Gravitational Waves: Astrophysics, Technical Challenges and Prospects for the Future

Rainer Weiss on behalf of the LIGO Scientific Collaboration

CTA Symposium

Bologna, Italy

May 7, 2019

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

Montana State University

American University Washington, DC

University of the West of Scotland UWS

Montclair State University

R·I·T

ICTP SAIFR

Tsinghua University

University of Strathclyde

Michigan

University of Glasgow

1754

NASA Goddard Space Flight Center

Whitman College

LSU

CITA–ICAT

UTB TSC

University of Cambridge

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

GEO 600

Universitat de les Illes Balears

Cardiff University

Georgia Tech

Syracuse University Founded AD 1870

Charles Sturt University

UF University of Florida

University of Wisconsin UW Milwaukee

Korean Gravitational-Wave Group

Universität Hamburg

ACIGA

University of Southampton

Penn State 1855

University of Rochester

Leibniz Universität Hannover

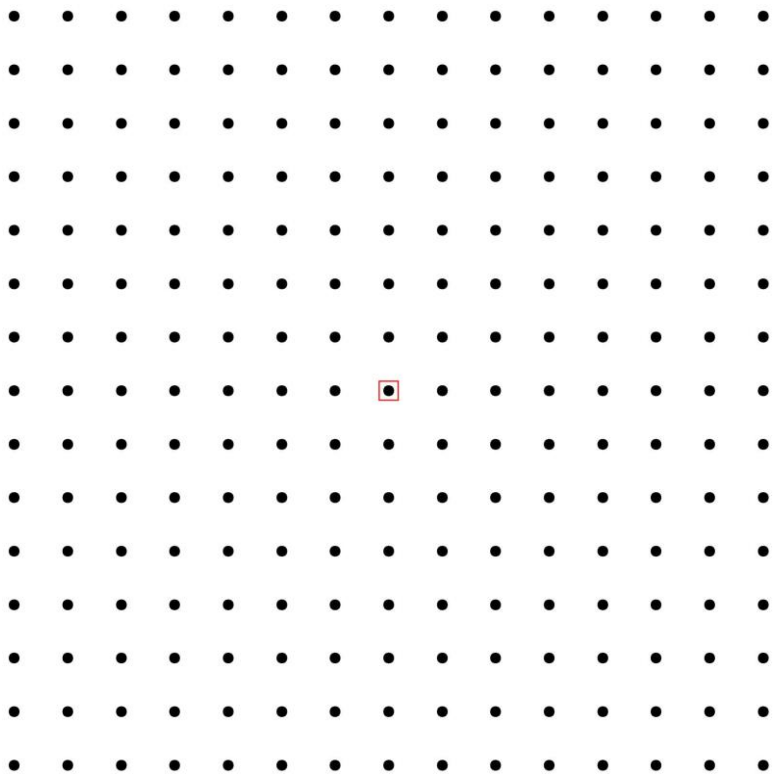
William Smith College

Science & Technology Facilities Council Rutherford Appleton Laboratory

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)



Gravitational waves

Einstein 1916 and 1918

- Sources: non-spherically symmetric accelerated masses
- Kinematics:
  - propagate at speed of light
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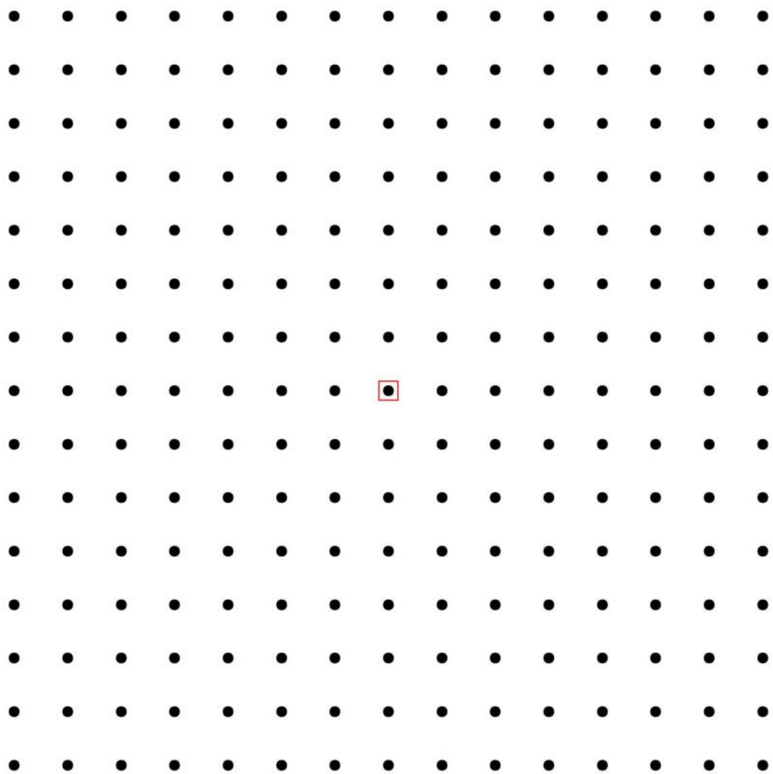
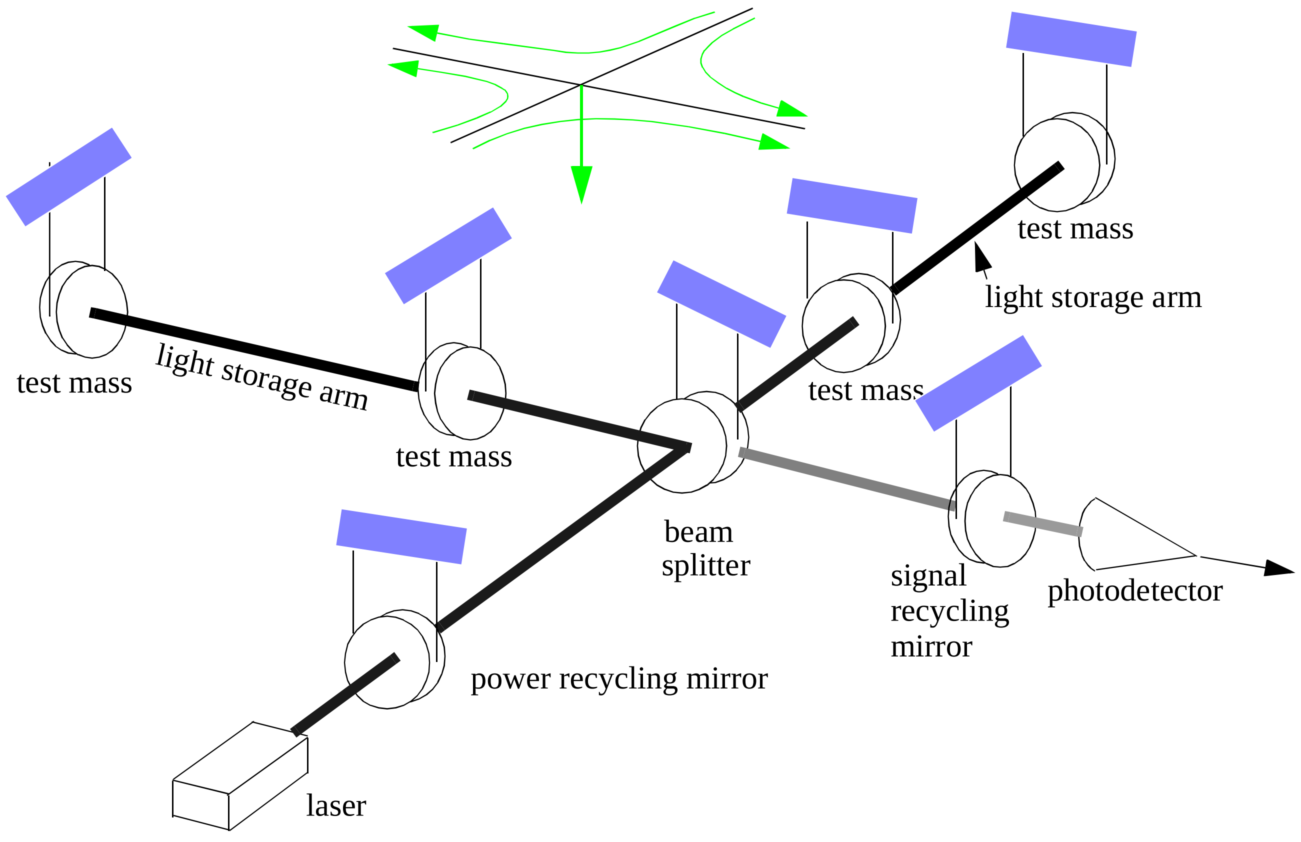
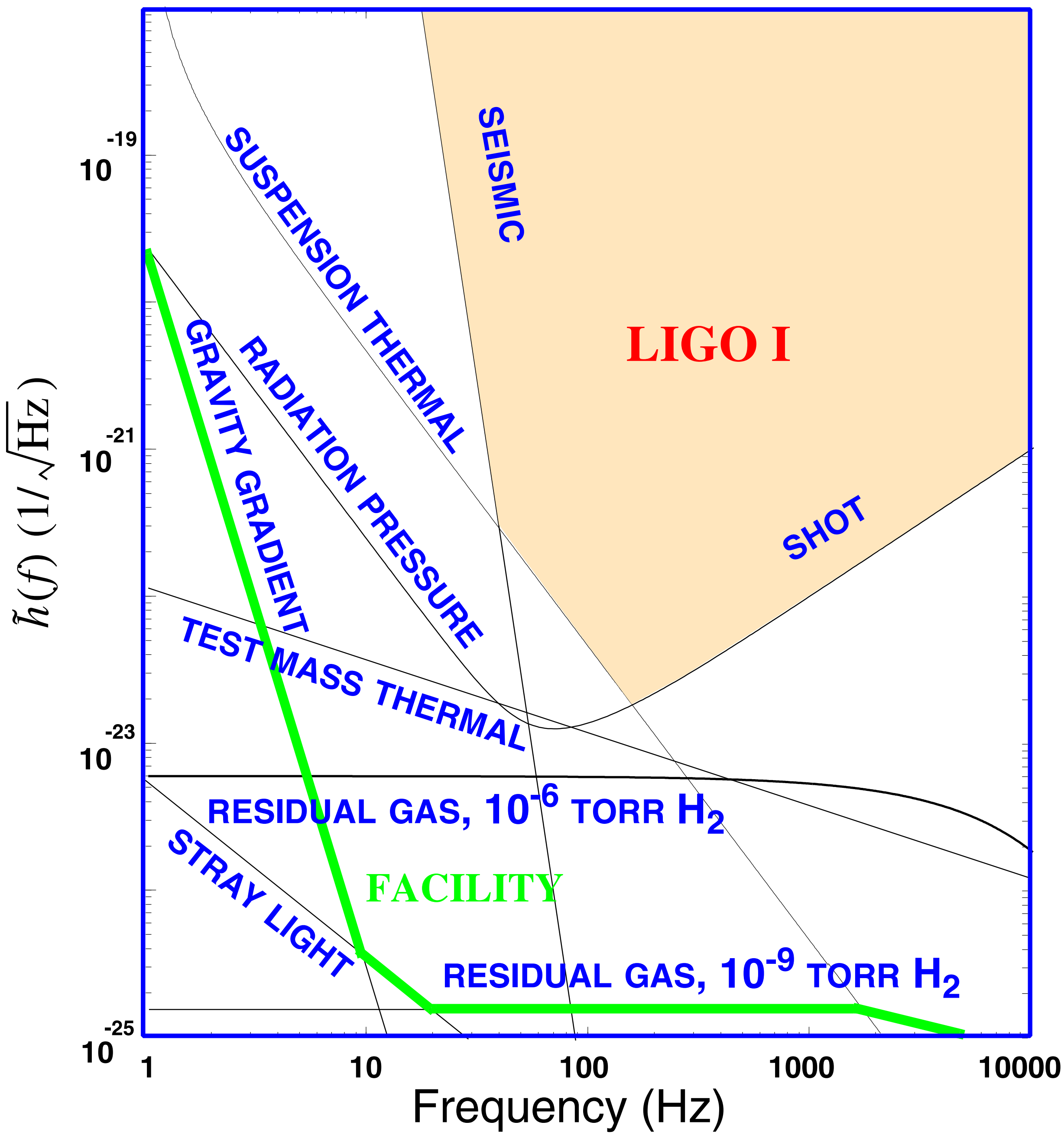
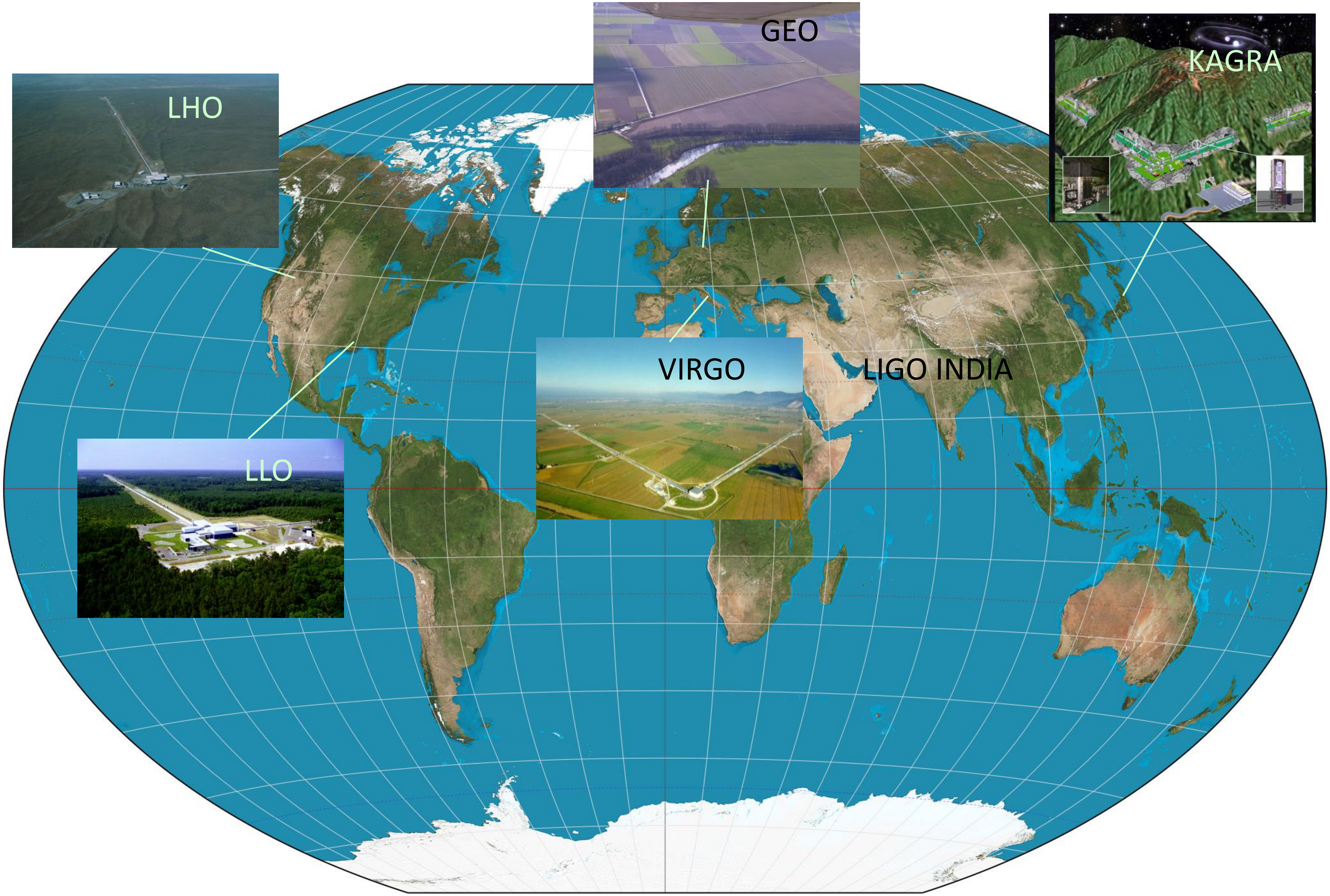


Advanced LIGO Fabry-Perot Michelson Interferometer Schematic



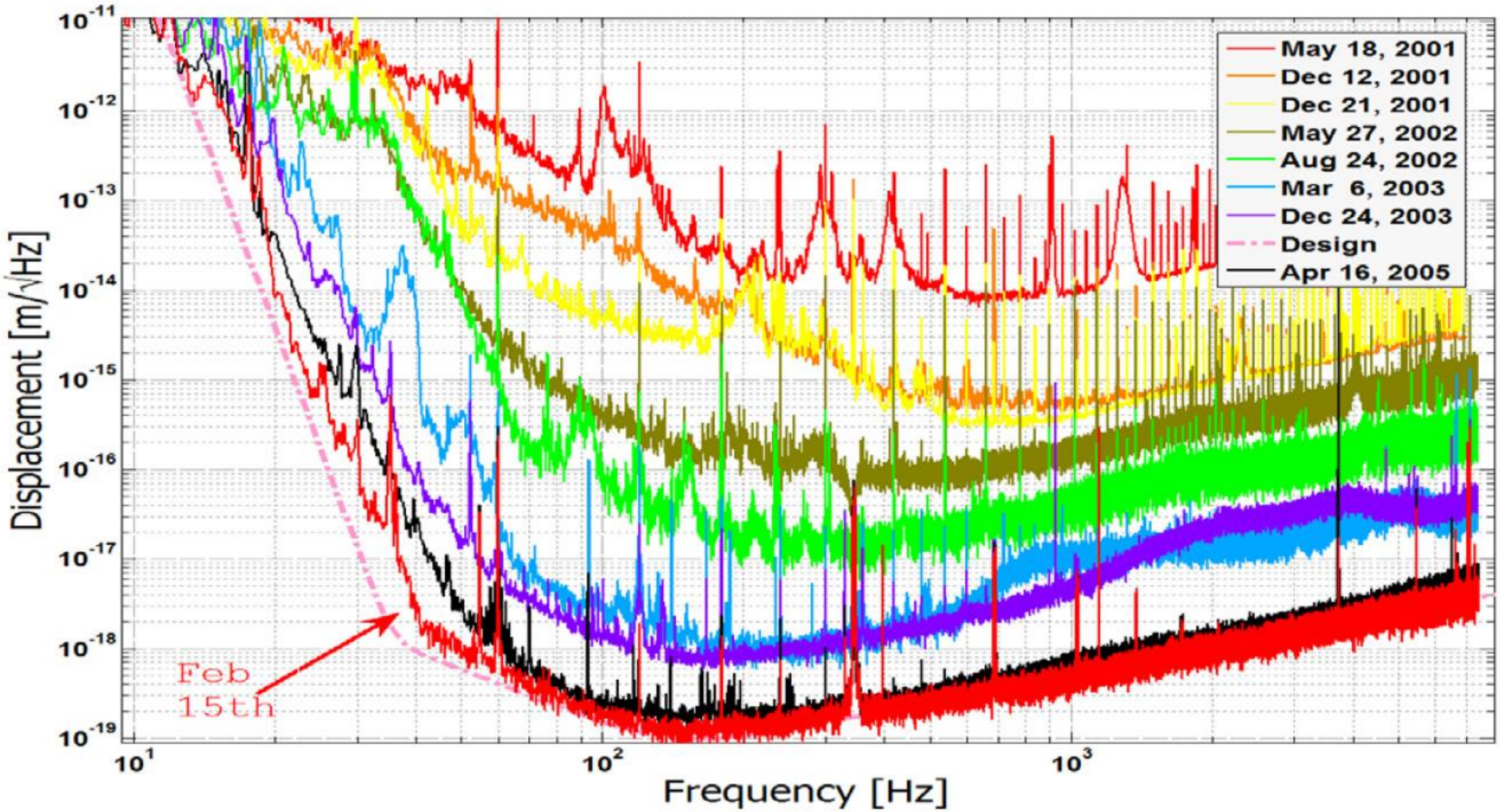
Initial LIGO Interferometer Noise Budget



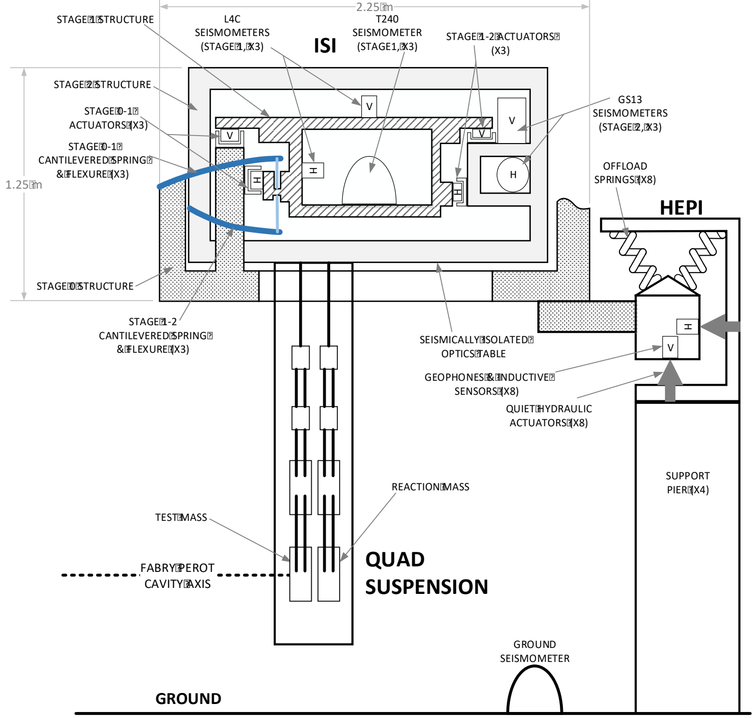


GEO
KAGRA
LHO
VIRGO
LIGO INDIA
LLO

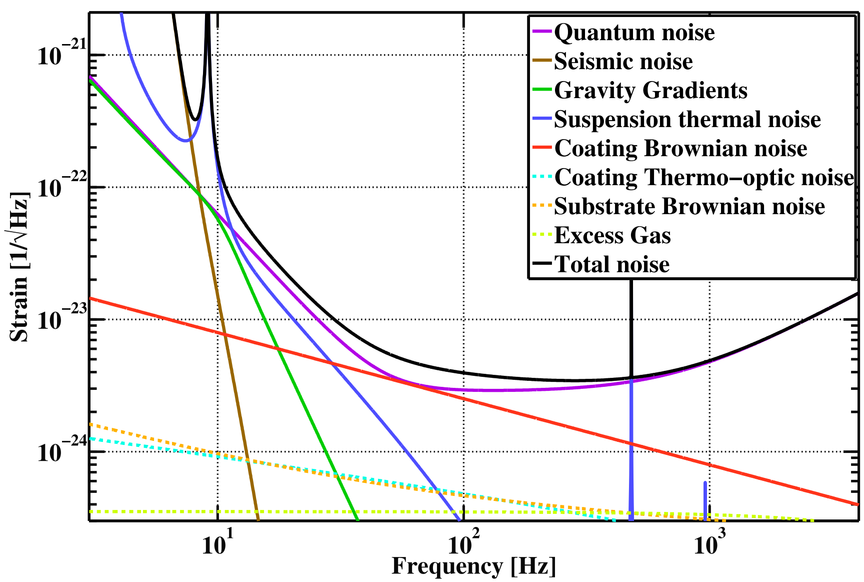
Evolution of the initial detector 2001 - 2006

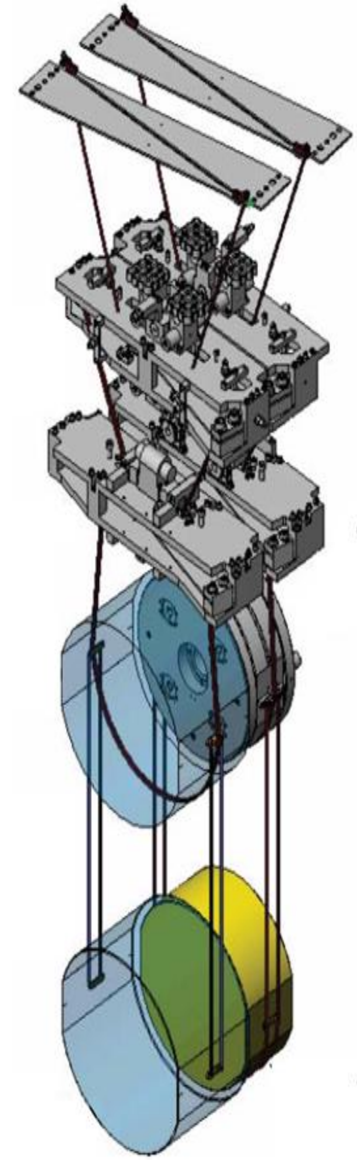


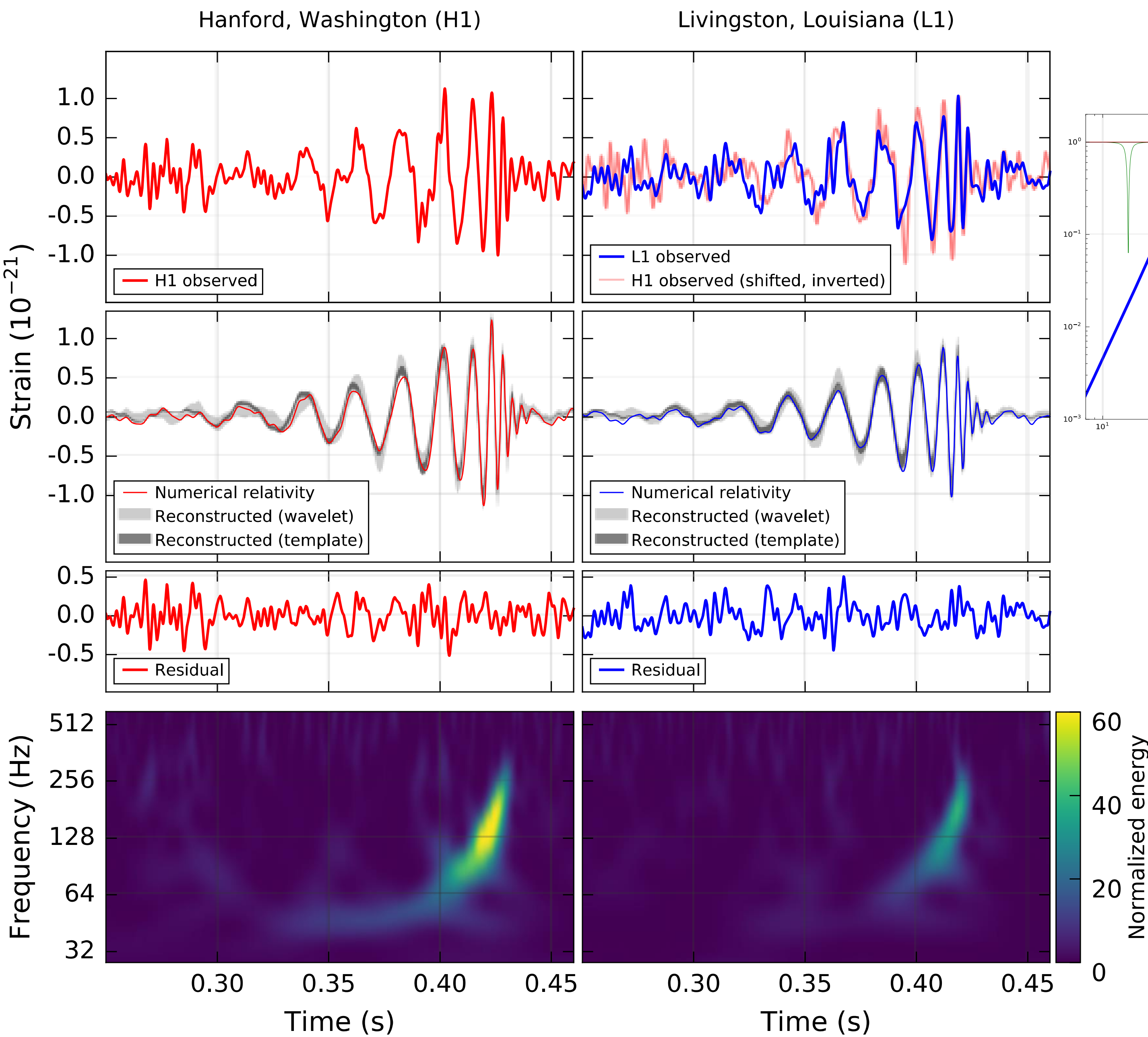
A clean non-detection

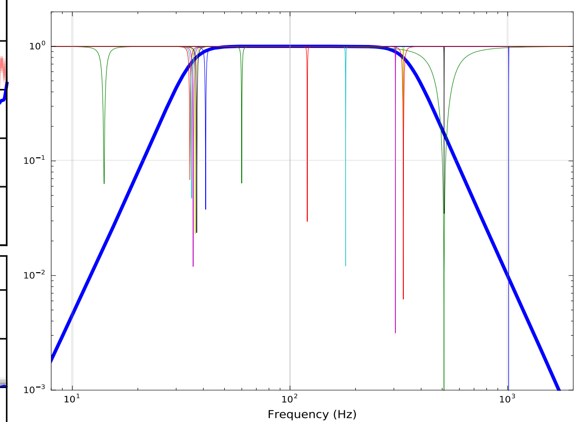


Advanced LIGO design noise budget

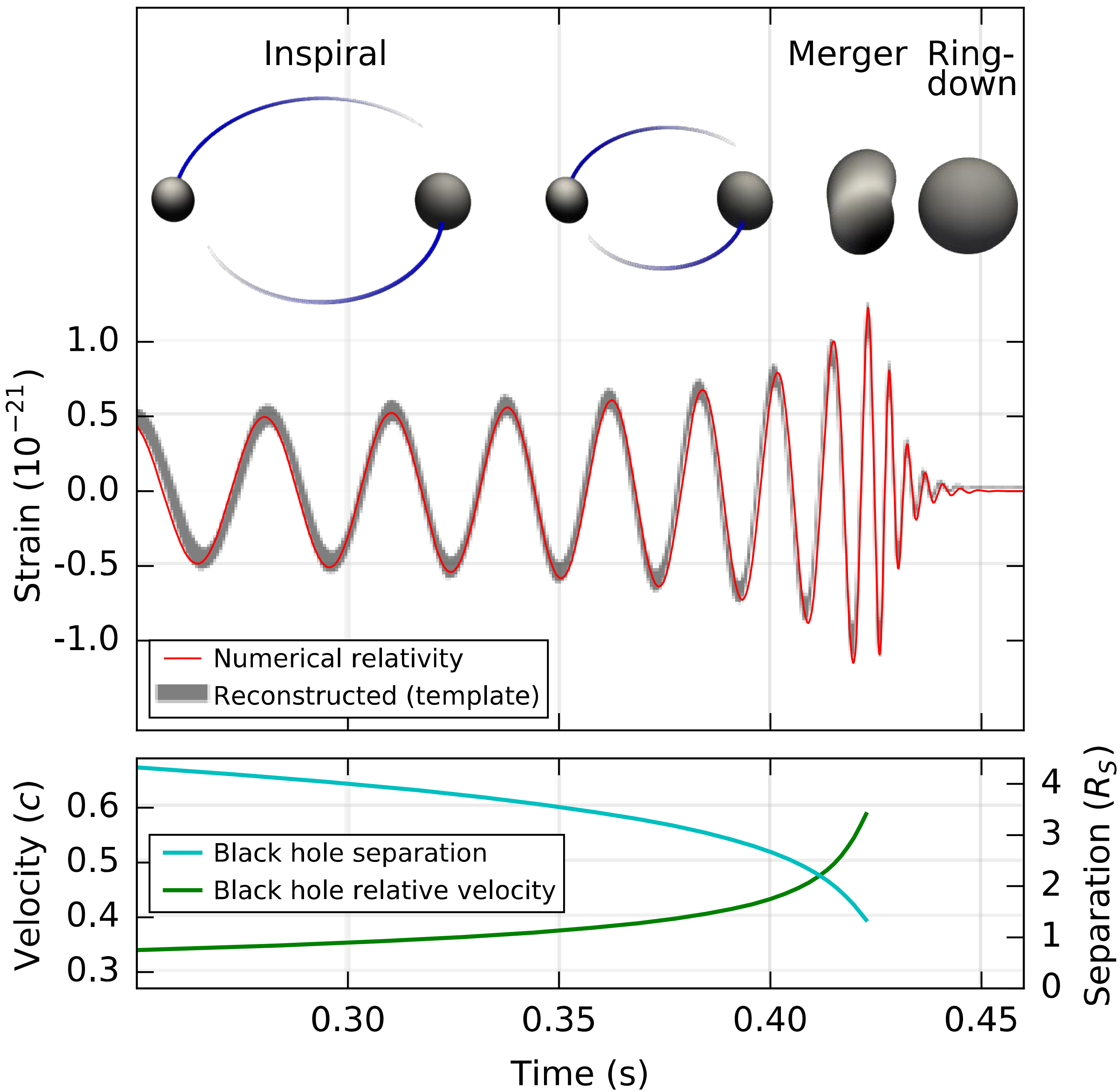






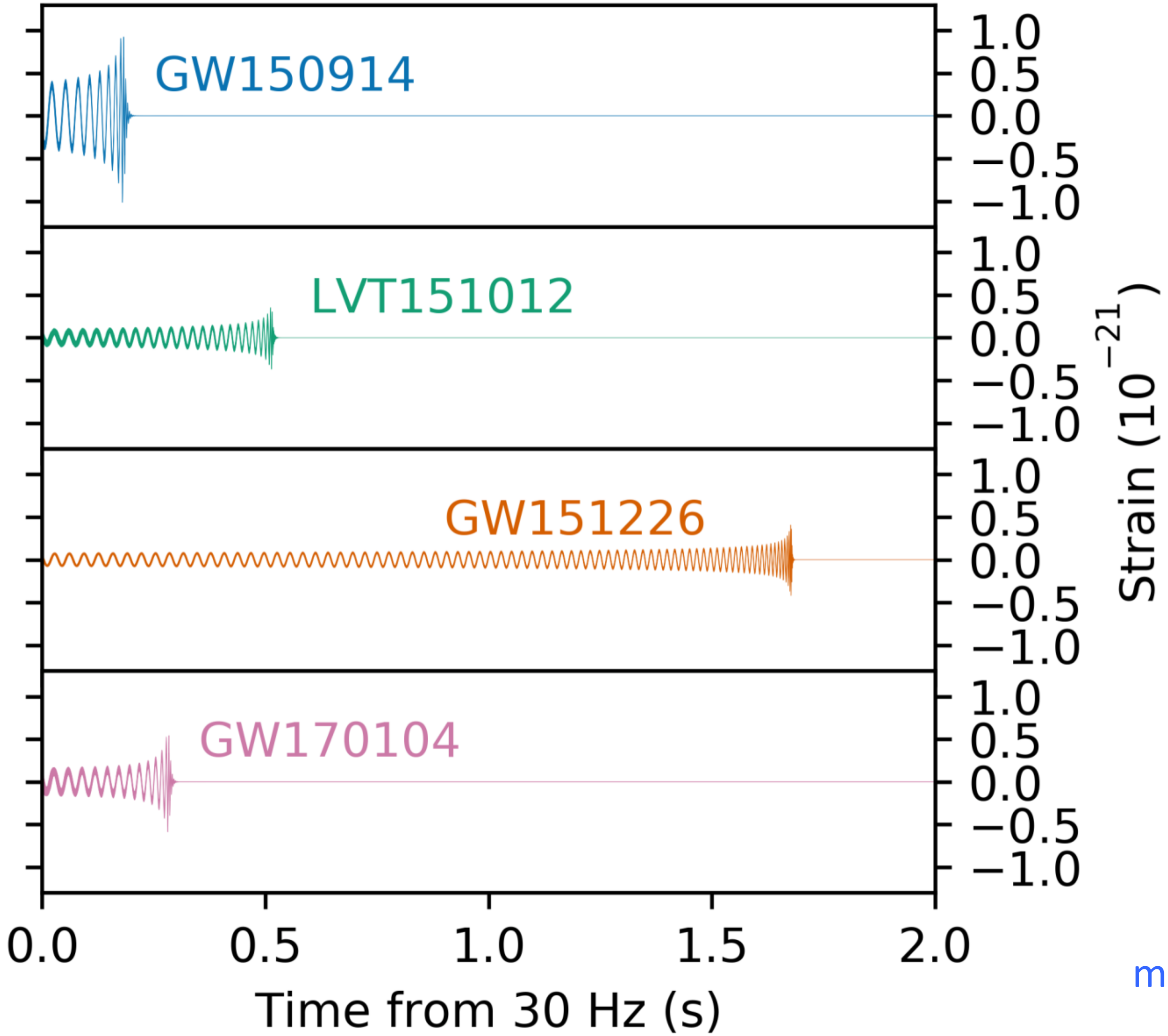


Simple high-low pass filter with notches



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)

Results of O1 and O2 run announced June 1, 2017



m1=36, m2= 29, Δm=3

if at 1 au

h ~10^{-6}

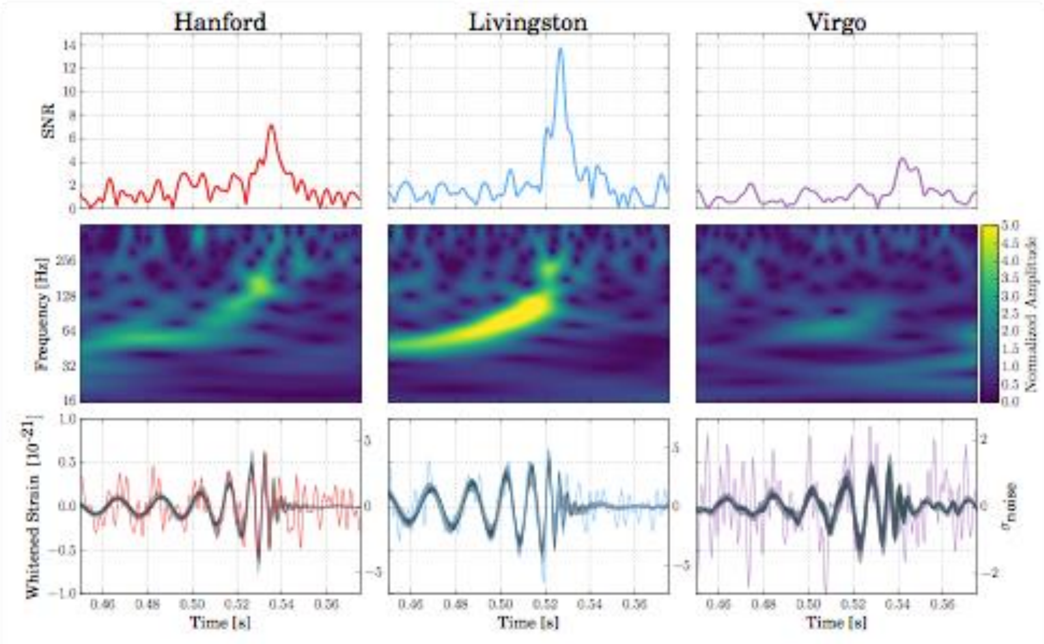
I_g~ 10^{25} w/m^2

m1=23, m2= 13, Δm=1.5

m1=14.2, m2= 7.5, Δm=1

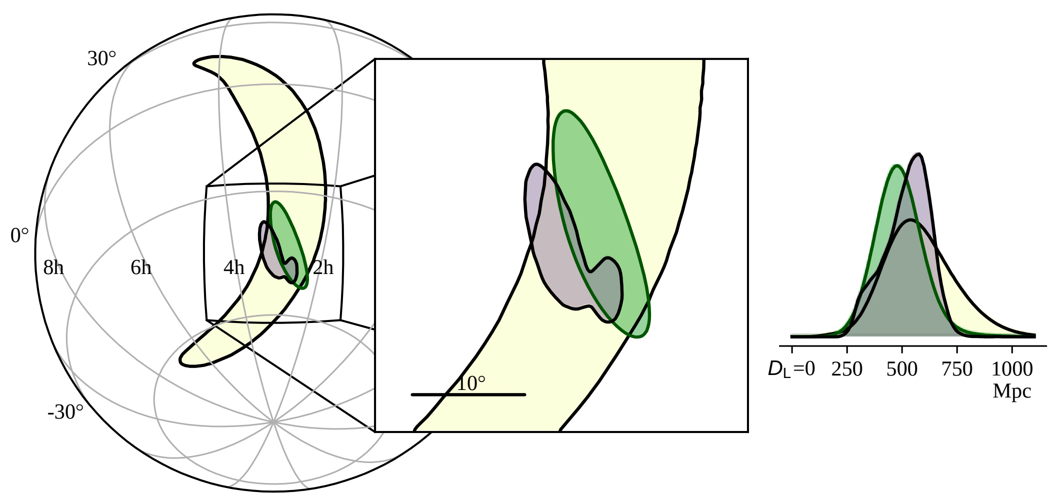
m1=31, m2= 19, Δm=2

masses in source frame

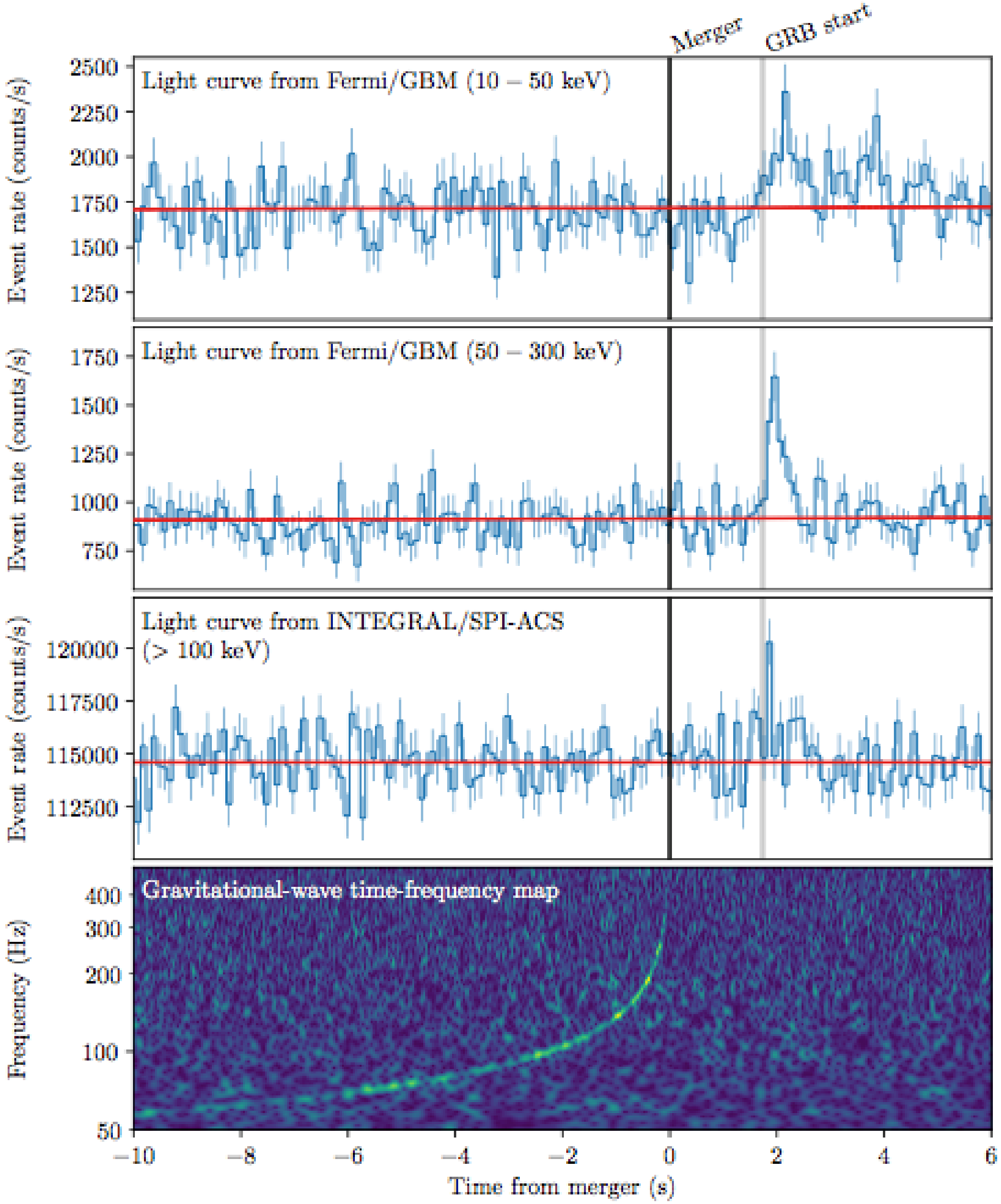


Triple coincidence GW 170814

M_1 = 30
M_2 = 25
ΔM = 2.7

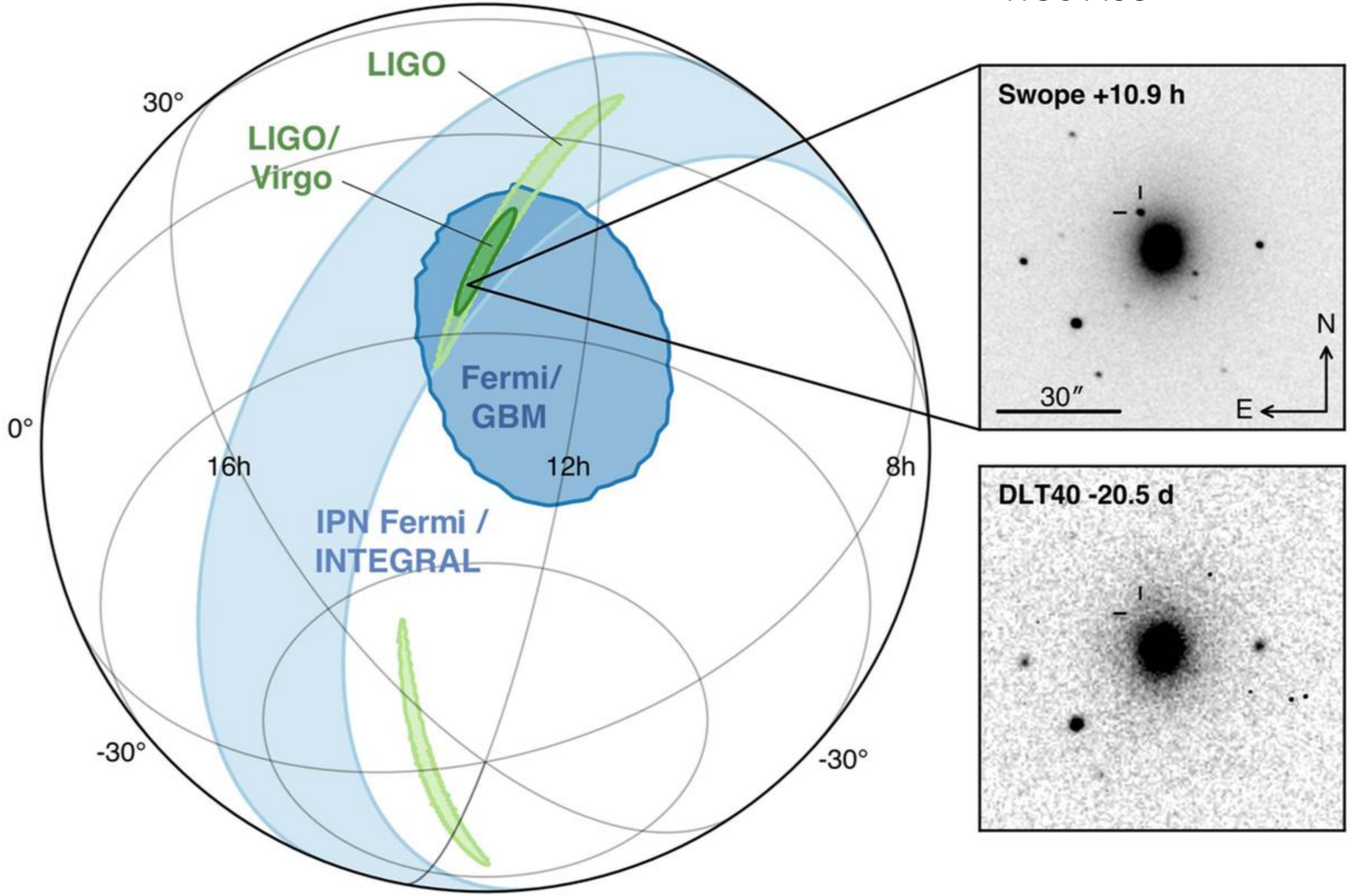


Localization on sky and distance

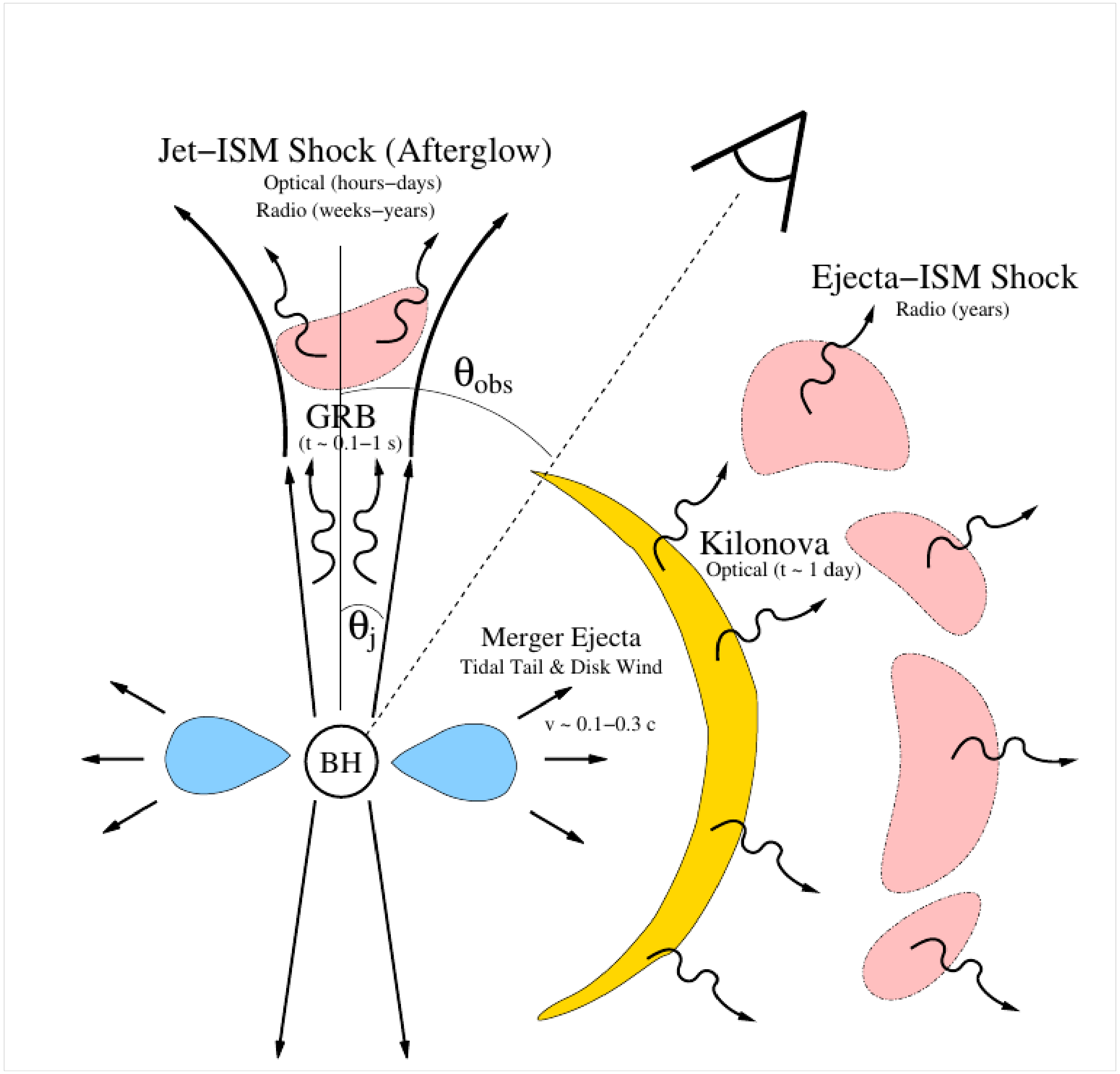


Merger
GRB start
Light curve from Fermi/GBM (10 – 50 keV)
Light curve from Fermi/GBM (50 – 300 keV)
Light curve from INTEGRAL/SPI-ACS (> 100 keV)
Gravitational-wave time-frequency map
Event rate (counts/s)
Frequency (Hz)
Time from merger (s)

NGC4493

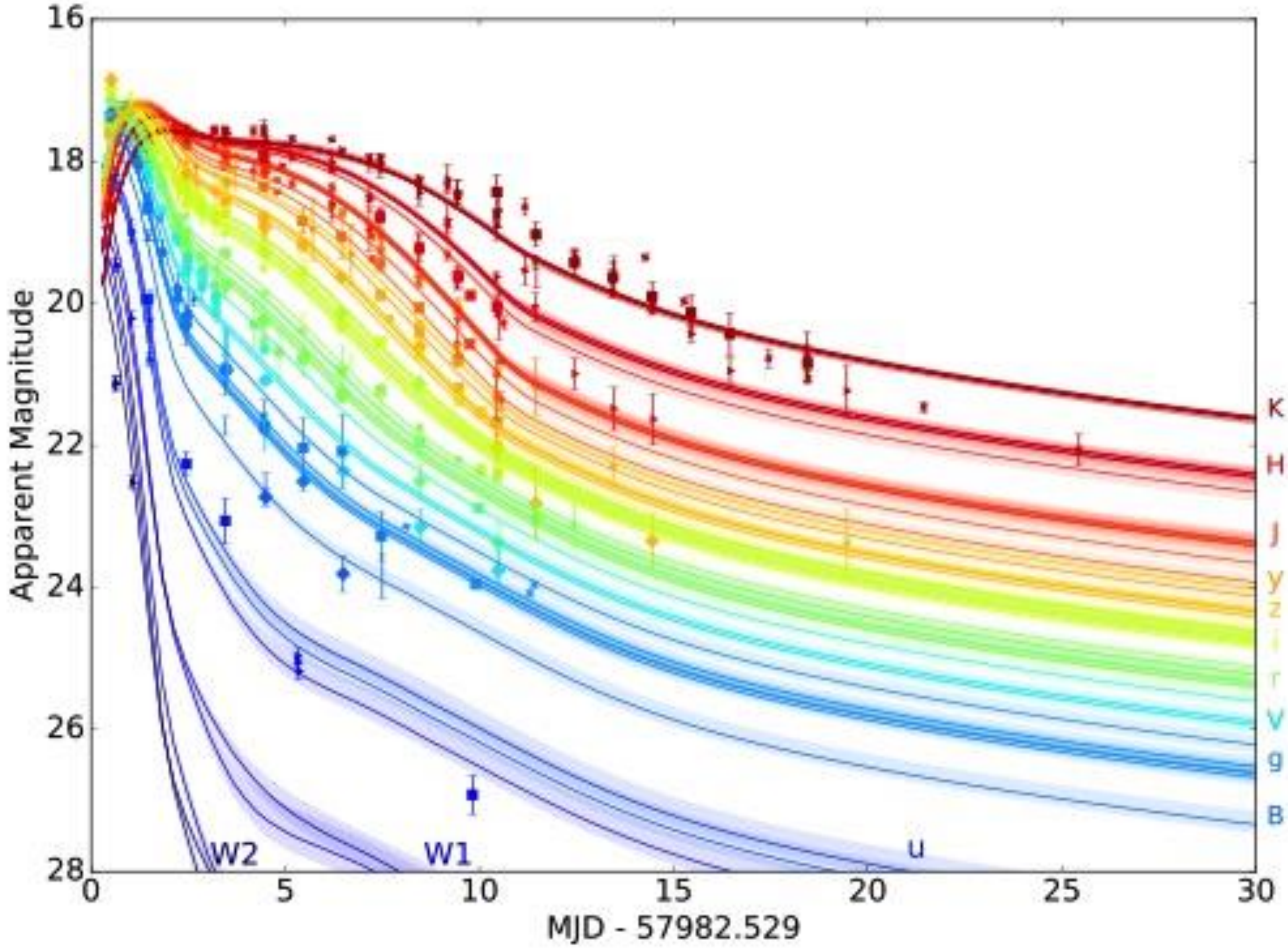


LIGO
LIGO/
Virgo
Fermi/
GBM
IPN Fermi /
INTEGRAL
30°
0°
-30°
-30°
16h
12h
8h
Swope +10.9 h
N
E
30″
DLT40 -20.5 d



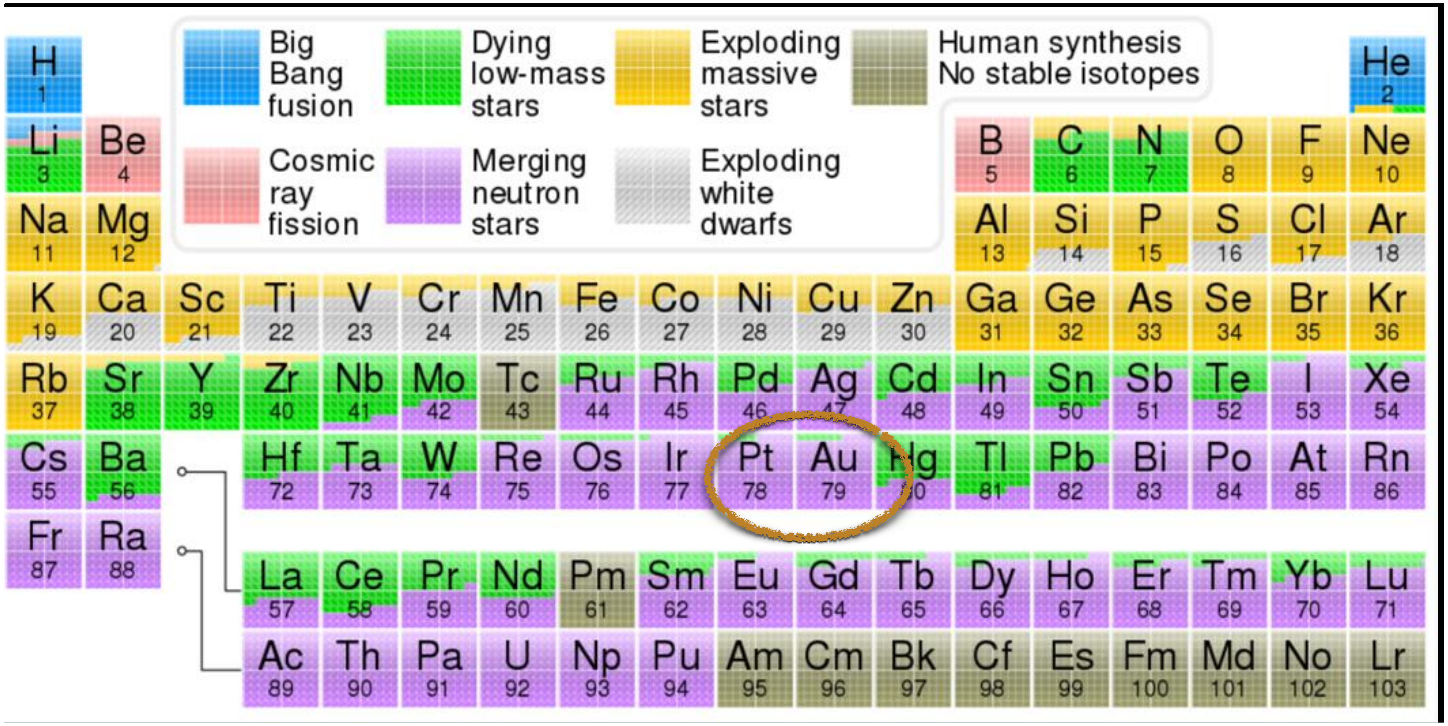
Jet−ISM Shock (Afterglow)
Optical (hours−days)
Radio (weeks−years)
Ejecta−ISM Shock
Radio (years)
θobs
GRB
(t ~ 0.1−1 s)
Kilonova
Optical (t ~ 1 day)
θj
Merger Ejecta
Tidal Tail & Disk Wind
v ~ 0.1−0.3 c
BH

Broad band kilonova spectra vs time

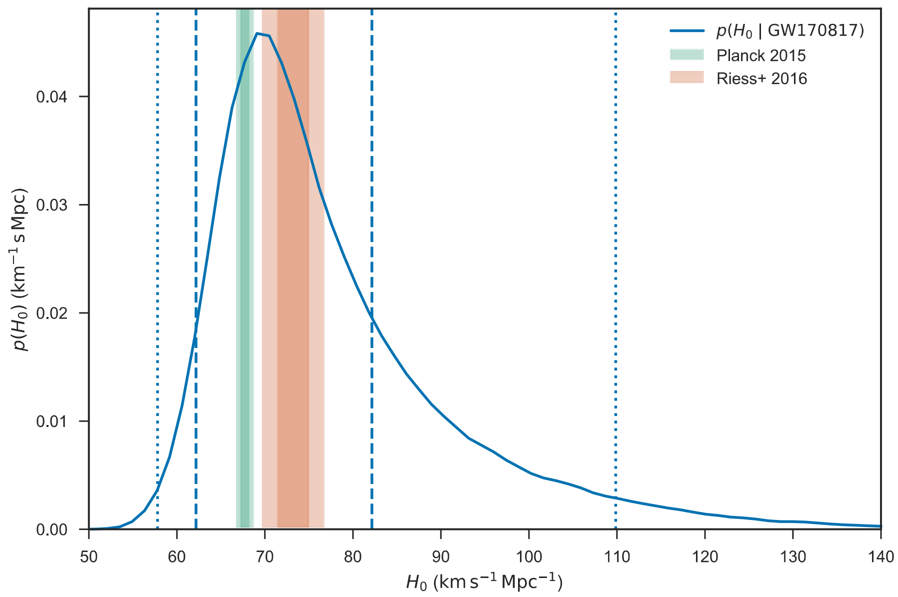


Villar et al arXiv astroph 1710.11576

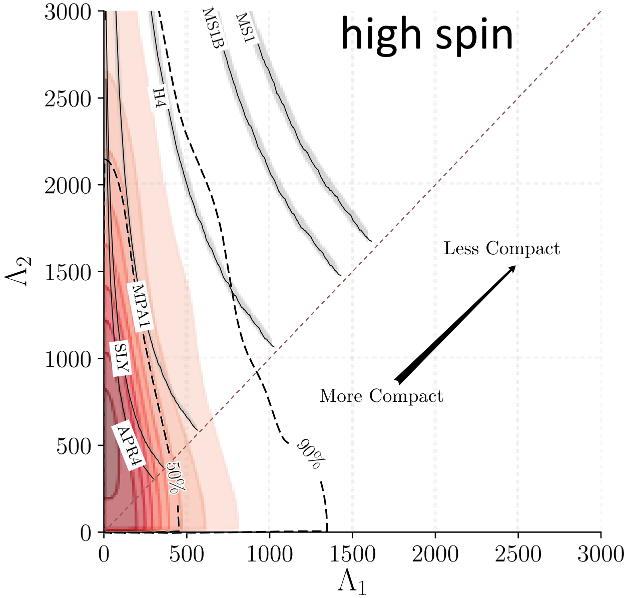
Origin of the elements

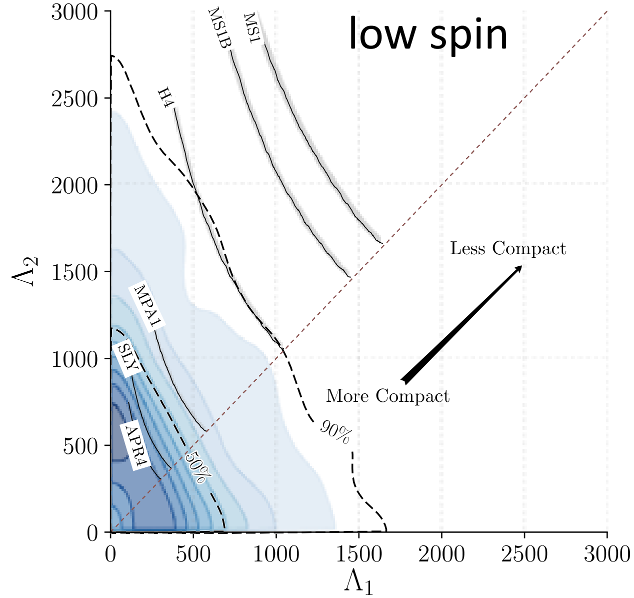


Hubble constant measurement: Galaxy z and distance from GW amplitude



Neutron Star Tidal Distortion

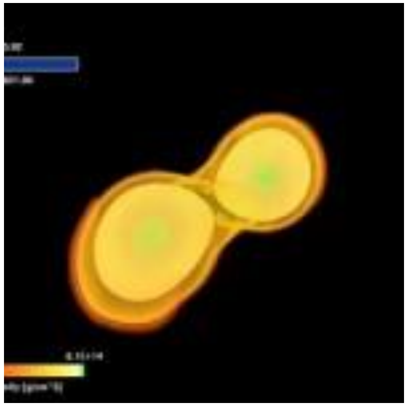


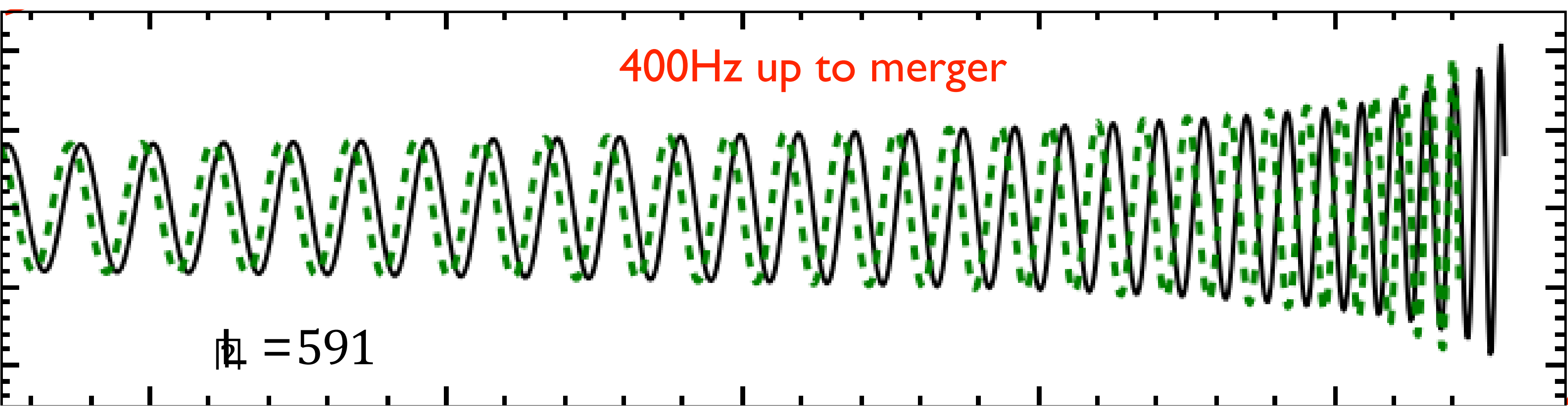


$$Q_{ij} = I \frac{d^2V(r)}{dx_i dx_j}$$

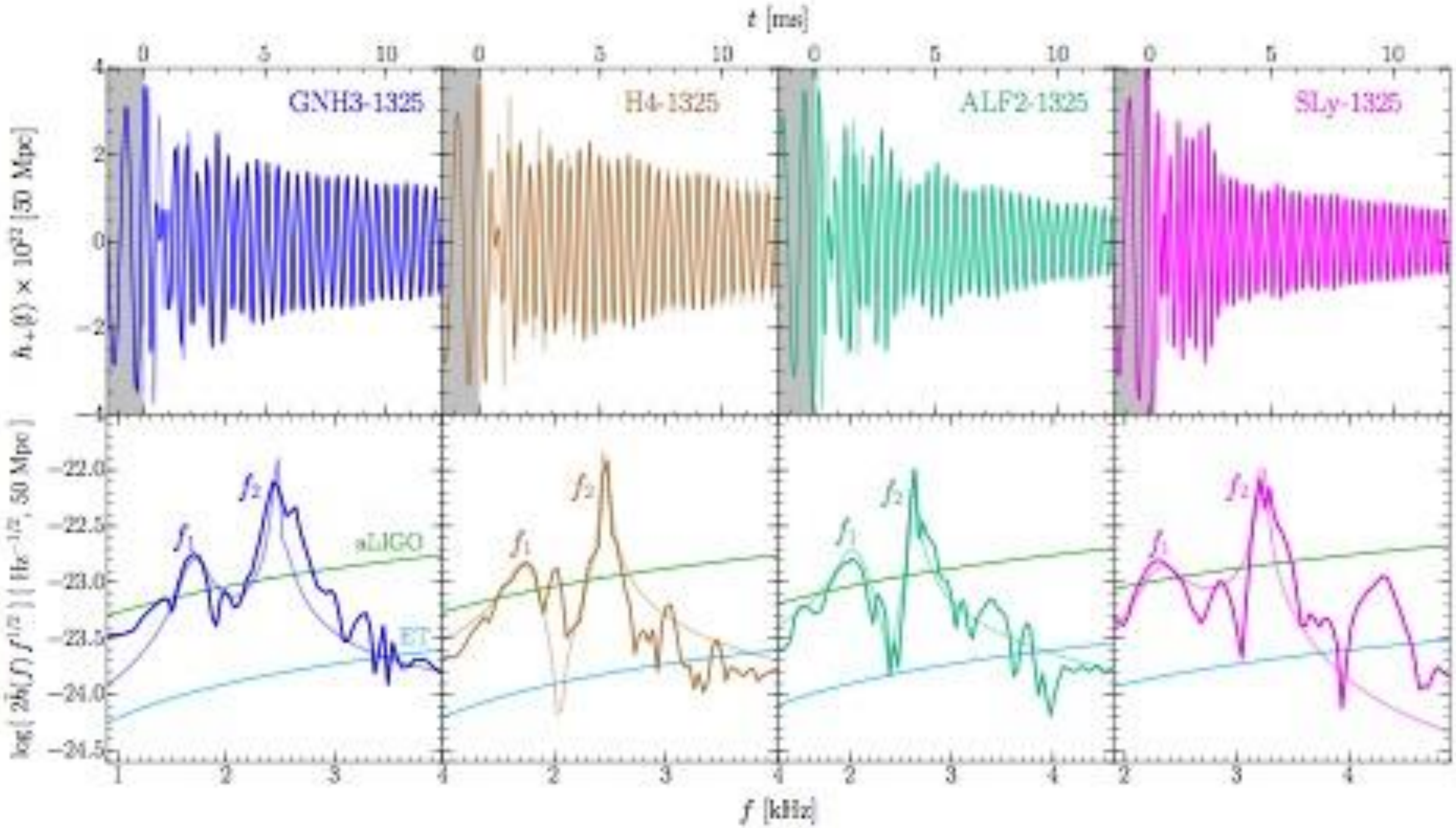
⍰

tidal distortion





Binary neutron star spectroscopy



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

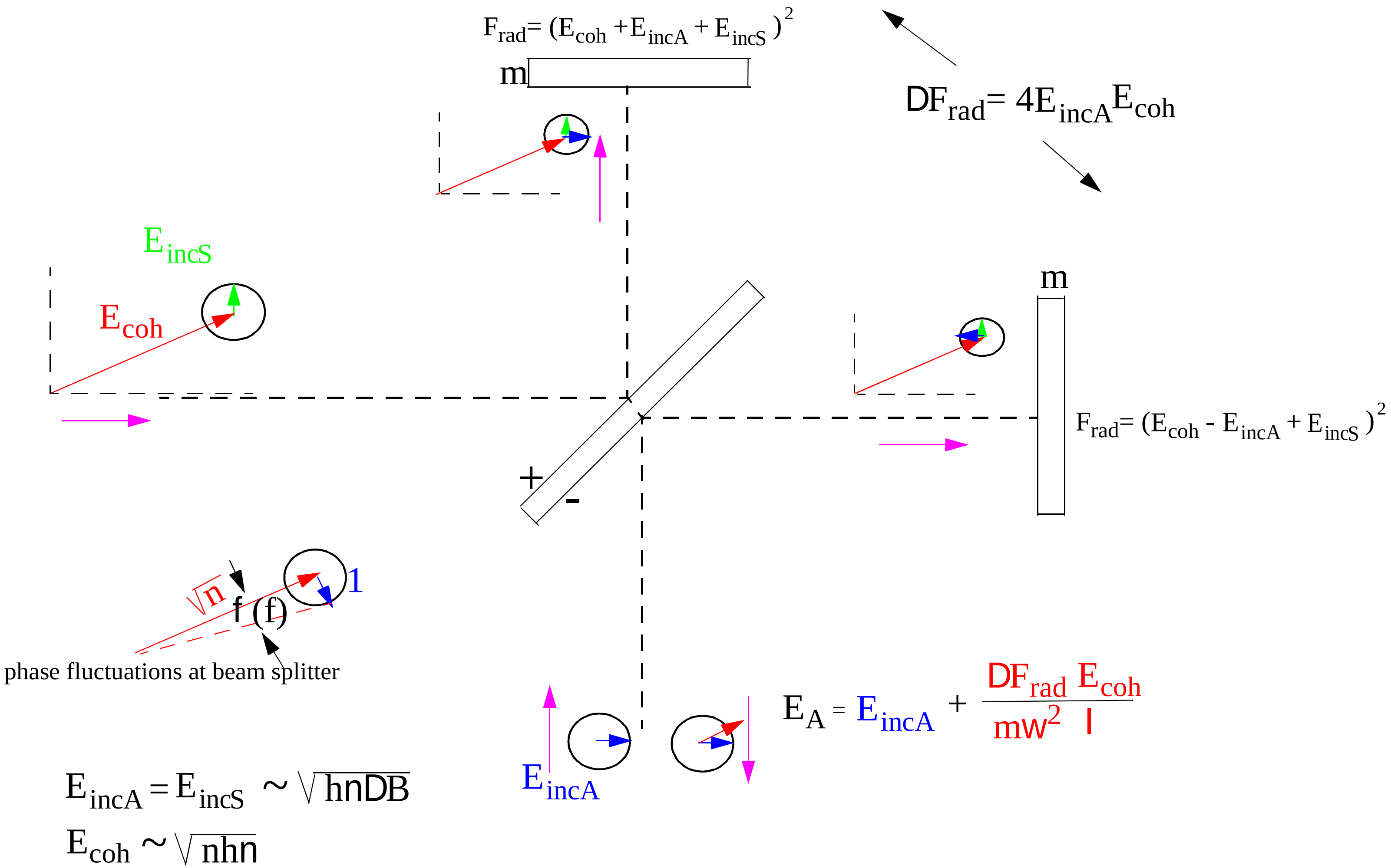
Technical Challenges and Development

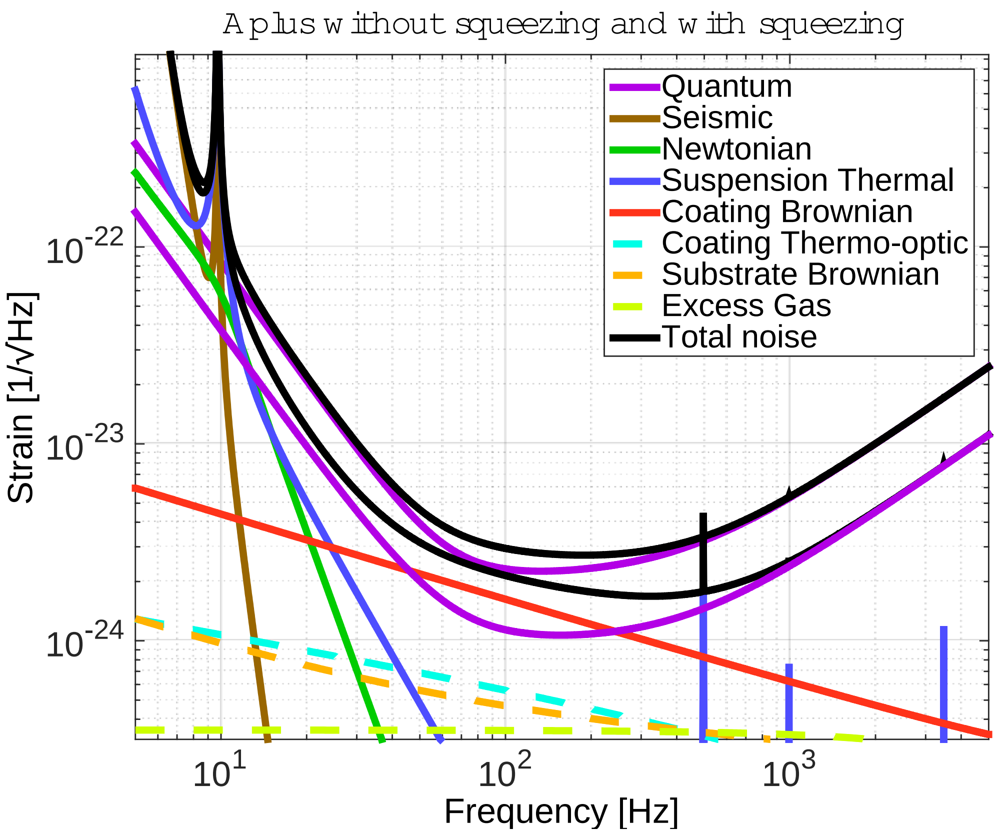
- Higher power and reduced quantum noise
  - Reduce and damp parametric instabilities
  - Remove hot spots in coatings
  - Higher thermal conductivity mirror materials
  - Frequency dependent squeezed light at anti-sym. port
- Thermal noise in mirror coatings and suspensions
  - Reduced mechanical losses in the mirror coatings
  - Larger test masses
- Charging of optics
  - Low optical loss conducting coating on the mirrors
- Noise in the optical alignment system
  - Reduction in angle to length coupling
- Scattering from moving sources

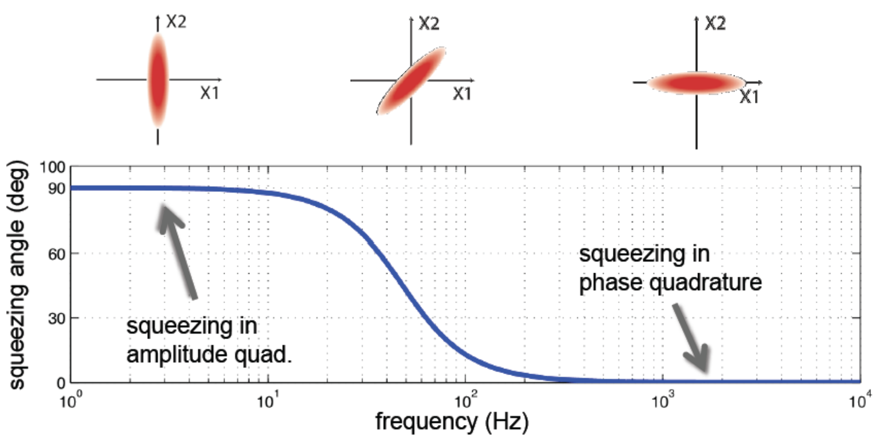
PHYSICAL REVIEW D VOLUME 23, NUMBER 8 15 APRIL 1981

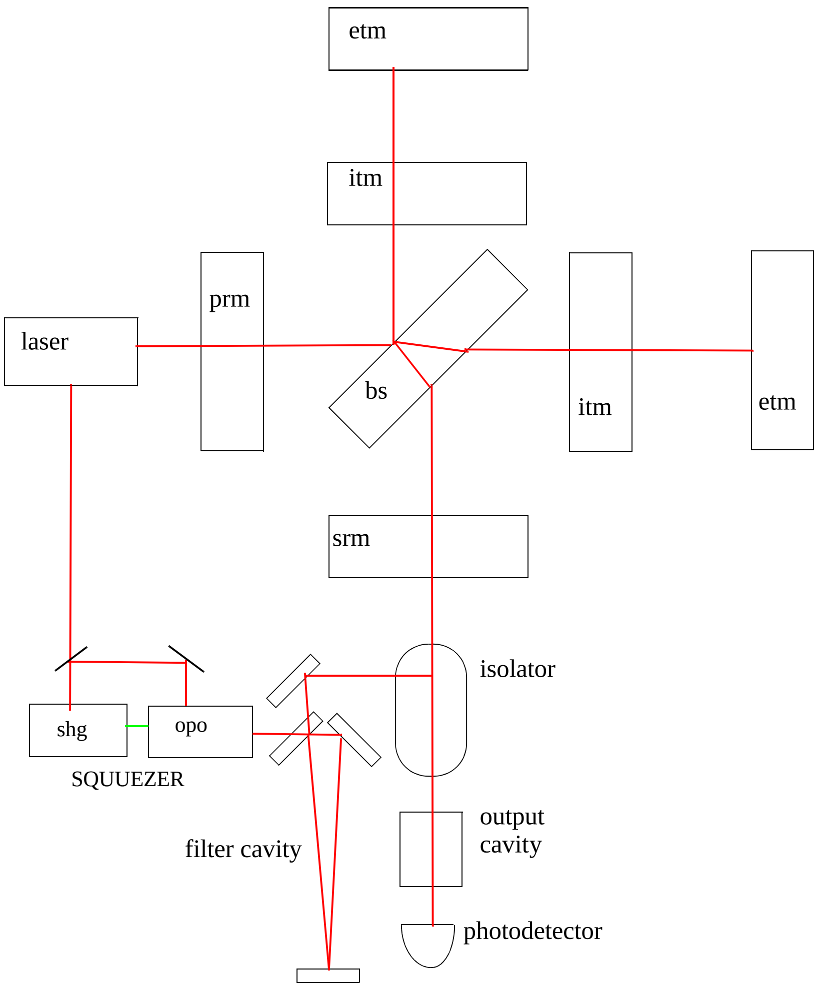
Quantum-mechanical noise in an interferometer

Carlton M. Caves
W. K. Kellogg Radiation Laboratory, California Institute of Technology, Pasadena, California 91125
(Received 15 August 1980)

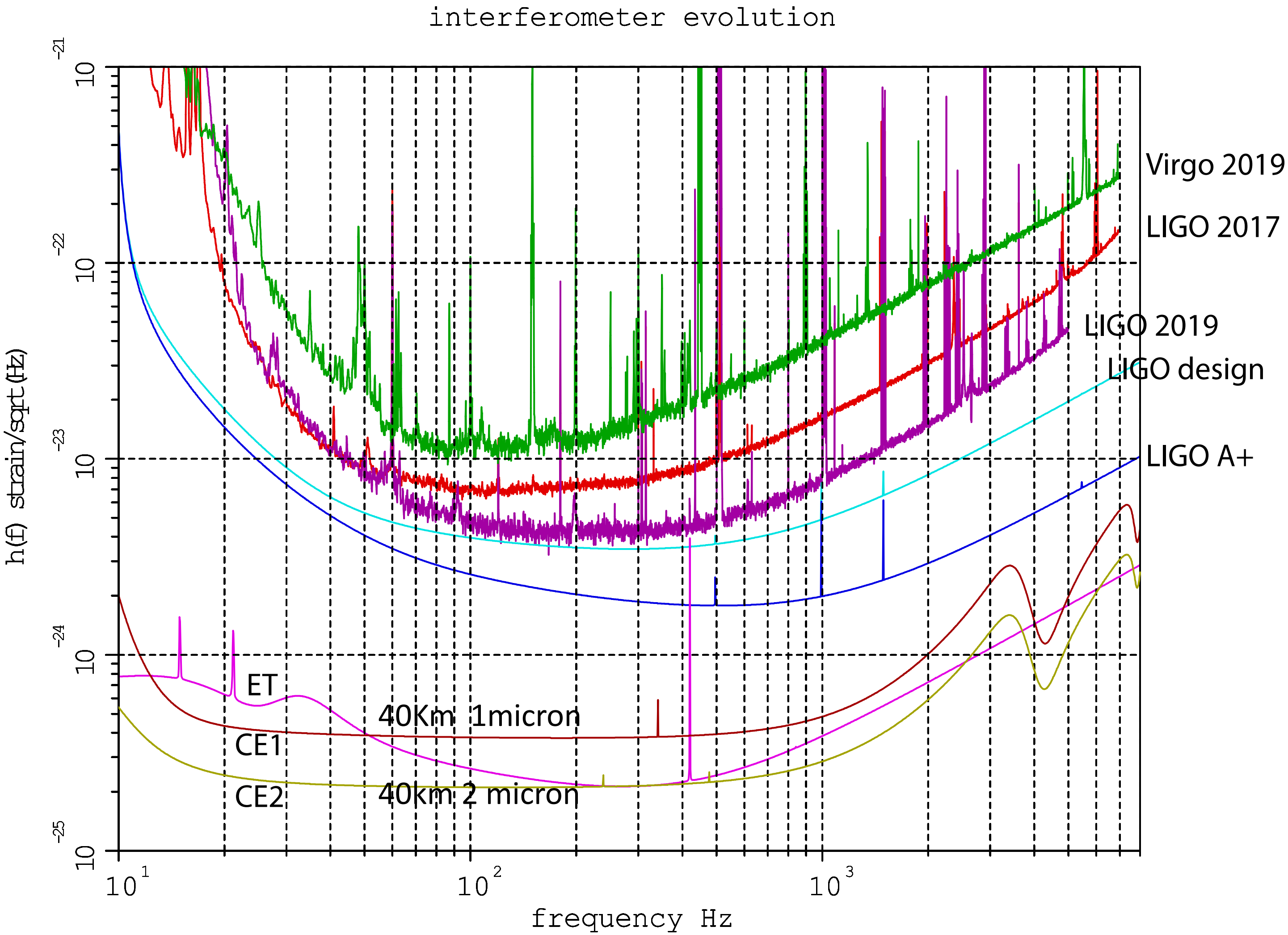




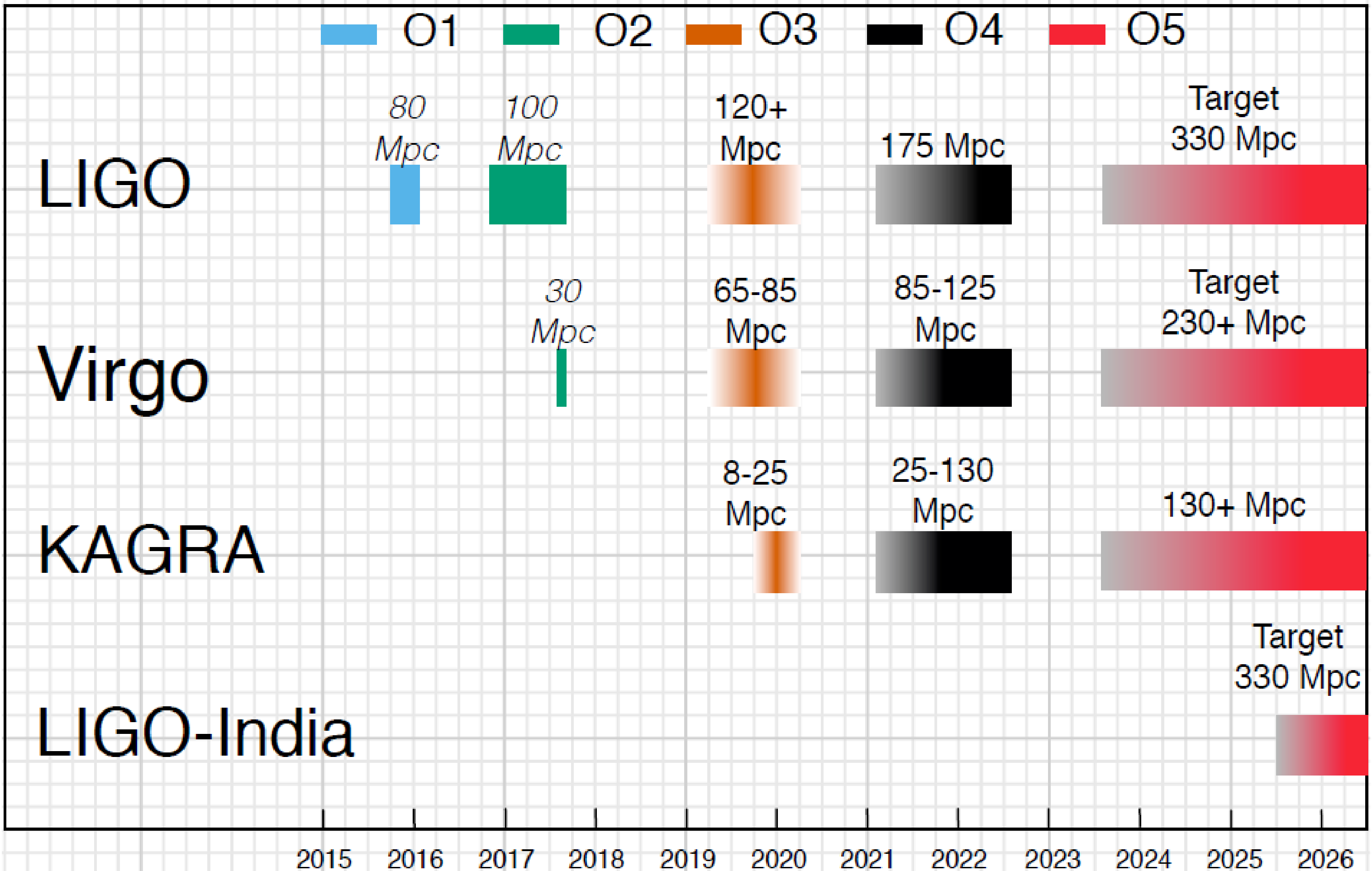




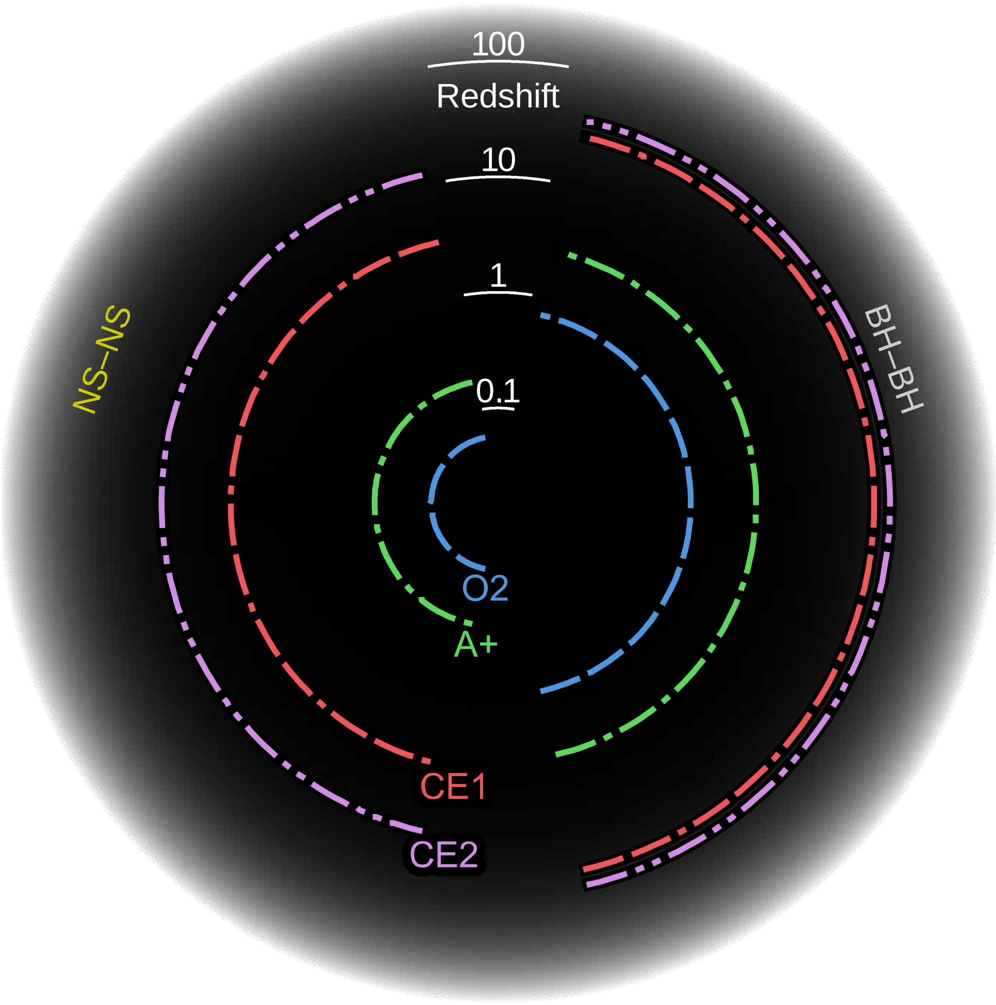
E.Oelker, T. Isogai, J.Miller, M.Tse, L.Barsotti,N.Mavalvala,M.Evans

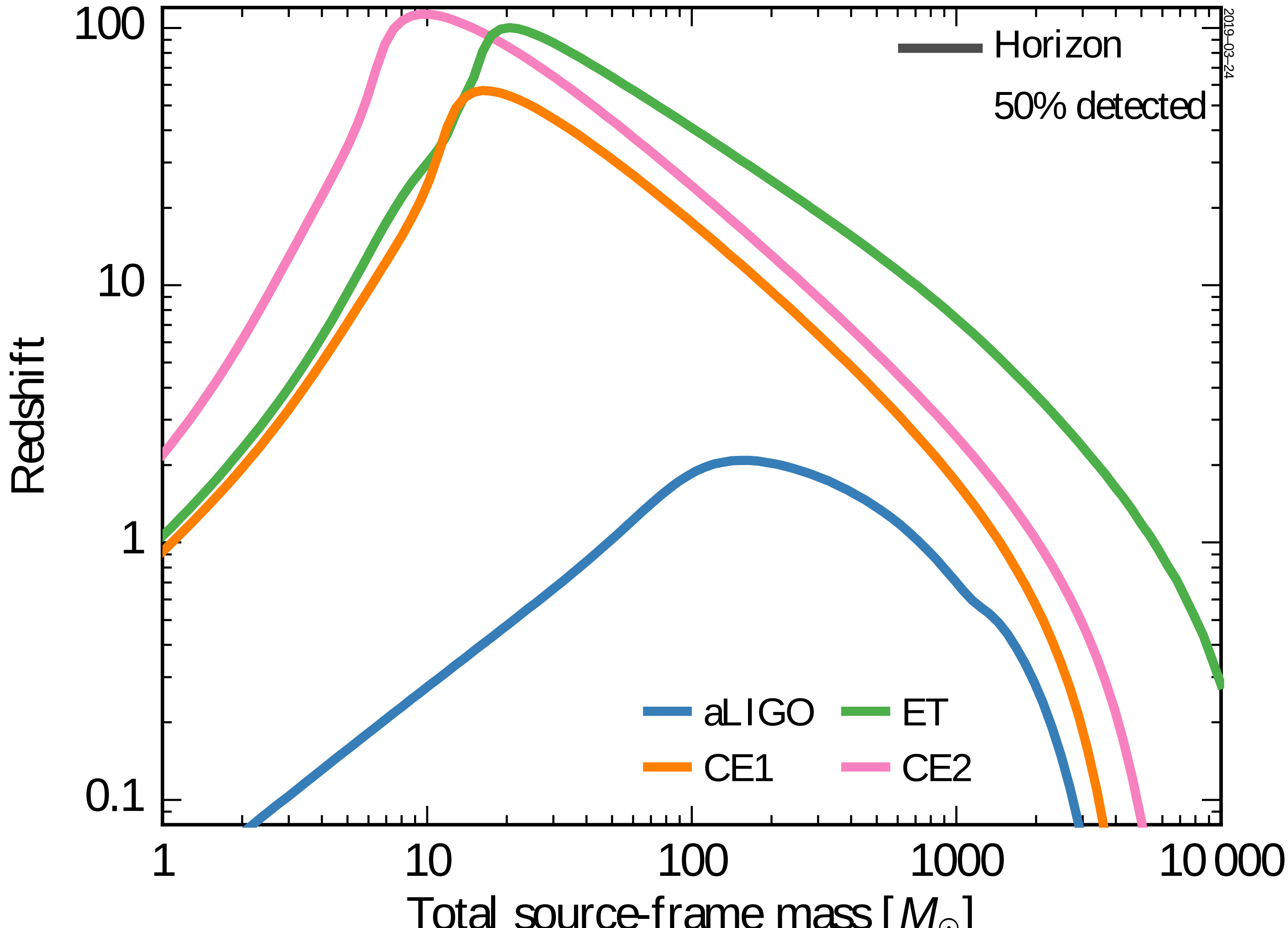


Pin(W)	SQ(db)	M(kg)
20	none	40
40	3	40
100	3	40
125	6fd	40
150	10fd	350
250	10fd	350

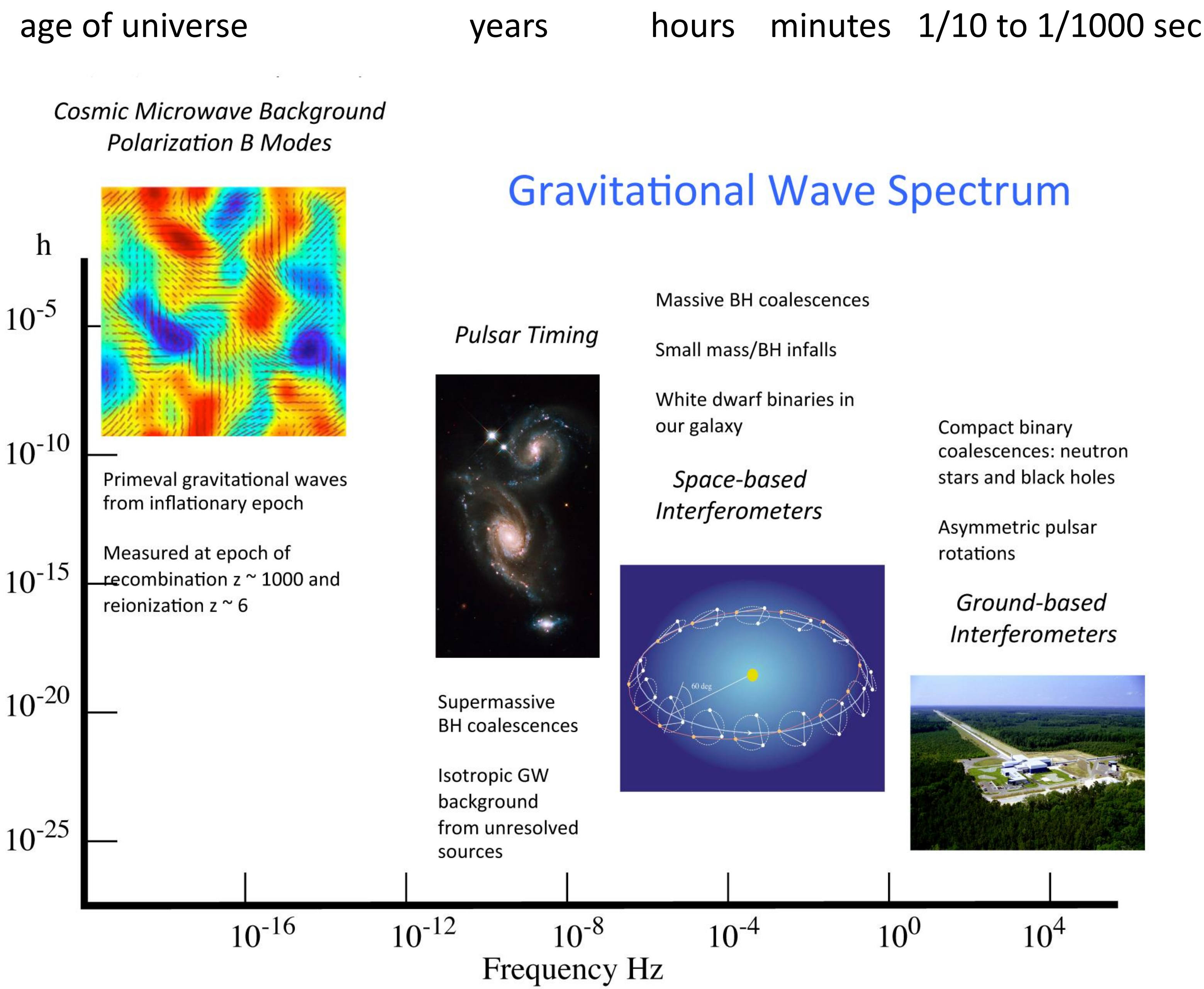

O1
O2
O3
O4
O5
LIGO
Virgo
KAGRA
LIGO-India
80 Mpc
100 Mpc
120+ Mpc
175 Mpc
Target 330 Mpc
30 Mpc
65-85 Mpc
85-125 Mpc
Target 230+ Mpc
8-25 Mpc
25-130 Mpc
130+ Mpc
Target 330 Mpc
2015
2016
2017
2018
2019
2020
2021
2022
2023
2024
2025
2026

R. Flaminio


100
Redshift
10
1
0.1
NS–NS
BH–BH
O2
A+
CE1
CE2



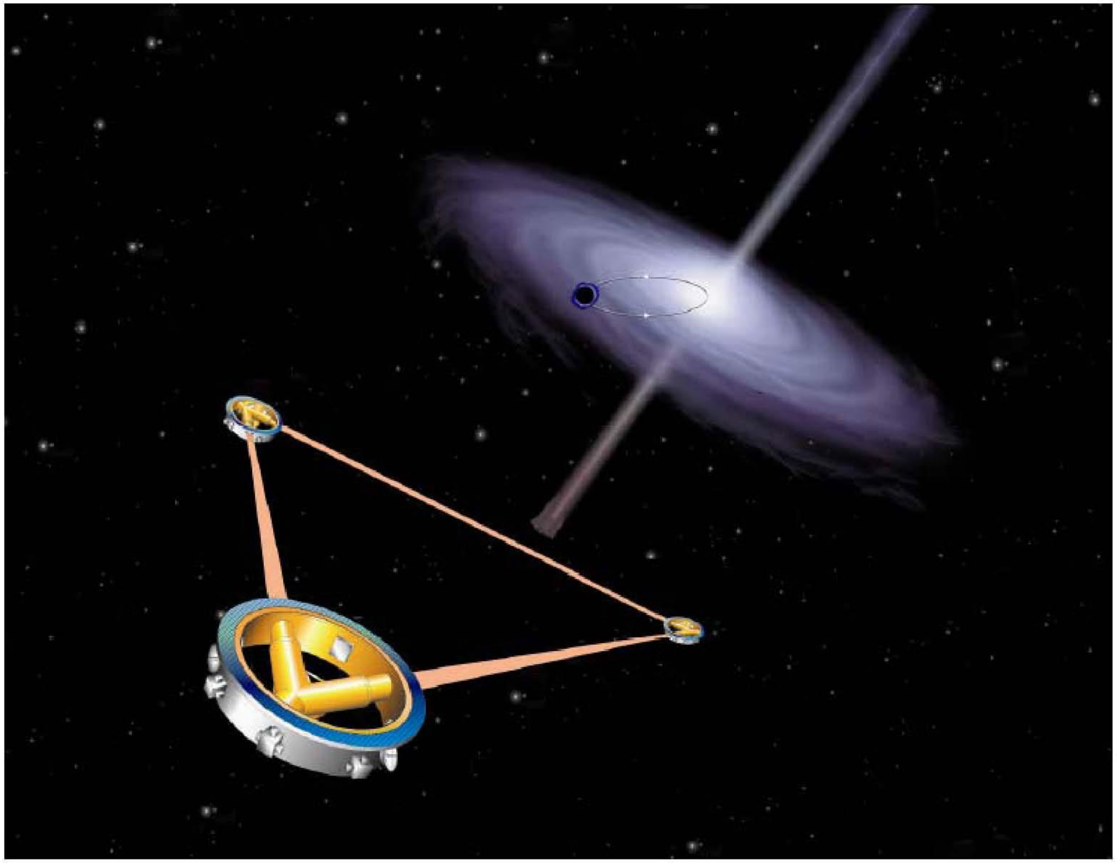
100
10
1
0.1
Redshift
1
10
100
1000
10 000
Total source-frame mass [$M_\odot$]
Horizon
50% detected
aLIGO
ET
CE1
CE2
2019–03–24



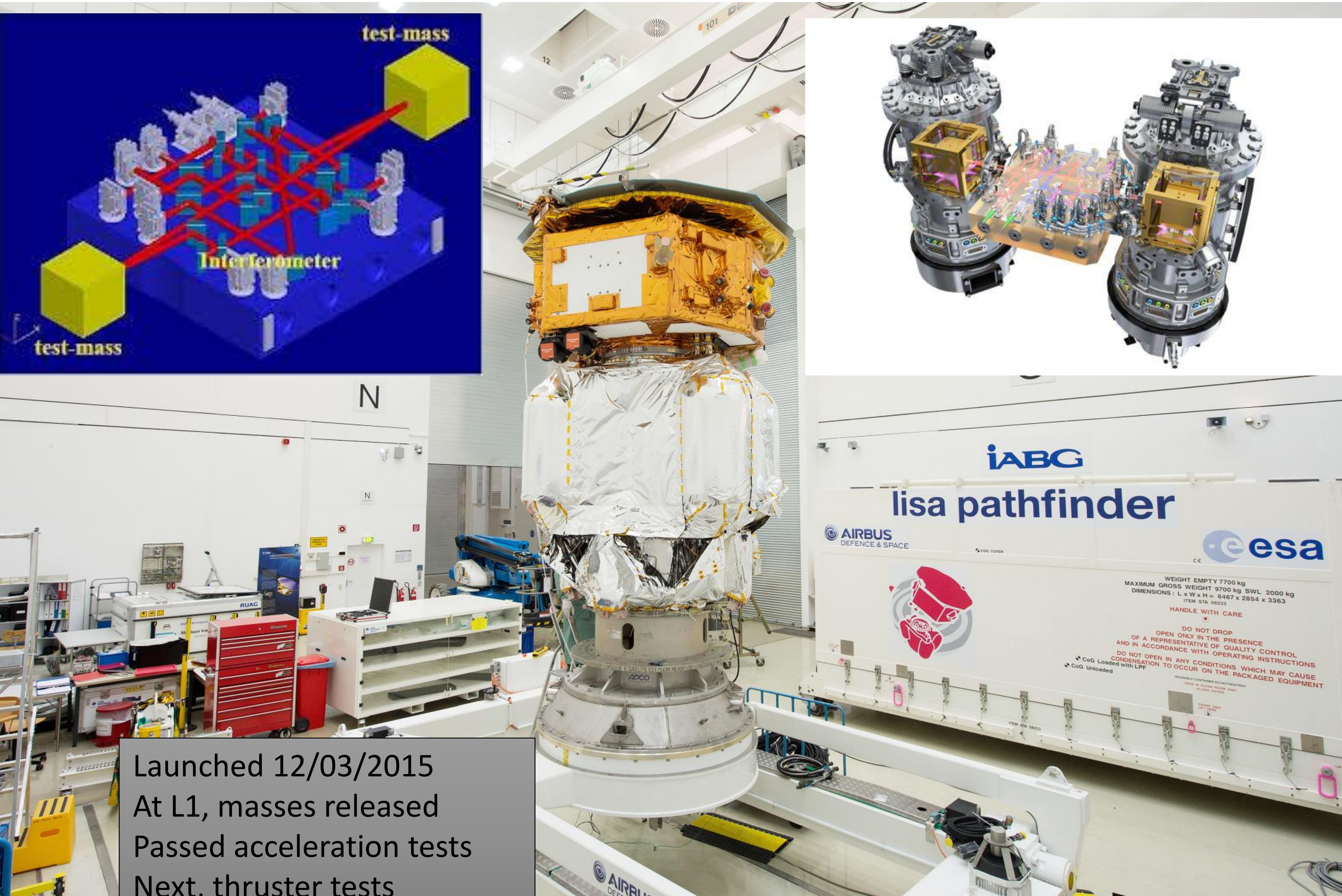
age of universe
years
hours
minutes
1/10 to 1/1000 sec
Gravitational Wave Spectrum
Cosmic Microwave Background
Polarization B Modes
h
10^-5
10^-10
10^-15
10^-20
10^-25
Primeval gravitational waves from inflationary epoch
Measured at epoch of recombination z ~ 1000 and reionization z ~ 6
Pulsar Timing
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

SPARE SLIDES

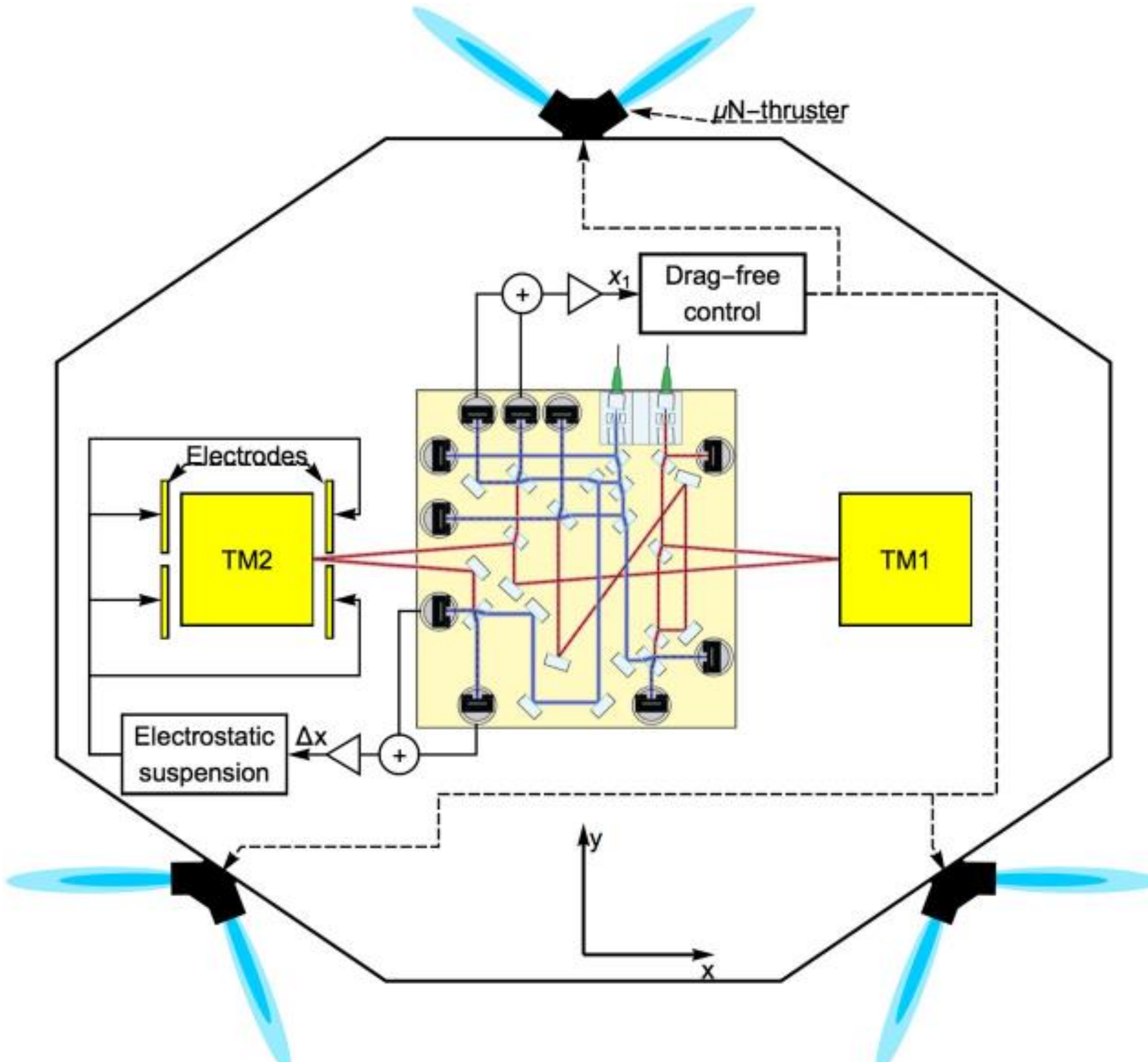
Mission Concept



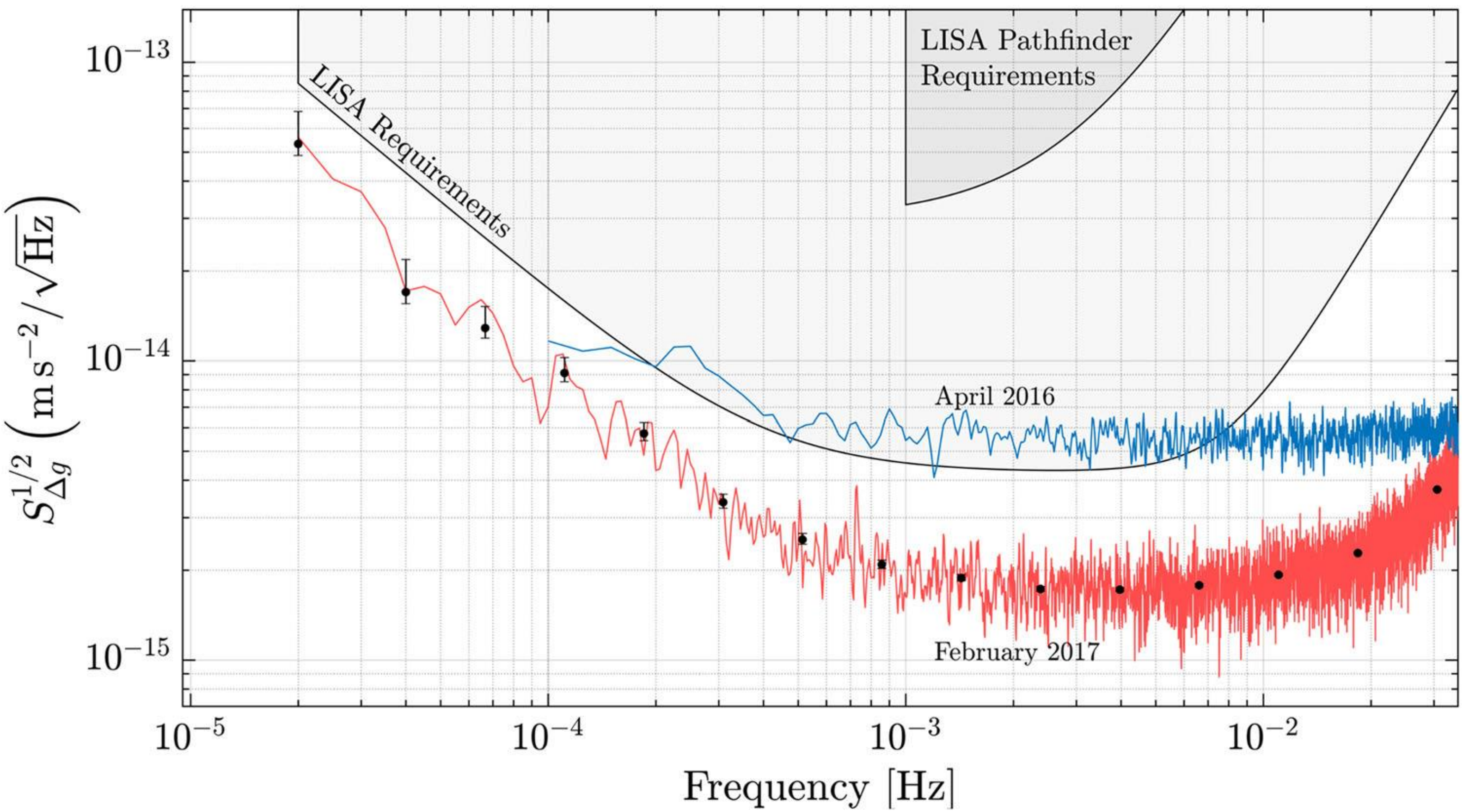
LISA Pathfinder



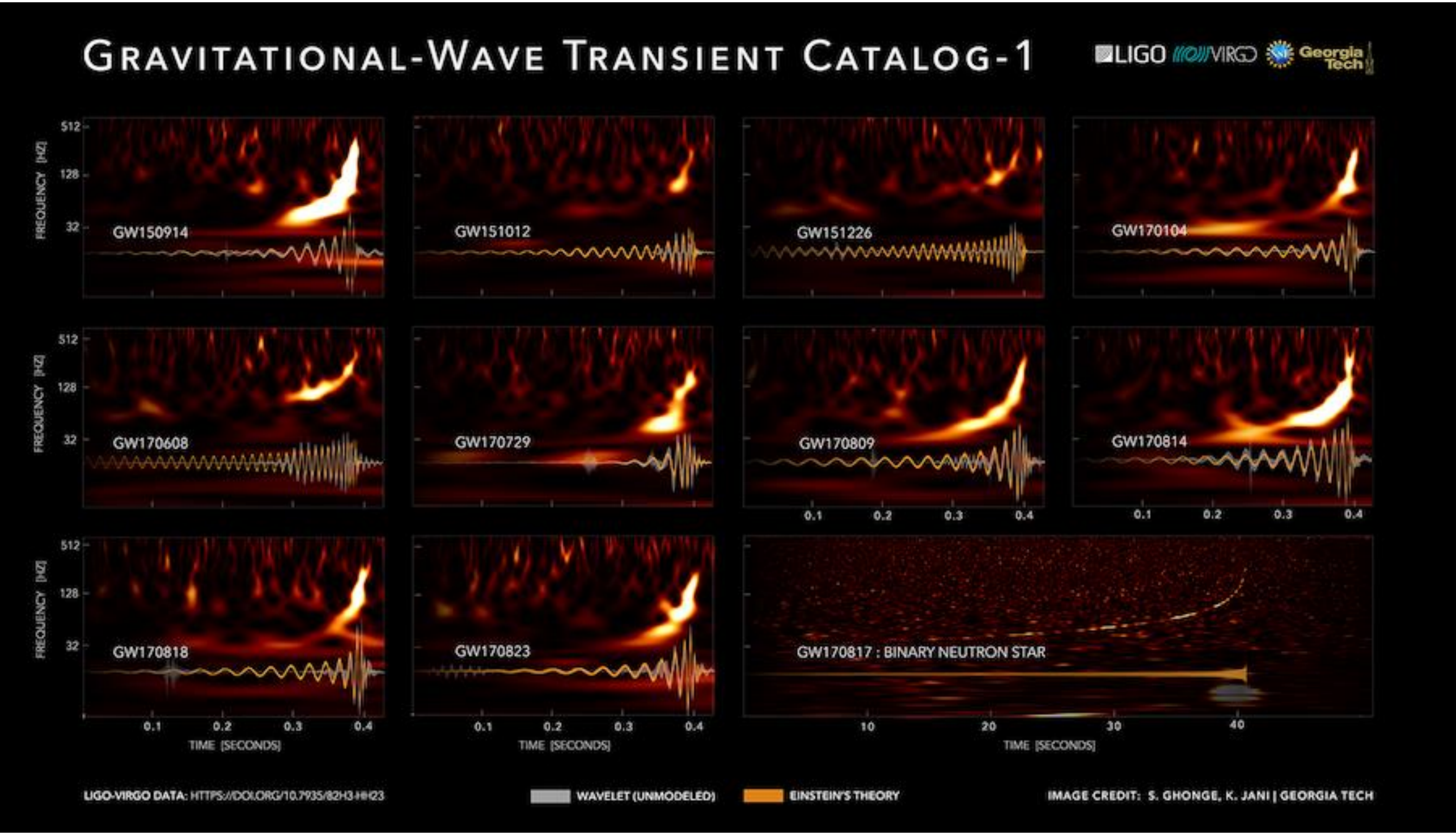
Launched 12/03/2015
At L1, masses released
Passed acceleration tests
Next, thruster tests



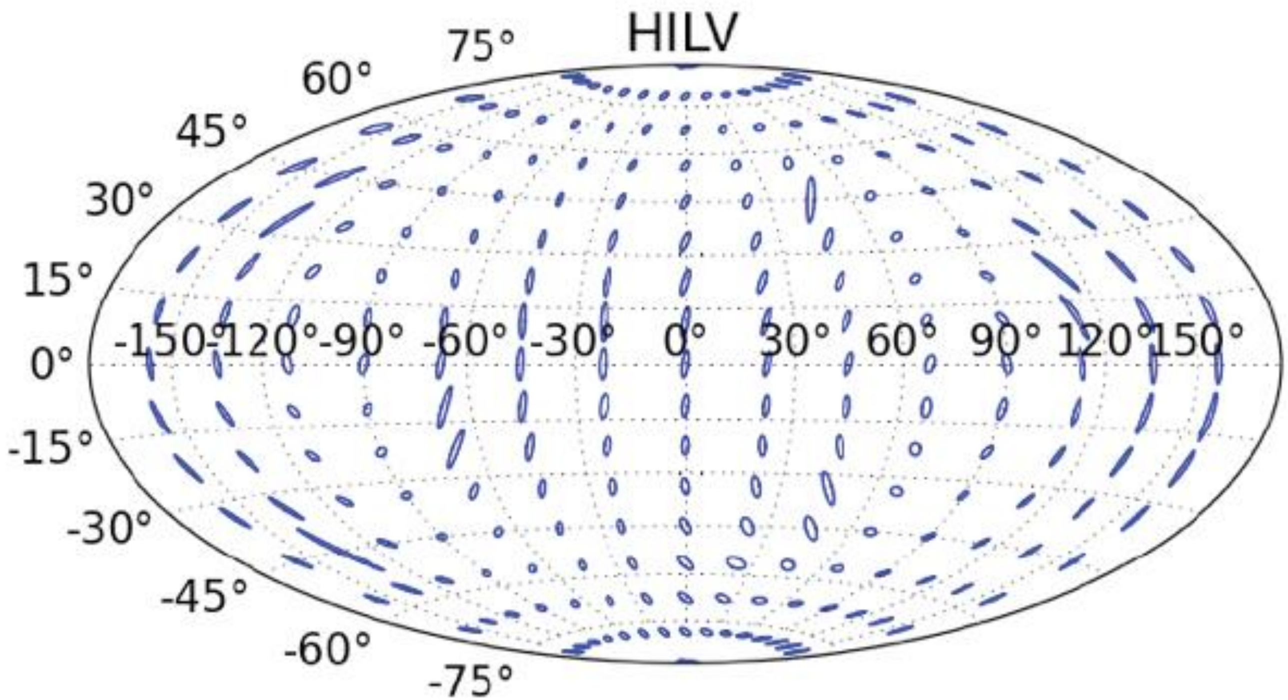
μN-thruster
x1
Drag-free
control
Electrodes
TM2
TM1
Electrostatic
suspension
Δx
y
x



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


GRAVITATIONAL-WAVE TRANSIENT CATALOG-1
LIGO
VIRGO
Georgia Tech
FREQUENCY [HZ]
512
128
32
GW150914
GW151012
GW151226
GW170104
GW170608
GW170729
GW170809
GW170814
GW170818
GW170823
GW170817 : BINARY NEUTRON STAR
0.1
0.2
0.3
0.4
10
20
30
40
TIME [SECONDS]
LIGO-VIRGO DATA: HTTPS://DOI.ORG/10.7935/82H3-HH23
WAVELET (UNMODELED)
EINSTEIN'S THEORY
IMAGE CREDIT: S. GHONGE, K. JANI | GEORGIA TECH

Localization with more detectors



Fairhurst 2011

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.

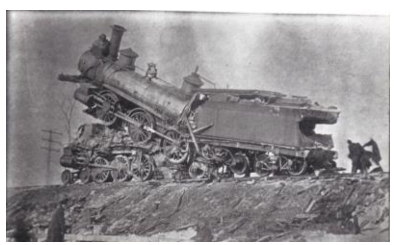
"…..in any case one can think of A will have a practically vanishing value."

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

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

1916 examples: train colllision — binary star decay

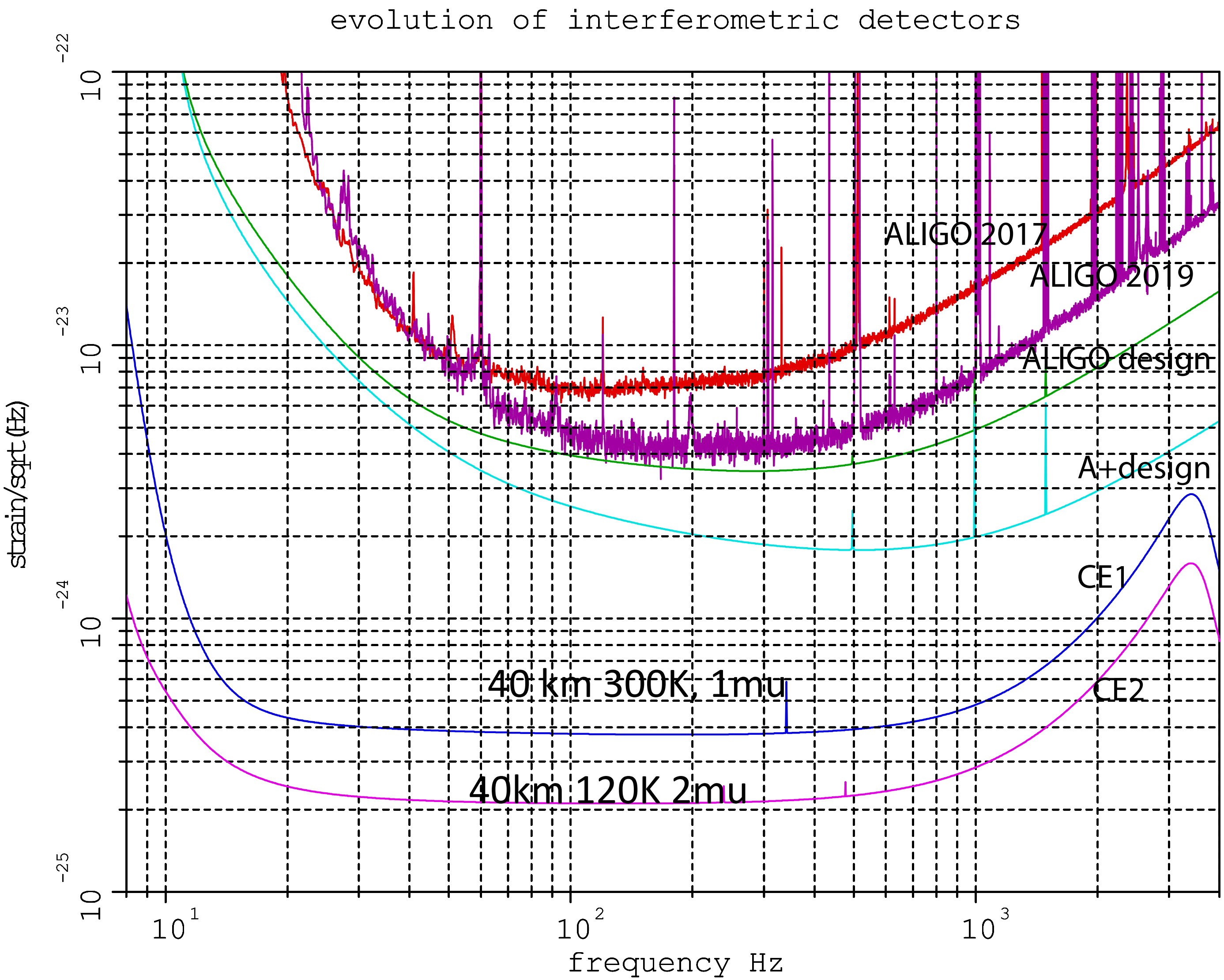
$m = 10^5$ kg
v = 100km/hr
$T_{collision}$ = 1/3 sec
$R_{radiation}$ = 300km
$h \sim 10^{-42}$



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

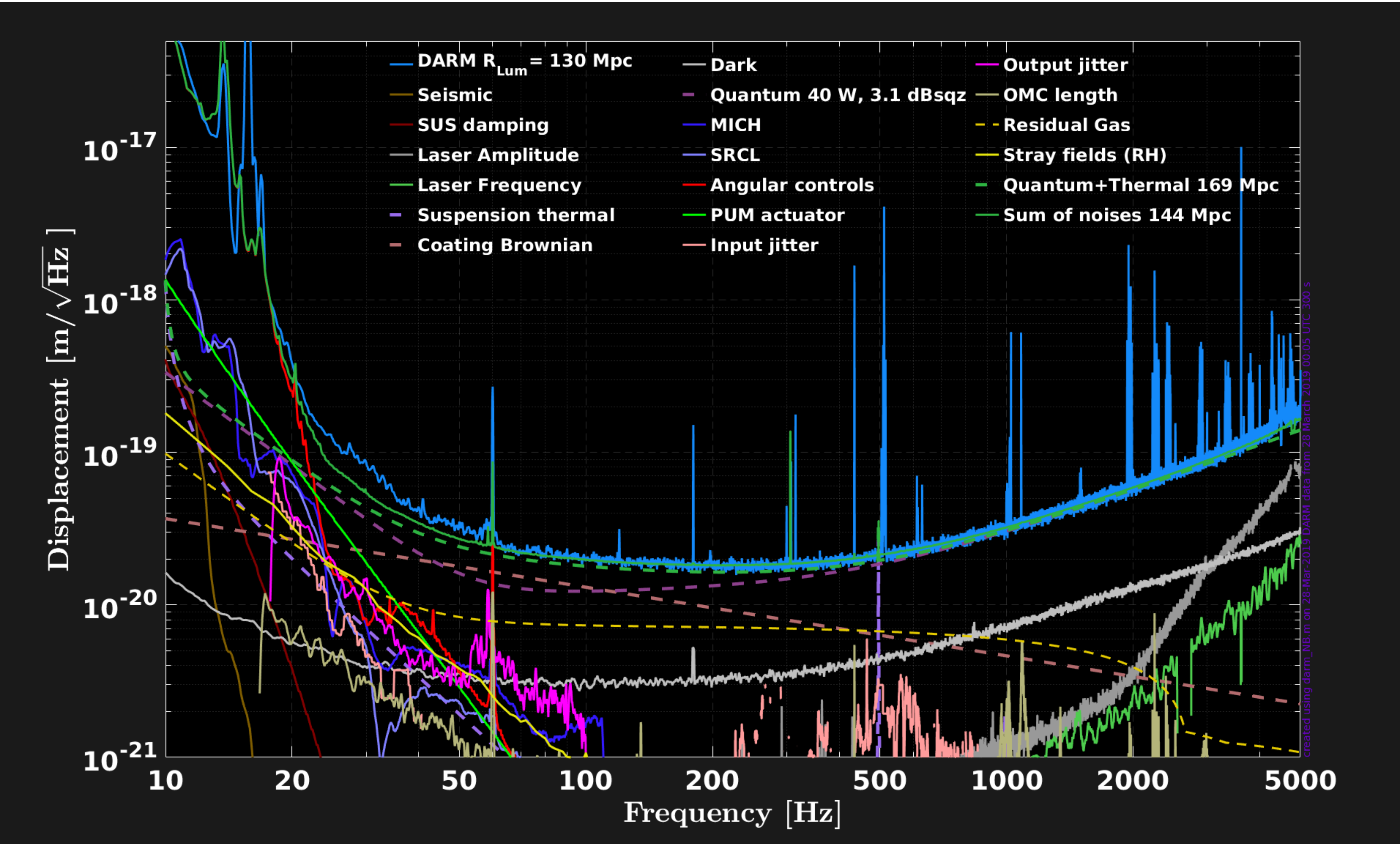
$h \sim 10^{-23}$ @ ½ day period

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

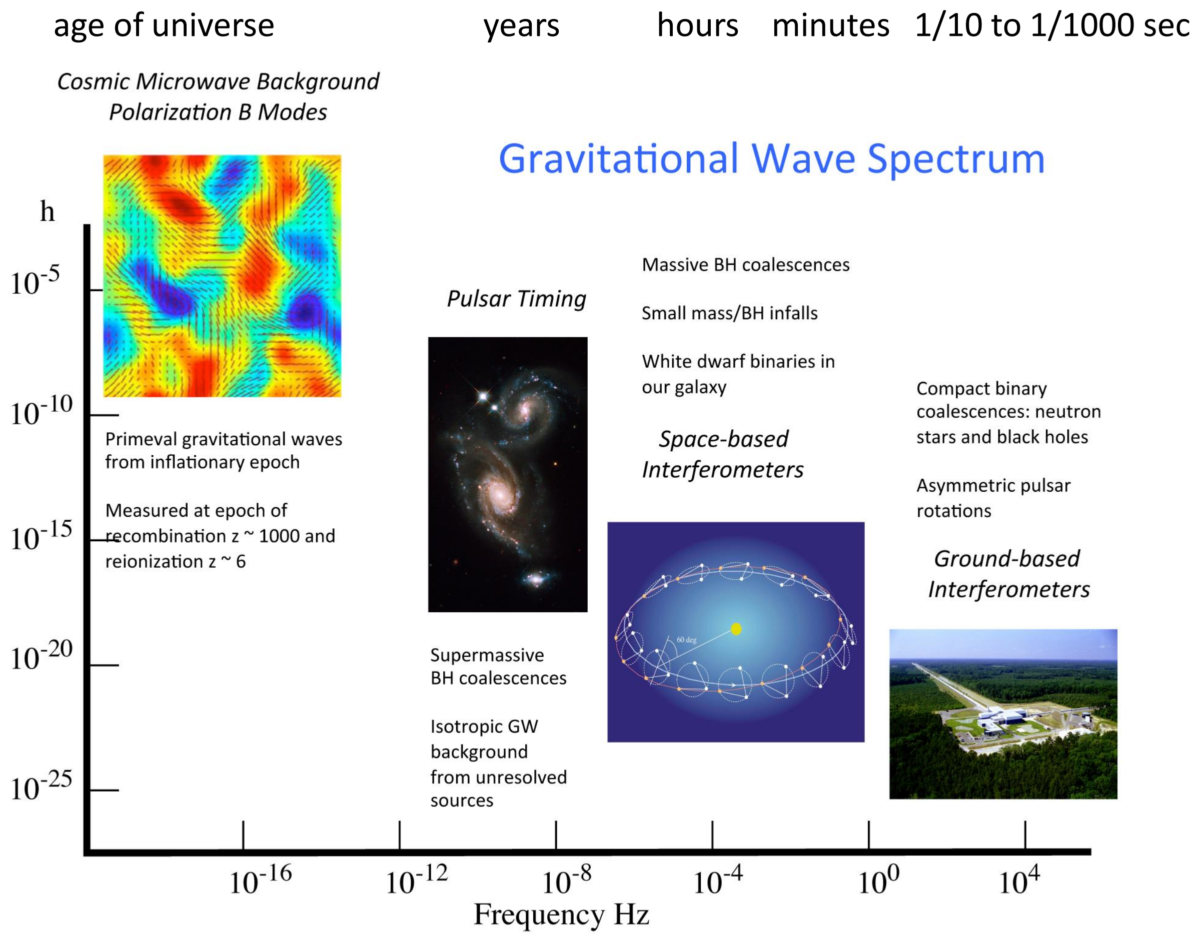


Pin(W)	SQ(db)	M(kg)
20	none	40
40	3	40
100	3	40
125	6fd	40
150	10fd	350
250	10fd	350

Noise budget at LLO March 2019



V. Frolov



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

AdV+: how good?

- Potential sensitivities

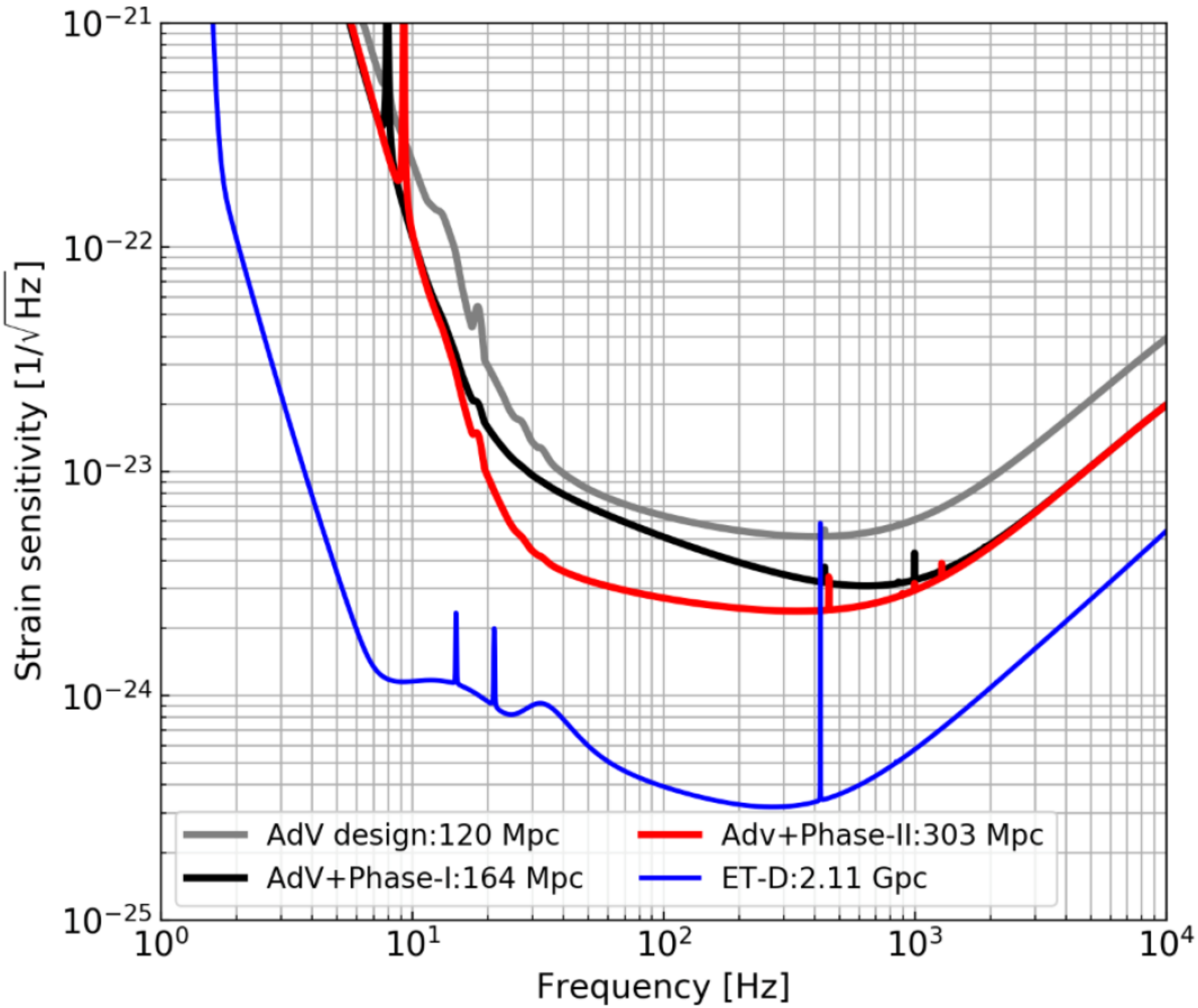
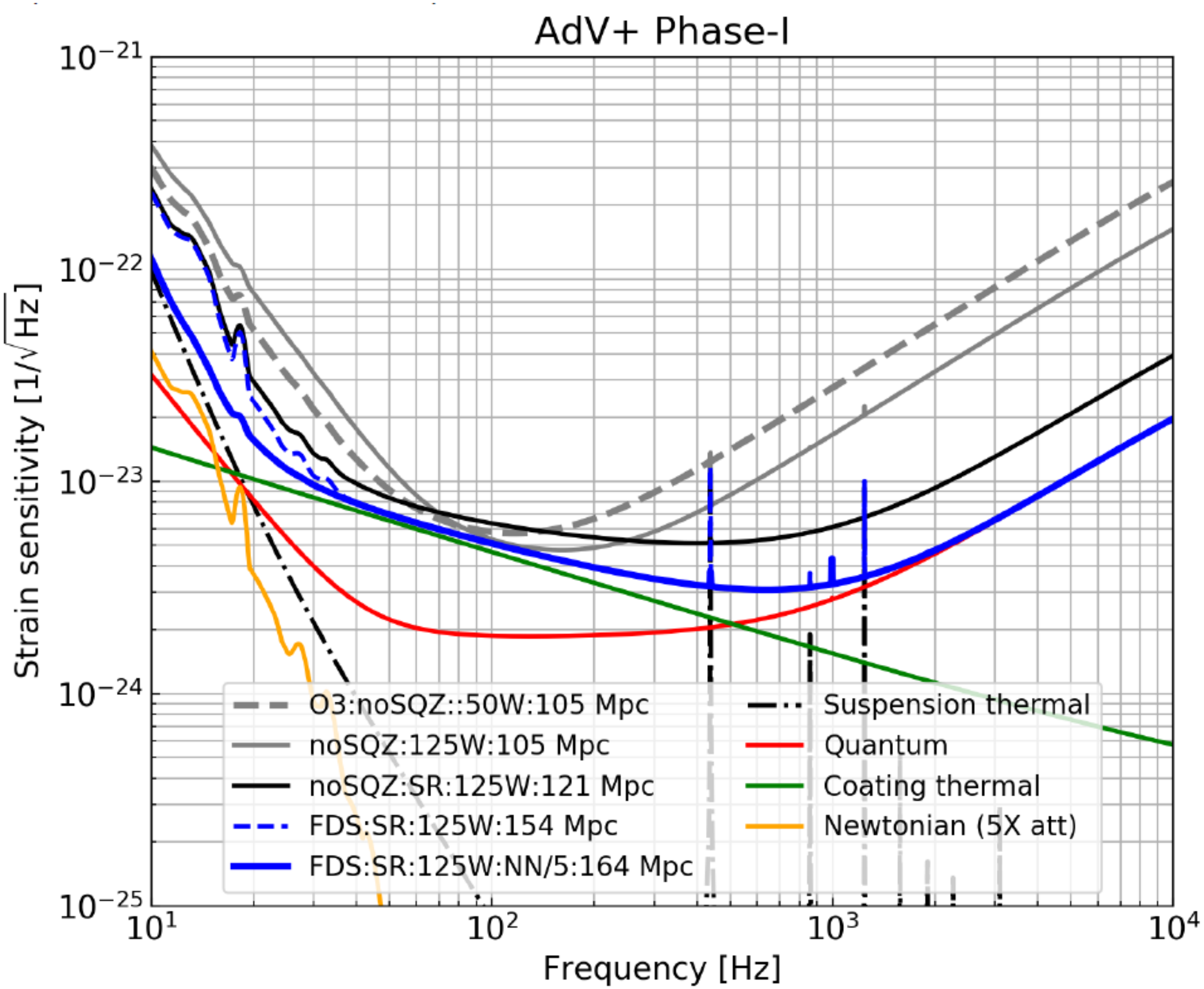


Figure 3.1: *Expected evolution of the Virgo sensitivity, and BNS range, after the completion of the two proposed upgrade phases. The design sensitivities of AdV and Einstein Telescope are also shown for reference.*

AdV+: how good?

- Phase I: “hitting the thermal noise wall”



AdV+: how good?

- Phase II: "pushing the thermal noise wall"

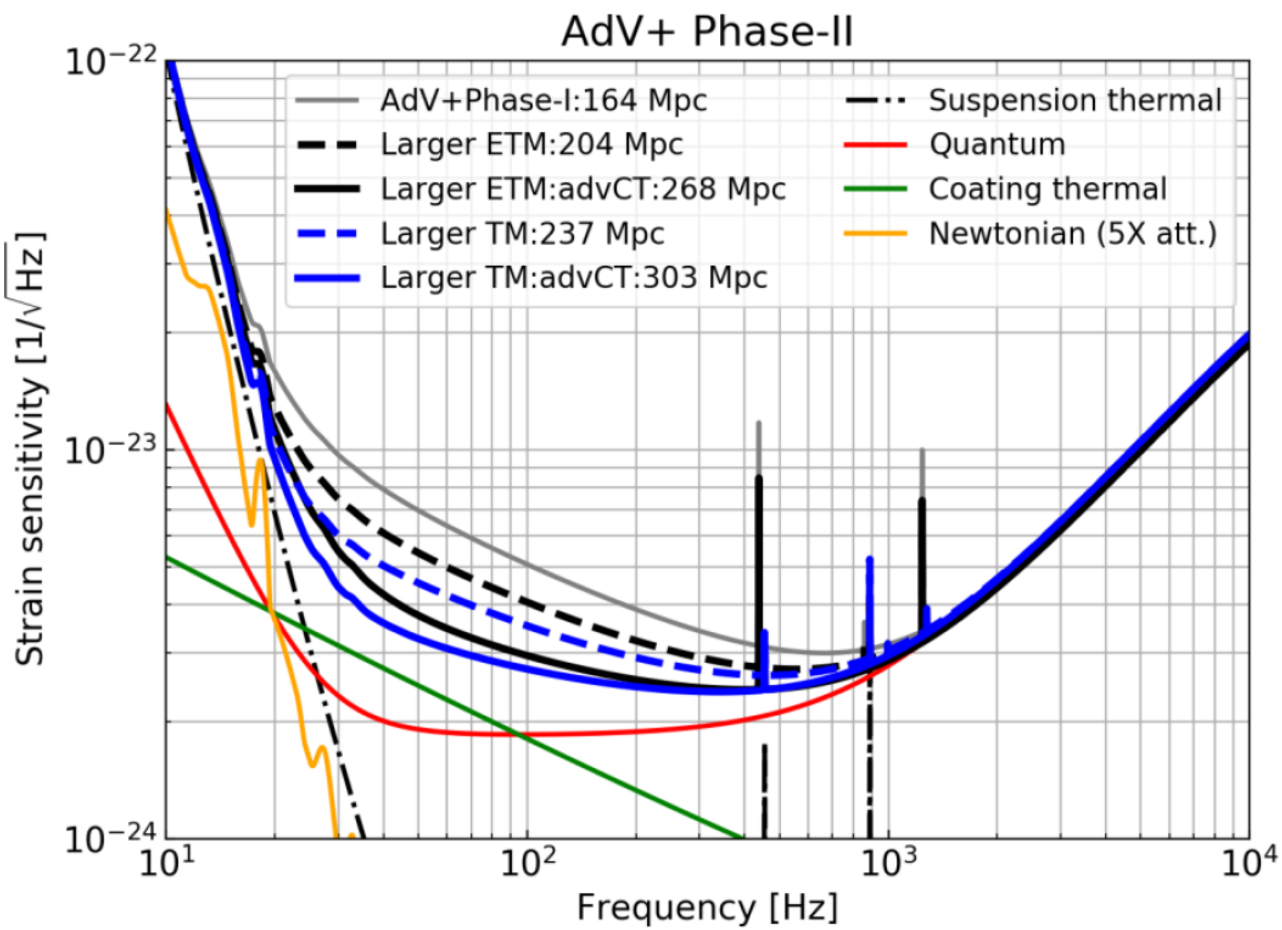
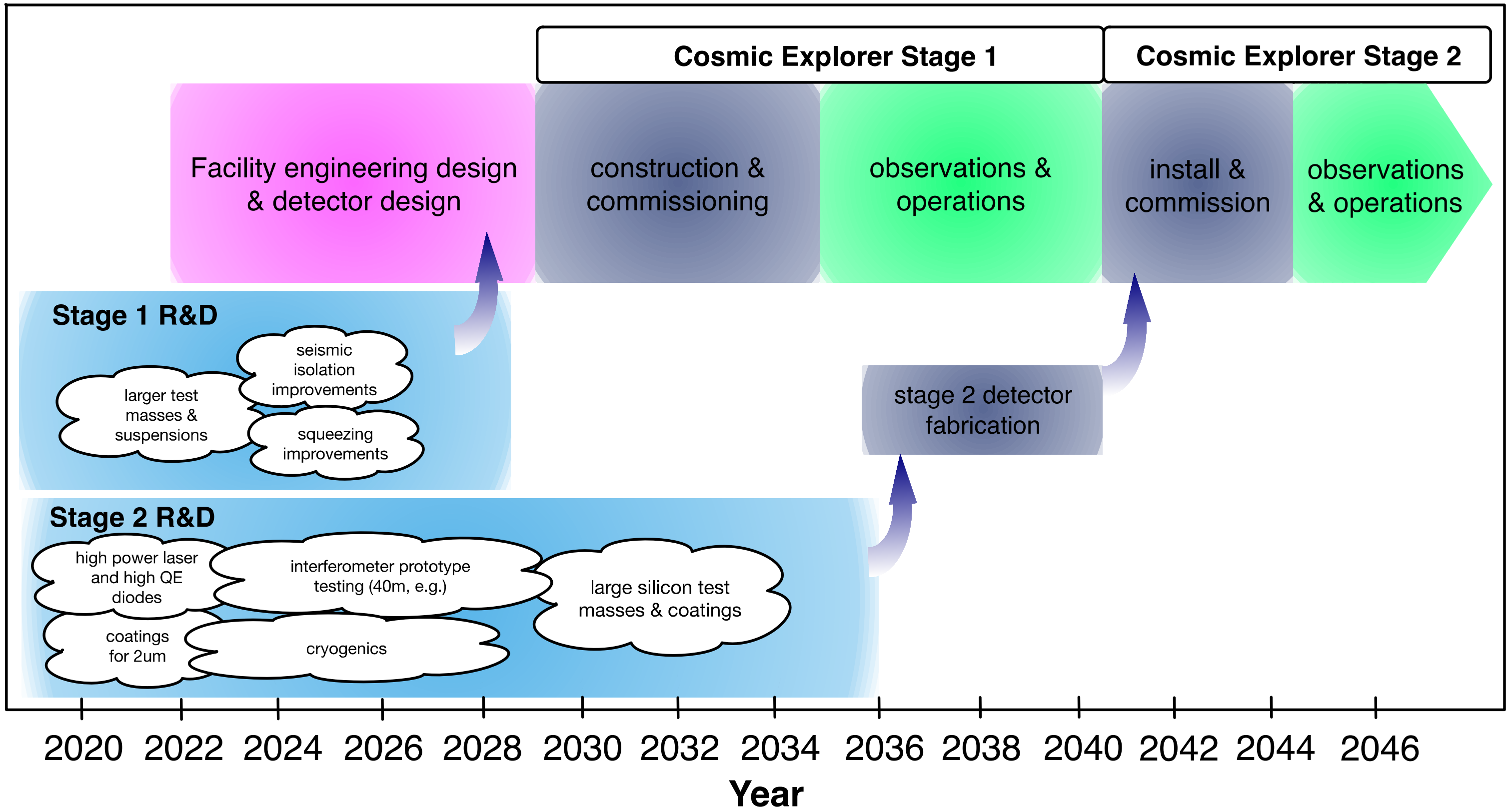


Figure 3.3: *Virgo sensitivity after the modification of the arm cavities optical design. The solid curves correspond to a factor of 3 reduction of coating losses with respect to the state-of-the-art (dashed curves). The results for the two possible configurations in which the beam size is increased either on ETMs only, or on all test masses are presented.*

Timeline of a Cosmic Explorer 40km Observatory



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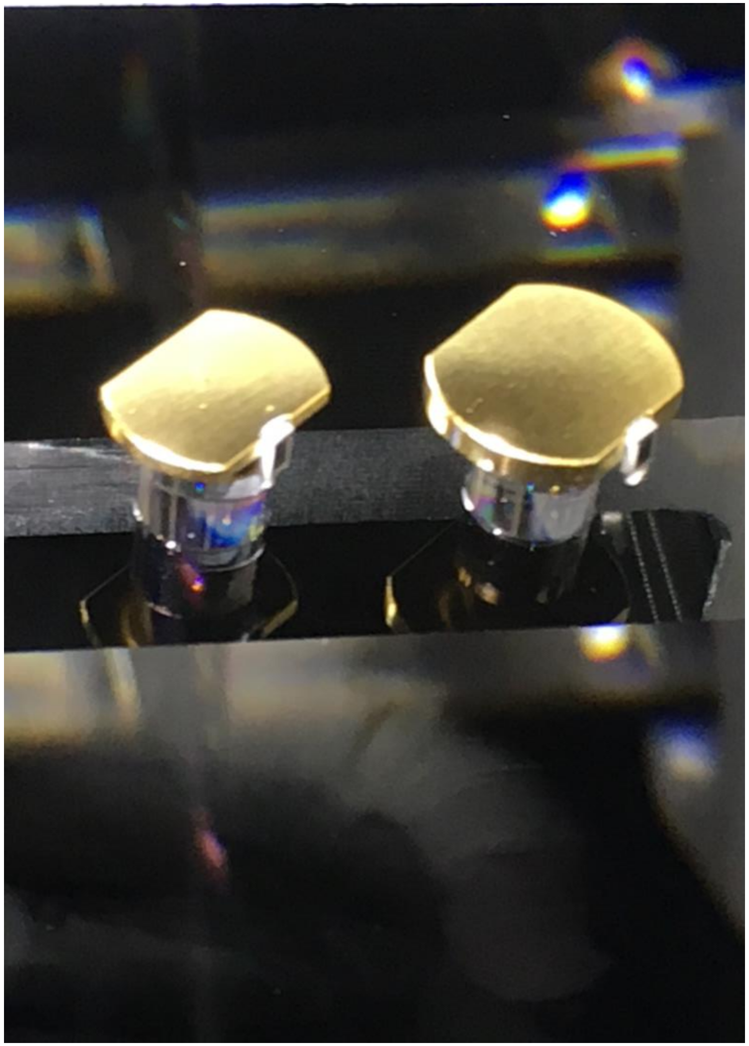
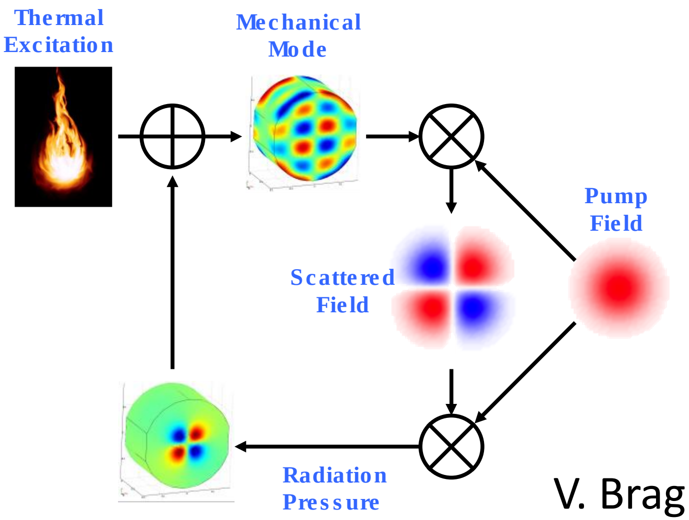
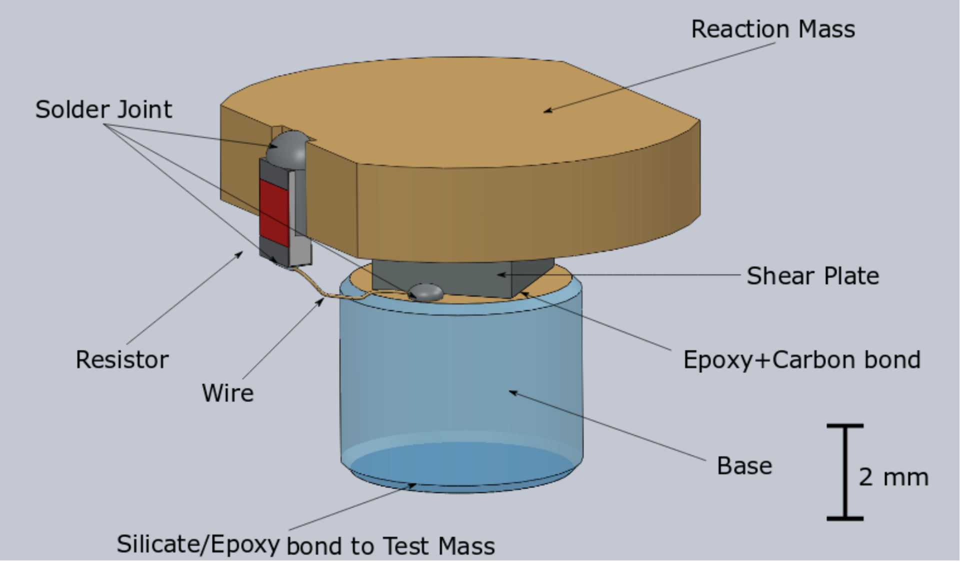
Acoustic mode damper for test mass : reduce parametric instability



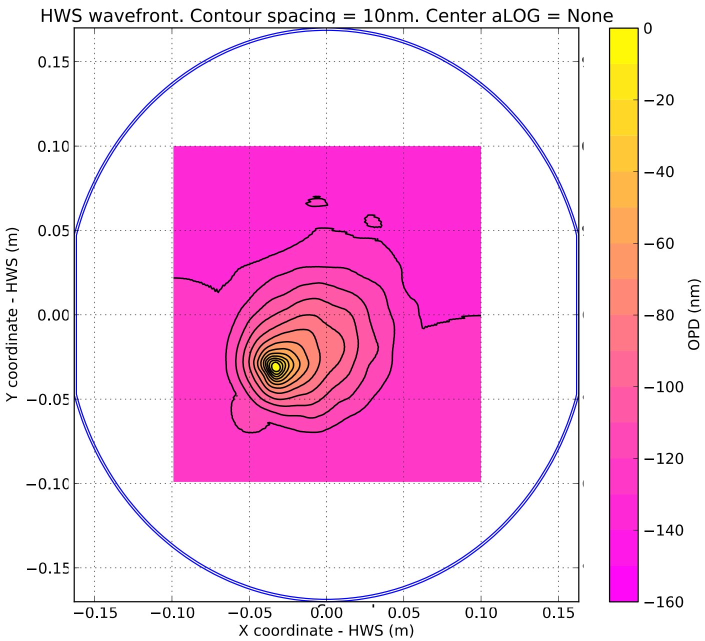


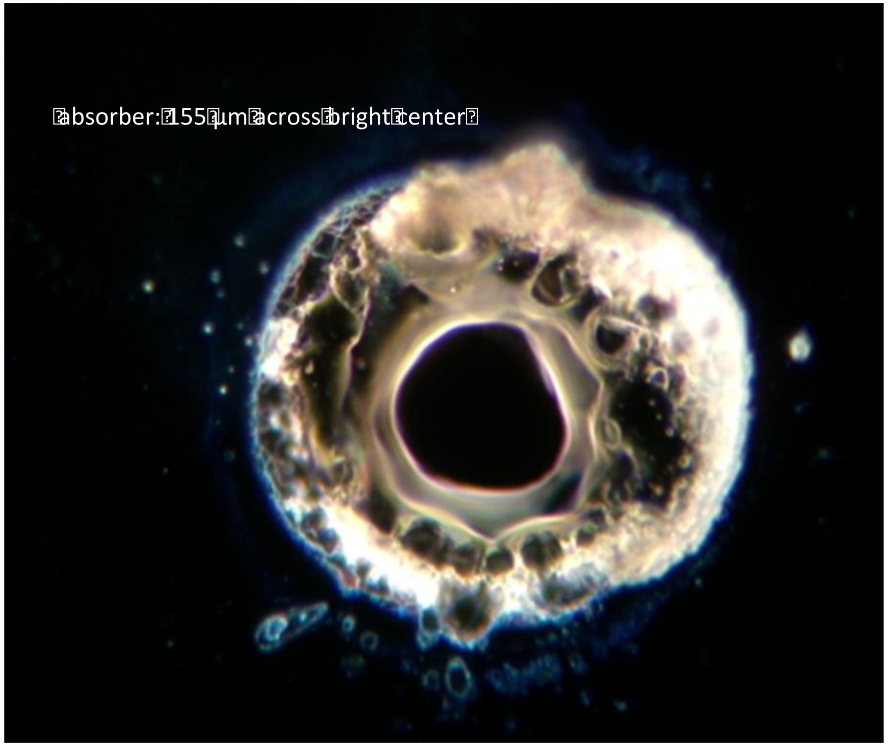
V. Braginsky



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

H1-ITMX point absorber (ITM03)





Michelson Interferometer Schematic and GW sidebands