Title: Probing the Universe with Gravitational Waves

Date: Nov 30, 2017 11:30 AM

URL: http://pirsa.org/17110047

Abstract: The observations of gravitational waves from the mergers of compact binary sources opens a new way to learn about the universe as well as to test General Relativity in the limit of strong gravitational interactions â€“ the dynamics of massive bodies traveling at relativistic speeds in a highly curved space-time. The lecture will describe some of the difficult history of gravitational waves proposed about 100 years ago. The concepts used in the instruments and the methods for data analysis that enable the measurement of gravitational wave strains of 10⁻²¹ and smaller will be presented. The results derived from the measured waveforms, their relation to the Einstein field equations and the astrophysical implications are discussed. The talk will end with a vision for the future of gravitational wave astronomy.

Probing the universe with gravitational waves

Rainer Weiss, MIT on behalf of
The LIGO Scientific Collaboration

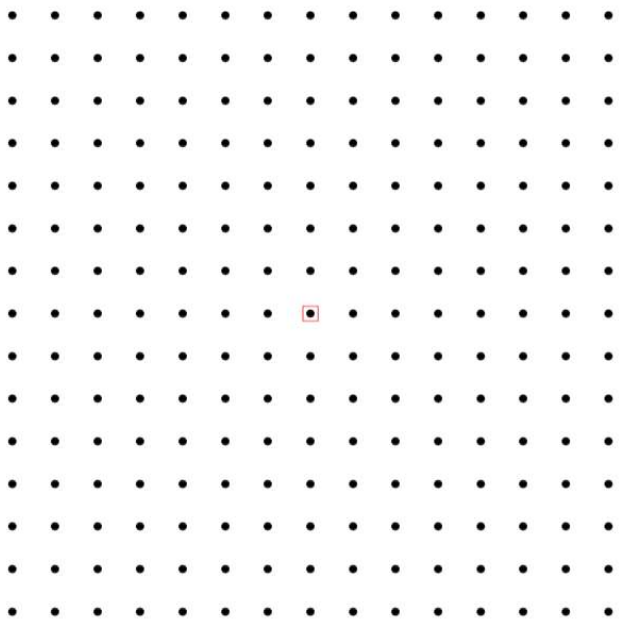
Perimeter Institute Colloquium

November 30, 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)



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."

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

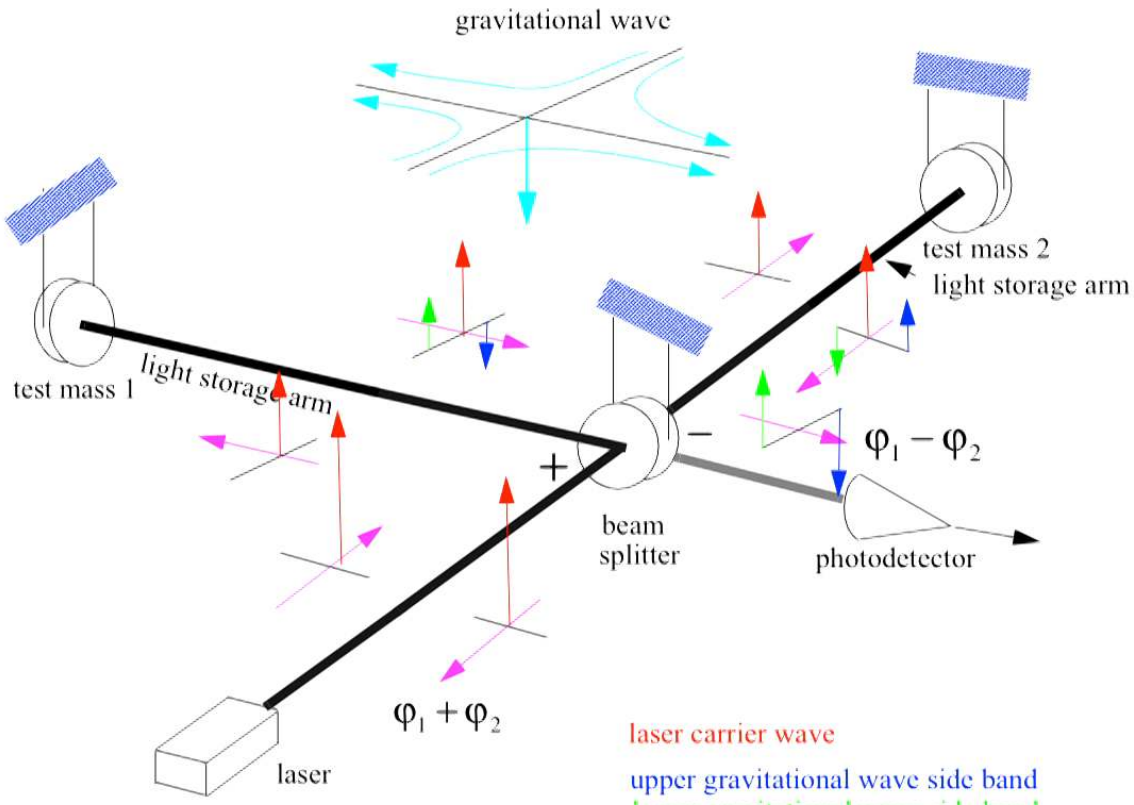
1916 examples: train colllision binary star decay

$m = 10^5$ 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

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

Michelson Interferometer Schematic and GW sidebands



The measurement challenge

Kip Thorne

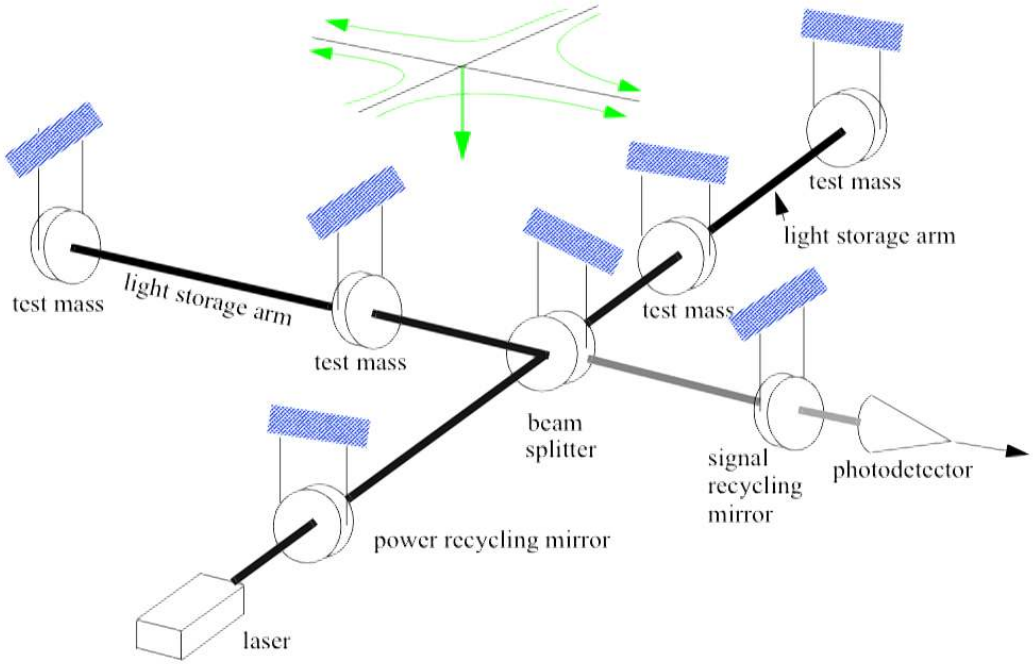
$$h = \frac{\Delta L}{L} \leq 10^{-21}$$

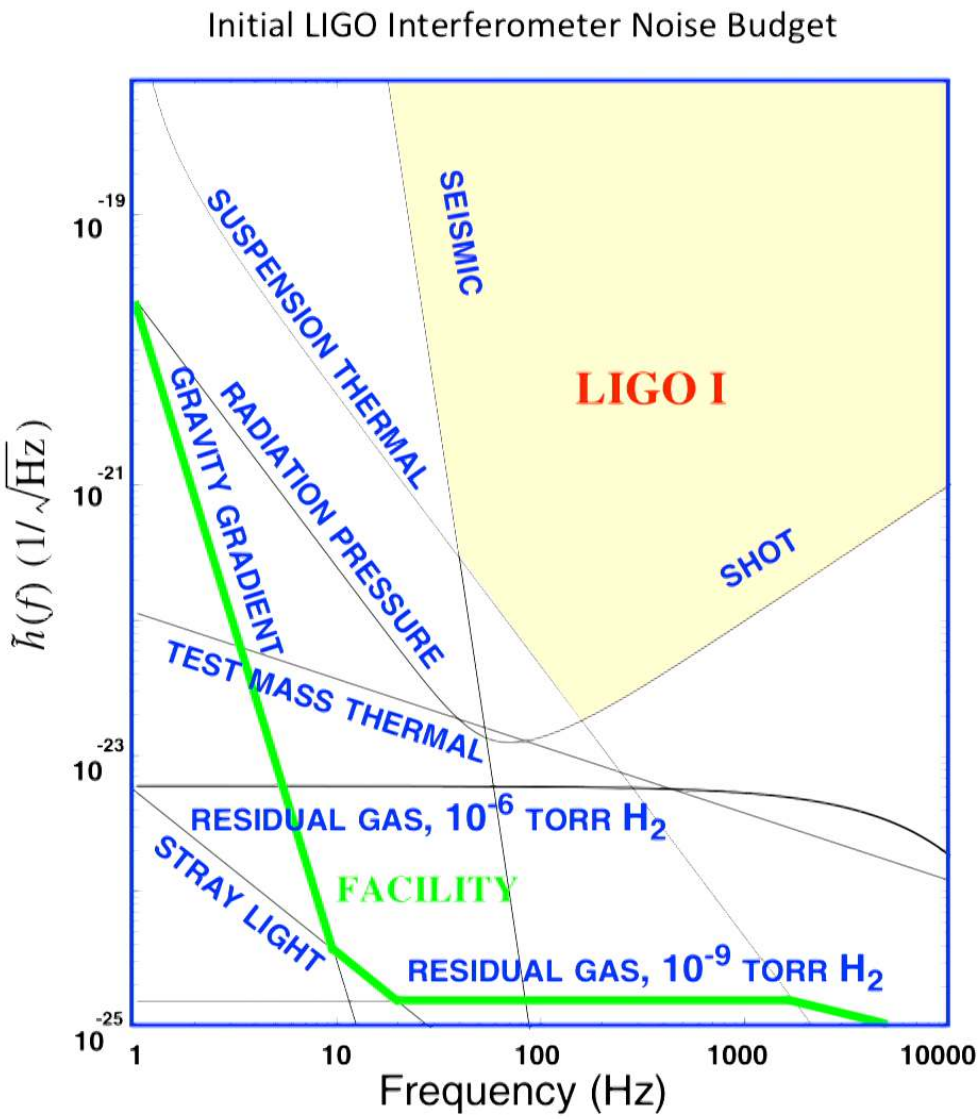
$$L = 4\text{km} \quad \Delta L \leq 4\text{x}10^{-18}\,\text{meters}$$

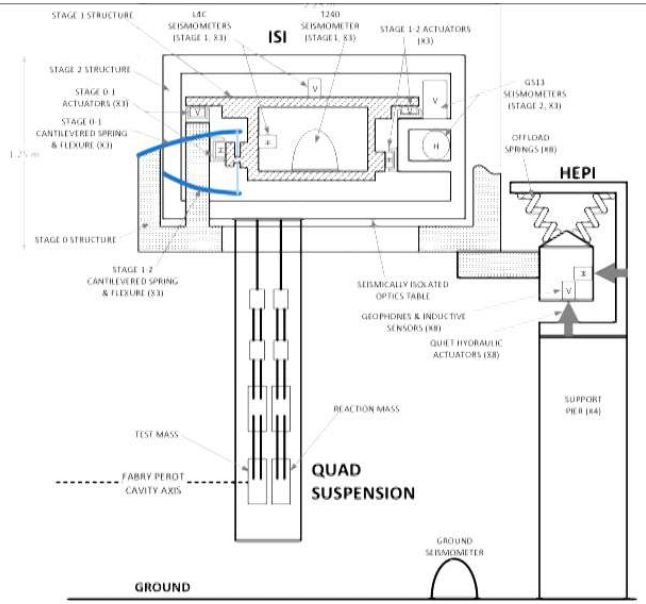
$$\Delta L \sim 10^{-12}\,\text{wavelength of light}$$

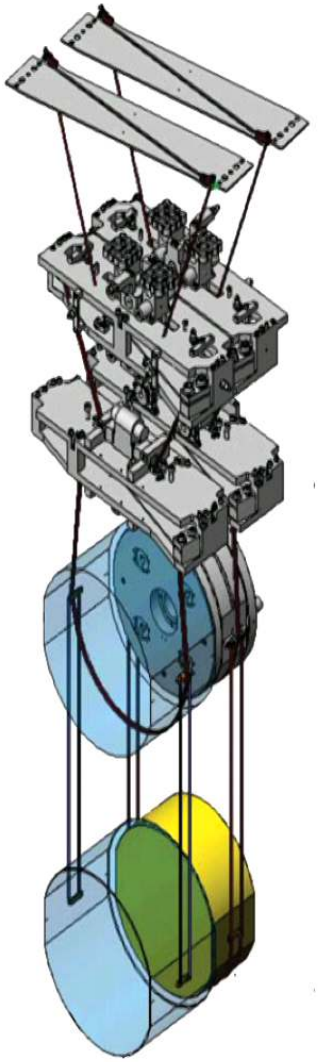
$$\Delta L \sim 10^{-12}\,\text{vibrations at earth's surface}$$

Advanced LIGO Fabry-Perot Michelson Interferometer Schematic

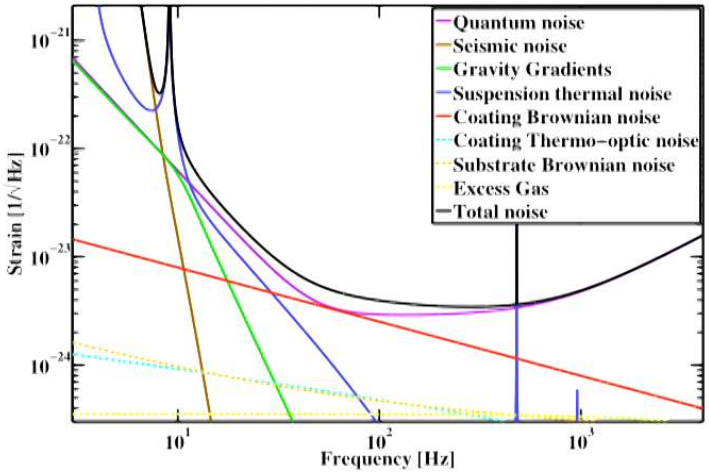


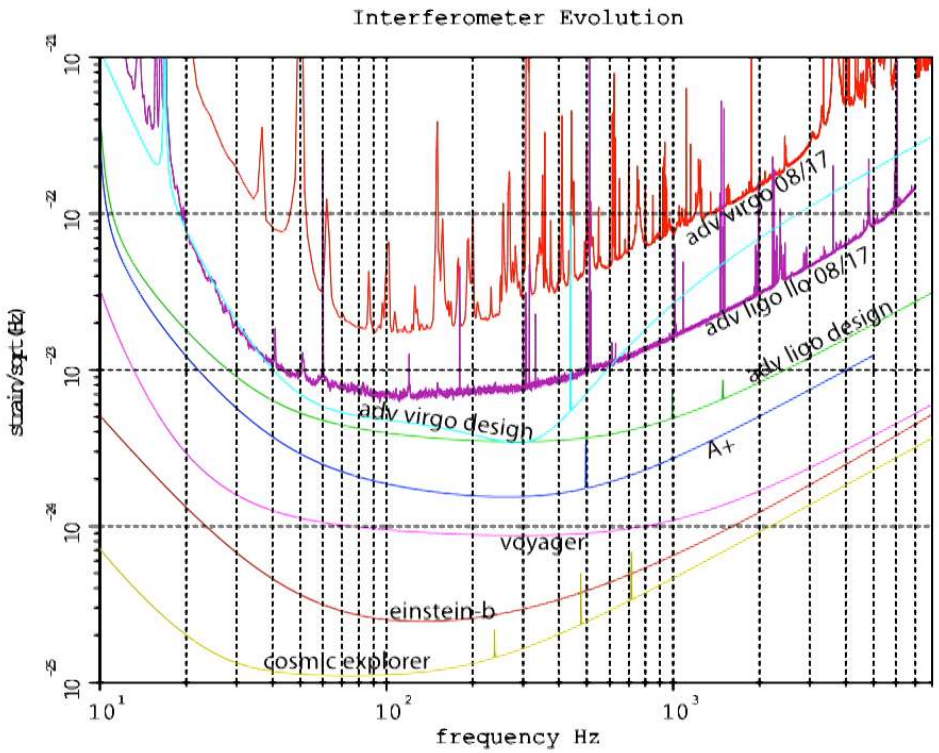

Initial LIGO Interferometer Noise Budget
SEISMIC
SUSPENSION THERMAL
RADIATION PRESSURE
GRAVITY GRADIENT
LIGO I
SHOT
TEST MASS THERMAL
RESIDUAL GAS, 10-6 TORR H2
FACILITY
STRAY LIGHT
RESIDUAL GAS, 10-9 TORR H2
h(f) (1/√Hz)
10-19
10-21
10-23
10-25
1
10
100
1000
10000
Frequency (Hz)

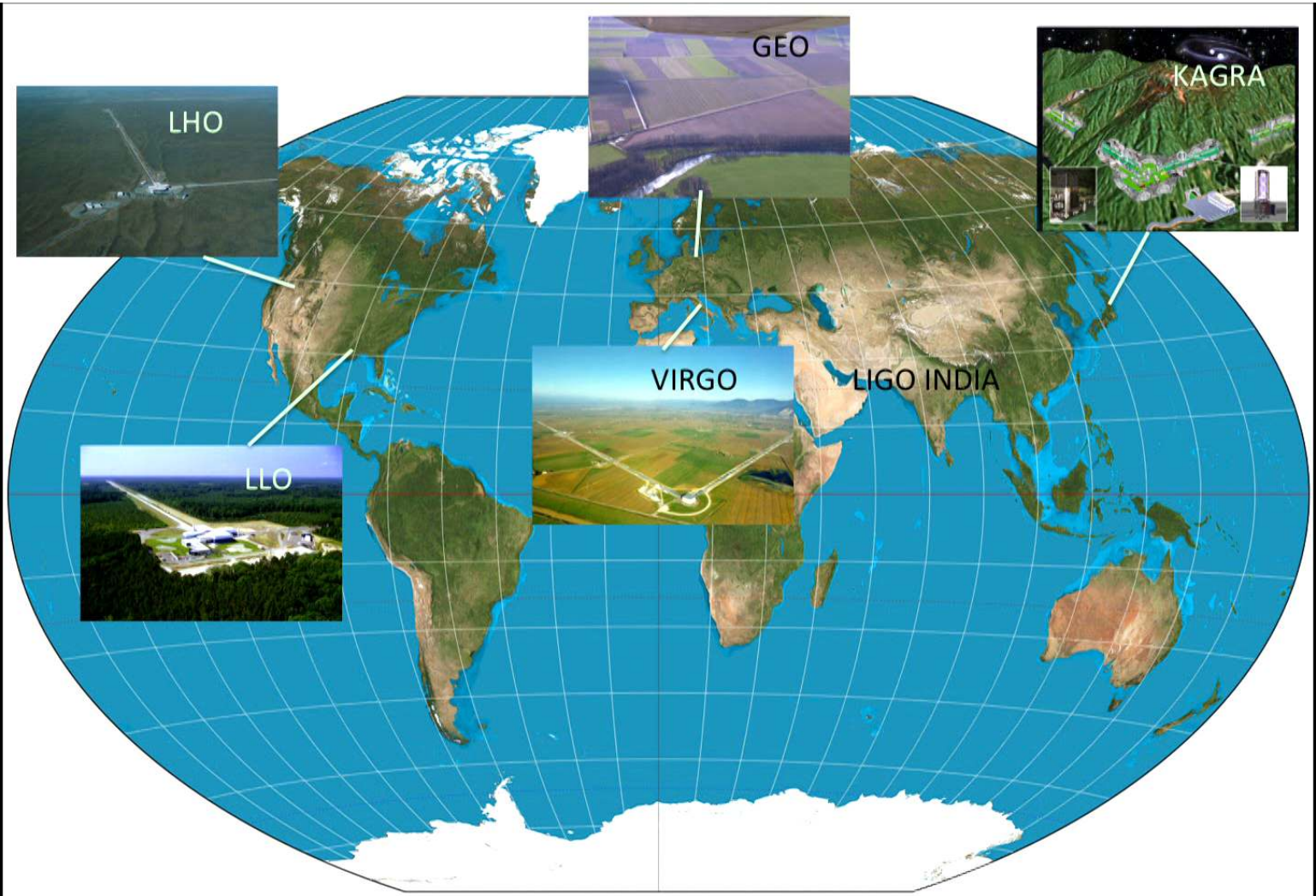


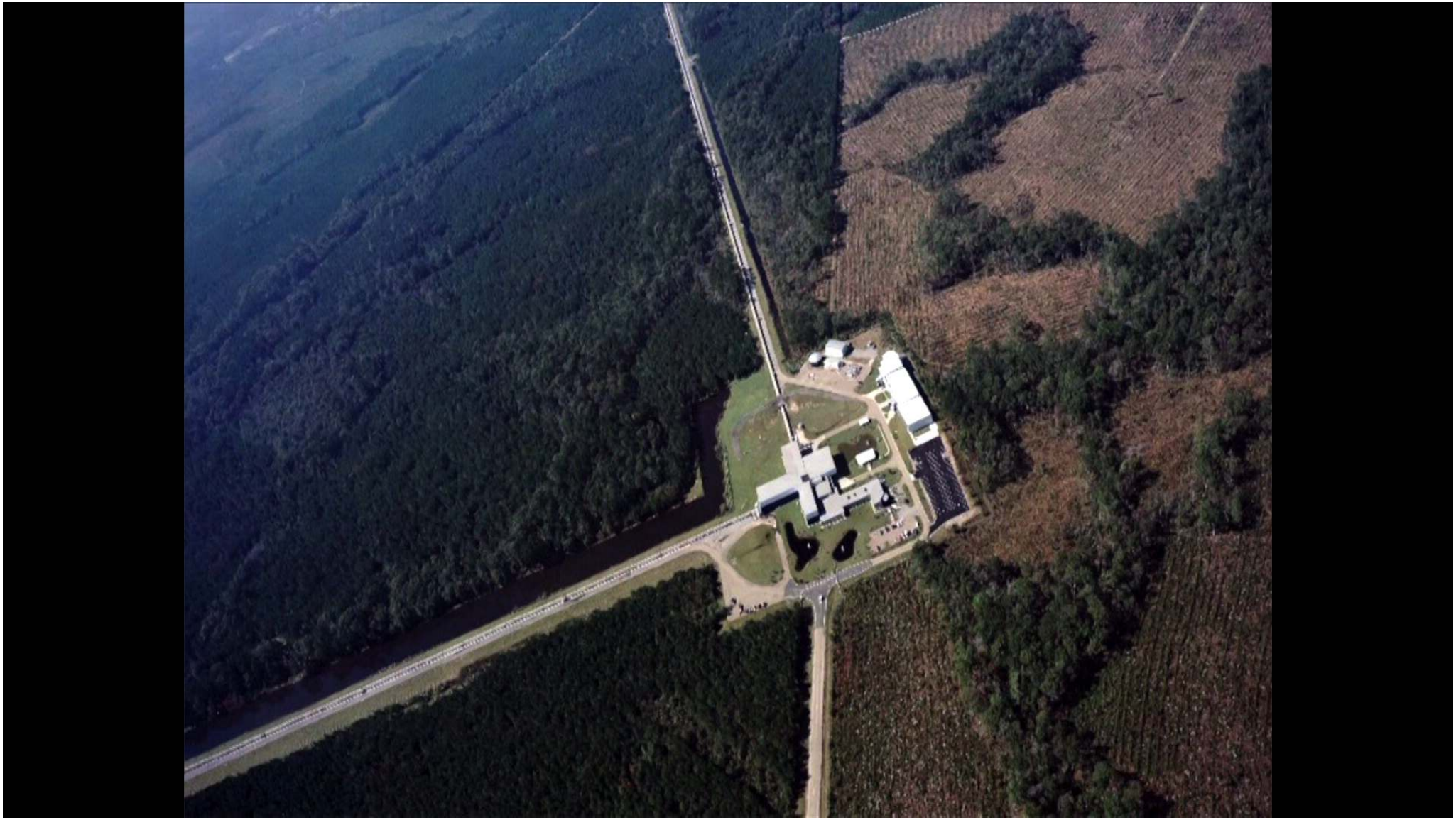


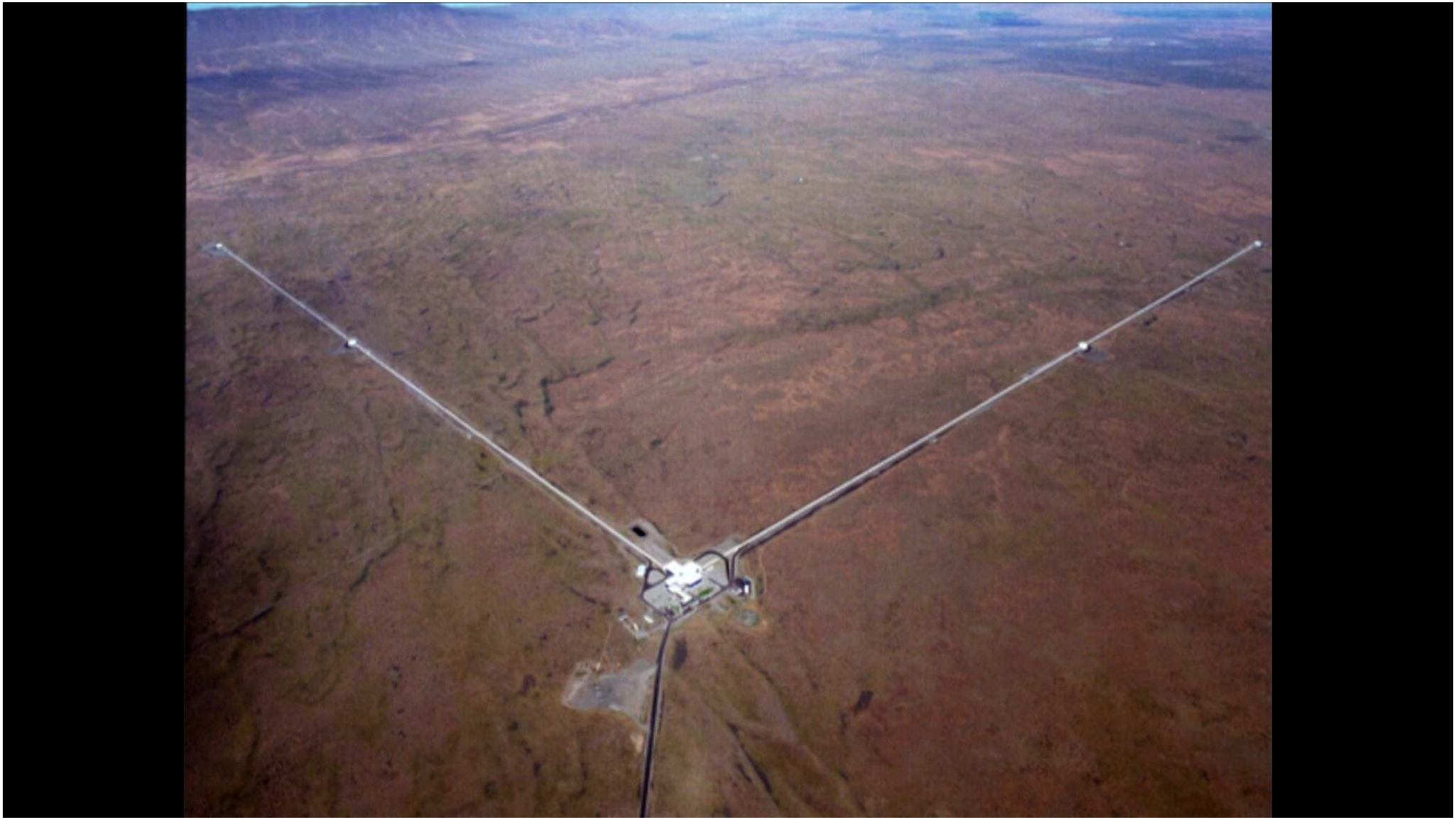
Advanced LIGO design noise budget

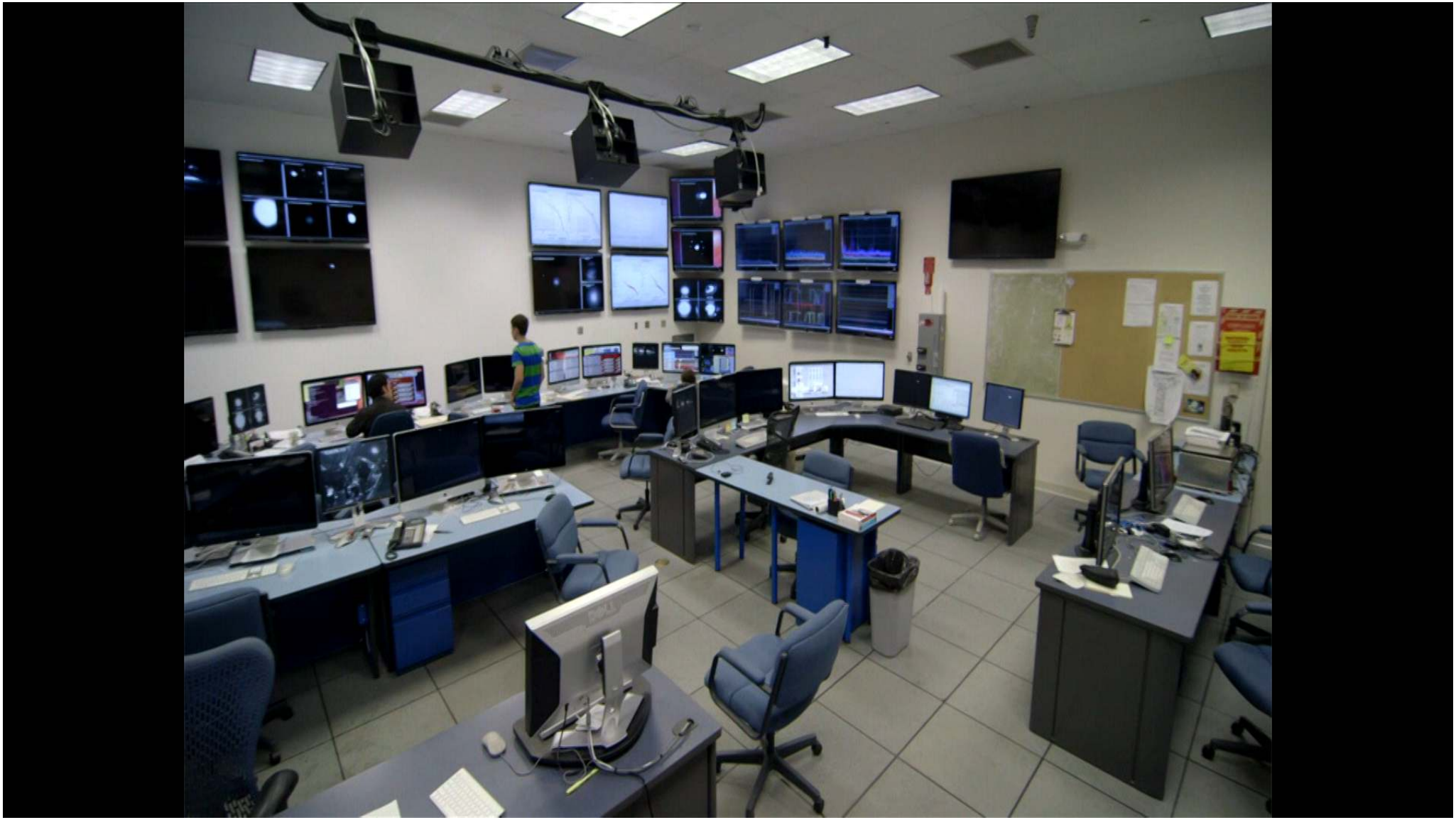



Interferometer Evolution
strain/sqrt(Hz)
frequency Hz
adv virgo 08/17
adv ligo llo 08/17
adv ligo design
adv virgo design
A+
voyager
einstein-b
cosmic explorer


GEO
KAGRA
LHO
VIRGO
LIGO INDIA
LLO

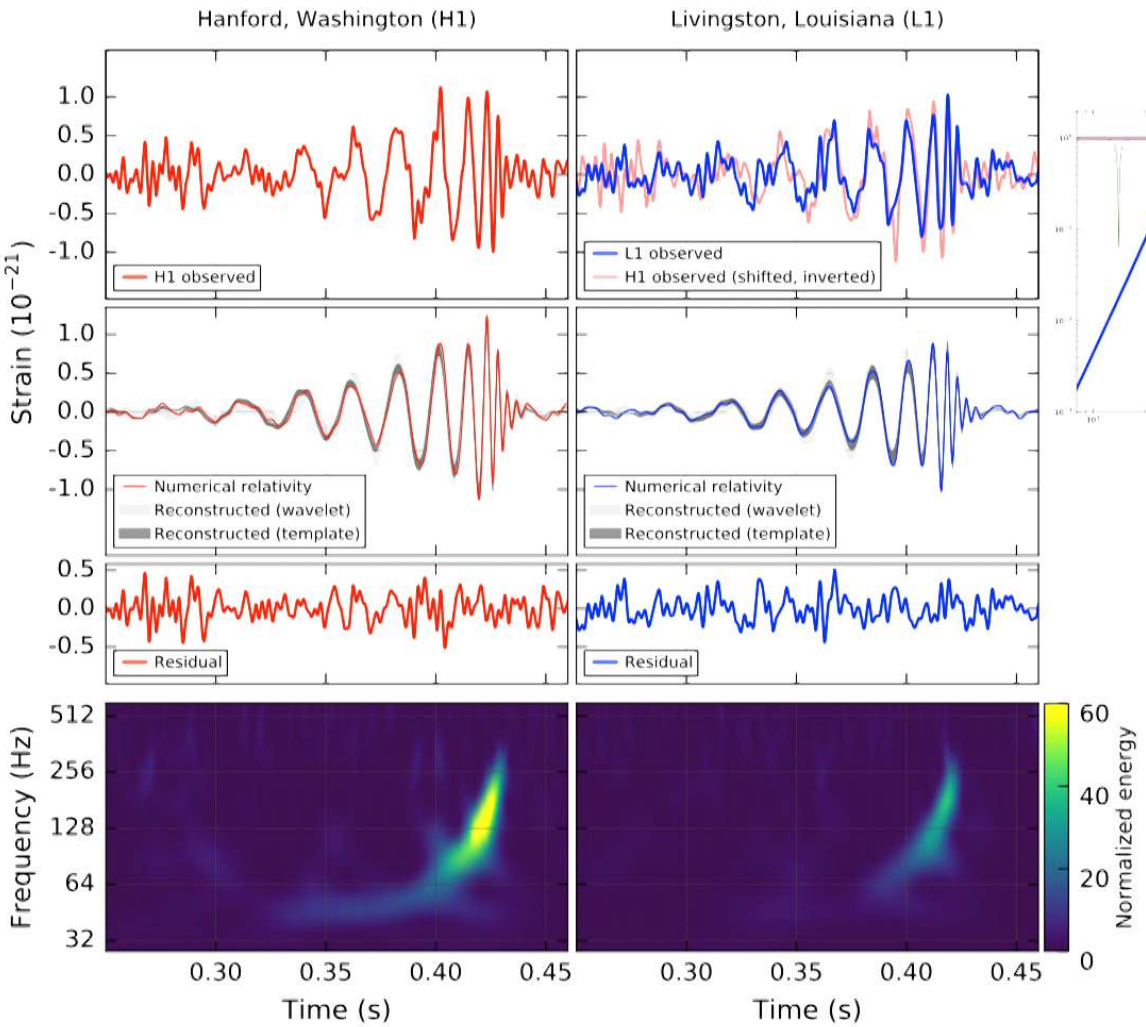


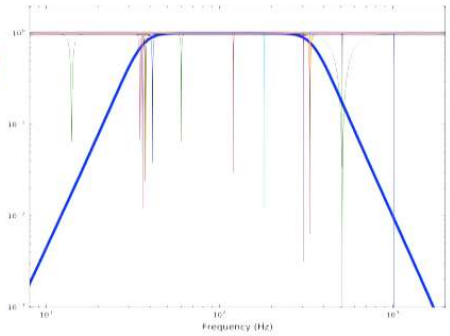




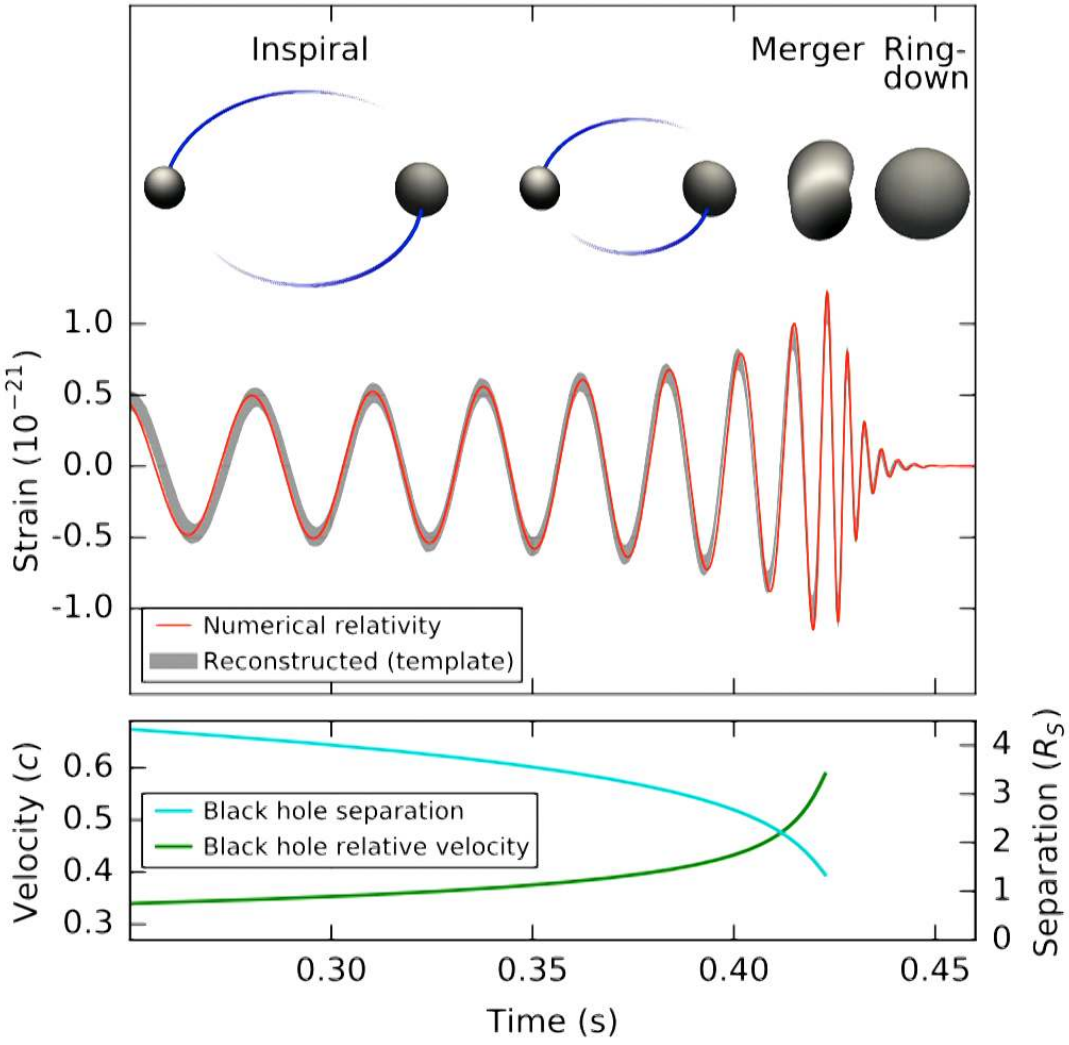
Criteria for transient detection

- 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



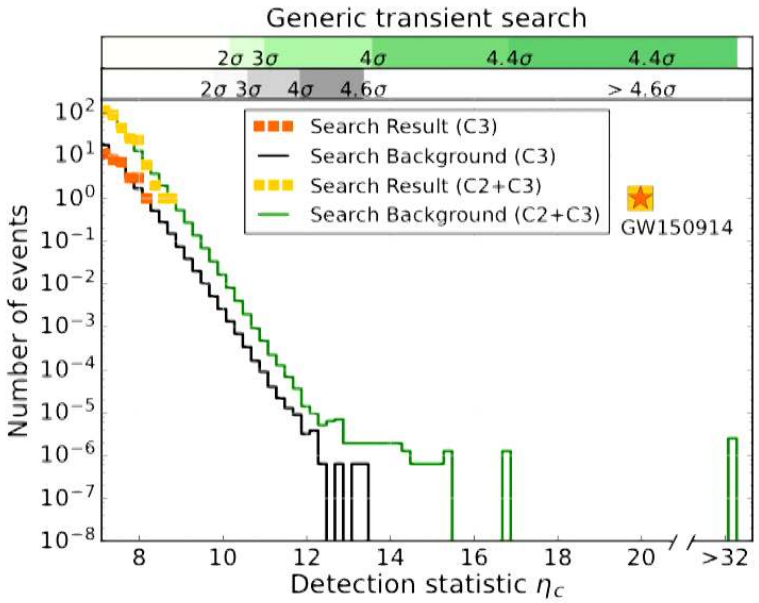


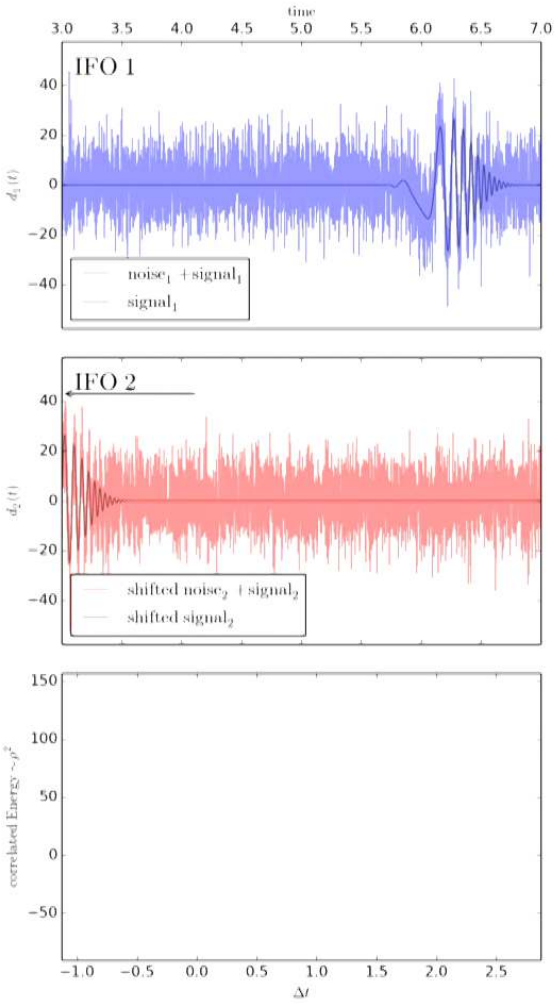
Simple high-low pass filter with notches


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

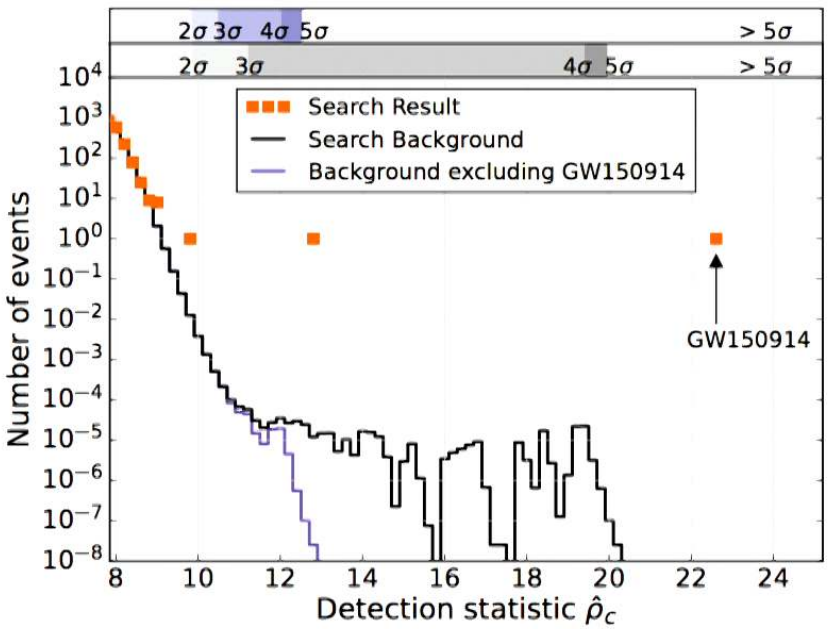
R.Essik





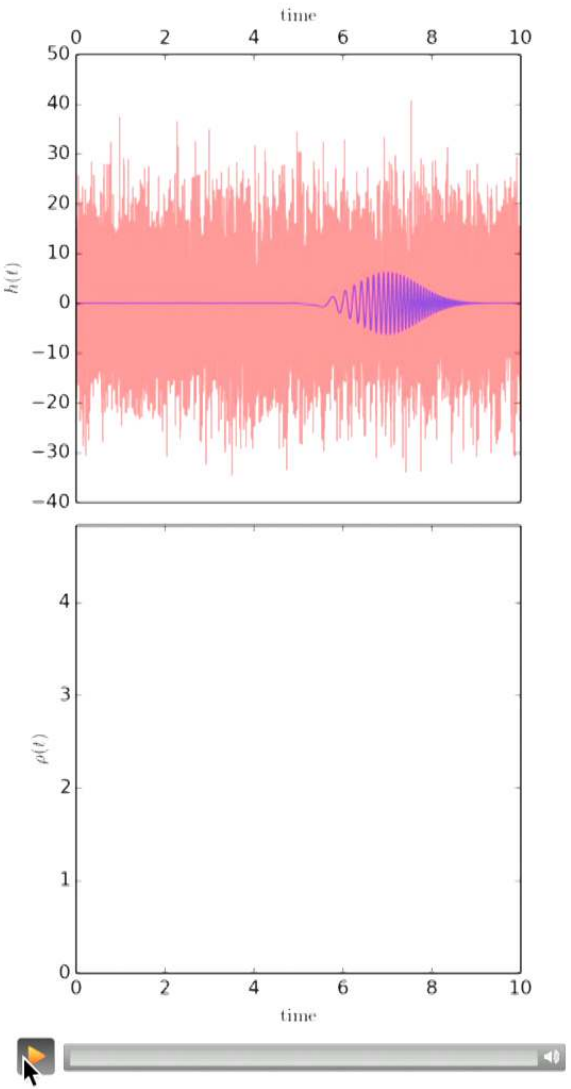
R.Essik

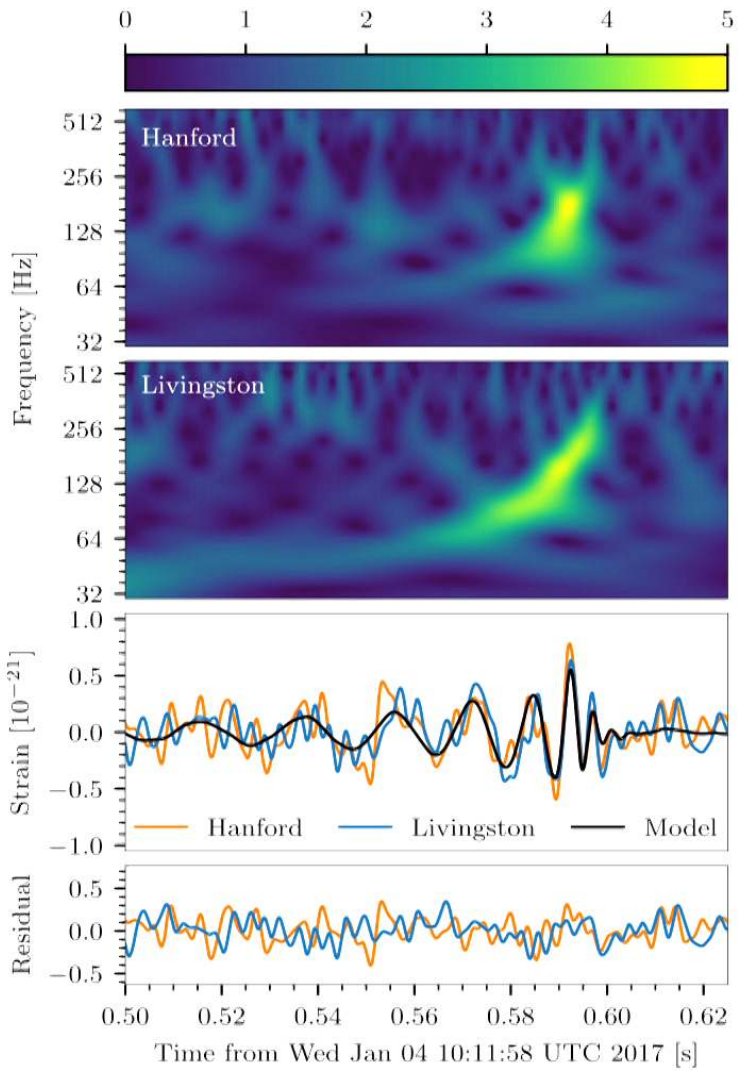
Modeled search followed by χ^2 cut



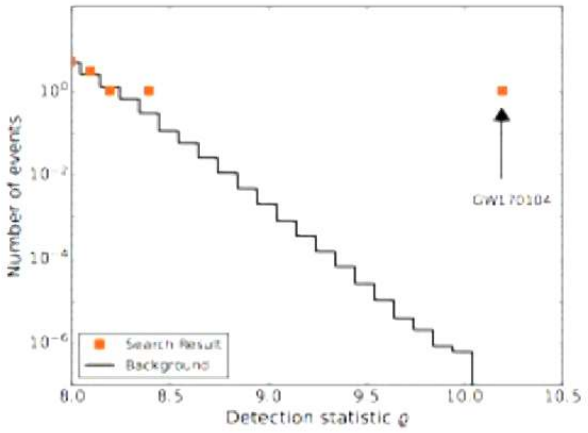
False alarm rate from time slides

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

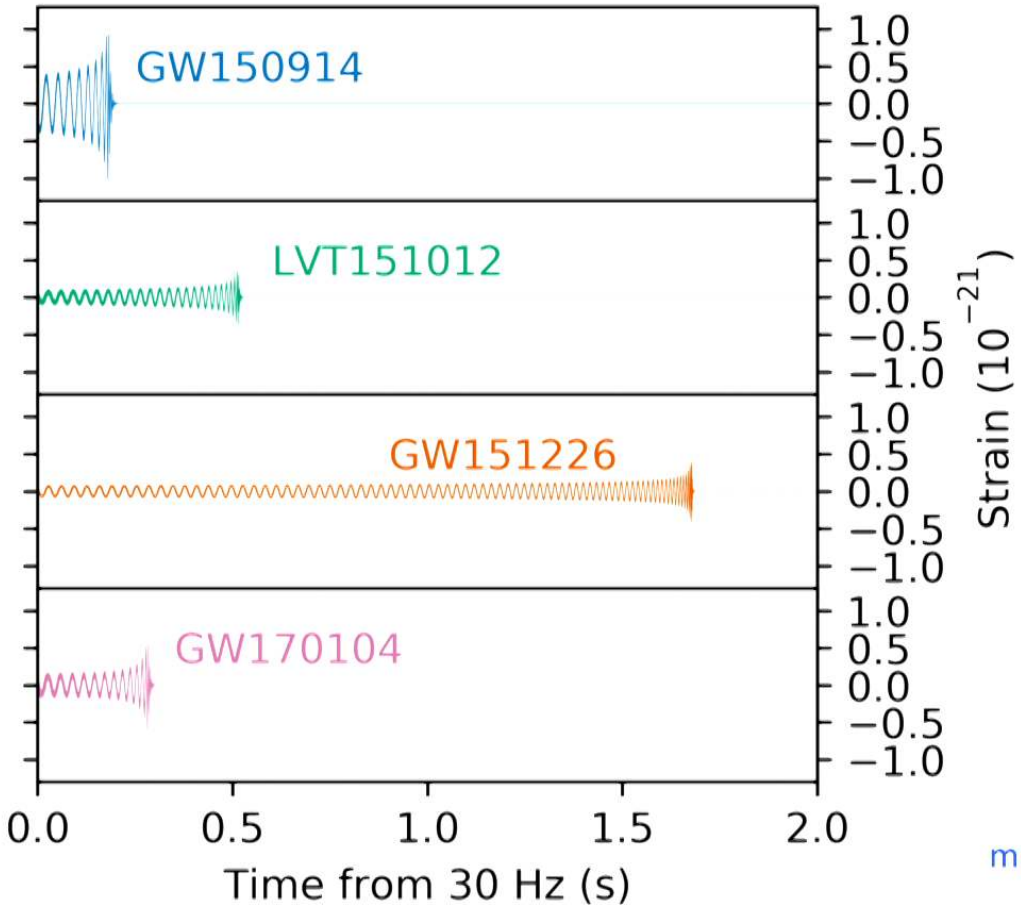



0
1
2
3
4
5
Hanford
Livingston
Frequency [Hz]
512
256
128
64
32
Strain [10^{-21}]
1.0
0.5
0.0
−0.5
−1.0
Hanford
Livingston
Model
Residual
0.50
0.52
0.54
0.56
0.58
0.60
0.62
Time from Wed Jan 04 10:11:58 UTC 2017 [s]

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

$h \sim 10^{-6}$

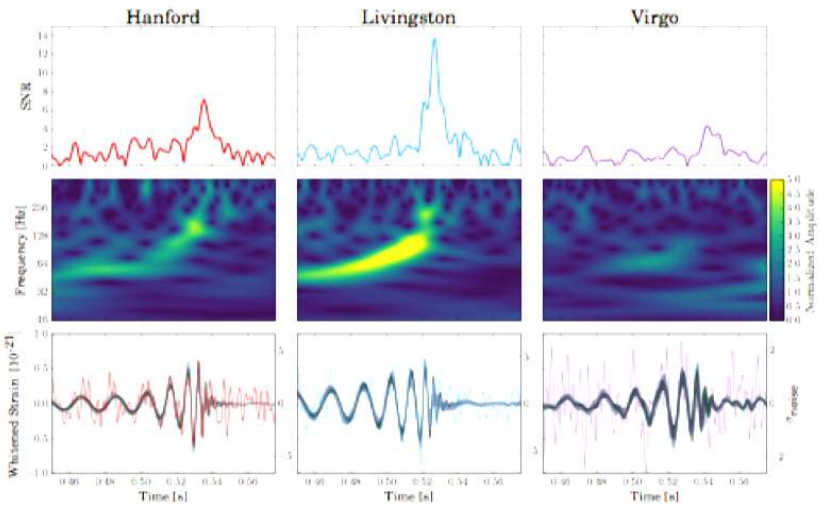
$I_g \sim 10^{25}$ w/m²

m1=23, m2= 13, Δm=1.5

m1=14.2, m2= 7.5, Δm=1

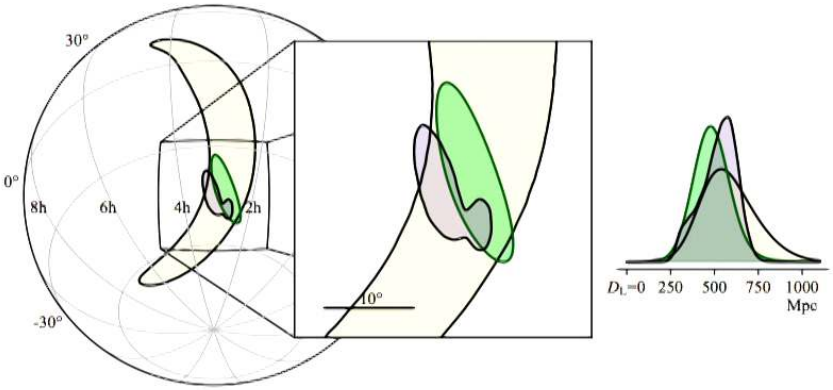
m1=31, m2= 19, Δm=2

masses in source frame



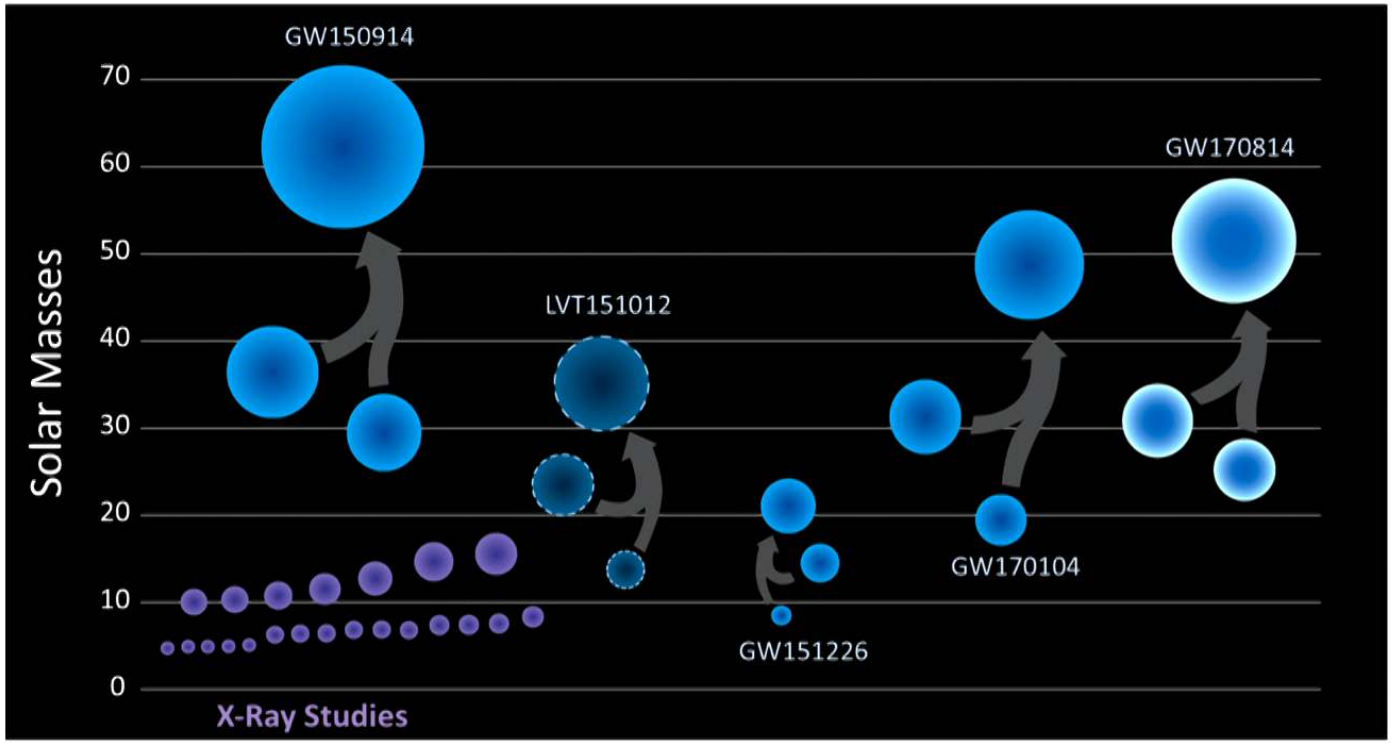
Triple coincidence
GW 170814

M_1 = 30
M_2 = 25
ΔM = 2.7

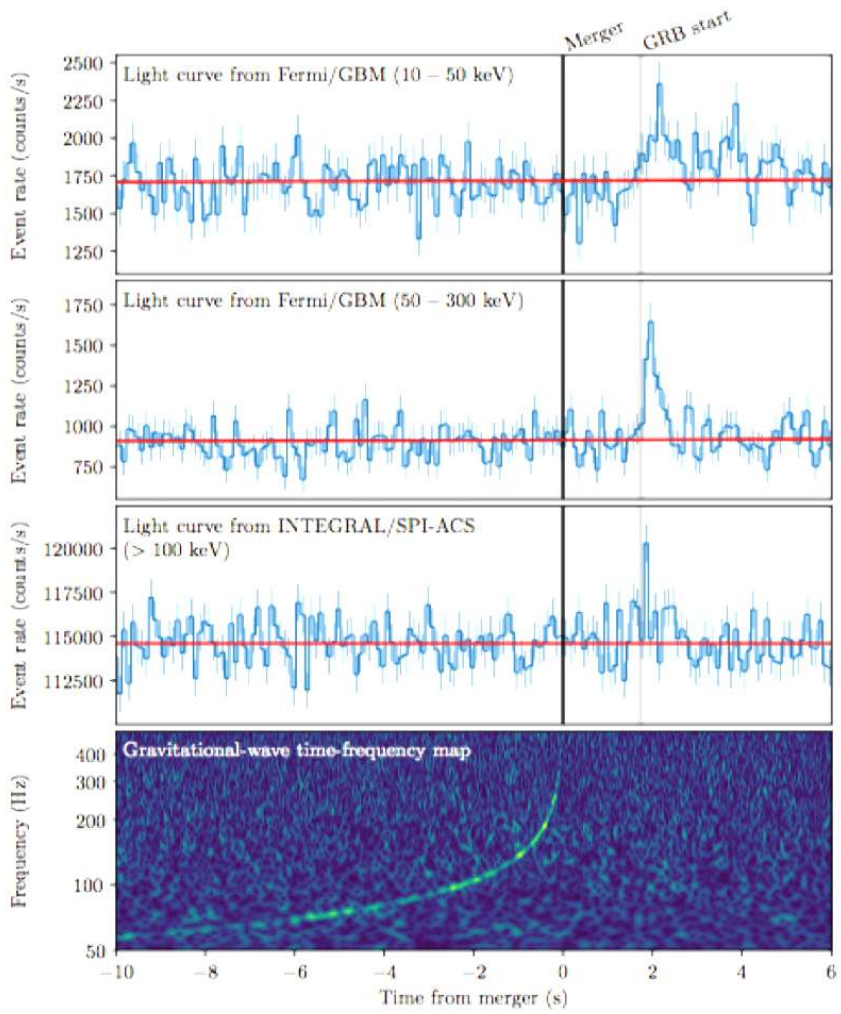


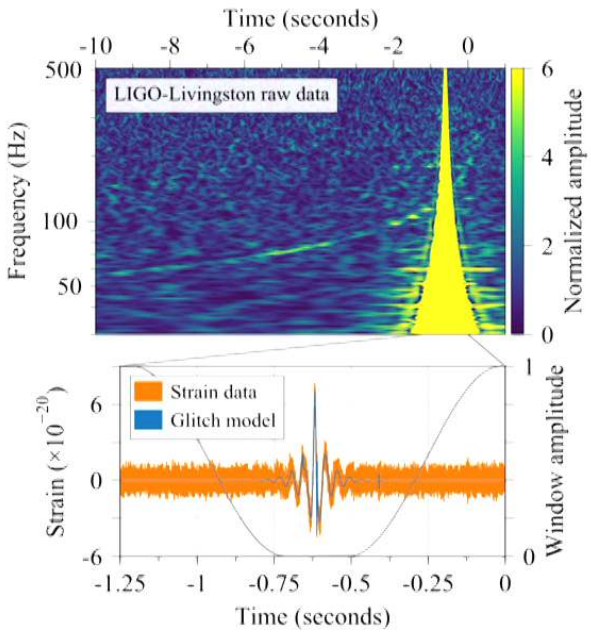
Localization on sky and distance

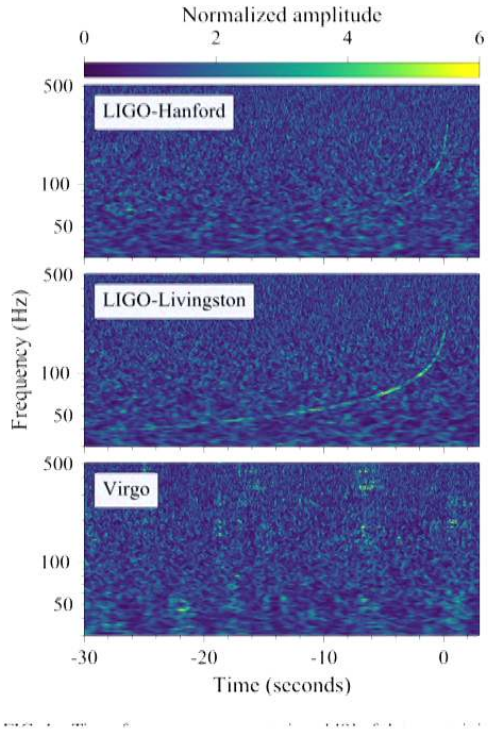
“Solar Mass” Black Holes

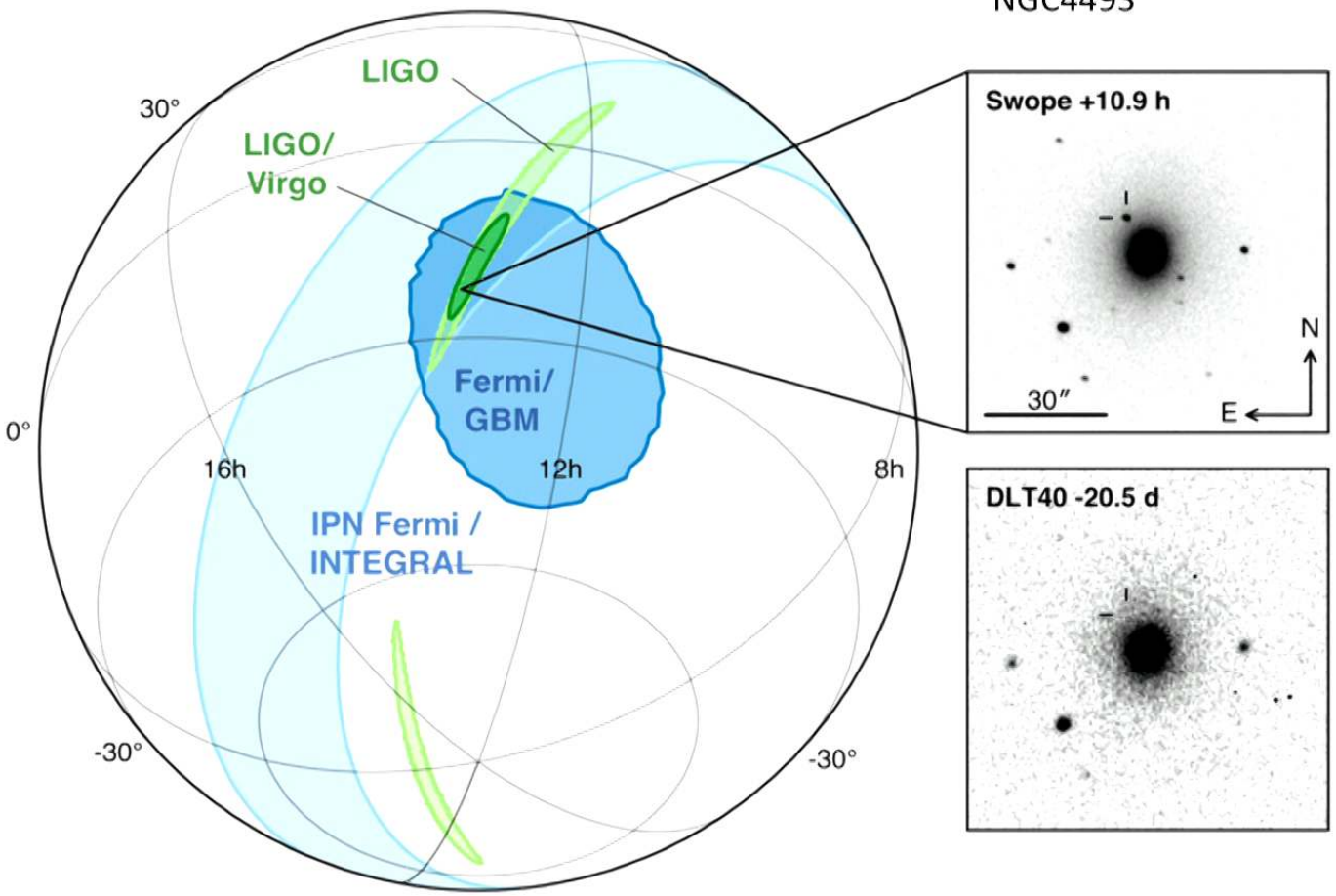


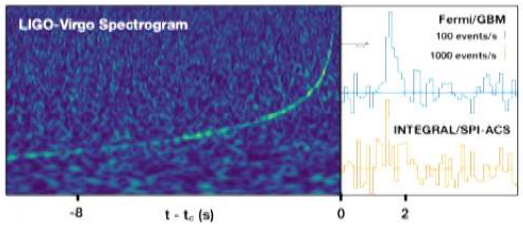
Credit: LIGO/Caltech/Sonoma State (Simonnet)

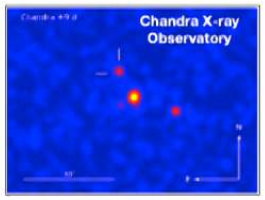

Merger
GRB start
Light curve from Fermi/GBM (10 – 50 keV)
Event rate (counts/s)
2500
2250
2000
1750
1500
1250
Light curve from Fermi/GBM (50 – 300 keV)
Event rate (counts/s)
1750
1500
1250
1000
750
Light curve from INTEGRAL/SPI-ACS
(> 100 keV)
Event rate (counts/s)
120000
117500
115000
112500
Gravitational-wave time-frequency map
Frequency (Hz)
400
300
200
100
50
−10
−8
−6
−4
−2
0
2
4
6
Time from merger (s)

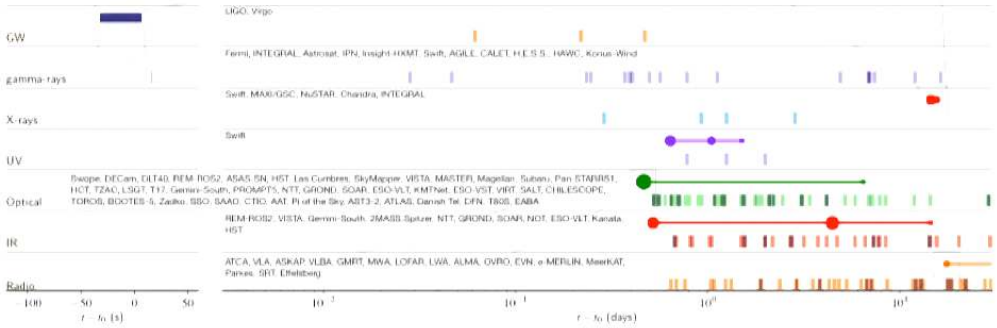

Time (seconds)
-10
-8
-6
-4
-2
0
500
100
50
Frequency (Hz)
LIGO-Livingston raw data
6
4
2
0
Normalized amplitude
Strain data
Glitch model
6
0
-6
Strain (×10^-20)
1
0
Window amplitude
-1.25
-1
-0.75
-0.5
-0.25
0
Time (seconds)

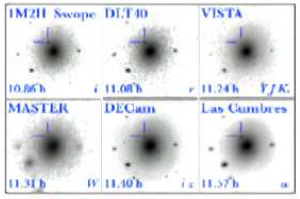

Normalized amplitude
0
2
4
6
LIGO-Hanford
LIGO-Livingston
Virgo
500
100
50
Frequency (Hz)
-30
-20
-10
0
Time (seconds)

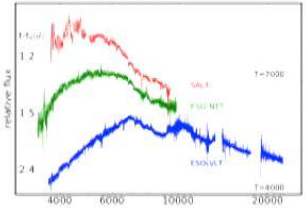

NGC4493
LIGO
LIGO/
Virgo
Fermi/
GBM
IPN Fermi /
INTEGRAL
30°
0°
-30°
16h
12h
8h
-30°
Swope +10.9 h
N
E
30″
DLT40 -20.5 d


LIGO-Virgo Spectrogram
Fermi/GBM
100 events/s
1000 events/s
INTEGRAL/SPI-ACS
-8
t - t0 (s)
0
2

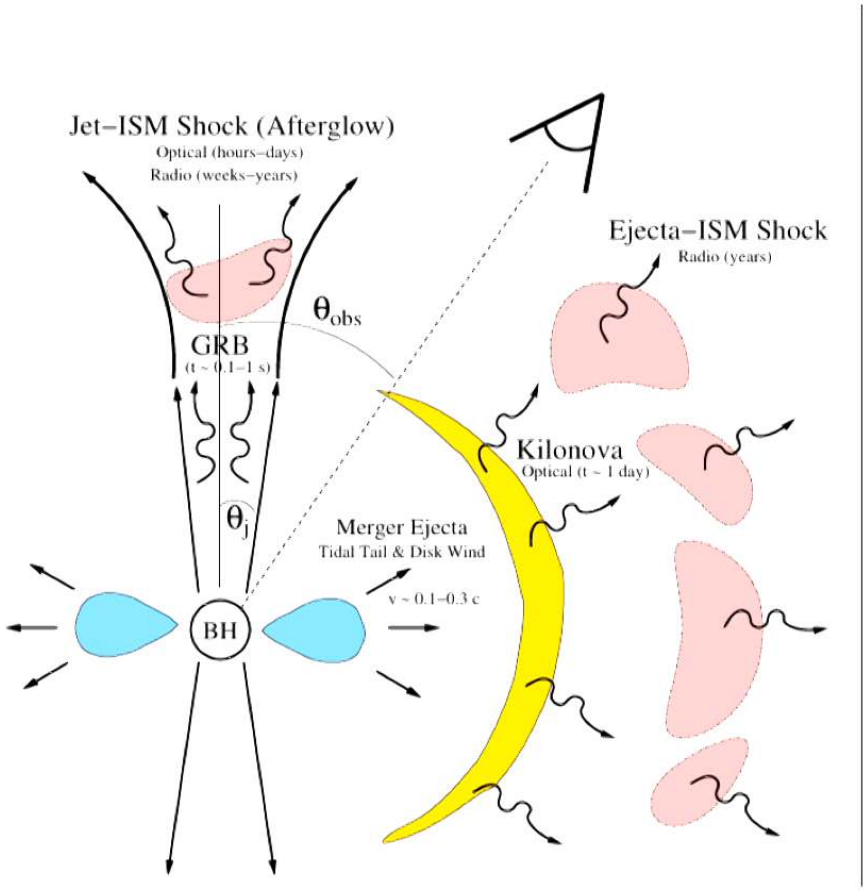

Chandra X-ray
Observatory


GW
gamma-rays
X-rays
UV
Optical
IR
Radio
LIGO, Virgo
Fermi, INTEGRAL, Agile, IPN, Insight-HXMT, Swift, AGILE, CALET, H.E.S.S., HAWC, Konus-Wind
Swift, MAXI/GSC, NuSTAR, Chandra, INTEGRAL
Swift
Swope, DECam, DLT40, REM-ROSS, ASAS-SN, HST, Las Cumbres, SkyMapper, VISTA, MASTER, Magellan, Subaru, Pan-STARRS1, HCT, TZAC, LSGT, T17, Gemini-South, PROMPT5, NTT, GROND, SOAR, ESO-VLT, KMTNet, ESO-VST, VIRT, SALT, CHILESCOPE, TOROS, BOOTES-5, Zadko, SSO, SAAO, CTIO, AAT, Pi of the Sky, AST3-2, ATLAS, Danish Tel, DFN, T80S, EABA
REM-ROSS, VISTA, Gemini-South, 2MASS,Spitzer, NTT, GROND, SOAR, NOT, ESO-VLT,Kanata, HST
ATCA, VLA, ASKAP, VLBA, GMRT, MWA, LOFAR, LWA, ALMA, OVRO, EVN, e-MERLIN, MeerKAT, Parkes, SRT, Effelsberg
100
50
0
50
t - t0 (s)
10^-2
10^-1
10^0
10^1
t - t0 (days)

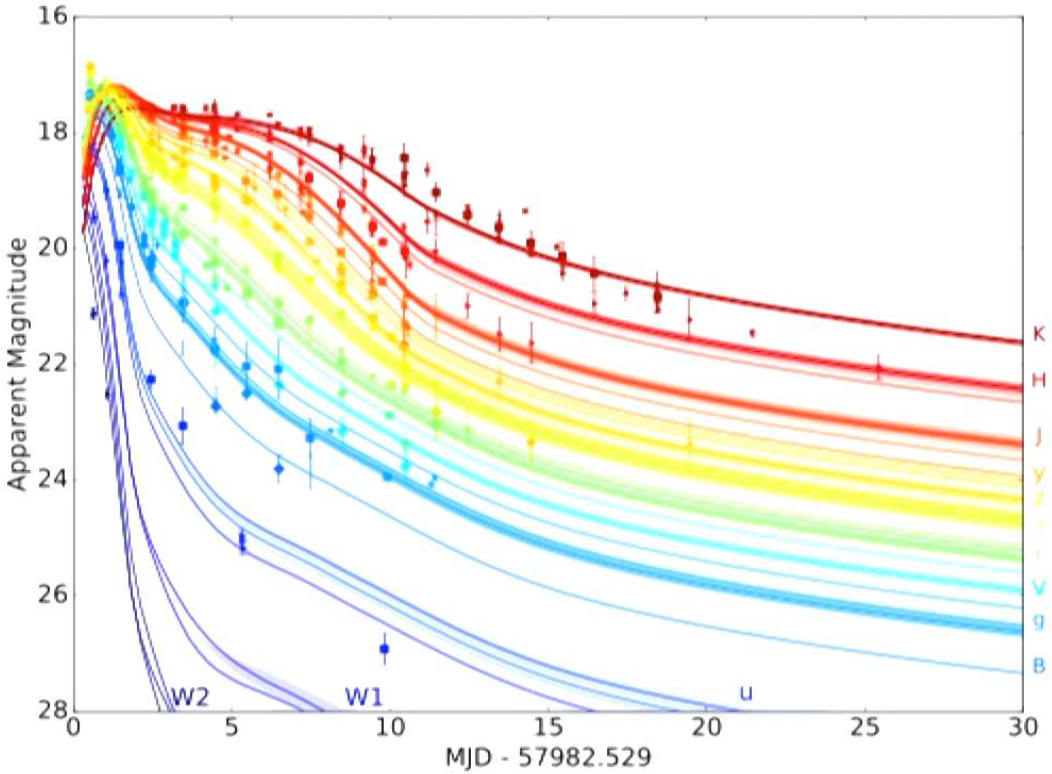

1M2H Swope
DLT40
VISTA
10.86 h
11.08 h
11.24 h
MASTER
DECam
Las Cumbres
11.31 h
11.40 h
11.57 h


relative flux
1.2
1.5
2.4
4000
6000
10000
20000

Jansky Very Large Array
Radio

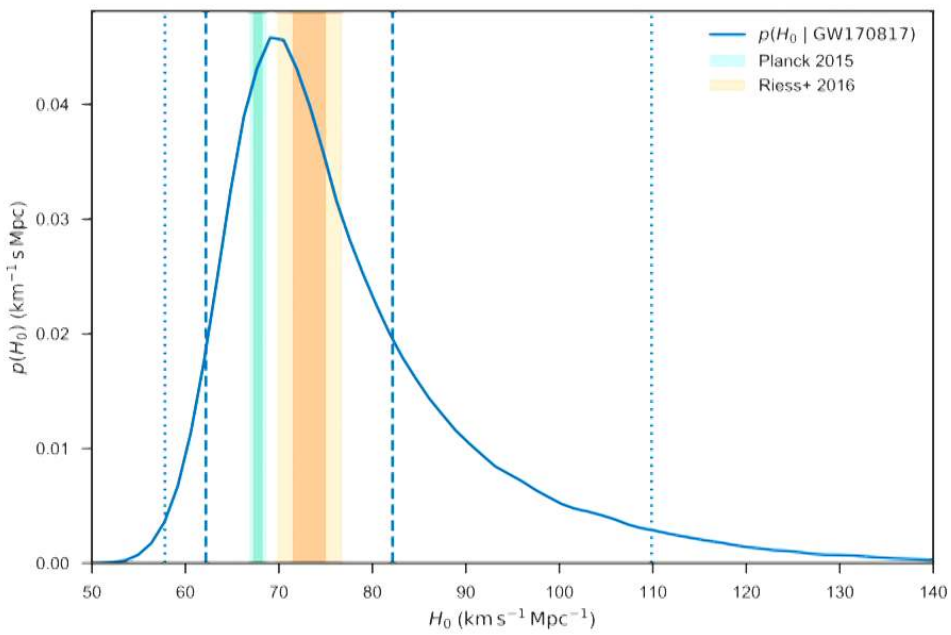

Jet–ISM Shock (Afterglow)
Optical (hours–days)
Radio (weeks–years)
Ejecta–ISM Shock
Radio (years)
θobs
GRB
(t ~ 0.1–1 s)
Kilonova
Optical (t ~ 1 day)
θj
Merger Ejecta
Tidal Tail & Disk Wind
v ~ 0.1–0.3 c
BH

Broad band kilonova spectra vs time



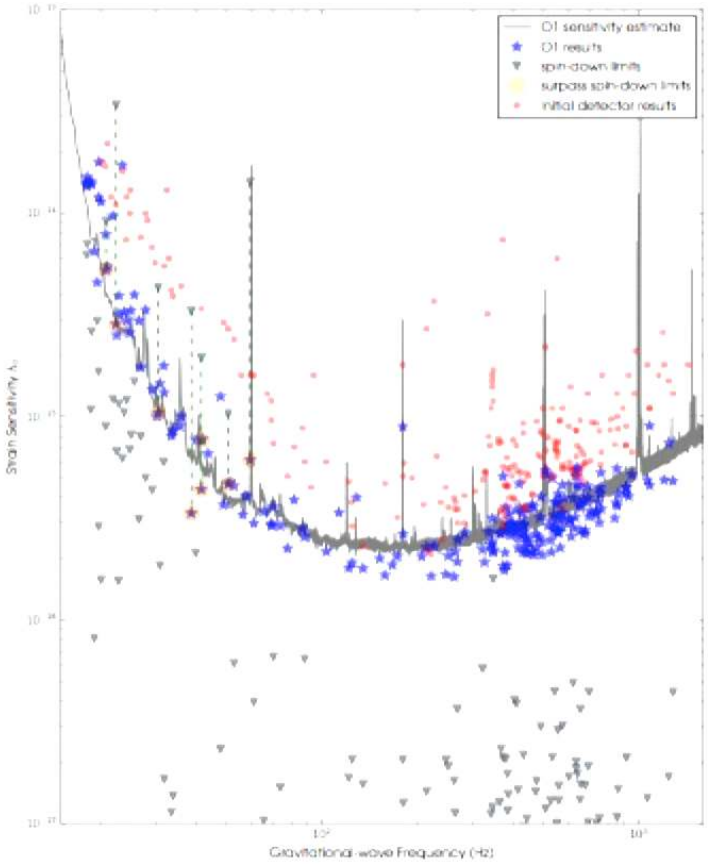
Villar et al arXiv astroph 1710.11576

Hubble constant measurement: Galaxy z and distance from GW amplitude

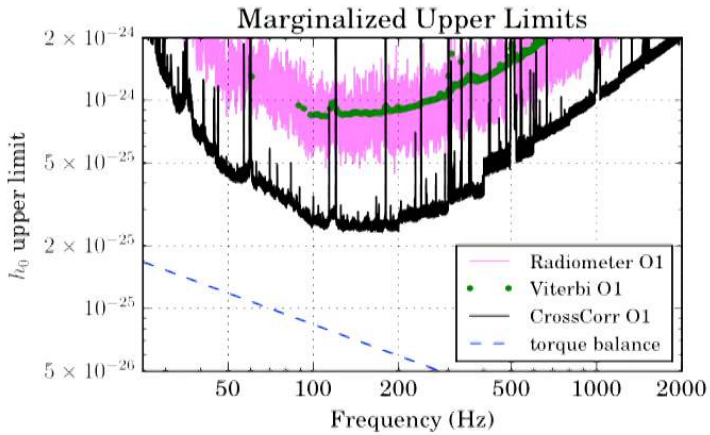


Classes of sources and searches

- 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



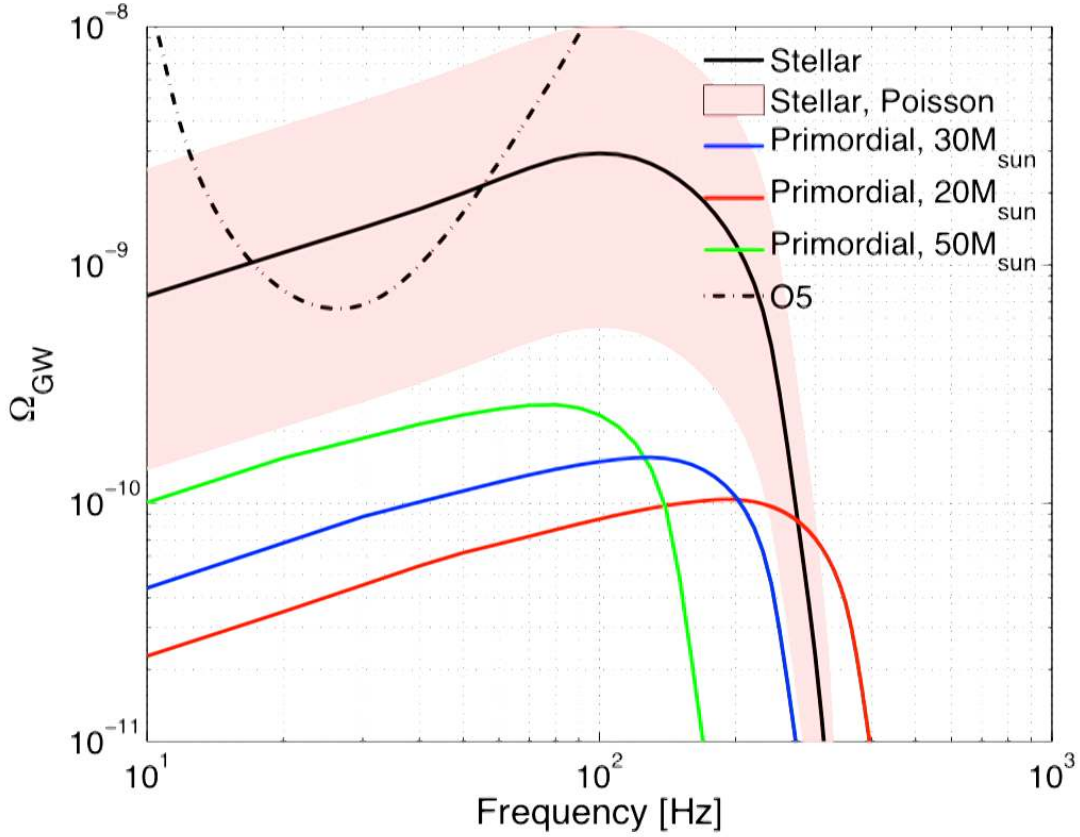
CW search periodic sources



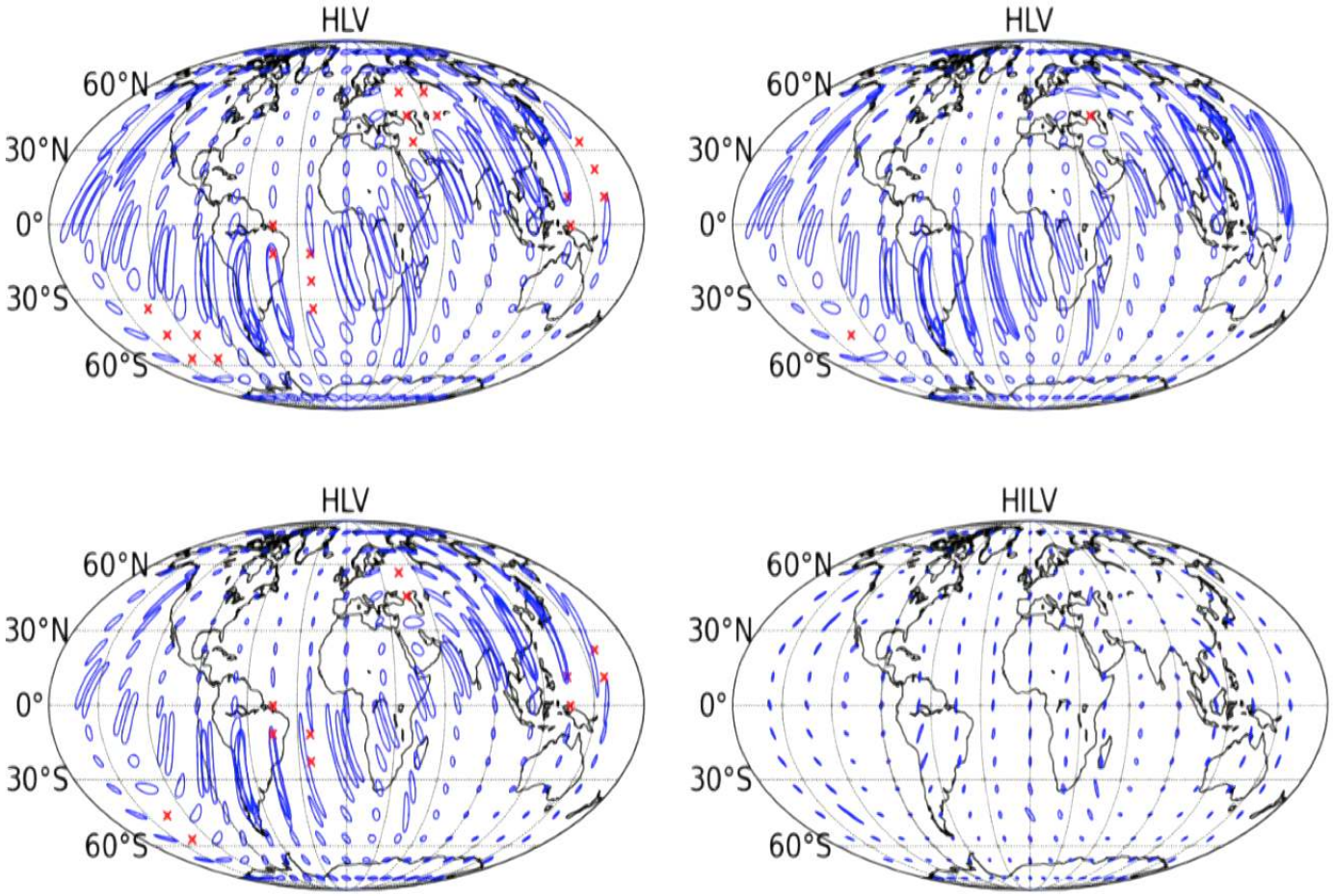
CW radiometer search
Scorpius X1

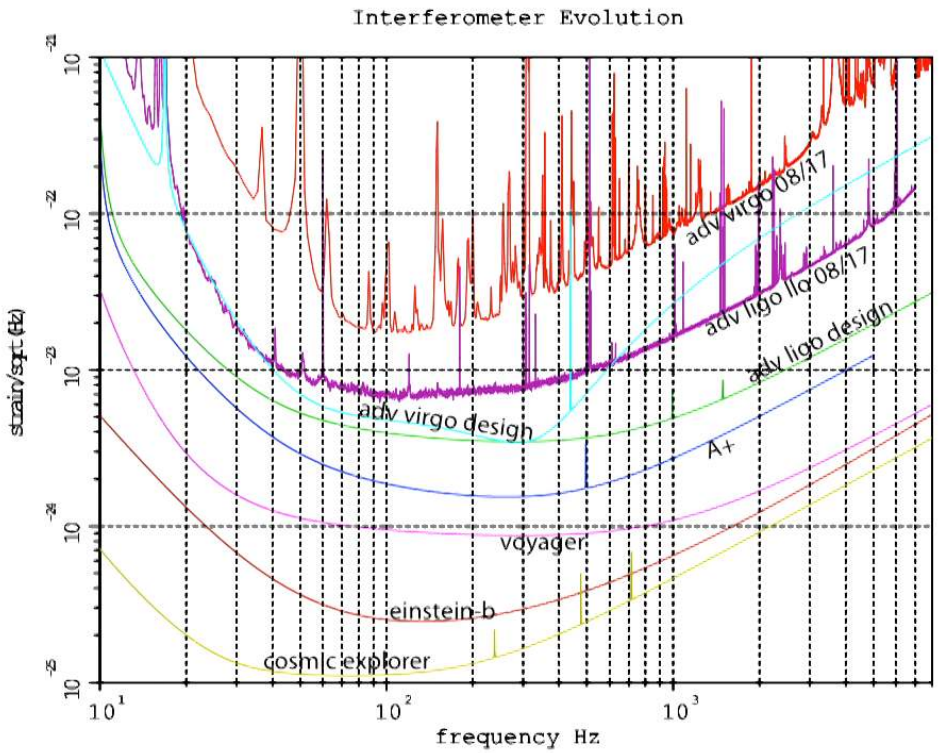
K. Riles preprint

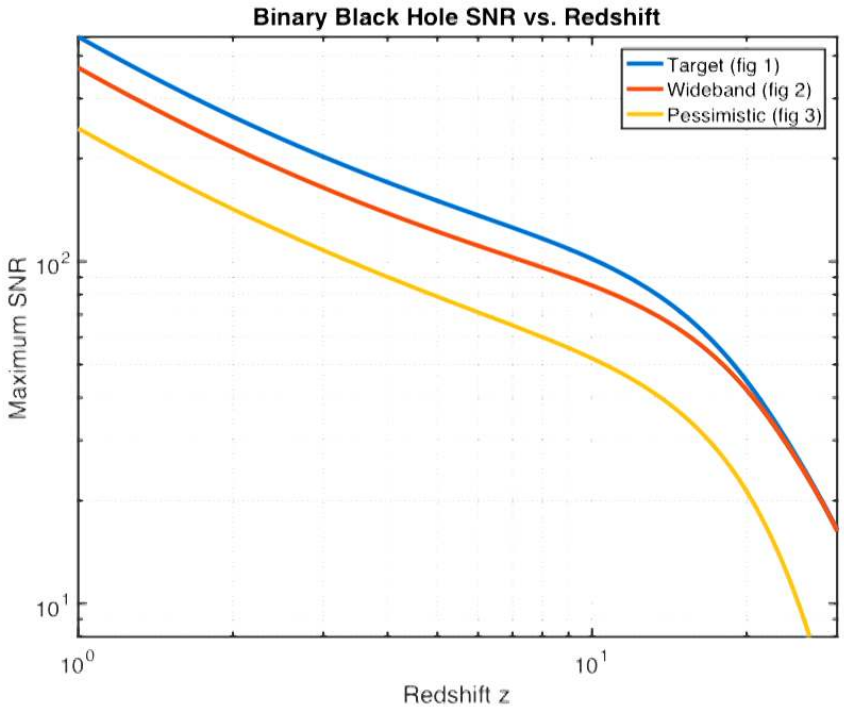
stochastic background of PBHs



(Mandic et al. 2017)

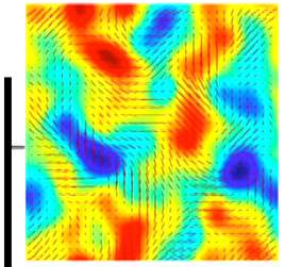

HLV
60°N
30°N
0°
30°S
60°S
HLV
60°N
30°N
0°
30°S
60°S
HLV
60°N
30°N
0°
30°S
60°S
HILV
60°N
30°N
0°
30°S
60°S


Interferometer Evolution
strain/sqrt(Hz)
frequency Hz
adv virgo 08/17
adv ligo llo 08/17
adv ligo design
adv virgo design
A+
voyager
einstein-b
cosmic explorer


Binary Black Hole SNR vs. Redshift
Target (fig 1)
Wideband (fig 2)
Pessimistic (fig 3)
Maximum SNR
10^2
10^1
10^0
10^1
Redshift z

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

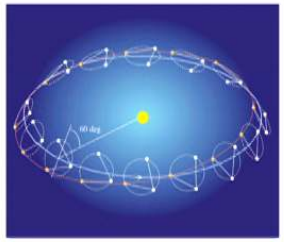
Isotropic GW background from unresolved sources

Massive BH coalescences

Small mass/BH infalls

White dwarf binaries in our galaxy

Space-based Interferometers



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