The Beginnings of Gravitational Wave Astronomy

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Hungarian Academy of Sciences

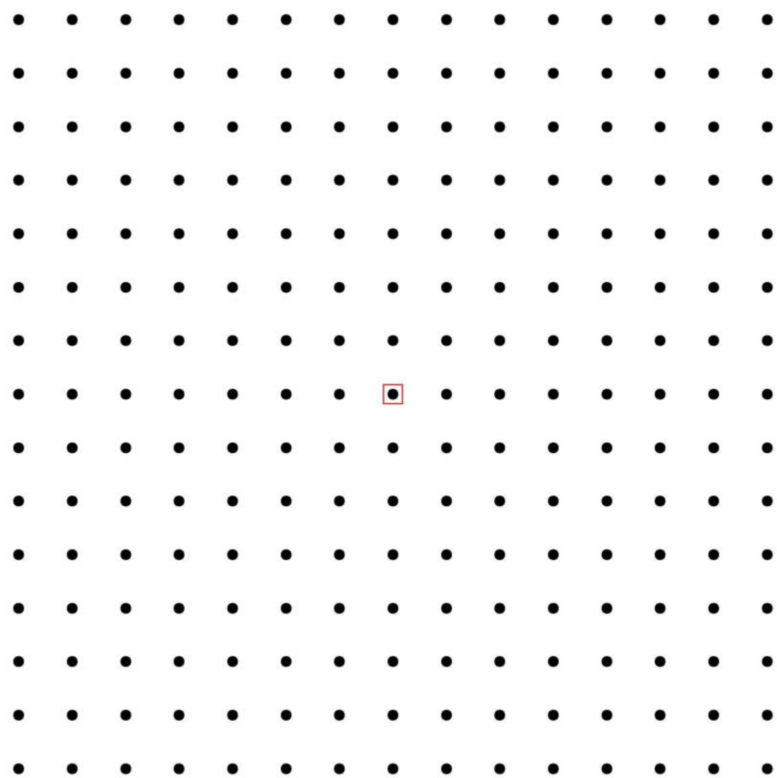
Budapest, Hungary

November 8, 2018

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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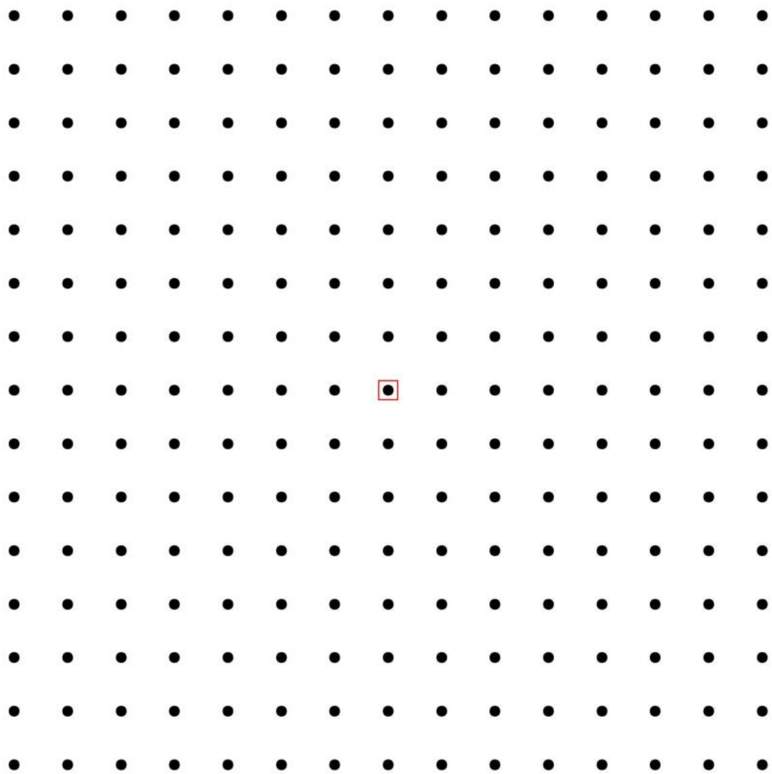
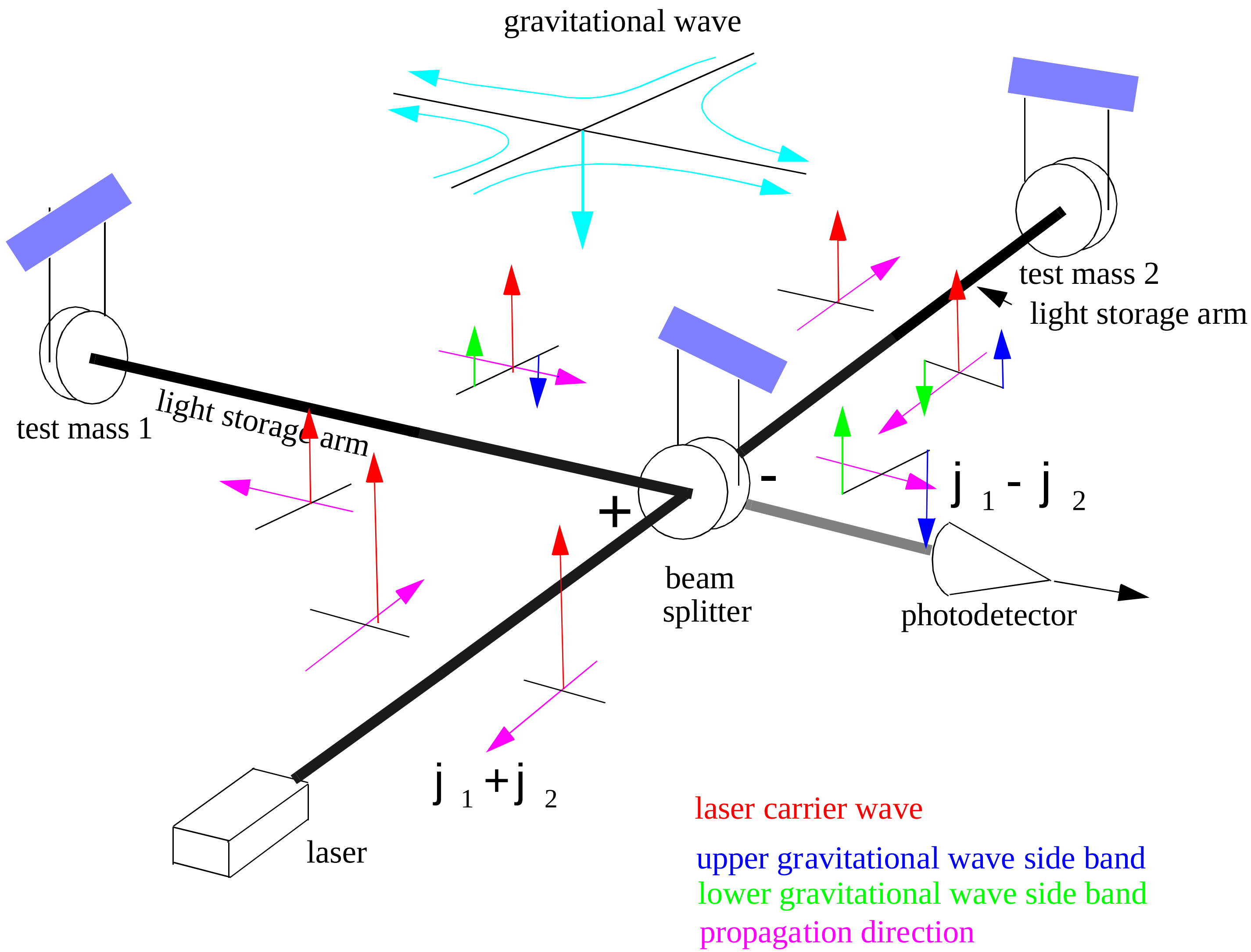
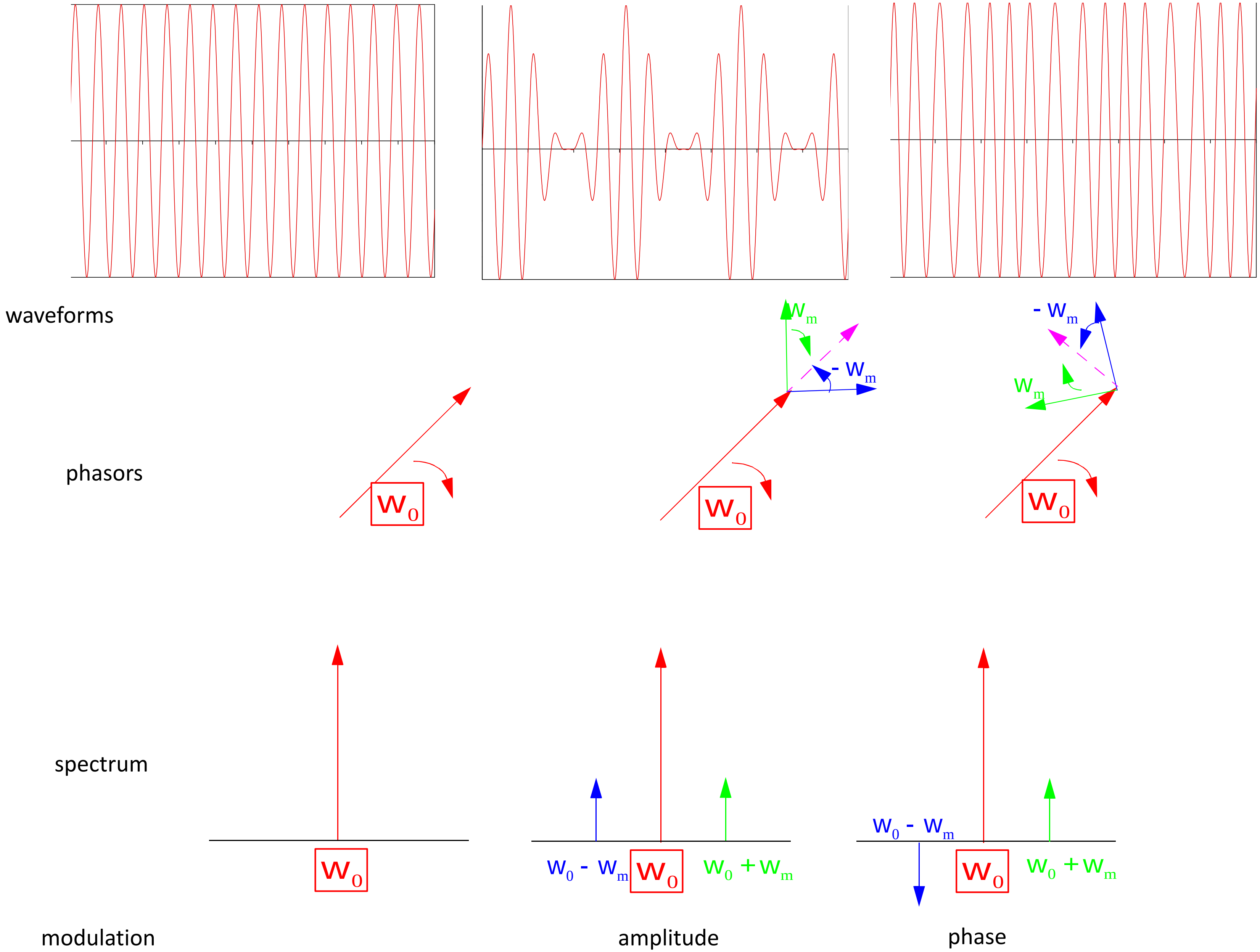


Michelson Interferometer Schematic and GW sidebands

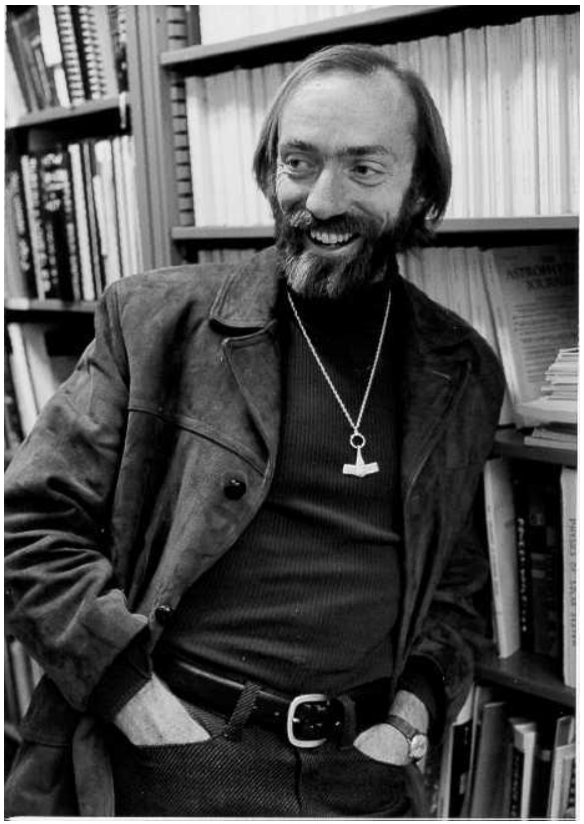




$$E(t) = \mathrm{Re}(e^{i\omega_0 t}) \qquad \mathrm{Re}(e^{i\omega_0 t}\left[1+\Gamma(e^{-i\omega_m t}+e^{i\omega_m t})\right]) \qquad \mathrm{Re}(e^{i\omega_0 t}\left[1+\Gamma(e^{-i\omega_m t}-e^{i\omega_m t})\right])$$

MODULATION: Amplitude and Phase

The measurement challenge



Kip Thorne

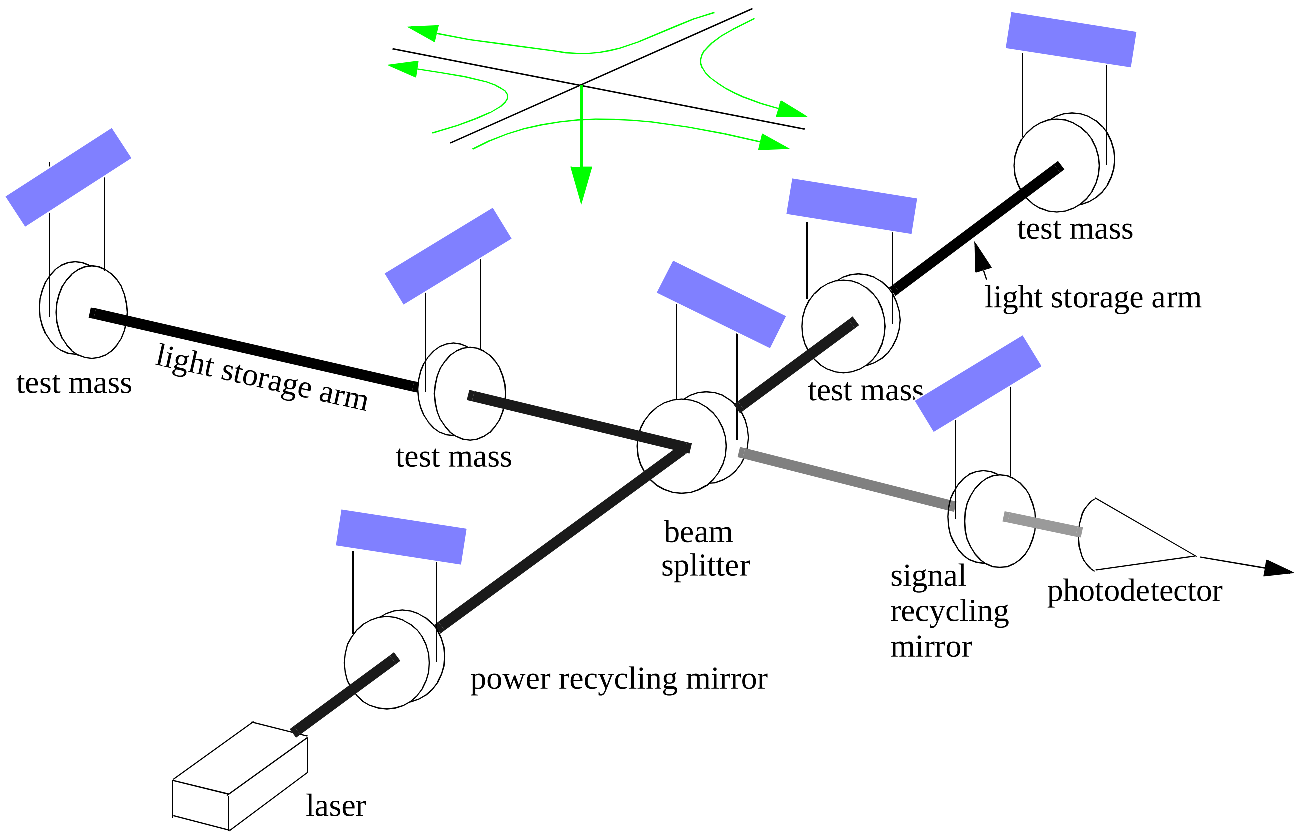
$$h = \frac{\Delta L}{L} \approx 10^{-21}$$

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

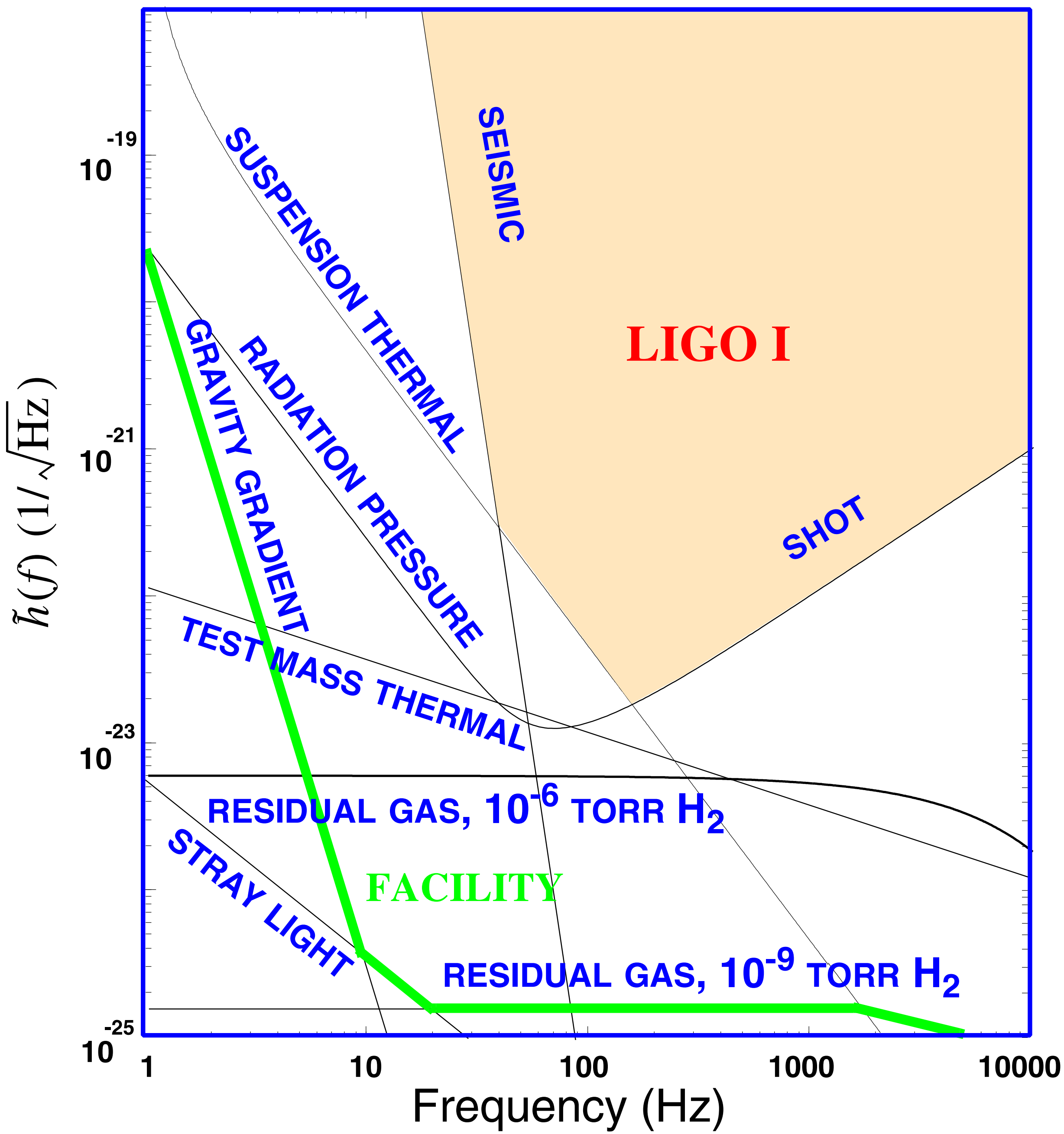
$$\Delta L \approx 10^{-12}\,\text{wavelength of light}$$

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

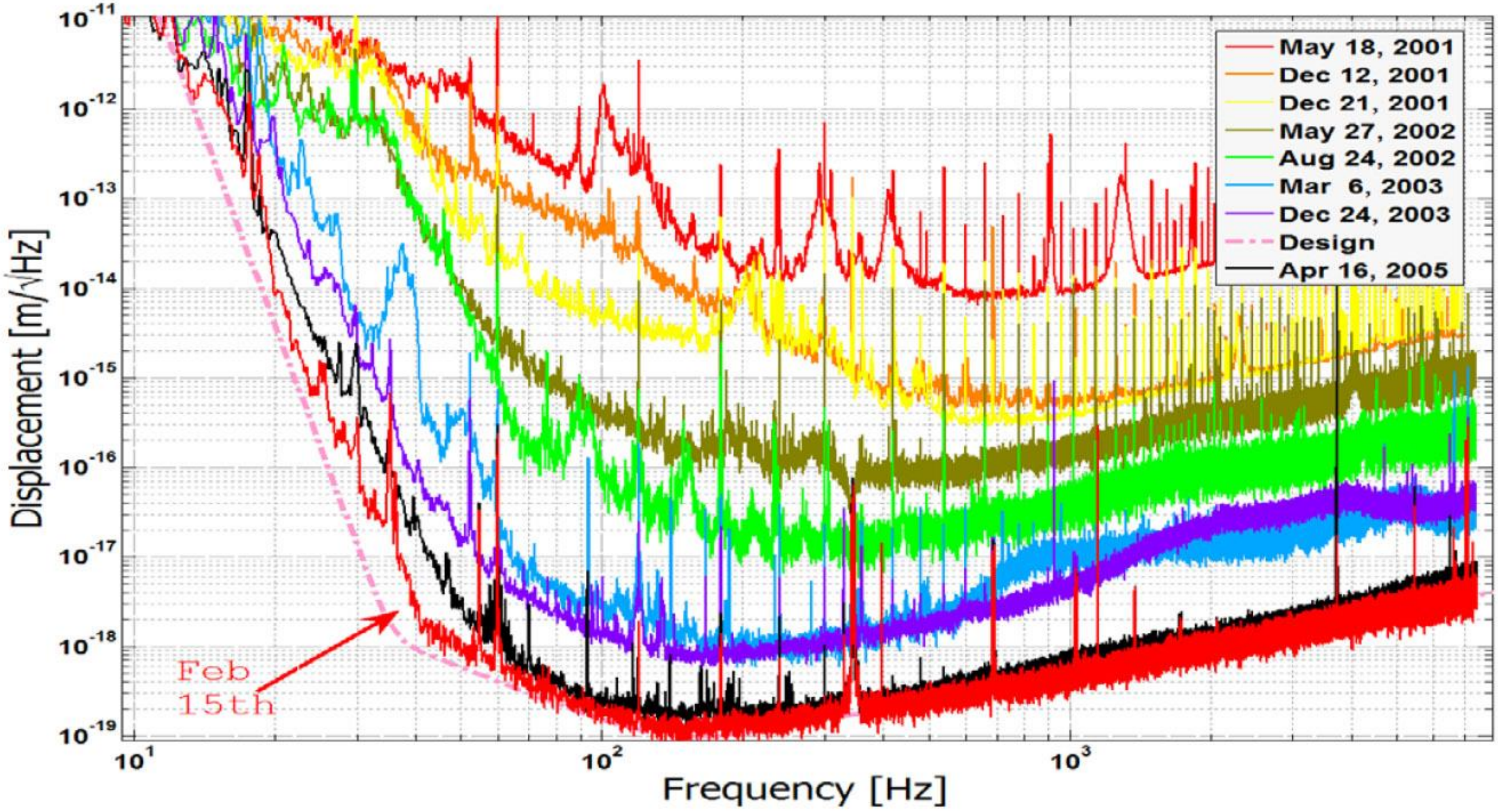
Advanced LIGO Fabry-Perot Michelson Interferometer Schematic



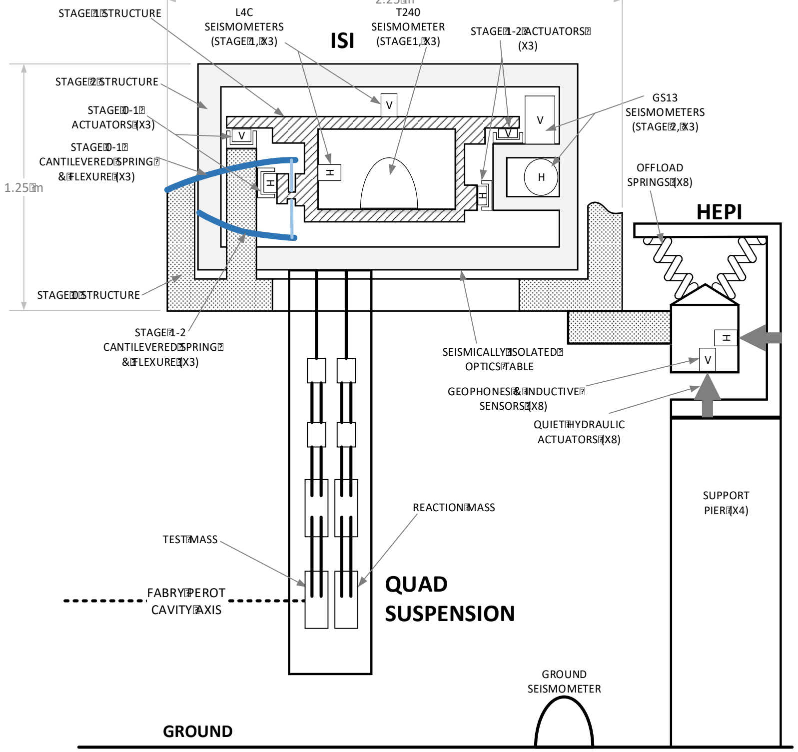
Initial LIGO Interferometer Noise Budget



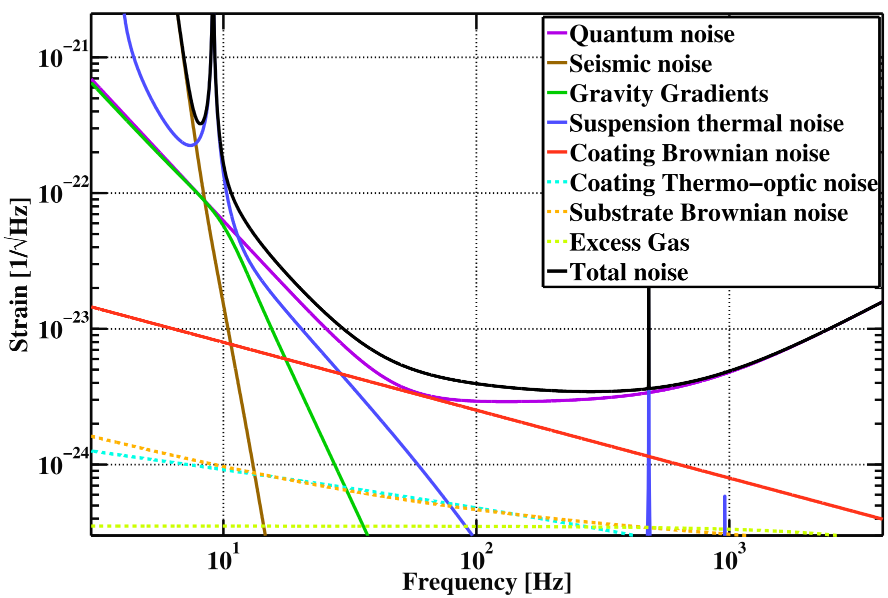
Evolution of the initial detector 2001 - 2006

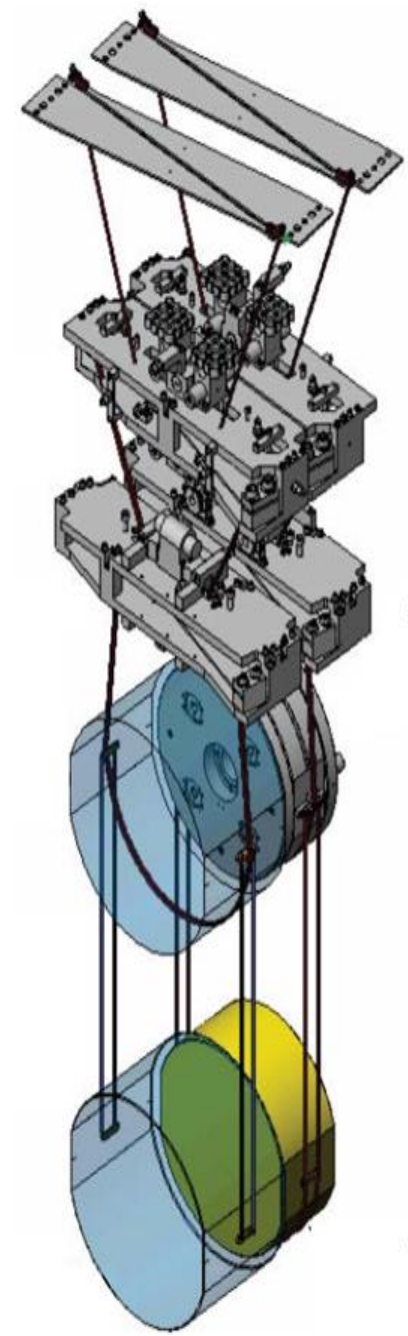


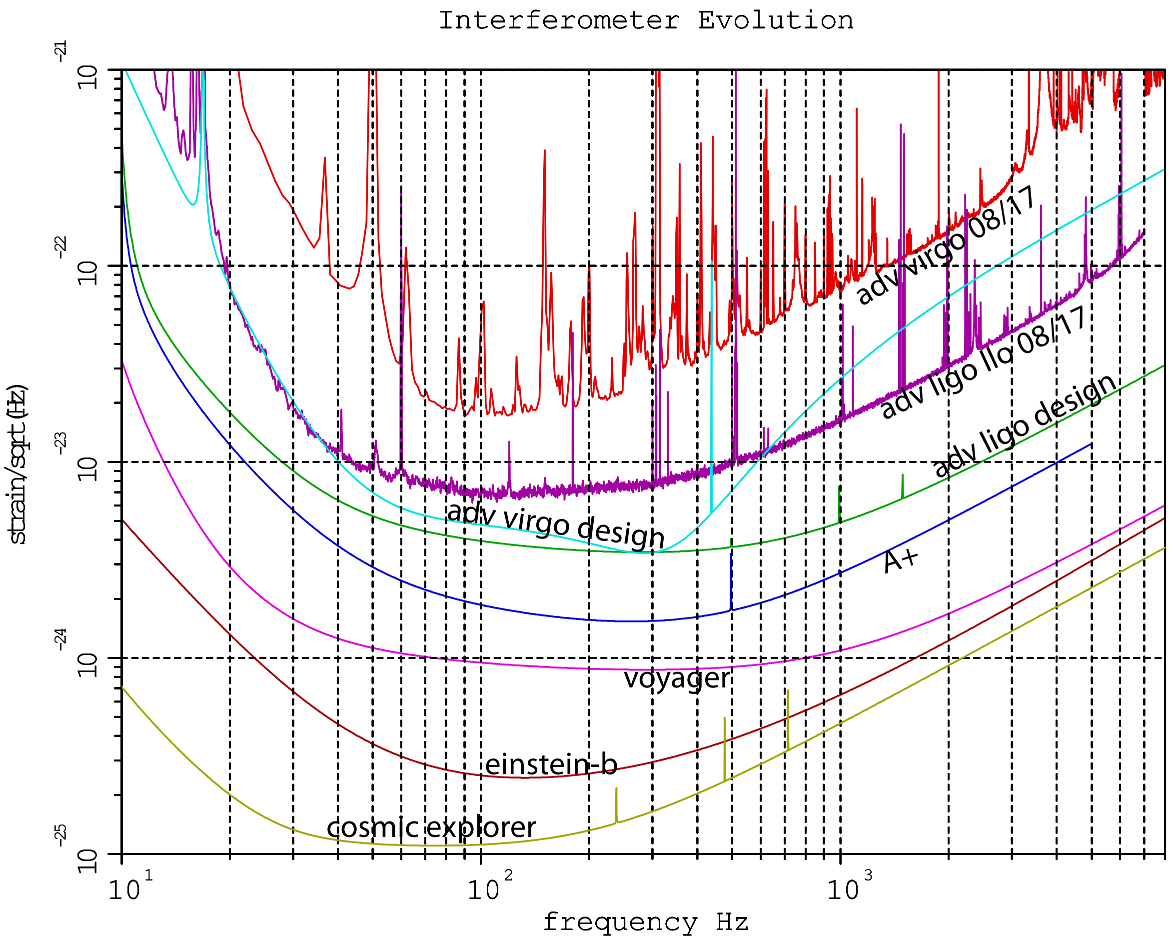
A clean non-detection



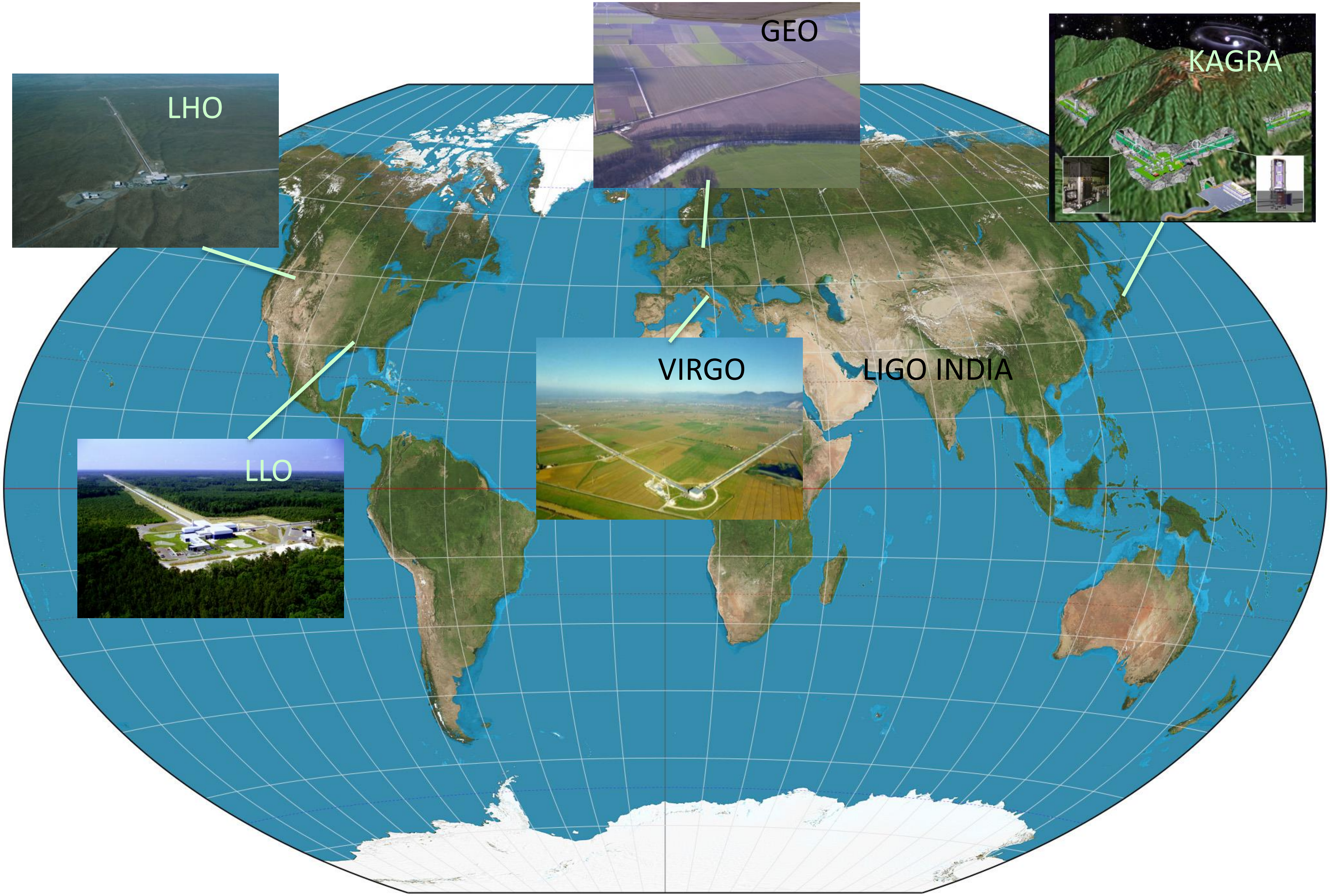
Advanced LIGO design noise budget





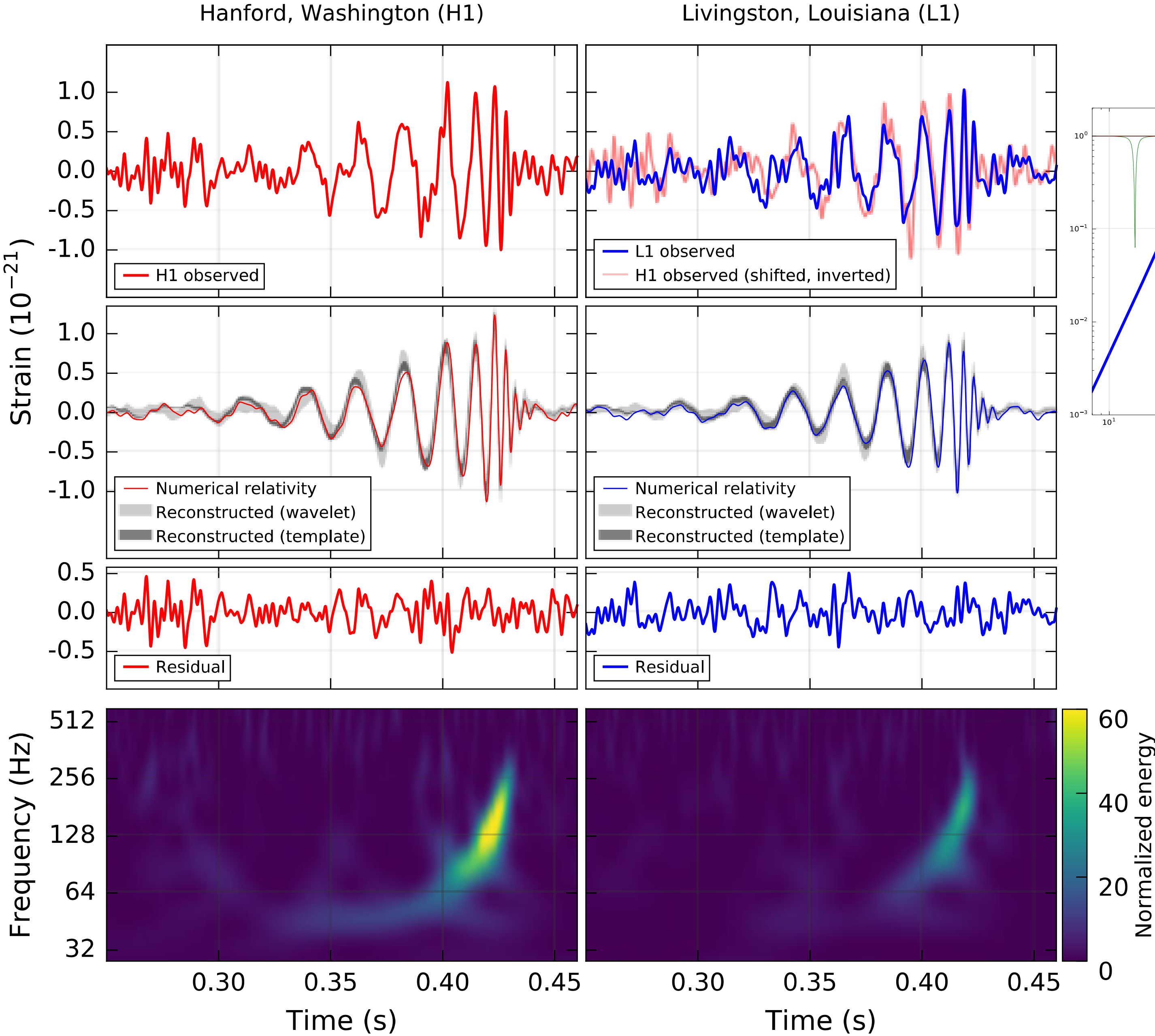


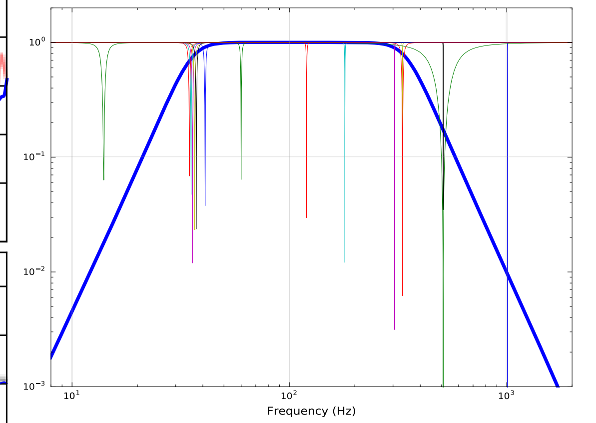
Interferometer Evolution
strain/sqrt (Hz)
frequency Hz
adv virgo 08/17
adv ligo llo 08/17
adv ligo design
adv virgo design
A+
voyager
einstein-b
cosmic explorer


GEO
KAGRA
LHO
VIRGO
LIGO INDIA
LLO

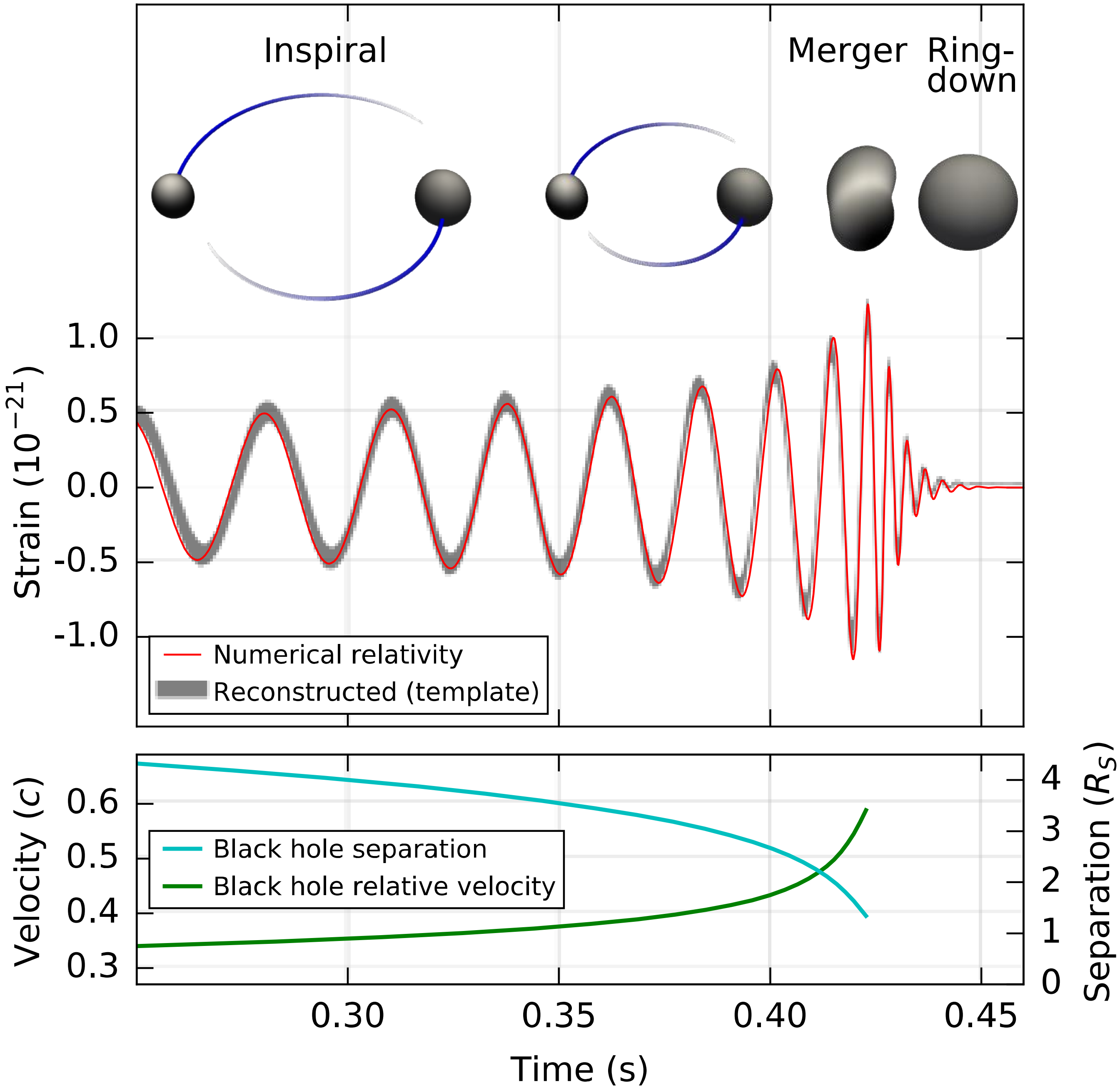
Criteria for transient detection

- 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





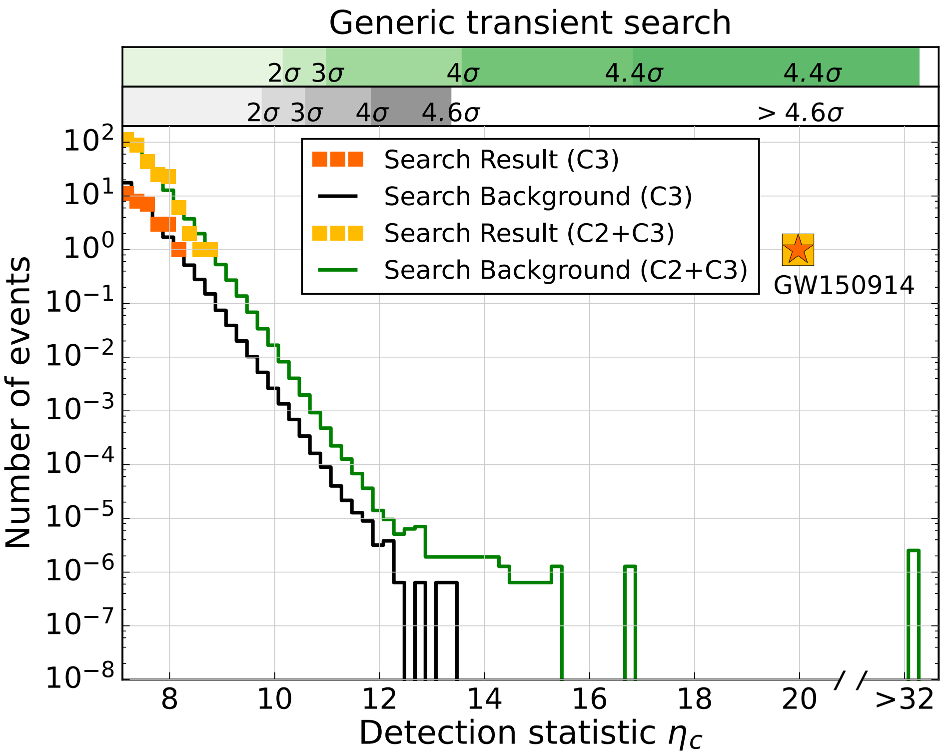
Simple high-low pass filter with notches

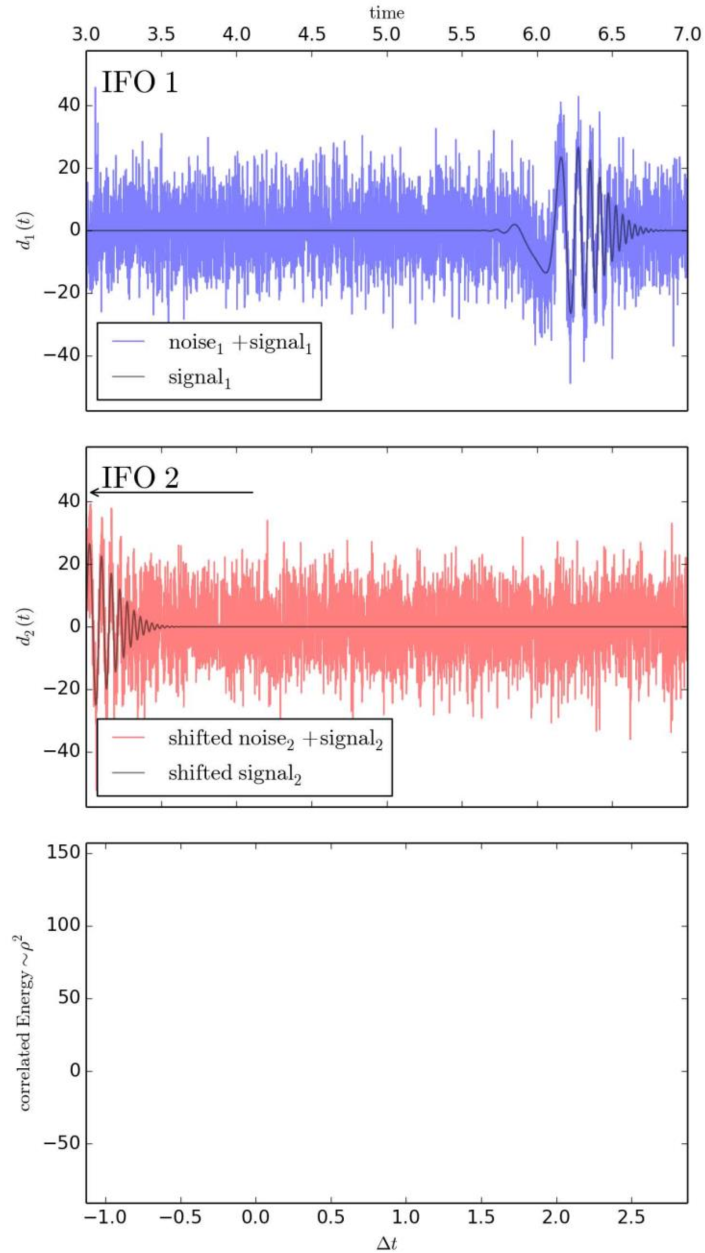


Inspiral
Merger
Ring-down
Strain (10^{-21})
1.0
0.5
0.0
-0.5
-1.0
Numerical relativity
Reconstructed (template)
Velocity (c)
0.6
0.5
0.4
0.3
Black hole separation
Black hole relative velocity
Separation (R_S)
4
3
2
1
0
0.30
0.35
0.40
0.45
Time (s)

Generic transient search

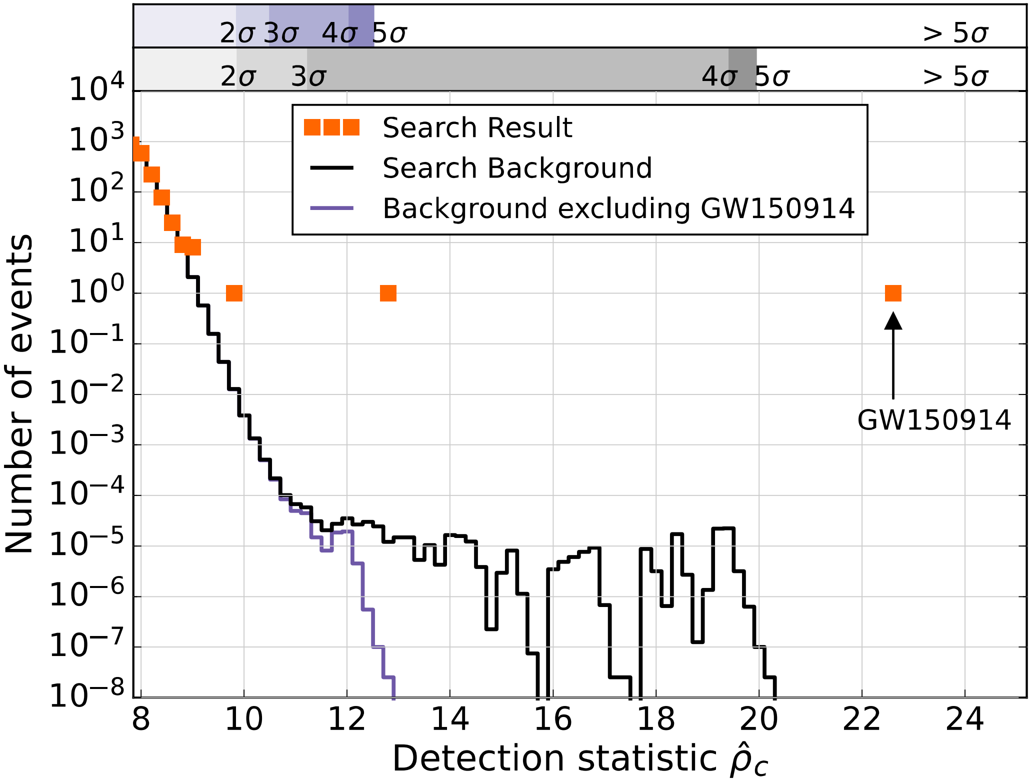
R.Essik

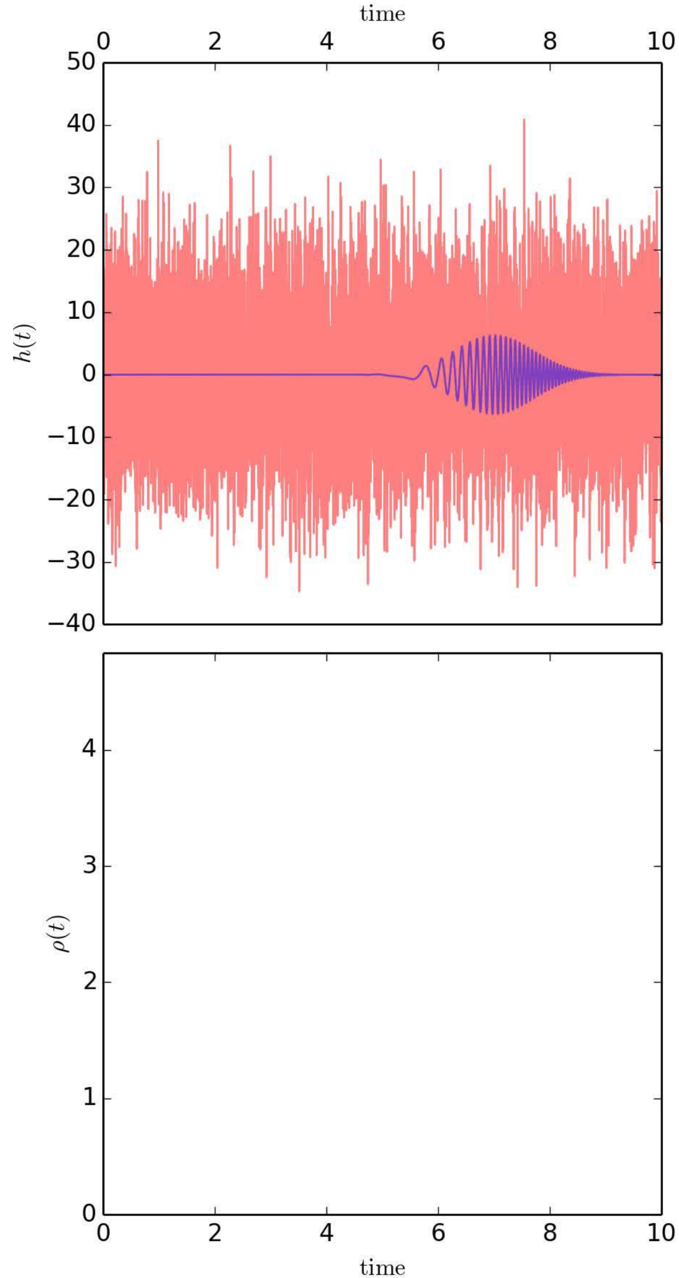




R.Essik

Modeled search followed by χ^2 cut

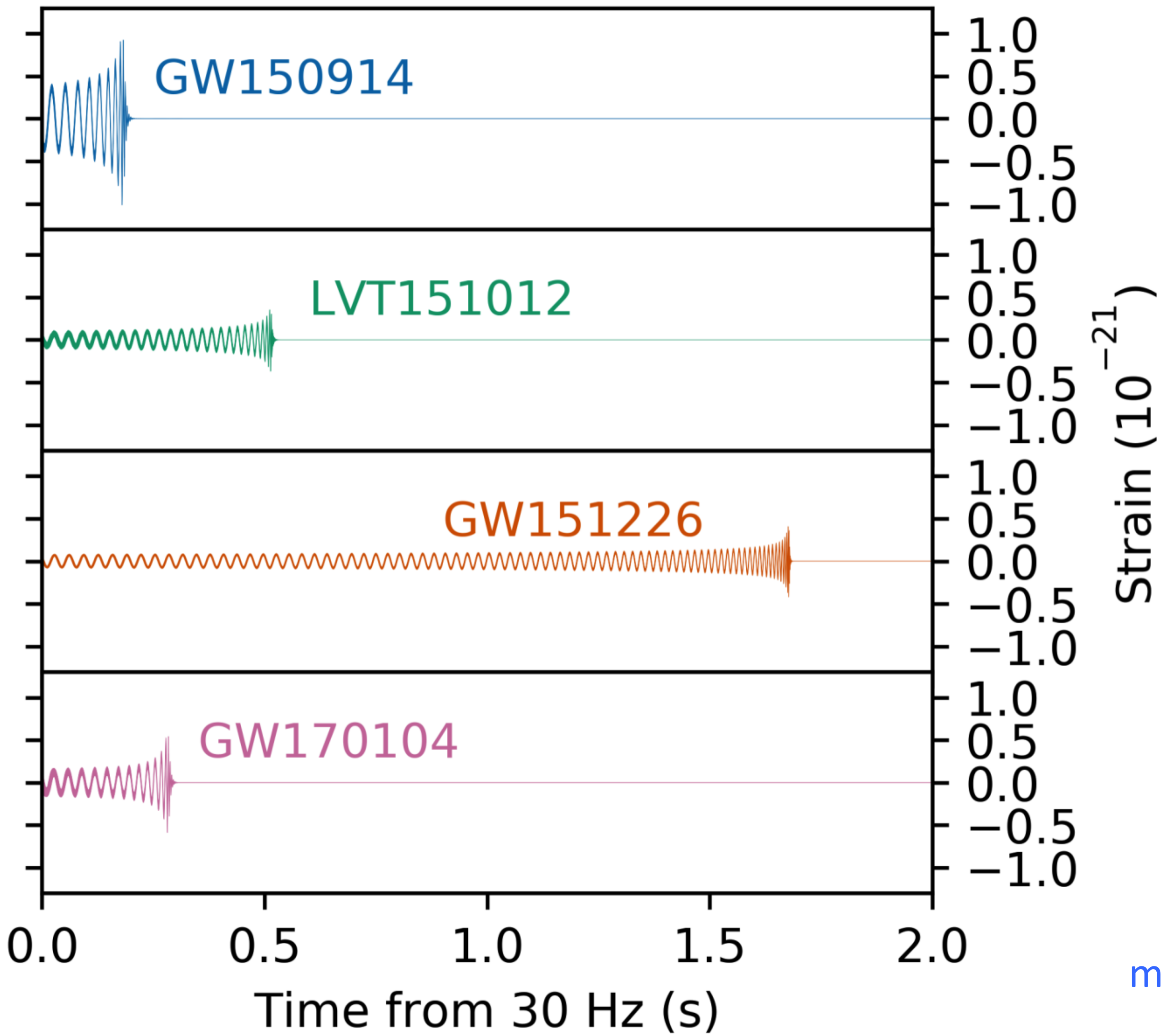




False alarm rate from time slides

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

Results of O1 and O2 run announced June 1, 2017



m1=36, m2= 29, Δm=3

if at 1 au

h ~10^{-6}

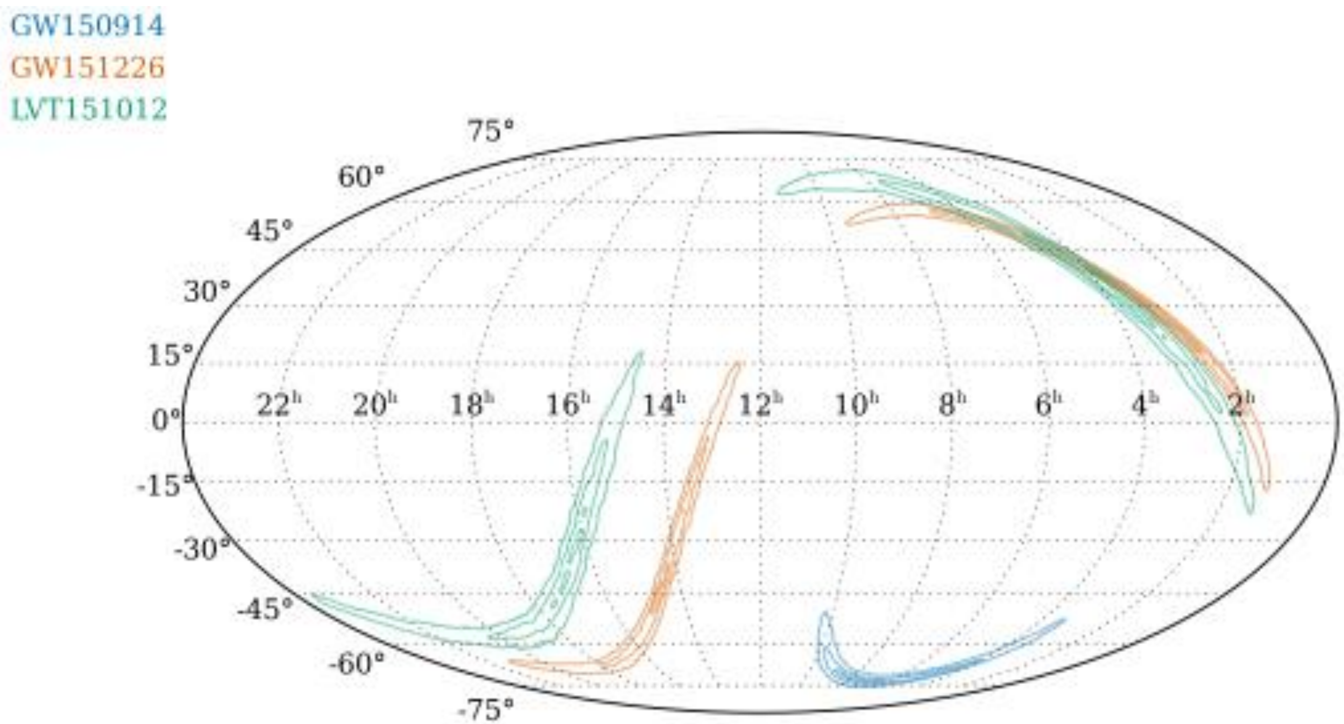
I_g~ 10^{25} w/m^2

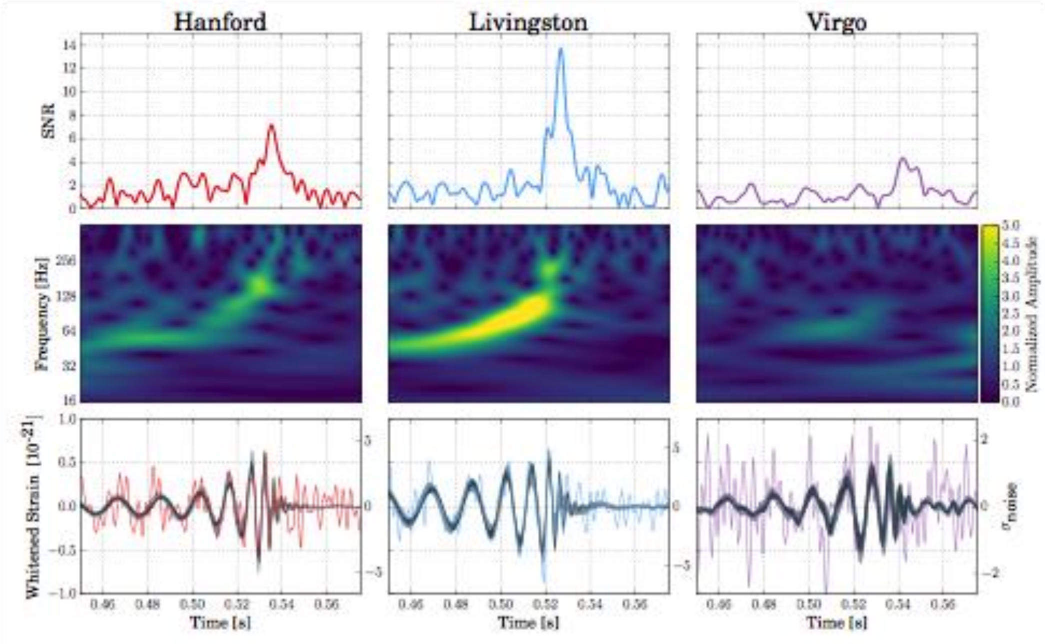
m1=23, m2= 13, Δm=1.5

m1=14.2, m2= 7.5, Δm=1

m1=31, m2= 19, Δm=2

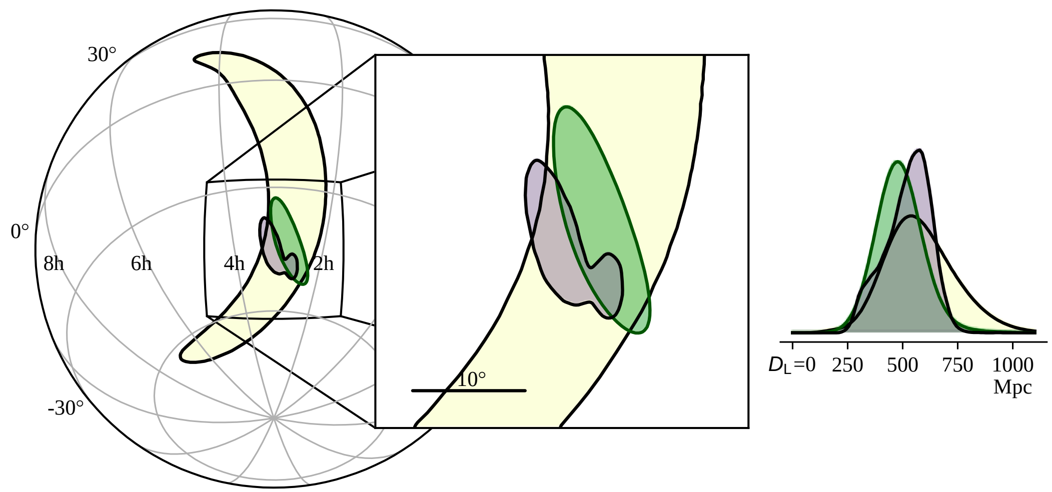
masses in source frame


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

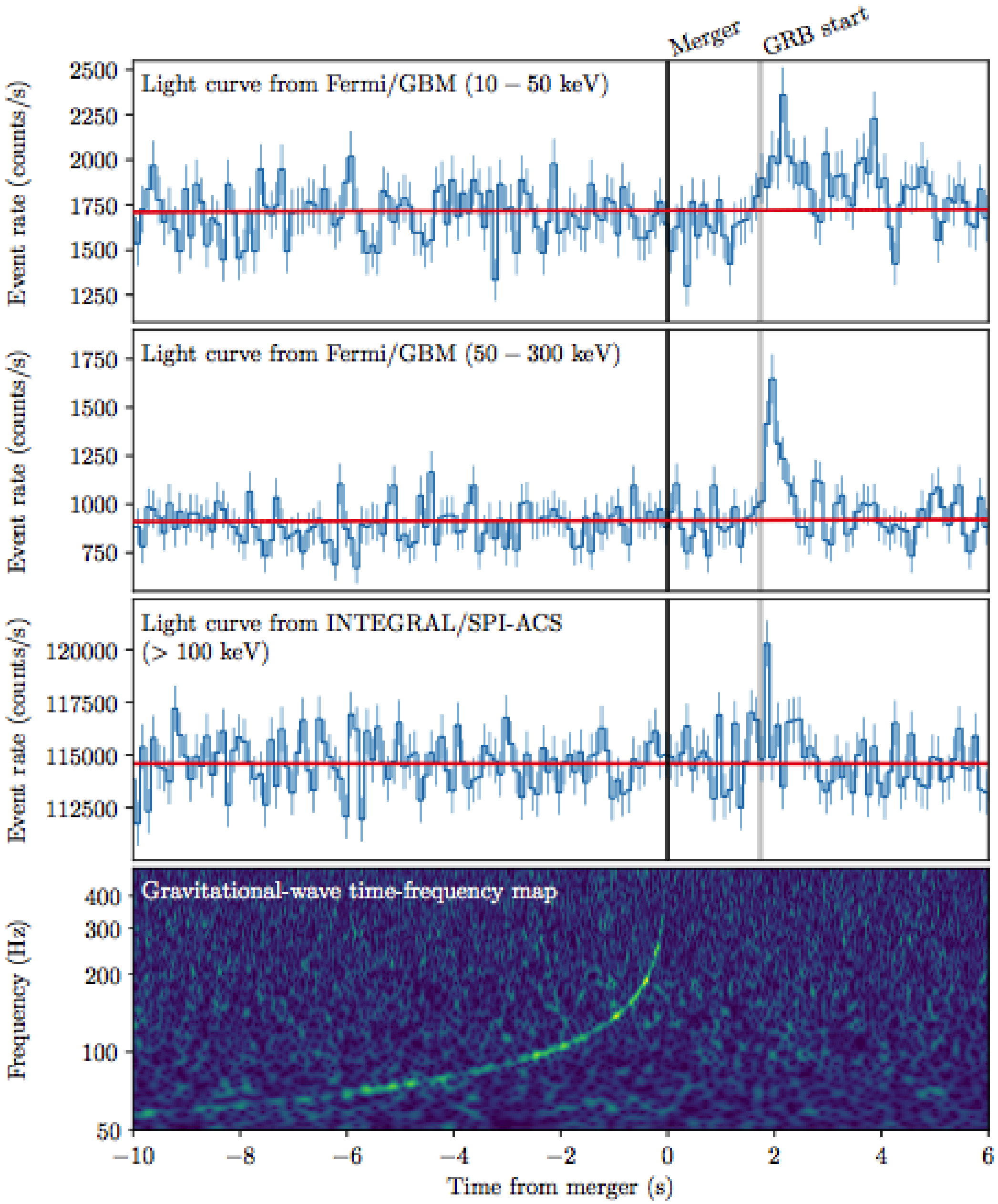


Triple coincidence
GW 170814

M_1 = 30
M_2 = 25
ΔM = 2.7

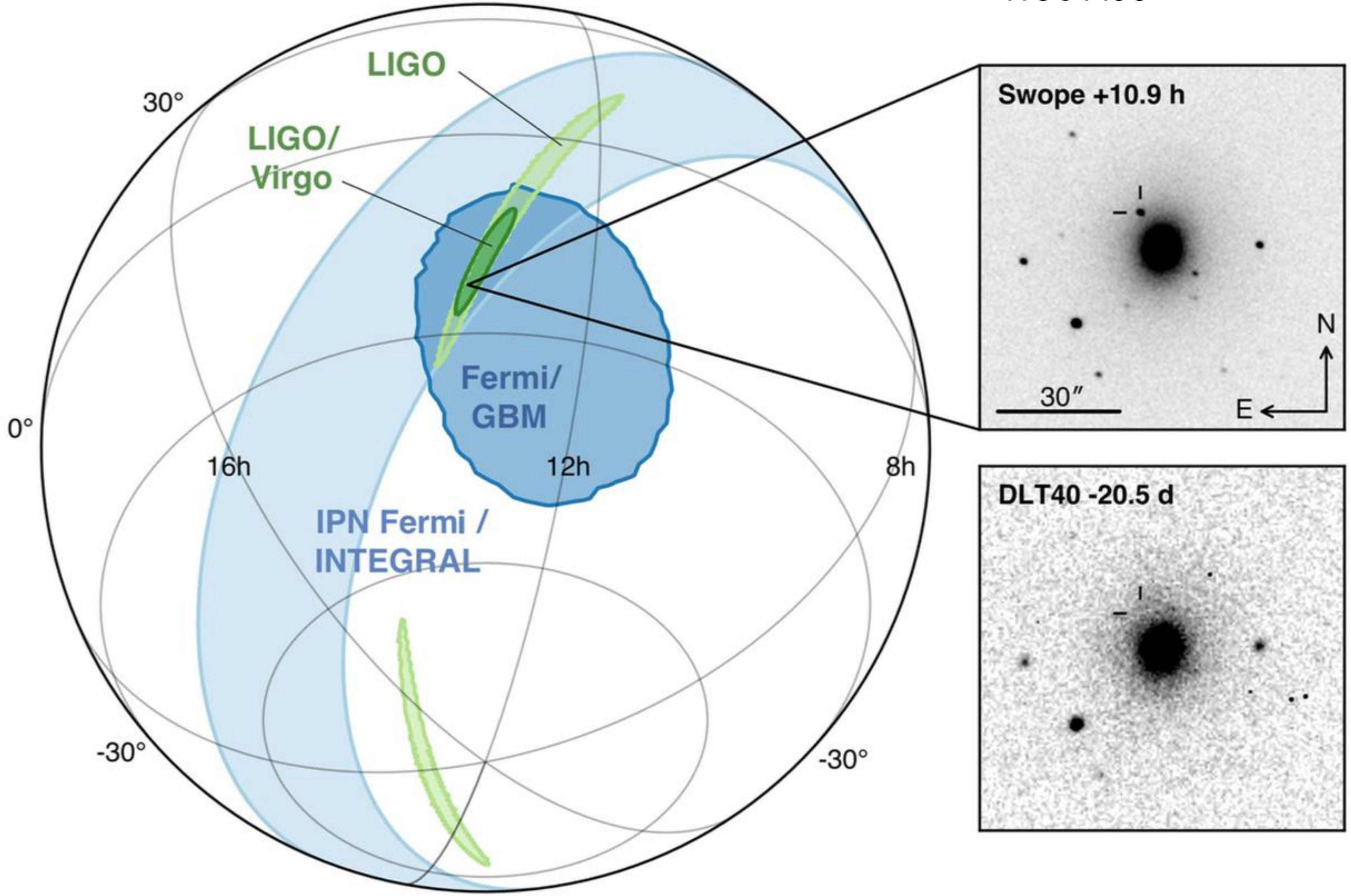


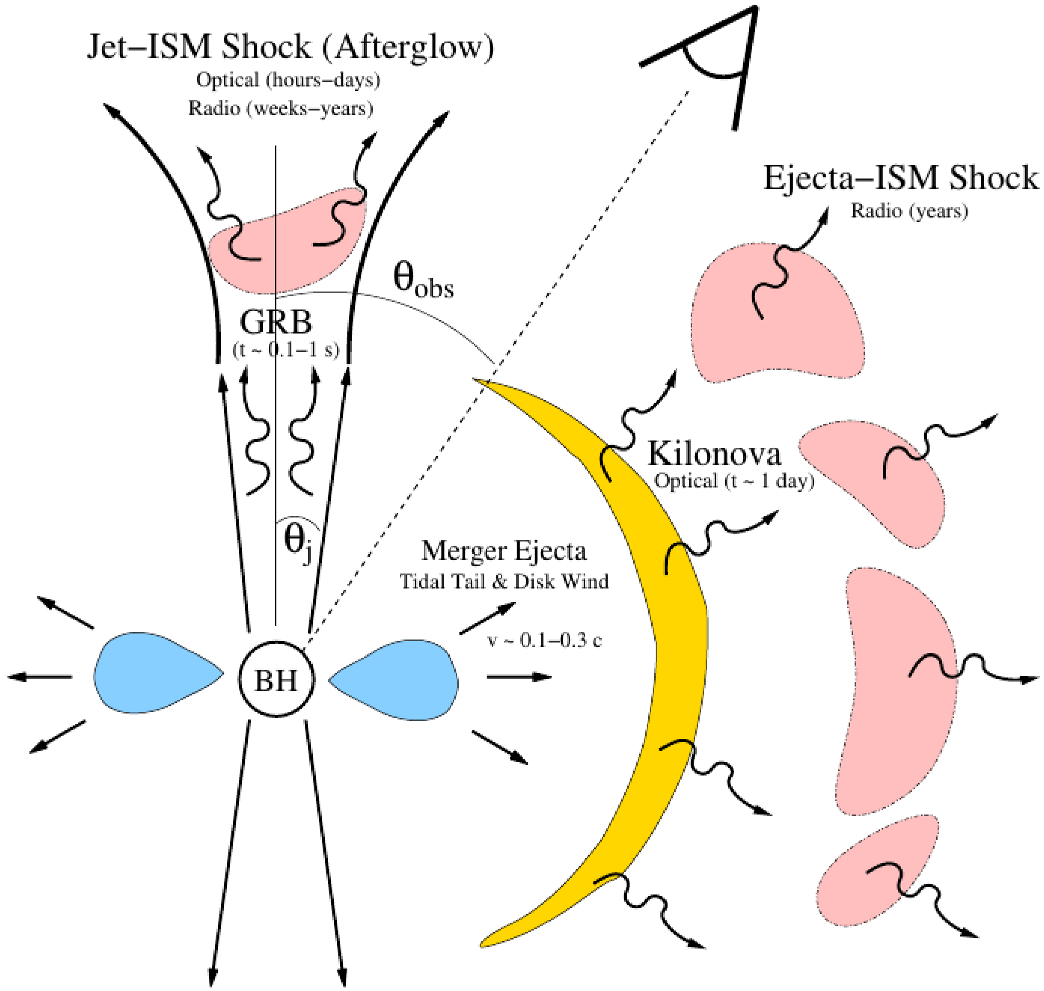
Localization on sky and distance



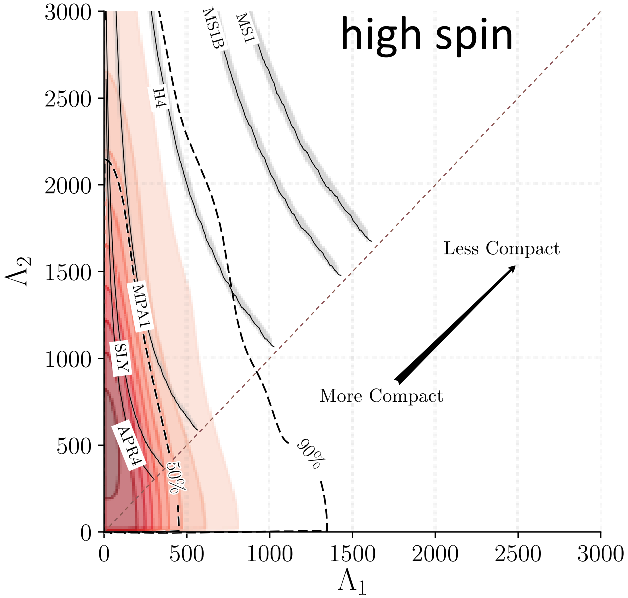
Merger
GRB start
Light curve from Fermi/GBM (10 – 50 keV)
Light curve from Fermi/GBM (50 – 300 keV)
Light curve from INTEGRAL/SPI-ACS
(> 100 keV)
Gravitational-wave time-frequency map
Event rate (counts/s)
Frequency (Hz)
Time from merger (s)
2500
2250
2000
1750
1500
1250
1000
750
120000
117500
115000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

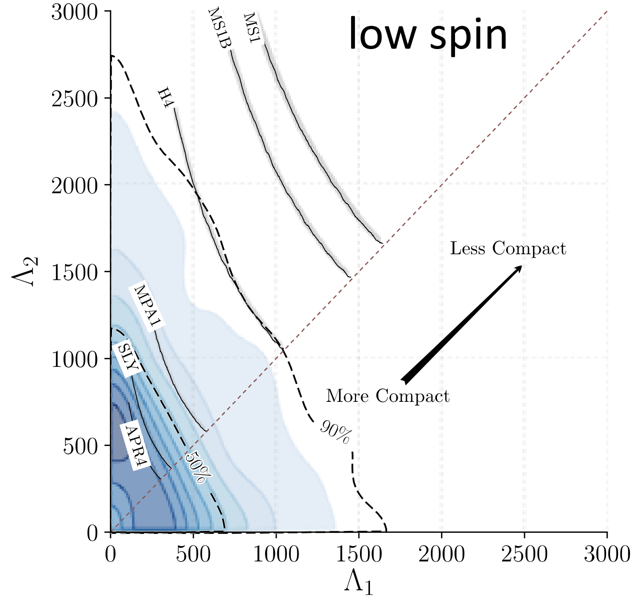
NGC4493


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


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

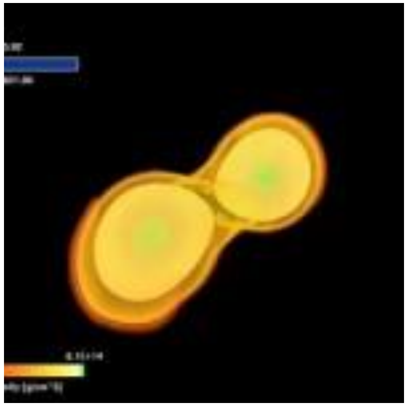
Neutron Star Tidal Distortion

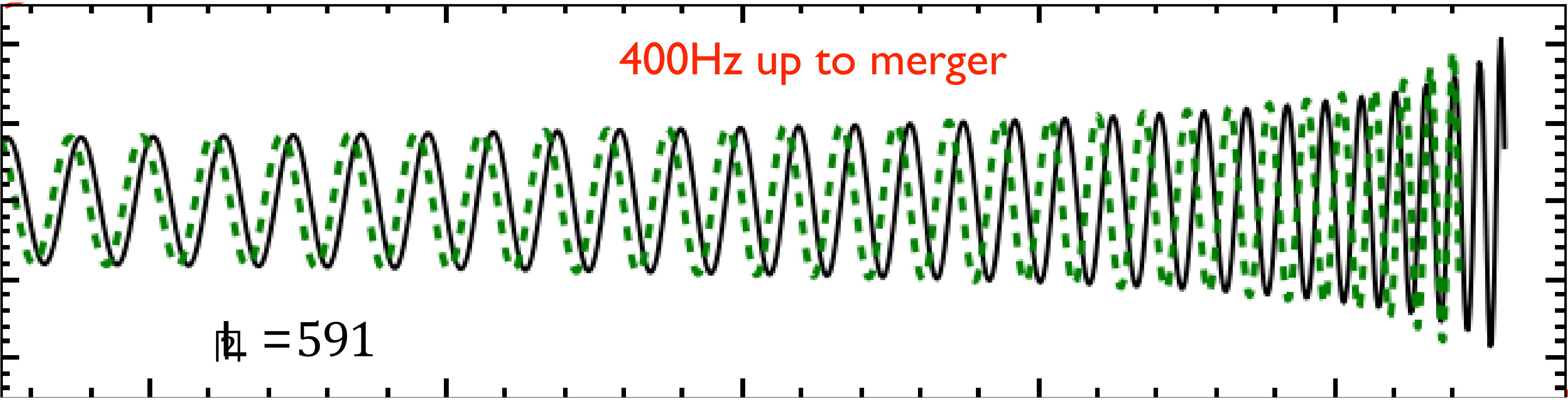




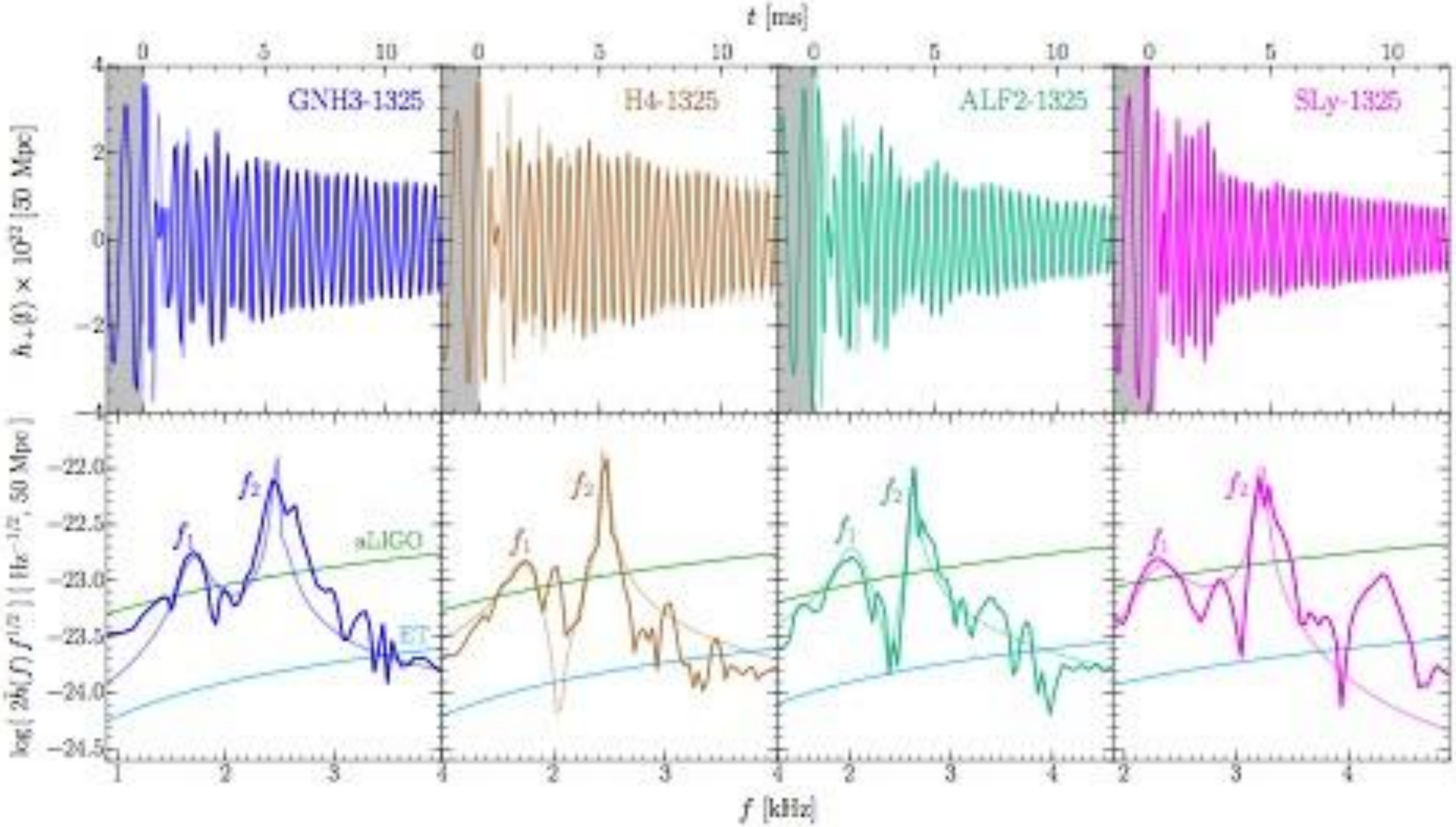
$$Q_{ij} = l \frac{d^2V(r)}{dx_i dx_j}$$

⍰ tidal distortion



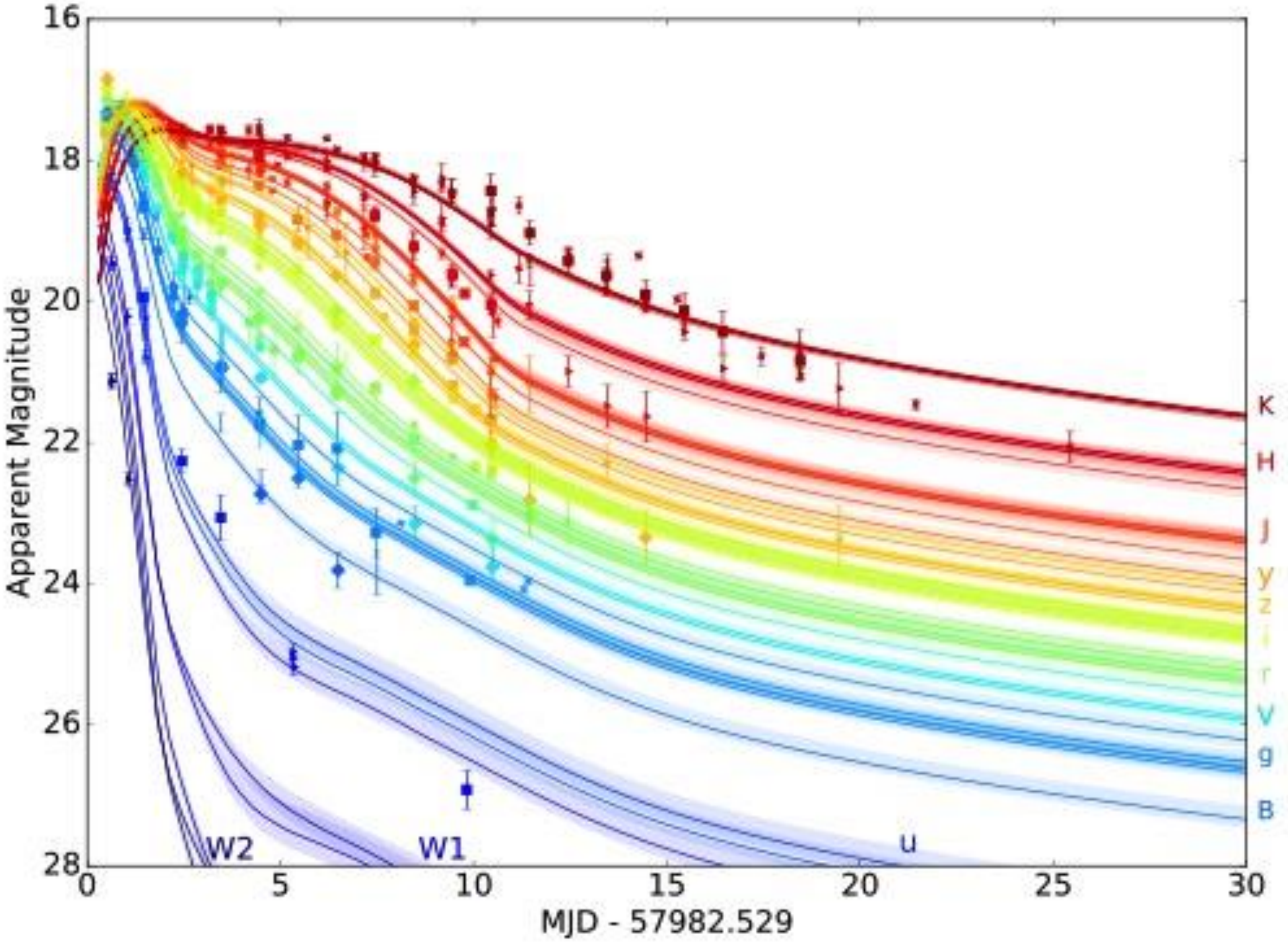


Binary neutron star spectroscopy



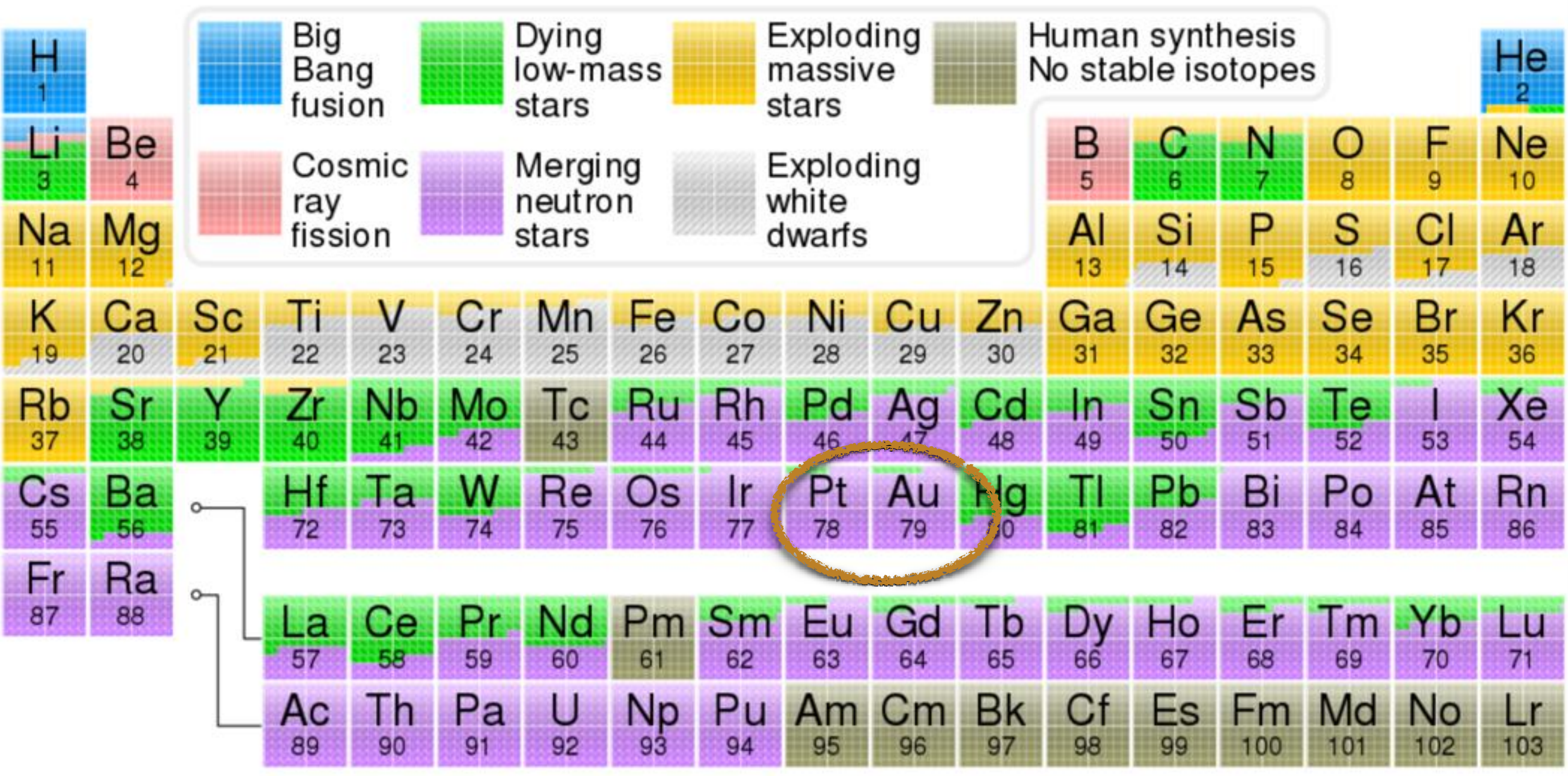
S.Bose,K.Chakravarti, L.Rezzolla, B.S. Sathyaprakash, K. Takami

Broad band kilonova spectra vs time

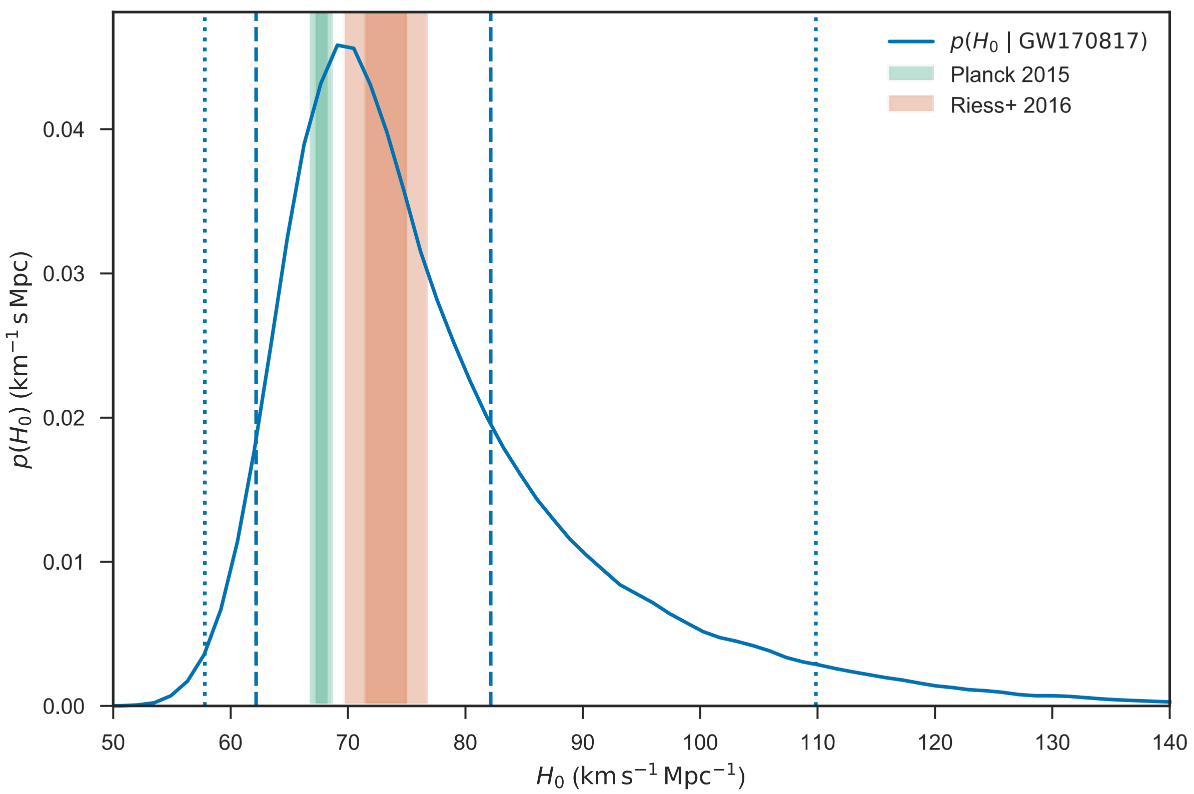


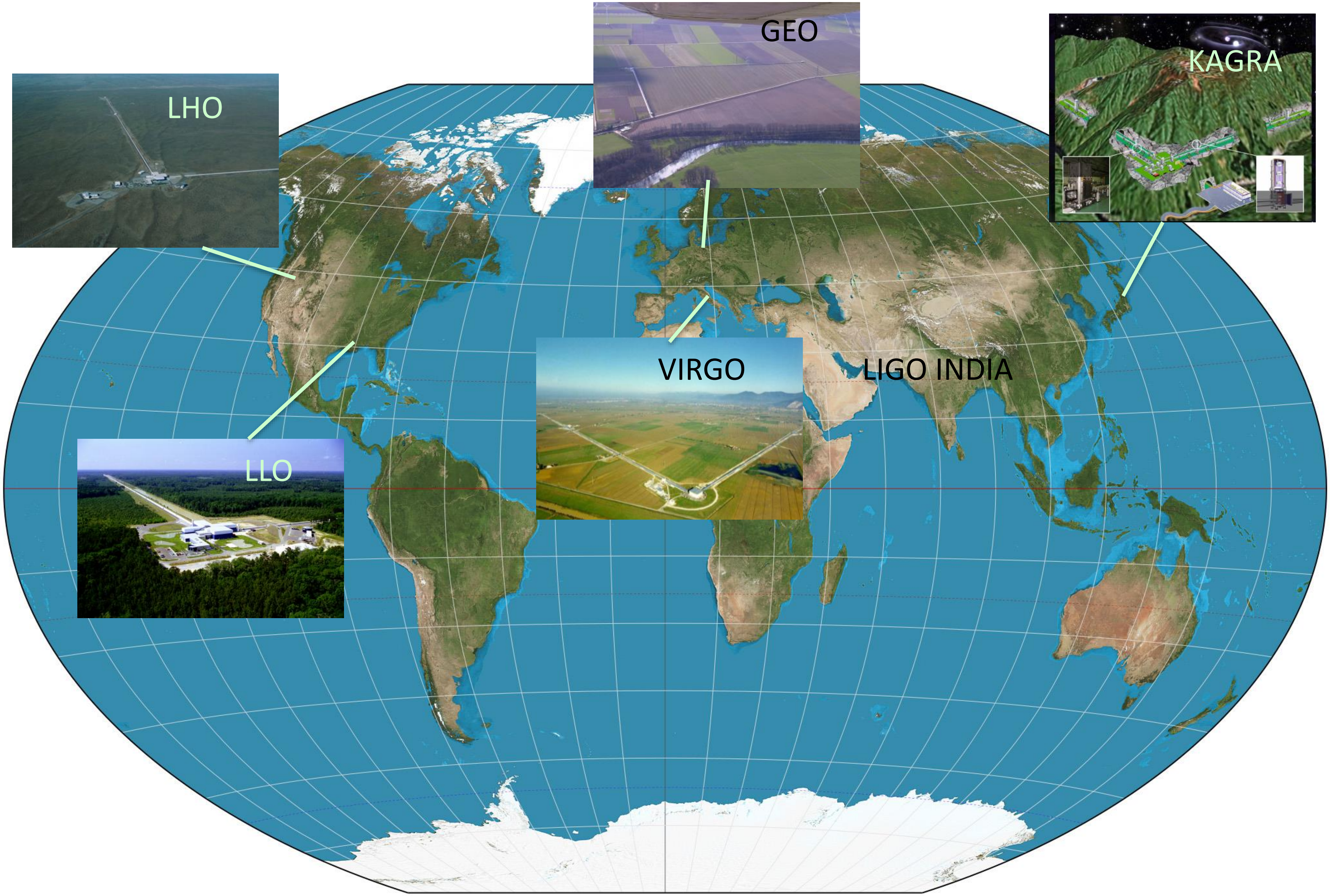
Villar et al arXiv astroph 1710.11576

Origin of the elements

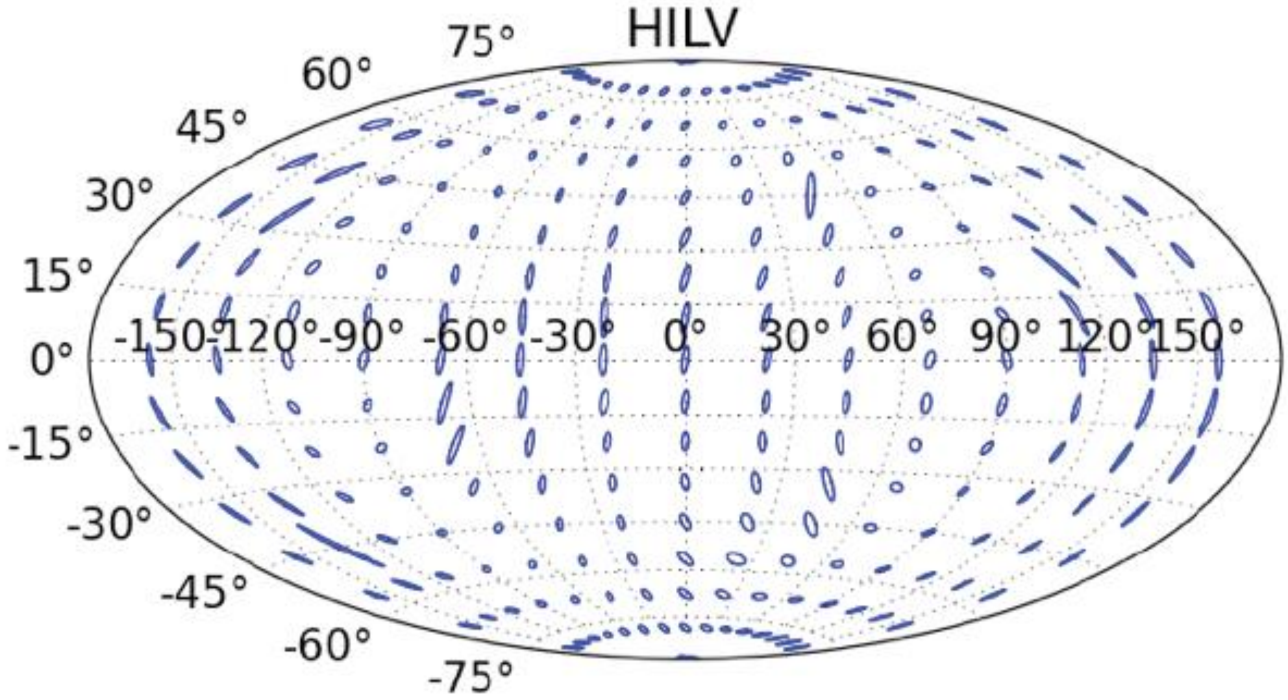


Hubble constant measurement: Galaxy z and distance from GW amplitude

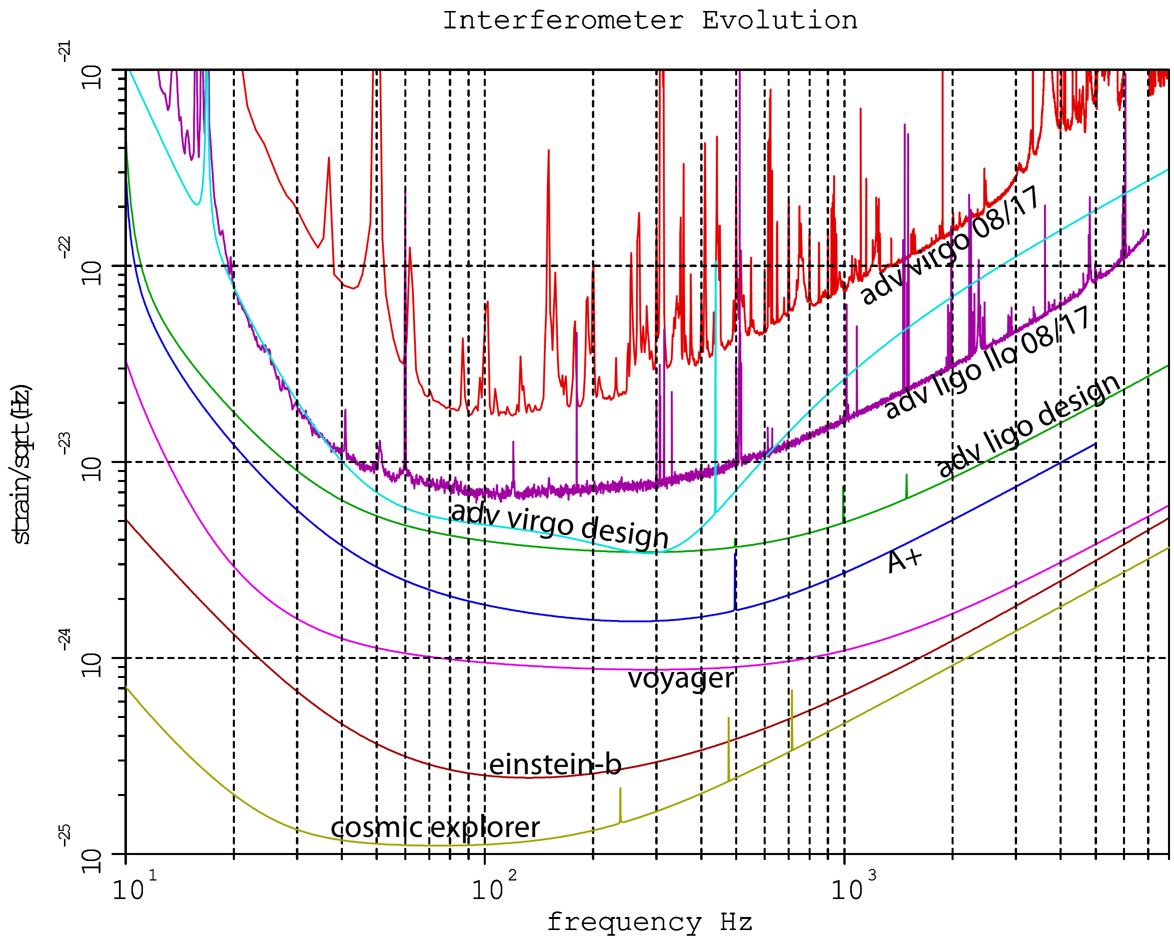



GEO
KAGRA
LHO
VIRGO
LIGO INDIA
LLO

Localization with more detectors

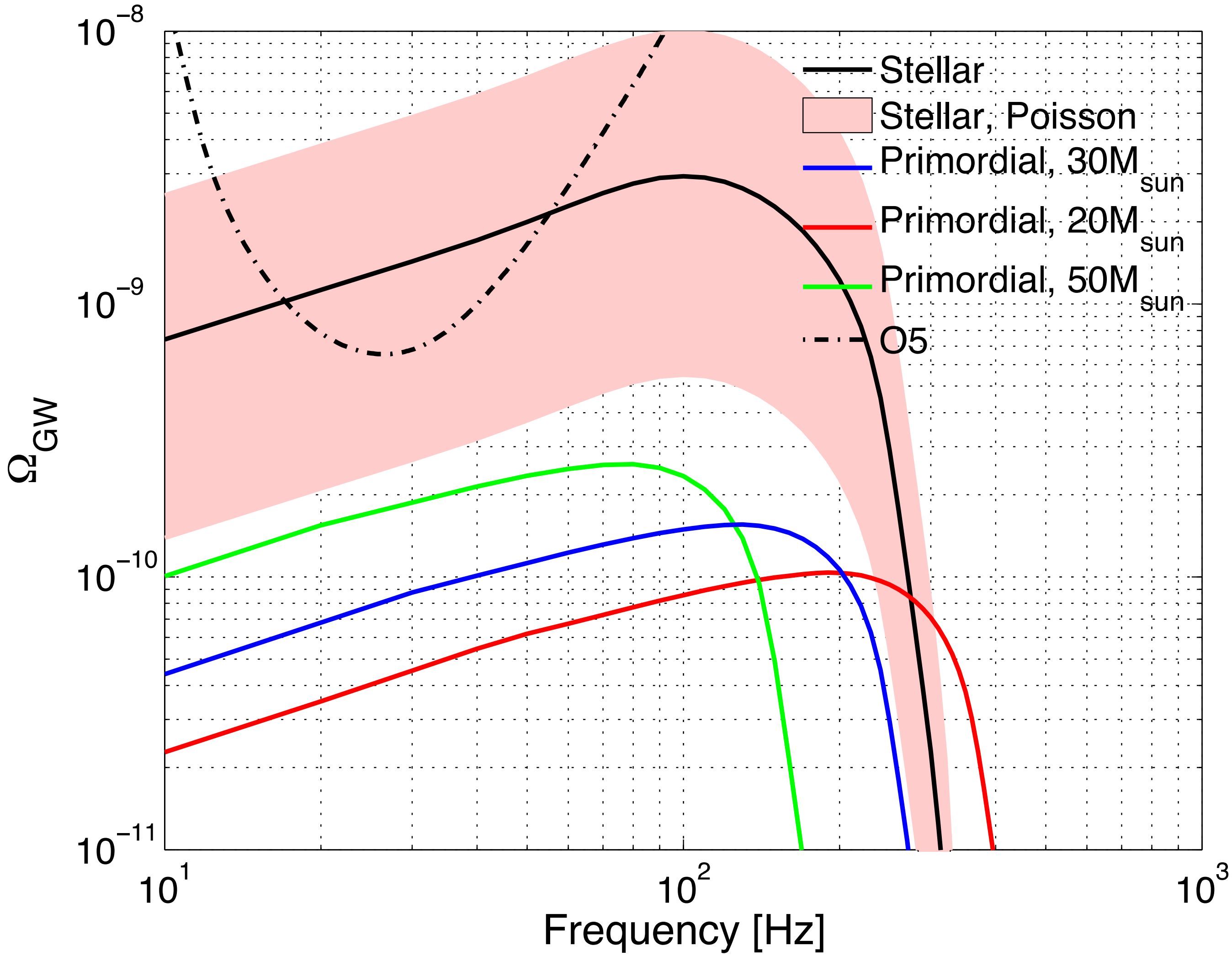


Fairhurst 2011

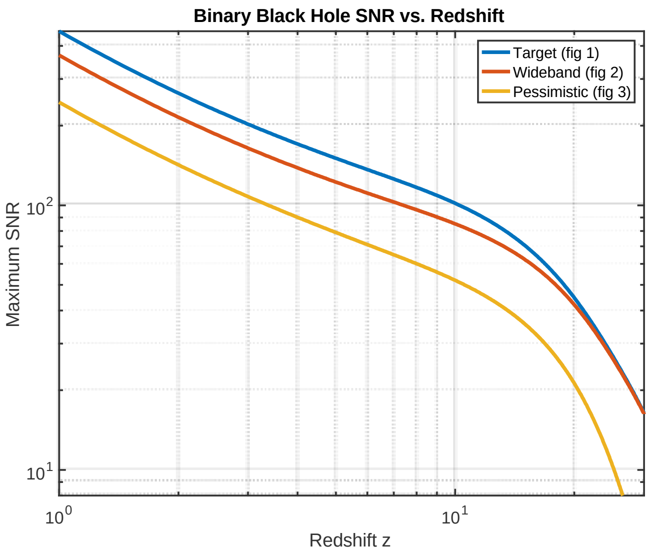


Interferometer Evolution
strain/sqrt (Hz)
frequency Hz
adv virgo 08/17
adv ligo llo 08/17
adv ligo design
adv virgo design
A+
voyager
einstein-b
cosmic explorer

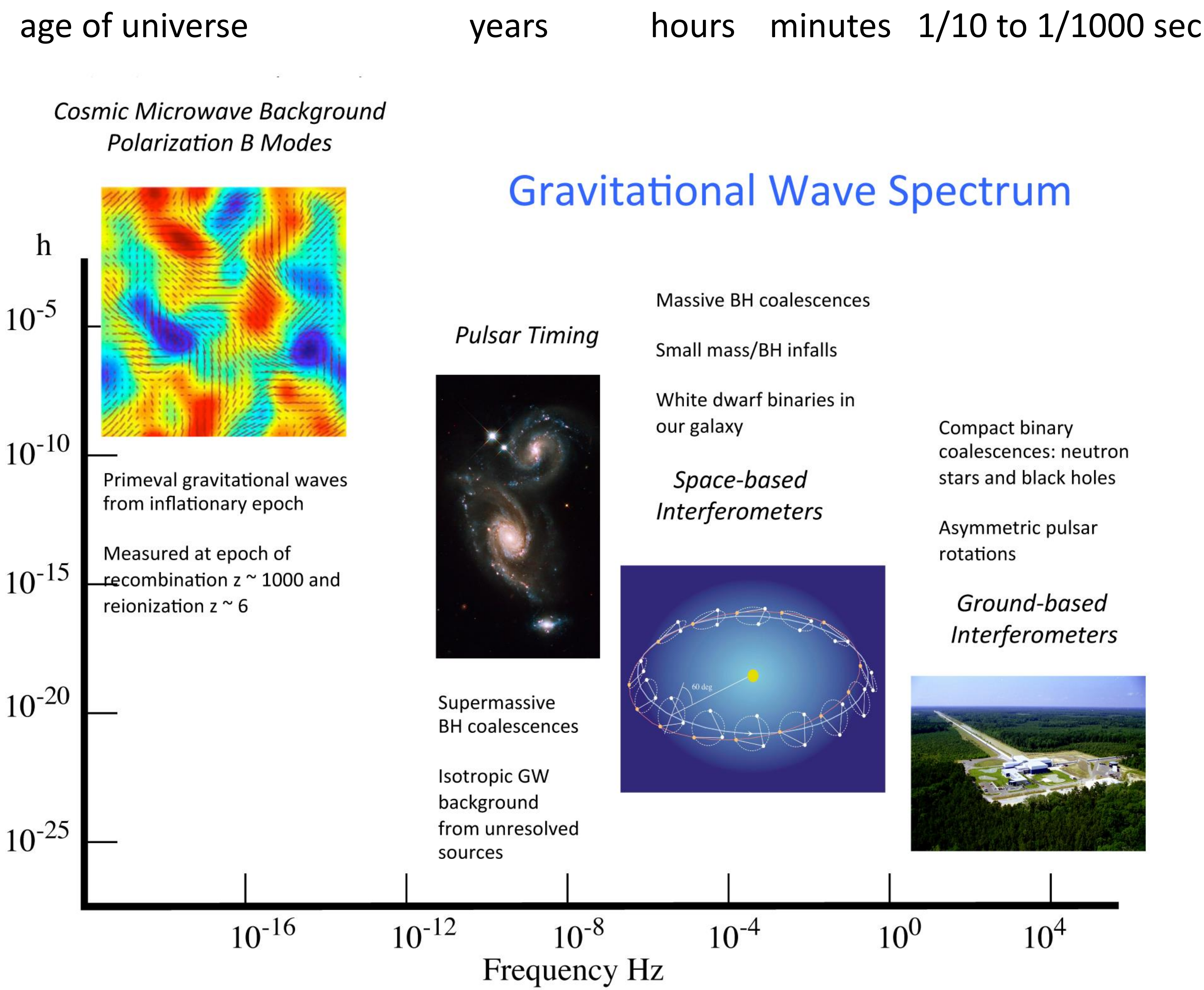
stochastic background of PBHs



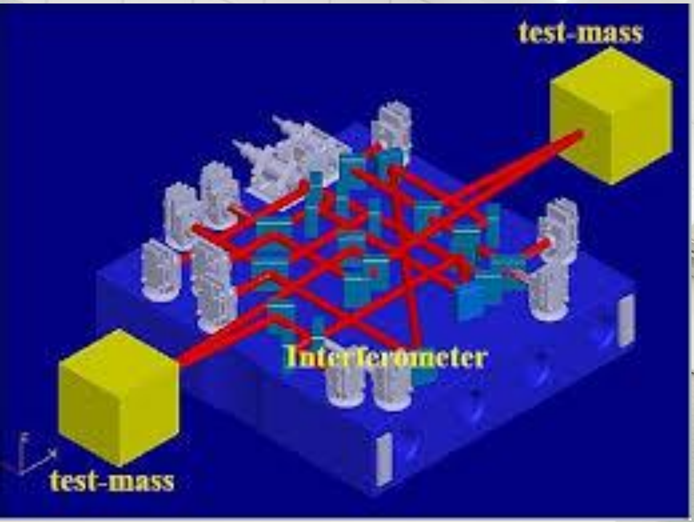
(Mandic et al. 2017)

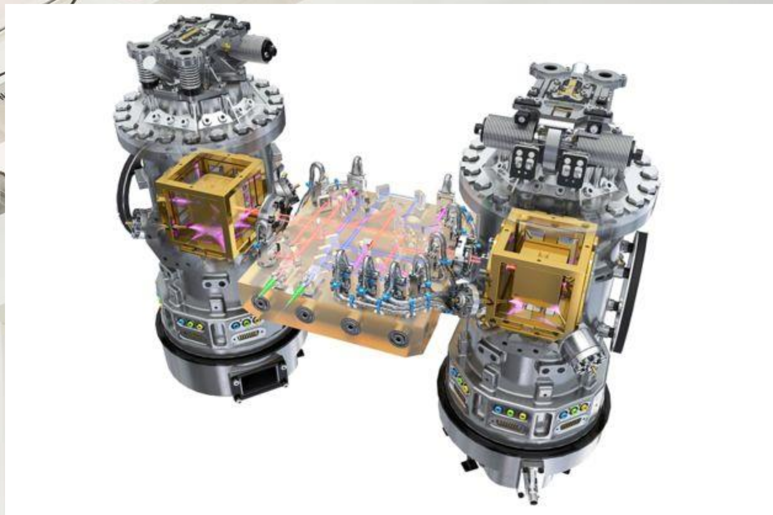


Binary Black Hole SNR vs. Redshift
Target (fig 1)
Wideband (fig 2)
Pessimistic (fig 3)
Maximum SNR
10^2
10^1
10^0
10^1
Redshift z

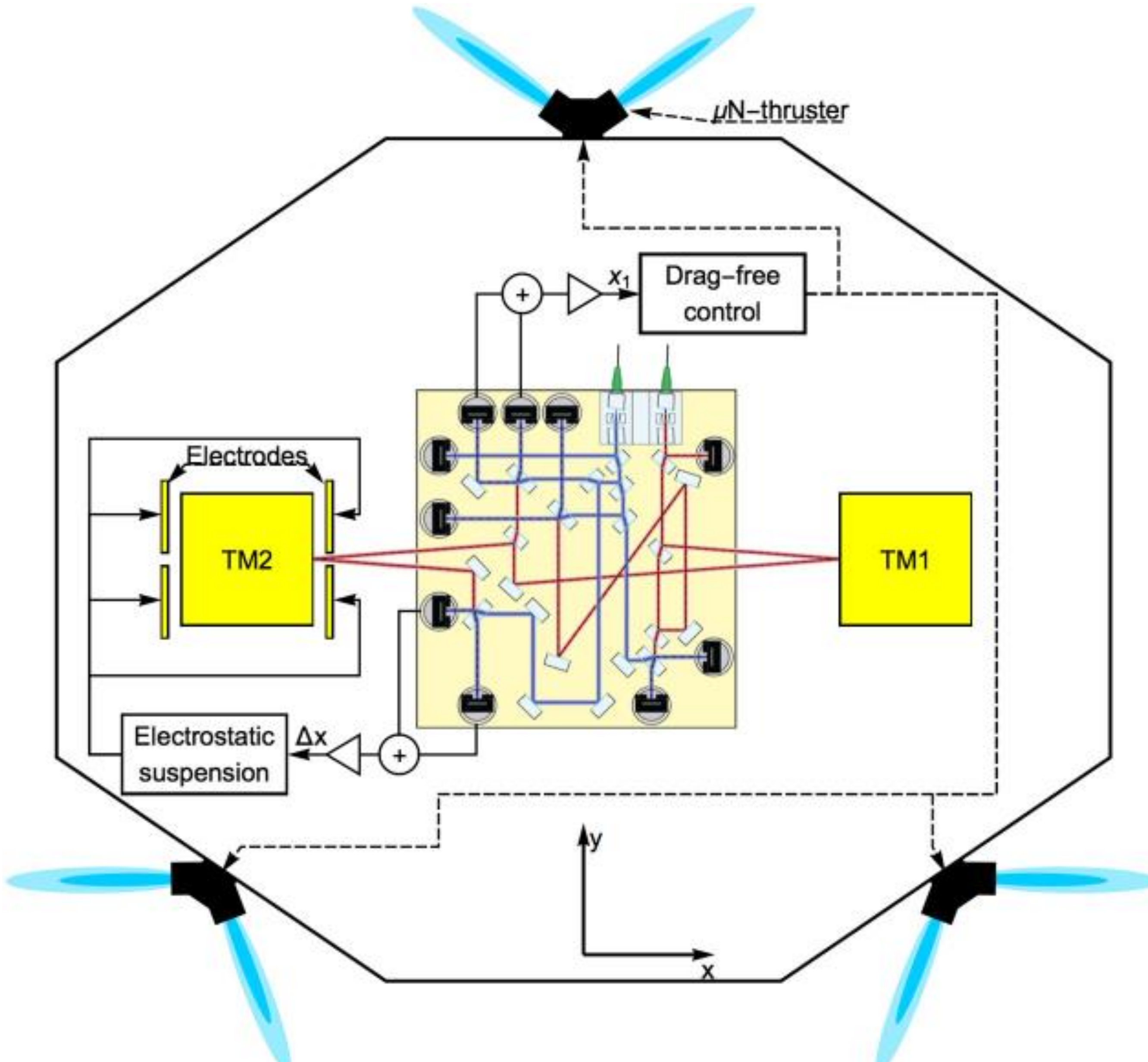

age of universe
years
hours
minutes
1/10 to 1/1000 sec
Cosmic Microwave Background
Polarization B Modes
Gravitational Wave Spectrum
h
10-5
10-10
10-15
10-20
10-25
Primeval gravitational waves
from inflationary epoch
Measured at epoch of
recombination z ~ 1000 and
reionization z ~ 6
Pulsar Timing
Supermassive
BH coalescences
Isotropic GW
background
from unresolved
sources
Massive BH coalescences
Small mass/BH infalls
White dwarf binaries in
our galaxy
Space-based
Interferometers
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

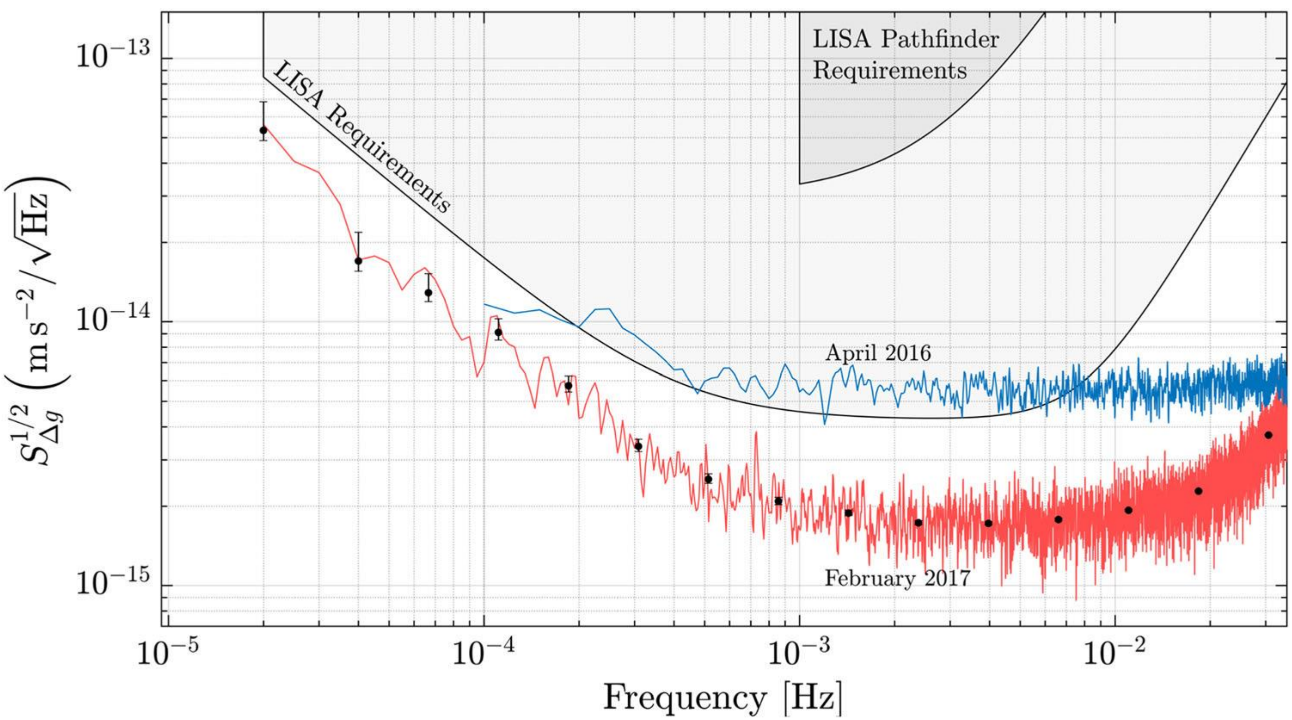
LISA Pathfinder

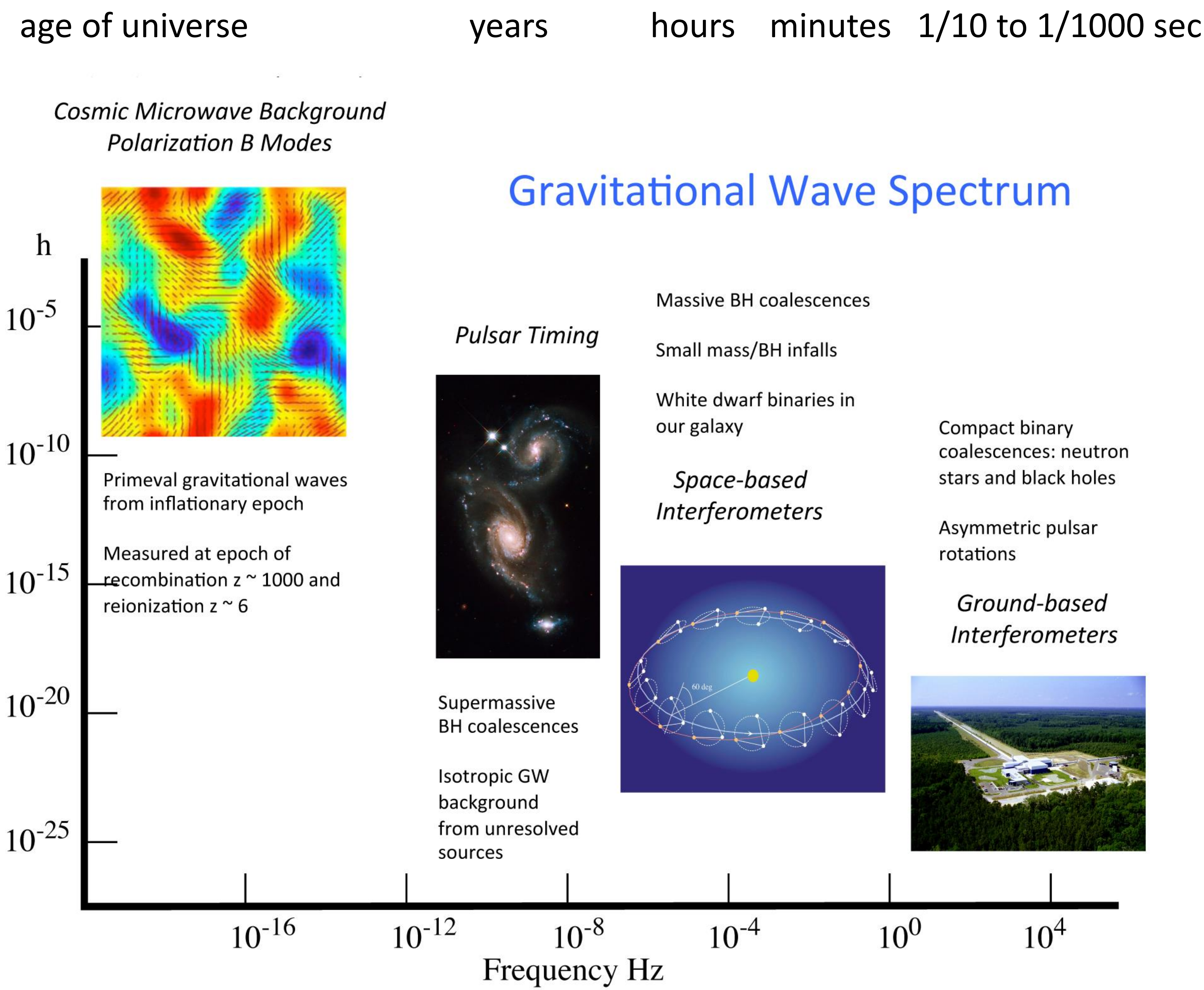




Launched 12/03/2015
At L1, masses released
Passed acceleration tests
Next, thruster tests


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


LISA Pathfinder Requirements
LISA Requirements
April 2016
February 2017
10^{-13}
10^{-14}
10^{-15}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
$S_{\Delta g}^{1/2}\left(\mathrm{m\,s^{-2}}/\sqrt{\mathrm{Hz}}\right)$
Frequency [Hz]


age of universe
years
hours
minutes
1/10 to 1/1000 sec
Gravitational Wave Spectrum
Cosmic Microwave Background Polarization B Modes
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

ANU The Australian National University

Texas Tech University

R·I·T

ICTP SAIFR

Montana State University

Sonoma State University

University of the West of Scotland UWS

Montclair State University

清華大學 Tsinghua University

American University Washington, DC

Whitman College

LSU

University of Strathclyde

Michigan

CITA–ICAT

University of Glasgow

1754

NASA Goddard Space Flight Center

UTB TSC

University of Cambridge

Massachusetts Institute of Technology

Southern University Agricultural & Mechanical College

The University of Western Australia

California Institute of Technology 1891

University of Minnesota

The University of Mississippi

The University of Adelaide Australia

The University of Melbourne

Embry-Riddle Aeronautical University

University of Washington

Northwestern University 1851

GEO 600

Universitat de les Illes Balears

Carleton College

Georgia Tech

Syracuse University Founded AD 1870

Cardiff University

Charles Sturt University

UF University of Florida

University of Wisconsin UW Milwaukee

Universität Hamburg

ACIGA

University of Southampton

Korean Gravitational-Wave Group

University of Rochester

Leibniz Universität Hannover

PennState 1855

Hobart and William Smith Colleges

Science & Technology Facilities Council Rutherford Appleton Laboratory

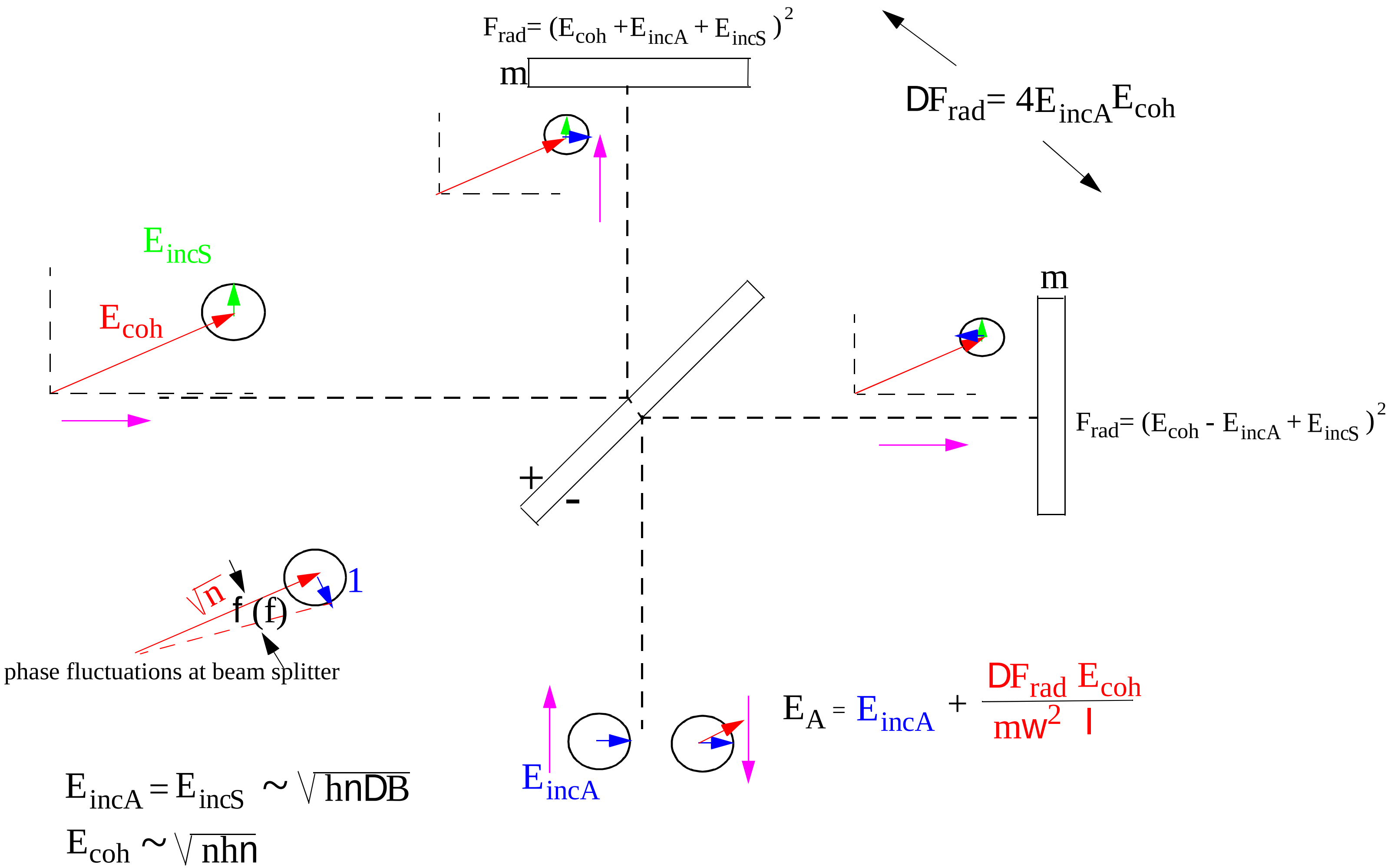
SPARE SLIDES

PHYSICAL REVIEW D VOLUME 23, NUMBER 8 15 APRIL 1981

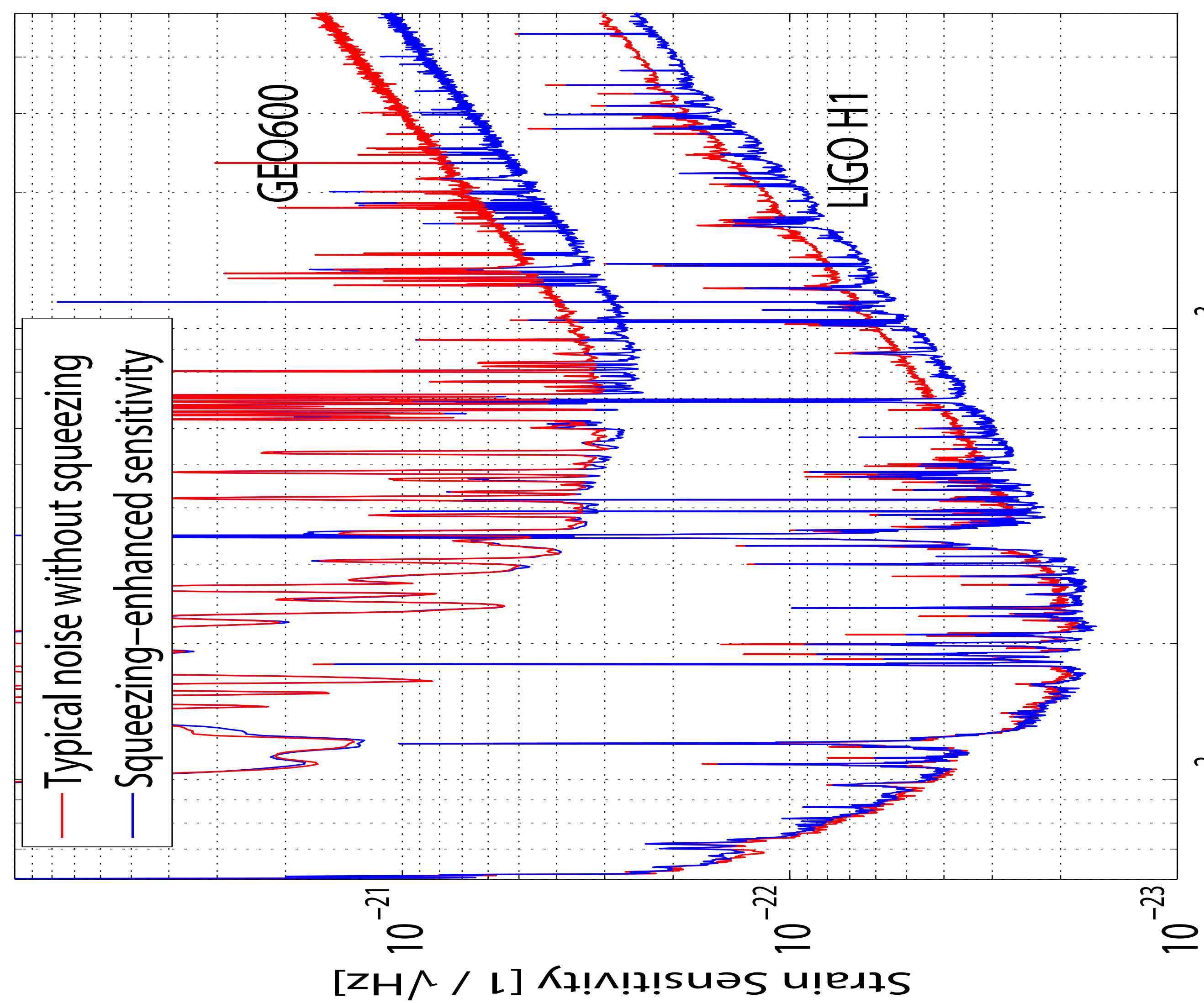
Quantum-mechanical noise in an interferometer

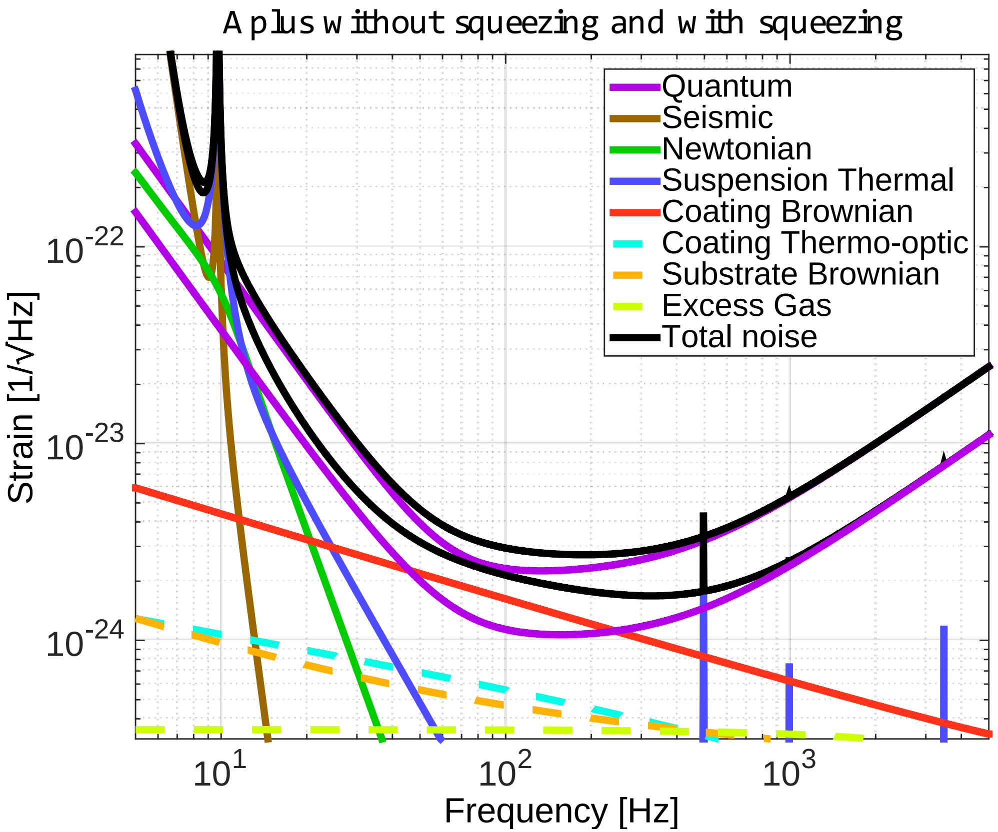
Carlton M. Caves
W. K. Kellogg Radiation Laboratory, California Institute of Technology, Pasadena, California 91125

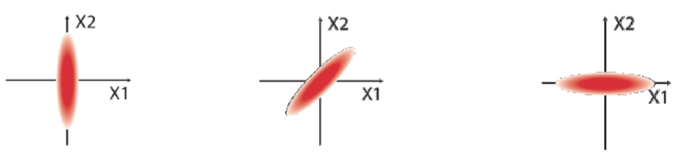
(Received 15 August 1980)

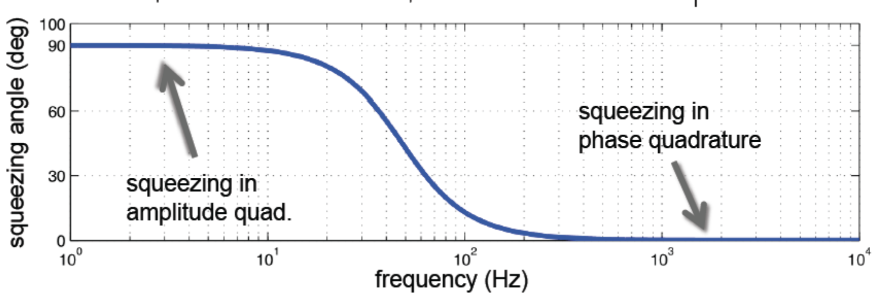


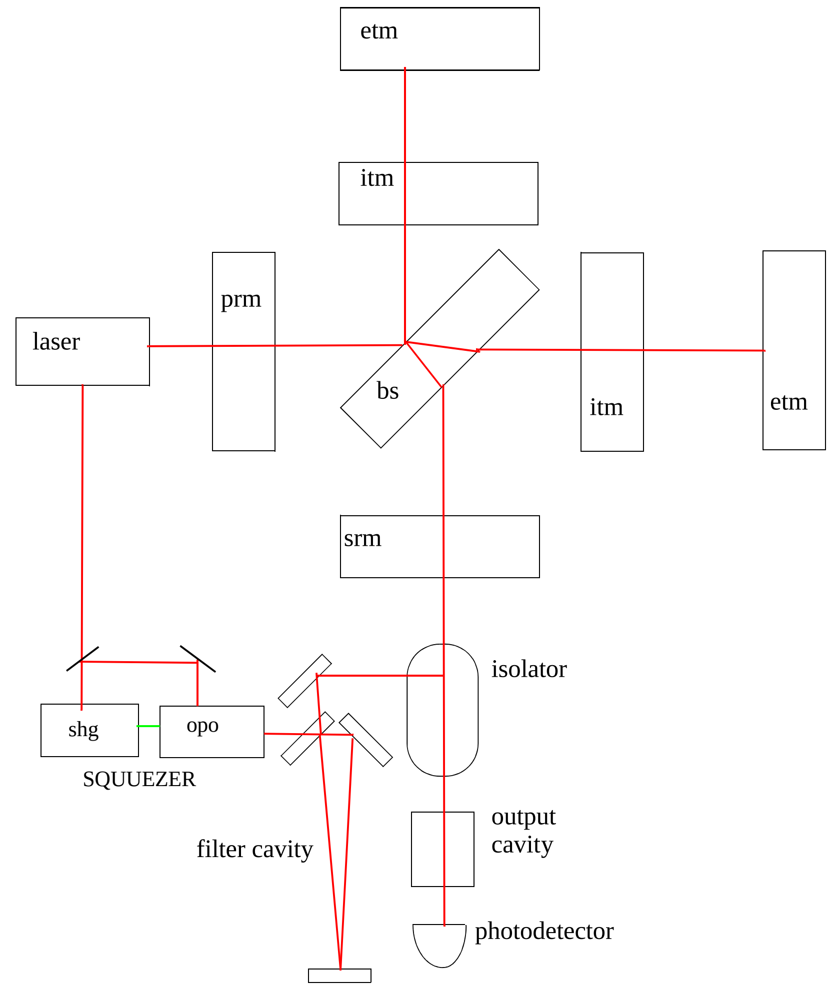
Squeezed light in gravitational wave interferometers





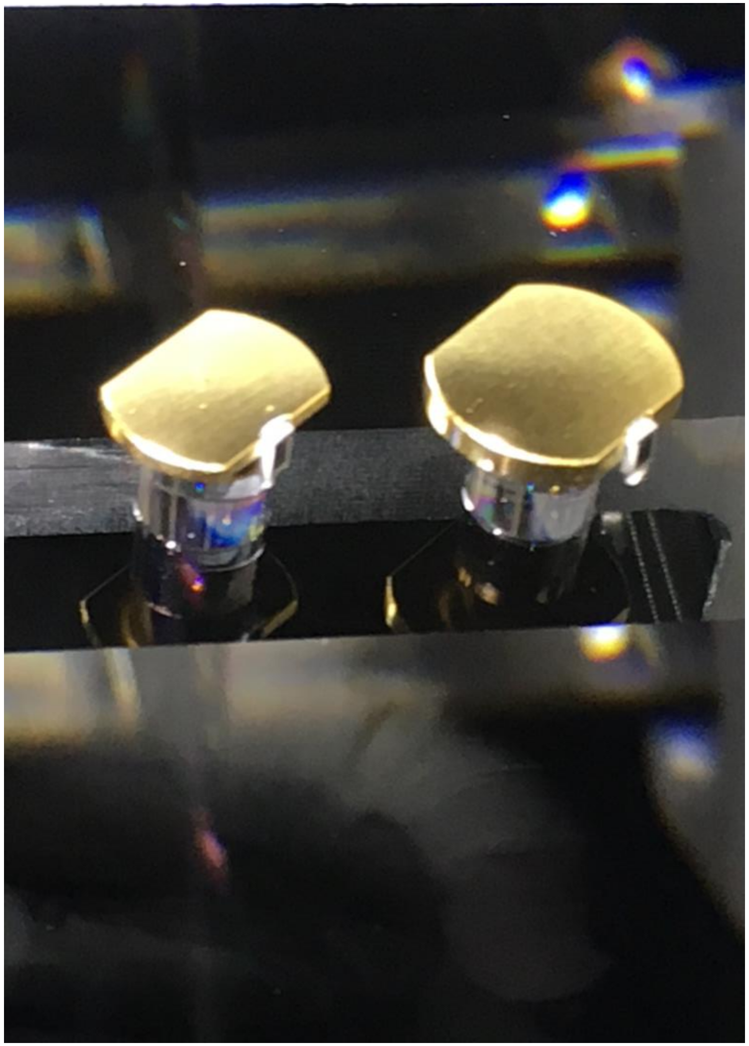


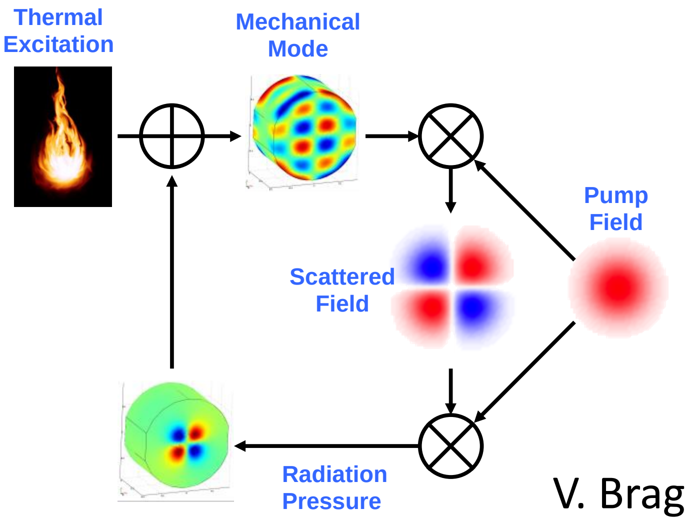




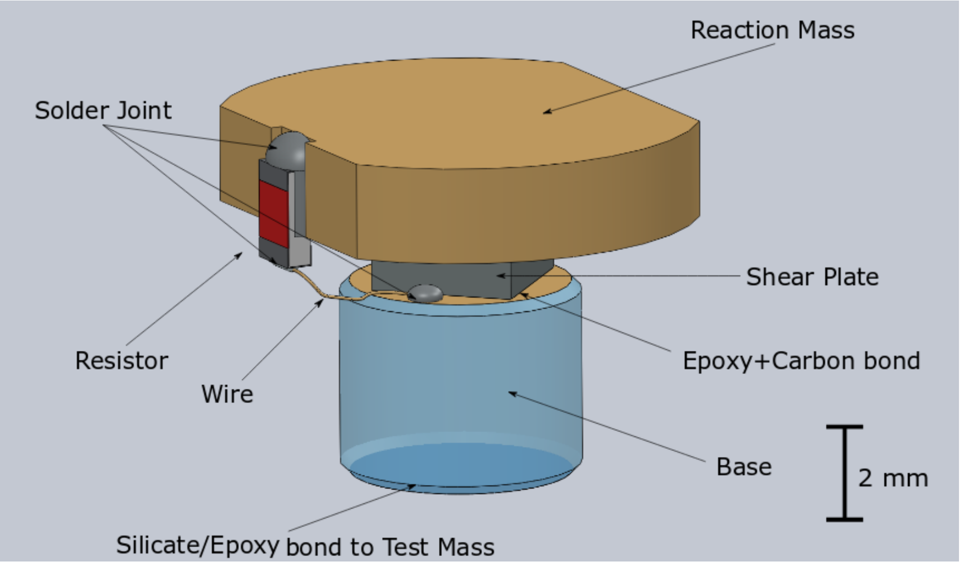
E.Oelker, T. Isogai, J.Miller, M.Tse, L.Barsotti,N.Mavalvala,M.Evans

Acoustic mode damper for test mass : reduce parametric instability

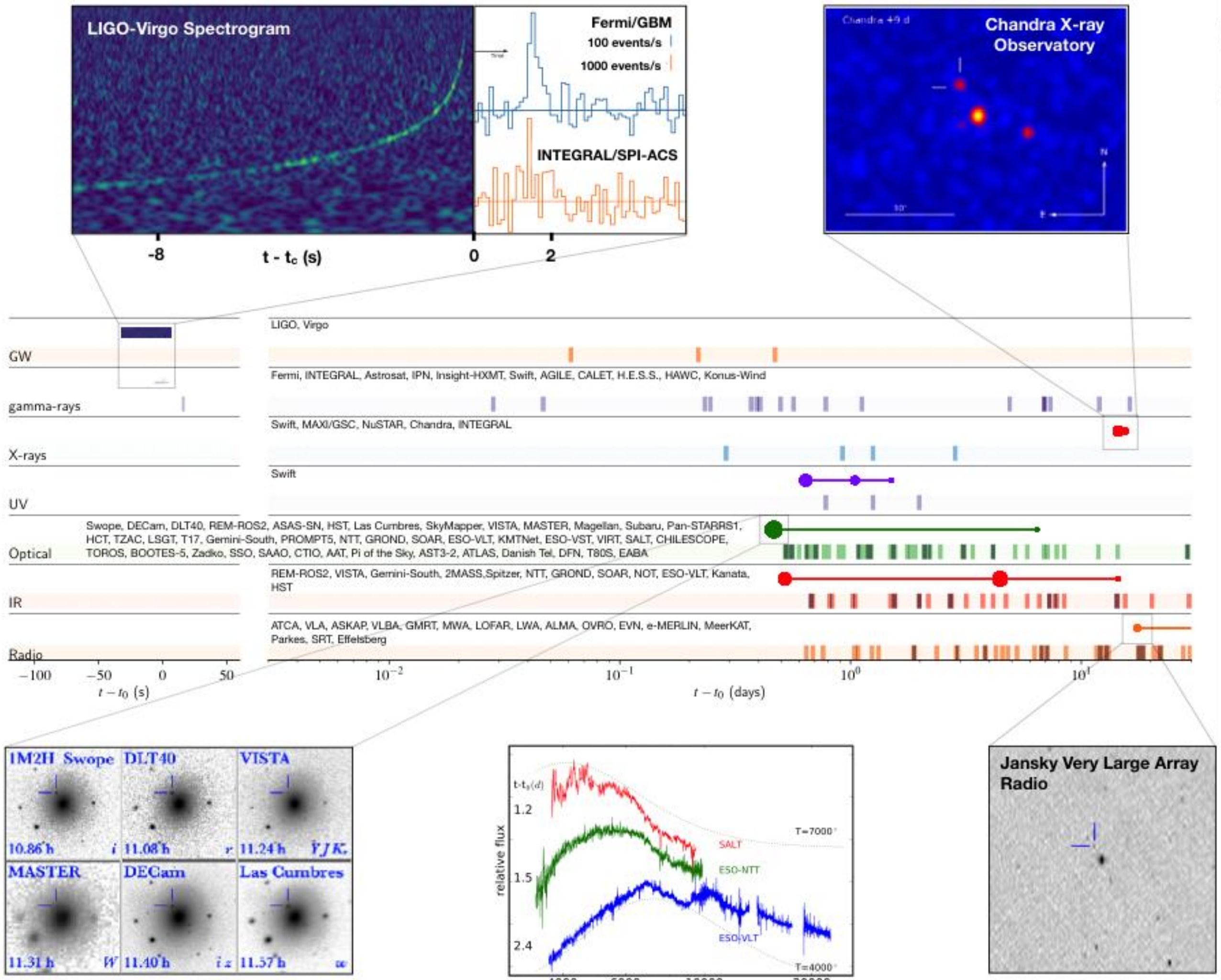




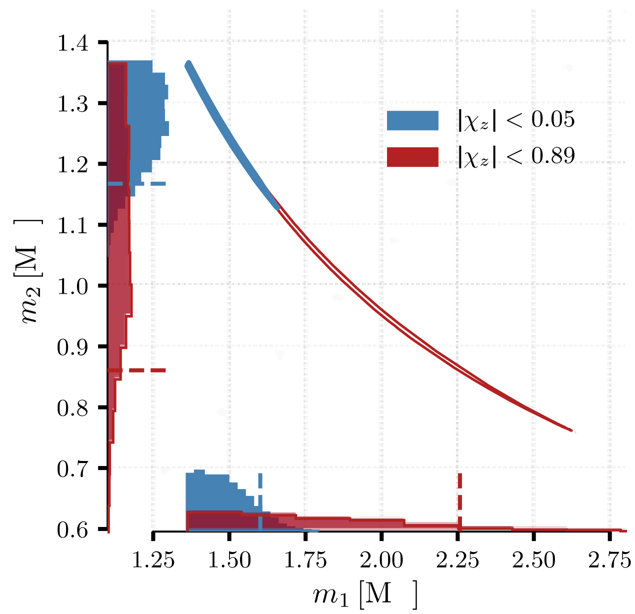
V. Braginsky



S.Gras, S. Biscans, M.Evans, L.Barsotti, P.Fritschel



LIGO-Virgo Spectrogram
Fermi/GBM
100 events/s
1000 events/s
INTEGRAL/SPI-ACS
t - tc (s)
Chandra X-ray Observatory
LIGO, Virgo
GW
Fermi, INTEGRAL, Astrosat, IPN, Insight-HXMT, Swift, AGILE, CALET, H.E.S.S., HAWC, Konus-Wind
gamma-rays
Swift, MAXI/GSC, NuSTAR, Chandra, INTEGRAL
X-rays
Swift
UV
Swope, DECam, DLT40, REM-ROS2, 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
Optical
REM-ROS2, VISTA, Gemini-South, 2MASS,Spitzer, NTT, GROND, SOAR, NOT, ESO-VLT, Kanata, HST
IR
ATCA, VLA, ASKAP, VLBA, GMRT, MWA, LOFAR, LWA, ALMA, OVRO, EVN, e-MERLIN, MeerKAT, Parkes, SRT, Effelsberg
Radio
t − t0 (s)
t − t0 (days)
1M2H Swope
DLT40
VISTA
MASTER
DECam
Las Cumbres
10.86 h
11.08 h
11.24 h
11.31 h
11.40 h
11.57 h
relative flux
SALT
ESO-NTT
ESO-VLT
T=7000
T=4000
Jansky Very Large Array Radio



1.4
1.3
1.2
1.1
1.0
0.9
0.8
0.7
0.6
m_2 [M]
1.25
1.50
1.75
2.00
2.25
2.50
2.75
m_1 [M]
$|\chi_z| < 0.05$
$|\chi_z| < 0.89$

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."

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

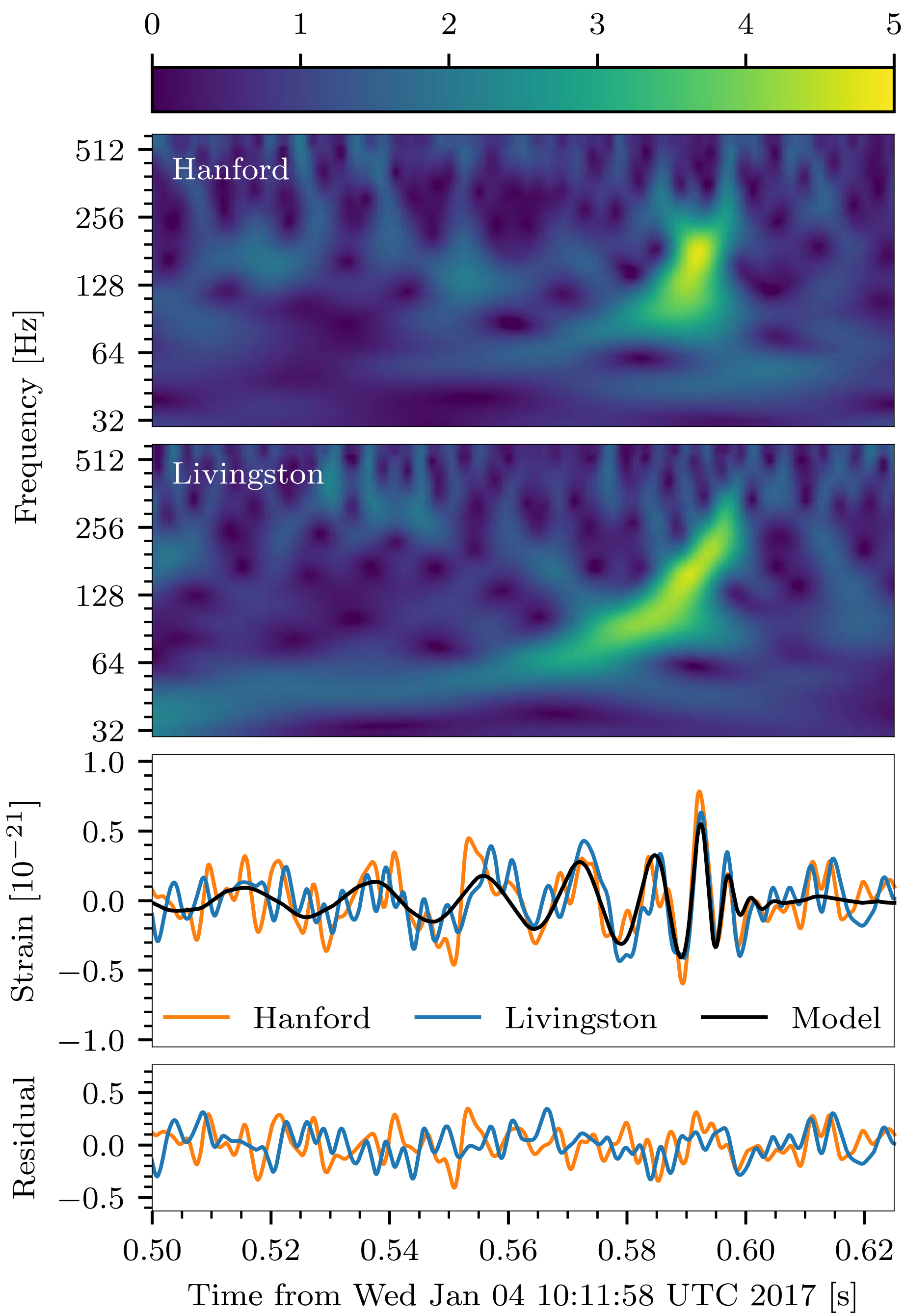
1916 examples: train colllision | binary star decay

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

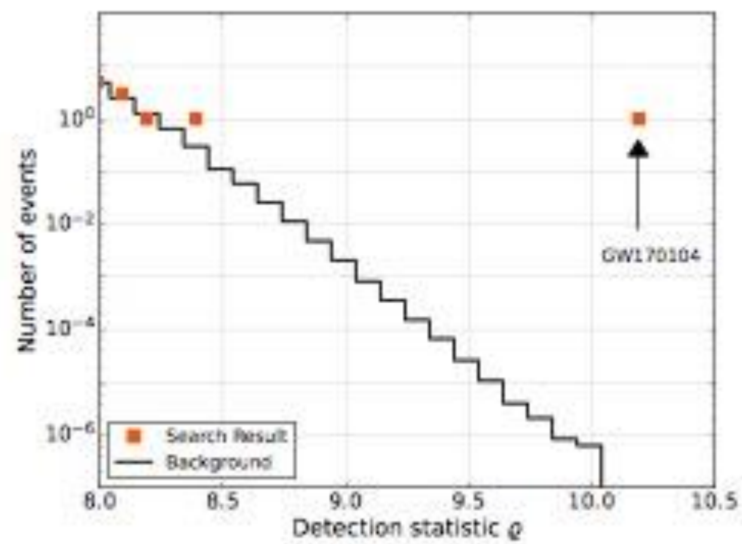
$m_1 = m_2$ = 1 solar mass
T_{orbit} = 1 day
R = 10 Kly

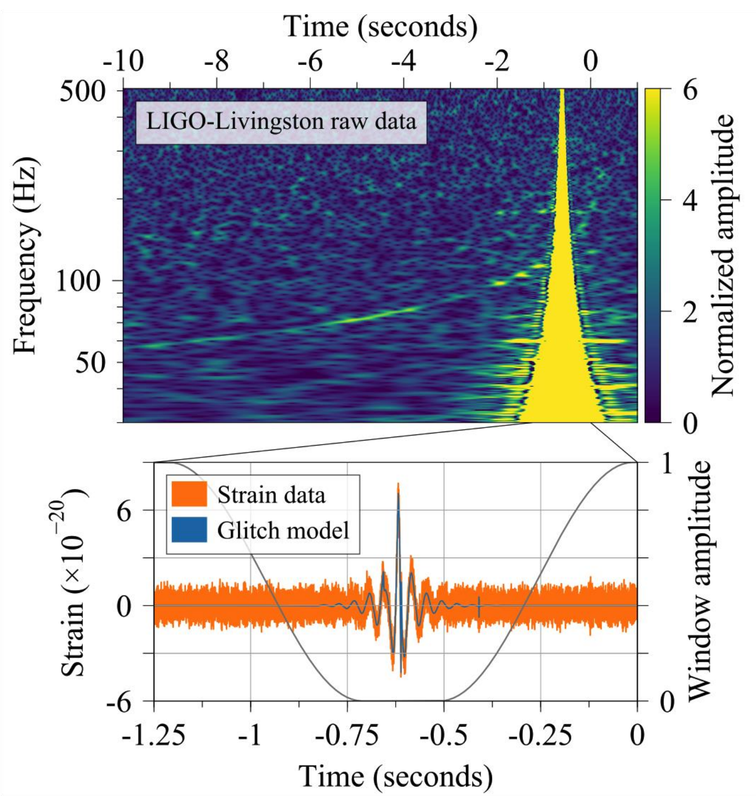
$h \sim 10^{-23}$ @ ½ day period

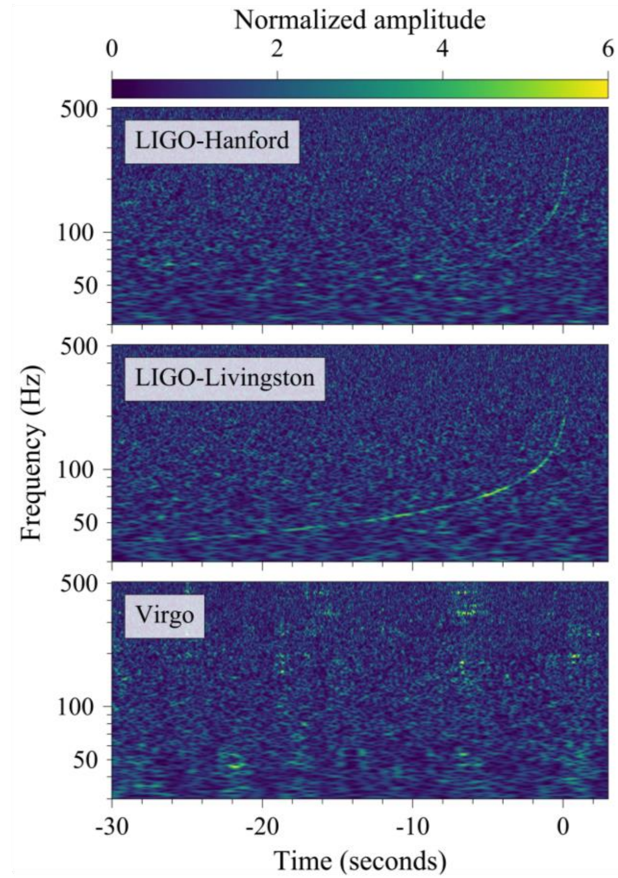
$$Q = \frac{2\pi E_{stored}}{\Delta E_{1period}} \sim 10^{15} \qquad \text{decay time} \sim 10^{13}\ \text{years}$$

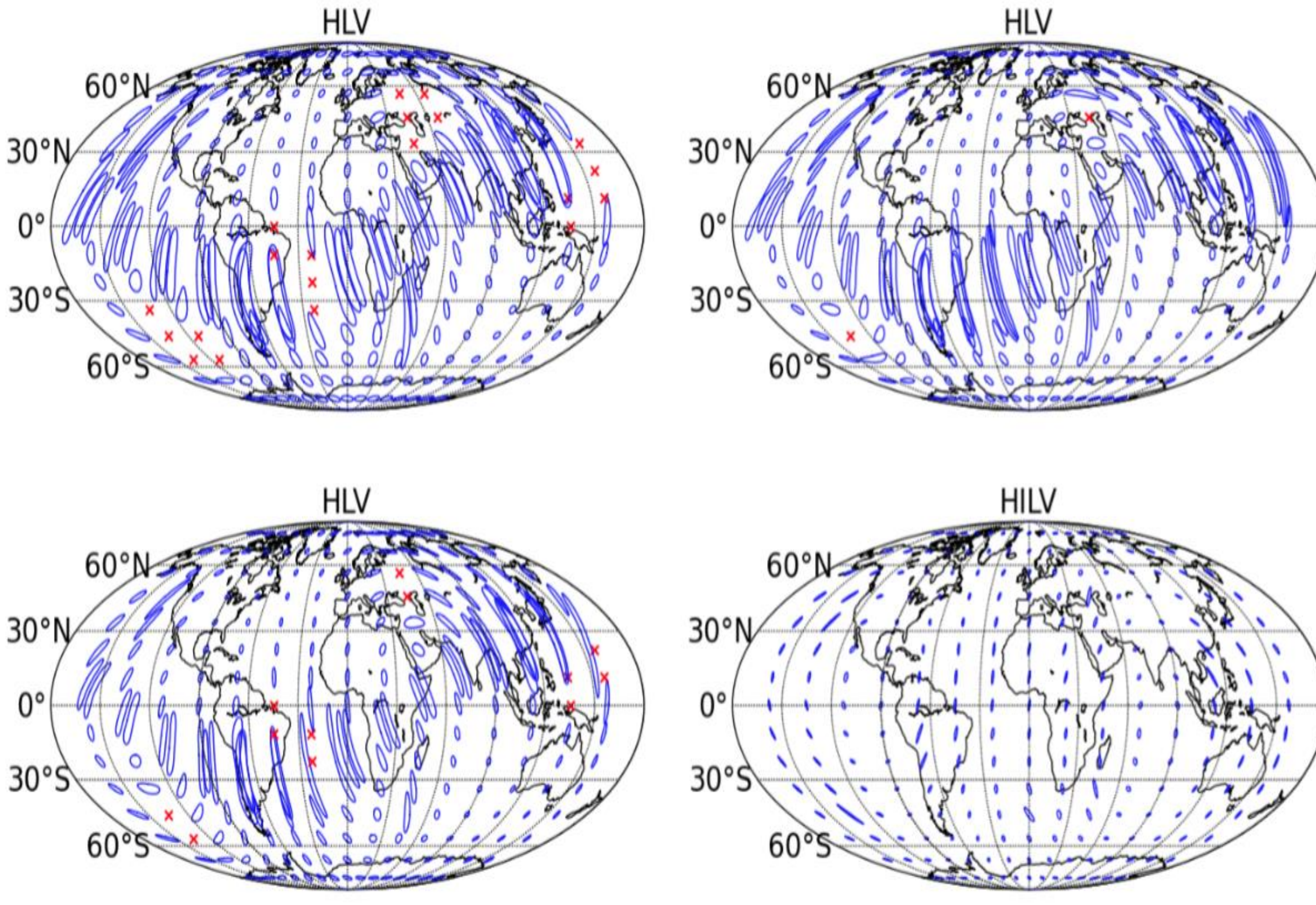

0 1 2 3 4 5
Hanford
Livingston
Frequency [Hz]
512
256
128
64
32
Strain [10^−21]
1.0
0.5
0.0
−0.5
−1.0
Hanford
Livingston
Model
Residual
0.5
0.0
−0.5
0.50 0.52 0.54 0.56 0.58 0.60 0.62
Time from Wed Jan 04 10:11:58 UTC 2017 [s]

GW 170104

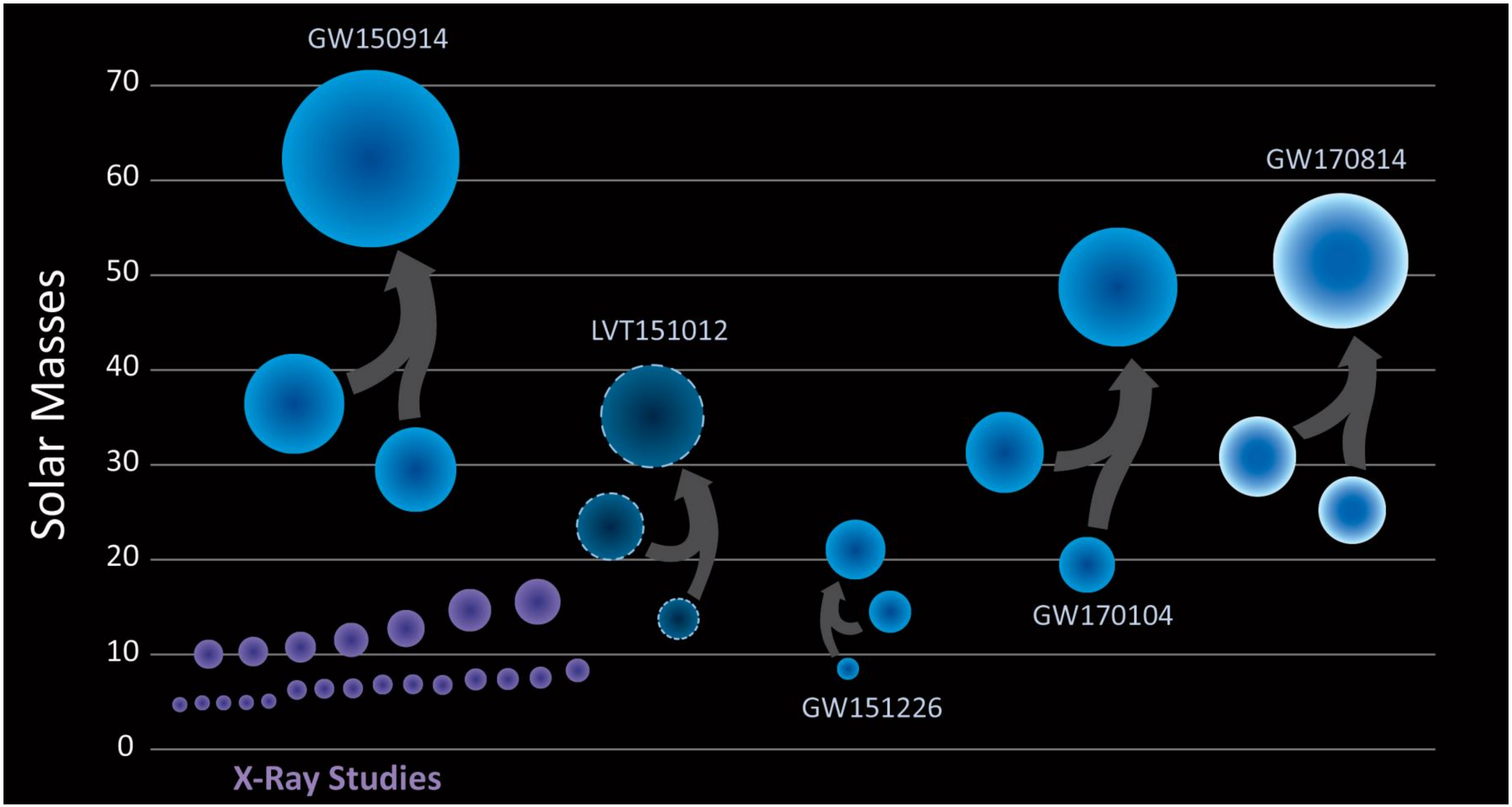

Number of events
GW170104
Search Result
Background
8.0 8.5 9.0 9.5 10.0 10.5
Detection statistic ρ


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)


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

“Solar Mass” Black Holes



Credit: LIGO/Caltech/Sonoma State (Simonnet)

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