuclear equation of state*

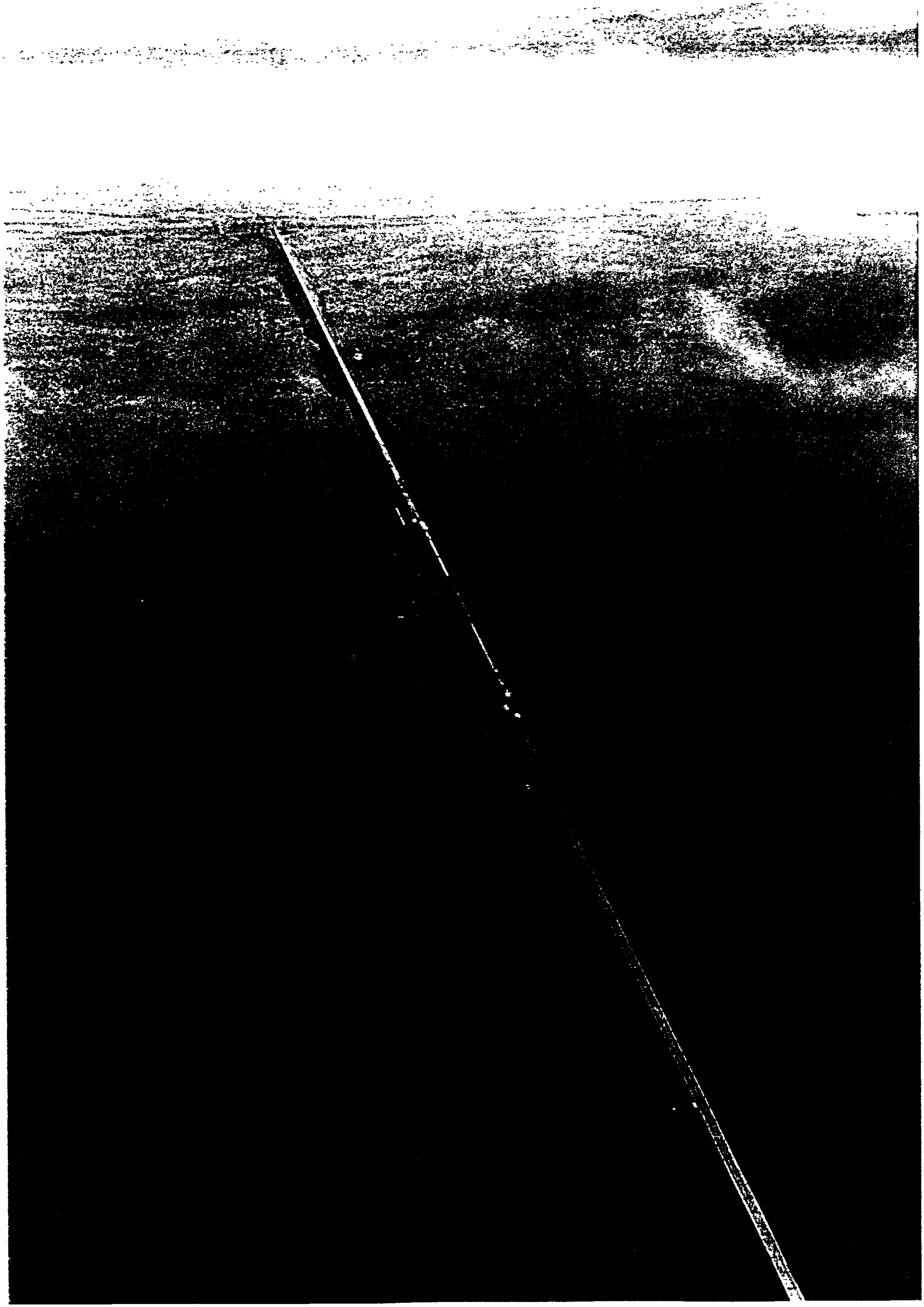
LIGO Plans

- Main Activity

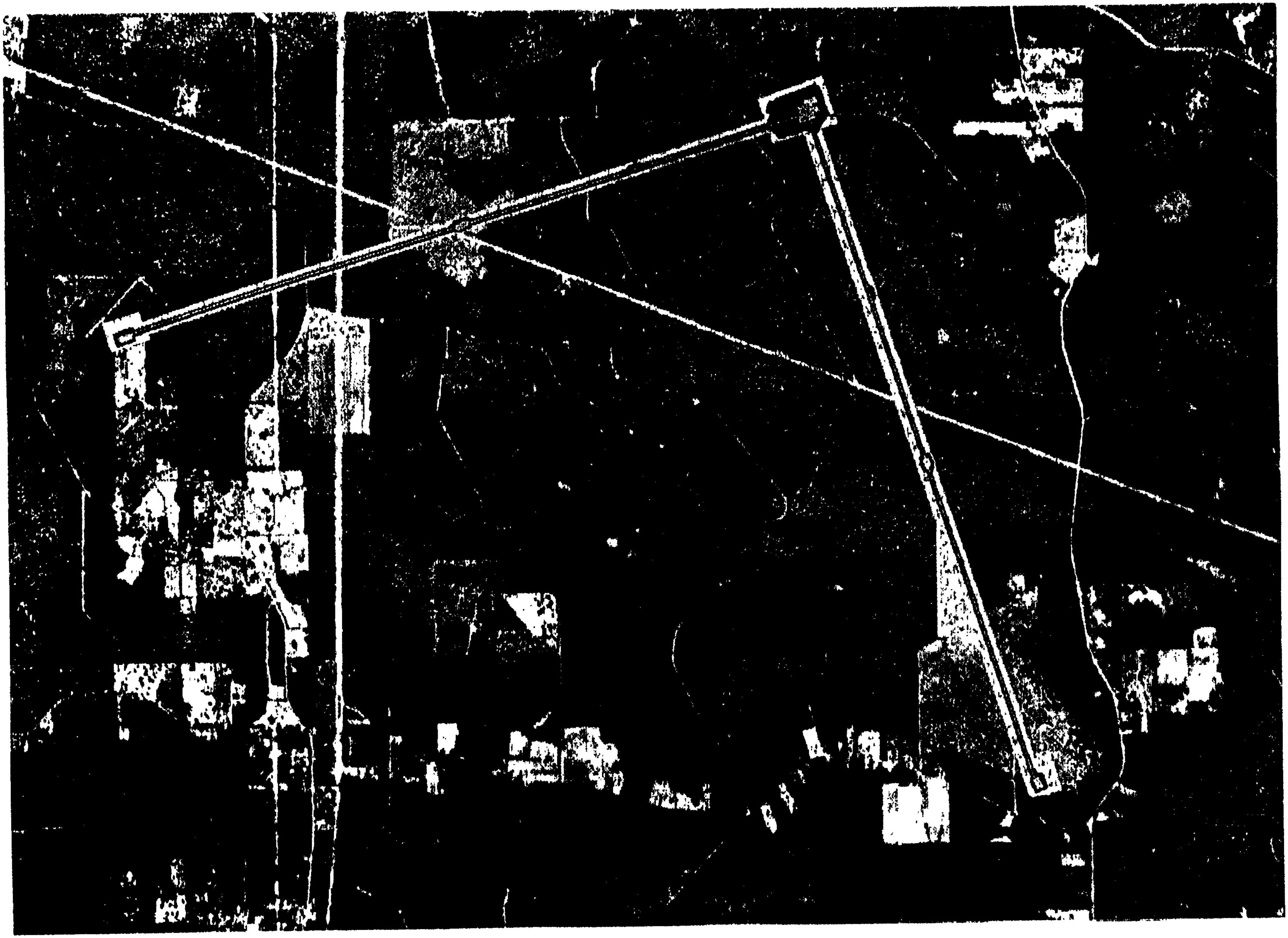
1996	Construction Underway	
		-mostly civil
1997	Facility Construction	
		-vacuum system
1998	Interferometer Construction	
		-complete facilities
1999	Construction Complete	
		-interferometers in vacuum
2000	Commission Detectors	
		-first light; testing
2001	Engineering Tests	
		-sensitivity; engineering run
2002	Initial LIGO Detector Run	
		- $h \sim 10^{-21}$


Hanford
3030 kilometers
MIT
CIT
Livingston

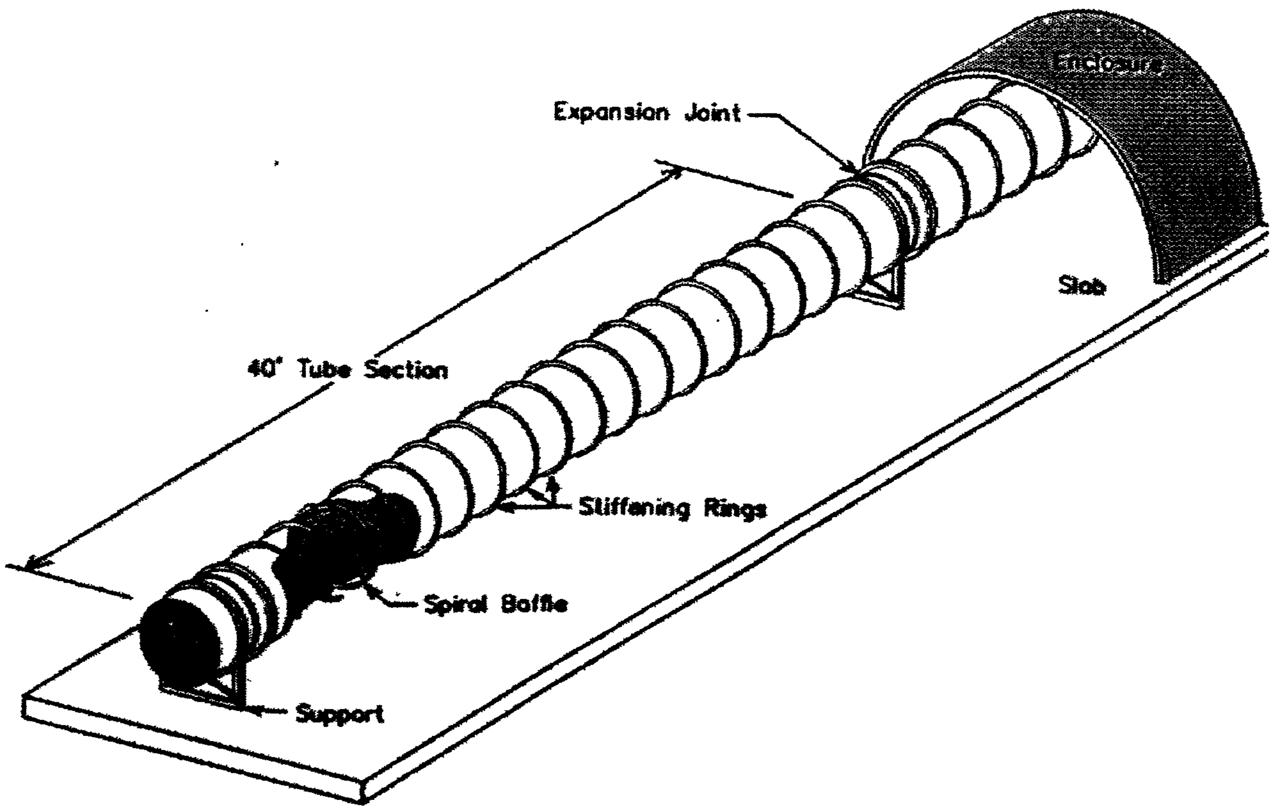


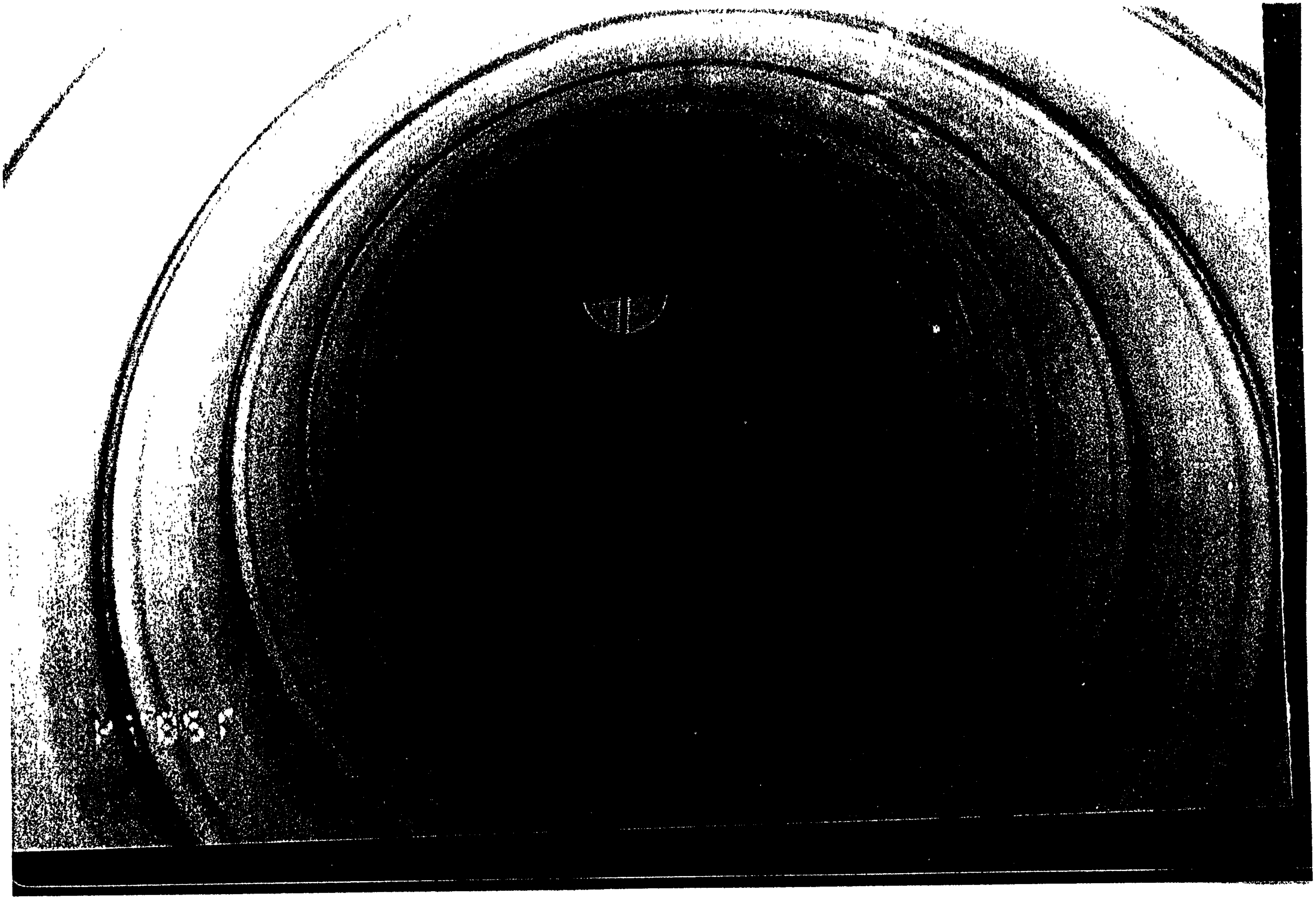


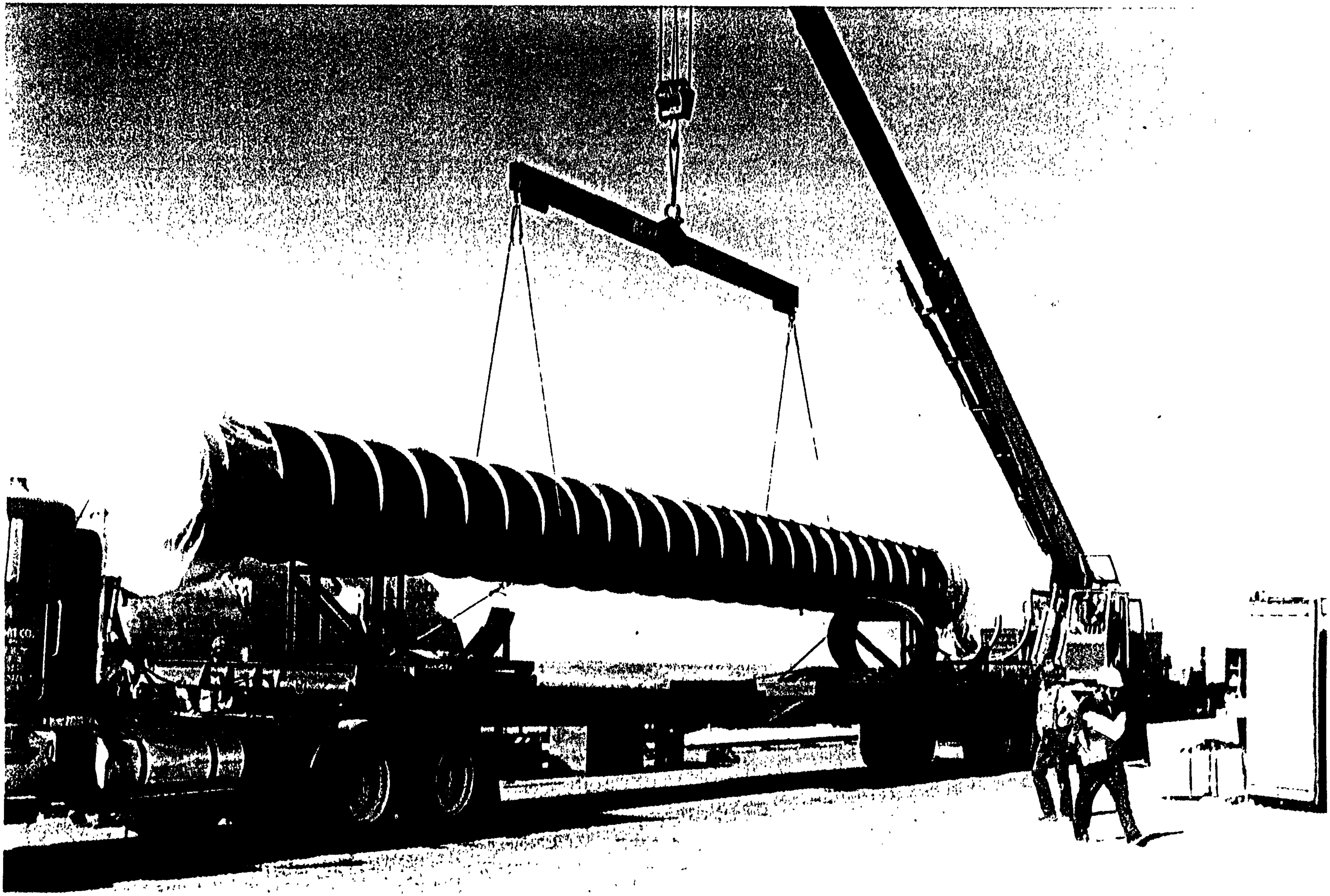
G960195-07 -O-94



Beam Tube


Enclosure
Expansion Joint
Slab
40' Tube Section
Stiffening Rings
Spiral Baffle
Support





Conclusions

- LIGO Construction is well Underway

- Direct Detection of Gravitational Waves Appears Realistic within 10 years

- Ultimate Sensitivities Capable of Opening a New Field of Observational Astronomy with Gravitational Waves is the Long Term Goal.

LIGO
some facts

- The Project
  - » construction cost ~$300M
  - » construction scheduled for completion in 1999

- Operations of LIGO Laboratory
  - » operating budget is ~$25M/year
  - » initial design sensitivity by 2002

- Caltech and LIGO
  - » faculty:B. Barish, K. Libbrecht; T. Prince, R.Vogt
  - » total staff ~ 80
  - » LIGO project management at Caltech
  - » LIGO central engineering support at Caltech
  - » LIGO data analysis center at Caltech
  - » Advanced R&D at Caltech (40m, etc)
  - » Detector support and operations
  - » Graduate Thesis
  - » Undergrad programs (NSF REU site, SURF)