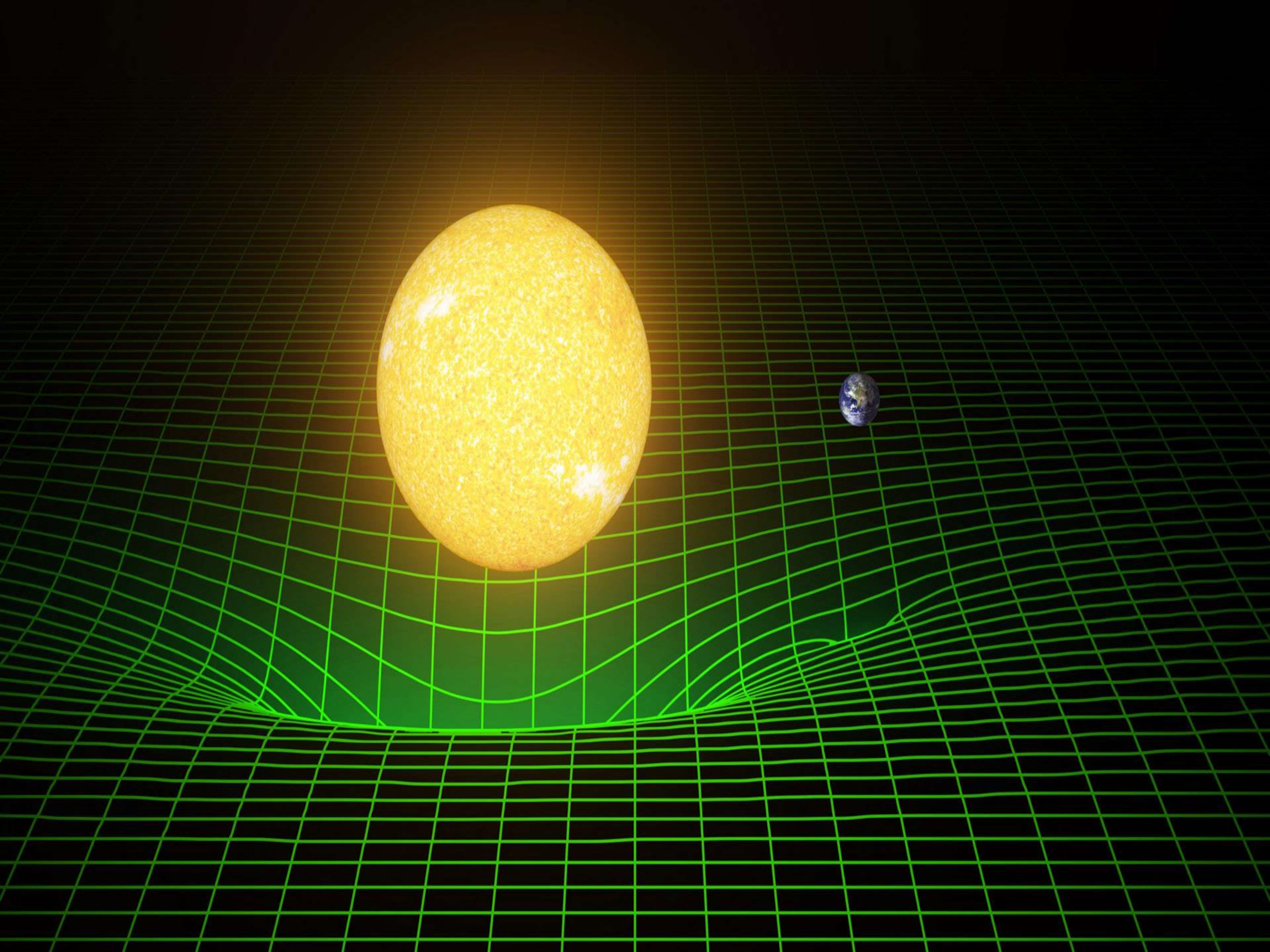
Observation of the merger of binary black holes: The opening of gravitational wave astronomy

R. Weiss, MIT, on behalf of the LIGO Scientific Collaboration

Fermi National Accelerator Labortory

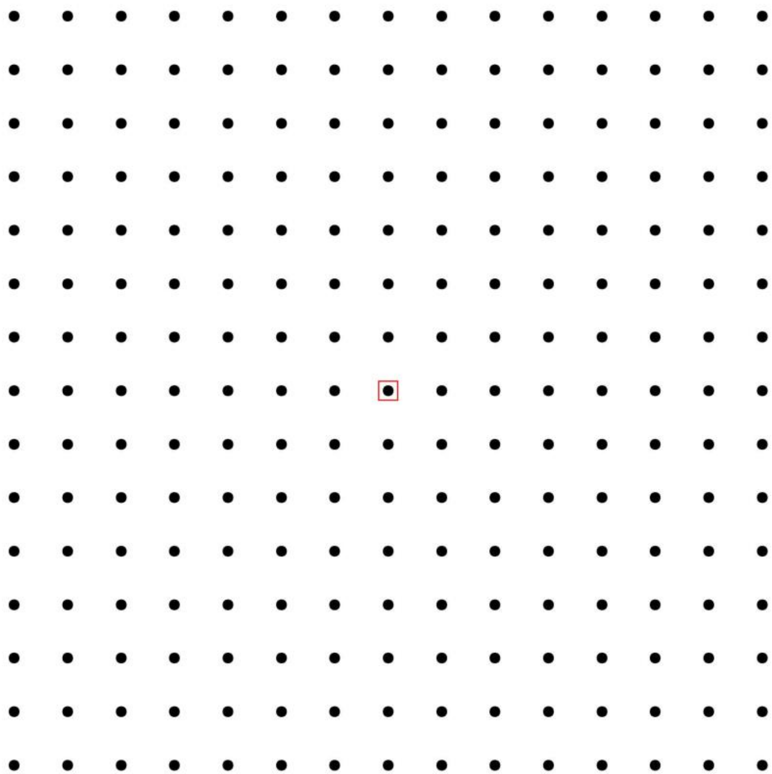
July 19, 2017



Gravitational waves

Einstein 1916 and 1918

- Sources: non-spherically symmetric accelerated masses
- Kinematics:
  - propagate at speed of light
  - transverse waves, strains in space (tension and compression)



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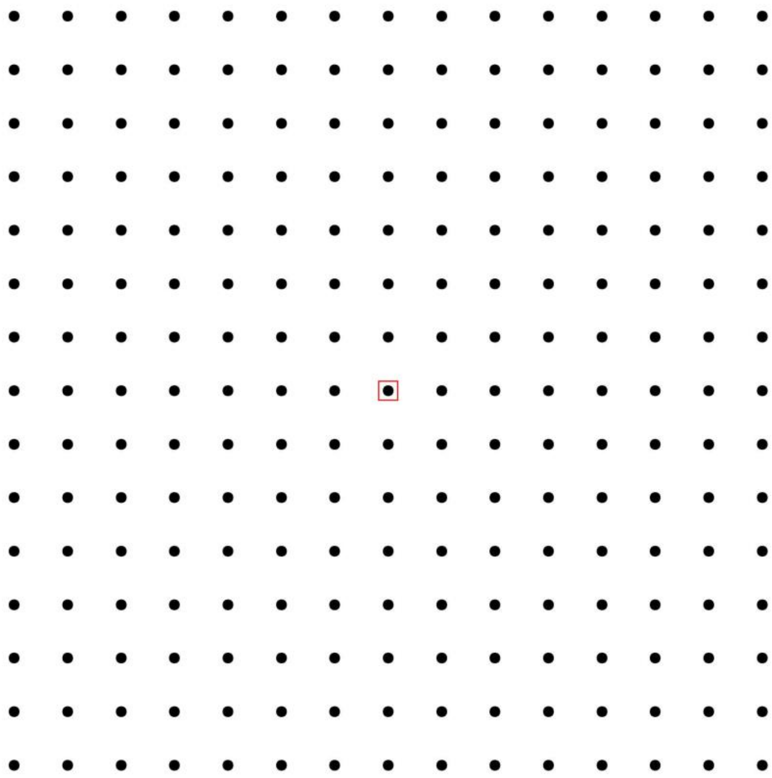


Einstein 1916

$$A = \frac{\varkappa}{24\pi} \sum_{\alpha\beta} \left(\frac{\partial^3 J_{\alpha\beta}}{\partial t^3} \right)^2. \qquad (21)$$

Würde man die Zeit in Sekunden, die Energie in Erg messen, so würde zu diesem Ausdruck der Zahlenfaktor $\frac{1}{c^4}$ hinzutreten. Berücksichtigt man außerdem, daß $\varkappa = 1.87 \cdot 10^{-27}$, so sieht man, daß A in allen nur denkbaren Fällen einen praktisch verschwindenden Wert haben muß.

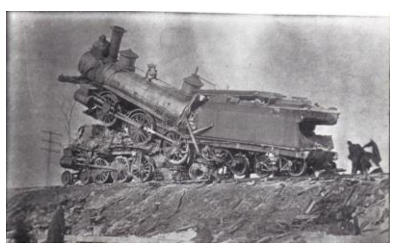
"…..in any case one can think of A will have a practically vanishing value."

$$h \approx \frac{j_{Newton}}{c^2} \frac{v^2}{c^2} = \frac{Gm}{Rc^2} \frac{v^2}{c^2}$$

$$S_g = \frac{c^3}{16\pi G} \left\langle \dot{h}_+^2 + \dot{h}_x^2 \right\rangle \qquad \frac{c^3}{16\pi G} = 7.8\text{x}10^{36} \text{ erg sec/ cm}^2$$

1916 examples: train colllision binary star decay

$m = 10^5$ kg
v = 100km/hr
$T_{collision}$ = 1/3 sec
$R_{radiation}$ = 300km
$h \sim 10^{-42}$



$m_1 = m_2$ = 1 solar mass
T_{orbit} = 1 day
R = 10 Kly

$h \sim 10^{-23}$ @ ½ day period

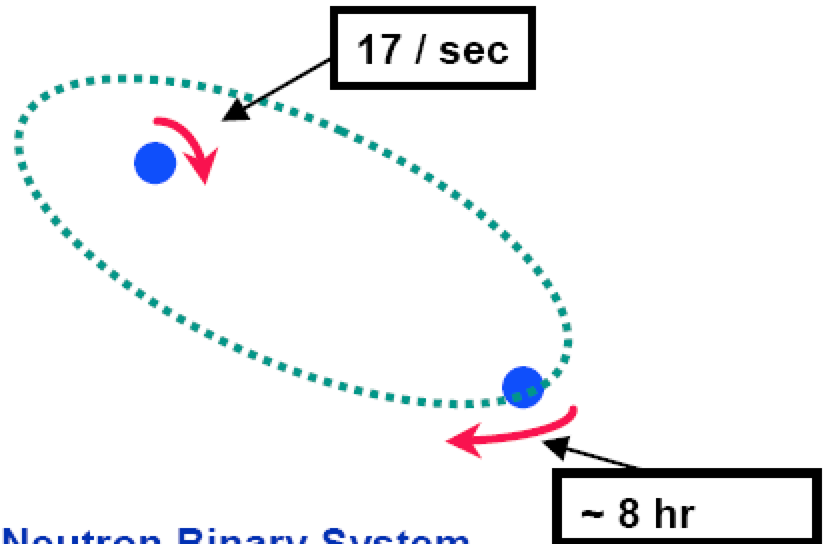
$$Q = \frac{2\pi E_{stored}}{\Delta E_{1period}} \sim 10^{15} \quad \text{decay time} \sim 10^{13} \text{ years}$$


Russel A. Hulse
Joseph H.Taylor Jr
Source: www.NSF.gov

Gravitational Waves
the evidence

Neutron Binary System – Hulse & Taylor

PSR 1913 + 16 -- Timing of pulsars



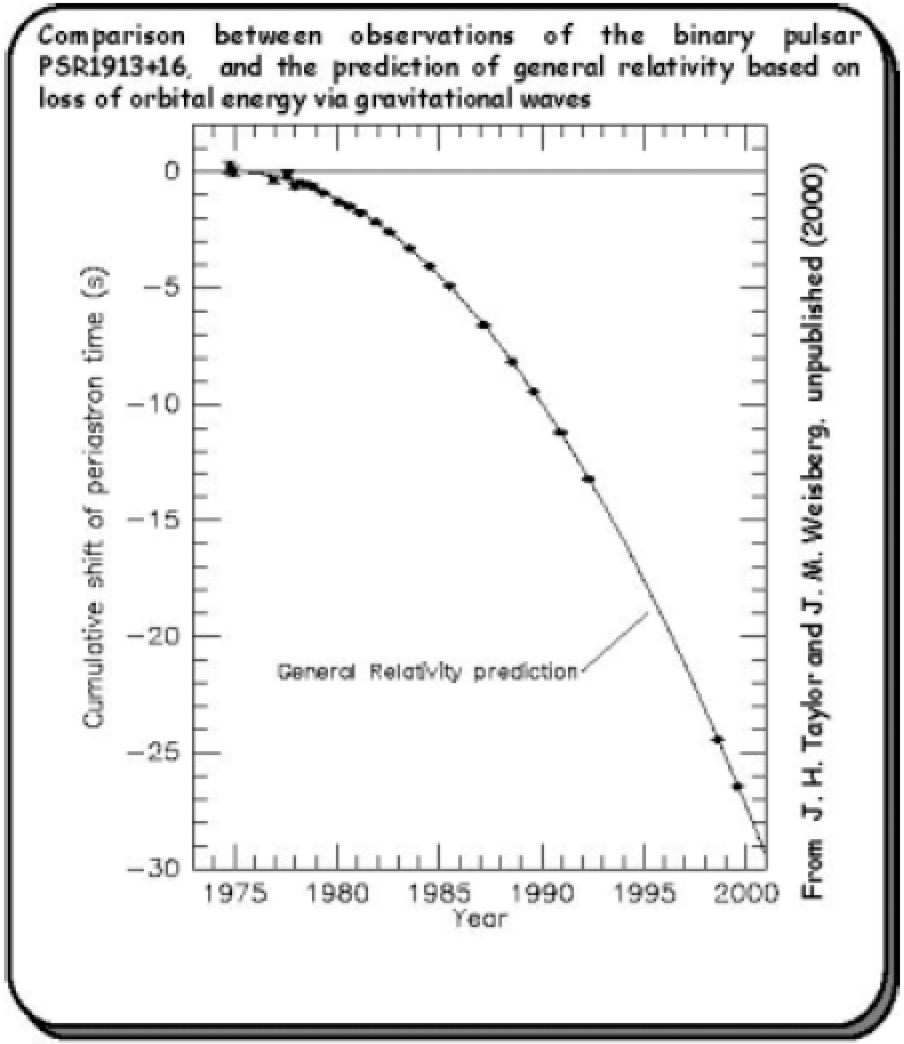
Neutron Binary System

- separated by 10^6 miles
- $m_1 = 1.4m_\odot$; $m_2 = 1.36m_\odot$; $\varepsilon = 0.617$

Prediction from general relativity

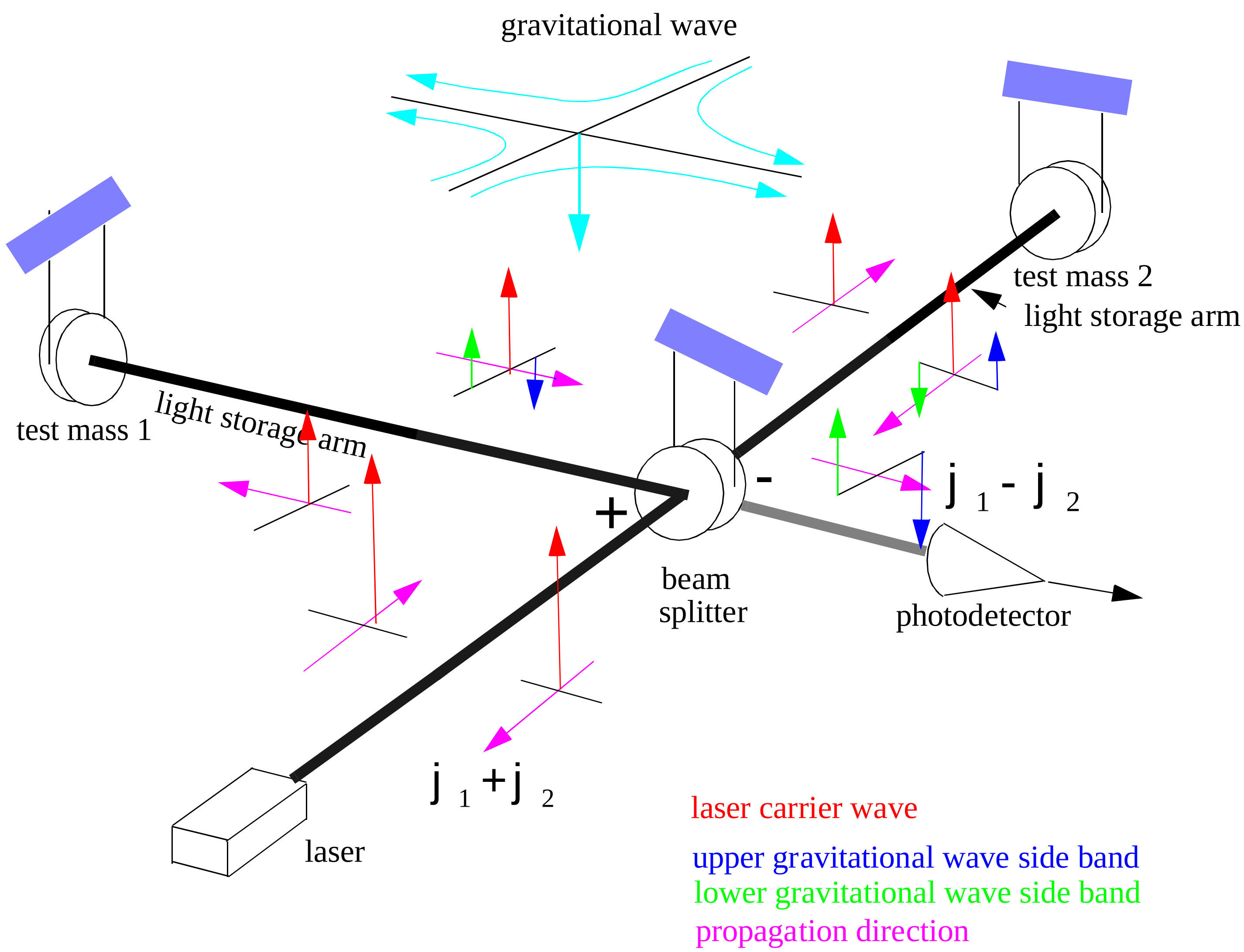
- spiral in by 3 mm/orbit
- rate of change orbital period

Emission of gravitational waves

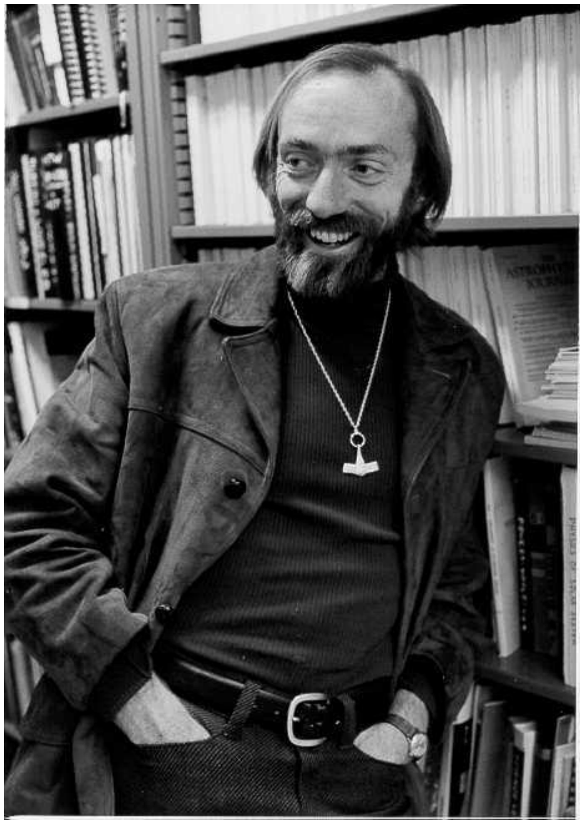


Joseph Weber 1919-2000

Michelson Interferometer Schematic and GW sidebands



The measurement challenge



Kip Thorne

$$h = \frac{\Delta L}{L} \leq 10^{-21}$$

$$L = 4\,\text{km} \quad \Delta L \leq 4 \times 10^{-18}\ \text{meters}$$

ΔL □ 10^{-12} wavelength of light

ΔL □ 10^{-12} vibrations at earth's surface

Initial interferometric GW detector groups late 1970's

H. Billing

L. Schnupp

K. Maischberger

W.Winkler

R. Schilling

A. Rudiger

Max Planck Garching

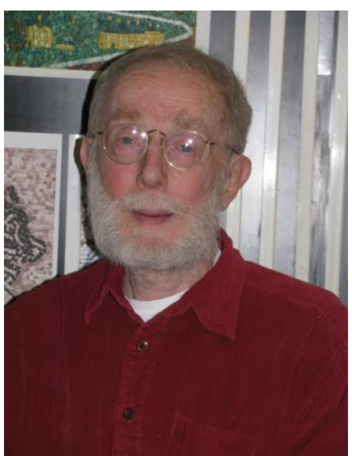
Glasgow

R. Drever

J. Hough

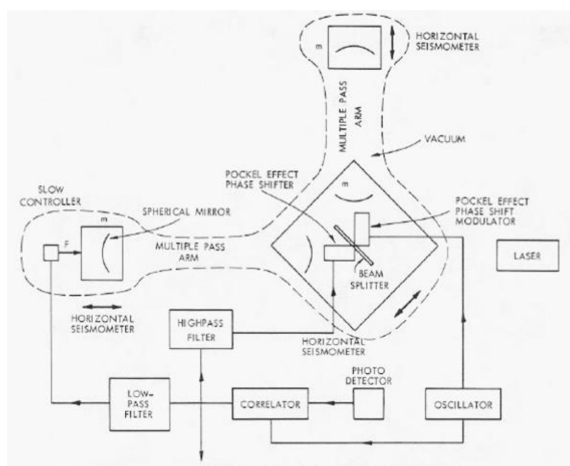
B. Meers

H. Ward



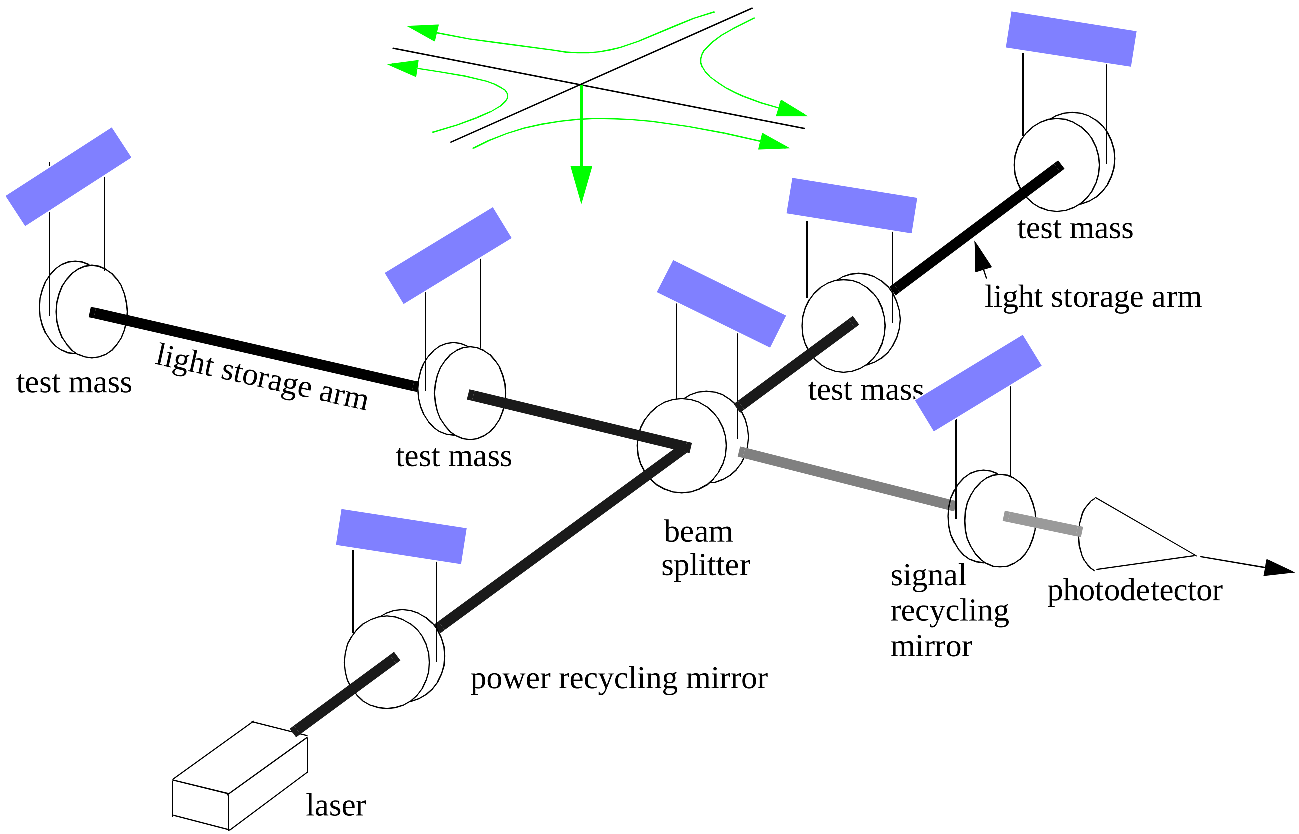
MIT

F.A.E. Pirani



J. Livas , D.H. Shoemaker, D. Dewey

Advanced LIGO Fabry-Perot Michelson Interferometer Schematic



R.Drever

R. Vogt

W. Althouse

K. Thorne

F. Raab

Proposal to the National Science Foundation

THE CONSTRUCTION, OPERATION, AND SUPPORTING RESEARCH AND DEVELOPMENT OF A

LASER INTERFEROMETER GRAVITATIONAL-WAVE OBSERVATORY

Submitted by the
CALIFORNIA INSTITUTE OF TECHNOLOGY

Rochus E. Vogt
Principal Investigator and Project Director
California Institute of Technology

Ronald W. P. Drever
Co-Investigator
California Institute of Technology

Frederick J. Raab
Co-Investigator
California Institute of Technology

Kip S. Thorne
Co-Investigator
California Institute of Technology

Rainer Weiss
Co-Investigator
Massachusetts Institute of Technology

F. Asiri

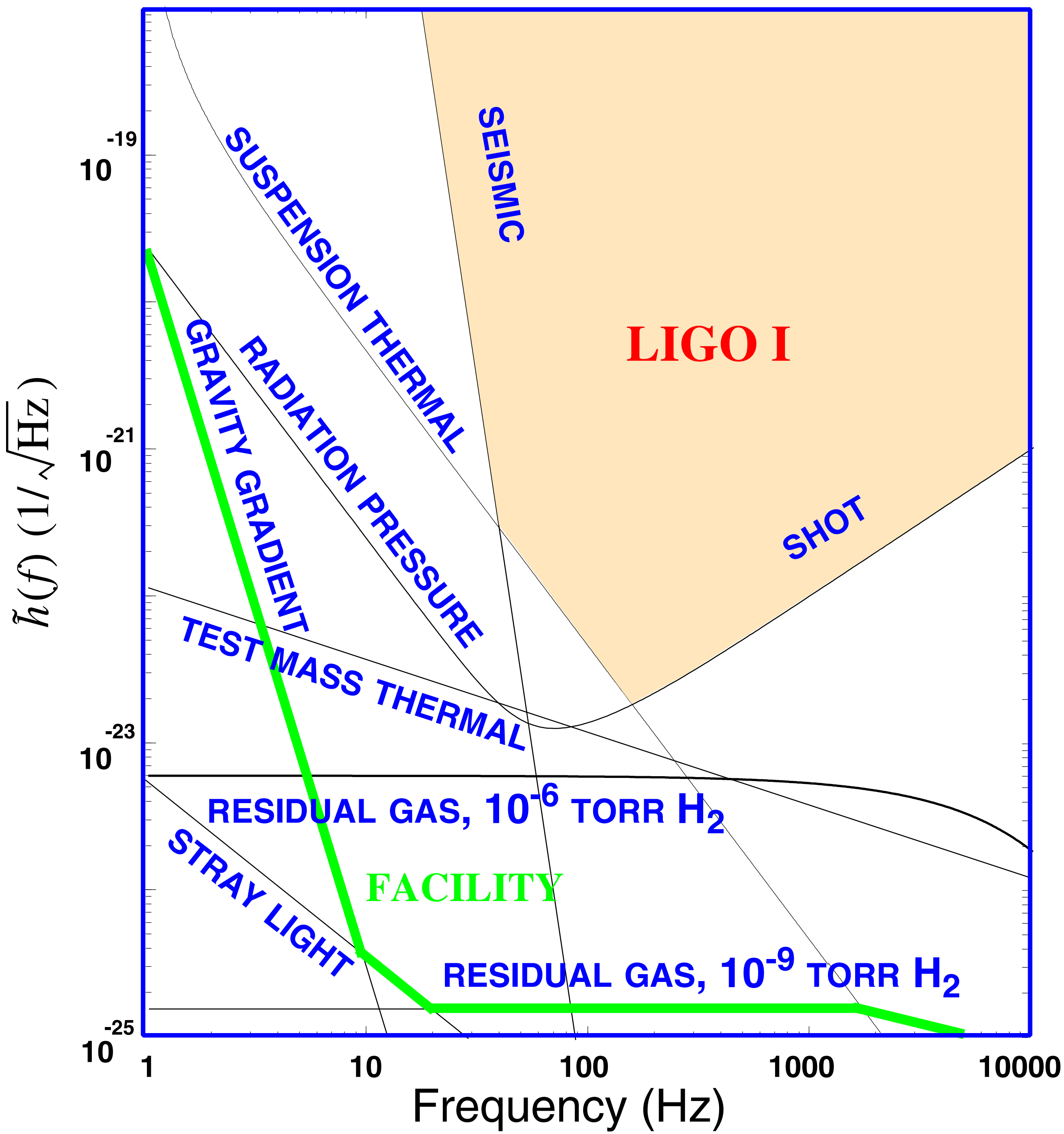
R. Savage

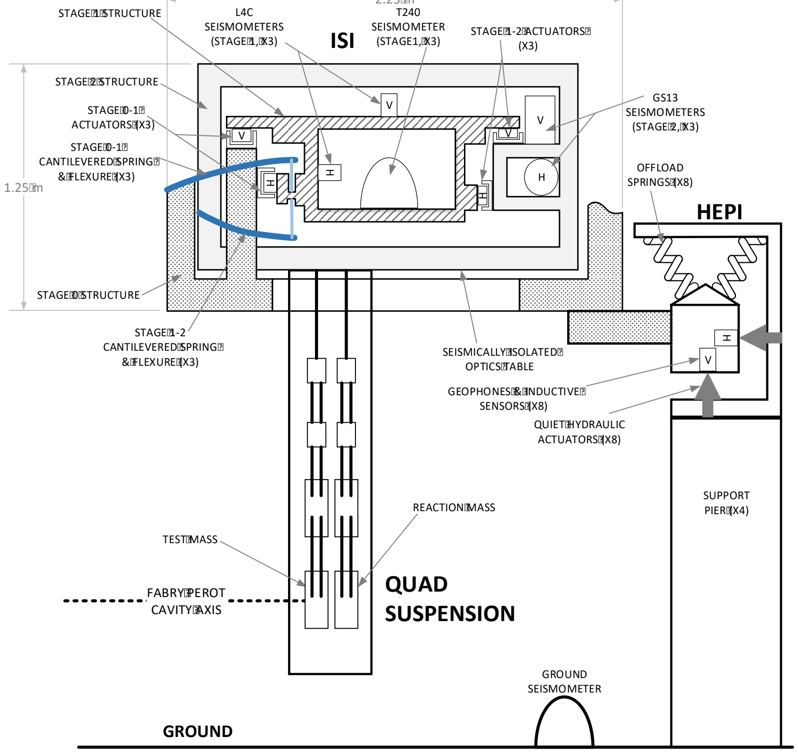
J. Worden

M. Zucker

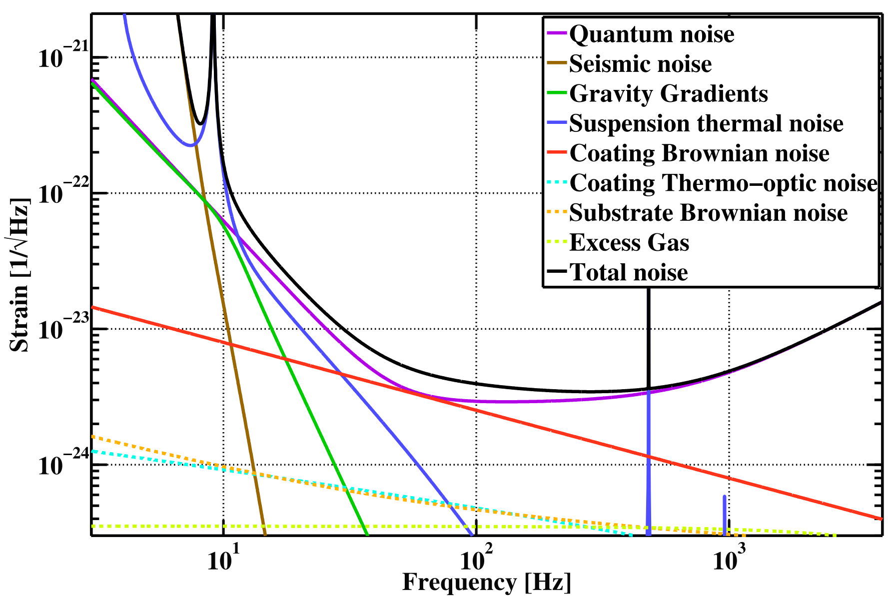
L.Jones

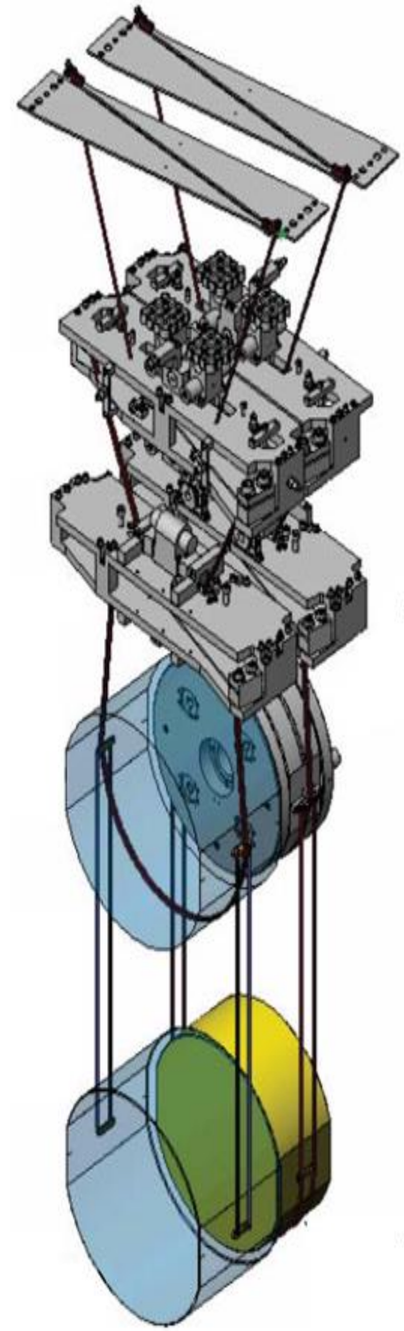
Initial LIGO Interferometer Noise Budget

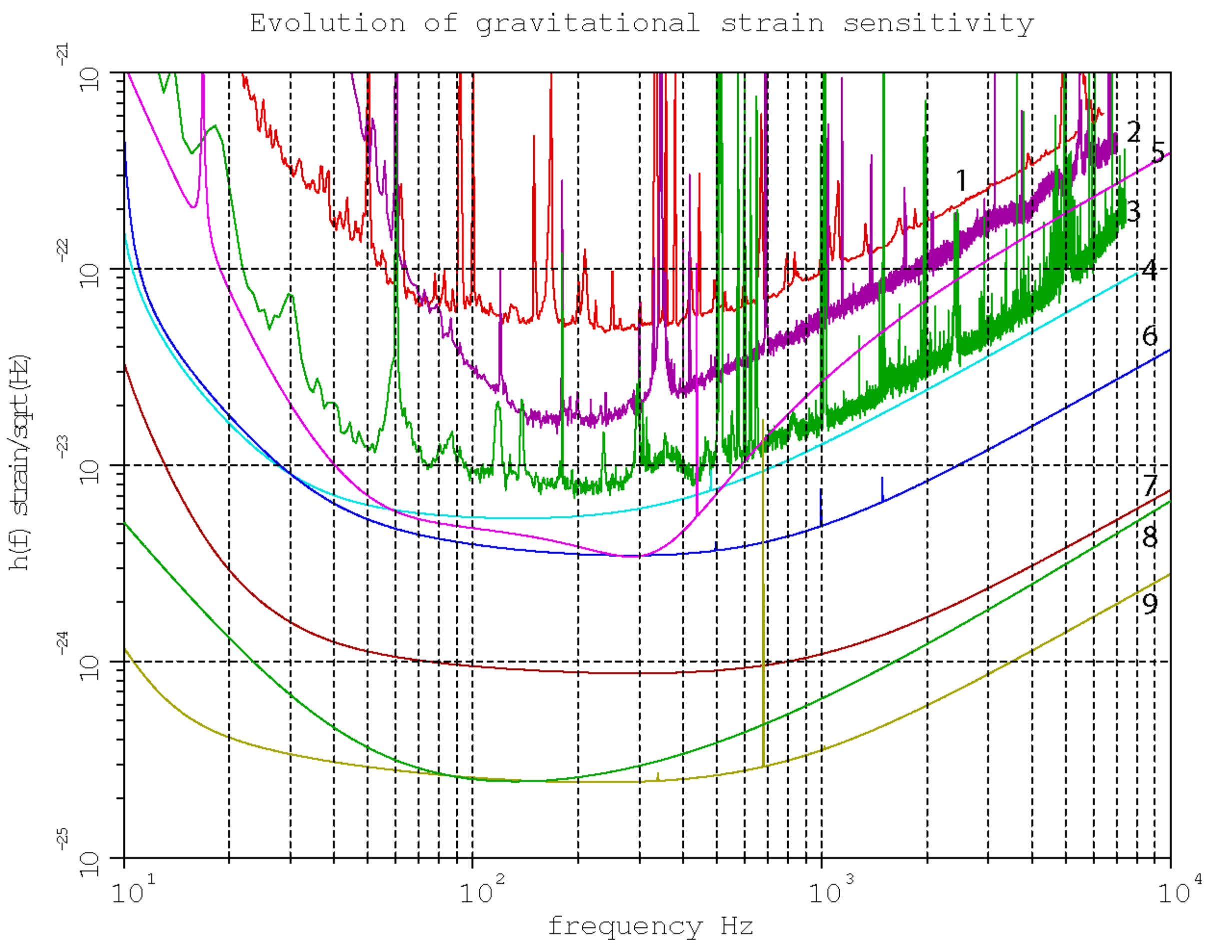




Advanced LIGO design noise budget

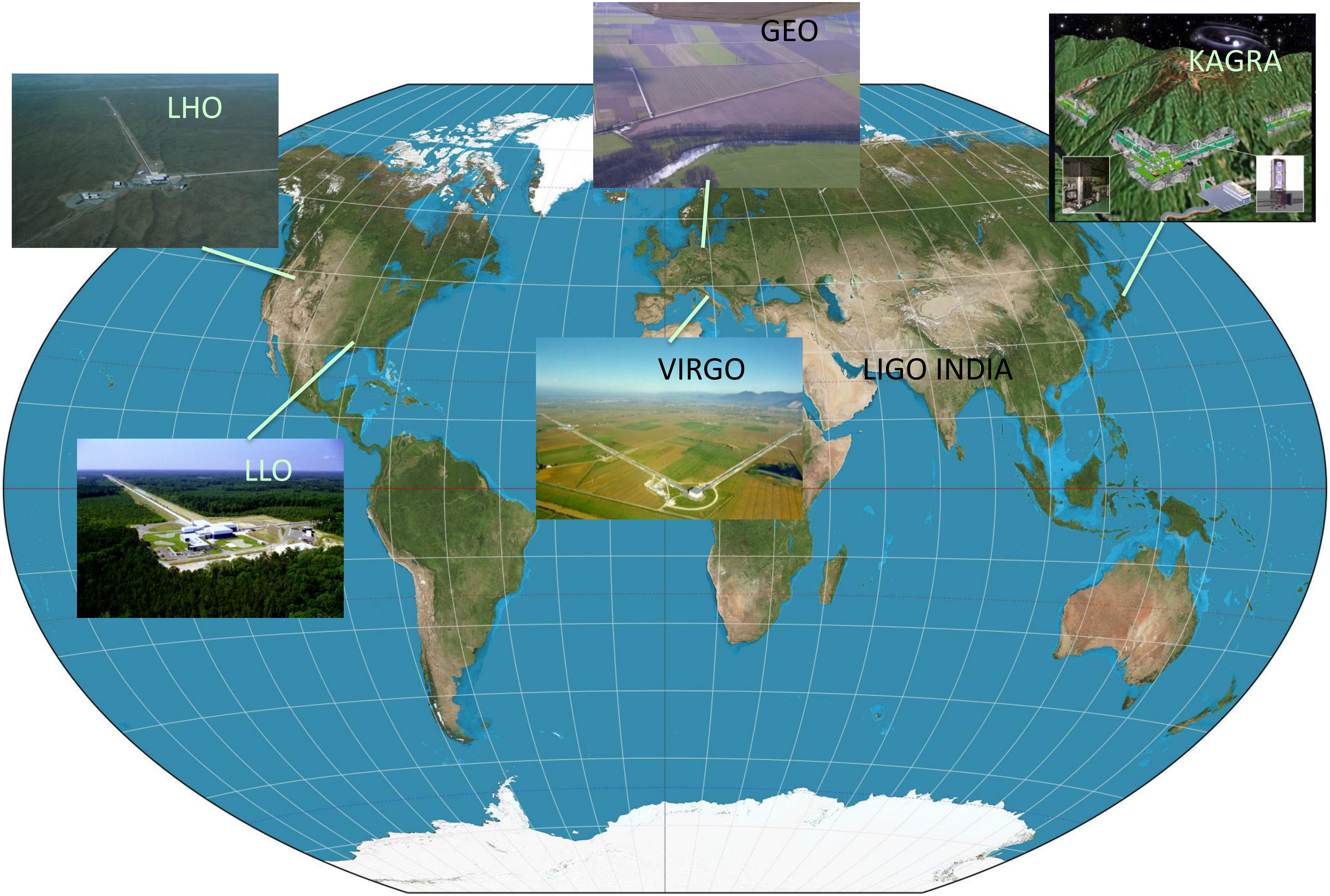






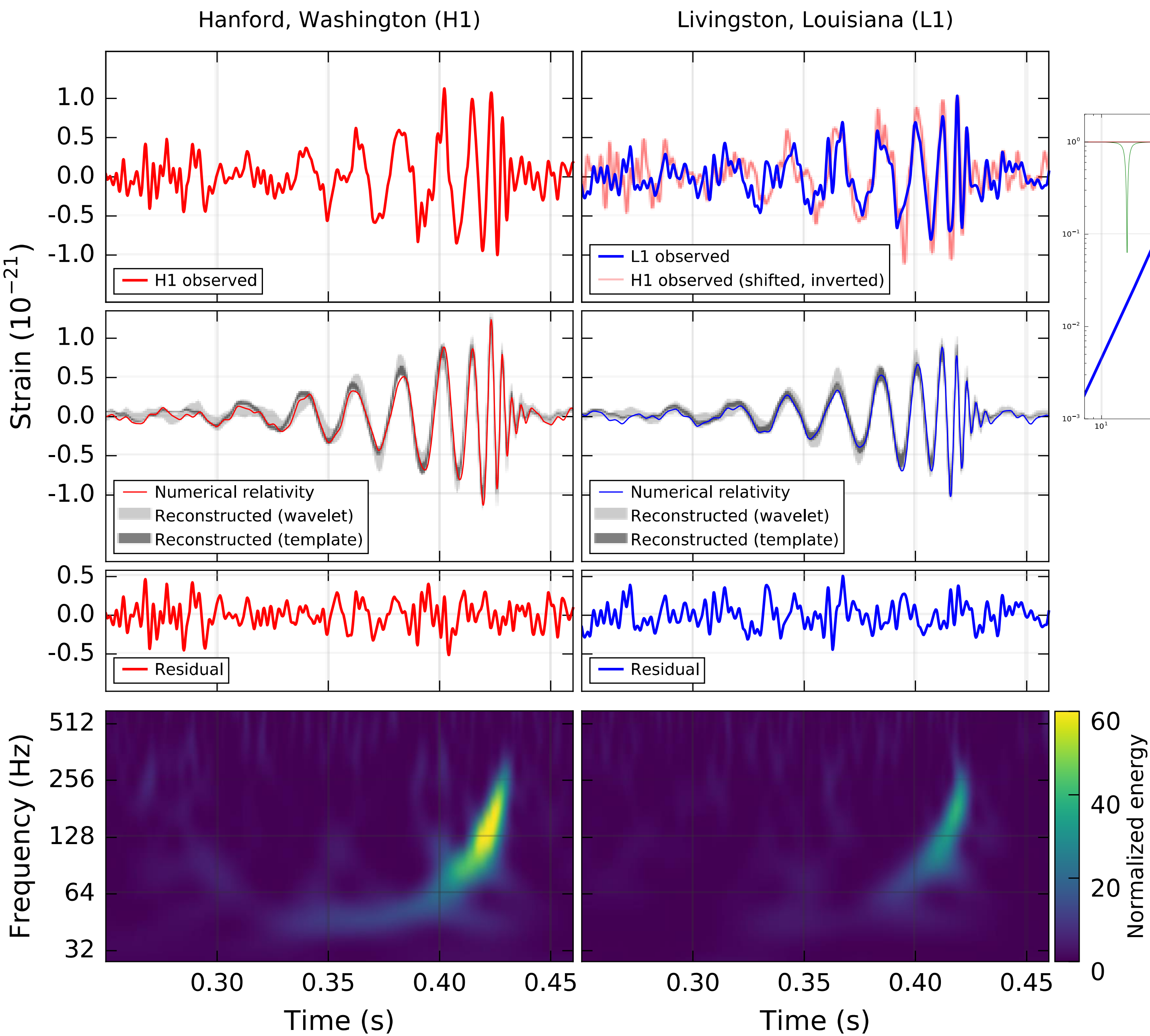
1 VIRGO 2009
2 Enhanced LIGO 2009
3 Advanced LIGO 65Mpc NS/NS 2015
4 Advanced LIGO 150Mpc NS/NS Low Power
5 Advanced VIRGO
6 Advanced LIGO 190Mpc NS/NS High Power
7 4km “Voyager” example 600Mpc NS/NS
8 Einstein telescope B
9 40km “Cosmic Explorer” example

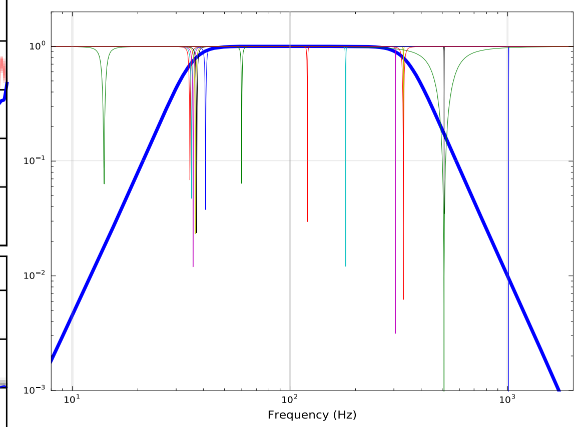
Epoch	Estimated Run Duration	$E_{GW} = 10^{-2} M_{\odot} c^2$ Burst Range (Mpc) LIGO	Virgo	BNS Range (Mpc) LIGO	Virgo	Number of BNS Detections	% BNS Localized within 5 deg^2	20 deg^2
2015	3 months	40 – 60	–	40 – 80	–	0.0004 – 3	–	–
2016–17	6 months	60 – 75	20 – 40	80 – 120	20 – 60	0.006 – 20	2	5 – 12
2017–18	9 months	75 – 90	40 – 50	120 – 170	60 – 85	0.04 – 100	1 – 2	10 – 12
2019+	(per year)	105	40 – 80	200	65 – 130	0.2 – 200	3 – 8	8 – 28
2022+ (India)	(per year)	105	80	200	130	0.4 – 400	17	48


GEO
KAGRA
LHO
VIRGO
LIGO INDIA
LLO

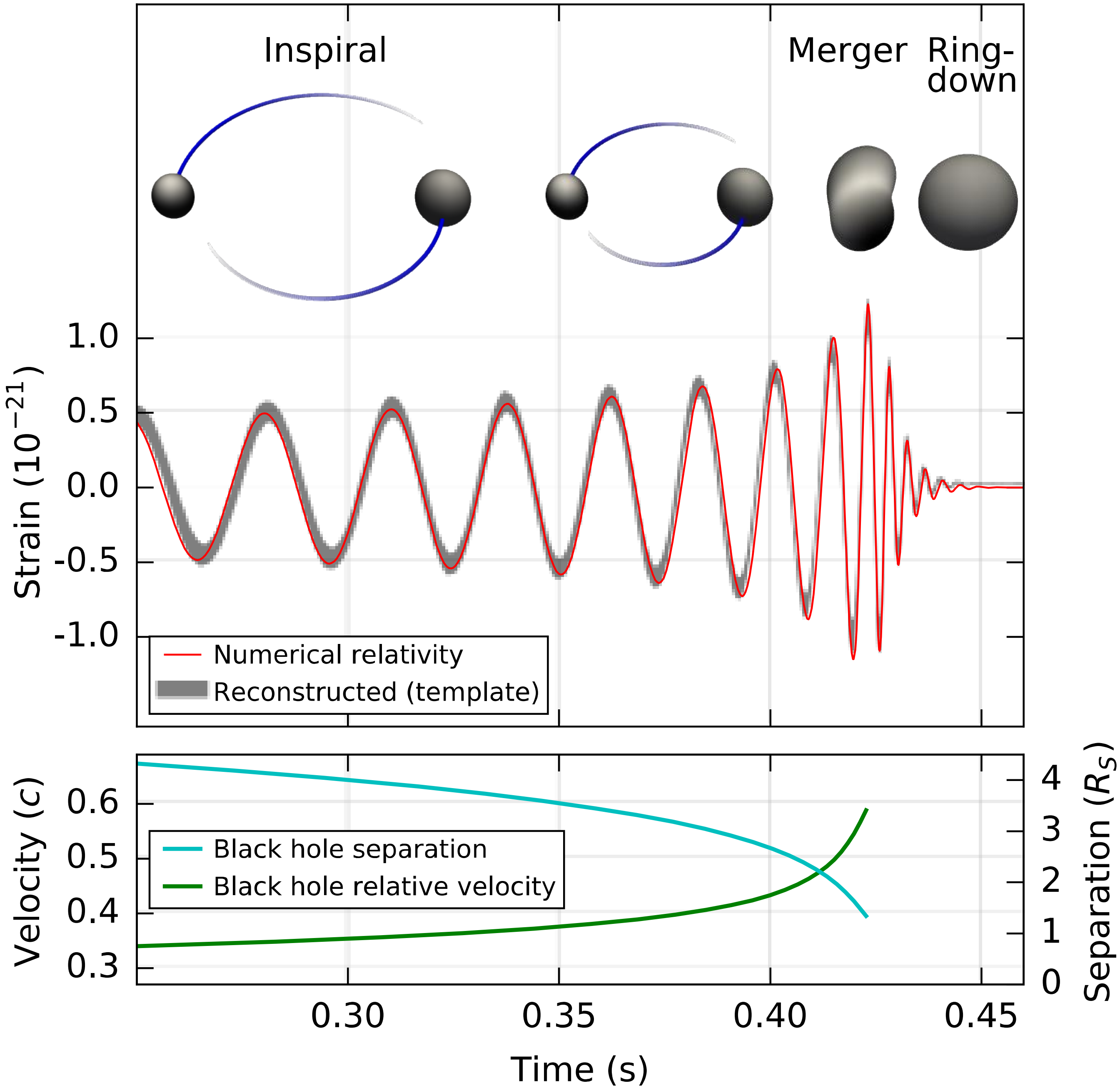
Criteria for transient detection

- The same waveform must be seen at the Louisiana and Washington sites within ± 10 msec
- The waveform at a site cannot be coincident with signals from the environmental monitors at the site
    - 3 axis seismometers
    - 3 axis accelerometers on the chambers
    - Tilt meters
    - Microphones
    - Magnetometers
    - RF monitors
    - Line voltage monitors
    - Wind speed monitors
- The waveform at a site cannot be coincident with auxiliary signals in the interferometer not directly associated with the gravitational wave output
    - Alignment control signals
    - Laser frequency and amplitude control signals
    - Approximately 10^5 sensing signals within the instrument





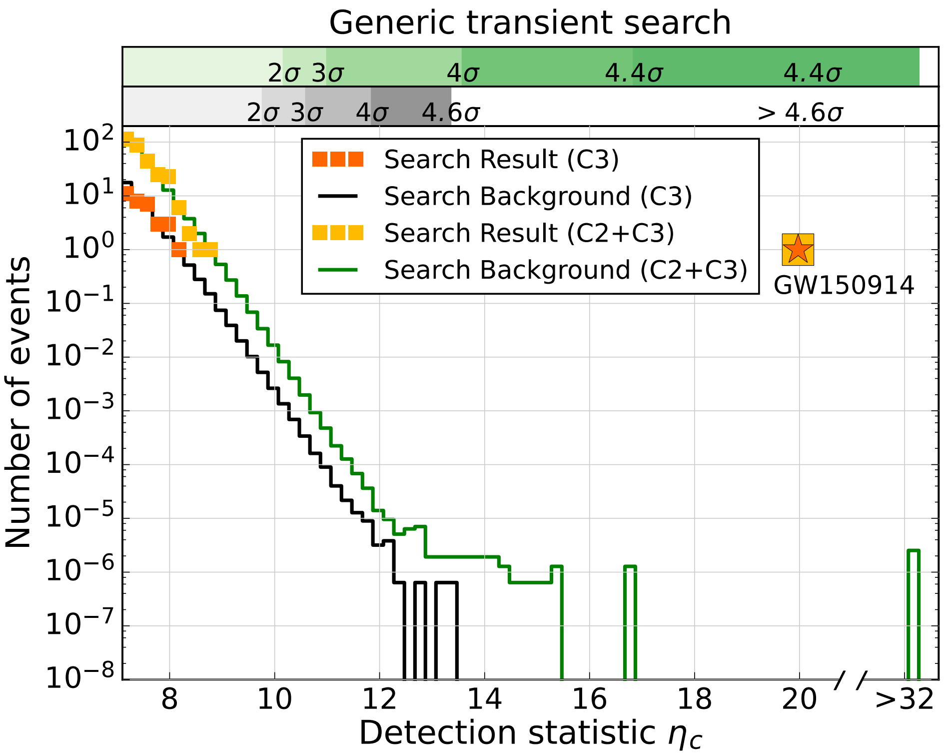
Simple high-low pass filter with notches

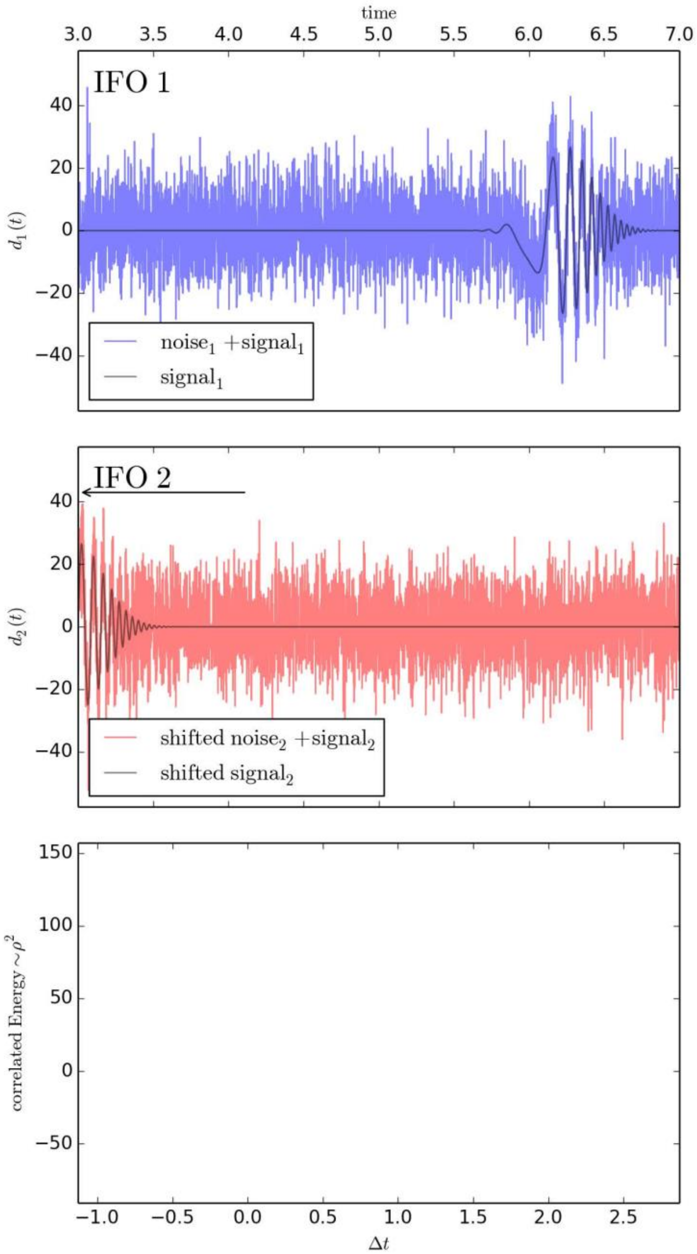


Inspiral
Merger
Ring-down
Strain (10^{-21})
1.0
0.5
0.0
-0.5
-1.0
Numerical relativity
Reconstructed (template)
Velocity (c)
0.6
0.5
0.4
0.3
Black hole separation
Black hole relative velocity
Separation (R_S)
4
3
2
1
0
0.30
0.35
0.40
0.45
Time (s)

Generic transient search

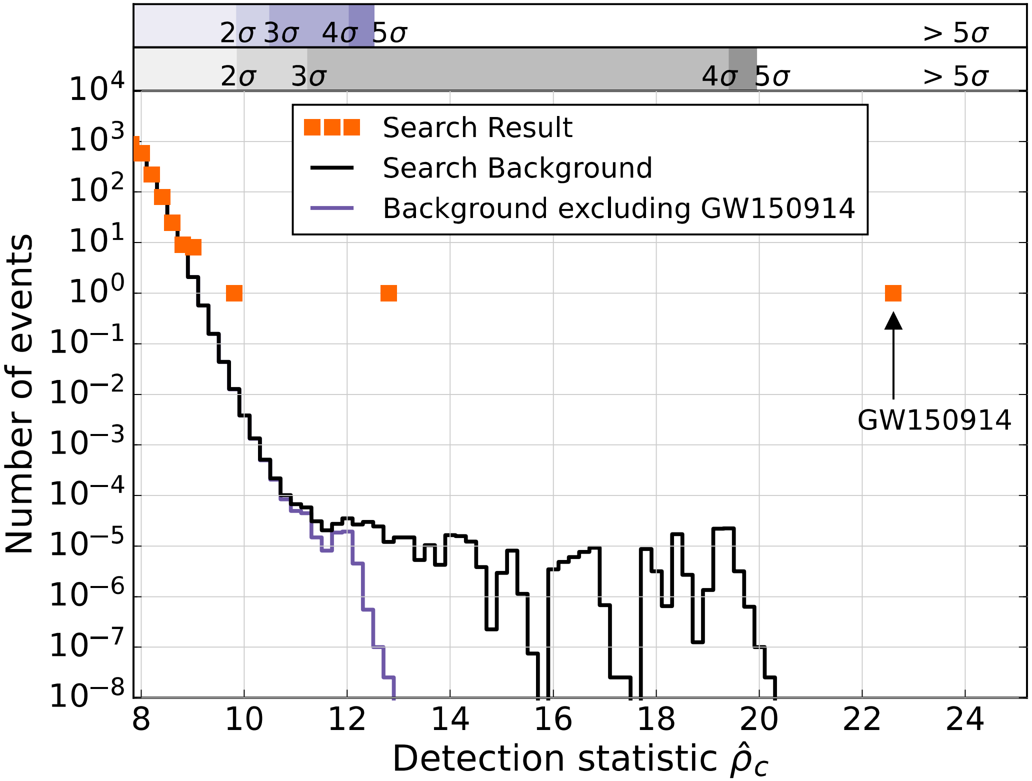
R.Essik

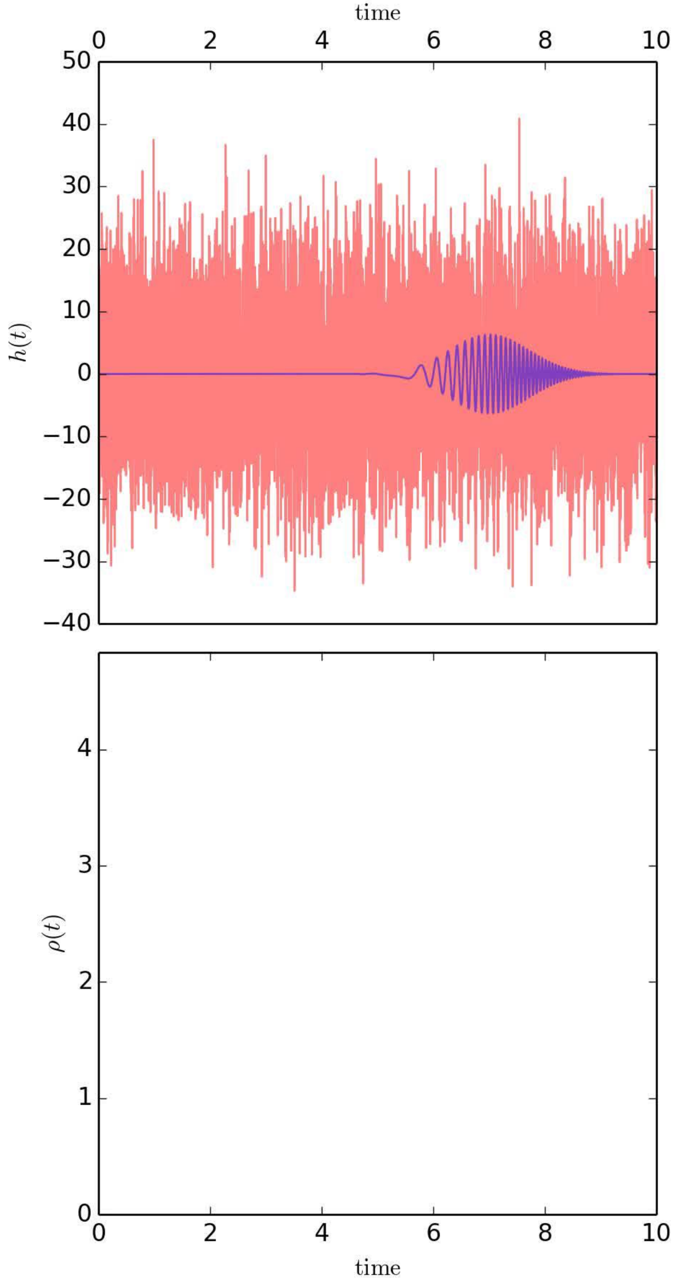




R.Essik

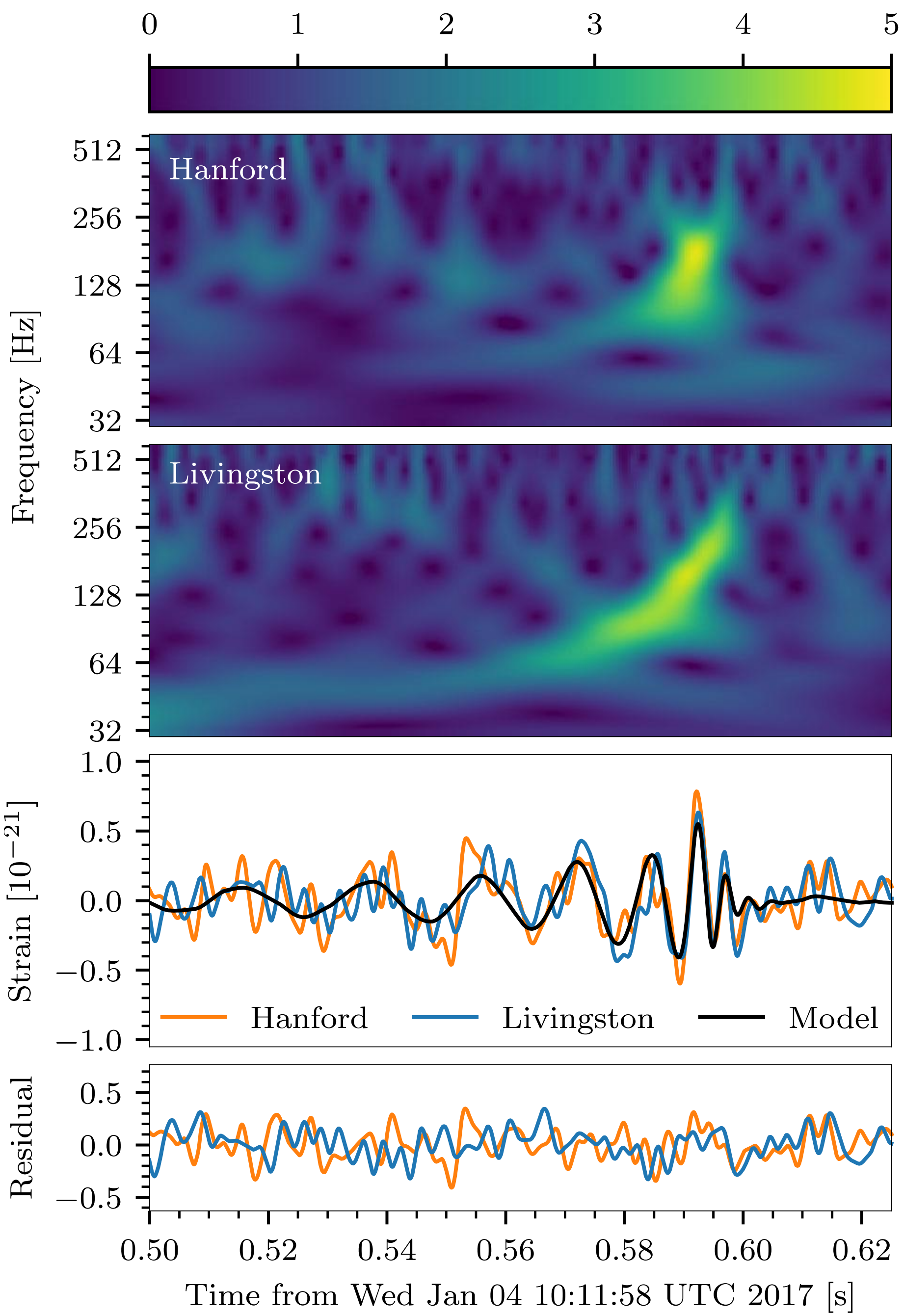
Modeled search followed by χ^2 cut



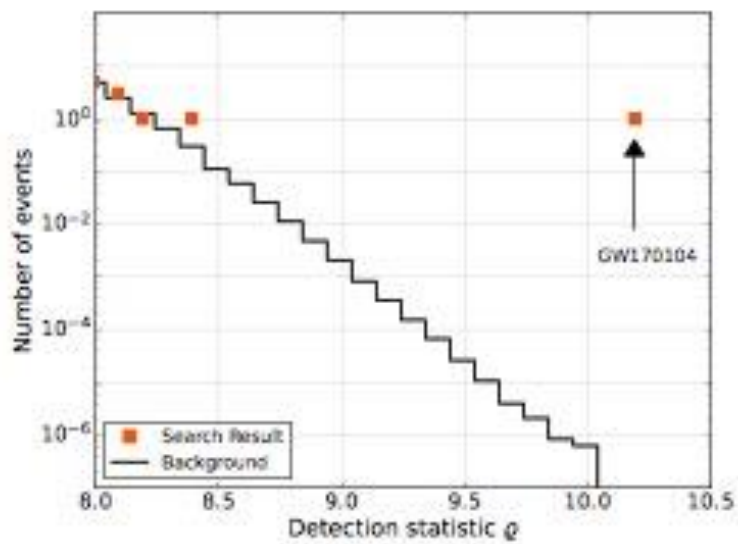


False alarm rate from time slides

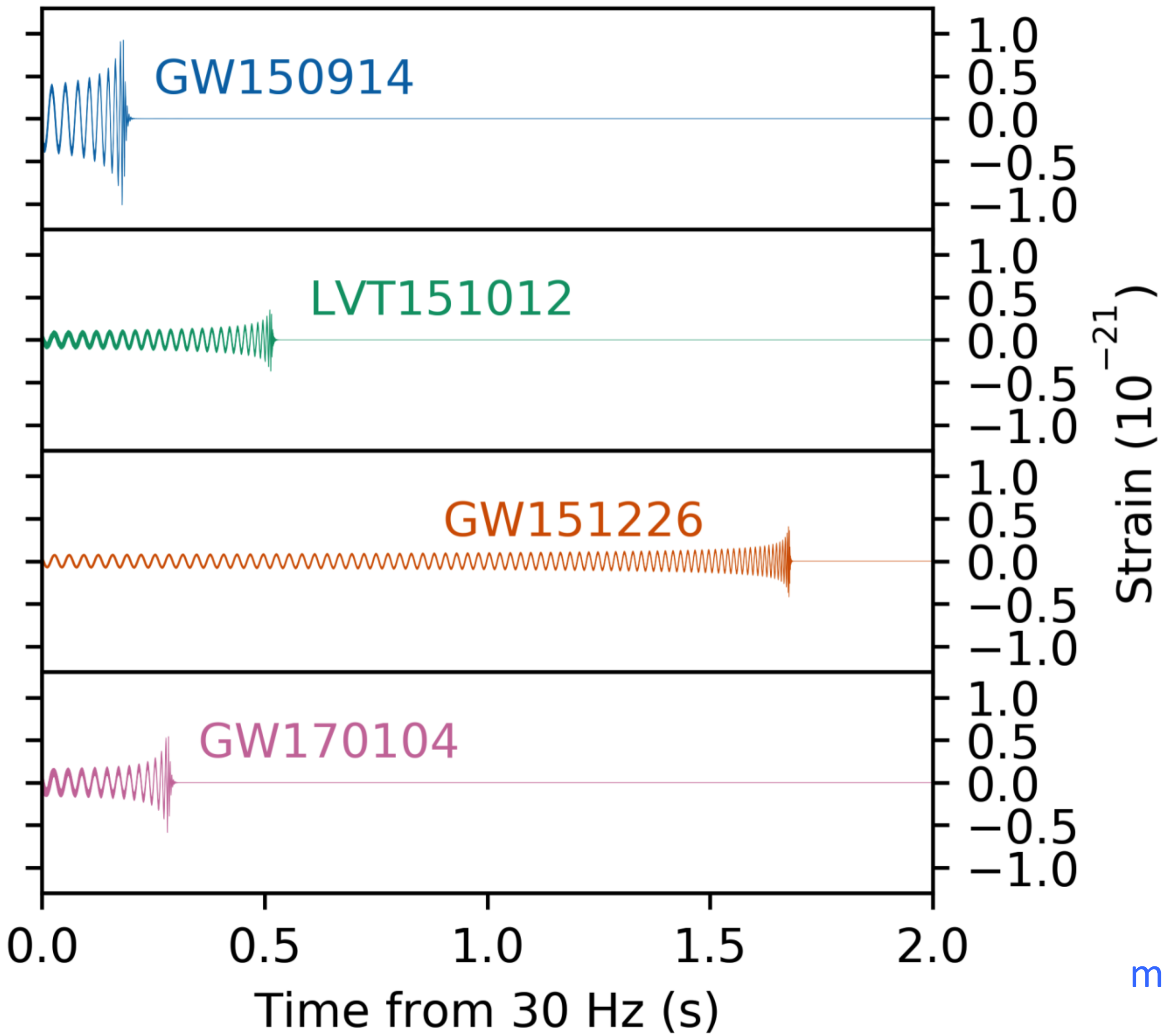
$$R = \frac{t_{corr}}{t_{total}^2} = \frac{1}{N_{ind} t_{total}}$$


0
1
2
3
4
5
512
256
128
64
32
Hanford
Livingston
Frequency [Hz]
1.0
0.5
0.0
−0.5
−1.0
Strain [10^{-21}]
Hanford
Livingston
Model
Residual
0.50
0.52
0.54
0.56
0.58
0.60
0.62
Time from Wed Jan 04 10:11:58 UTC 2017 [s]

GW 170104


Number of events
Search Result
Background
GW170104
8.0
8.5
9.0
9.5
10.0
10.5
Detection statistic ρ

Results of O1 and O2 run announced June 1, 2017



m1=36, m2= 29, Δm=3

if at 1 au

h ~10^{-6}

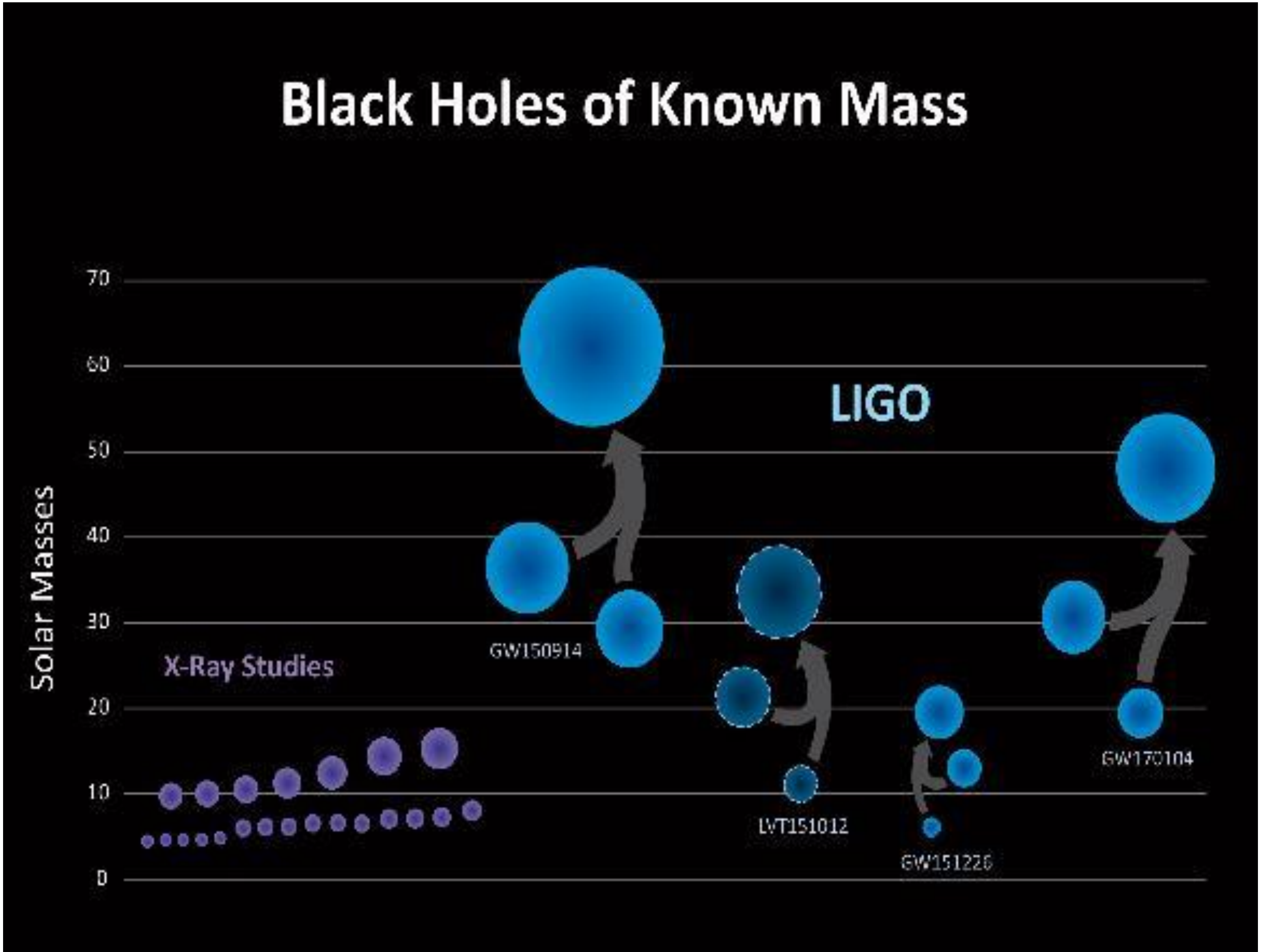
I_g~ 10^{25} w/m^2

m1=23, m2= 13, Δm=1.5

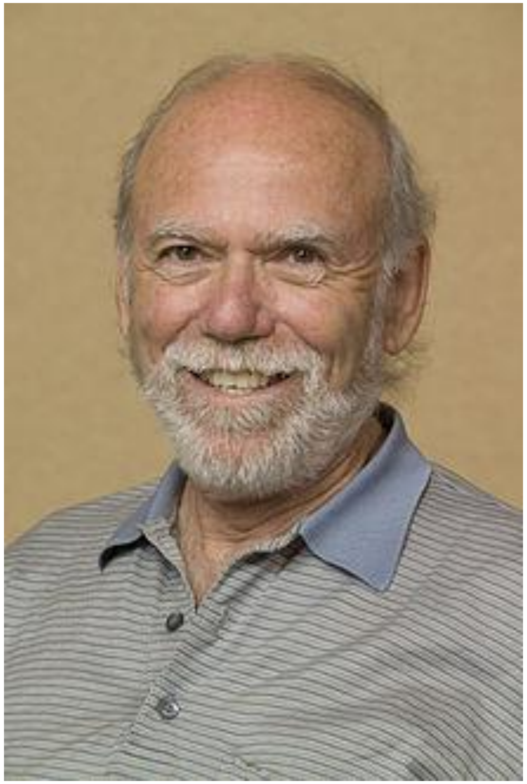
m1=14.2, m2= 7.5, Δm=1

m1=31, m2= 19, Δm=2

masses in source frame


Black Holes of Known Mass
Solar Masses
70
60
50
40
30
20
10
0
X-Ray Studies
LIGO
GW150914
LVT151012
GW151226
GW170104

The real start 1994



B. Barish

S. Whitcomb

G. Sanders

A. Lazzarini

D. Coyne

LSC

LIGO Laboratory

Advanced LIGO Project

P. Saulson
2nd Spokesperson

J. Marx
3rd LIGO Director

D. Coyne

D. Shoemaker

D. Reitze
3rd LSC Spokesperson
4th LIGO Director

P. Fritschel

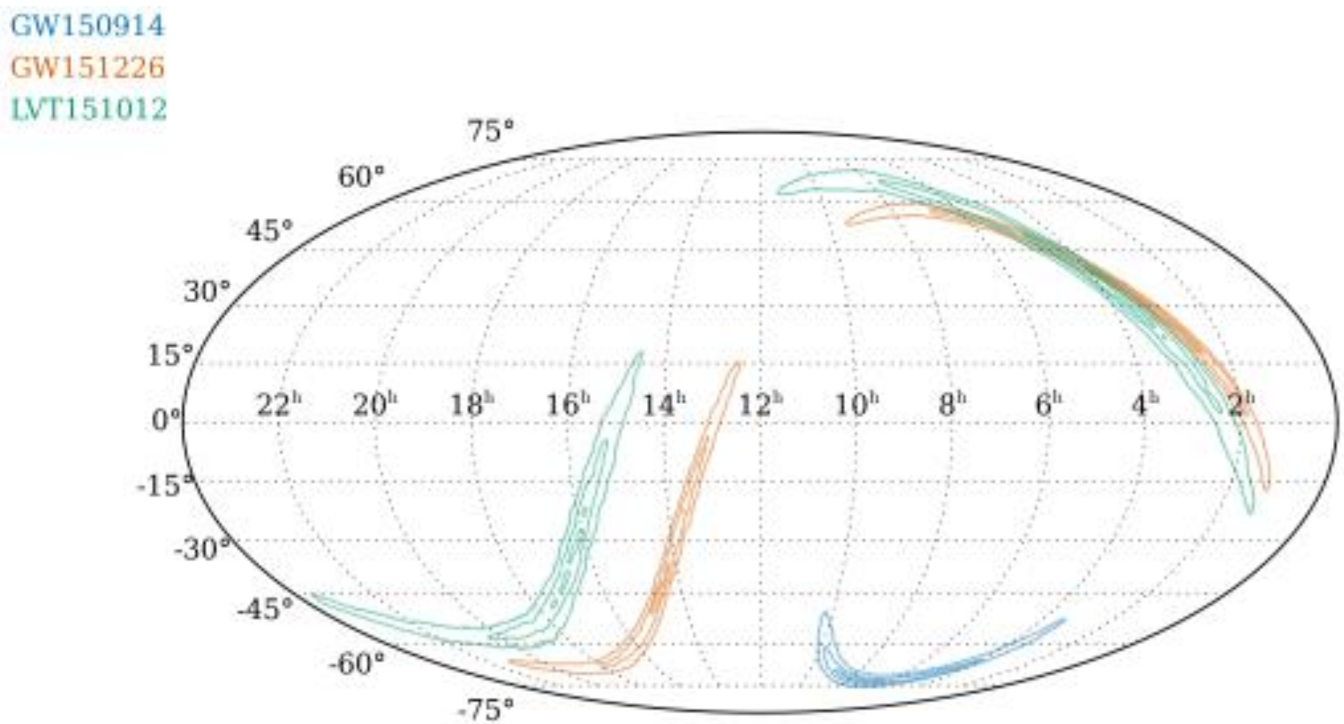
V. Frolov

G. Gonzalez
4th Spokesperson

D. Sigg

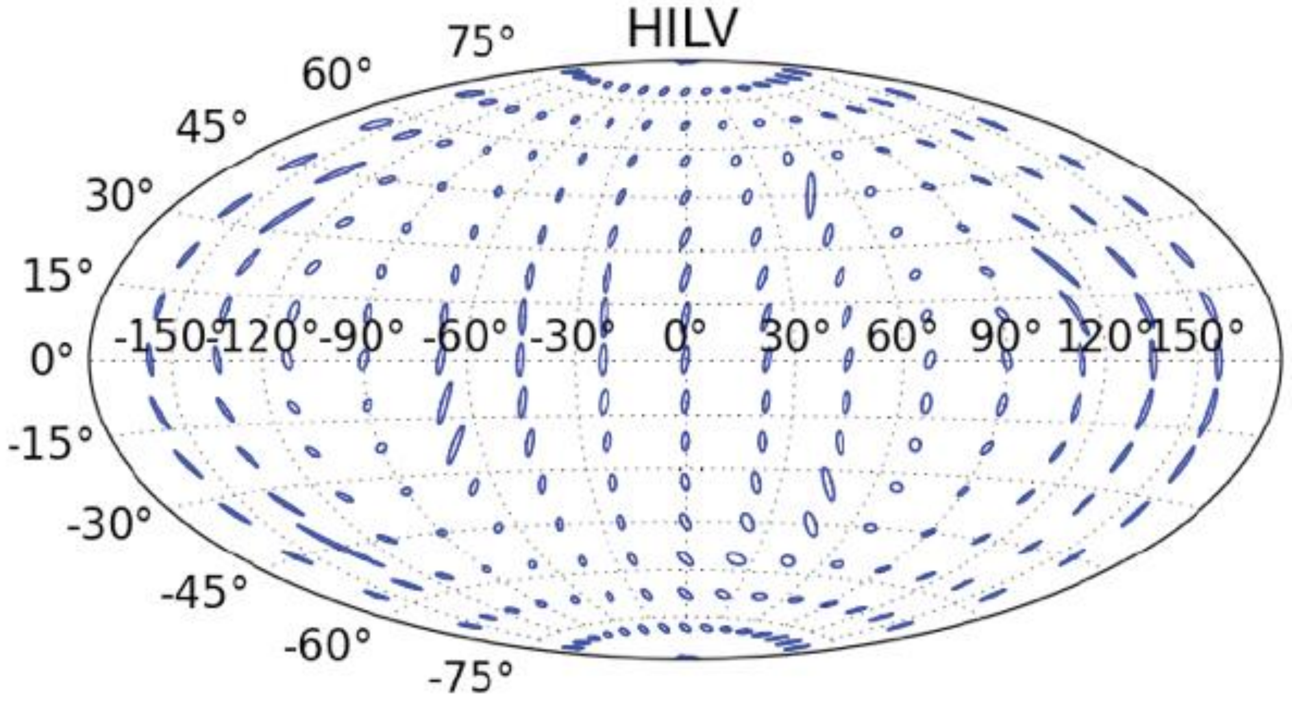
Classes of sources and searches

- Compact binary inspiral: template search
  - BH/BH
  - NS/NS and BH/NS
- Low duty cycle transients: wavelets,T/f clusters
  - Supernova
  - BH normal modes
  - Unknown types of sources
- Triggered searches
  - Gamma ray bursts
  - EM transients
- Periodic CW sources
  - Pulsars
  - Low mass x-ray binaries (quasi periodic)
- Stochastic background
  - Cosmological isotropic background
  - Foreground sources : gravitational wave radiometry

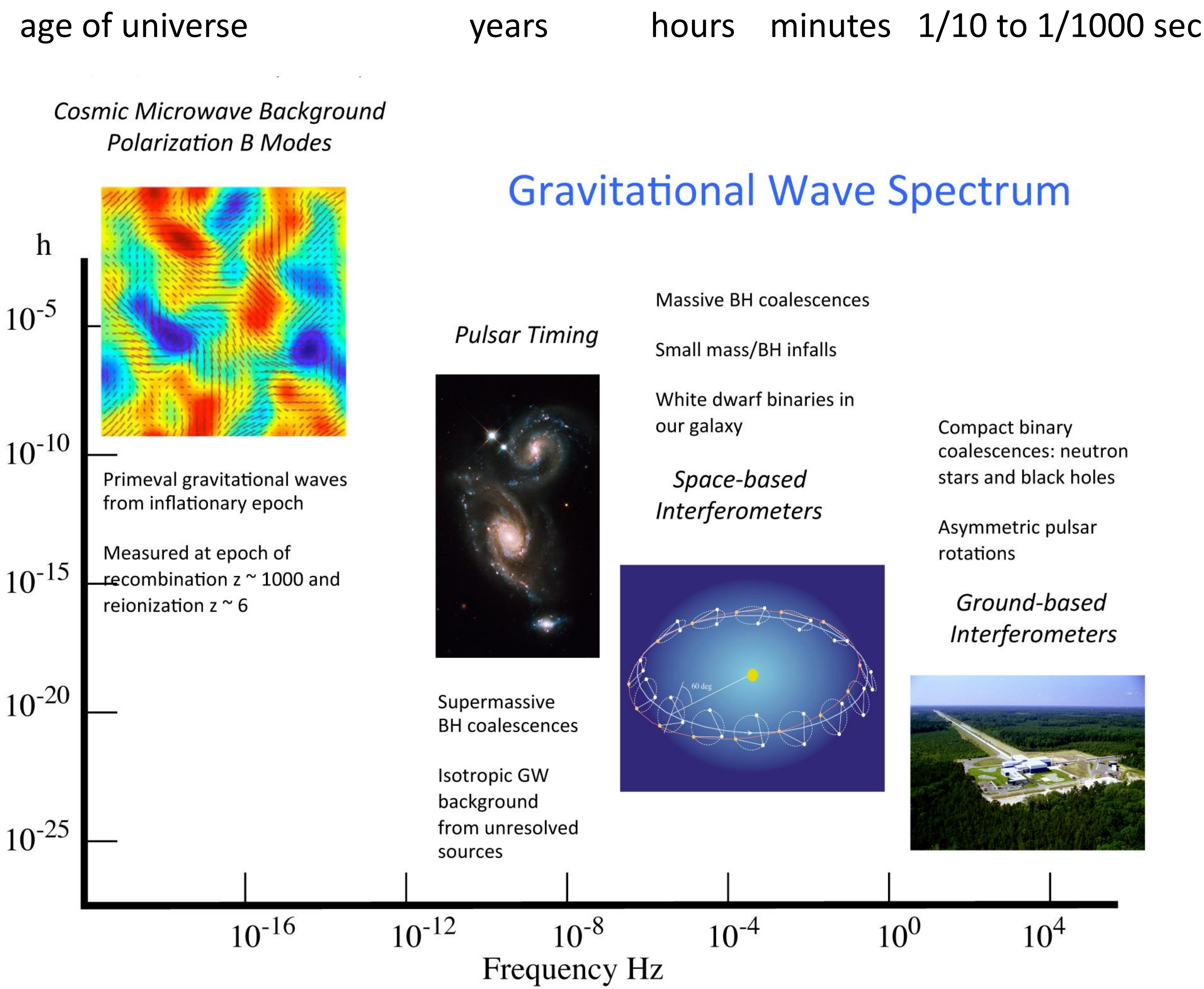


GW150914
GW151226
LVT151012
75°
60°
45°
30°
15°
0°
-15°
-30°
-45°
-60°
-75°
22h
20h
18h
16h
14h
12h
10h
8h
6h
4h
2h

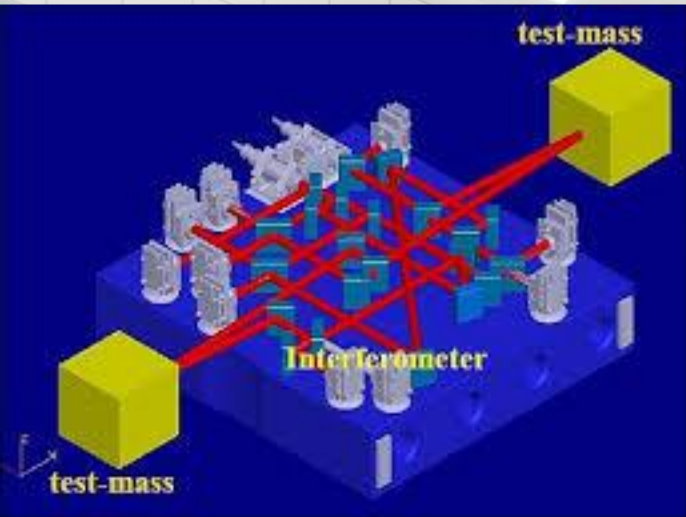
Localization with more detectors

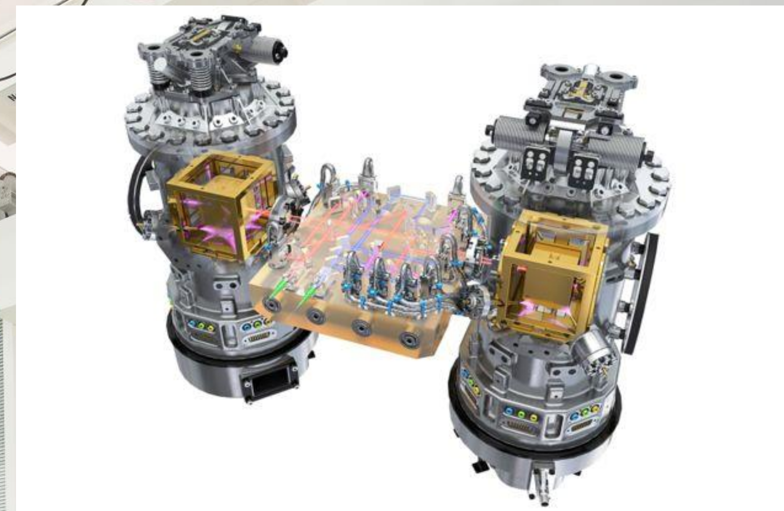


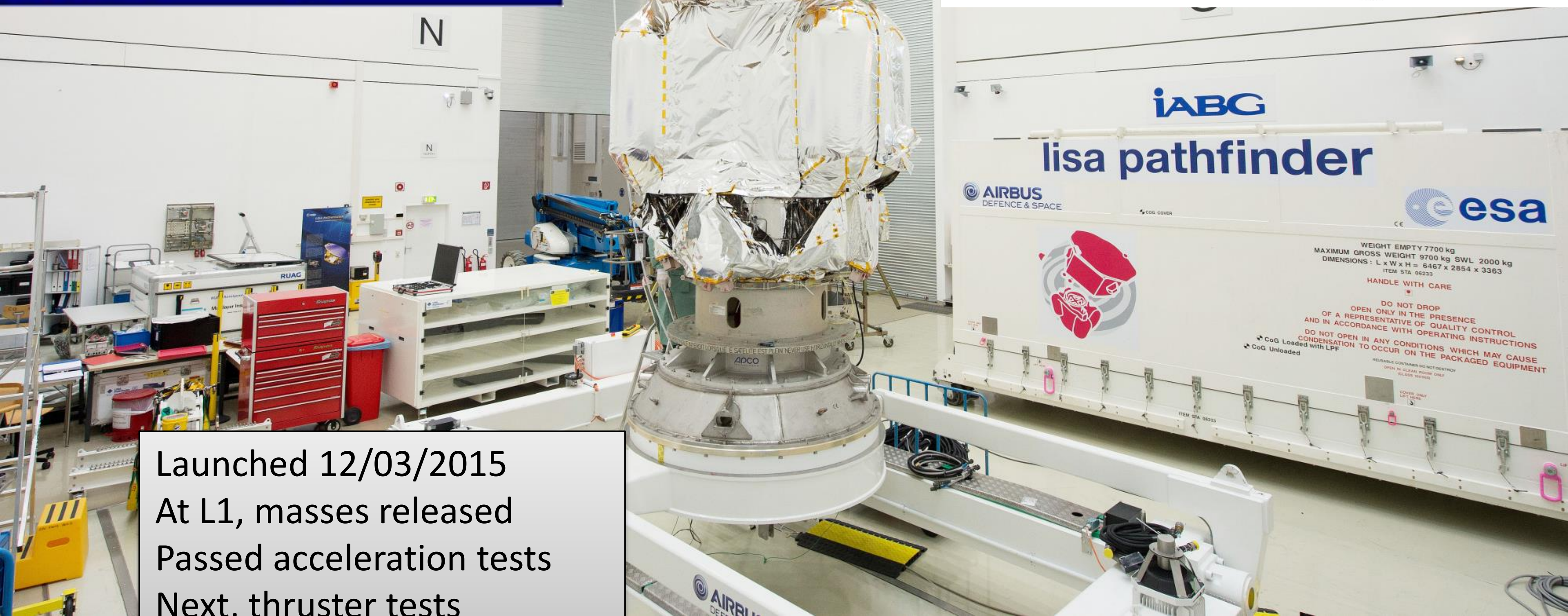
Fairhurst 2011


age of universe
years
hours
minutes
1/10 to 1/1000 sec
Cosmic Microwave Background Polarization B Modes
Gravitational Wave Spectrum
h
10-5
10-10
10-15
10-20
10-25
Primeval gravitational waves from inflationary epoch
Measured at epoch of recombination z ~ 1000 and reionization z ~ 6
Pulsar Timing
Supermassive BH coalescences
Isotropic GW background from unresolved sources
Massive BH coalescences
Small mass/BH infalls
White dwarf binaries in our galaxy
Space-based Interferometers
60 deg
Compact binary coalescences: neutron stars and black holes
Asymmetric pulsar rotations
Ground-based Interferometers
10-16
10-12
10-8
10-4
100
104
Frequency Hz

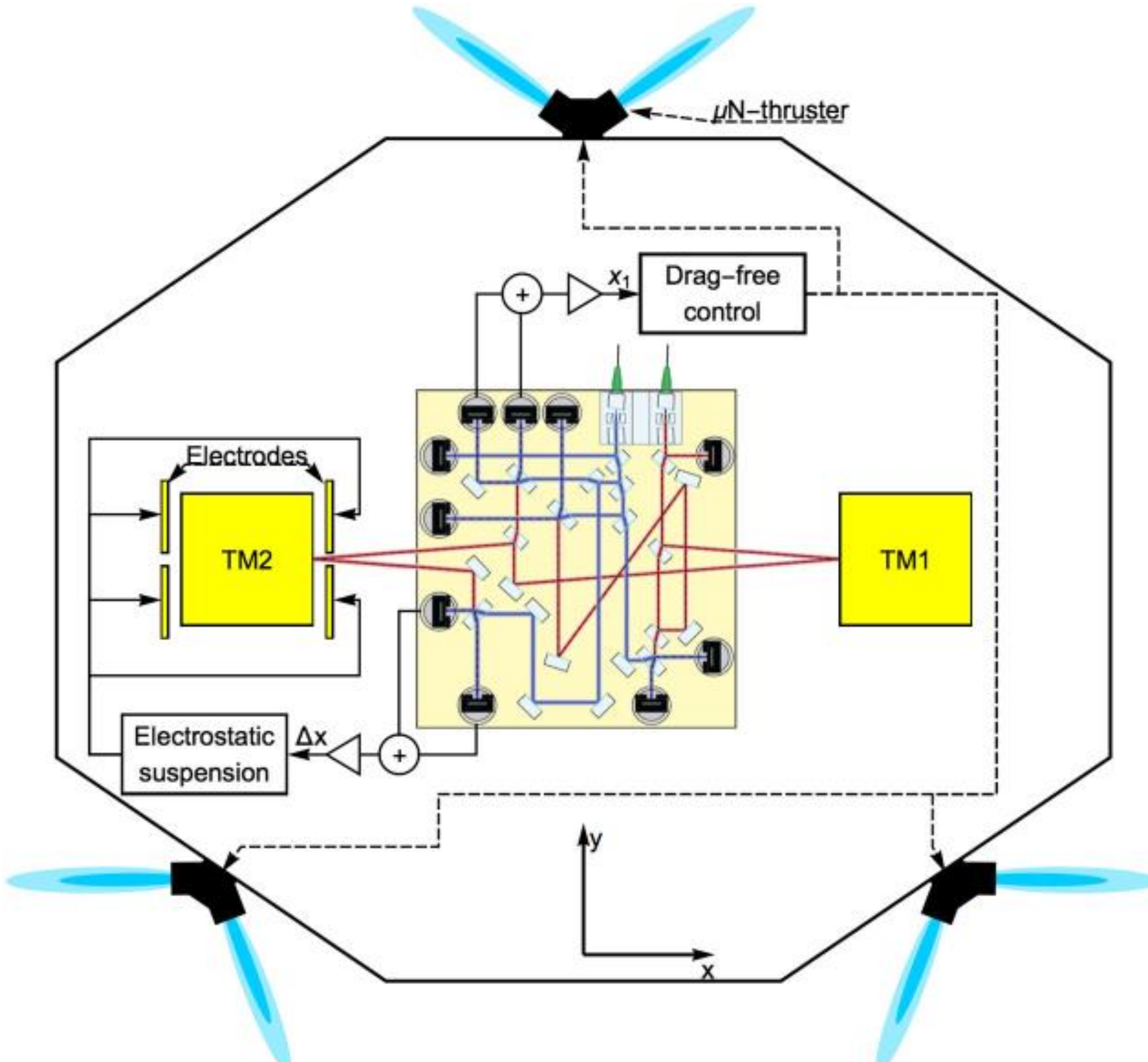
LISA Pathfinder

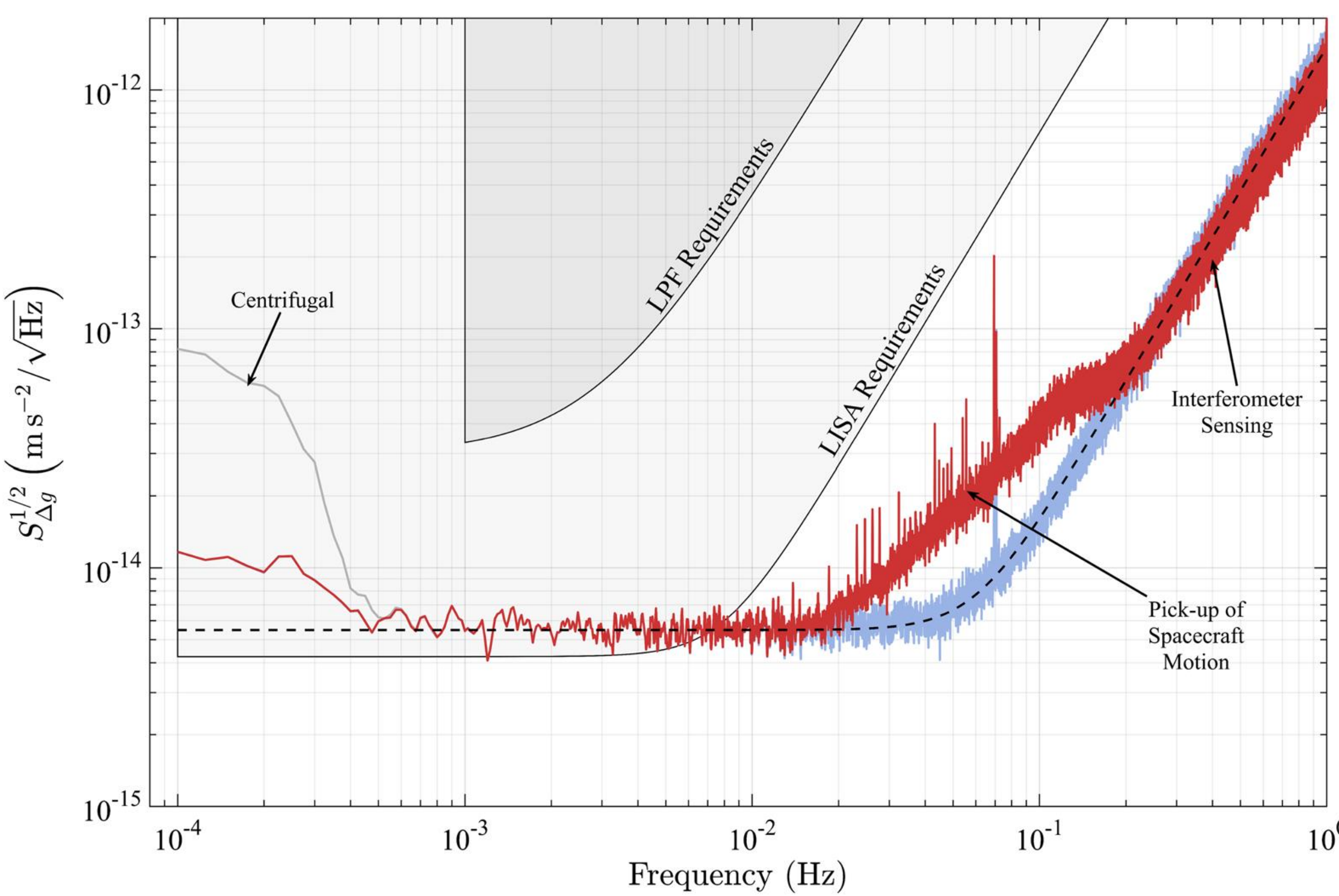


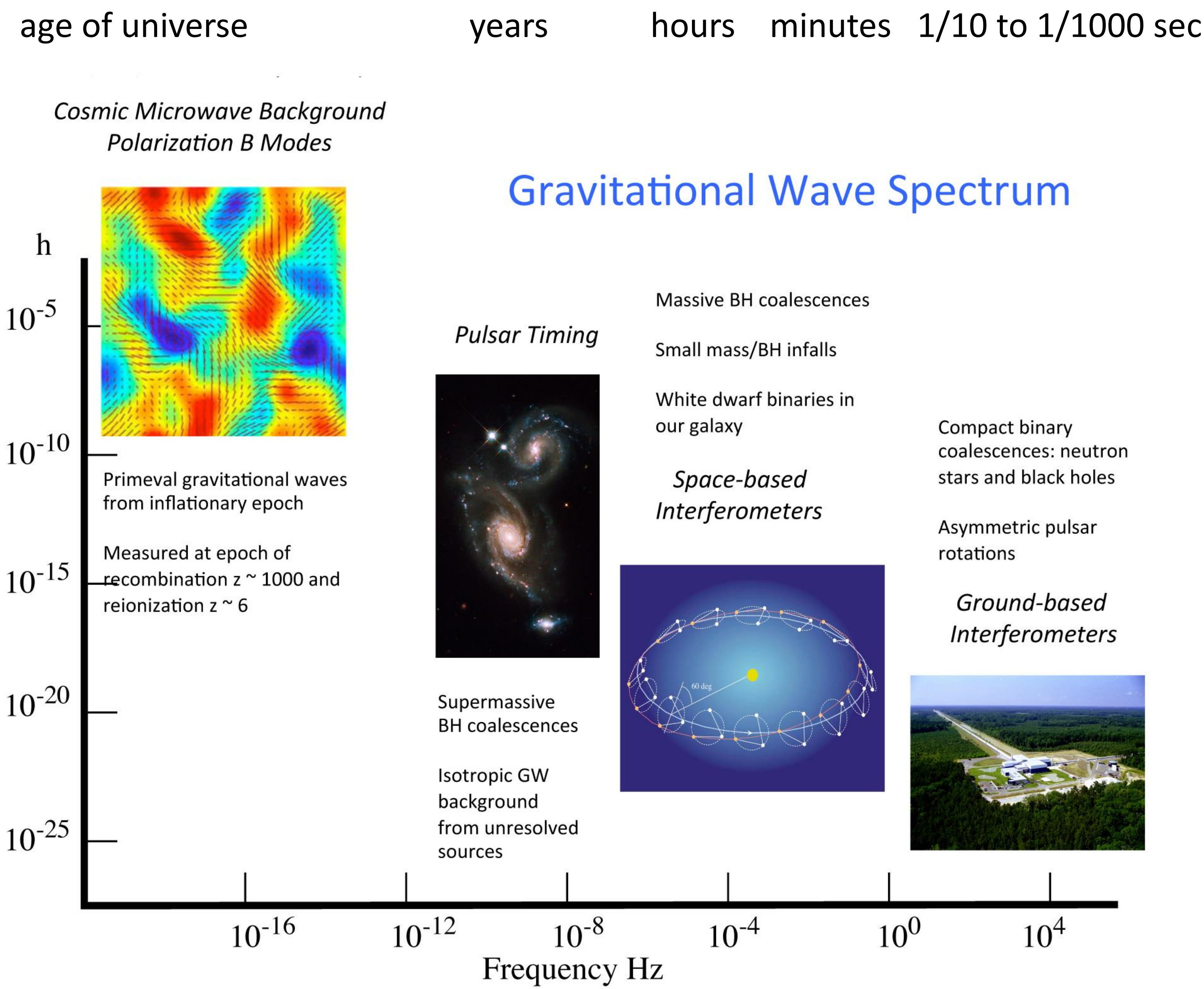




Launched 12/03/2015
At L1, masses released
Passed acceleration tests
Next, thruster tests


μN−thruster
x_1
Drag−free control
Electrodes
TM2
TM1
Electrostatic suspension
Δx
y
x


Centrifugal
LPF Requirements
LISA Requirements
Interferometer Sensing
Pick-up of Spacecraft Motion
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^{0}
Frequency (Hz)
$S_{\Delta g}^{1/2}\left(\mathrm{m\,s^{-2}/\sqrt{Hz}}\right)$


age of universe
years
hours
minutes
1/10 to 1/1000 sec
Cosmic Microwave Background Polarization B Modes
Gravitational Wave Spectrum
h
10^{-5}
10^{-10}
10^{-15}
10^{-20}
10^{-25}
Primeval gravitational waves from inflationary epoch
Measured at epoch of recombination z ~ 1000 and reionization z ~ 6
Pulsar Timing
Supermassive BH coalescences
Isotropic GW background from unresolved sources
Massive BH coalescences
Small mass/BH infalls
White dwarf binaries in our galaxy
Space-based Interferometers
60 deg
Compact binary coalescences: neutron stars and black holes
Asymmetric pulsar rotations
Ground-based Interferometers
10^{-16}
10^{-12}
10^{-8}
10^{-4}
10^{0}
10^{4}
Frequency Hz

LIGO Scientific Collaboration

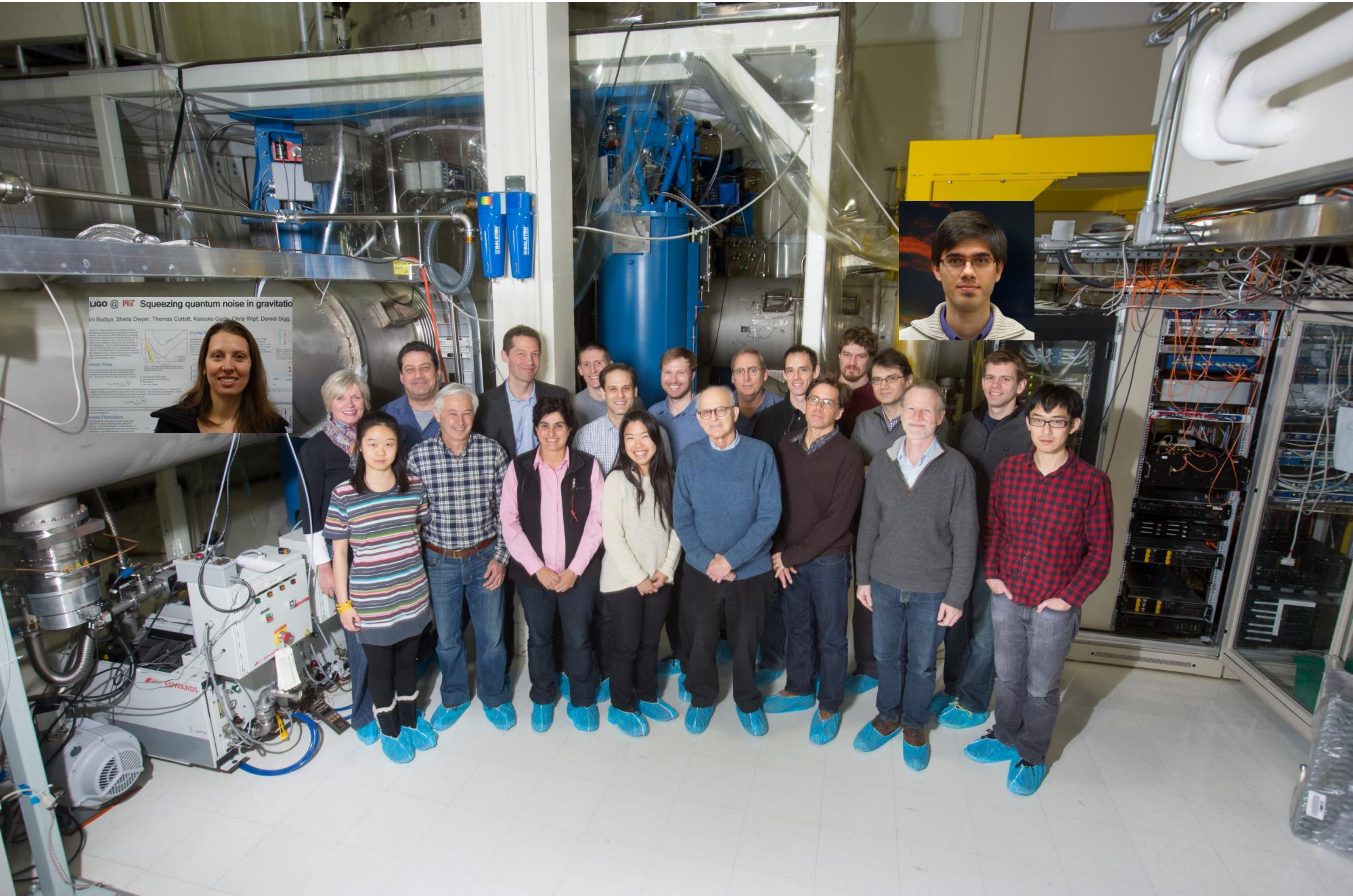
LIGO

LSC

Trinity University
University of Maryland 1856
Andrews University
Washington State University
California State University Fullerton
indigo
The Australian National University ANU
Texas Tech University
R·I·T
ICTP SAIFR
Montana State University
Sonoma State University
University of the West of Scotland UWS
Montclair State University
Tsinghua University 清華大學
American University Washington, DC
University of Strathclyde
Michigan
University of Glasgow
Columbia 1754
NASA Goddard Space Flight Center
Leland Stanford Junior University 1891
Whitman College
LSU
CITA–ICAT
UTB TSC
University of Cambridge
Massachusetts Institute of Technology
Southern University Agricultural & Mechanical College
The University of Western Australia
Universitas Szegediensis
California Institute of Technology 1891
University of Minnesota
The University of Mississippi
The University of Adelaide Australia
The University of Melbourne
UO
GEO 600
Embry-Riddle Aeronautical University
Universitas Budapestinensis de Rolando Eötvös nominata
University of Washington
Northwestern University 1851
Cardiff University
Carleton College Northfield, Minn. 1866
Universitat de les Illes Balears
Georgia Tech
Syracuse University Founded AD 1870
Charles Sturt University
UF University of Florida
University of Wisconsin Milwaukee UWM
Tsing Hua University
Universität Hamburg
ACIGA
University of Southampton
Korean Gravitational-Wave Group
Penn State 1855
Hobart and William Smith Colleges
Science & Technology Facilities Council Rutherford Appleton Laboratory
University of Rochester
Leibniz Universität Hannover

LIGO HANFORD OBSERVATORY STAFF

LIGO LIVINGSTON OBSERVATORY STAFF



MIT LIGO LABORATORY GROUP

CALTECH LIGO LABORATORY GROUP

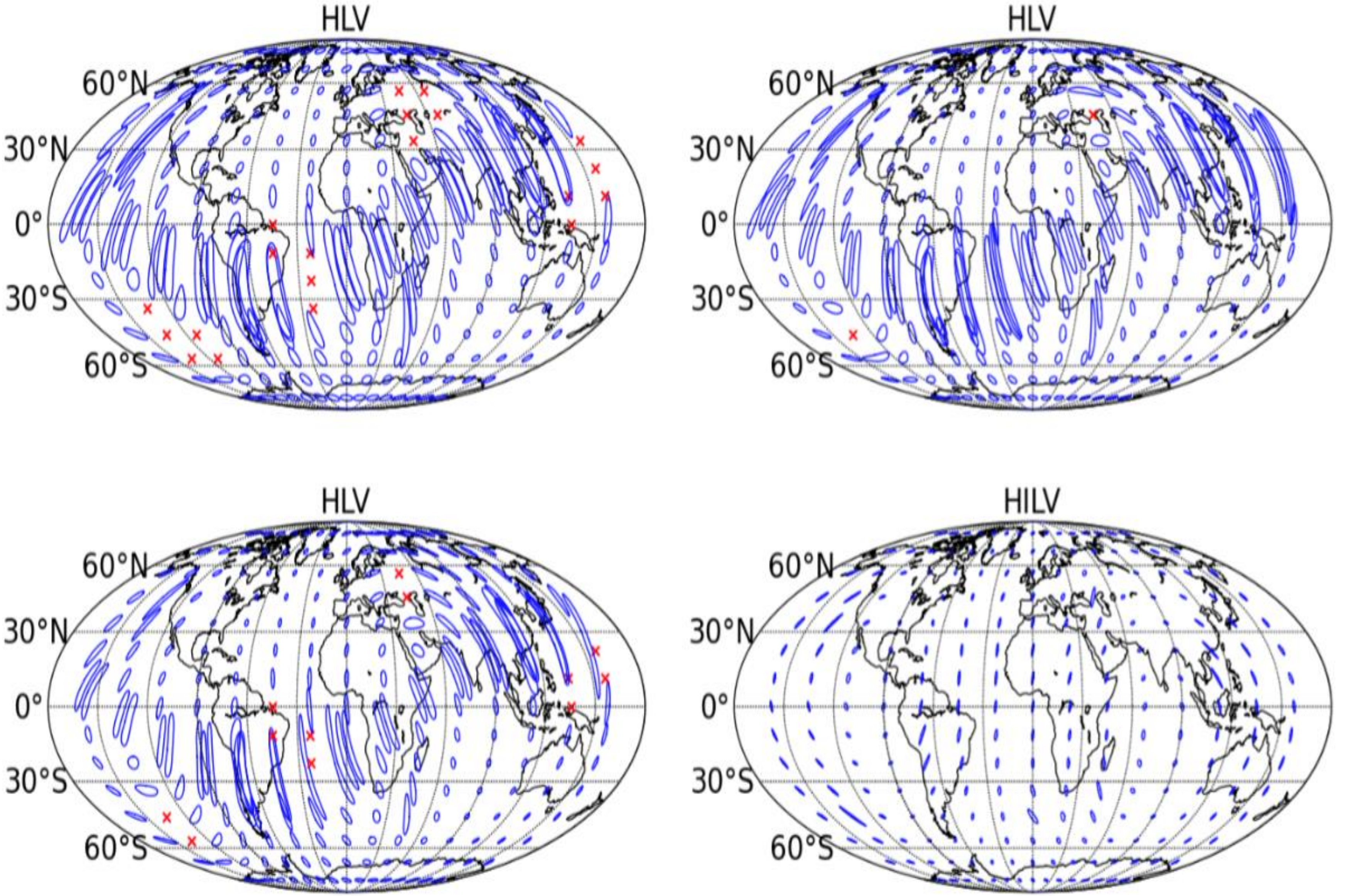
Spare slides follow

After Feb 11, 2016

Matt Weber

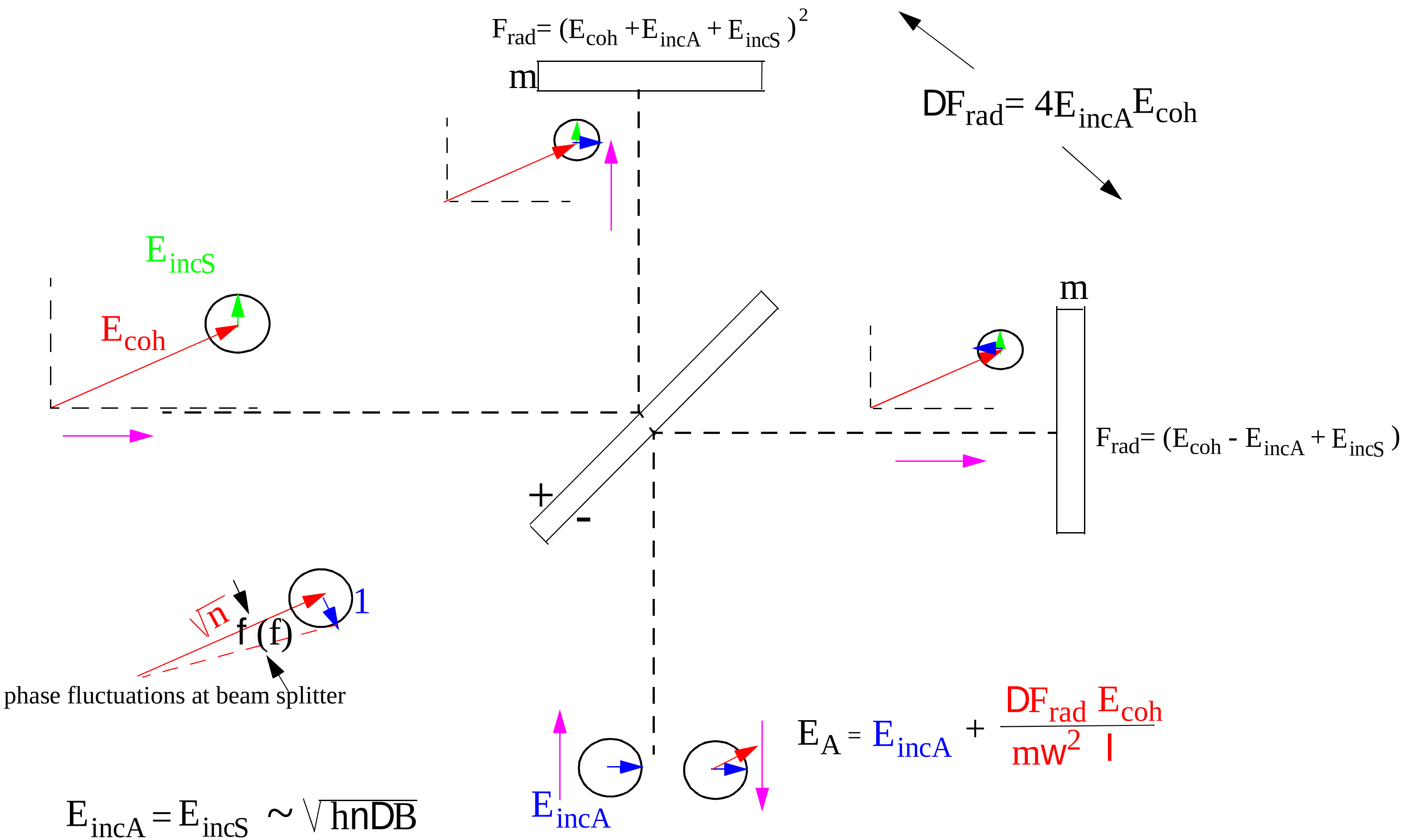
"Was that you I heard just now, or was it two black holes colliding

New Yorker Feb 12,, 2016


HLV
60°N
30°N
0°
30°S
60°S
HLV
60°N
30°N
0°
30°S
60°S
HLV
60°N
30°N
0°
30°S
60°S
HILV
60°N
30°N
0°
30°S
60°S

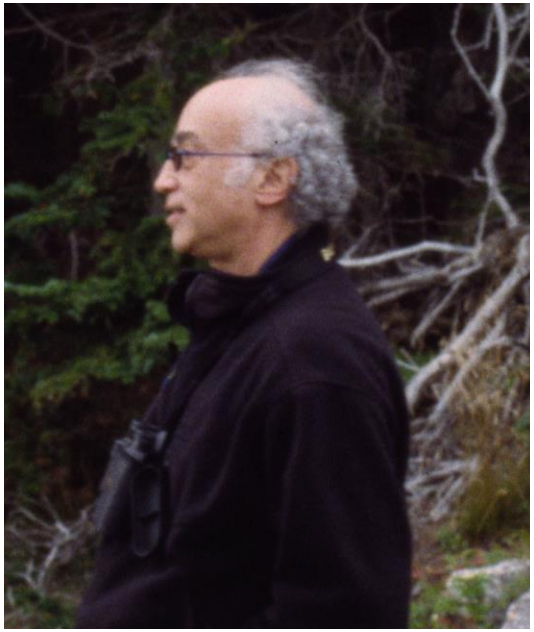
==

Quantum Noise in the Michelson Interferometer



$$E_{incA} = E_{incS} \sim \sqrt{hnDB}$$

$$E_{coh} \sim \sqrt{nhn}$$



PHYSICAL REVIEW VOLUME 166, NUMBER 5 25 FEBRUARY 1968

Gravitational Radiation in the Limit of High Frequency. II. Nonlinear Terms and the Effective Stress Tensor*

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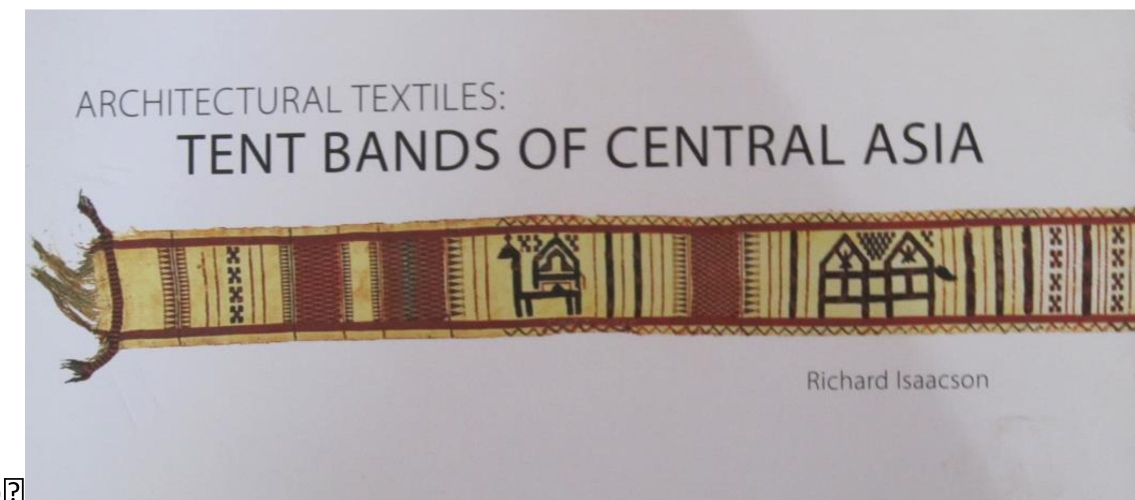
Department of Physics and Astronomy, University of Maryland, College Park, Maryland
(Received 14 July 1967)

The high-frequency expansion of a vacuum gravitational field in powers of its small wavelength is continued. We go beyond the previously discussed linearization of the field equations to consider the lowest-order nonlinearities. These are shown to provide a natural, gauge-invariant, averaged stress tensor for the effective energy localized in the high-frequency gravitational waves. Under the assumption of the WKB form for the field, this stress tensor is found to have the same algebraic structure as that for an electromagnetic null field. A Poynting vector is used to investigate the flow of energy and momentum by gravitational waves, and it is seen that high-frequency waves propagate along null hypersurfaces and are not backscattered by the lowest-order nonlinearities. Expressions for the total energy and momentum carried by the field to flat null infinity are given in terms of coordinate-independent hypersurface integrals valid within regions of high field strength. The formalism is applied to the case of spherical gravitational waves where a news function is obtained and where the source is found to lose exactly the energy and momentum contained in the radiation field. Second-order terms in the metric are found to be finite and free of divergences of the $(\ln r)/r$ variety.

R. Isaacson (Gravitation at NSF)

M. Bardon (Director of Physics NSF)



Plane gravitational waves

Transverse Plane Wave Solutions with "Electric" and "Magnetic" Terms

Geometric Interpretation

$$ds^2 = g_{ij} dx^i dx^j$$

$$g_{ij} = \eta_{ij} + h_{ij} \qquad \text{weak field}$$

$$\eta_{ij} = \begin{pmatrix} 1 & & & 0 \\ & -1 & & \\ 0 & & -1 & \\ & & & -1 \end{pmatrix} \qquad \text{Minkowski Metric of Special Relativity}$$

Gravity Wave Propagating in the x_1 Direction

$$h_{ij} = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & h_{22} & h_{23} \\ 0 & 0 & h_{32} & h_{33} \end{pmatrix} \qquad \text{all } h_{ij} \ll 1$$

Plane Wave

$$\mathbf{h_{22} = -h_{33}} \qquad \mathbf{h_{23} = h_{32}}$$

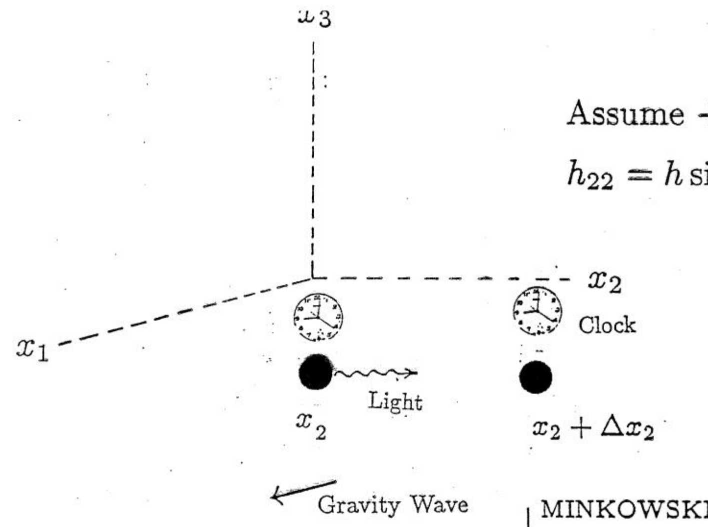
$+$ polarization **$\times$polarization**

And All Only Function of $x_1 - ct$

Timing light in the gravitational wave

Assume + Polarization

$h_{22} = h\sin(kx_1 - \omega t)$



MINKOWSKI

$$\Delta s^2 = 0 = c^2 \Delta t^2 - \Big(1 + h\sin(kx_1 - \omega t)\Big)\Delta x_2^2$$

LIGHT RAY

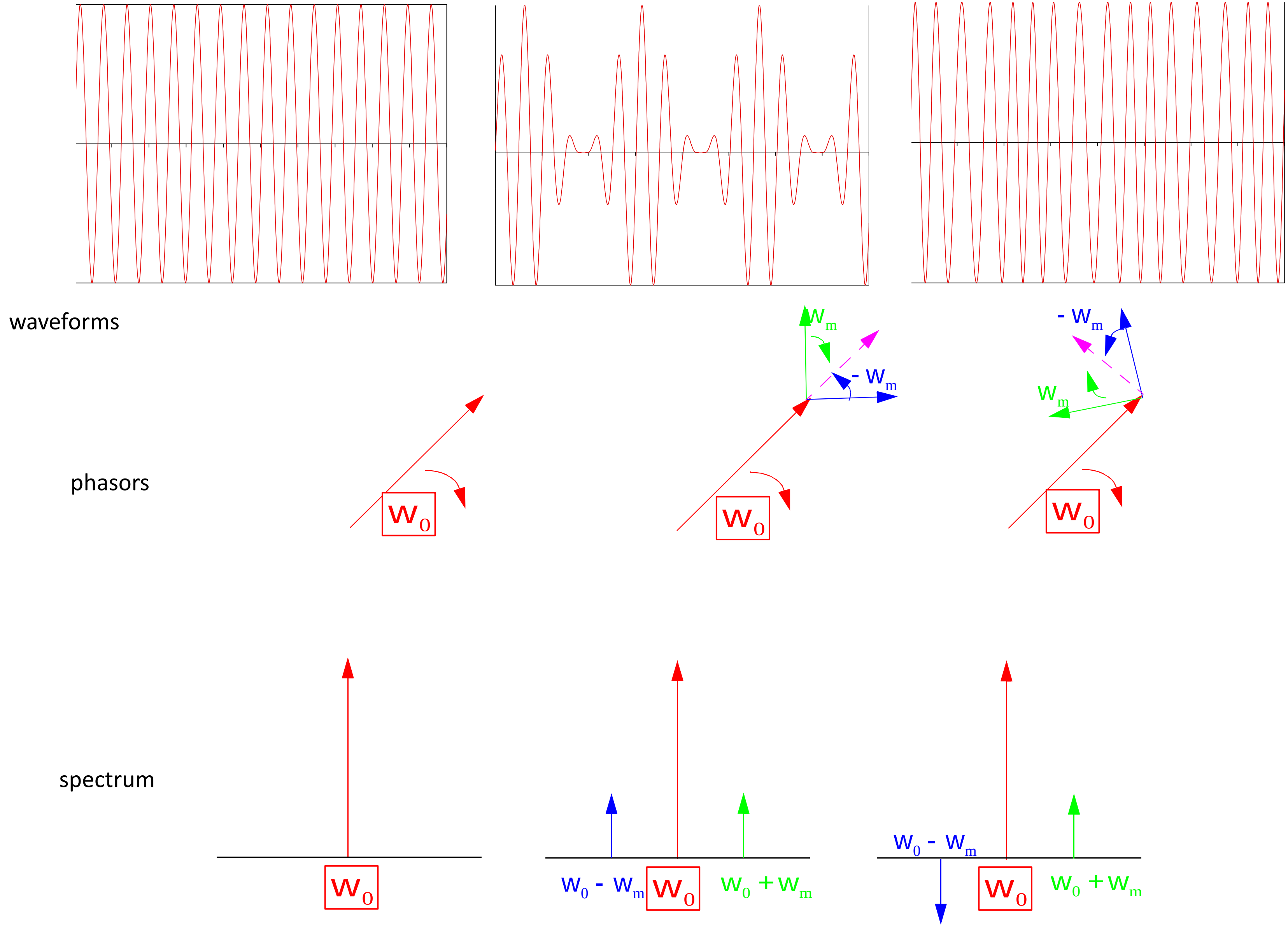
Let $\Delta t \ll \dfrac{1}{\omega}$ $\quad h \ll 1$

$$c\,\Delta t \cong \Big(1 + \frac{h}{2}\sin(kx_1 - \omega t)\Big)\Delta x_2$$

INFERRED DISTANCE BETWEEN POINTS

$$\frac{\delta(c\,\Delta t)}{\Delta x_2} = \frac{h}{2}\sin(kx_1 - \omega t)$$ Time Dependent **Strain**

$$\frac{\Delta l}{l} = \frac{h}{2}$$ The Measurable Quantity

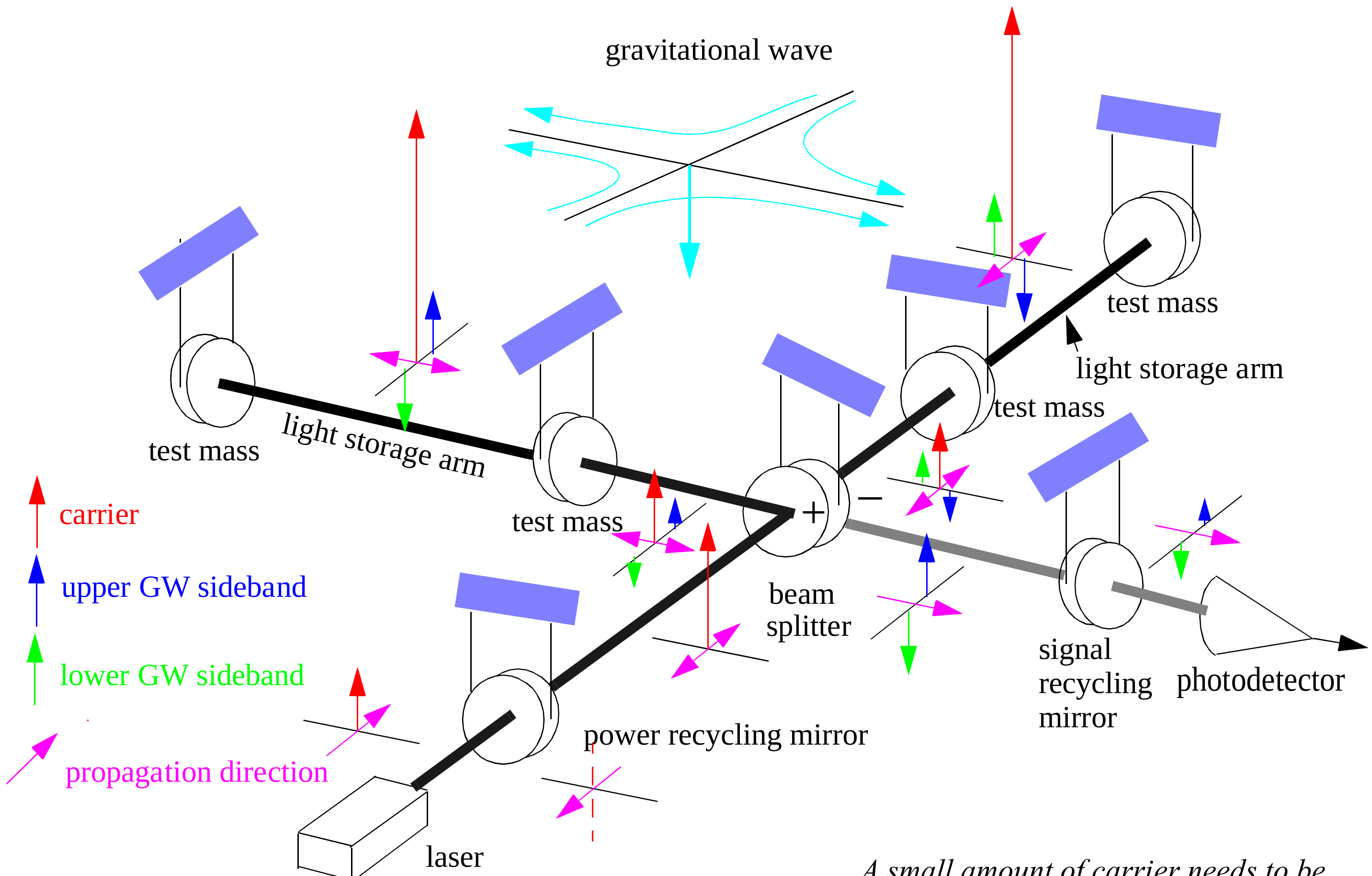


modulation amplitude phase

$$E(t) = \quad \mathrm{Re}(e^{i\omega_0 t}) \quad \mathrm{Re}(e^{i\omega_0 t}\left[1+\Gamma(e^{-i\omega_m t}+e^{i\omega_m t})\right]) \quad \mathrm{Re}(e^{i\omega_0 t}\left[1+\Gamma(e^{-i\omega_m t}-e^{i\omega_m t})\right])$$

MODULATION: Amplitude and Phase

Advanced LIGO Fabry-Perot Michelson Interferometer with GW sidebands



A small amount of carrier needs to be leaked to the photodetector to make the GW sidebands detectable

PENDULUM THERMAL NOISE

Pendulum Brownian motion

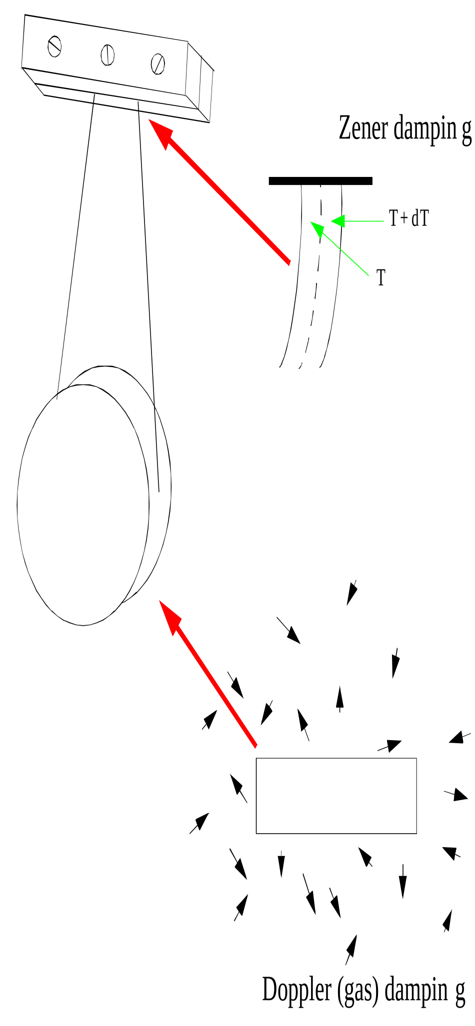
Dissipation leads to fluctuations

Tc = coherence or damping time
= Q x period of oscillator

Exchange with surroundings:

$$E(\text{thermal}) = \frac{kT\ t}{Tc}$$

Large Tc => smaller fluctuations



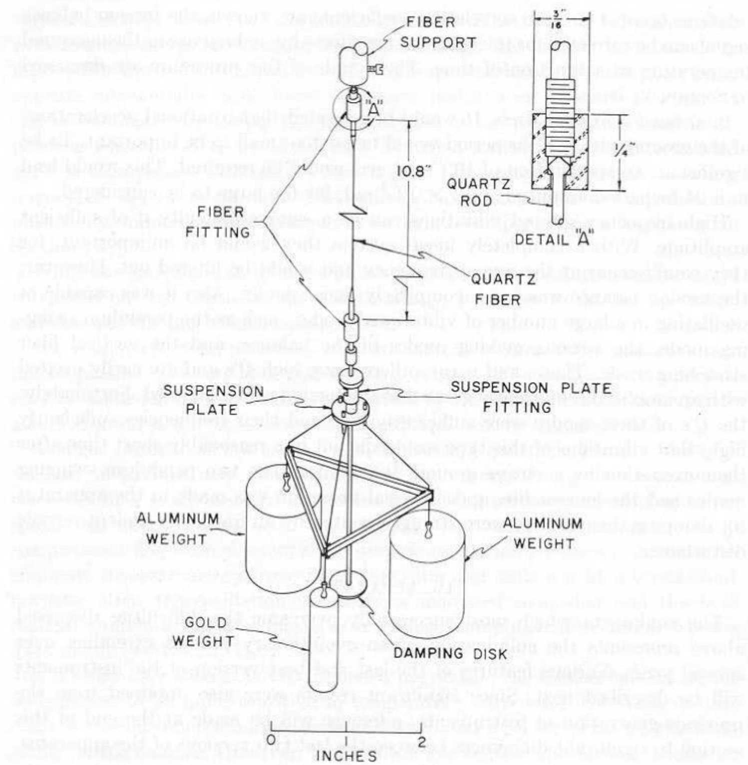


FIG. 3. The torsion balance suspension. The construction of both upper and lower fiber fittings is illustrated in Detail "A."

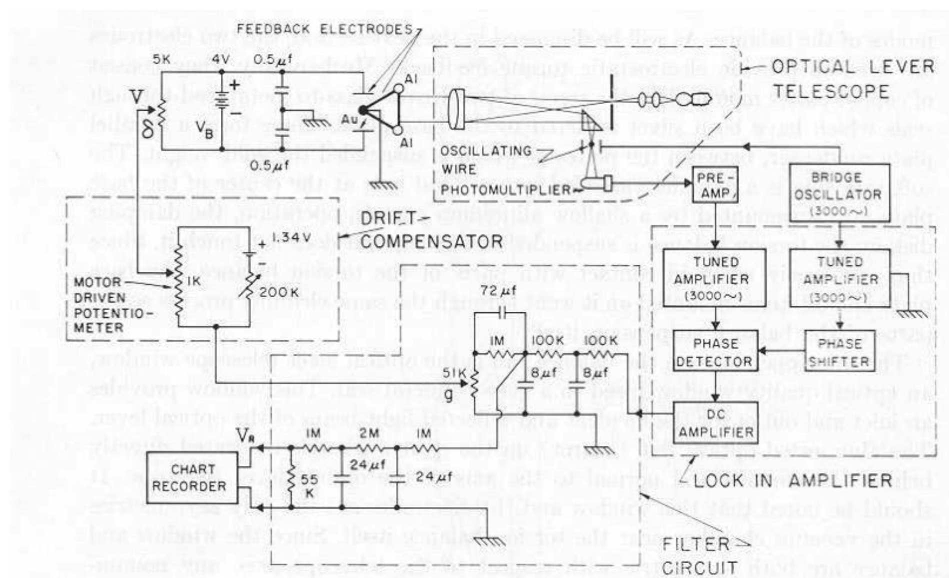
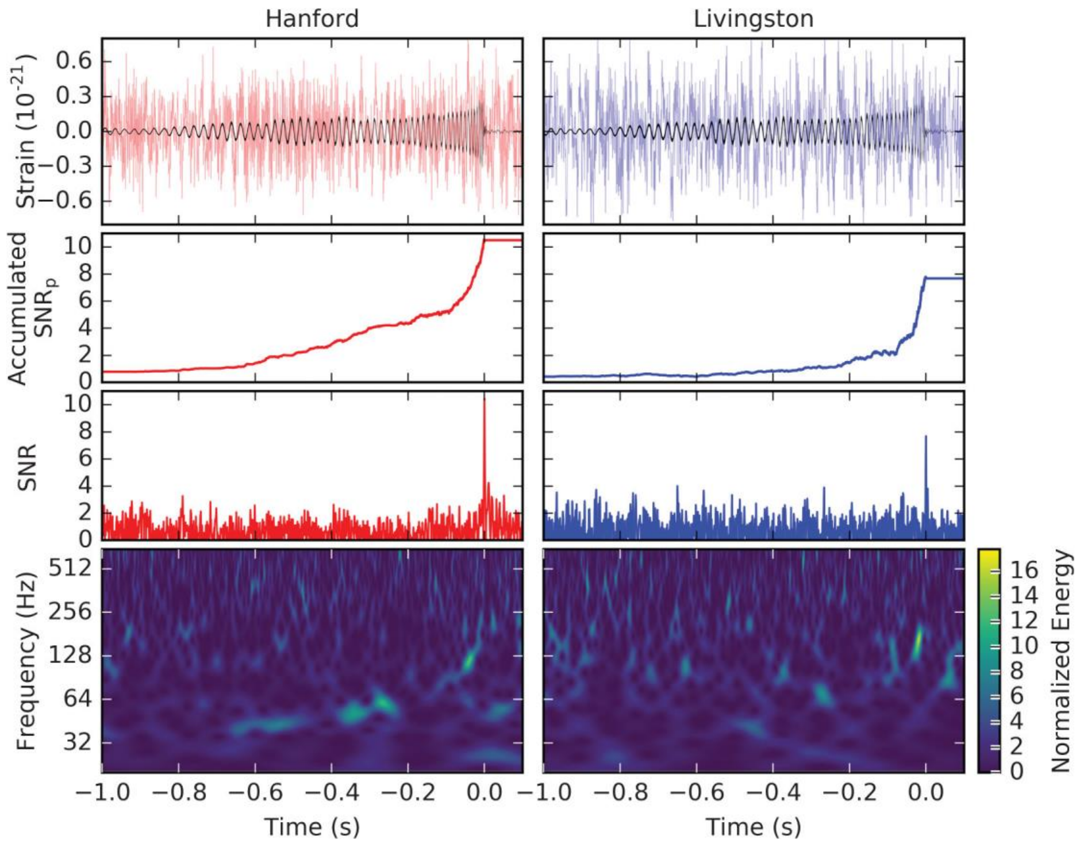


FIG. 6. Block diagram of the optical lever detection system

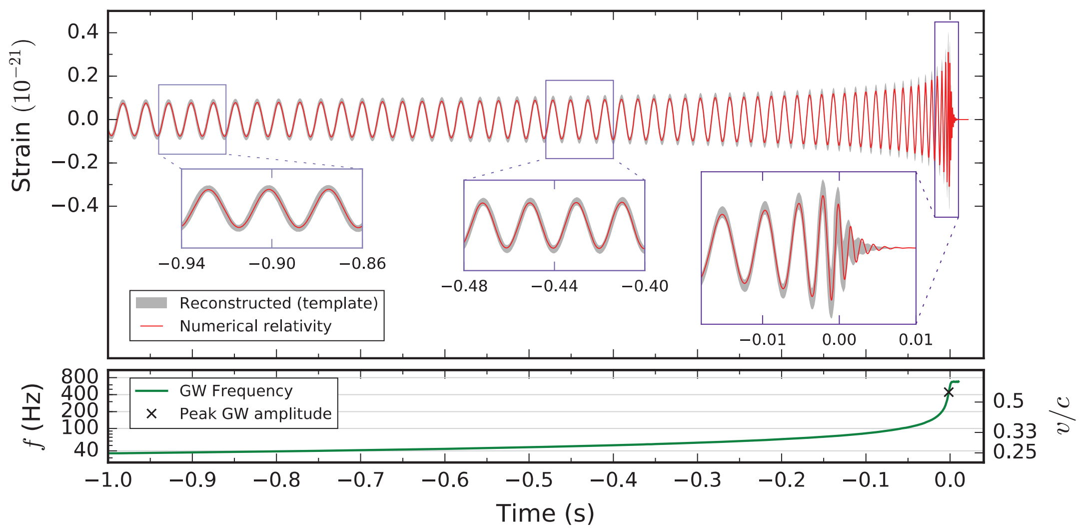
P.G. Roll, R. Krotkov, R.H.Dicke

Principle of Equivalence Experiment

Servo cooling of a mechanical system



Hanford
Livingston
Strain (10^{-21})
0.6
0.3
0.0
−0.3
−0.6
Accumulated SNR_p
10
8
6
4
2
0
SNR
Frequency (Hz)
512
256
128
64
32
Normalized Energy
16
14
12
10
8
6
4
2
0
−1.0
−0.8
−0.6
−0.4
−0.2
0.0
Time (s)
Time (s)



Strain (10^{-21})
0.4
0.2
0.0
−0.2
−0.4
−0.94
−0.90
−0.86
−0.48
−0.44
−0.40
−0.01
0.00
0.01
Reconstructed (template)
Numerical relativity
f (Hz)
800
400
200
100
40
GW Frequency
Peak GW amplitude
0.5
0.33
0.25
v/c
−1.0
−0.9
−0.8
−0.7
−0.6
−0.5
−0.4
−0.3
−0.2
−0.1
0.0
Time (s)

What is needed

Requirements:

$$h = \frac{\Delta L}{L} < 10^{-22} \quad h(f) < 10^{-23}\ \text{strain}/\sqrt{\text{Hz}}\ @\,100\text{Hz}$$

$$x < 10^{-18}\ \text{meters} \quad x(f) < 10^{-19}\ \text{meters}/\sqrt{\text{Hz}}\ @\,100\text{Hz}$$

What stands in the way:

Sensing the displacement

Quantum phase fluctuations: shot noise

Scattering at surfaces and gas

Optical distortion and loss

Laser amplitude and frequency noise

$$\phi(f) < 10^{-12}\ \text{radians}/\sqrt{\text{Hz}}\ @\,100\text{Hz} \quad \lambda = 1\text{m}$$

Believing that GW are causing the displacement

Seismic vibrations

Thermal fluctuations: suspensions and mirror surfaces

Quantum amplitude fluctuations: radiation pressure

Newtonian gravitational force fluctuations: $f < 20$ Hz

$$F(f) < 10^{-12}\ \text{newtons}/\sqrt{\text{Hz}}\ @\,100\ \text{Hz}$$

FRINGE SENSING

wavelength 1×10^{-6} m

$$h = \frac{x}{L} \sim \frac{\lambda}{Lb\sqrt{\dot{N}t}}$$

arm length = 4000 m

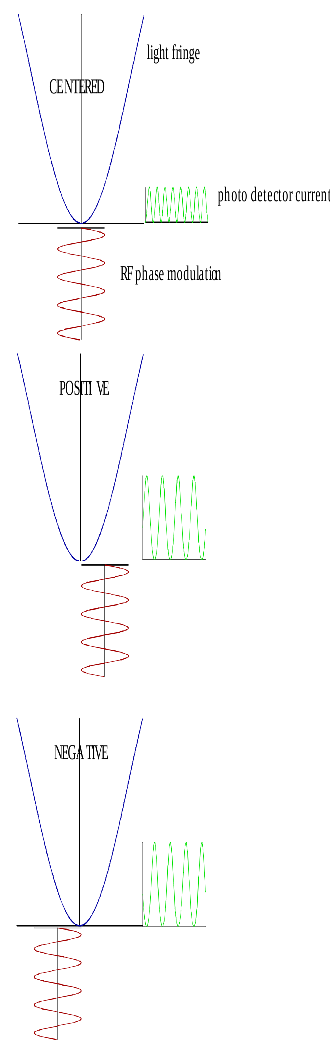
integration time

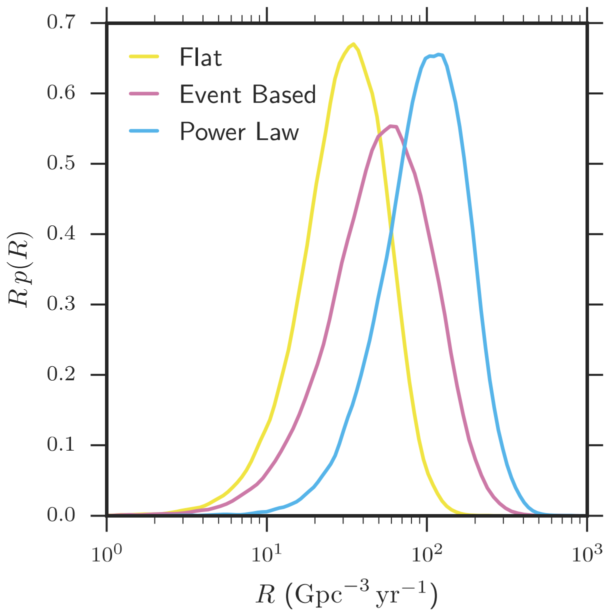
equivalent # of passes = 100

number of quanta/second at the beam splitter

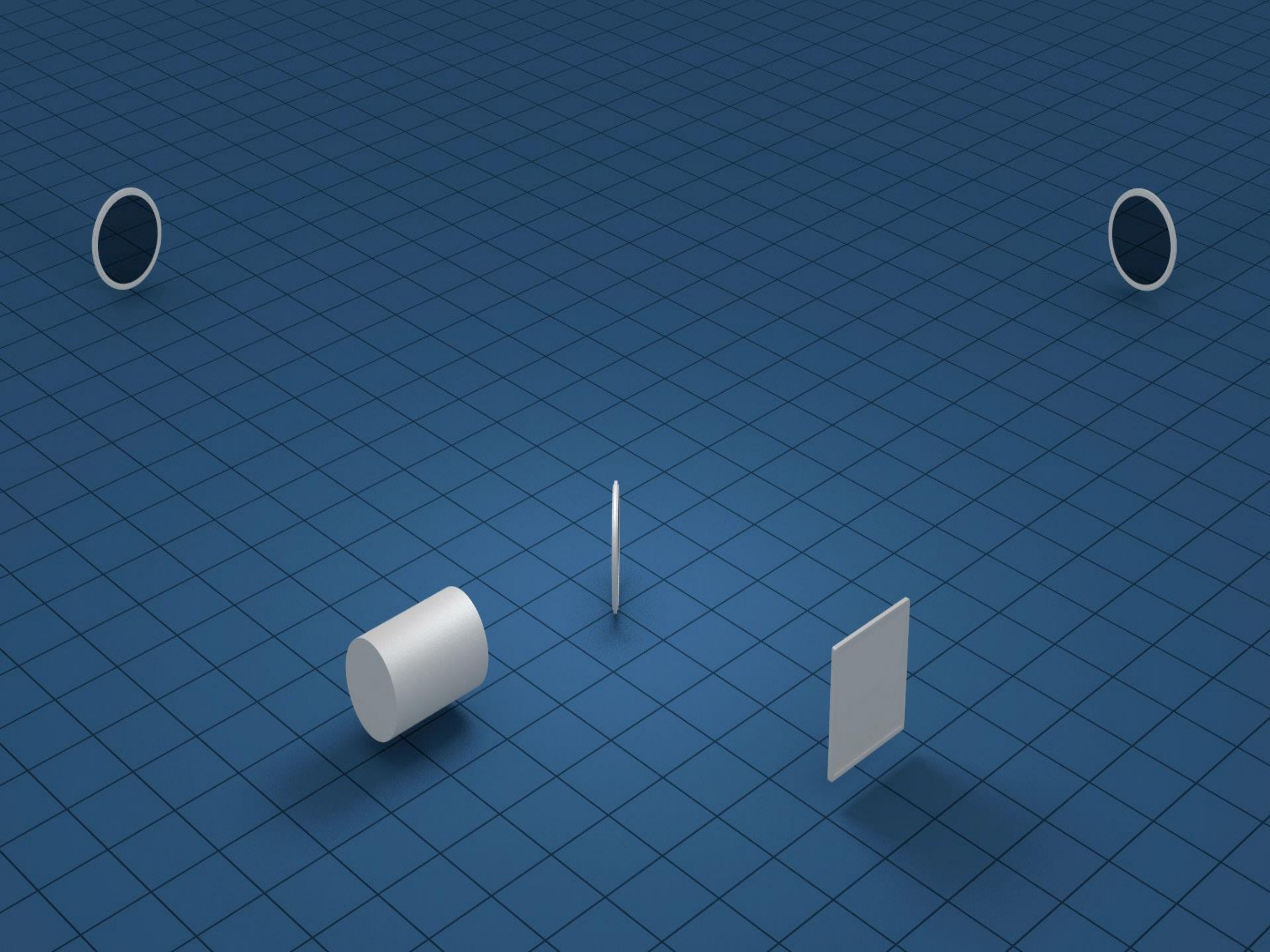
300 watts at beam splitter = 10^{21} identical photons/sec

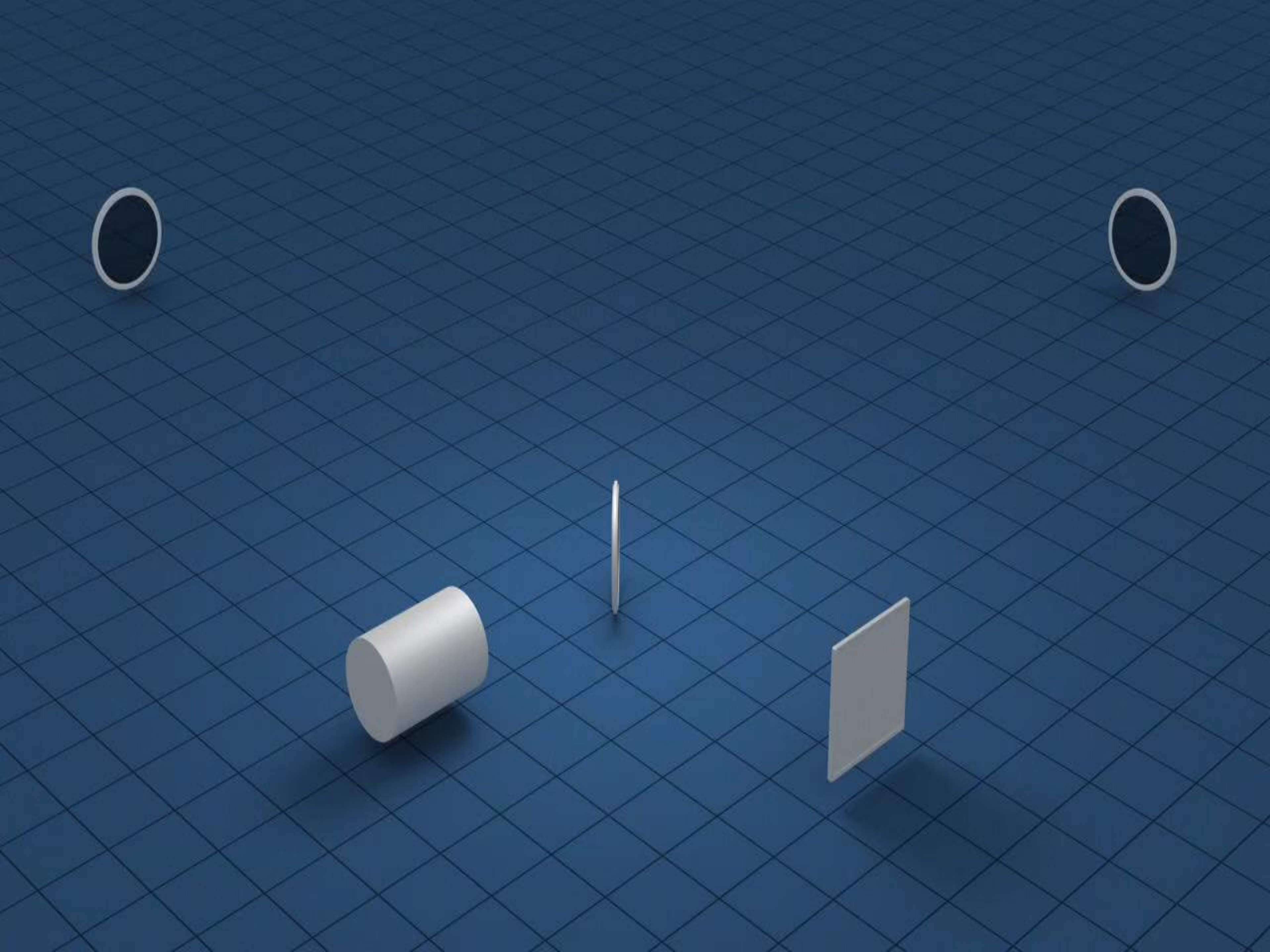
$h = 6 \times 10^{-22}$ integration time 10^{-2} sec





0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
$R\,p(R)$
Flat
Event Based
Power Law
10^0
10^1
10^2
10^3
R (Gpc^{-3} yr^{-1})

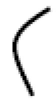


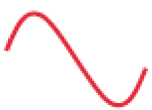


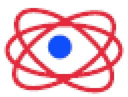
LIGO

How Small is 10^{-18} Meter?

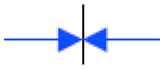
One meter, about 40 inches

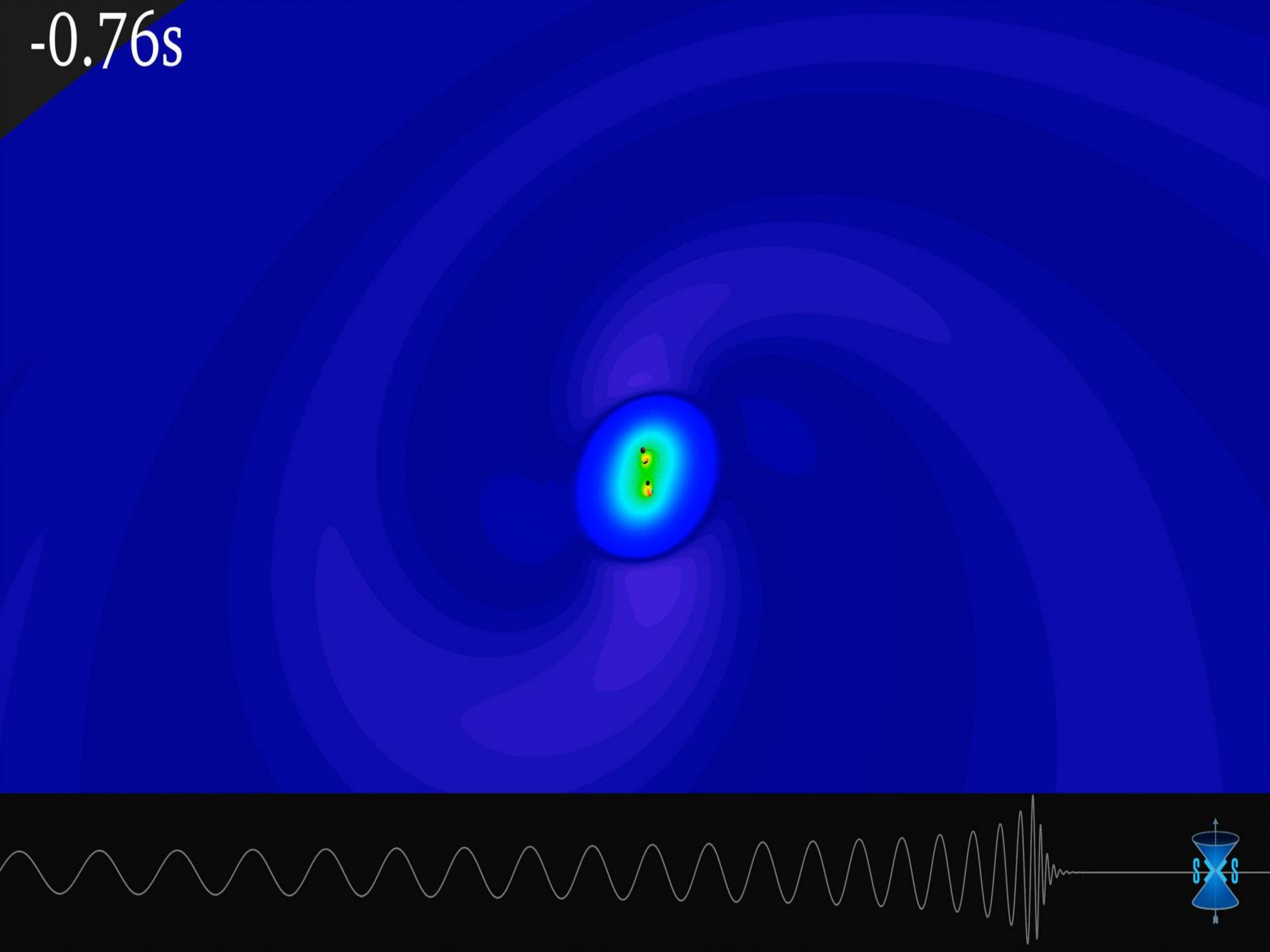
÷10,000  *Human hair, about 100 microns*

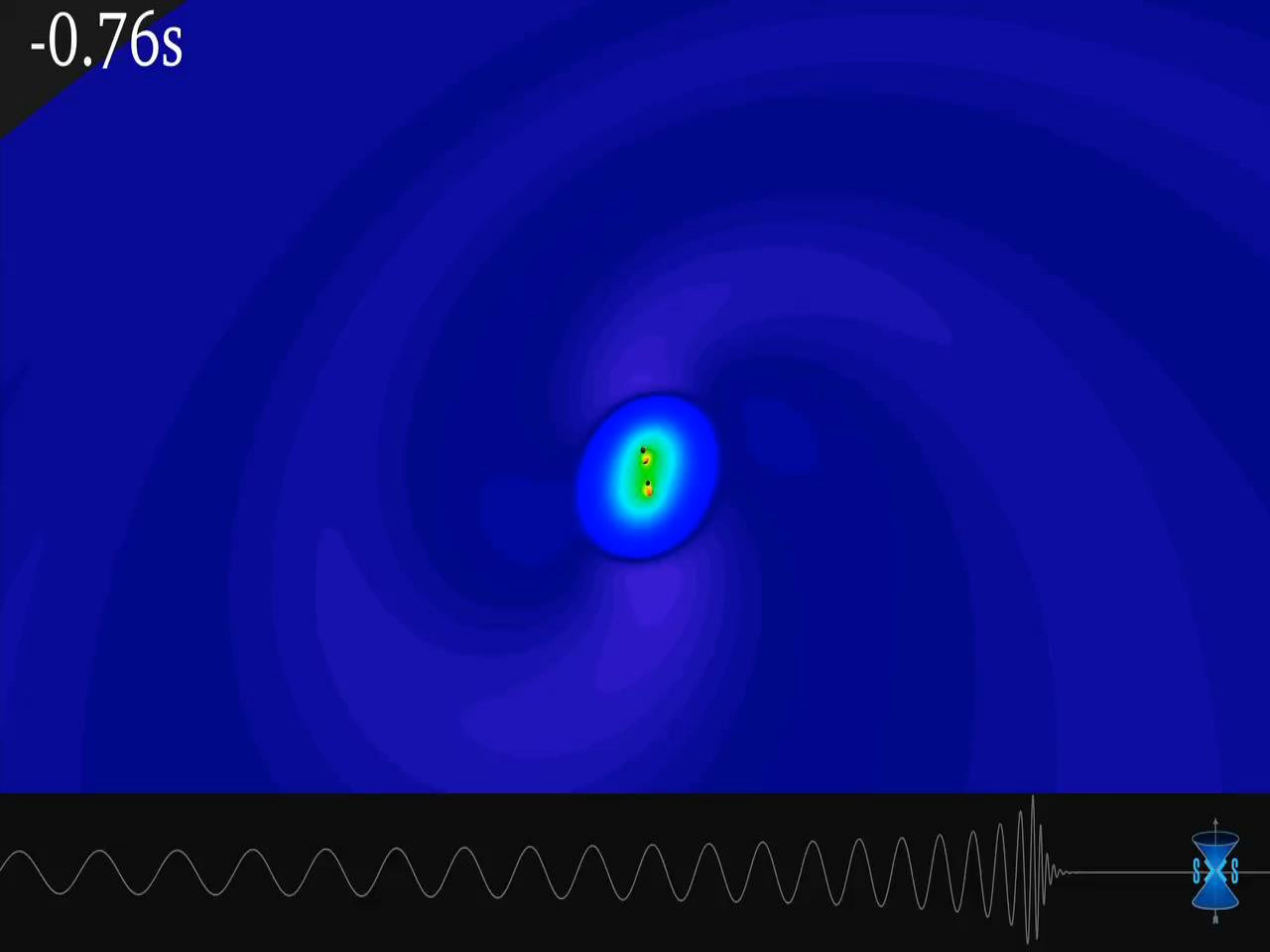
÷100  *Wavelength of light, about 1 micron*

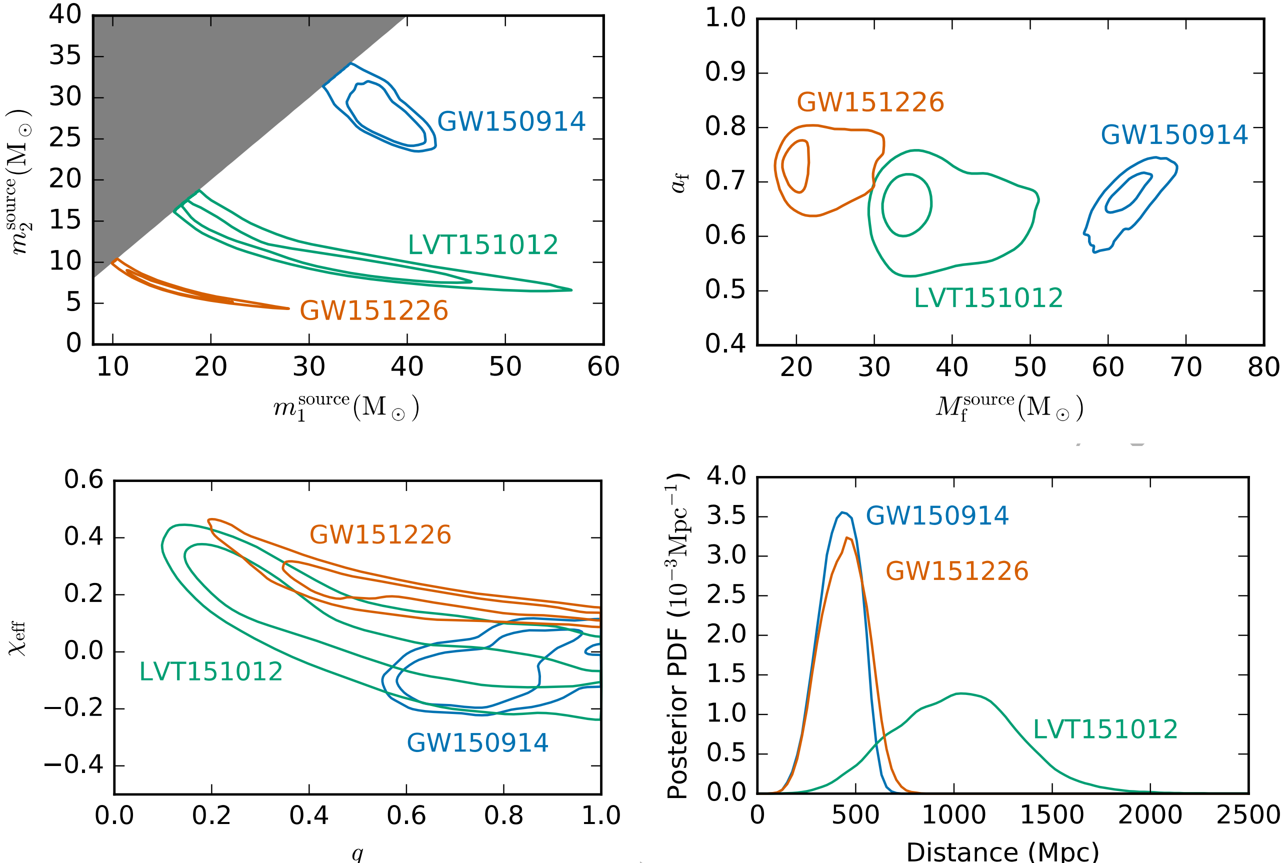
÷10,000  *Atomic diameter, 10^{-10} meter*

÷100,000  *Nuclear diameter, 10^{-15} meter*

÷1,000  *LIGO sensitivity, 10^{-18} meter*


-0.76s


-0.76s



GW150914
LVT151012
GW151226
$m_1^{\rm source} (\rm M_\odot)$
$m_2^{\rm source} (\rm M_\odot)$
a_f
$M_f^{\rm source} (\rm M_\odot)$
$\chi_{\rm eff}$
q
Posterior PDF $(10^{-3}\rm Mpc^{-1})$
Distance (Mpc)

Acoustic bar GW Detector groups

R. Garwin

W. Fairbank

E. Amaldi

1965-1975
Room T bars

- Bell Labs
- Frascati
- Glasgow
- IBM
- Rochester
- Max Planck
- Rome

1975-1990+
Cryogenic bars

- Frascati
- Louisiana
- Moscow
- Perth
- Rochester
- Stanford

2000 ->
Spherical cryogenic detectors

- Brazil
- Netherlands

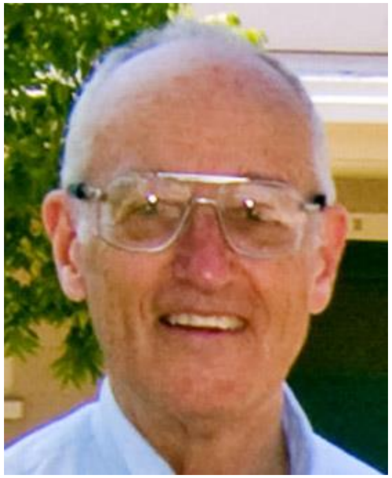
A. Tyson

W. Hamilton

P. Michelson

Stanford Contributions to LIGO

1.06 micron solid state frequency and amplitude stabilized laser (1986)



Robert Byer

Dan DeBra

Active hydraulic seismic isolation system (2000)

Advanced Detector active seismic isolation system (2010)

Peter Michelson

Brian Lantz

Low thermal noise optical coating research (2017)

Marty Fejer

Brett Shapiro