LIGO PROJECT ROOTS/HISTORY

1916	Einstein / General Relativity / Gravitational Waves (GWs)
1957	J. Wheeler & J. Weber (sabbatical visitor) write paper on GWs
1959 / 60	J. Weber starts bar detector work
mid 1960's	Dyson, Thorne & students study GW sources
1969	J. Weber claims discovery of GWs
>1969	Theoretical work on GWs intensifies
1970's	Analytical and early laboratory development of laser-interferometric GW detectors
1979	Caltech and MIT groups funded by NSF to develop laser interferometric GW detectors
1983	Caltech and MIT groups joined in shotgun wedding
1983 / 84	Caltech / MIT proposals to build km-scale laser-interferometric GW detectors (LIGO)
	J. Taylor and colleagues demonstrate existence of GWs by indirect means (pulsar orbit decay)
1986	Cambridge, Mass. — Blue Ribbon review of LIGO
1987	LIGO program reorganized. Steering committee replaced by a director. Caltech/MIT team unified. Fabry-Perot system selected. LIGO conceptual design initiated.
Dec. 1989	LIGO construction proposal submitted to NSF
May 1990	NSB approves LIGO proposal
1990	President's budget proposal for FY '91 includes LIGO new start ($47 M)
	Congress reduces LIGO line item to $0.5 M, recommends further R&D and design
	NSB authorizes national site solicitation
1991	President's budget proposal for FY '92 includes LIGO new start ($23.5 M)
	Congress appropriates $23.5 M for LIGO new start in FY '92
	NSF cuts FY '92 LIGO funding

LIGO designed to

- detect gravitational waves by direct means
- study their wave forms
- with broad-band capability (10 Hz — 10 kHz)
- with sensitivity for "standard signal" (coalescing NS's) to the edge of observable universe $\left(h_B \sim 10^{-23}\right)$

More specifically, we are pursuing the following objectives:

LIGO GOALS

PAYOFFS FOR PHYSICS

- DIRECT CONFIRMATION OF EXISTENCE OF GRAVITATIONAL WAVES. TEST OF STRONG-FIELD GENERAL RELATIVITY
- MEASUREMENT OF GRAVITON PROPERTIES. GENERAL RELATIVITY PREDICTS

$$v = c$$
$$m = 0$$
$$s = 2$$

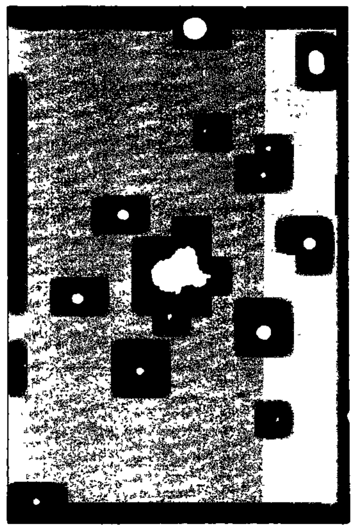
- VERIFICATION OF EXISTENCE AND DYNAMICS OF BLACK HOLES

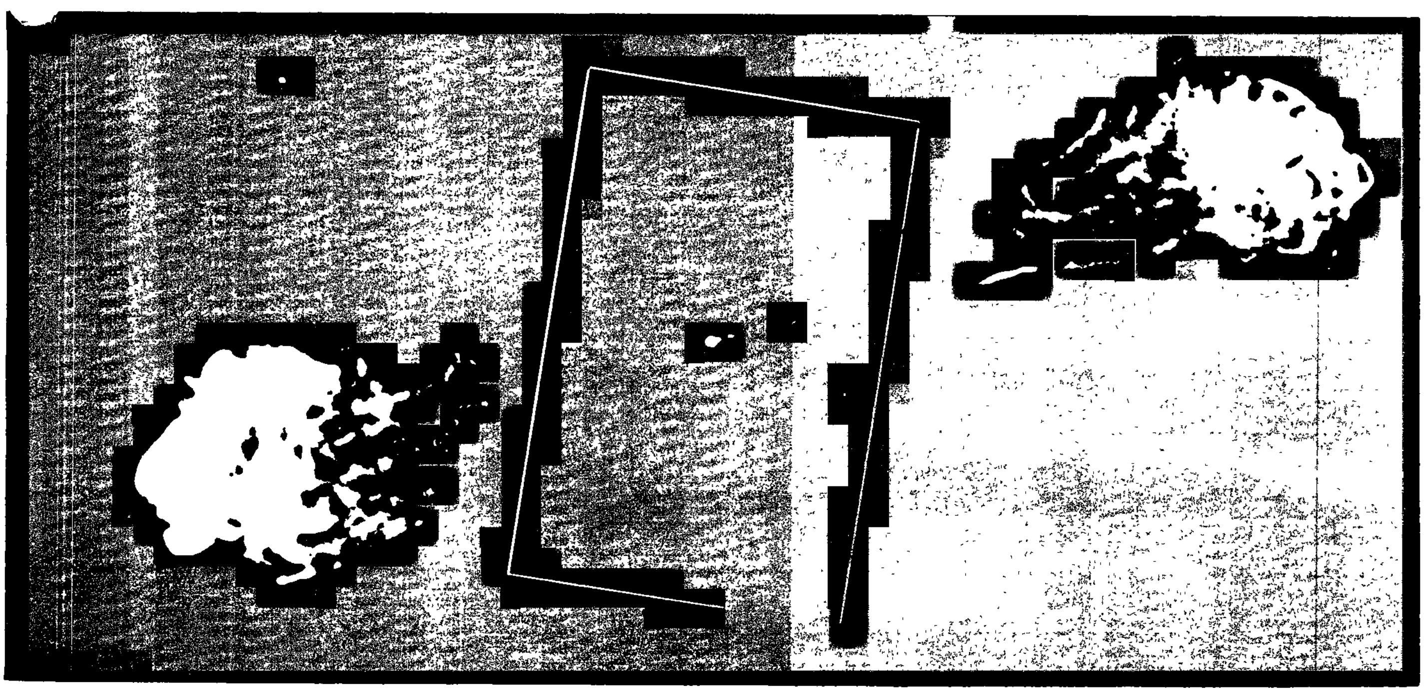
PAYOFFS FOR ASTROPHYSICS

NEW WINDOW ONTO UNIVERSE

- COALESCING BLACK HOLES / HIGHLY NON-LINEAR DYNAMIC GRAVITY
- HIGHLY DYNAMICAL NEUTRON STAR PHENOMENA / PHYSICS OF NEUTRON STARS
- SUPERNOVAE / CREATION OF NEUTRON STARS
- COALESCING BINARIES / STANDARD CANDLES FOR DISTANCES
- PRIMORDIAL WAVES / INITIAL CONDITIONS AND EARLY EVOLUTION OF UNIVERSE
- LARGE SCALE MASS DISTRIBUTION OF UNIVERSE

- PHENOMENA *UNPREDICTABLE* BY E.M. ASTRONOMY AND *UNPREDICTED* BY THEORETICAL RELATIVISTS





- **DO GRAVITATIONAL WAVES EXIST?**

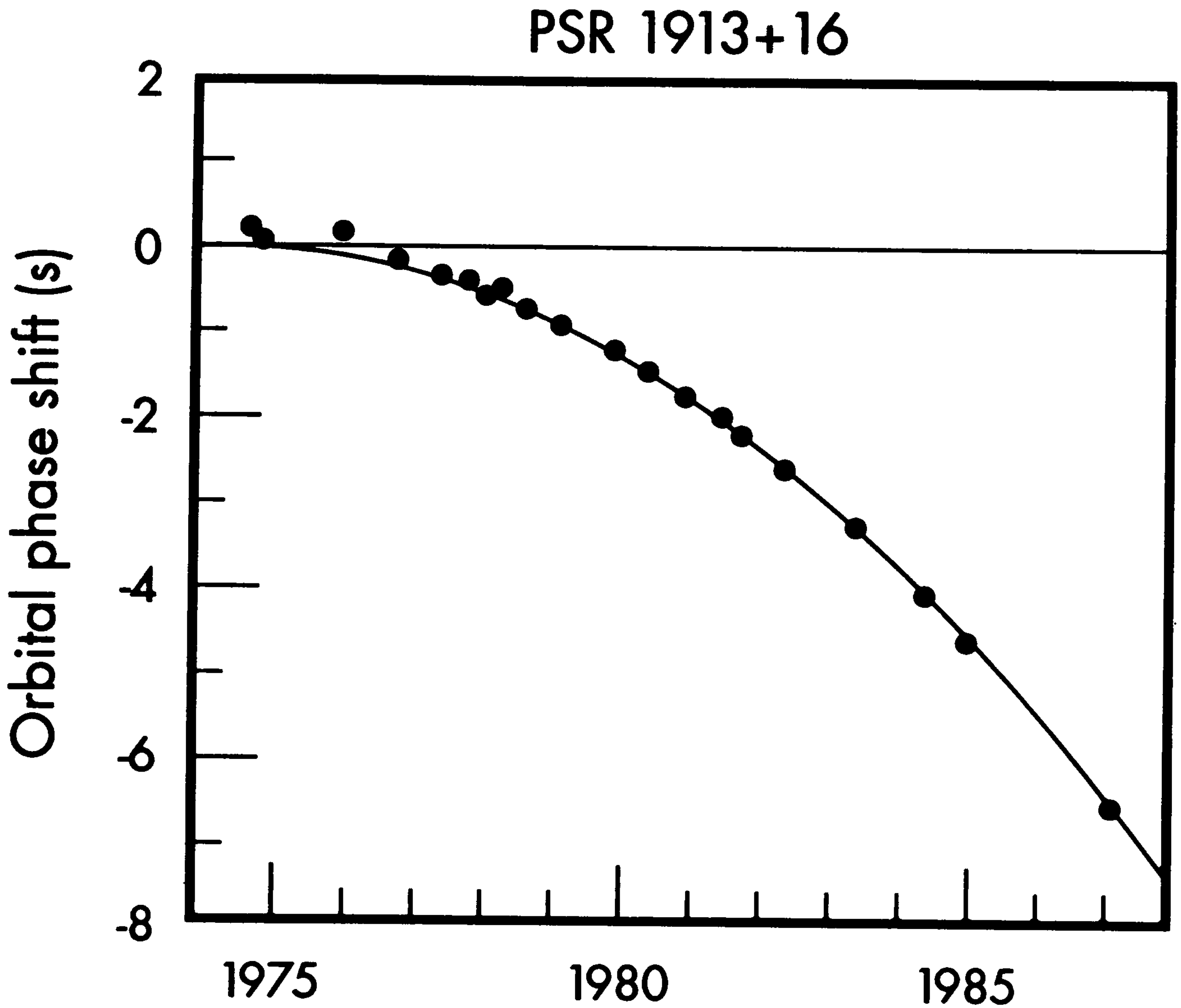
  1. **MANY OF US ARE STAKING OUR PROFESSIONAL LIVES ON IT!**

  2. **PREDICTION:**

     EINSTEIN (1916): GENERAL THEORY OF RELATIVITY
     PRESENT GENERATION OF THEORETICAL ASTROPHYSICISTS

  3. **INDIRECT OBSERVATION:**

     TAYLOR ET. AL: BINARY PULSAR SYSTEM'S ORBITAL DECAY (BY GRAVITATIONAL WAVES) AGREES WITH EINSTEIN PREDICTION


PSR 1913+16
Orbital phase shift (s)
2
0
-2
-4
-6
-8
1975
1980
1985

GRAVITATIONAL WAVES contrasted with EM WAVES

	ELECTROMAGNETIC	GRAVITATIONAL
Emission Mechanisms	Individual atoms, molecules, electrons Incoherent superposition	Coherent motions of large masses or spacetime curvature
Examples of Sources	Stellar atmospheres Interstellar gas Accretion discs	Supernova cores Colliding neutron stars or black holes Vibrating cosmic strings
Interaction with Matter	Dispersion Absorption	No dispersion (almost) No absorption (almost)
Primordial Radiation	From $z \sim 1000$ $\tau \sim 10^6$ yrs	From Planck era $\tau \sim 10^{-43}$ sec

LIGO

EM waves travel through space without affecting it

GW's are perturbations in the curvature of space time, i.e., they are travelling perturbations of space itself

While EMW's and GW's often may come from the same source, their information content derives from very different physical processes.

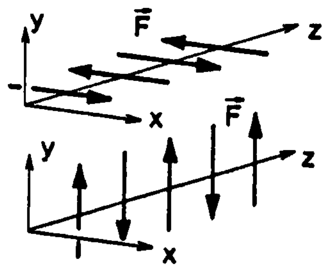
We cannot use EM knowledge to predict strength of GW's.

Most GW sources might never be seen by EM astronomy and vice versa.

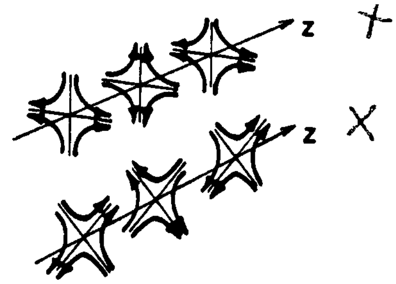
PHYSICS OF GRAVITATIONAL WAVES

GRAVITON: $m = 0$
$v = c$
$s = 2$

FORCE FIELDS: transverse polarization: h_+, $h_\times$



electric field



gravitational field

STRAIN AMPLITUDE:

$$h \propto \ddot{Q} \sim (\ddot{M}L^2) \sim (Mv^2) \sim E_{kin}^{ns}$$

$$h \sim \frac{G}{c^4}\frac{E_{kin}^{ns}}{r} \sim 10^{-20}\left[\frac{E_{kin}^{ns}}{M_\odot c^2}\right]\left[\frac{10Mpc}{r}\right]$$

for $E_{kin}^{ns} \sim M_\odot c^2$

$h \sim 10^{-17}$ (our galaxy)

$\sim 10^{-20}$ (Virgo cluster)

$\sim 10^{-23}$ (cosmological distances)

SIGNAL FREQUENCIES:

$f_{\text{BH pulsation}} \sim \frac{1\text{kHz}}{M/10M_\odot}$

$f_{\text{BH coalescence}}$: < 10Hz to $f_{\text{BH pulsation}}$

$f_{\text{NS pulsation}} \sim$ 1 kHz

$f_{\text{NS coalescence}}$: < 10Hz to $f_{\text{NS pulsation}}$

LIGO

GW's from Sun-Earth system:

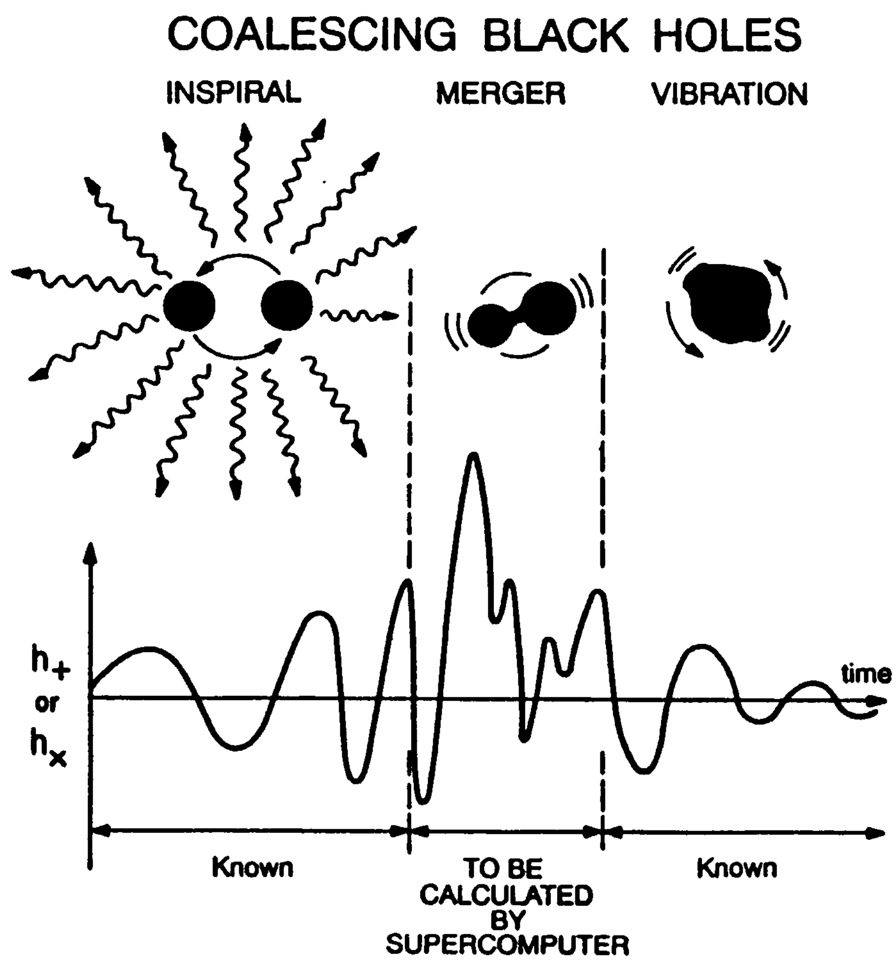
$$f \sim 10^{-8}\ \mathrm{Hz}$$

$$\tau \sim 1\ \mathrm{l.y.}(10^{18}\mathrm{cm})$$

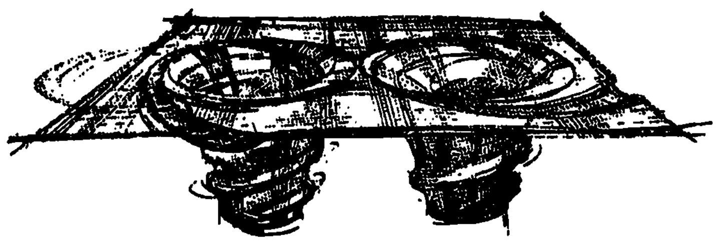
$$\mathrm{h} \sim 10^{-28}$$

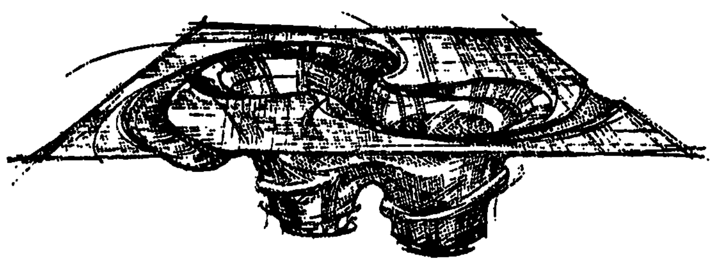
GW Information Obtained by Waveform Analysis

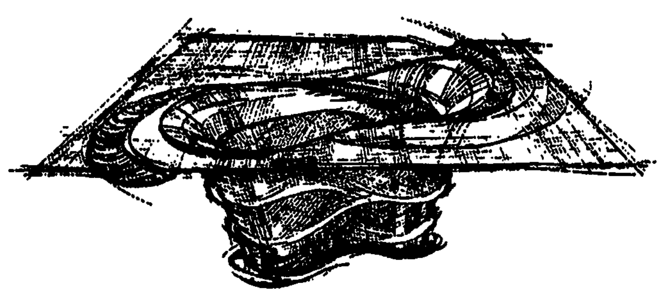
- Almost All Electromagnetic Astronomy Is Based on Spatial or Spectral Analysis
- Extraction of Information From Gravitational Wave Depends on Waveform Analysis

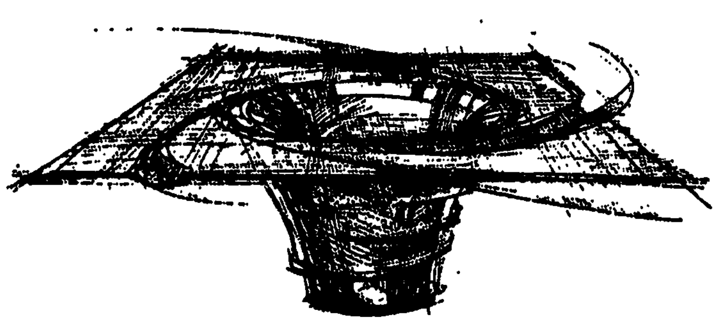


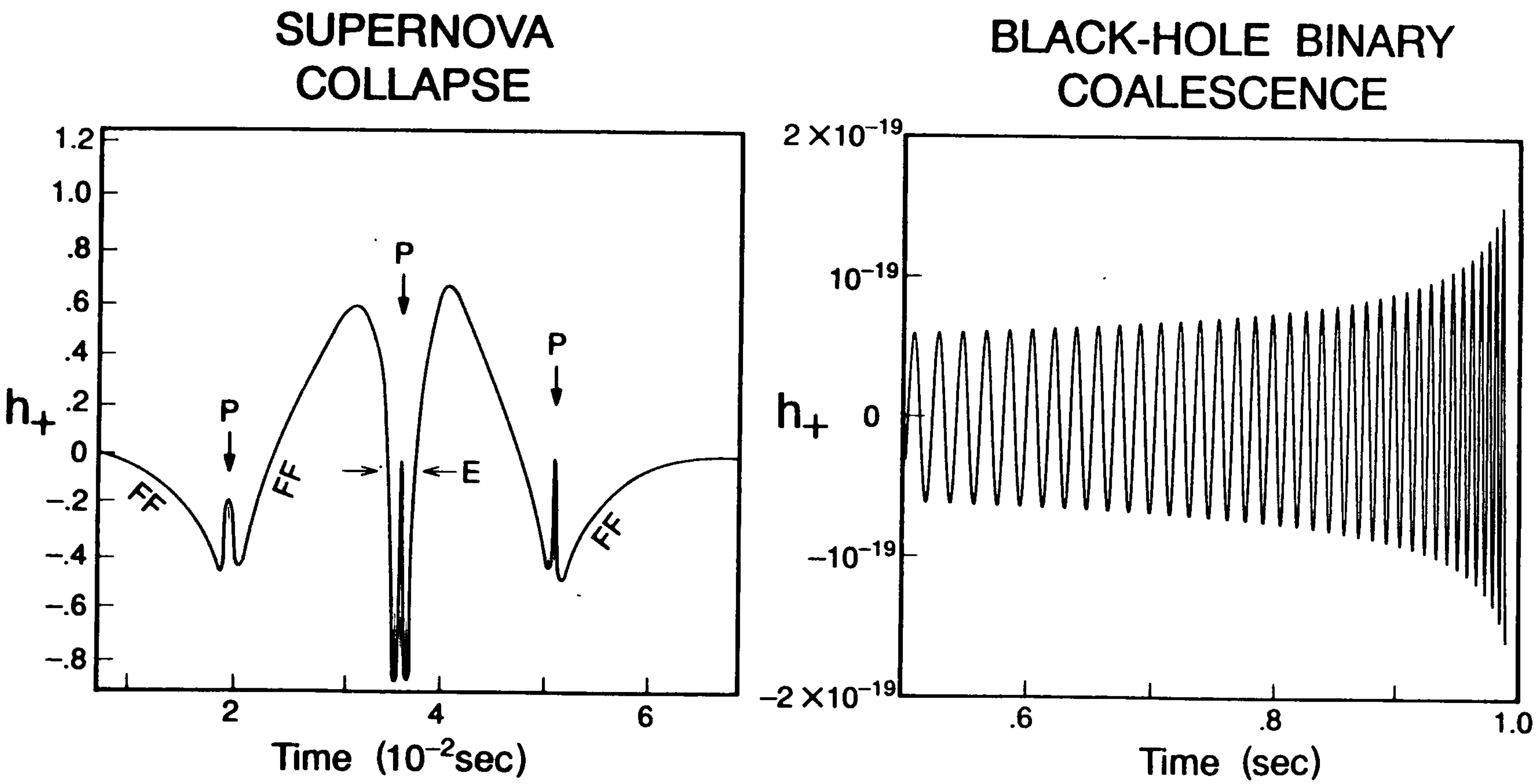
LIGO










SUPERNOVA COLLAPSE
1.2
1.0
.8
.6
.4
.2
0
−.2
−.4
−.6
−.8
h+
P
P
P
FF
FF
FF
FF
E
2
4
6
Time (10−2sec)
BLACK-HOLE BINARY COALESCENCE
2×10−19
10−19
0
−10−19
−2×10−19
h+
.6
.8
1.0
Time (sec)

Wave-form analysis:

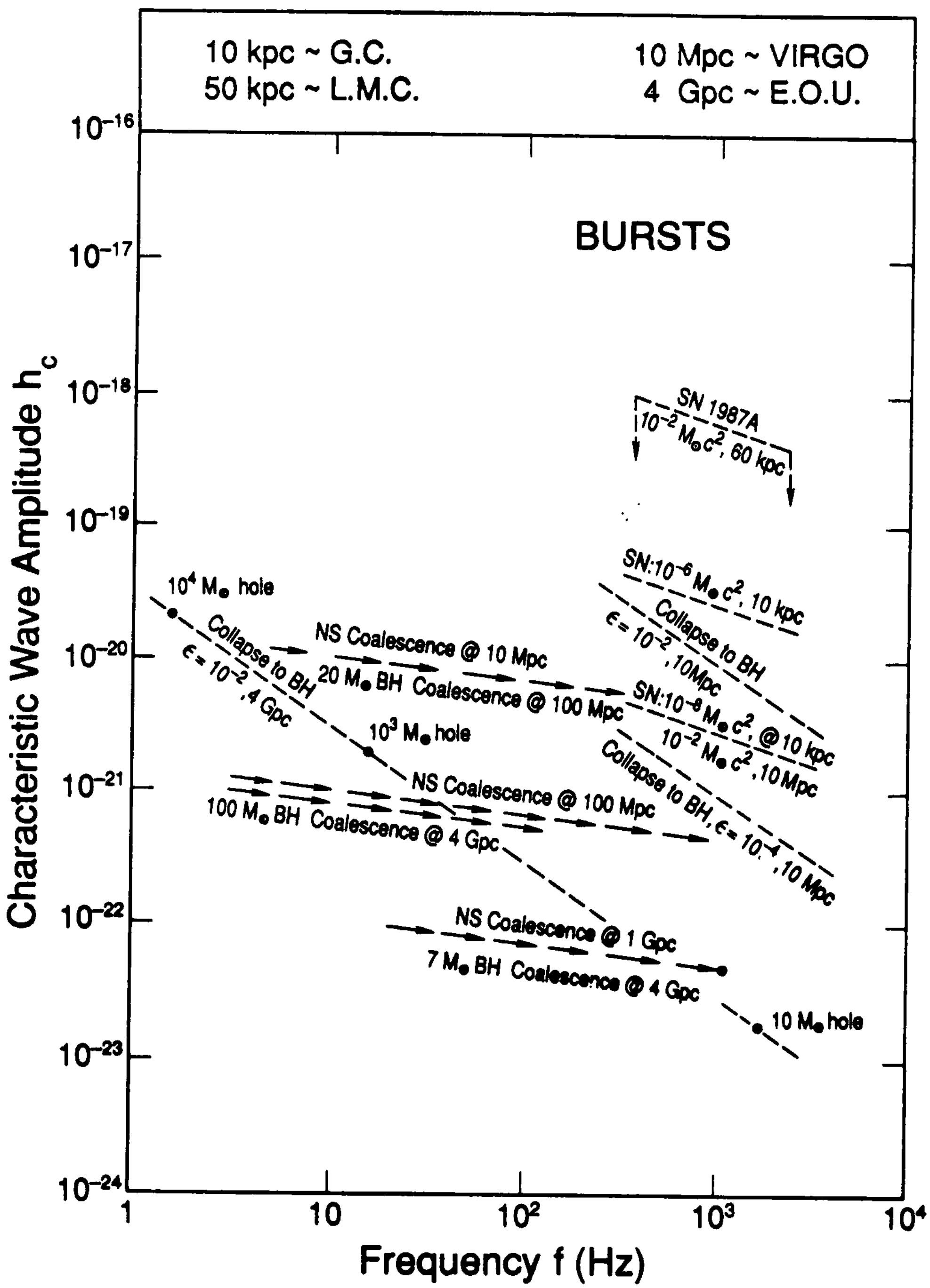
- If $h_\times(t) = \text{const.}\, h_+(t)$: source axisymmetric
- Since $t_{min} \sim 0.5\,\text{msec}$: source must be NS or several $M_\odot$ BH
- From double time integration:

  FF regions: non-spherical free-fall motion

  P's represent sharp acceleration opposite to free-fall: collapse formed NS that bounced 3 times

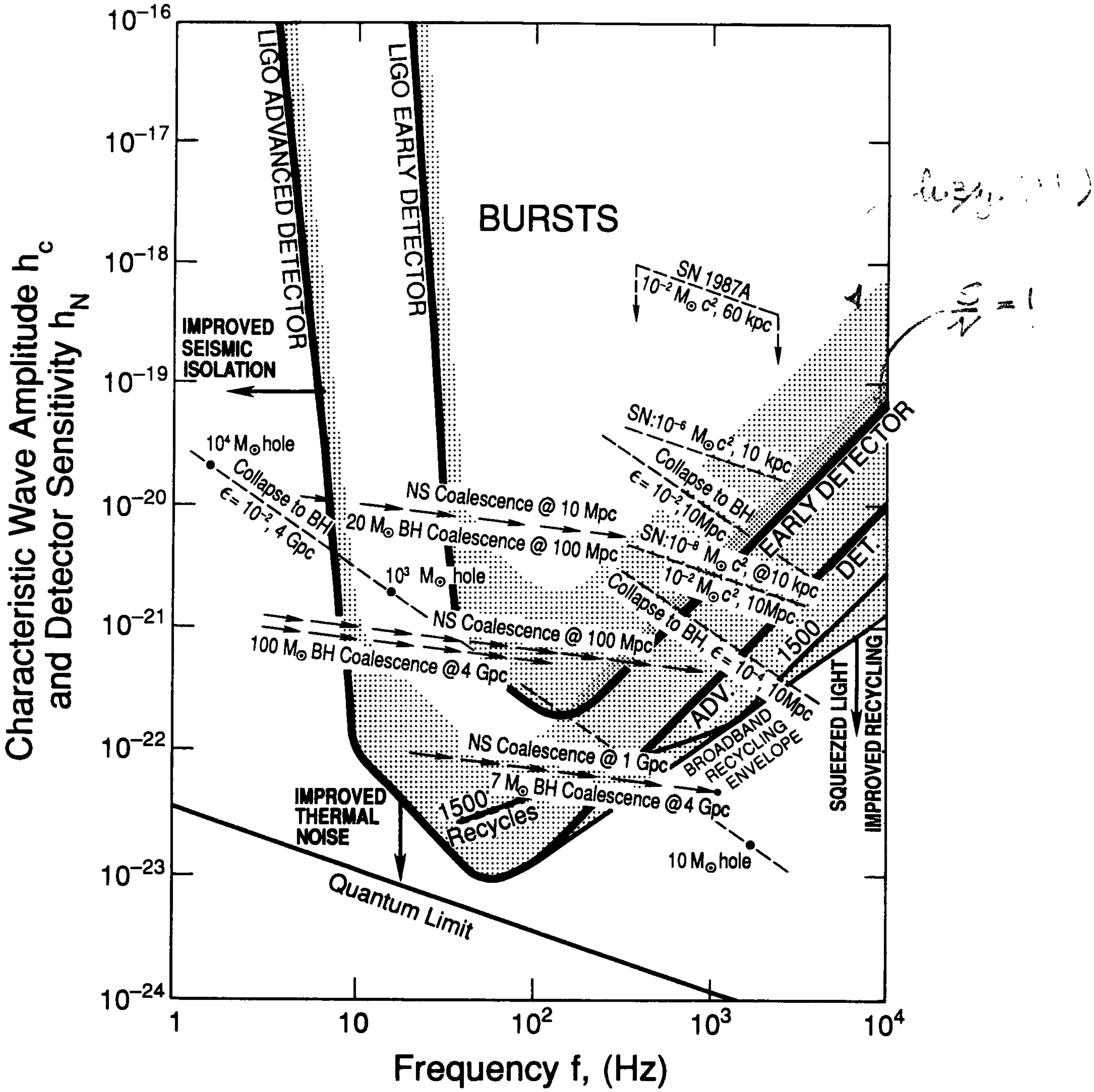
  E: other axis bounced once

∴ Collapsing star centrifugally flattened by rotation, its pole collapsed fast and bounced 3 times, while its equator collapsed more slowly and bounced once.



10 kpc ~ G.C.
50 kpc ~ L.M.C.
10 Mpc ~ VIRGO
4 Gpc ~ E.O.U.
BURSTS
SN 1987A
10⁻² M⊙c², 60 kpc
SN:10⁻⁶ M⊙ c², 10 kpc
Collapse to BH
ε = 10⁻², 10Mpc
SN:10⁻⁸ M⊙ c², @ 10 kpc
10⁻² M⊙ c², 10 Mpc
Collapse to BH, ε = 10⁻⁴, 10 Mpc
10⁴ M⊙ hole
Collapse to BH
ε = 10⁻², 4 Gpc
NS Coalescence @ 10 Mpc
20 M⊙ BH Coalescence @ 100 Mpc
10³ M⊙ hole
NS Coalescence @ 100 Mpc
100 M⊙ BH Coalescence @ 4 Gpc
NS Coalescence @ 1 Gpc
7 M⊙ BH Coalescence @ 4 Gpc
10 M⊙ hole
Characteristic Wave Amplitude h_c
Frequency f (Hz)
10⁻¹⁶
10⁻¹⁷
10⁻¹⁸
10⁻¹⁹
10⁻²⁰
10⁻²¹
10⁻²²
10⁻²³
10⁻²⁴
1
10
10²
10³
10⁴

early detector = existing technology

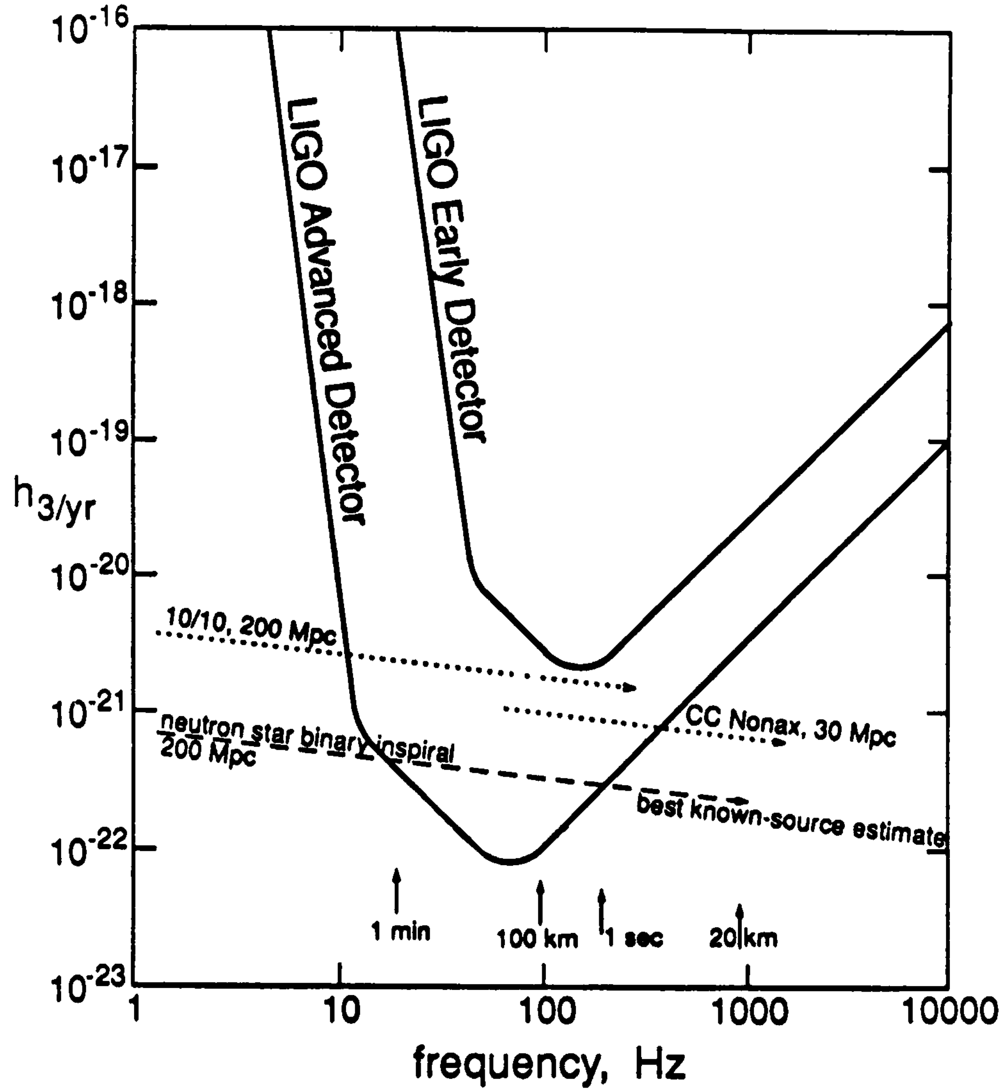


It is not enough to have sensitivity for nearby (strong) but possibly infrequent (small volume of space) sources.

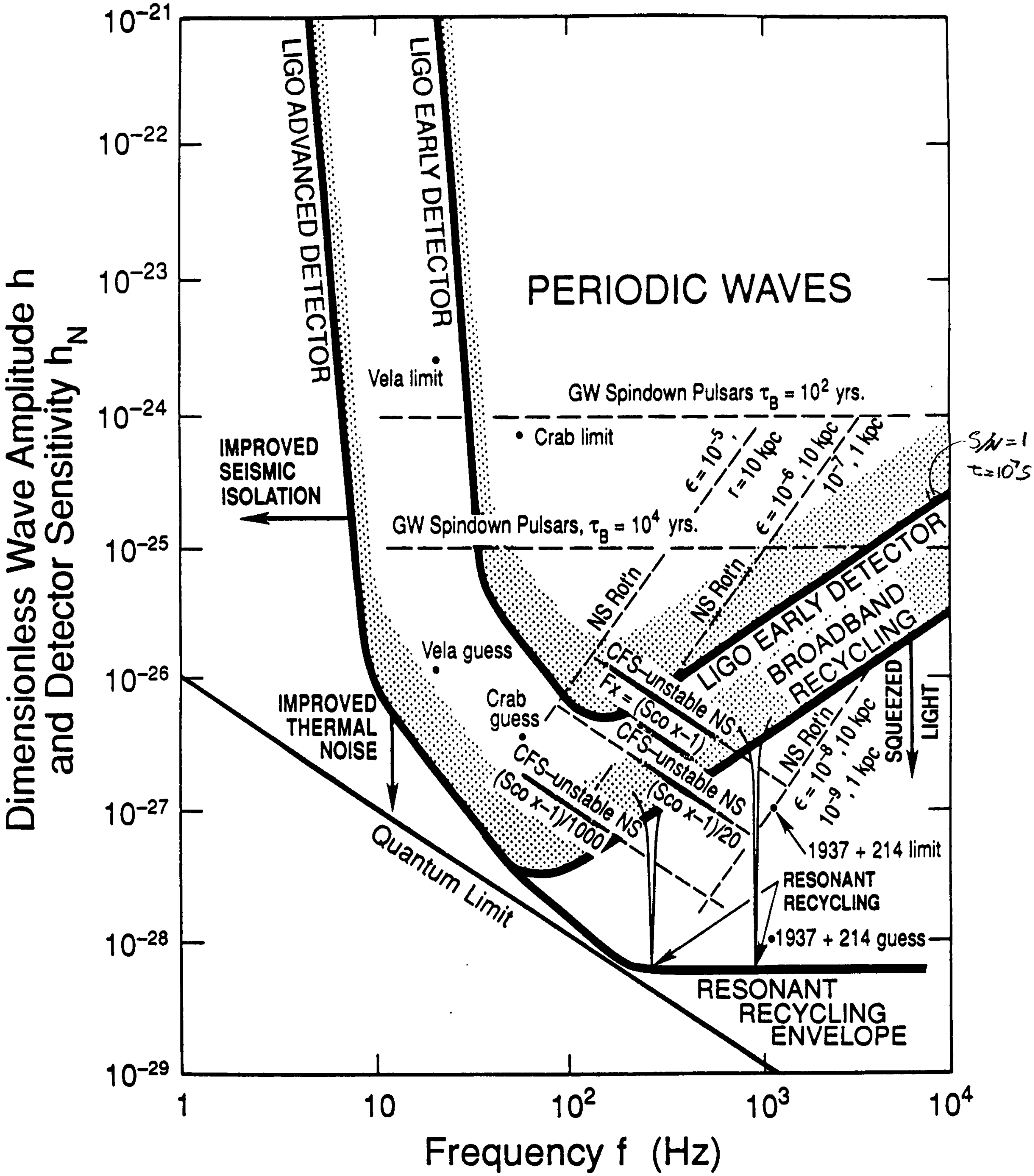
We define credible detection program (in early discovery mode) as 3 or more events per year

$$h_{3/yr} = 11\ h_{rms}$$

representing a 90% confidence figure for the detection of bursts arriving 3 times per year from random, unknown directions at random, unknown times, with random polarizations (in detectors free from non-Gaussian noise bursts).



10-16
10-17
10-18
10-19
h3/yr
10-20
10-21
10-22
10-23
1
10
100
1000
10000
frequency, Hz
LIGO Advanced Detector
LIGO Early Detector
10/10, 200 Mpc
CC Nonax, 30 Mpc
neutron star binary inspiral
200 Mpc
best known-source estimate
1 min
100 km
1 sec
20 km


PERIODIC WAVES
LIGO ADVANCED DETECTOR
LIGO EARLY DETECTOR
Vela limit
GW Spindown Pulsars τ_B = 10^2 yrs.
Crab limit
IMPROVED SEISMIC ISOLATION
GW Spindown Pulsars, τ_B = 10^4 yrs.
ε = 10^-5, r = 10 kpc
ε = 10^-6, 10 kpc
10^-7, 1 kpc
S/N = 1
τ = 10^7 s
NS Rot'n
LIGO EARLY DETECTOR BROADBAND RECYCLING
Vela guess
Crab guess
IMPROVED THERMAL NOISE
CFS–unstable NS Fx = (Sco x-1)
CFS–unstable NS (Sco x-1)/20
CFS–unstable NS (Sco x-1)/1000
ε = 10^-8, 10 kpc
10^-9, 1 kpc
SQUEEZED LIGHT
1937 + 214 limit
RESONANT RECYCLING
1937 + 214 guess
Quantum Limit
RESONANT RECYCLING ENVELOPE
10^-21
10^-22
10^-23
10^-24
10^-25
10^-26
10^-27
10^-28
10^-29
1
10
10^2
10^3
10^4
Frequency f (Hz)
Dimensionless Wave Amplitude h and Detector Sensitivity h_N

Detection:

Gravitational wave determined by time dependent behavior of amplitude and polarization of dimensionless strain h(t).

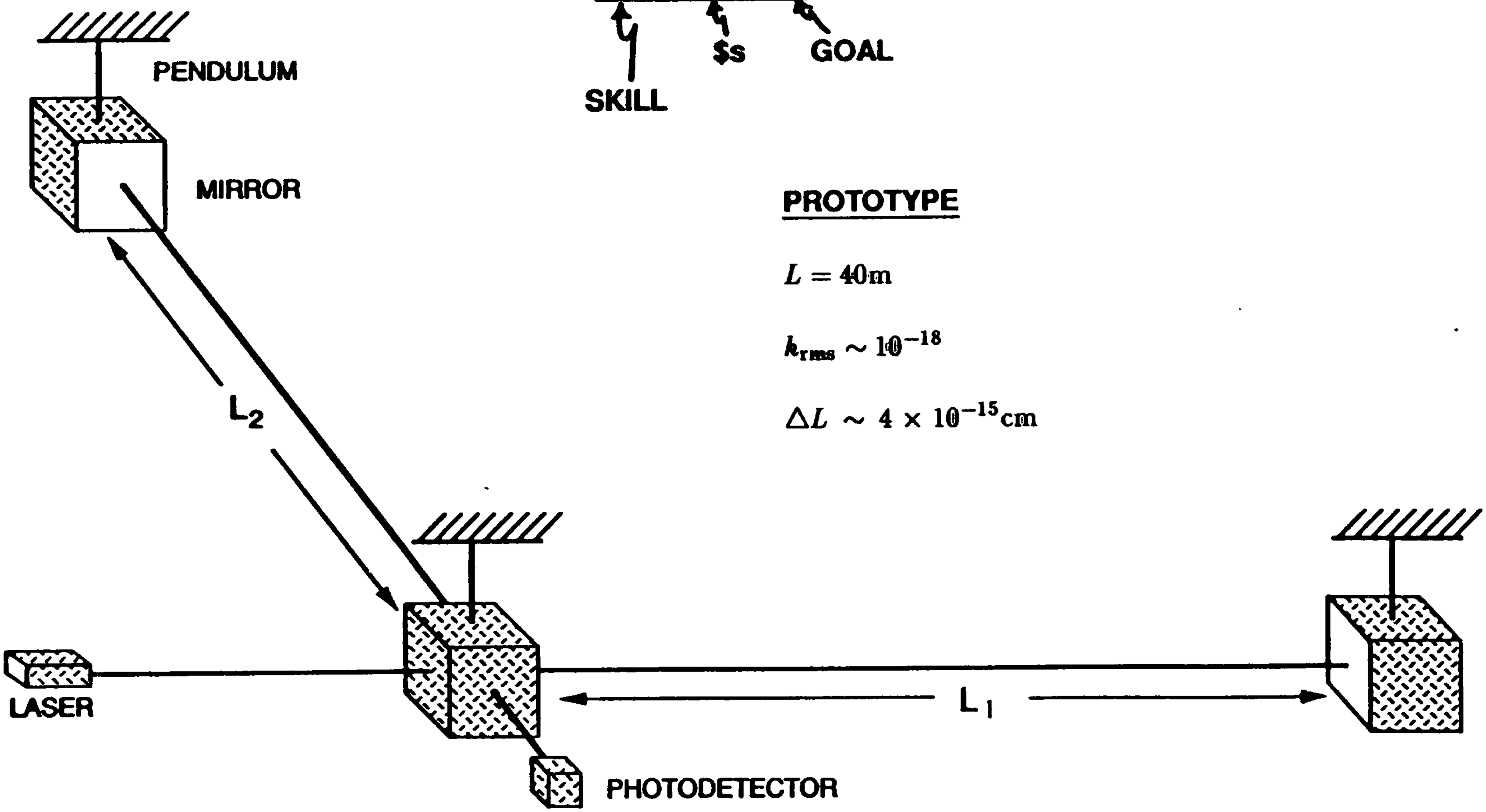
h(t) determines change in separation $\Delta L(t)$ of two free objects separated by distance L

ΔL measured by laser interferometry

LIGO: "FREE-MASS", BROAD-BAND DETECTOR
LASER INTERFEROMETRY MEASURES $\Delta L = \Delta L_1 - \Delta L_2$

$$\boxed{\Delta L / L = h}$$

SKILL — $s — GOAL



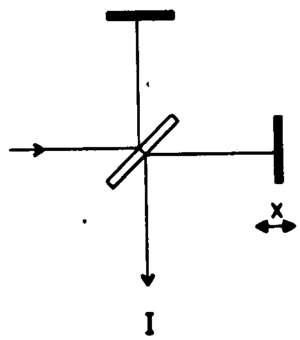
PROTOTYPE

$L = 40\text{m}$

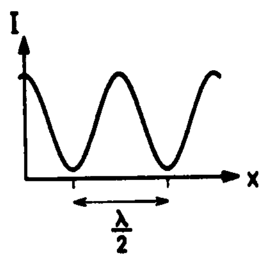
$h_{\text{rms}} \sim 10^{-18}$

$\Delta L \sim 4 \times 10^{-15}\text{cm}$

FRINGE RESOLUTION



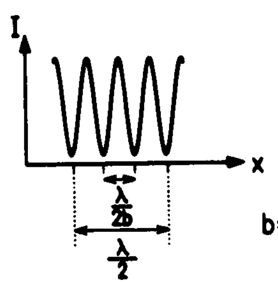
SINGLE BOUNCE MICHELSON INTERFEROMETER



$$\Delta x \sim \frac{\lambda}{\sqrt{N}}$$

(1W: $\frac{dN}{dt} \sim 10^{18}$ PHOTONS/SEC)

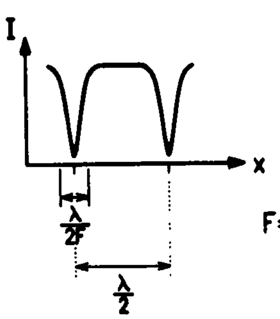
MULTIPATH MICHELSON (DELAY LINE) INTERFEROMETER



$$\Delta x \sim \frac{\lambda}{b\sqrt{N}}$$

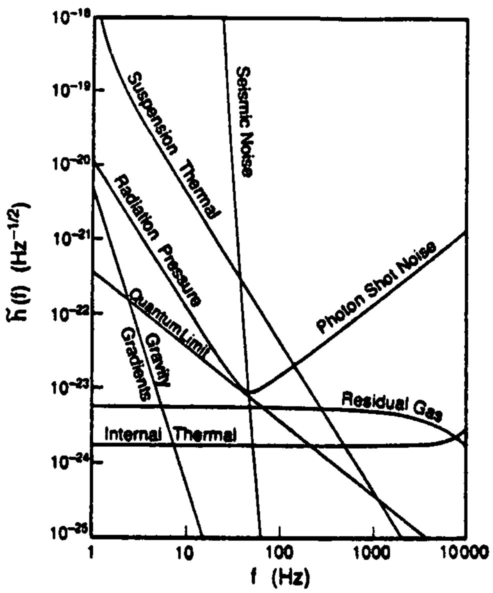
b=NUMBERS OF BOUNCES

FABRY-PEROT INTERFEROMETER

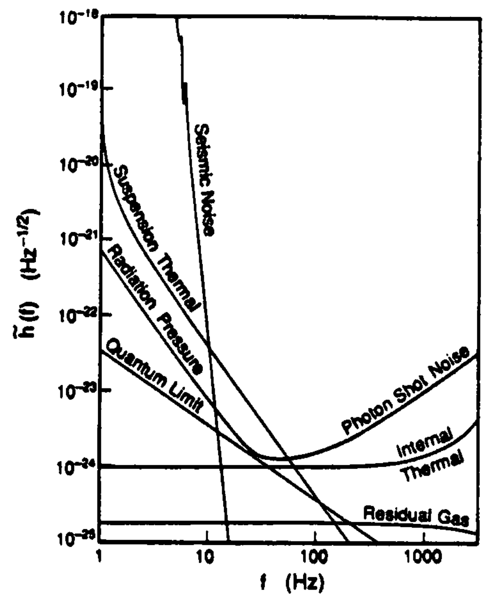


$$\Delta x \sim \frac{\lambda}{F\sqrt{N}}$$

F=FINESSE= $\frac{\text{SEPARATION}}{\text{WIDTH}}$



Spectra of noise sources for early LIGO detector. Note: $\left[\tilde{h}(f)\right]^2$ is the spectral density of $h(t)$; the rms noise amplitude in a search for broad-band gravitational-wave bursts is $h_{rms} = \tilde{h}(f)\sqrt{f}$. Detector parameters are: Laser 5 Watt, Mirror Losses 50 ppm, Recycling Factor 30, Test Masses 10 kg, Suspension $Q = 10^7$, Vacuum $H_2 = 10^{-6}$ torr, $H_2O = 10^{-7}$ torr.



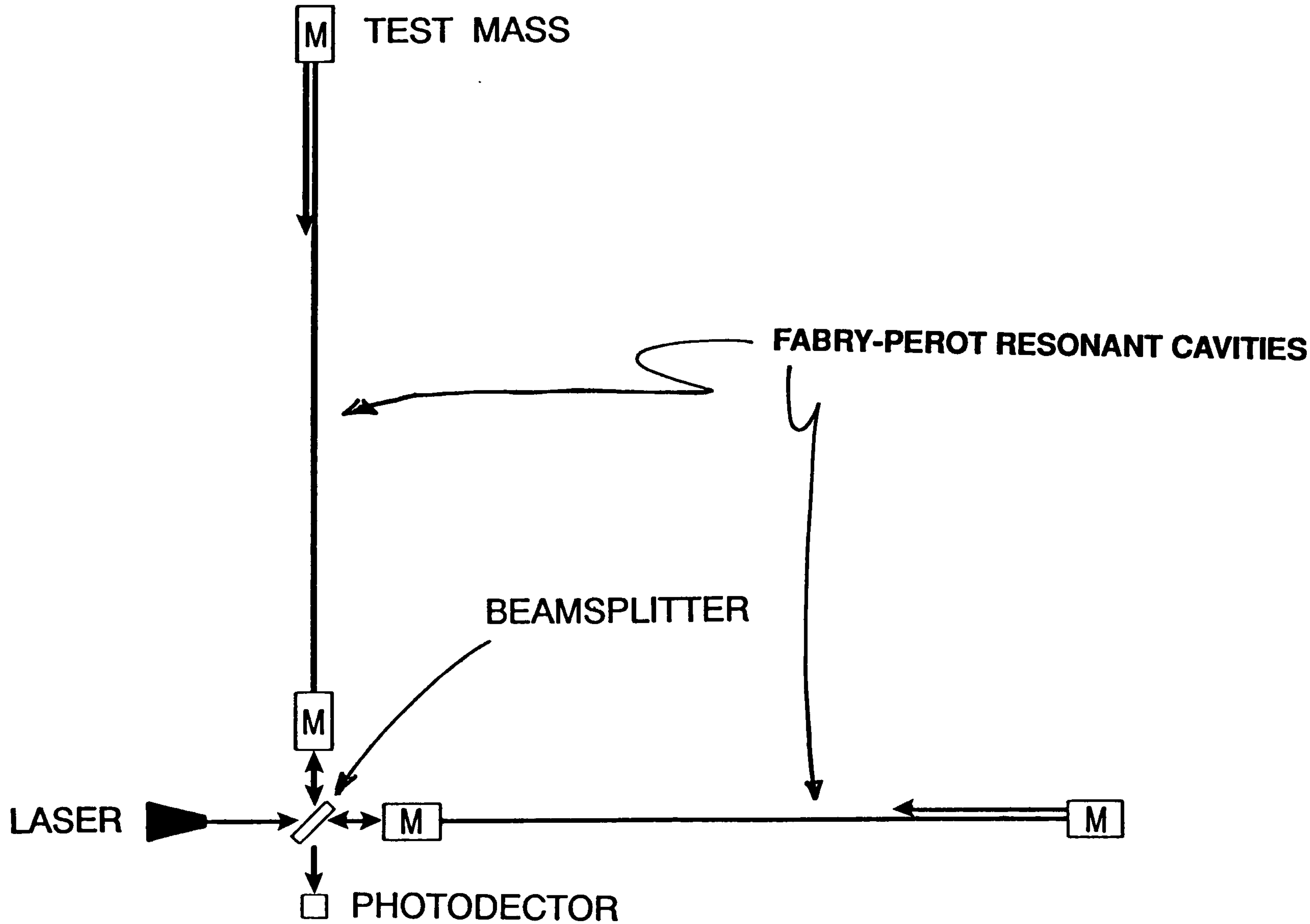
Spectra of noise sources for advanced LIGO detector. Detector parameters: Laser 60 Watt, Mirror Losses 20 ppm, Recycling Factor 100, Test Masses 1 ton, Suspension $Q = 10^9$, Vacuum $H_2 = 10^{-9}$ torr, $H_2O = 10^{-10}$ torr.

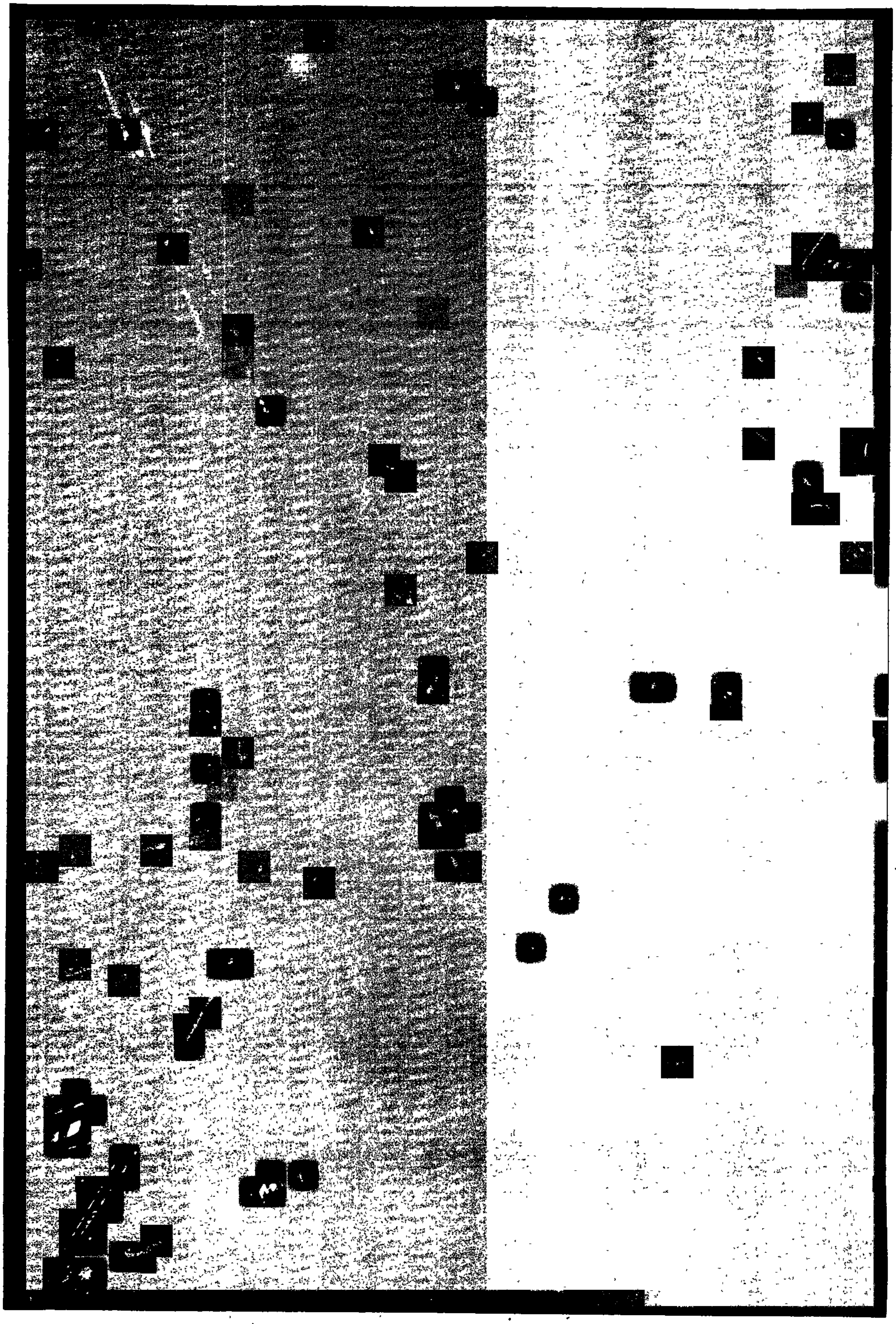
PROTOTYPE INTERFEROMETER

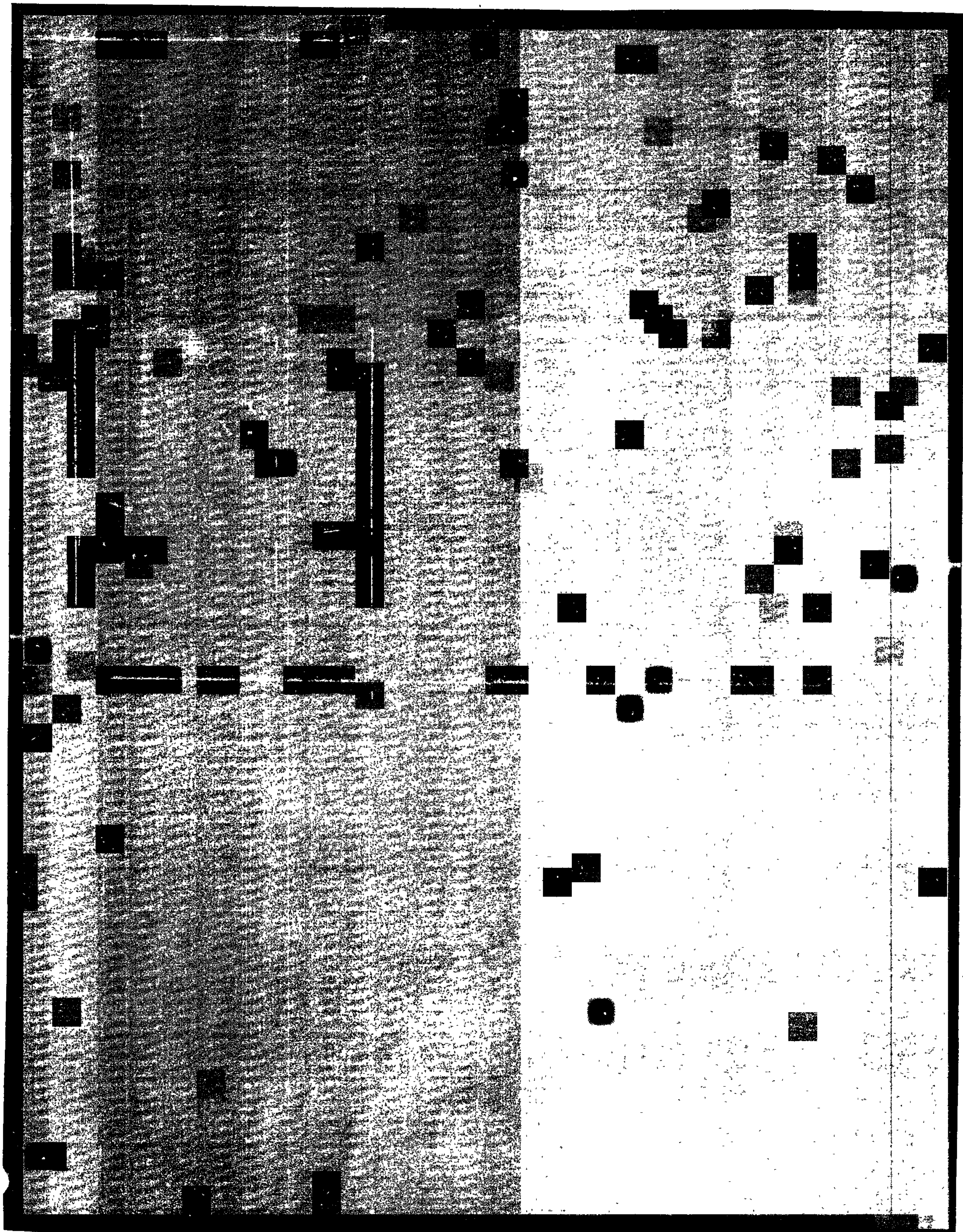
Prototype is a test bed for selected full-scale LIGO techniques and systems.

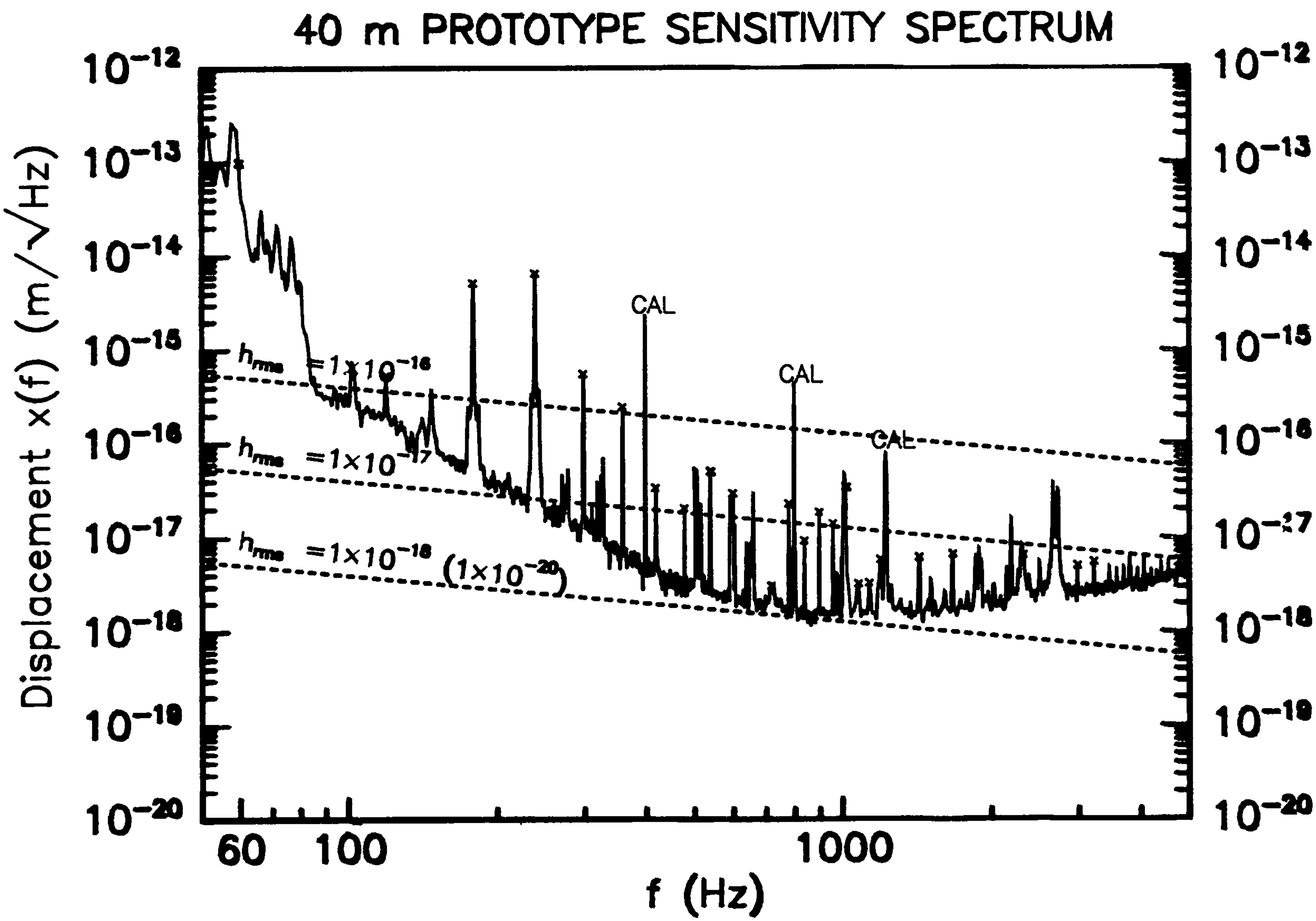
Predicted performance of LIGO interferometers must be pieced together from individual tests, without any unified demonstration.

Laboratory-scale interferometers are fundamentally different from LIGO-scale interferometers; since e.g., noise sources scale differently with arm-length and frequency.


M
TEST MASS
FABRY-PEROT RESONANT CAVITIES
BEAMSPLITTER
M
LASER
M
M
PHOTODECTOR







40 m PROTOTYPE SENSITIVITY SPECTRUM
Displacement x(f) (m/√Hz)
f (Hz)
60
100
1000
10^−12
10^−13
10^−14
10^−15
10^−16
10^−17
10^−18
10^−19
10^−20
h_rms =1×10^−16
h_rms =1×10^−17
h_rms =1×10^−18 (1×10^−20)
CAL
CAL
CAL

LIGO works on the same principles of the 40–m prototype, with the separation of the test masses scaled up by a factor of 100 (L = 4 km).

In addition, LIGO is designed as an operating observatory (as opposed to the prototype which serves development and demonstration purposes) — and this requires greater automation, sophistication, and reliability.

Details in SEW discussion!

LIGO OBSERVATORY

OBSERVATORY ≡ 2 LIGO facilities located far apart (noise uncorrelated) operating in unison (coincidence) to eliminate spurious events simulating gravitational waves

Noise has Gaussian and non-Gaussian components

- Fluctuating gravitational gradients
- Ground vibrations
- Mechanical strain releases
- Fluctuation in gas pressure
- Magnetic field fluctuations
- Cosmic rays

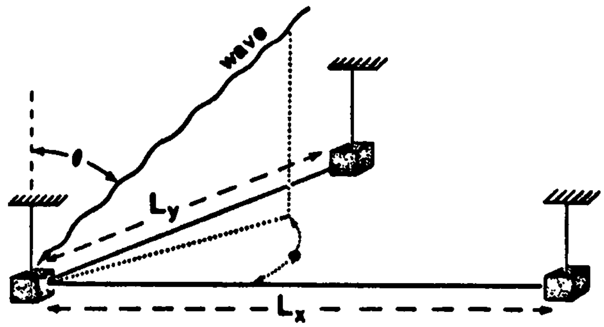
LIGO detector consists of 3 interferometers:

Site 1: 1 full length IF (L)
1 half length IF (L/2)

Site 2: 1 full length IF (L)

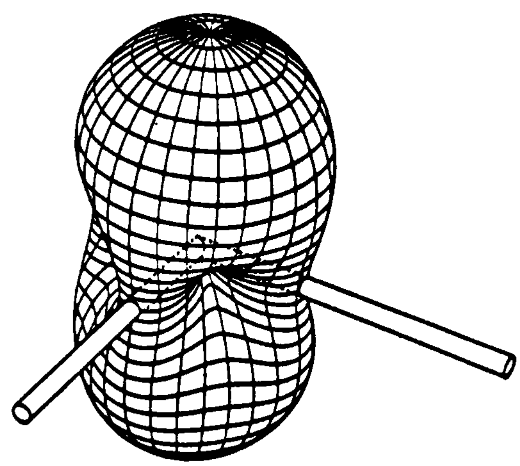
Triple coincidence allows reliable detection of < 1 event/year

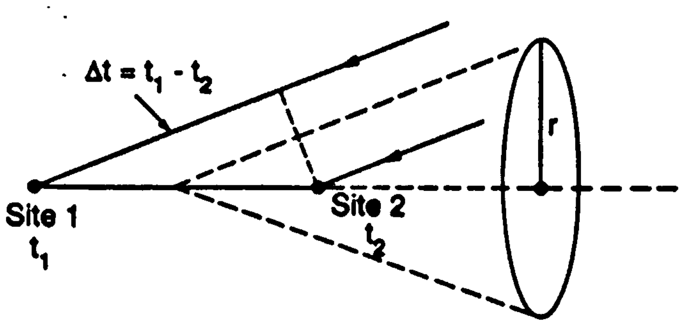
LIGO DIRECTIONAL SENSITIVITY



$$\frac{\Delta L}{L} = F_{+}(\theta,\phi)h_{+}(t) + F_{\times}(\theta,\phi)h_{\times}(t)$$

$$F_{+} = \tfrac{1}{2}(1 + cos^2\theta)cos2\phi$$
$$F_{\times} = cos\theta sin2\phi$$

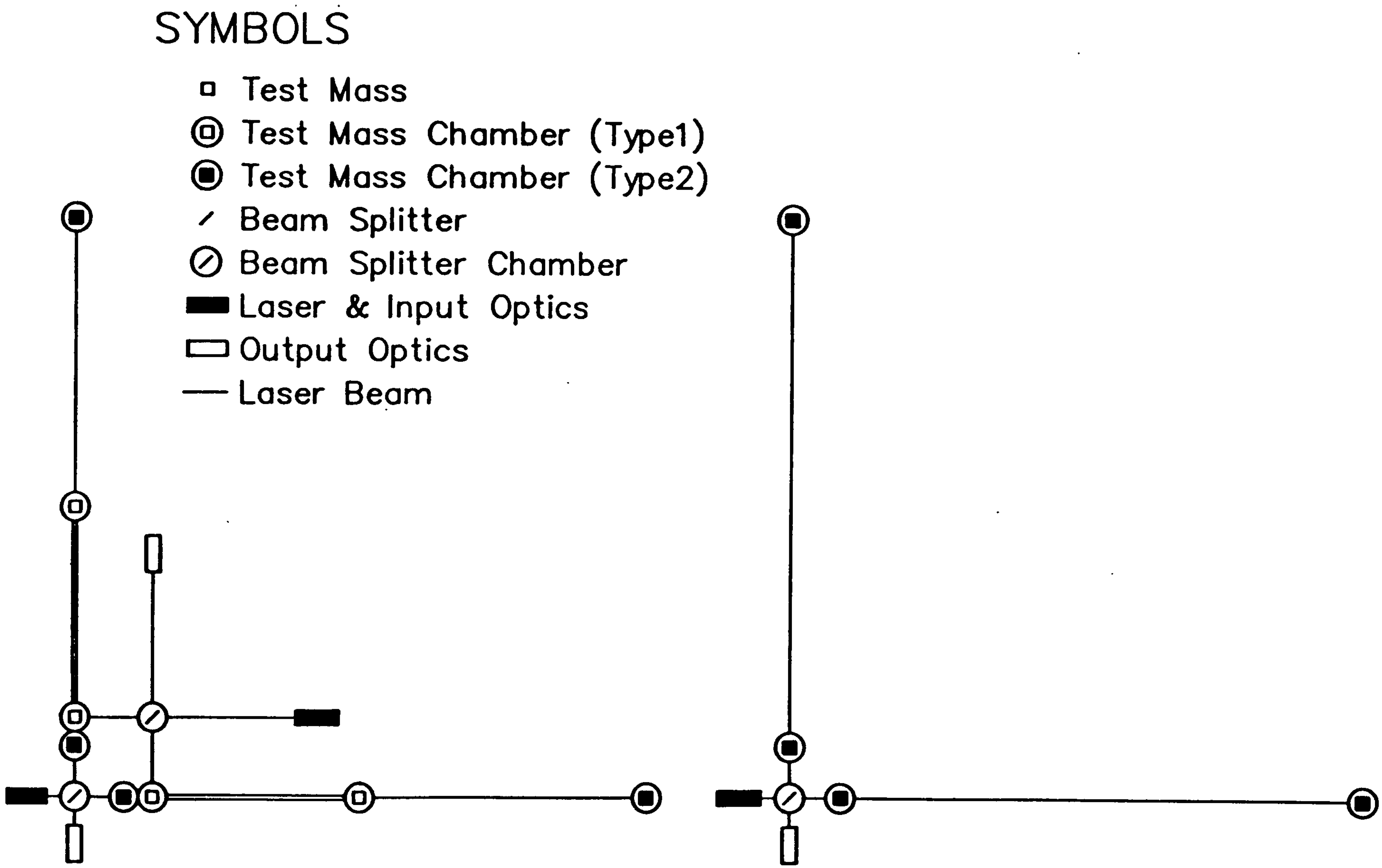




# SITES	ERROR BOX
2	Circle
3	$3' - 5'$ (U.S. - Europe) $\Delta\Omega = \frac{2c^2\Delta\tau_{12}\Delta\tau_{13}}{A\cos\theta}$
4	$1' - 2'$ (U.S. - Europe - Australia)

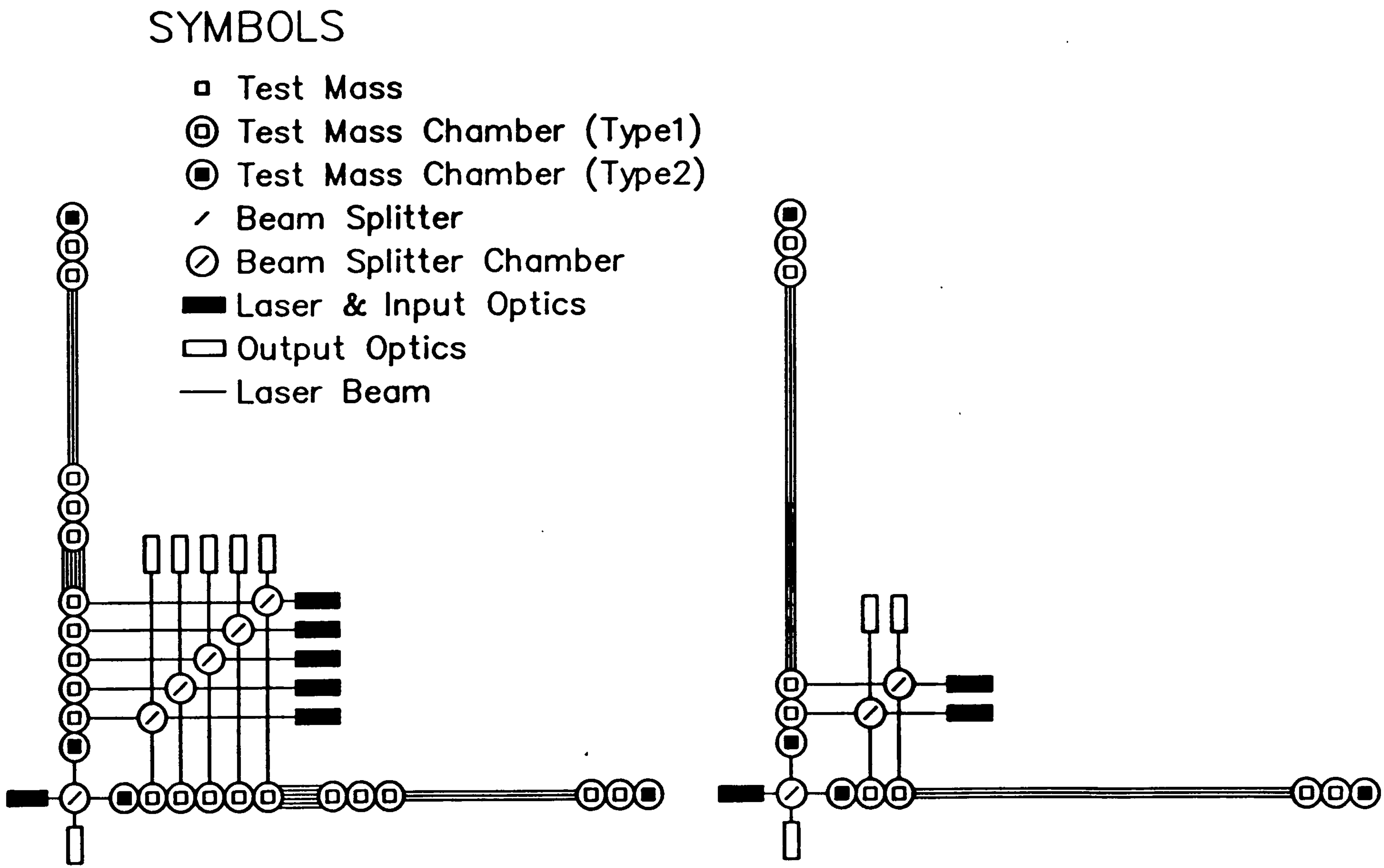
LIGO SCIENCE CAPABILITIES

Facilities	Measurement Capability	Science Capability
I. 2 U.S. Sites	$(ah_+ + bh_\times)$, θ	1. *Physics:* • Confirmation of existence of gravitational waves • Propagation speed of gravitational waves (from periodic sources, or from burst sources if event also observed in electromagnetic band) • Graviton spin (from periodic sources) • Existence of Black Holes (if sufficient number of events) 2. *Astrophysics:* • Classification of signals • Statistics on types of sources (burst, periodic, semi-periodic...) • Distances and mass information for spiralling binaries • Source location on cone (from "time of flight") • Search for stochastic background
II. 2 U.S. + 1 abroad or 3 U.S.	h_+, $h_\times$, θ, ϕ	All of I, plus 1. *Physics:* • Graviton spin (from polarization of waves) • Test of general relativity in strong-gravity, high-speed regime (via Black Hole waveforms) 2. *Astrophysics:* • Source location (θ, ϕ) • Waveforms give information on sources: e.g., core dynamics of supernovae, pulsar deformations, starquakes • Sky survey of sources
III. 2 U.S. + several abroad	h_+, $h_\times$, θ, ϕ	All of II, but at higher sensitivity; more accurate source locations



Site 1
Phase A

Site 2
Phase A



Site 1
Phase C

Site 2
Phase C

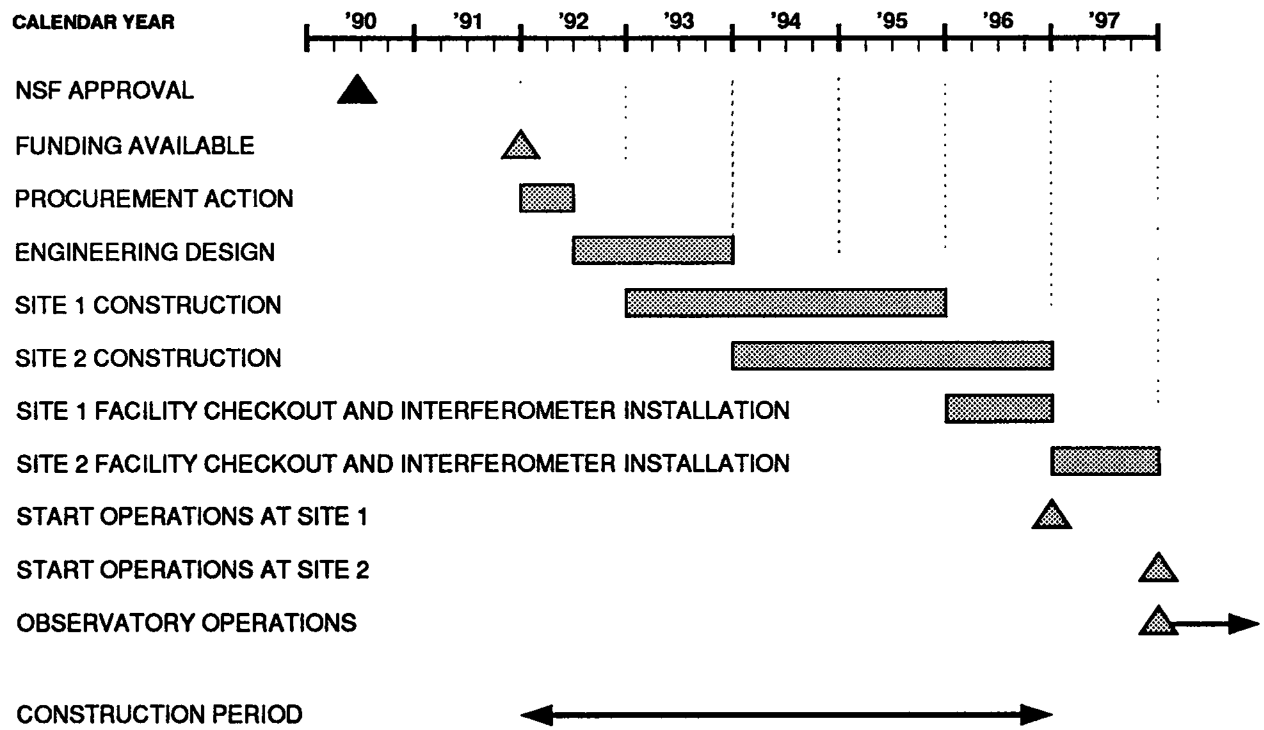
LIGO is a new facility, designed to serve a new scientific discipline.

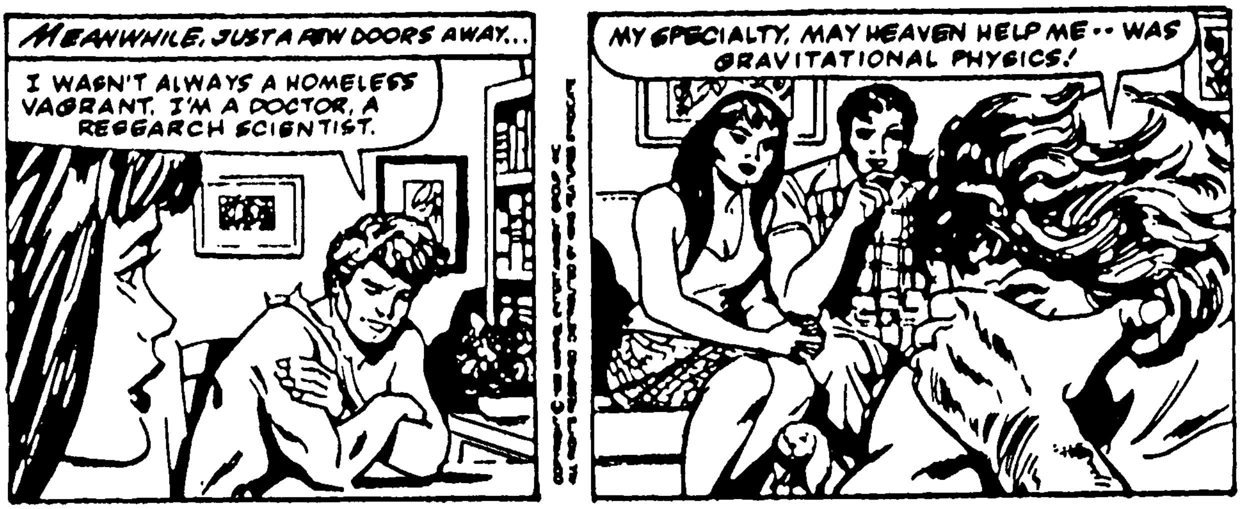
LIGO technology and operations are different from what exists today.

LIGO hardware and operations philosophy closer to physics and particle accelerators.

LIGO usage and actual operations closer to astronomical observatory.

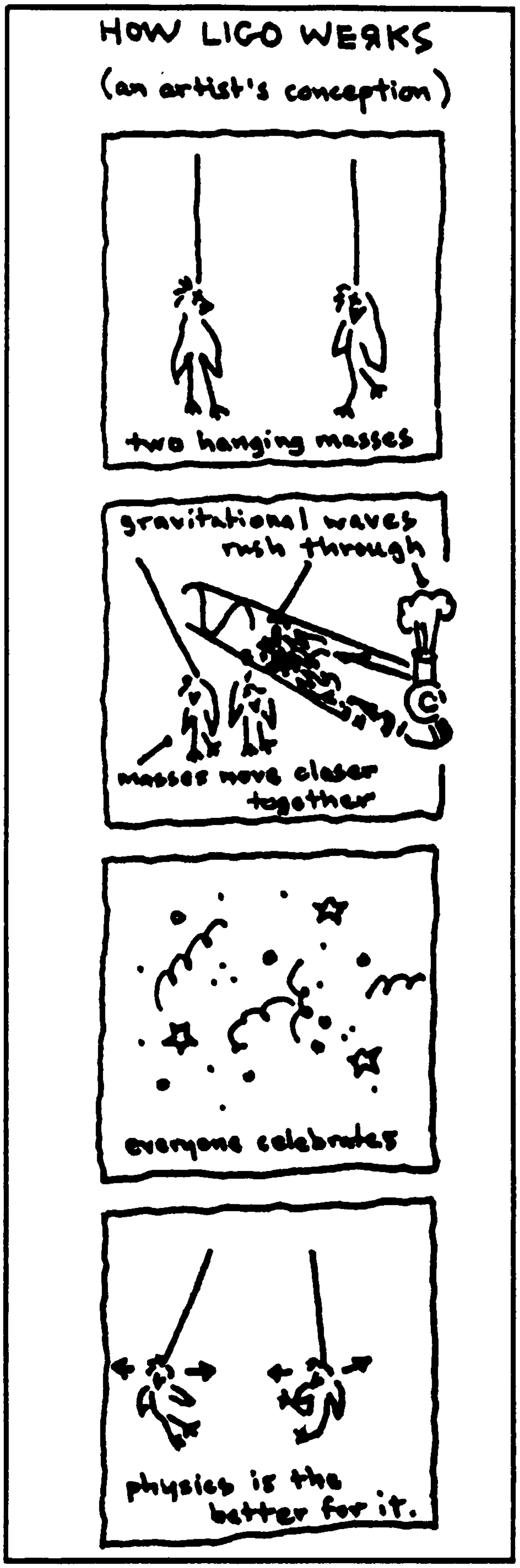
LIGO PROJECT SCHEDULE




MEANWHILE, JUST A FEW DOORS AWAY...
I WASN'T ALWAYS A HOMELESS VAGRANT. I'M A DOCTOR, A RESEARCH SCIENTIST.
MY SPECIALTY, MAY HEAVEN HELP ME -- WAS GRAVITATIONAL PHYSICS!

"There is nothing more difficult to take in hand,
more perilous to conduct,
or more uncertain in its success,
than to take the lead
in the introduction of a new order of things."

—MACHIAVELLI, *The Prince* (1513)


HOW LIGO WERKS
(an artist's conception)
two hanging masses
gravitational waves rush through
masses move closer together
everyone celebrates
physics is the better for it.

LIGO SITE EVALUATION REVIEW COMMITTEE CHARTER

In general terms, the Review Committee is asked to review the technical site evaluation performed by the LIGO team. In particular, the Committee considerations should include the following:

Do the procedures followed by the LIGO team comply with the site selection criteria and guidelines approved by the National Science Board (Appendix A of the Site Evaluation report)?

Do the procedures appear to have been used objectively and accurately, and do the resulting evaluations appear to be fair?

Does the Committee have any general comments?

To discharge its formal responsibilities, the Committee is asked to generate a statement of its findings which will be forwarded to NSF by Caltech, along with the LIGO Site Evaluations report.

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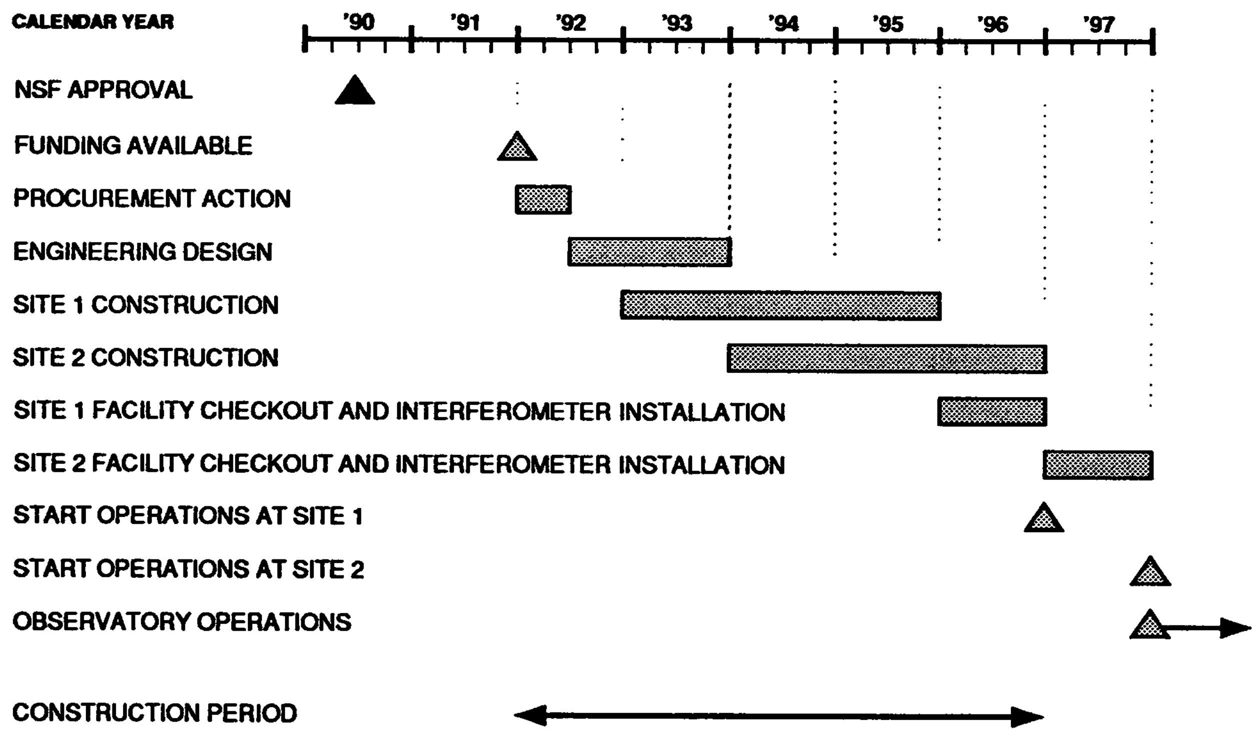
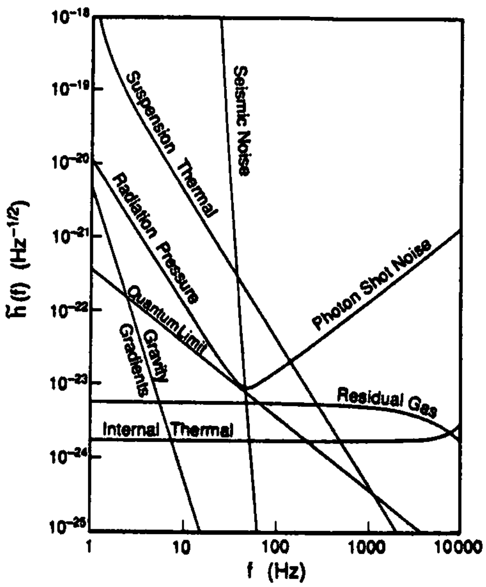
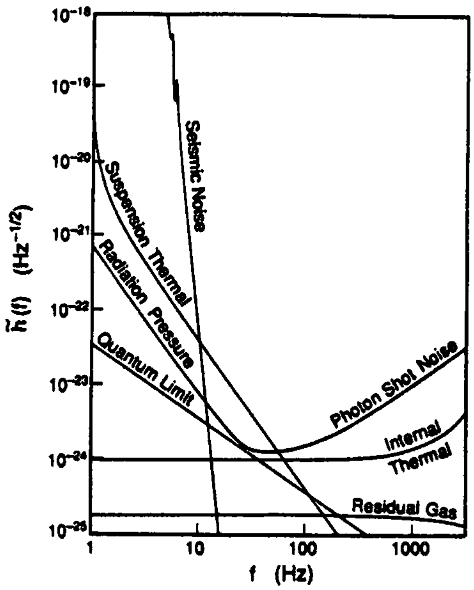




Spectra of noise sources for early LIGO detector. Note: $\left[\tilde{h}(f)\right]^2$ is the spectral density of $h(t)$; the rms noise amplitude in a search for broad-band gravitational-wave bursts is $h_{rms} = \tilde{h}(f)\sqrt{f}$. Detector parameters are: Laser 5 Watt, Mirror Losses 50 ppm, Recycling Factor 30, Test Masses 10 kg, Suspension $Q = 10^7$, Vacuum $H_2 = 10^{-6}$ torr, $H_2O = 10^{-7}$ torr.



Spectra of noise sources for advanced LIGO detector. Detector parameters: Laser 60 Watt, Mirror Losses 20 ppm, Recycling Factor 100, Test Masses 1 ton, Suspension $Q = 10^9$, Vacuum $H_2 = 10^{-9}$ torr, $H_2O = 10^{-10}$ torr.

LIGO GOALS

PAYOFFS FOR PHYSICS

- DIRECT CONFIRMATION OF EXISTENCE OF GRAVITATIONAL WAVES. TEST OF STRONG-FIELD GENERAL RELATIVITY
- MEASUREMENT OF GRAVITON PROPERTIES. GENERAL RELATIVITY PREDICTS

$$v = c$$
$$m = 0$$
$$s = 2$$

- VERIFICATION OF EXISTENCE AND DYNAMICS OF BLACK HOLES

PAYOFFS FOR ASTROPHYSICS

NEW WINDOW ONTO UNIVERSE

- COALESCING BLACK HOLES / HIGHLY NON-LINEAR DYNAMIC GRAVITY
- HIGHLY DYNAMICAL NEUTRON STAR PHENOMENA / PHYSICS OF NEUTRON STARS
- SUPERNOVAE / CREATION OF NEUTRON STARS
- COALESCING BINARIES / STANDARD CANDLES FOR DISTANCES
- PRIMORDIAL WAVES / INITIAL CONDITIONS AND EARLY EVOLUTION OF UNIVERSE
- LARGE SCALE MASS DISTRIBUTION OF UNIVERSE

- PHENOMENA *UNPREDICTABLE* BY E.M. ASTRONOMY AND *UNPREDICTED* BY THEORETICAL RELATIVISTS

LIGO PROJECT ROOTS/HISTORY

1916	Einstein / General Relativity / Gravitational Waves (GWs)
1957	J. Wheeler & J. Weber (sabbatical visitor) write paper on GWs
1959 / 60	J. Weber starts bar detector work
mid 1960's	Dyson, Thorne & students study GW sources
1969	J. Weber claims discovery of GWs
>1969	Theoretical work on GWs intensifies
1970's	Analytical and early laboratory development of laser-interferometric GW detectors
1979	Caltech and MIT groups funded by NSF to develop laser interferometric GW detectors
1983	Caltech and MIT groups joined in shotgun wedding
1983 / 84	Caltech / MIT proposals to build km-scale laser-interferometric GW detectors (LIGO)
	J. Taylor and colleagues demonstrate existence of GWs by indirect means (pulsar orbit decay)
1986	Cambridge, Mass. — Blue Ribbon review of LIGO
1987	LIGO program reorganized. Steering committee replaced by a director. Caltech/MIT team unified. Fabry-Perot system selected. LIGO conceptual design initiated.
Dec. 1989	LIGO construction proposal submitted to NSF
May 1990	NSB approves LIGO proposal
1990	President's budget proposal for FY '91 includes LIGO new start ($47 M)
	Congress reduces LIGO line item to $0.5 M, recommends further R&D and design
	NSB authorizes national site solicitation
1991	President's budget proposal for FY '92 includes LIGO new start ($23.5 M)
	Congress appropriates $23.5 M for LIGO new start in FY '92
	NSF cuts FY '92 LIGO funding

LIGO OBSERVATORY

OBSERVATORY ≡ 2 LIGO facilities located far apart (noise uncorrelated) operating in unison (coincidence) to eliminate spurious events simulating gravitational waves

Noise has Gaussian and non-Gaussian components

- Fluctuating gravitational gradients
- Ground vibrations
- Mechanical strain releases
- Fluctuation in gas pressure
- Magnetic field fluctuations
- Cosmic rays

LIGO detector consists of 3 interferometers:

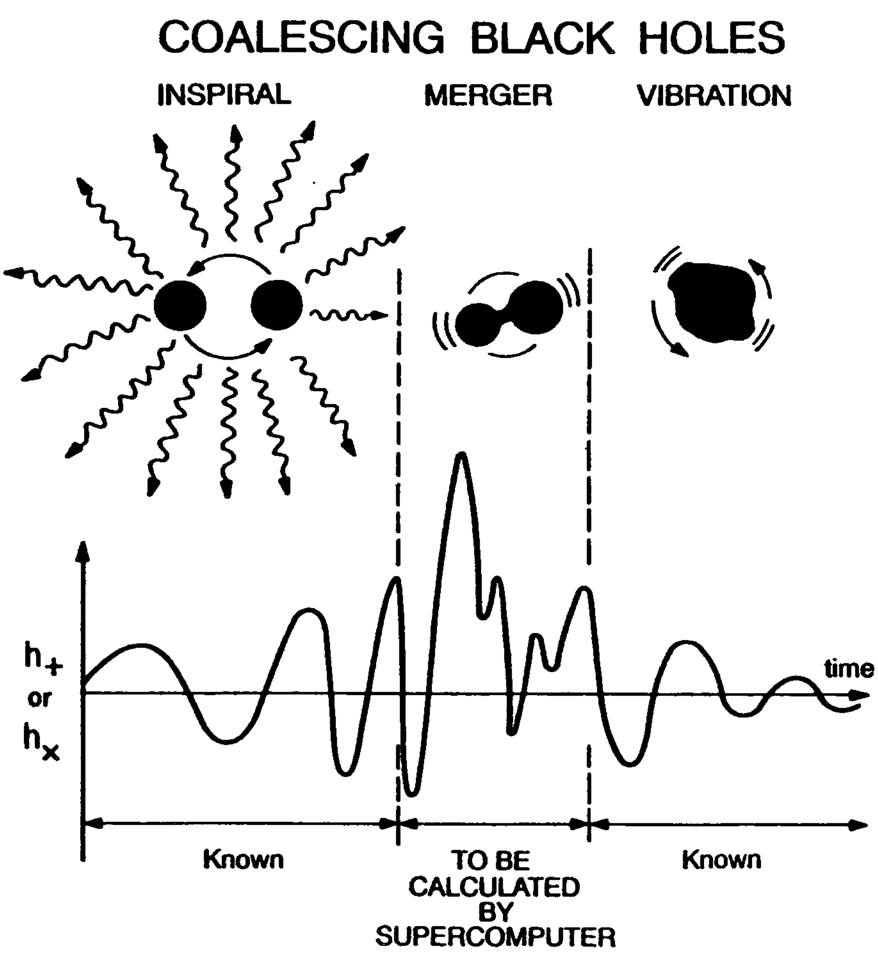
Site 1: 1 full length IF (L)
1 half length IF (L/2)

Site 2: 1 full length IF (L)

Triple coincidence allows reliable detection of
< 1 event/year

GW Information Obtained by Waveform Analysis

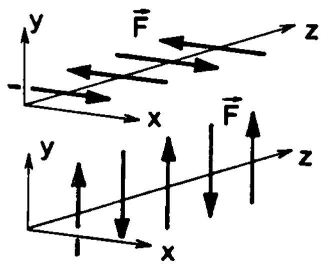
- **Almost All Electromagnetic Astronomy Is Based on Spatial or Spectral Analysis**
- **Extraction of Information From Gravitational Wave Depends on Waveform Analysis**



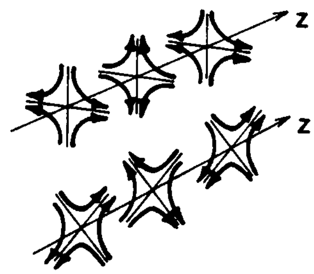
PHYSICS OF GRAVITATIONAL WAVES

GRAVITON: m = 0
v = c
s = 2

FORCE FIELDS: transverse polarization: h_+, $h_\times$



electric field



gravitational field

STRAIN AMPLITUDE:

$$h \propto \ddot{Q} \sim (\ddot{ML^2}) \sim (Mv^2) \sim E_{kin}^{ns}$$

$$h \sim \frac{G}{c^4}\frac{E_{kin}^{ns}}{r} \sim 10^{-20}\left[\frac{E_{kin}^{ns}}{M_\odot c^2}\right]\left[\frac{10Mpc}{r}\right]$$

for $E_{kin}^{ns} \sim M_\odot c^2$

$h \sim 10^{-17}$ (our galaxy)

$\sim 10^{-20}$ (Virgo cluster)

$\sim 10^{-23}$ (cosmological distances)

SIGNAL FREQUENCIES:

$f_{BH\ pulsation} \sim \frac{1kHz}{M/10M_\odot}$

$f_{BH\ coalescence}$: < 10Hz to $f_{BH\ pulsation}$

$f_{NS\ pulsation} \sim$ 1 kHz

$f_{NS\ coalescence}$: < 10Hz to $f_{NS\ pulsation}$

GRAVITATIONAL WAVES contrasted with EM WAVES

	ELECTROMAGNETIC	GRAVITATIONAL
Emission Mechanisms	Individual atoms, molecules, electrons Incoherent superposition	Coherent motions of large masses or spacetime curvature
Examples of Sources	Stellar atmospheres Interstellar gas Accretion discs	Supernova cores Colliding neutron stars or black holes Vibrating cosmic strings
Interaction with Matter	Dispersion Absorption	No dispersion (almost) No absorption (almost)
Primordial Radiation	From $z \sim 1000$ $\tau \sim 10^6$ yrs	From Planck era $\tau \sim 10^{-43}$ sec

- **DO GRAVITATIONAL WAVES EXIST?**

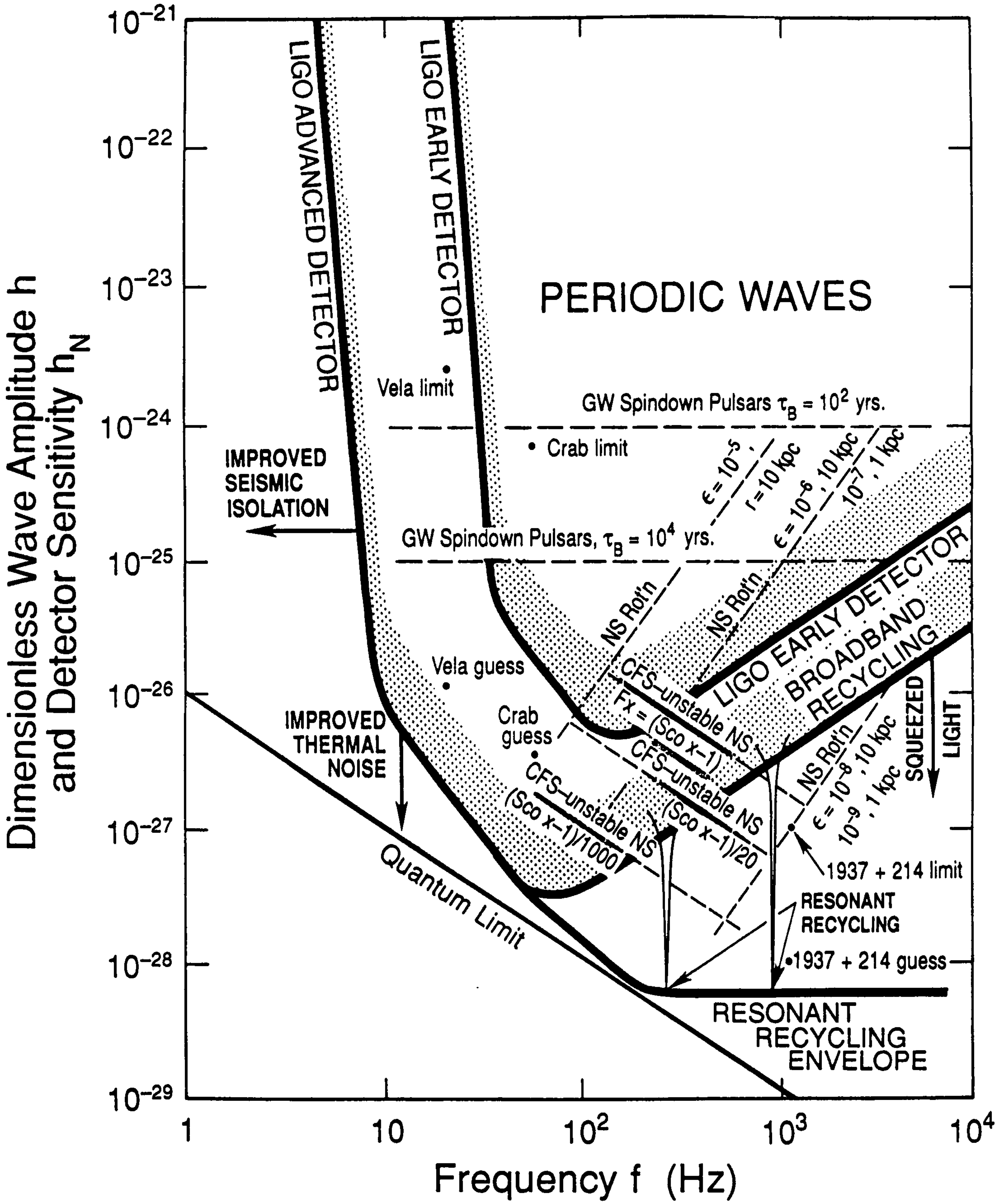
  1. **MANY OF US ARE STAKING OUR PROFESSIONAL LIVES ON IT!**

  2. **PREDICTION:**

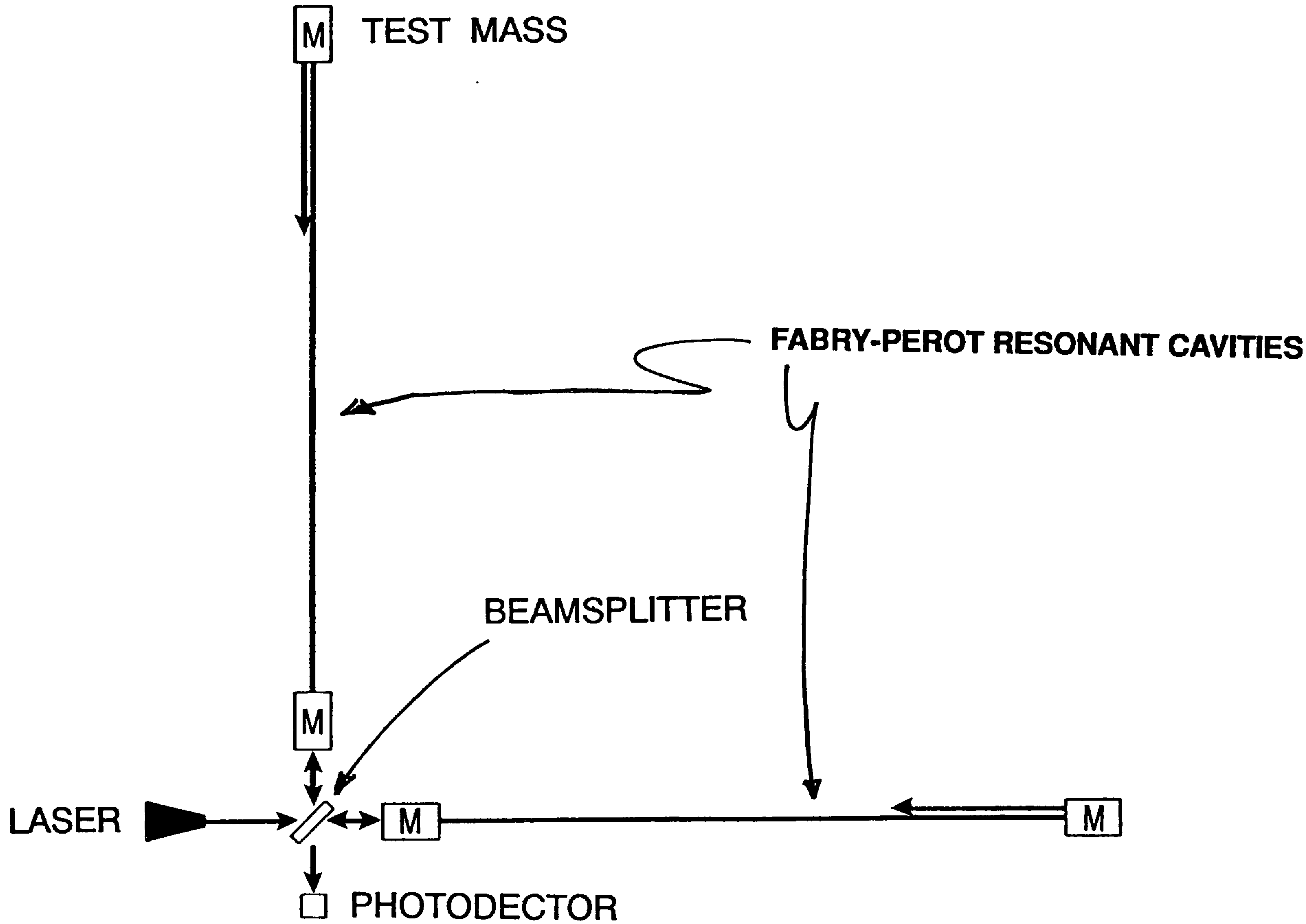
     EINSTEIN (1916): GENERAL THEORY OF RELATIVITY
     PRESENT GENERATION OF THEORETICAL ASTROPHYSICISTS

  3. **INDIRECT OBSERVATION:**

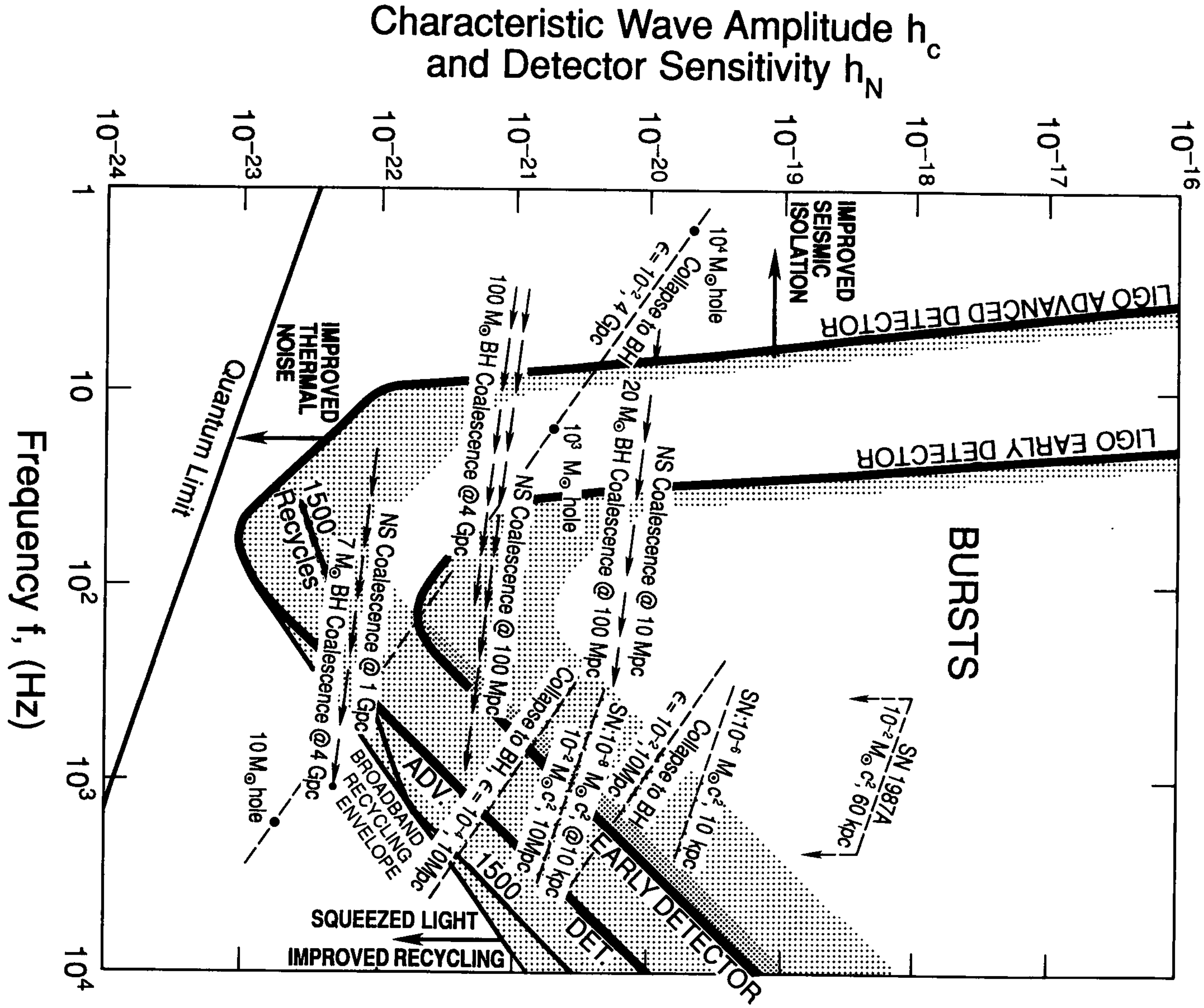
     TAYLOR ET. AL: BINARY PULSAR SYSTEM'S ORBITAL DECAY (BY GRAVITATIONAL WAVES) AGREES WITH EINSTEIN PREDICTION



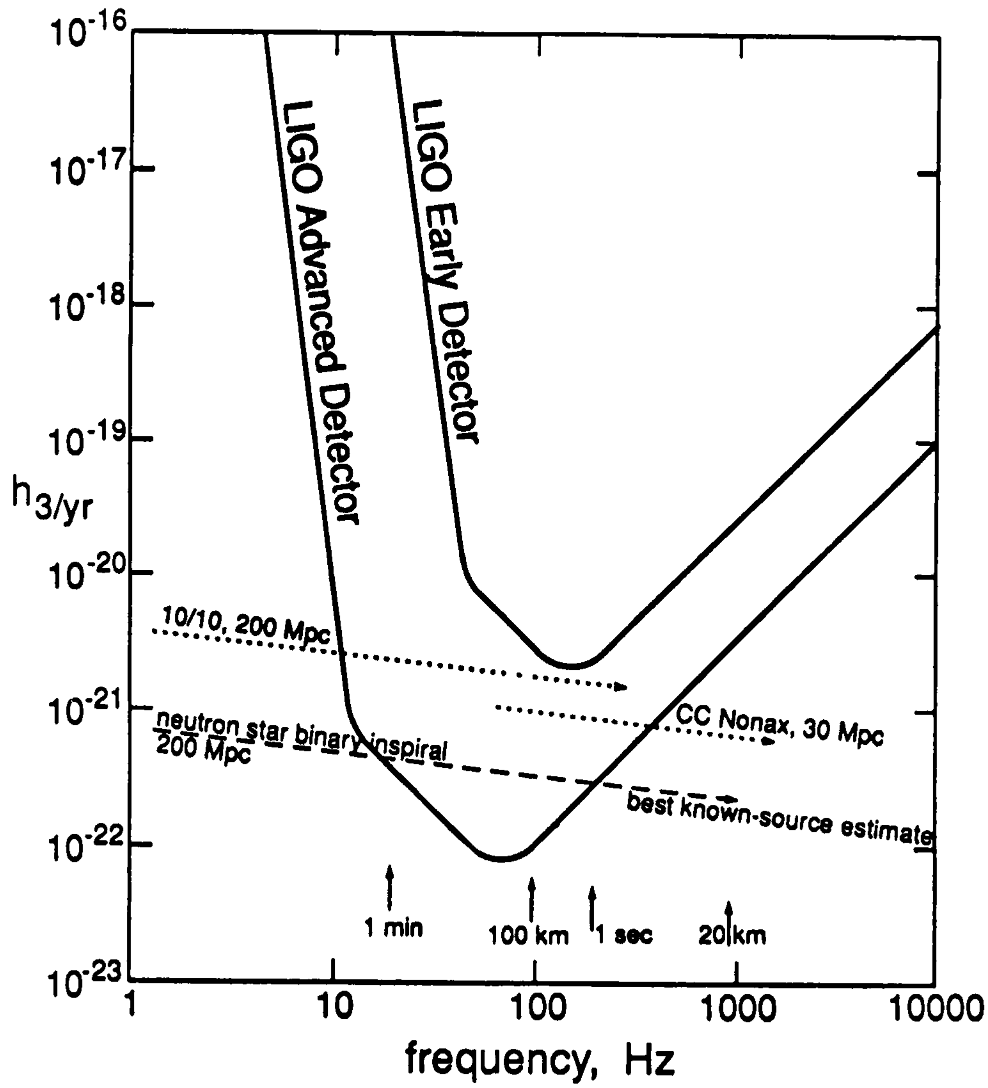
PERIODIC WAVES
LIGO ADVANCED DETECTOR
LIGO EARLY DETECTOR
Vela limit
GW Spindown Pulsars τB = 10² yrs.
Crab limit
IMPROVED SEISMIC ISOLATION
GW Spindown Pulsars, τB = 10⁴ yrs.
ε = 10⁻⁵, r = 10 kpc
ε = 10⁻⁶, 10 kpc
10⁻⁷, 1 kpc
NS Rot'n
LIGO EARLY DETECTOR BROADBAND RECYCLING
Vela guess
CFS–unstable NS Fx = (Sco x–1)
CFS–unstable NS (Sco x–1)/20
CFS–unstable NS (Sco x–1)/1000
Crab guess
IMPROVED THERMAL NOISE
SQUEEZED LIGHT
ε = 10⁻⁸, 10 kpc
10⁻⁹, 1 kpc
1937 + 214 limit
RESONANT RECYCLING
1937 + 214 guess
Quantum Limit
RESONANT RECYCLING ENVELOPE
Dimensionless Wave Amplitude h and Detector Sensitivity hN
Frequency f (Hz)
10⁻²¹
10⁻²²
10⁻²³
10⁻²⁴
10⁻²⁵
10⁻²⁶
10⁻²⁷
10⁻²⁸
10⁻²⁹
1
10
10²
10³
10⁴



TEST MASS
M
FABRY-PEROT RESONANT CAVITIES
BEAMSPLITTER
M
LASER
M
M
PHOTODECTOR



Characteristic Wave Amplitude h_c
and Detector Sensitivity h_N
10^{-24}
10^{-23}
10^{-22}
10^{-21}
10^{-20}
10^{-19}
10^{-18}
10^{-17}
10^{-16}
Frequency f, (Hz)
1
10
10^2
10^3
10^4
Quantum Limit
IMPROVED THERMAL NOISE
IMPROVED SEISMIC ISOLATION
LIGO ADVANCED DETECTOR
LIGO EARLY DETECTOR
BURSTS
$10^4 M_\odot$ hole
Collapse to BH
$\epsilon = 10^{-2}$, 4 Gpc
$10^3 M_\odot$ hole
$10 M_\odot$ hole
100 $M_\odot$ BH Coalescence @ 4 Gpc
20 $M_\odot$ BH Coalescence @ 100 Mpc
NS Coalescence @ 10 Mpc
NS Coalescence @ 100 Mpc
NS Coalescence @ 1 Gpc
7 $M_\odot$ BH Coalescence @ 4 Gpc
1500 Recycles
Collapse to BH, $\epsilon = 10^{-4}$, 10 Mpc
SN: $10^{-6} M_\odot c^2$, 10 kpc
Collapse to BH
$\epsilon = 10^{-2}$, 10Mpc
SN: $10^{-6} M_\odot c^2$, @10 kpc
$10^{-2} M_\odot c^2$, 10Mpc
SN 1987A
$10^{-2} M_\odot c^2$, 60 kpc
BROADBAND RECYCLING ENVELOPE
ADV.
1500
DET.
EARLY DETECTOR
SQUEEZED LIGHT
IMPROVED RECYCLING


LIGO Early Detector
LIGO Advanced Detector
10/10, 200 Mpc
CC Nonax, 30 Mpc
neutron star binary inspiral
200 Mpc
best known-source estimate
1 min
100 km
1 sec
20 km
$h_{3/yr}$
10^{-16}
10^{-17}
10^{-18}
10^{-19}
10^{-20}
10^{-21}
10^{-22}
10^{-23}
1
10
100
1000
10000
frequency, Hz

LIGO designed to

- detect gravitational waves by direct means
- study their wave forms
- with broad-band capability (10 Hz — 10 kHz)
- with sensitivity for "standard signal" (coalescing NS's) to the edge of observable universe $\left(h_B \sim 10^{-23}\right)$

More specifically, we are pursuing the following objectives:

EM waves travel through space without affecting it

GW's are perturbations in the curvature of space time, i.e., they are travelling perturbations of space itself

While EMW's and GW's often may come from the same source, their information content derives from very different physical processes.

We cannot use EM knowledge to predict strength of GW's.

Most GW sources might never be seen by EM astronomy and vice versa.

GW's from Sun-Earth system:

$$f \sim 10^{-8}\ \mathrm{Hz}$$

$$\tau \sim 1\ \mathrm{l.y.}(10^{18}\mathrm{cm})$$

$$\mathrm{h} \sim 10^{-28}$$

Wave-form analysis:

- **If** $h_\times(t) = \text{const.}\, h_+(t)$: **source axisymmetric**
- **Since** $t_{min} \sim 0.5\,\text{msec}$: **source must be NS or several** $M_\odot$ BH
- **From double time integration:**

  FF regions: non-spherical free-fall motion

  P's represent sharp acceleration opposite to free-fall: collapse formed NS that bounced 3 times

  E: other axis bounced once

Collapsing star centrifugally flattened by rotation, its pole collapsed fast and bounced 3 times, while its equator collapsed more slowly and bounced once.

It is not enough to have sensitivity for nearby (strong) but possibly infrequent (small volume of space) sources.

We define credible detection program (in early discovery mode) as 3 or more events per year

$$h_{3/yr} = 11\, h_{rms}$$

representing a 90% confidence figure for the detection of bursts arriving 3 times per year from random, unknown directions at random, unknown times, with random polarizations (in detectors free from non-Gaussian noise bursts).

Detection:

Gravitational wave determined by time dependent behavior of amplitude and polarization of dimensionless strain h(t).

h(t) determines change in separation $\triangle L(t)$ of two free objects separated by distance L

$\triangle L$ measured by laser interferometry

PROTOTYPE INTERFEROMETER

Prototype is a test bed for selected full-scale LIGO techniques and systems.

Predicted performance of LIGO interferometers must be pieced together from individual tests, without any unified demonstration.

Laboratory-scale interferometers are fundamentally different from LIGO-scale interferometers; since e.g., noise sources scale differently with arm-length and frequency.

LIGO works on the same principles of the 40–m prototype, with the separation of the test masses scaled up by a factor of 100 (L = 4 km).

In addition, LIGO is designed as an operating observatory (as opposed to the prototype which serves development and demonstration purposes) — and this requires greater automation, sophistication, and reliability.

Details in SEW discussion!

LIGO is a new facility, designed to serve a new scientific discipline.

LIGO technology and operations are different from what exists today.

LIGO hardware and operations philosophy closer to physics and particle accelerators.

LIGO usage and actual operations closer to astronomical observatory.