Title: Probing the Universe with Gravitational Waves

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Abstract: <p>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.</p>

Probing the universe with gravitational waves

Rainer Weiss, MIT on behalf of
The LIGO Scientific Collaboration

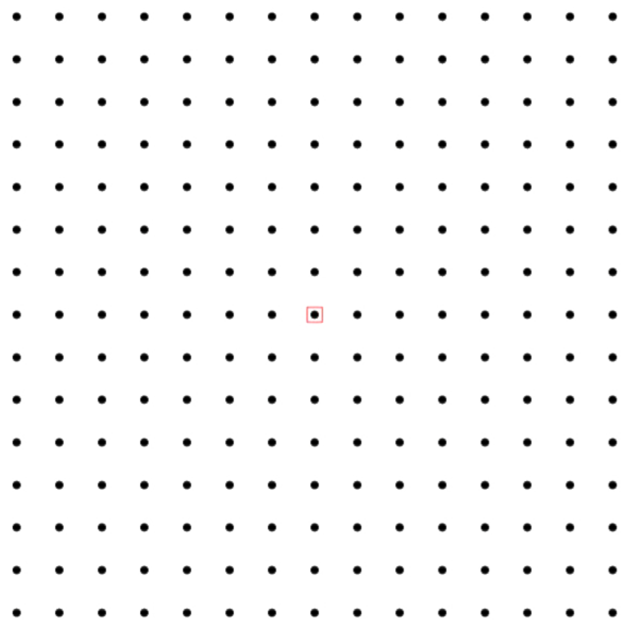
Perimeter Institute Colloquium

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."

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

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

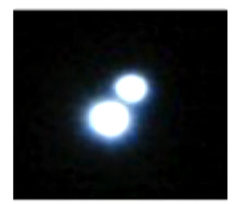
1916 examples: train colllision

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

binary star decay

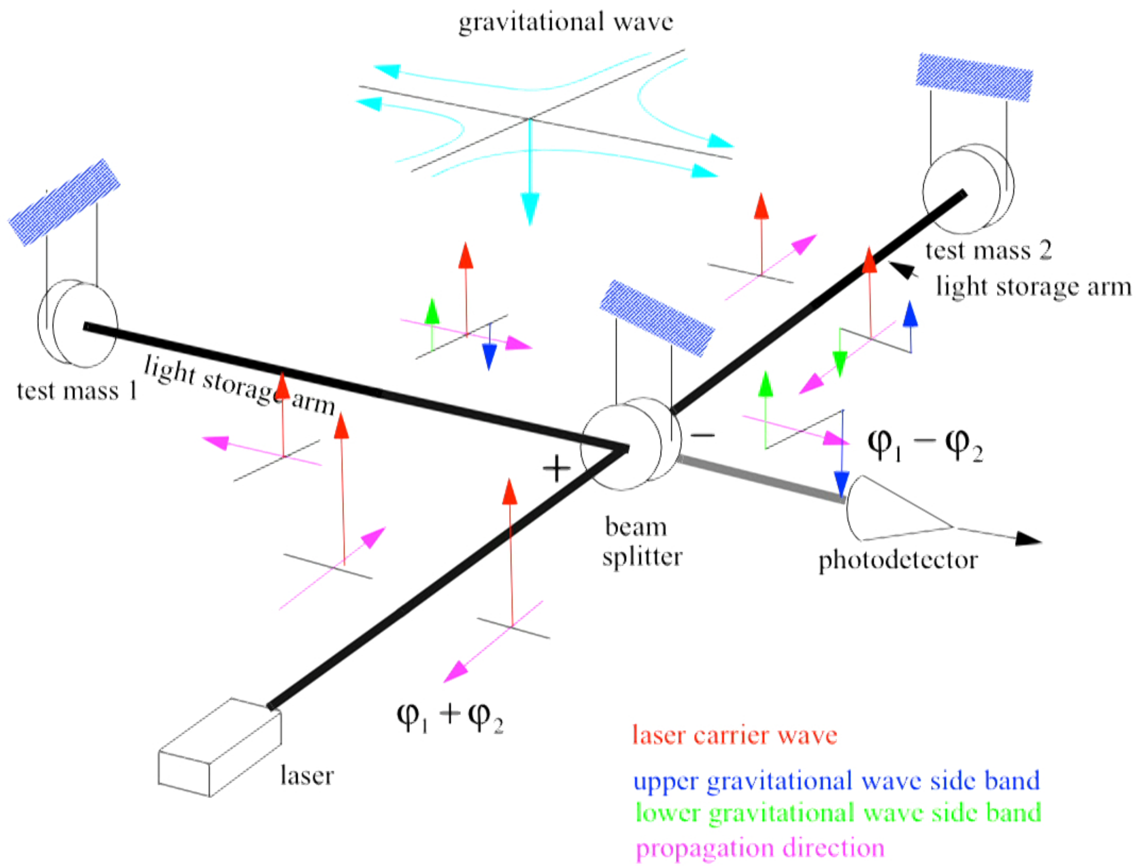
$m_1 = m_2$ = 1 solar mass
T_{orbit} = 1 day
R = 10 Kly

$h \sim 10^{-23}$ @ 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

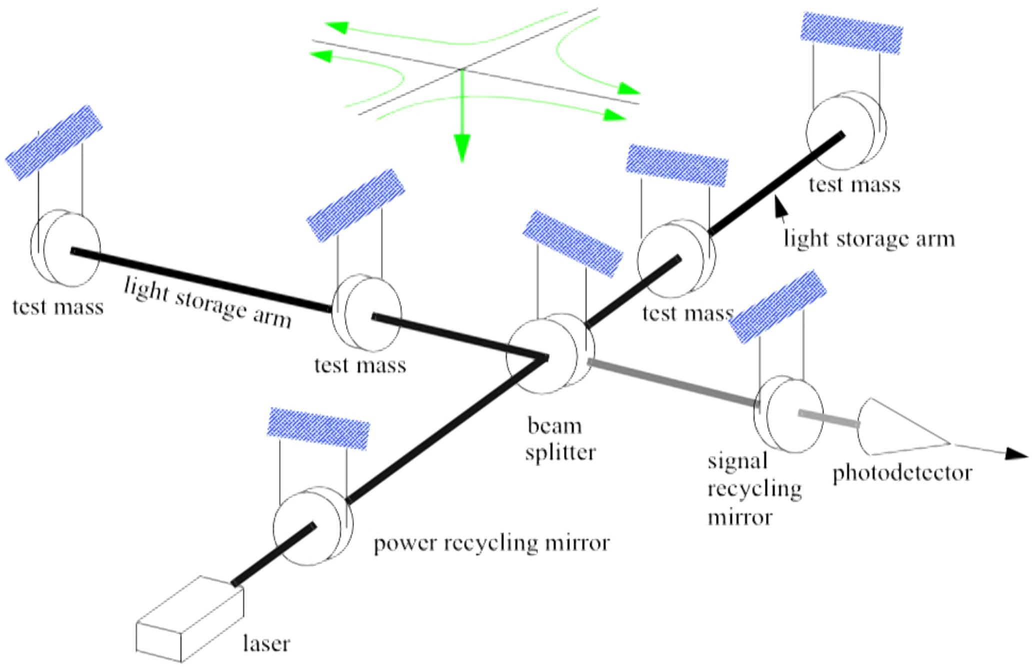
$$h = \frac{\Delta L}{L} \leq 10^{-21}$$

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

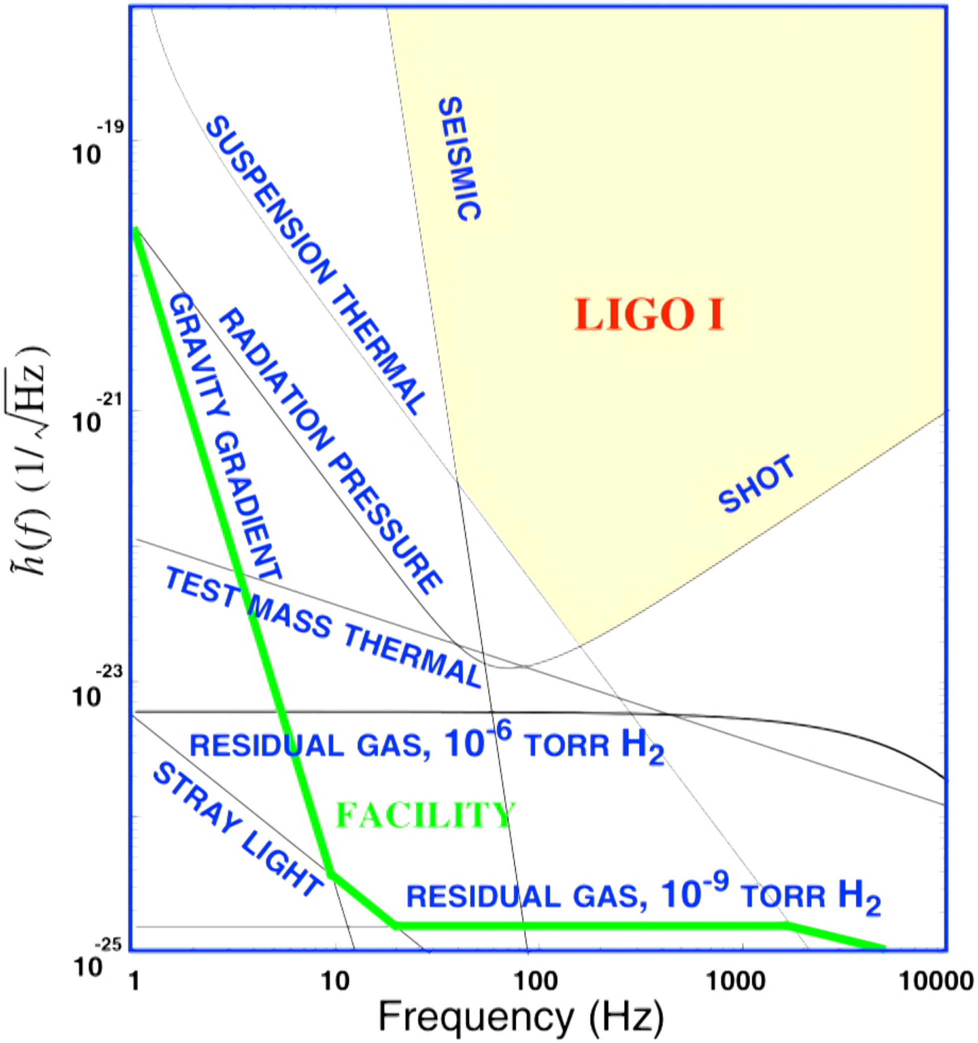
$$\Delta L \sim 10^{-12}\,\text{wavelength of light}$$

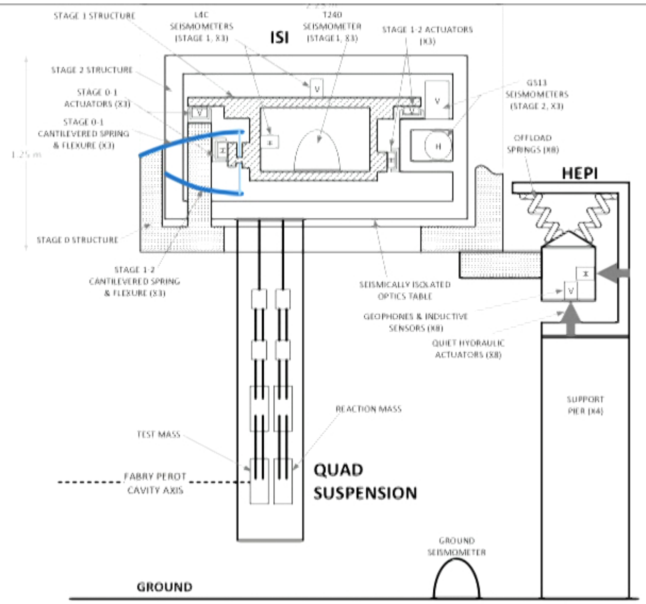
$$\Delta L \sim 10^{-12}\,\text{vibrations at earth's surface}$$

Advanced LIGO Fabry-Perot Michelson Interferometer Schematic

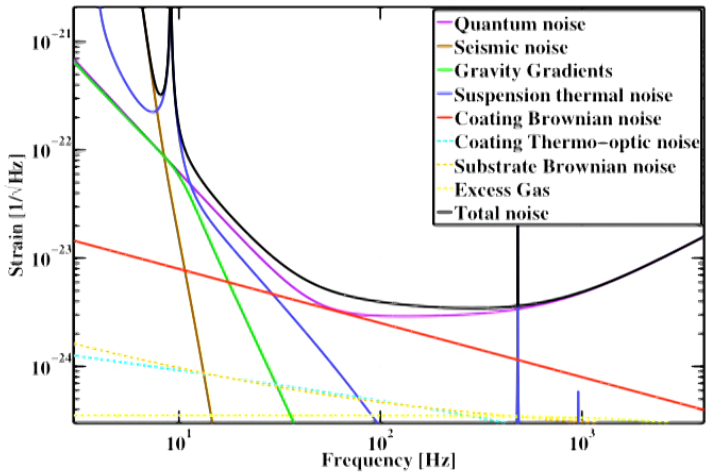


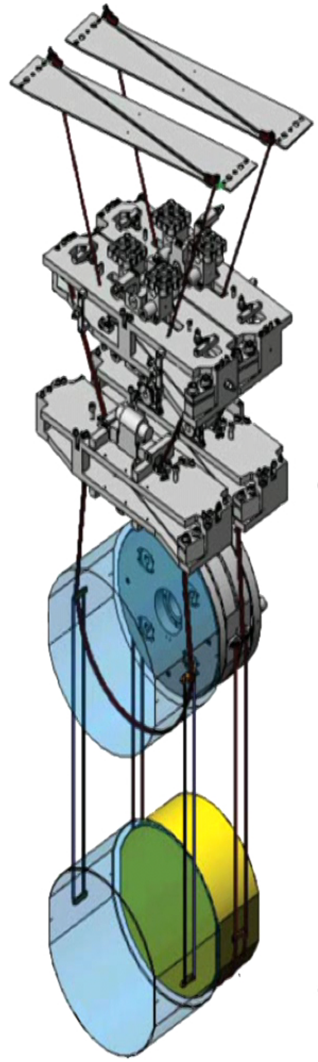
Initial LIGO Interferometer Noise Budget

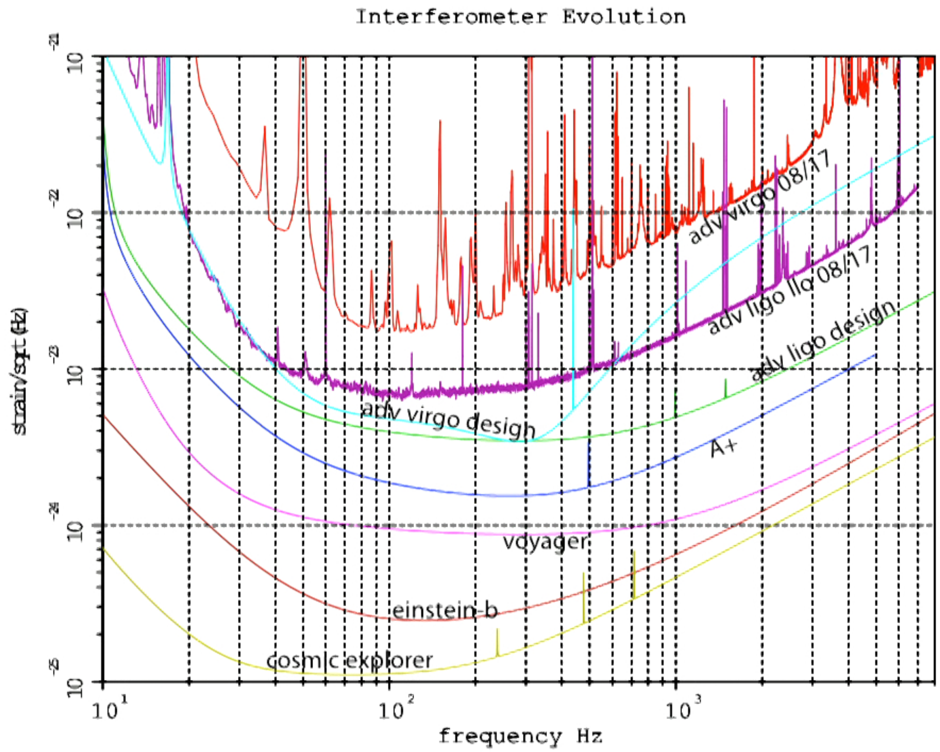


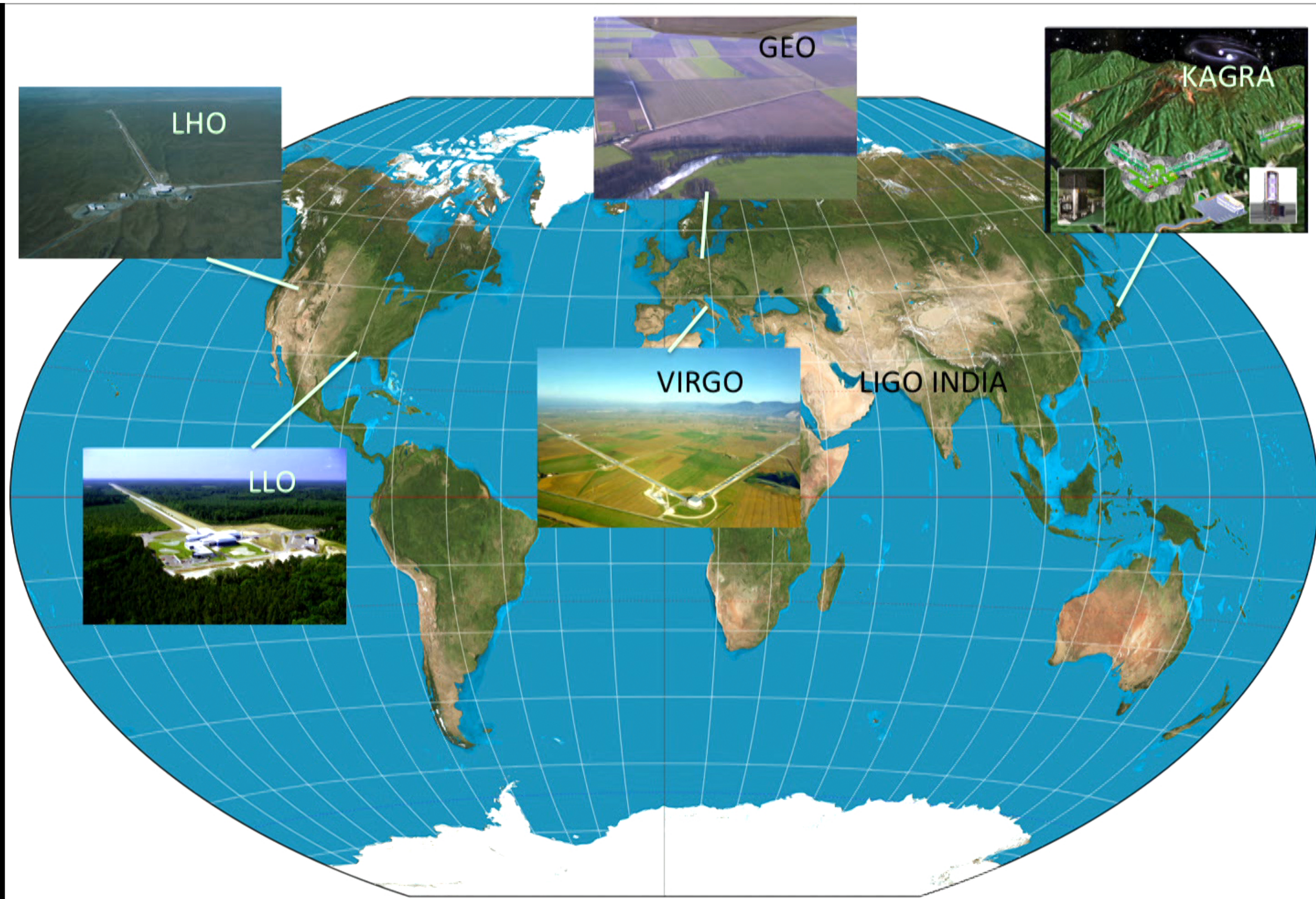


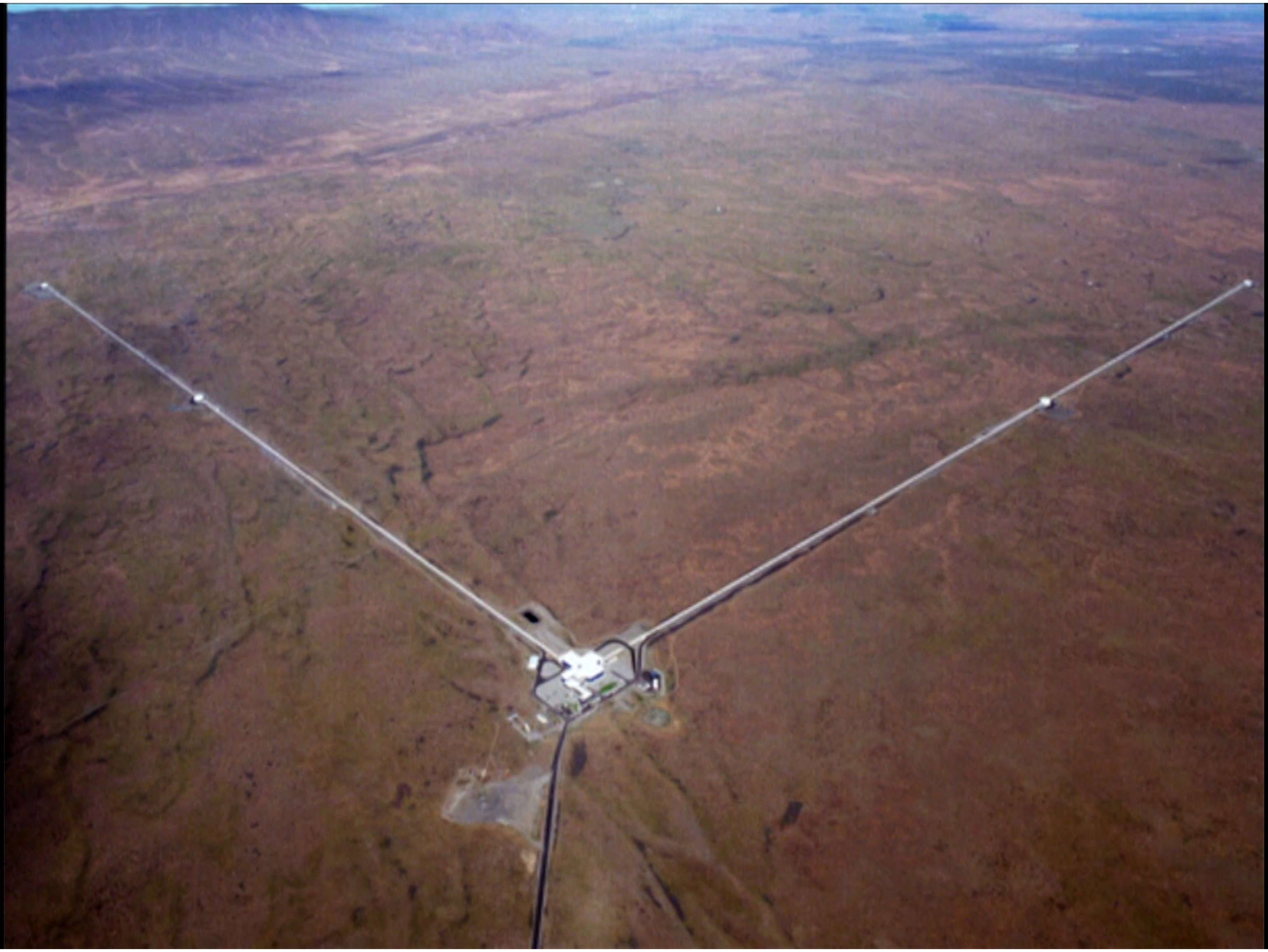
Advanced LIGO design noise budget





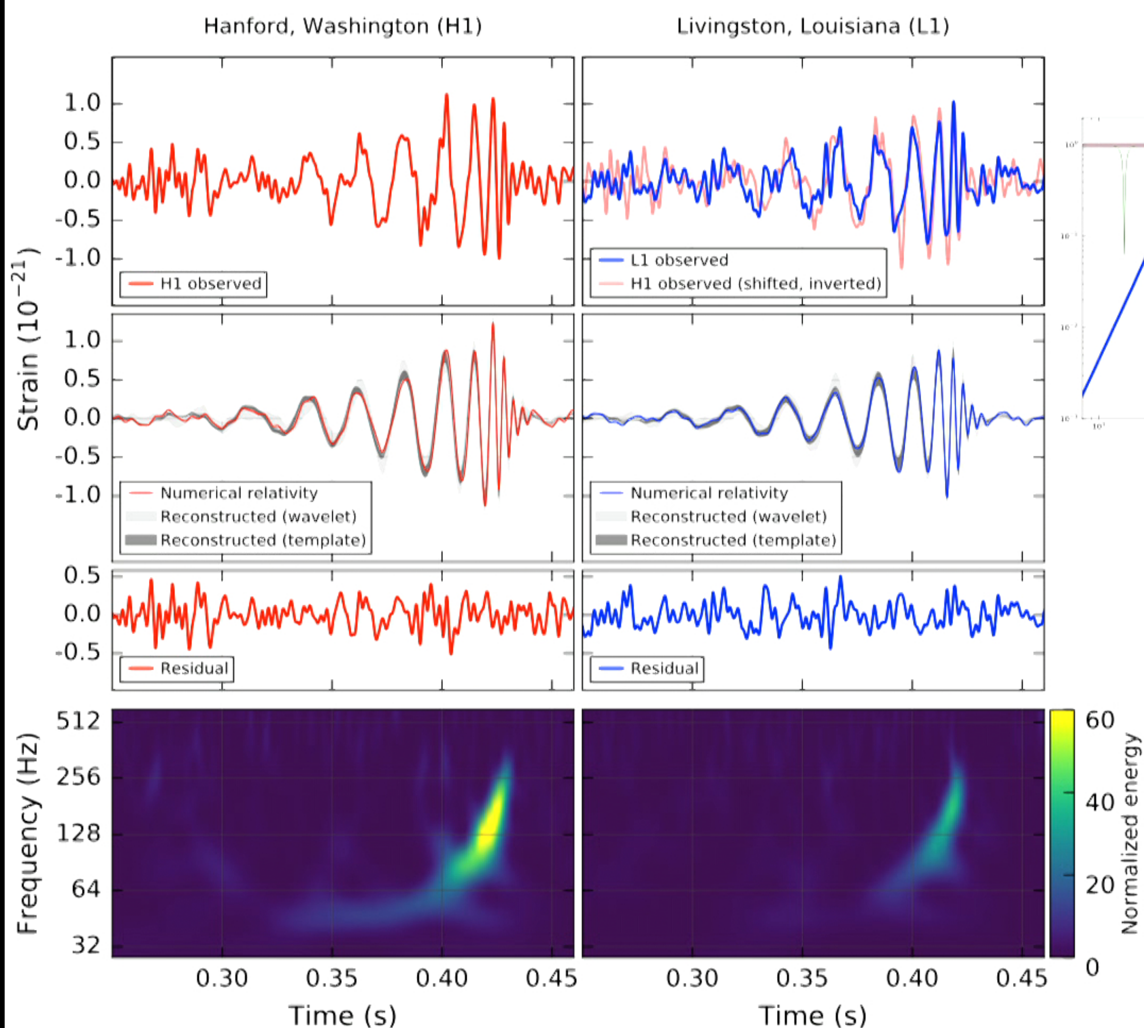

Interferometer Evolution
strain/sqrt(Hz)
frequency Hz
adv virgo 08/17
adv ligo llo 08/17
adv ligo design
adv virgo design
A+
voyager
einstein b
cosmic explorer

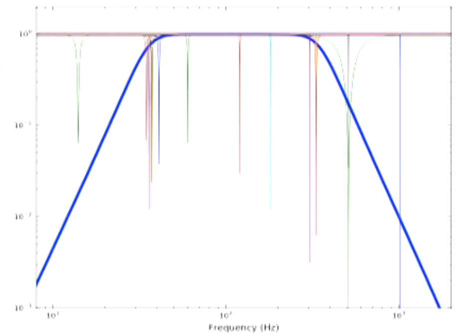

GEO
KAGRA
LHO
VIRGO
LIGO INDIA
LLO



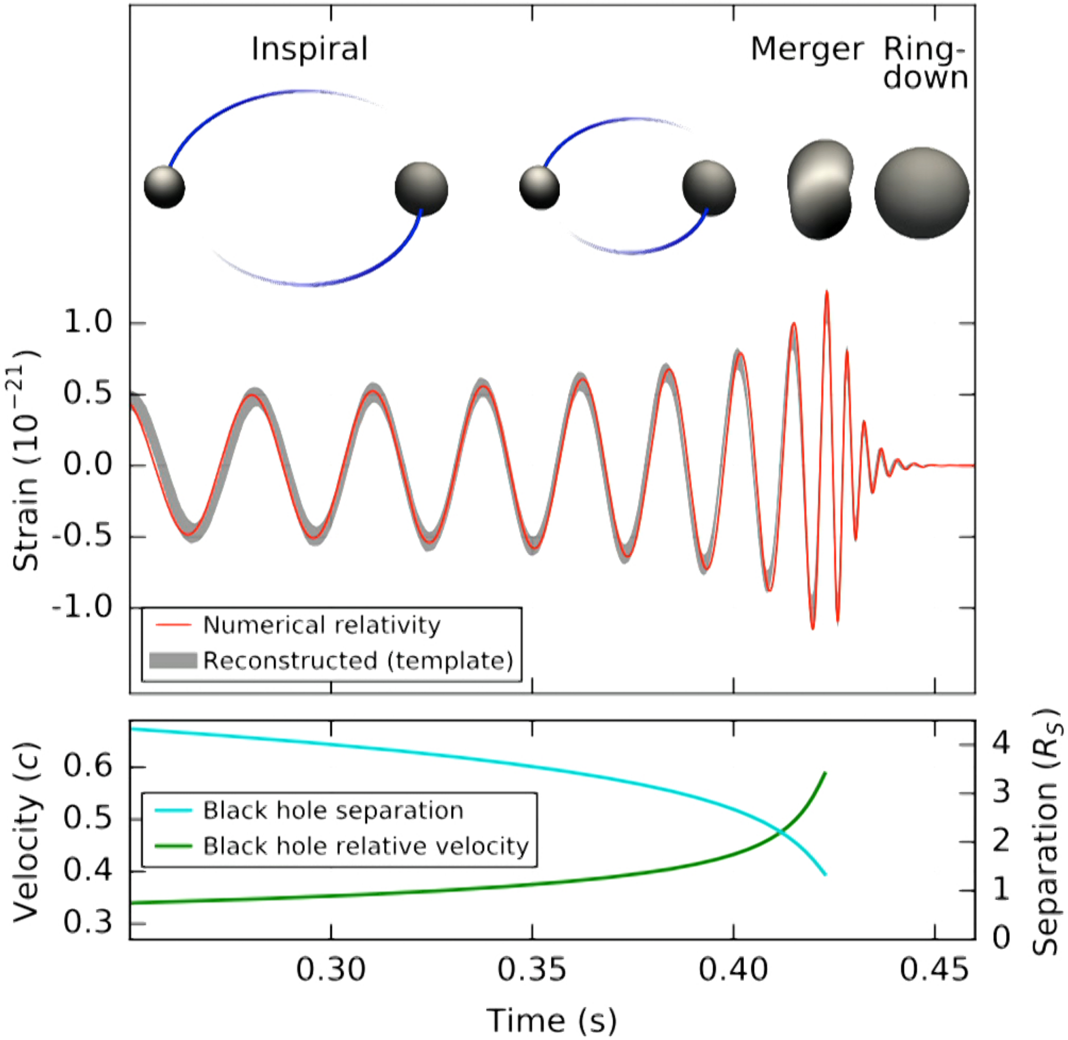
Criteria for transient detection

- 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



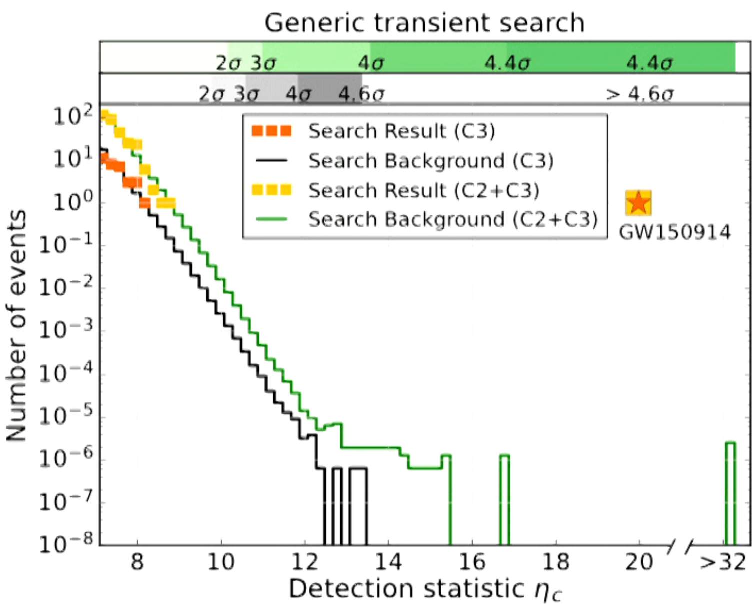


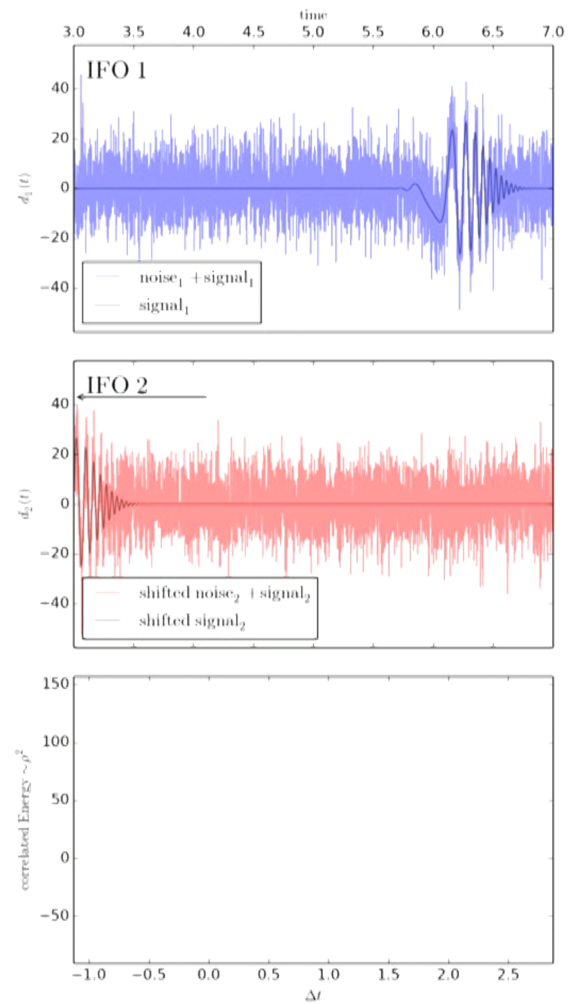
Simple high-low pass
filter with notches


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

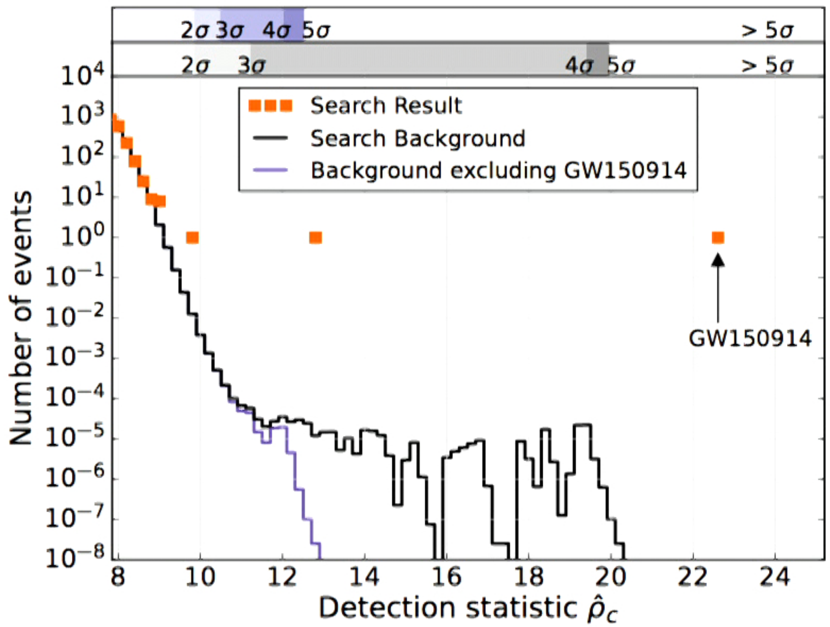
R.Essik

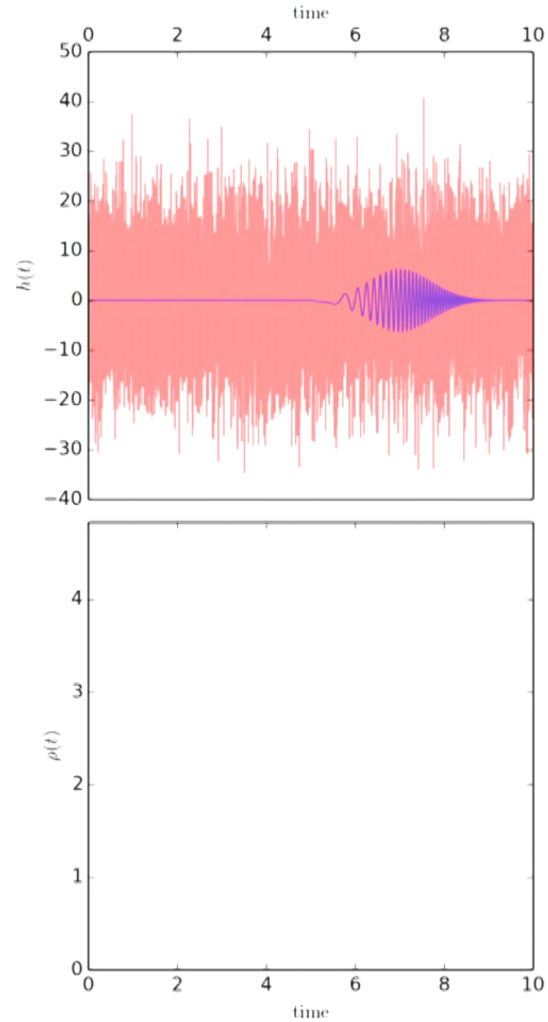




R.Essik

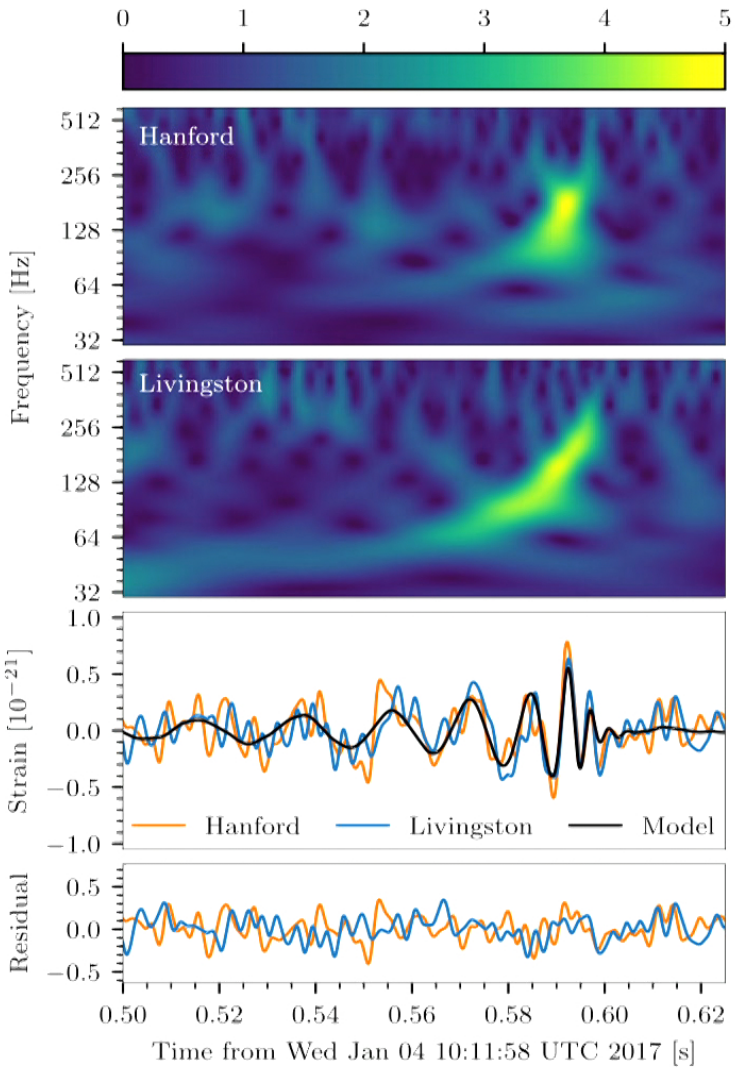
Modeled search followed by χ^2 cut



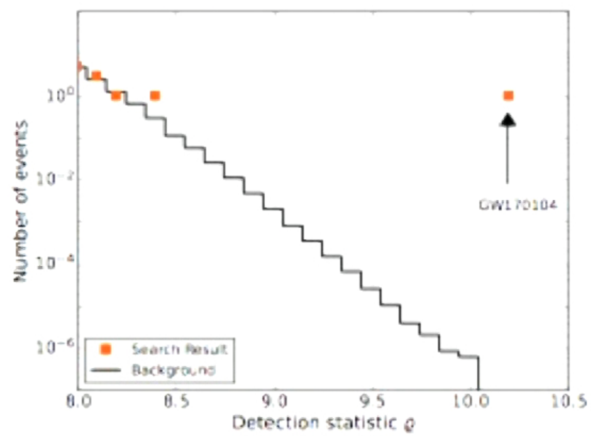


False alarm rate from time slides

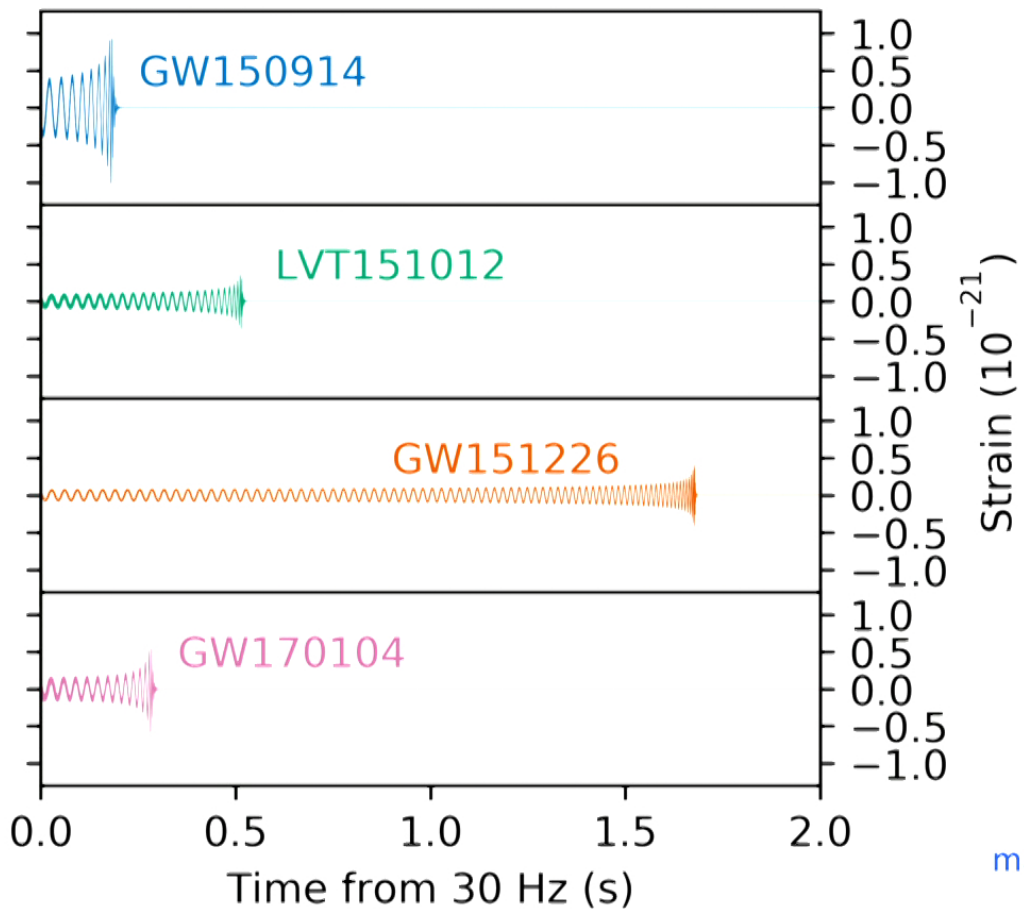
$$R = \frac{t_{corr}}{\tau_{total}^2} = \frac{1}{N_{ind}\tau_{total}}$$


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
0.5
0.0
−0.5
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
10^{0}
10^{-2}
10^{-4}
10^{-6}
GW170104
Search Result
Background
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}

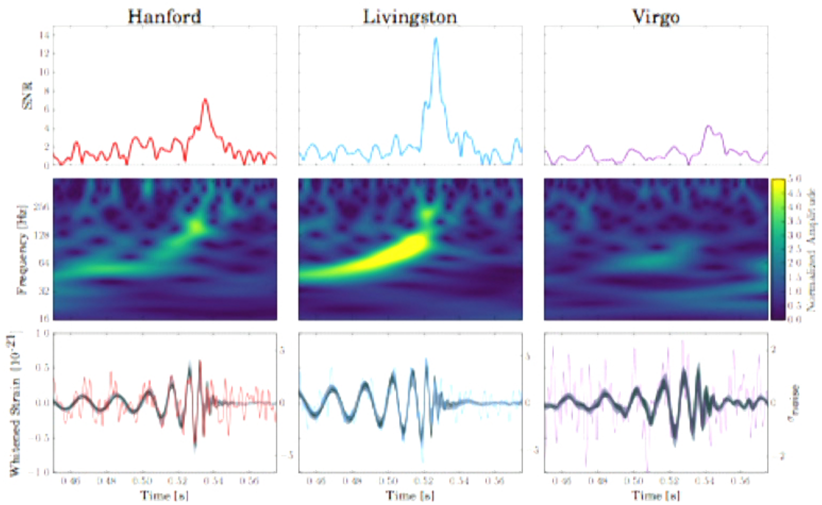
I_g~ 10^{25} w/m^2

m1=23, m2= 13, Δm=1.5

m1=14.2, m2= 7.5, Δm=1

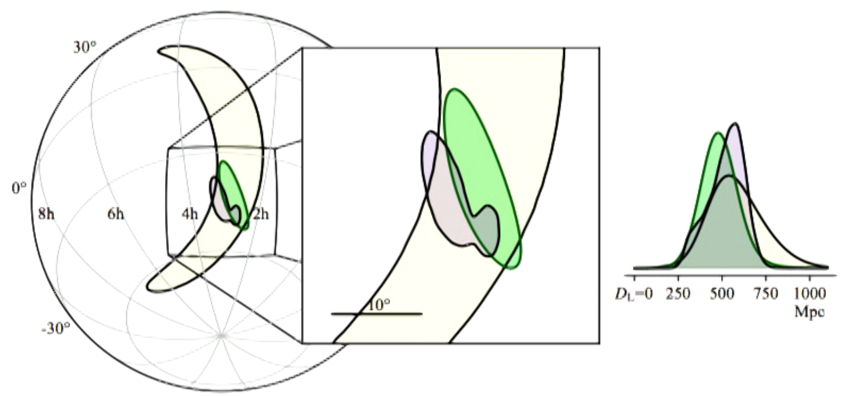
m1=31, m2= 19, Δm=2

masses in source frame



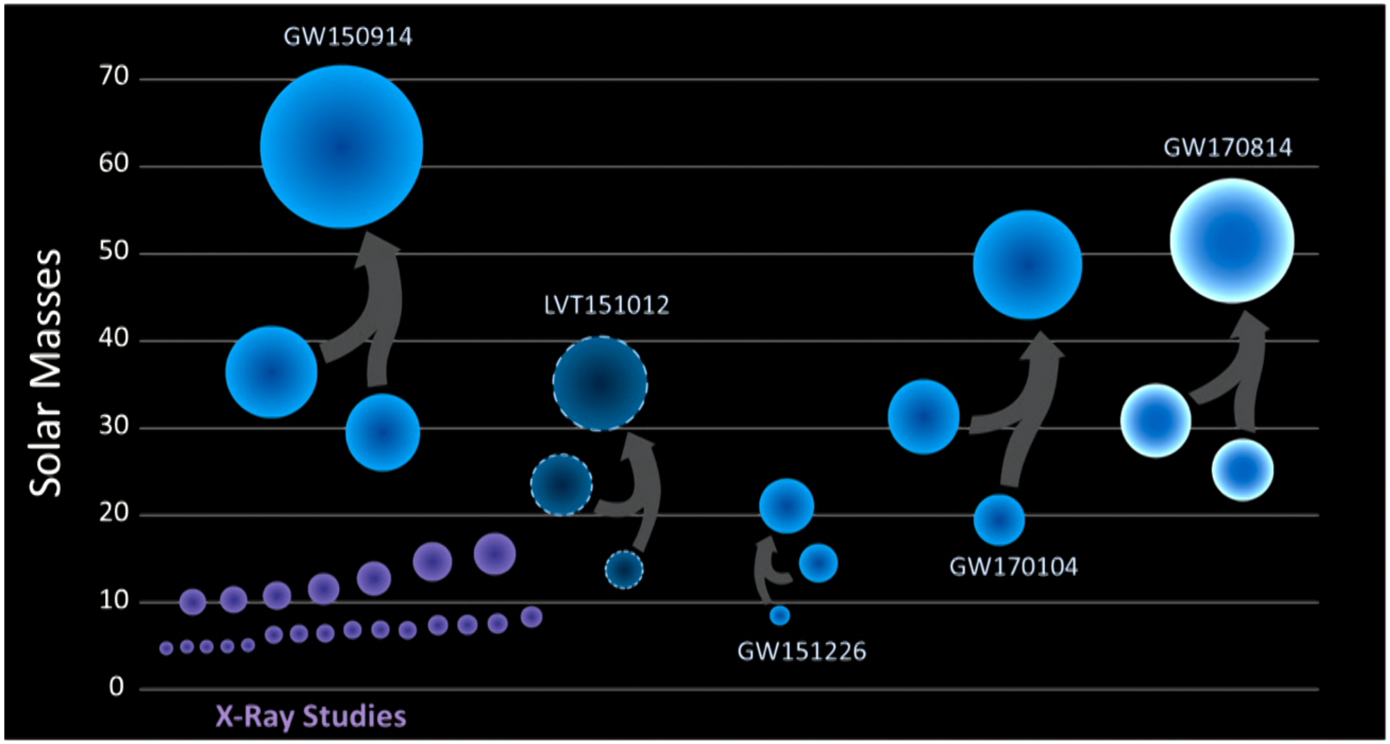
Triple coincidence
GW 170814

M_1 = 30
M_2 = 25
ΔM = 2.7

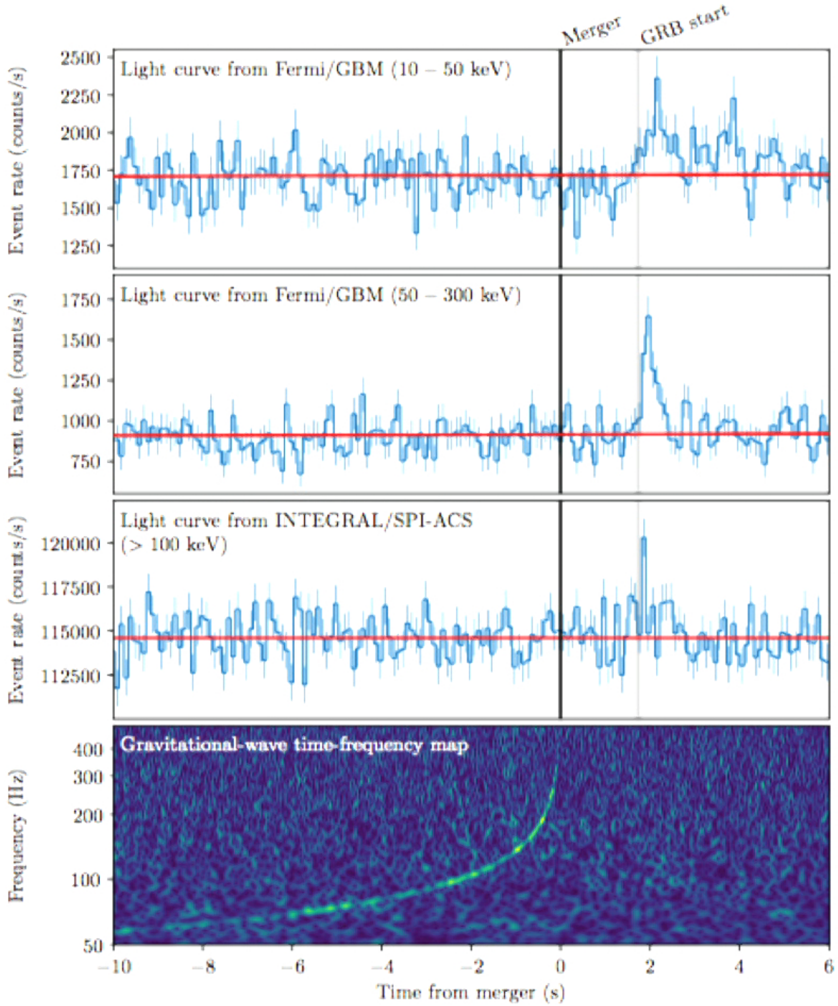


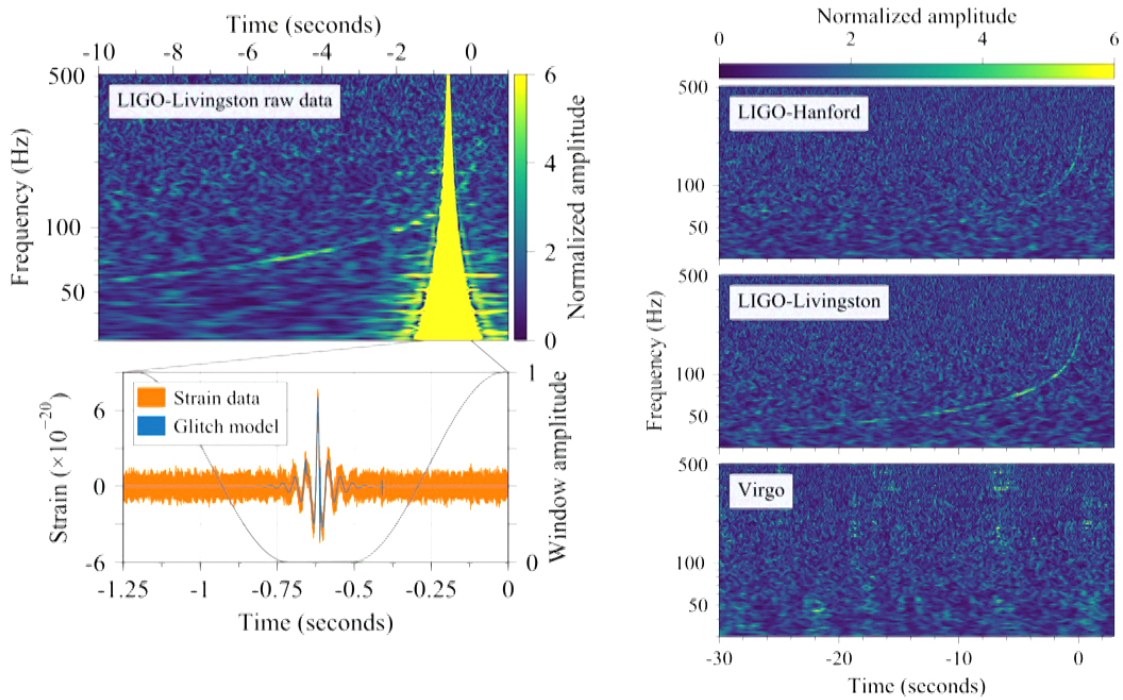
Localization on sky and distance

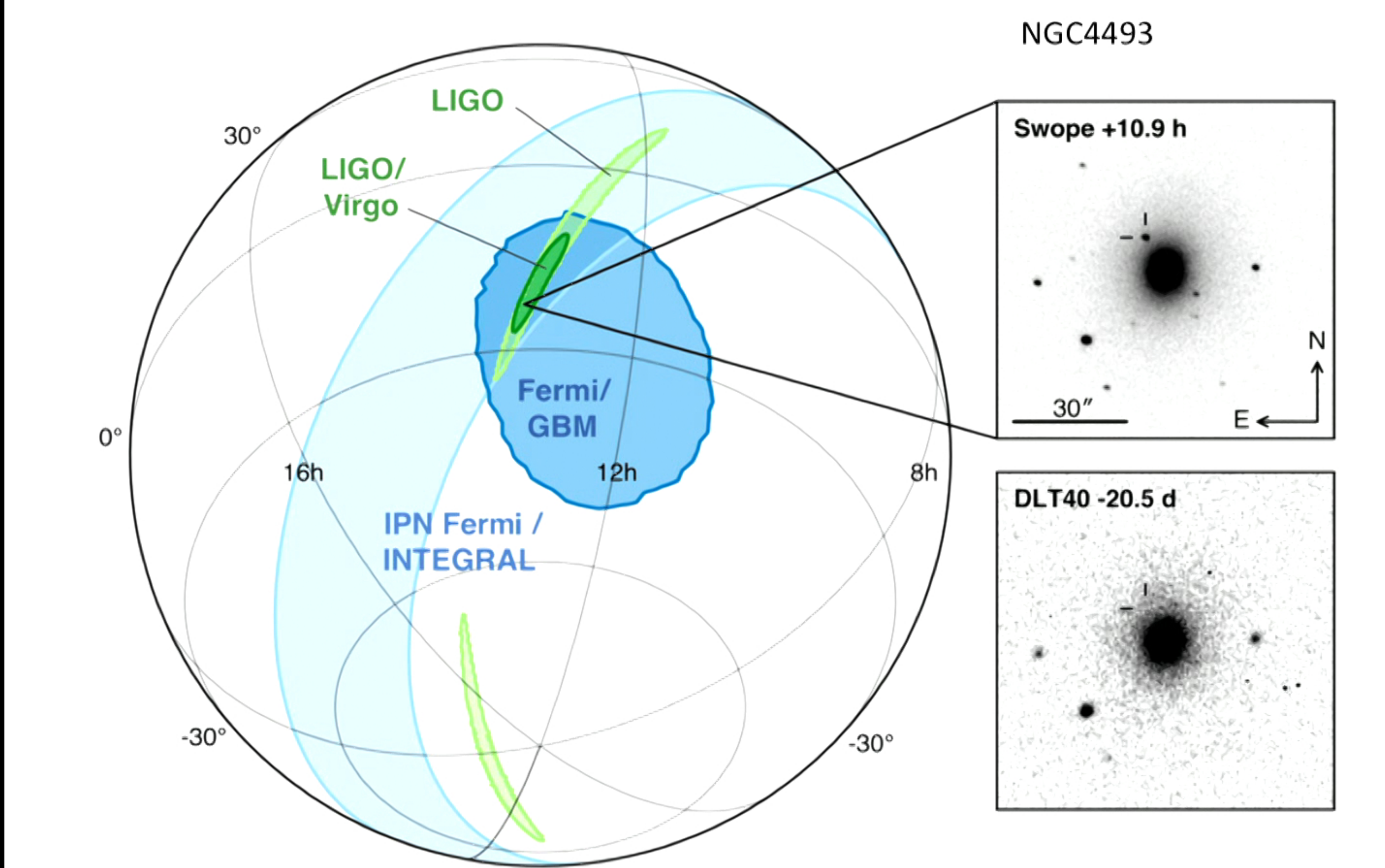
“Solar Mass” Black Holes

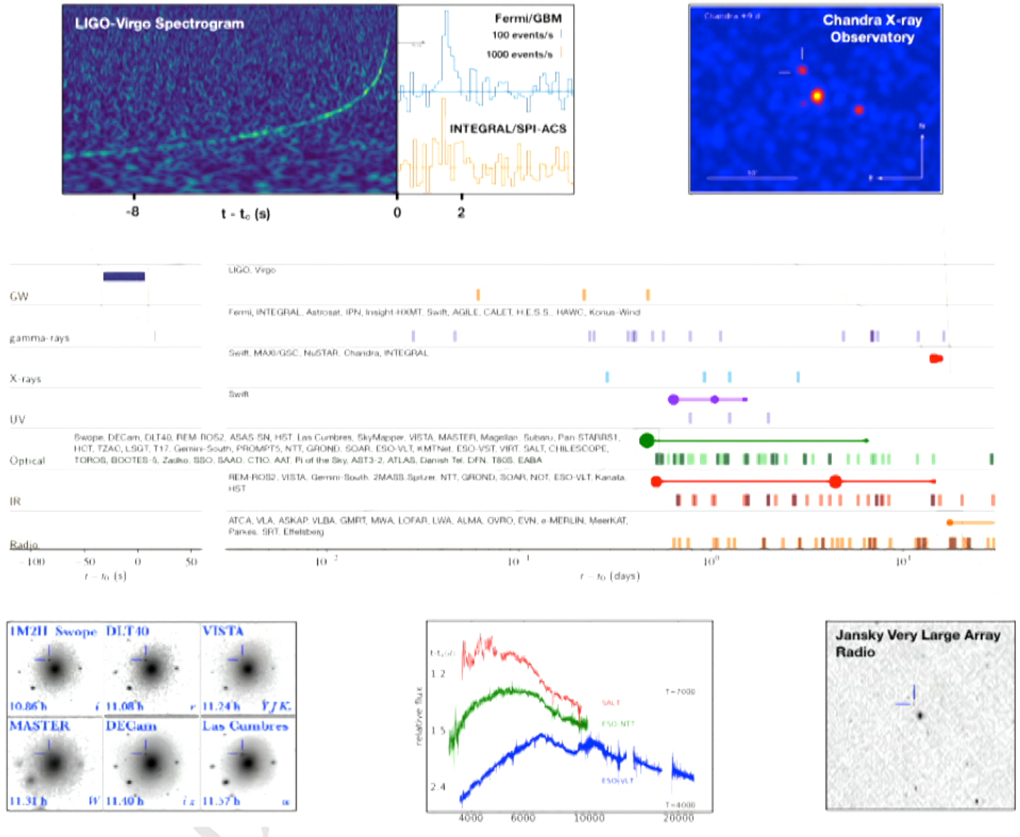


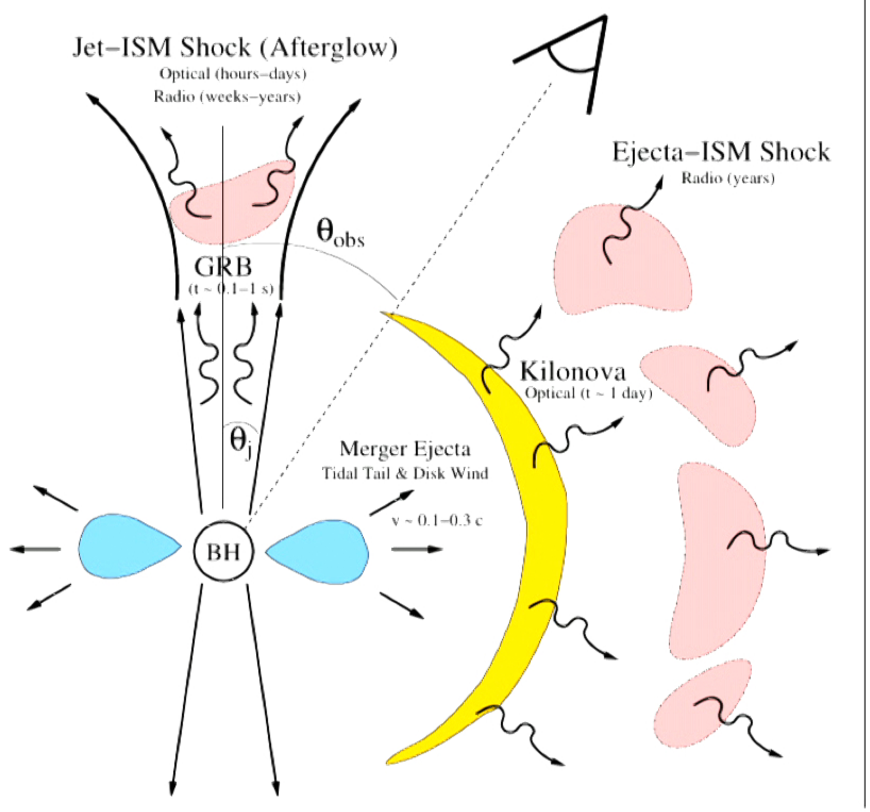
Credit: LIGO/Caltech/Sonoma State (Simonnet)


Merger
GRB start
Light curve from Fermi/GBM (10 – 50 keV)
Light curve from Fermi/GBM (50 – 300 keV)
Light curve from INTEGRAL/SPI-ACS
(> 100 keV)
Gravitational-wave time-frequency map
Event rate (counts/s)
Frequency (Hz)
Time from merger (s)

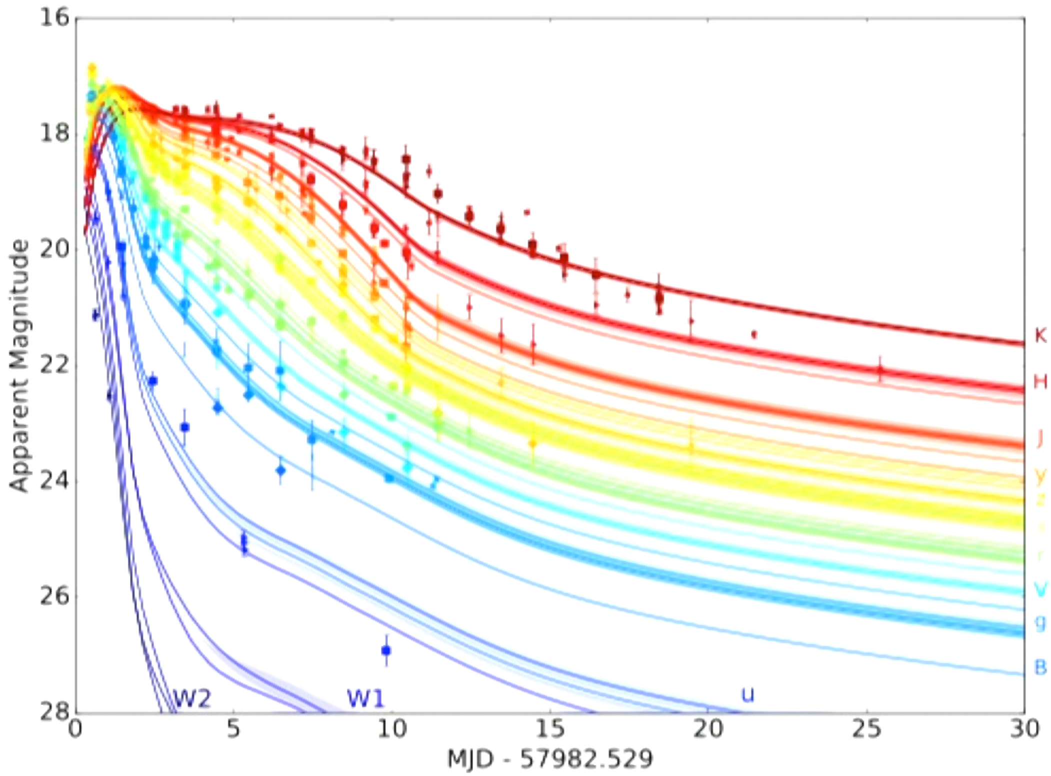

Time (seconds)
LIGO-Livingston raw data
Frequency (Hz)
Normalized amplitude
Strain data
Glitch model
Strain (×10^-20)
Window amplitude
Time (seconds)
Normalized amplitude
LIGO-Hanford
LIGO-Livingston
Virgo
Frequency (Hz)
Time (seconds)


NGC4493
LIGO
LIGO/
Virgo
30°
0°
16h
12h
8h
-30°
-30°
Fermi/
GBM
IPN Fermi /
INTEGRAL
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 - t$_c$ (s)
0
2
Chandra X-ray Observatory
GW
gamma-rays
X-rays
UV
Optical
IR
Radio
LIGO, Virgo
Swift
1M2H Swope
DLT40
VISTA
MASTER
DECam
Las Cumbres
Jansky Very Large Array Radio
4000
6000
10000
20000

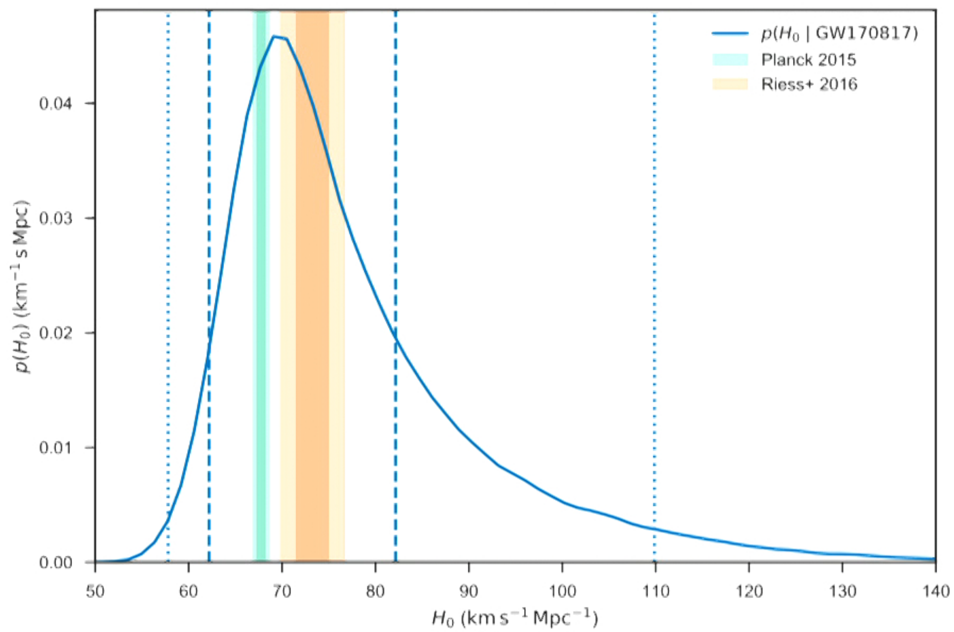

Jet–ISM Shock (Afterglow)
Optical (hours–days)
Radio (weeks–years)
Ejecta–ISM Shock
Radio (years)
θobs
GRB
(t ~ 0.1–1 s)
Kilonova
Optical (t ~ 1 day)
θj
Merger Ejecta
Tidal Tail & Disk Wind
v ~ 0.1–0.3 c
BH

Broad band kilonova spectra vs time



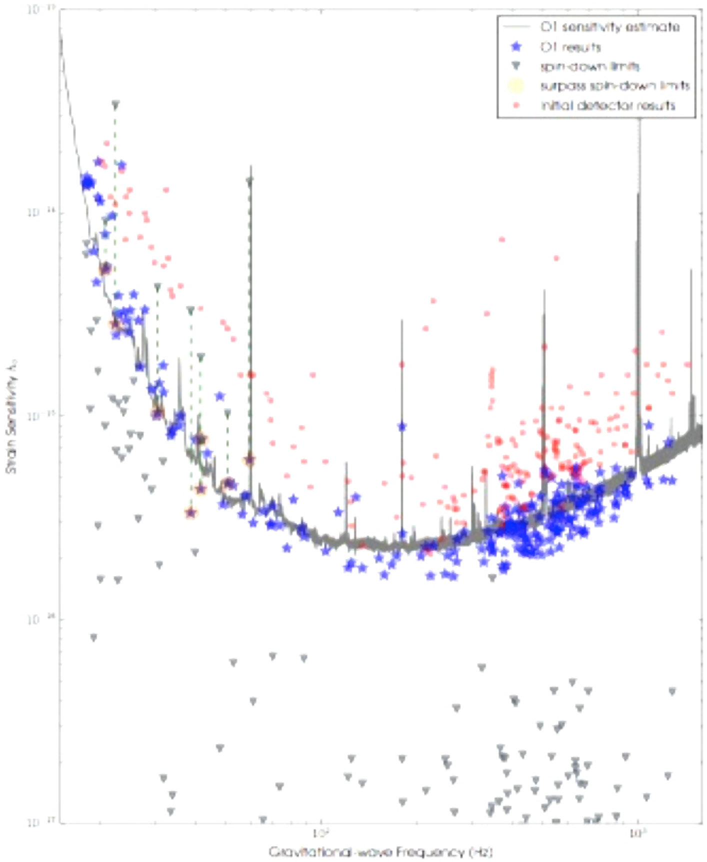
Villar et al arXiv astroph 1710.11576

Hubble constant measurement: Galaxy z and distance from GW amplitude

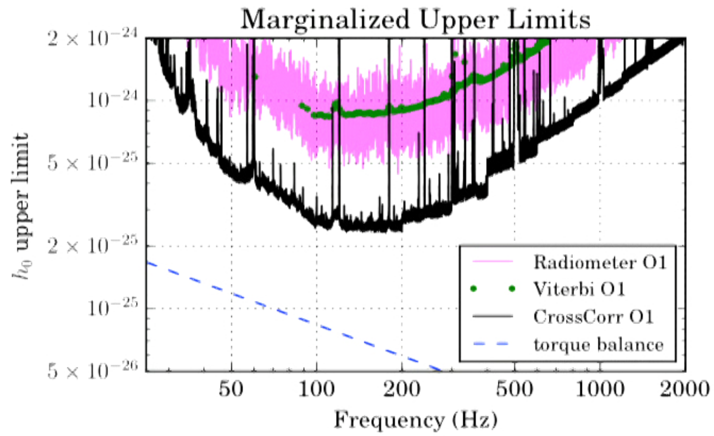


Classes of sources and searches

- 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



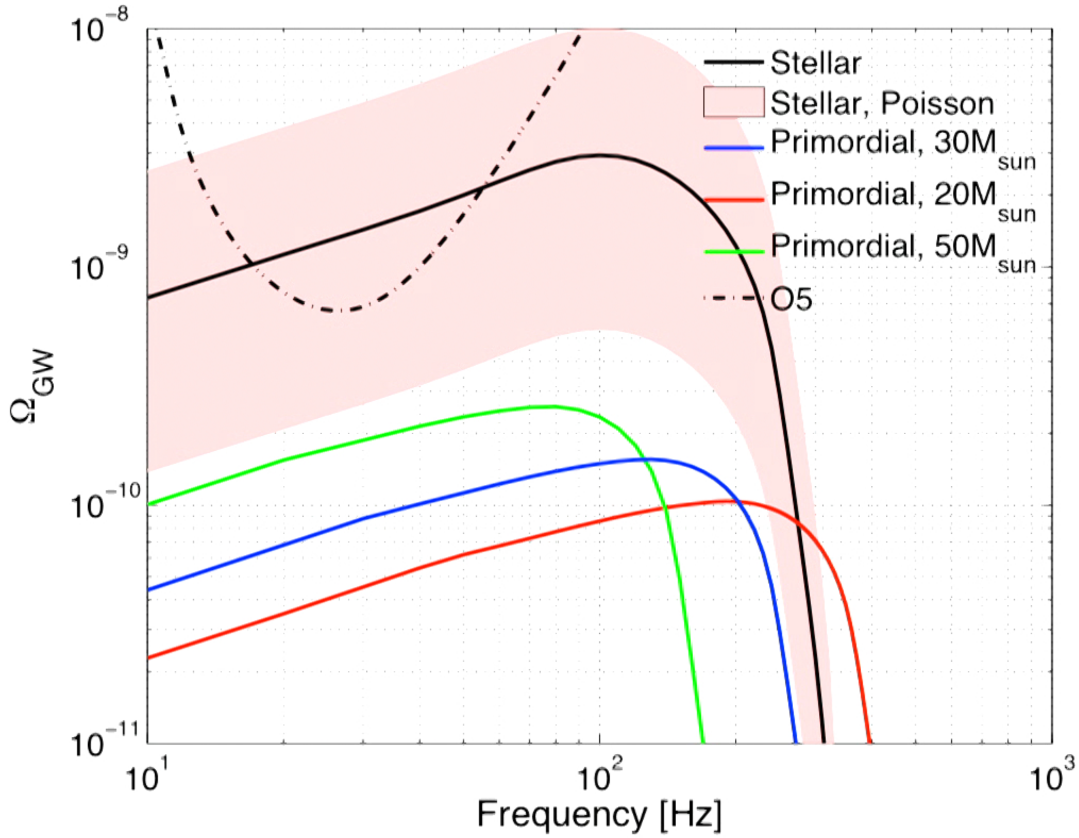
CW search periodic sources



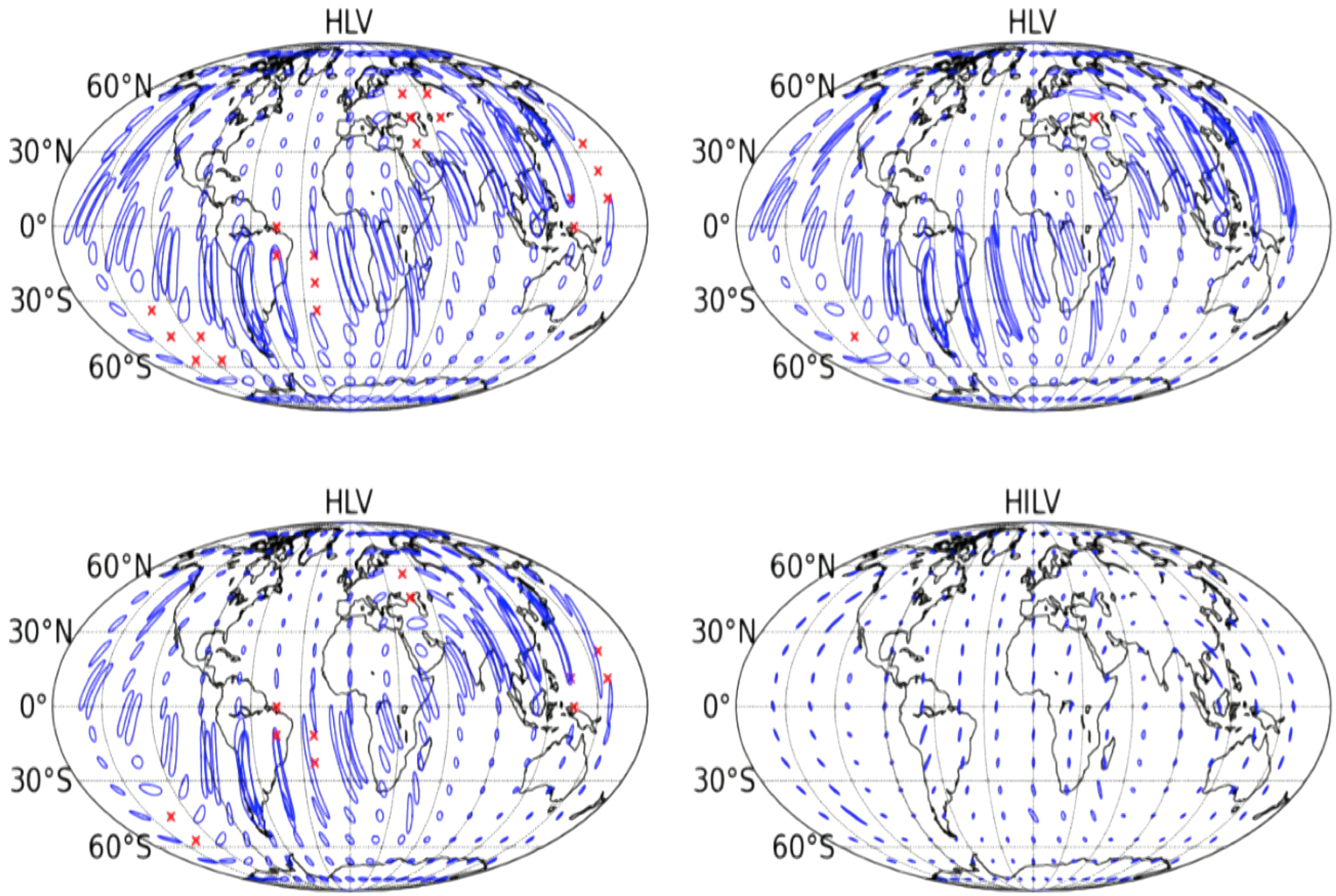
CW radiometer search
Scorpius X1

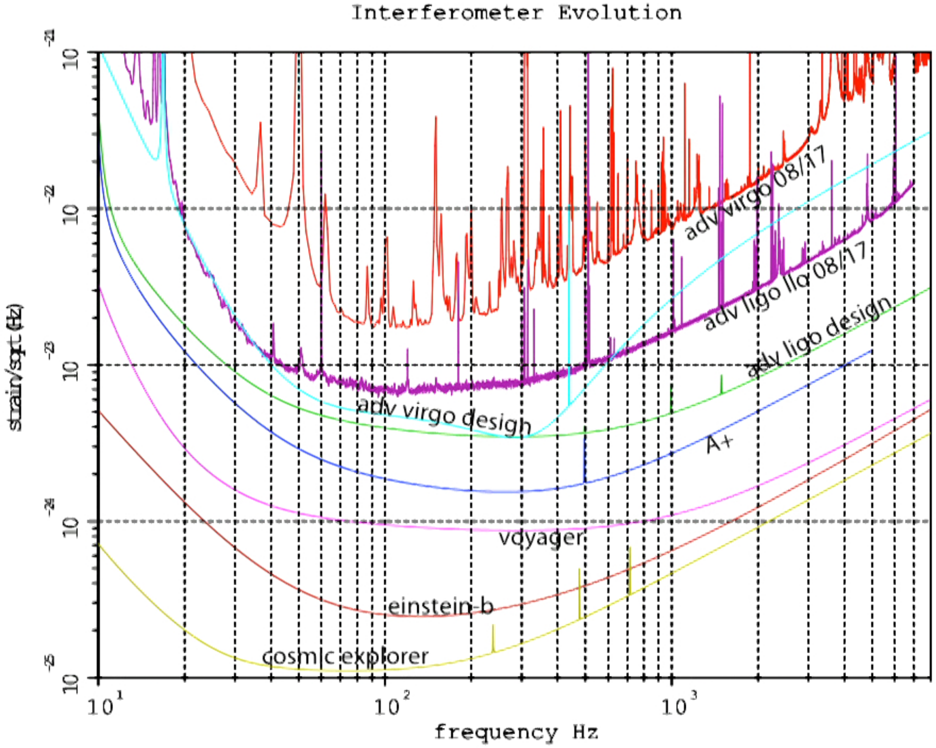
K. Riles preprint

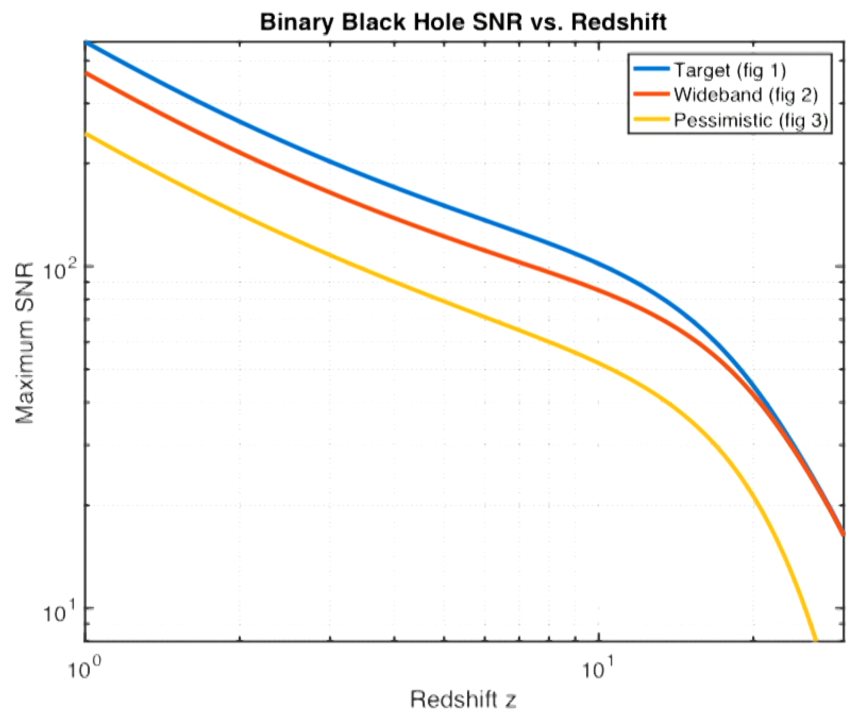
stochastic background of PBHs

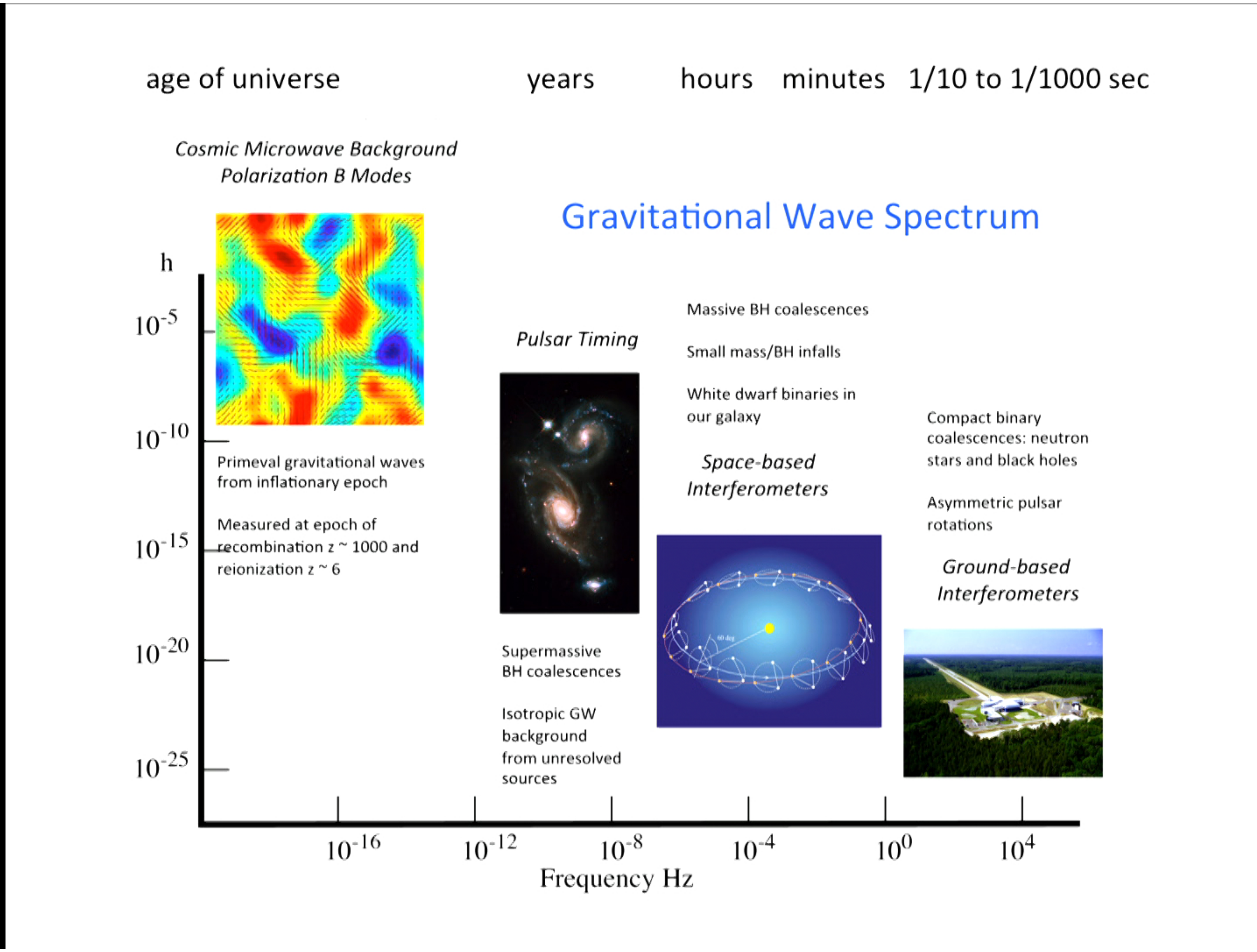


(Mandic et al. 2017)


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