Gravitational Waves: From Idea to Discovery

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California Institute of Technology

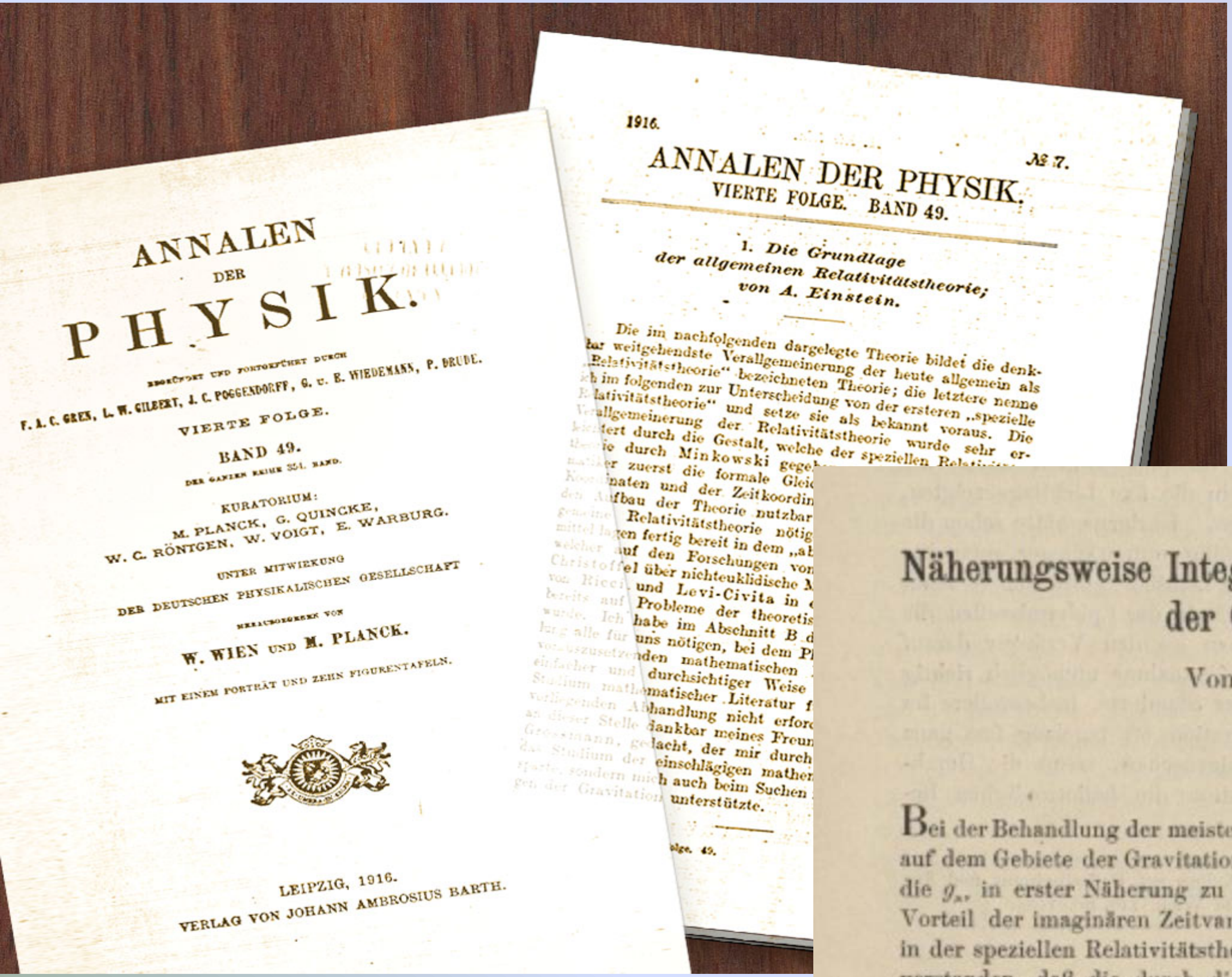
June 4, 2018

For the LIGO Scientific Collaboration and the Virgo Collaboration

LIGO-G1801078-v1

Credit: NSF/LIGO/Sonoma State University/A. Simonnet

A Century of General Relativity

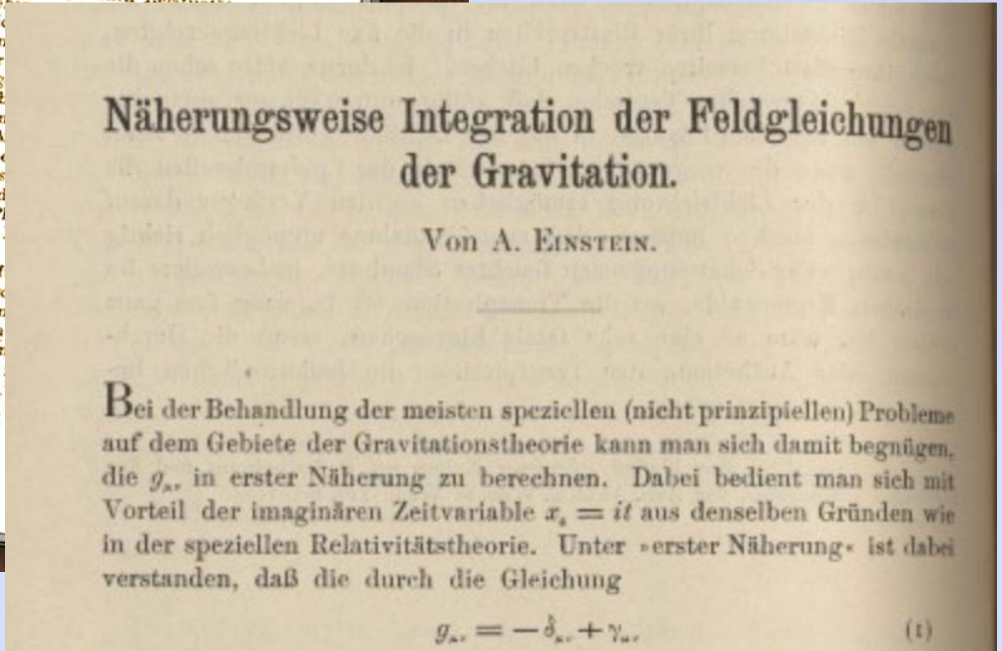


ANNALEN DER PHYSIK.
BEGRÜNDET UND FORTGEFÜHRT DURCH
F. A. C. GREN, L. W. GILBERT, J. C. POGGENDORFF, G. u. E. WIEDEMANN, P. DRUDE.
VIERTE FOLGE.
BAND 49.
DER GANZEN REIHE 354. BAND.
KURATORIUM:
M. PLANCK, G. QUINCKE,
W. C. RÖNTGEN, W. VOIGT, E. WARBURG.
UNTER MITWIRKUNG
DER DEUTSCHEN PHYSIKALISCHEN GESELLSCHAFT
HERAUSGEGEBEN VON
W. WIEN UND M. PLANCK.
MIT EINEM PORTRÄT UND ZEHN FIGURENTAFELN.
LEIPZIG, 1916.
VERLAG VON JOHANN AMBROSIUS BARTH.

1916. № 7.
ANNALEN DER PHYSIK.
VIERTE FOLGE. BAND 49.

1. Die Grundlage der allgemeinen Relativitätstheorie; von A. Einstein.

Die im nachfolgenden dargelegte Theorie bildet die denkbar weitgehendste Verallgemeinerung der heute allgemein als „Relativitätstheorie" bezeichneten Theorie; die letztere nenne ich im folgenden zur Unterscheidung von der ersteren „spezielle Relativitätstheorie" und setze sie als bekannt voraus. Die Verallgemeinerung der Relativitätstheorie wurde sehr erleichtert durch die Gestalt, welche der speziellen Relativitätstheorie durch Minkowski gegeb…

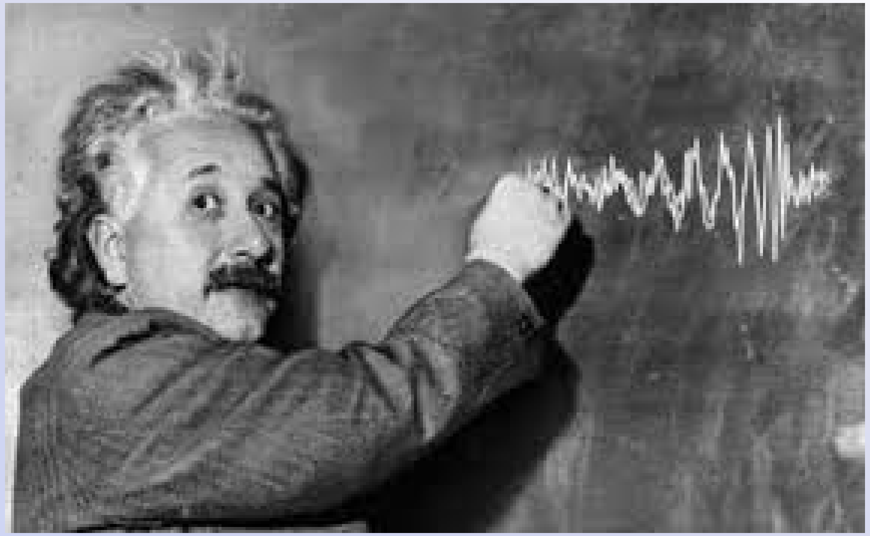


Näherungsweise Integration der Feldgleichungen der Gravitation.

Von A. Einstein.

Bei der Behandlung der meisten speziellen (nicht prinzipiellen) Probleme auf dem Gebiete der Gravitationstheorie kann man sich damit begnügen, die $g_{\mu\nu}$ in erster Näherung zu berechnen. Dabei bedient man sich mit Vorteil der imaginären Zeitvariable $x_4 = it$ aus denselben Gründen wie in der speziellen Relativitätstheorie. Unter »erster Näherung« ist dabei verstanden, daß die durch die Gleichung

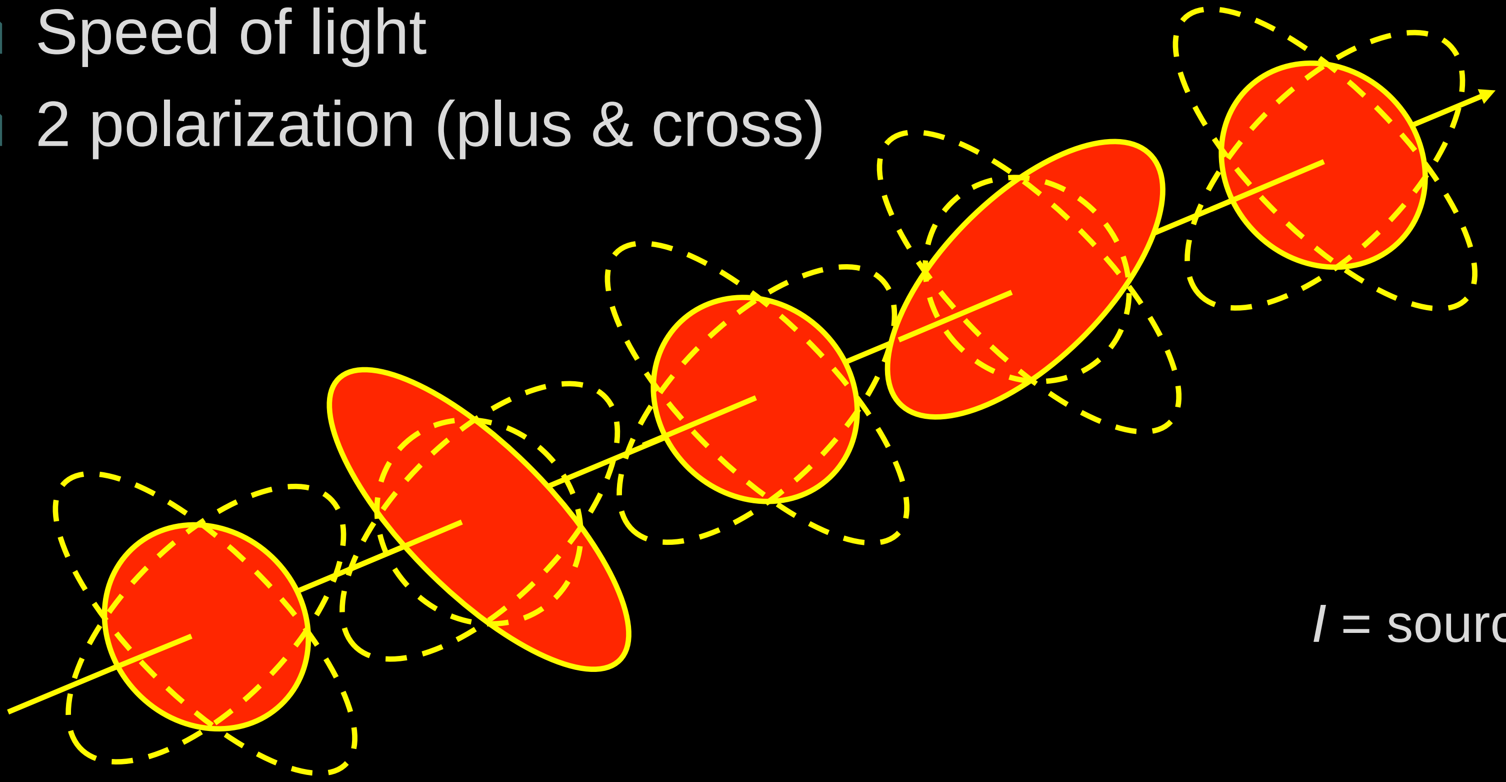
$$g_{\mu\nu} = -\delta_{\mu\nu} + \gamma_{\mu\nu} \quad (1)$$



Karl Schwarzschild

Gravitational Waves

- Perturbations of the space-time metric produced by rapid changes in shape and orientation of massive objects.
- Speed of light
- 2 polarization (plus & cross)



$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$$

$$h(t) = \frac{1}{R}\frac{2G}{c^4}\ddot{I}(t)$$

h = dimensionless strain
I = source mass quadrupole moment
R = source distance

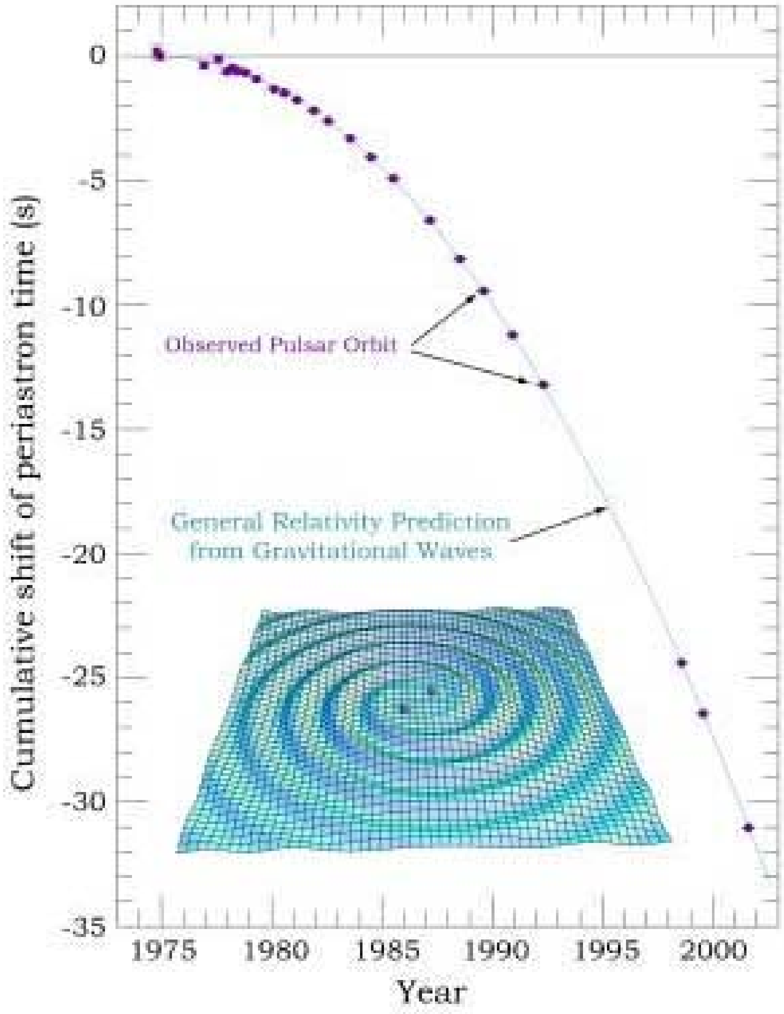
Indirect Evidence of gravitational radiation: PSR 1913+16

- 1974:
  Hulse and Taylor discover binary neutron star

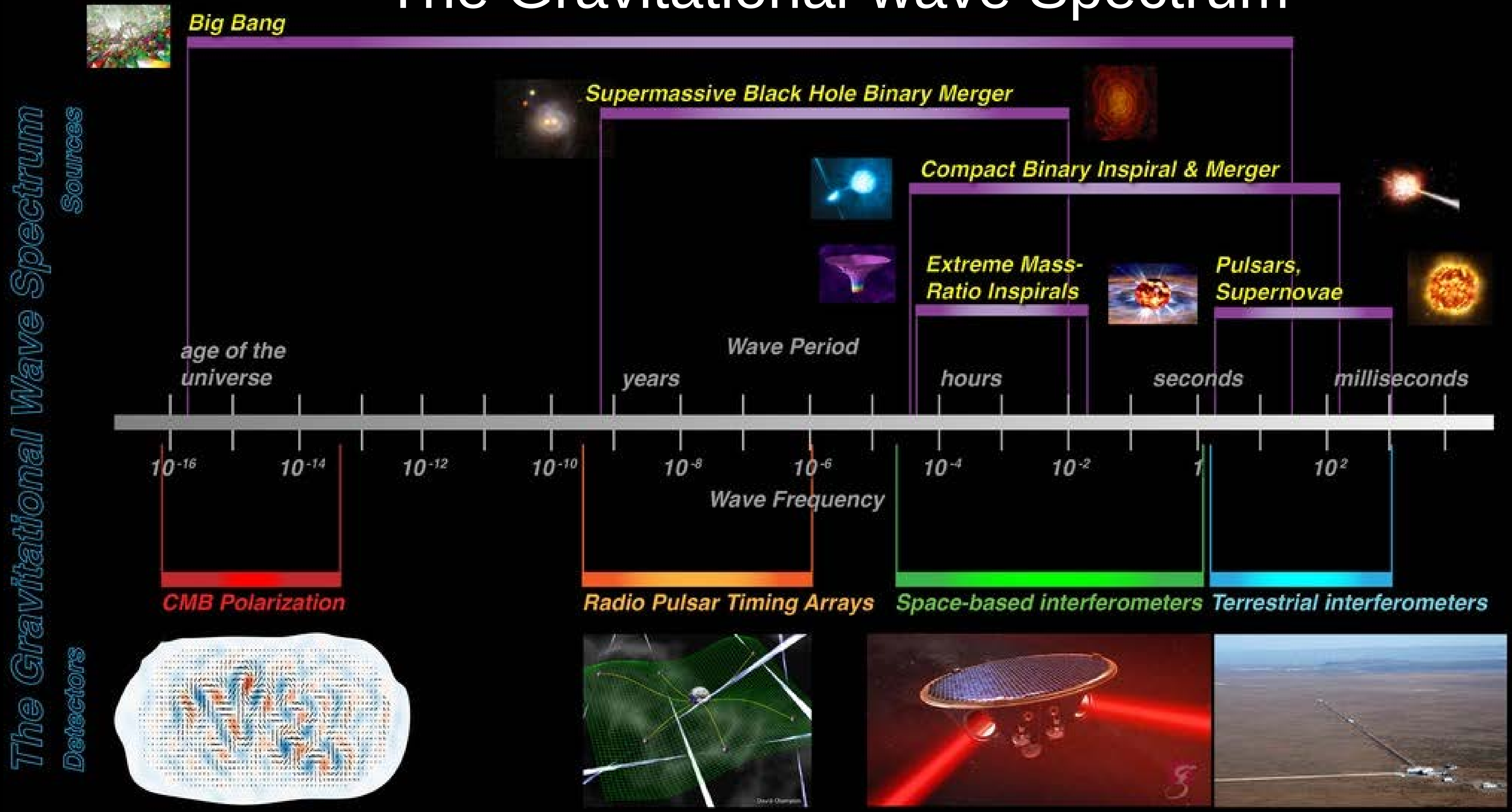

J. Taylor


R. Hulse

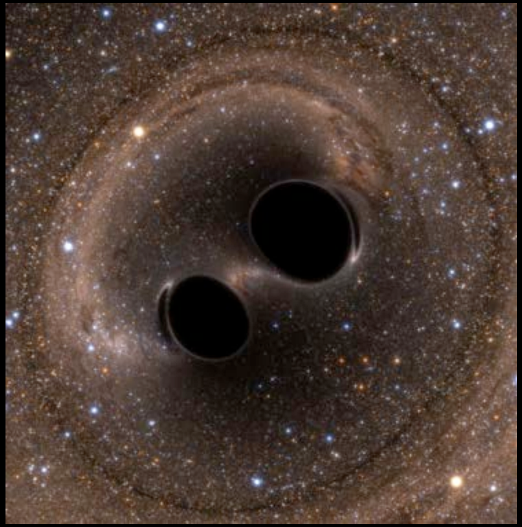
- Observed over the course of decades
  Slow orbital decay
  Gravitational waves carrying away orbital energy
- Nobel Prize in Physics 1993
- Coalescence in about ~300 million years
- GW emission strongest near the end



The Gravitational-wave Spectrum



Astrophysical Targets for Ground-based Detectors

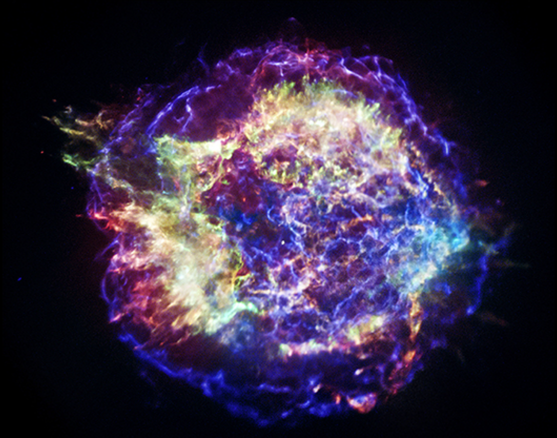


Credit: Bohn, Hebert, Throwe, SXS

Coalescing Binary Systems

Black Holes

Neutron stars



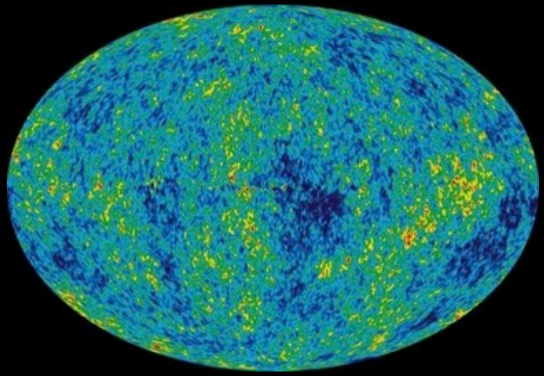
Credit: NASA/CXC/SAO

'Bursts'

Asymmetric core collapse supernovae

cosmic strings

???



NASA/WMAP Science Team

Cosmic GW Background

Stochastic, incoherent background

Casey Reed, Penn State

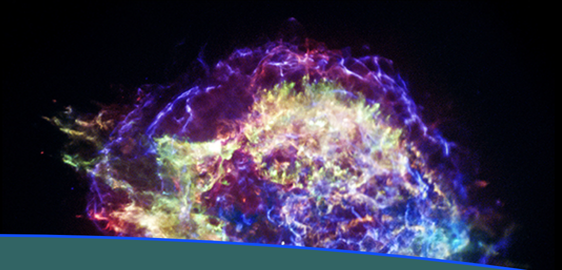
Continuous Sources

Spinning neutron stars

crustal deformations, accretion

Astrophysical Targets for Ground-based Detectors

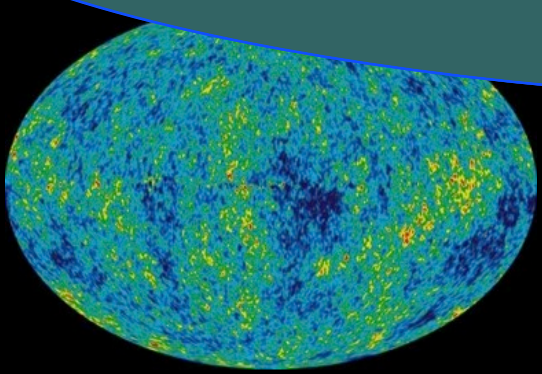
Coalescing Binary Systems



'Bursts'

Asymmetric core collapse supernovae

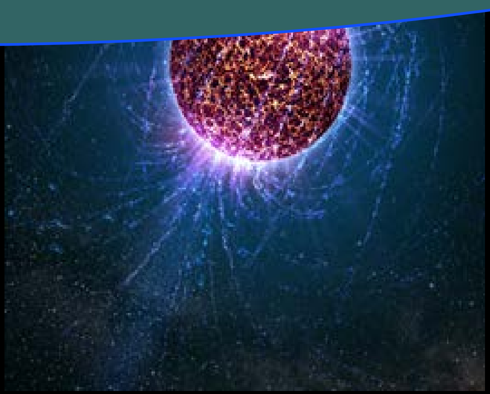
Plus, potentially something unexpected



NASA/WMAP Science Team

Background

Stochastic, incoherent background



Casey Reed, Penn State

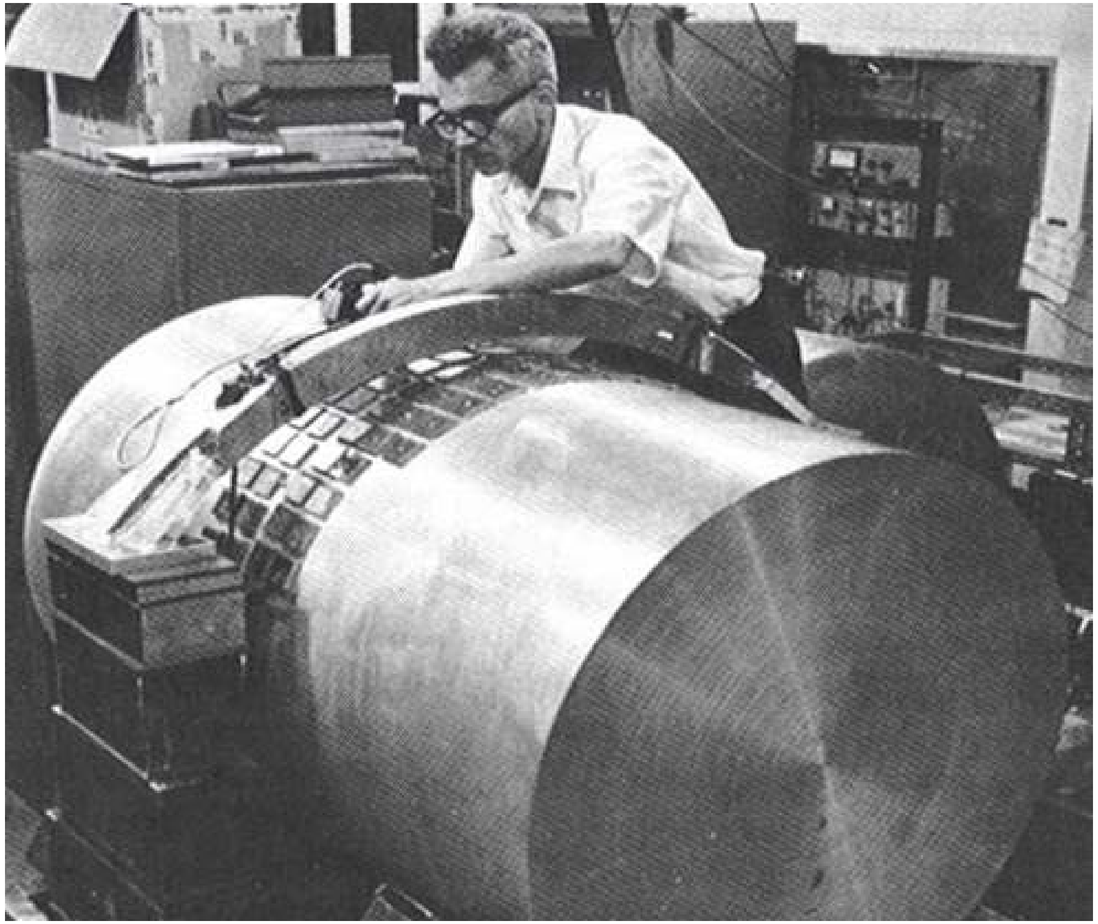
Sources

Spinning neutron stars

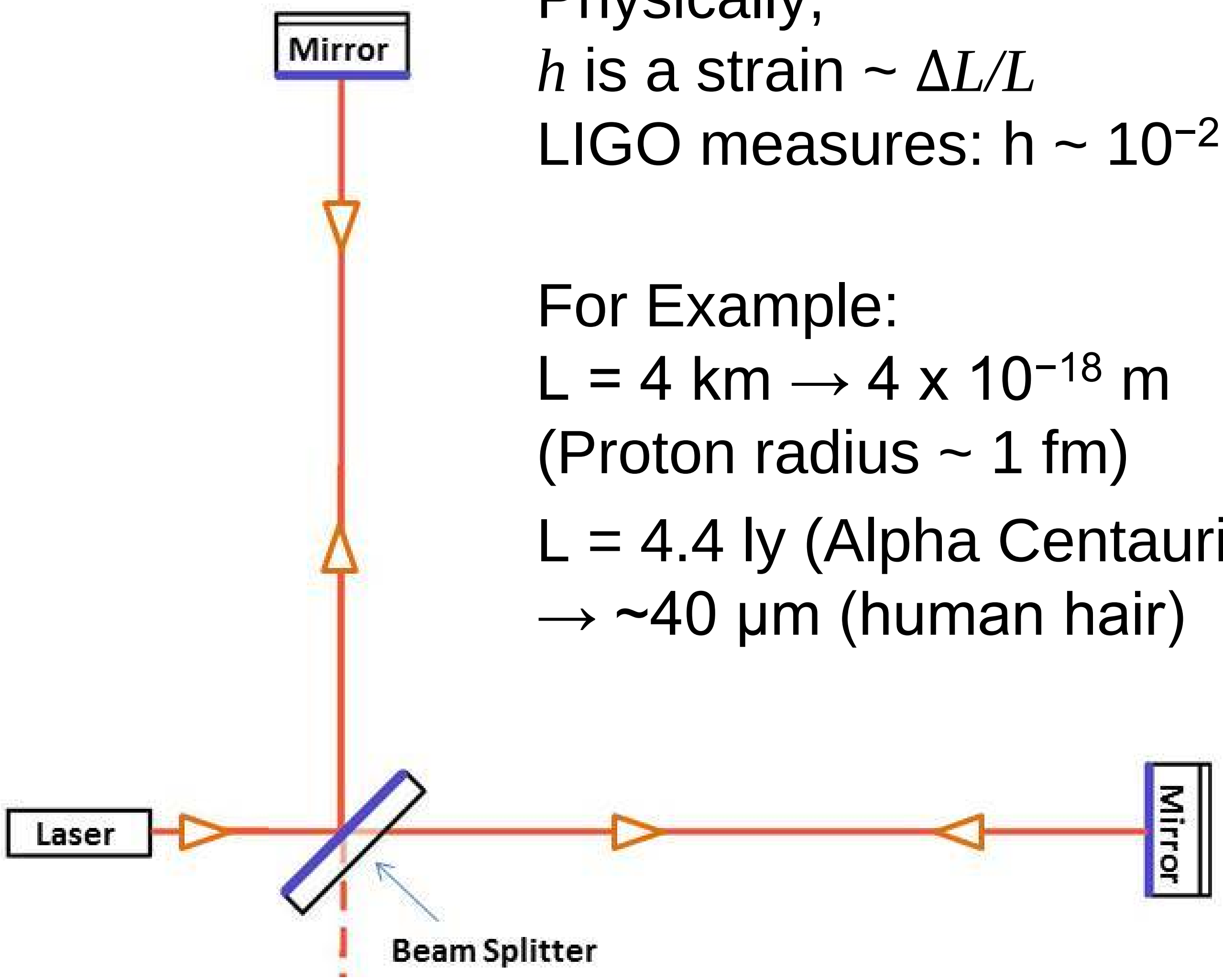
crustal deformations, accretion

Terrestrial Detection of Gravitational Waves

- 1960s: Joseph Weber constructs resonant bar detectors
- Claims several detections per day
  Not reproducible by similar experiments in US, Europe, Japan
  Theoretical objections:
  Milky Way should be losing energy at a noticeable rate!
- If not this way, how would one detect gravitational waves?



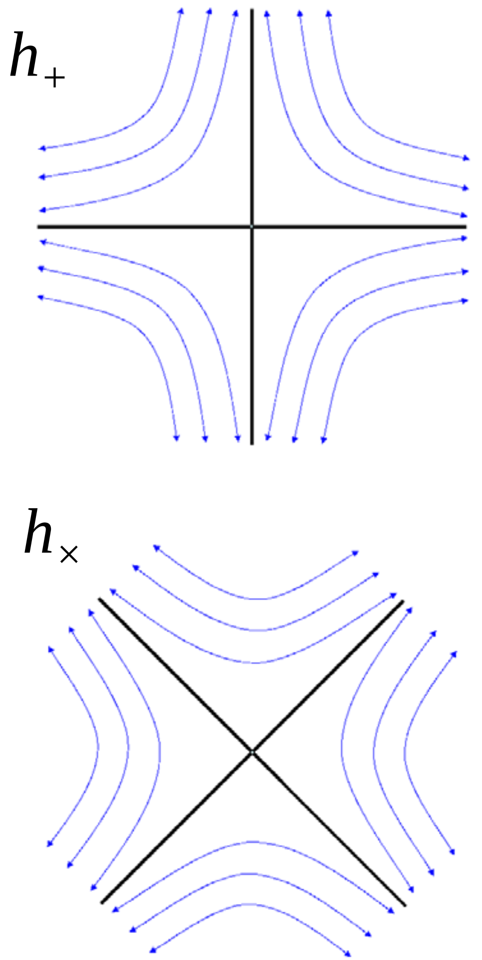
Michelson Interferometer

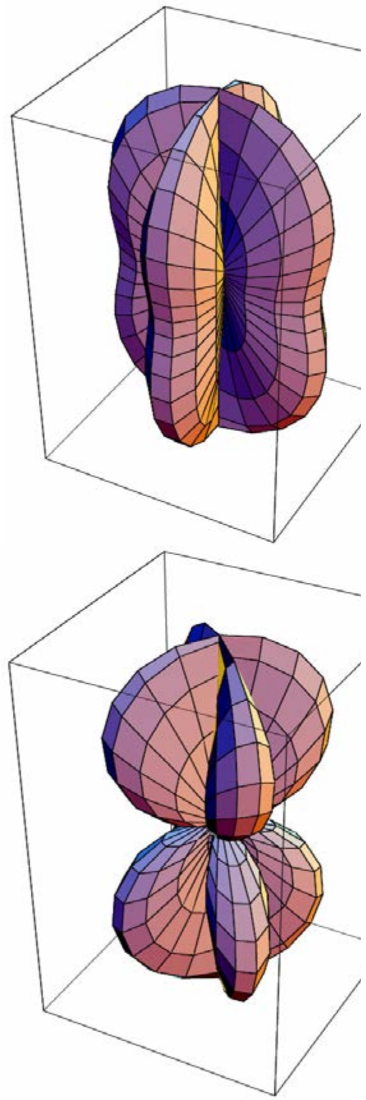


Physically,
h is a strain ~ $\Delta L/L$
LIGO measures: h ~ 10^{-21}

For Example:
L = 4 km → 4 x 10^{-18} m
(Proton radius ~ 1 fm)

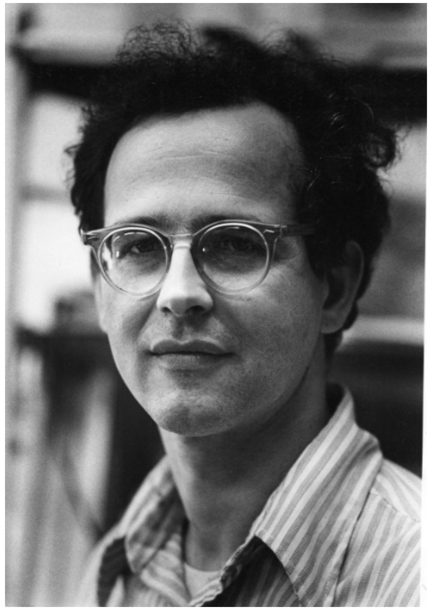
L = 4.4 ly (Alpha Centauri)
→ ~40 μm (human hair)



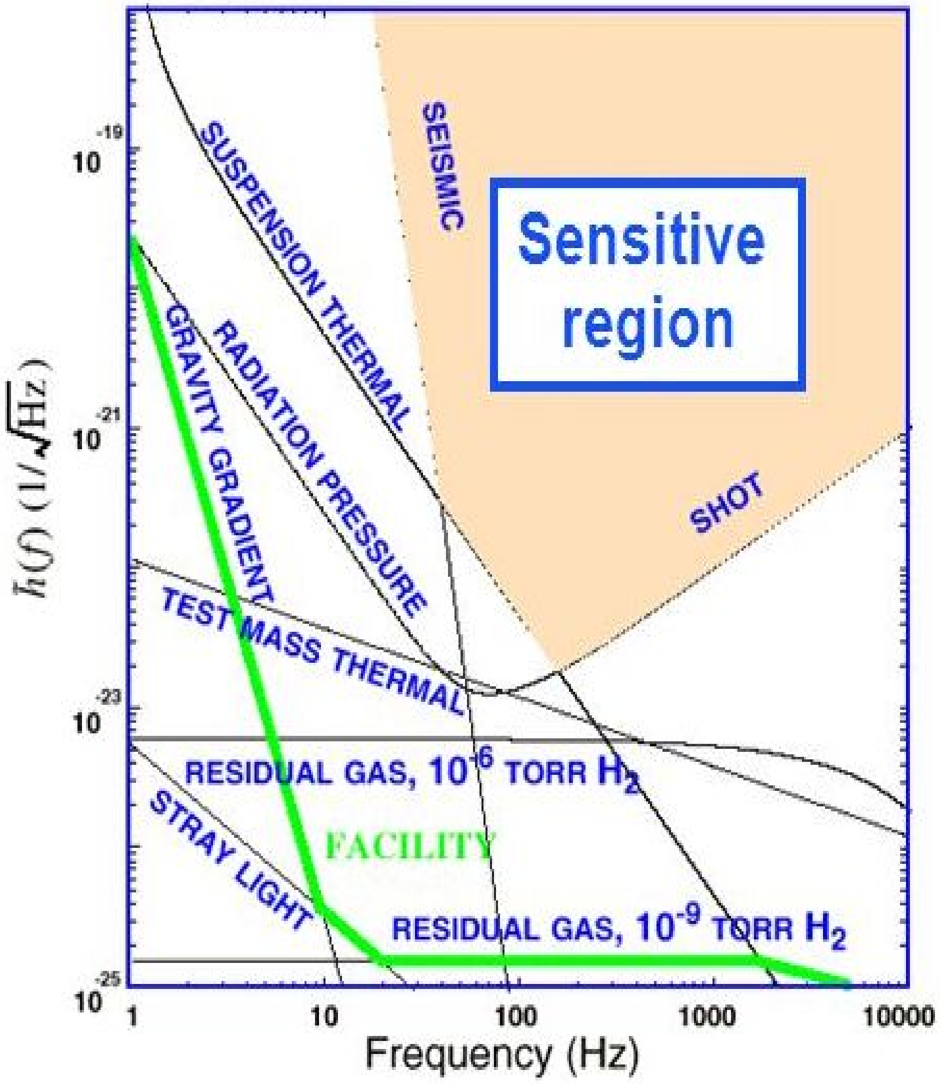


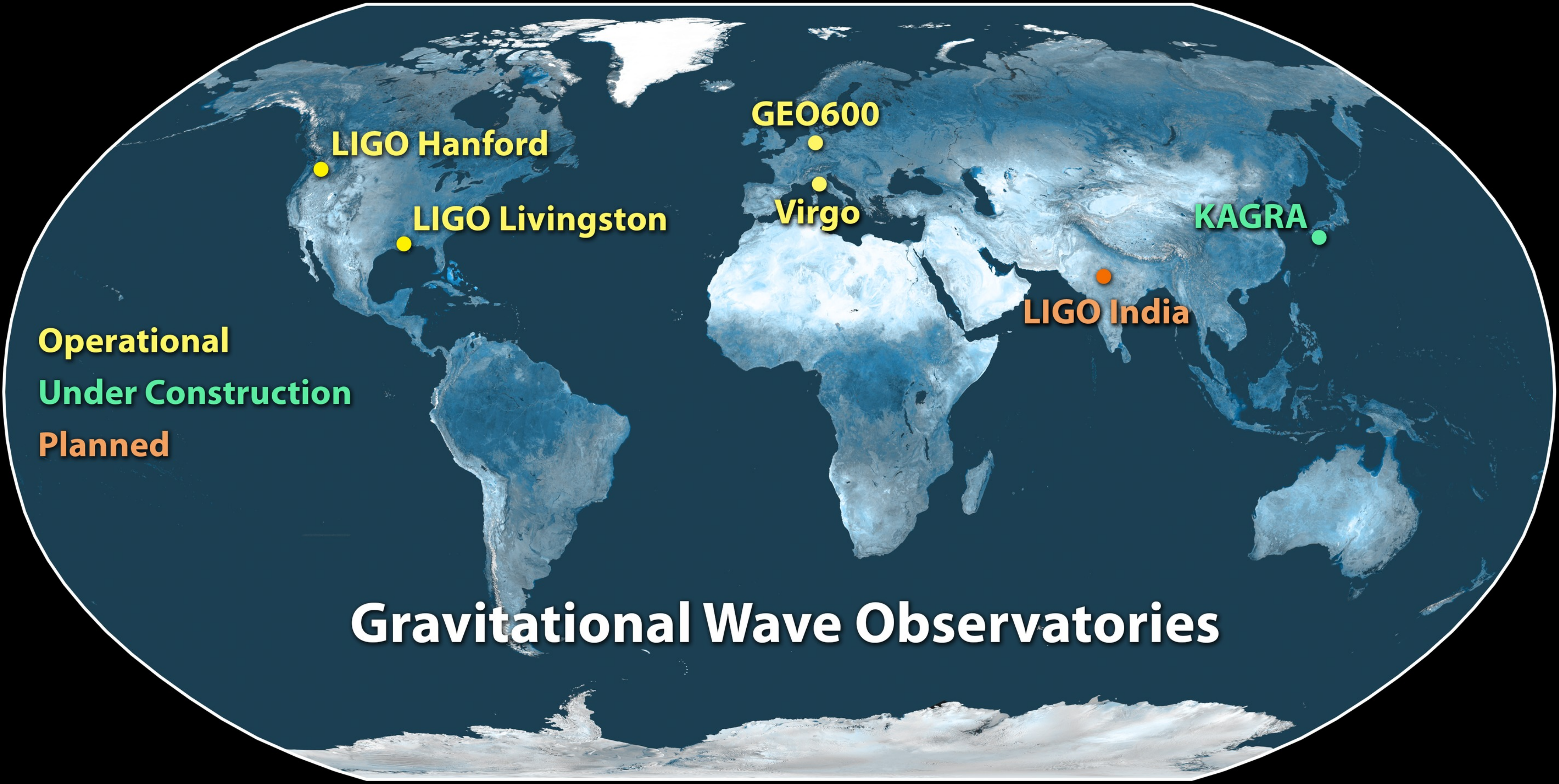
Interferometric Detectors

- Design study 1971 by Rai Weiss
- Major noise sources:
  Seismic
  Thermal
  Photon Shot Noise
- Need for km long laser interferometers!



Rainer Weiss (1972)

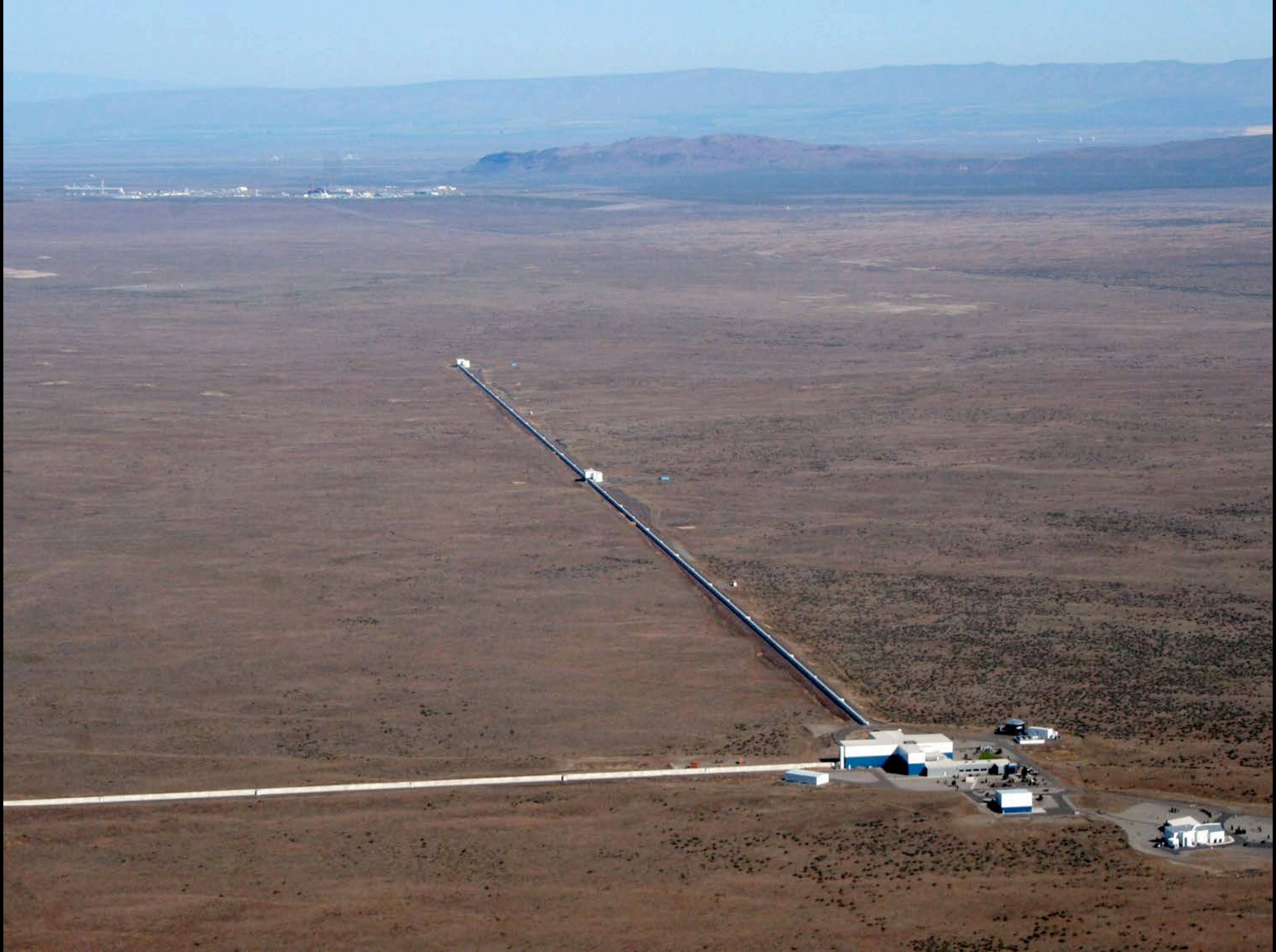



GEO600
LIGO Hanford
Virgo
LIGO Livingston
KAGRA
LIGO India
Operational
Under Construction
Planned
Gravitational Wave Observatories

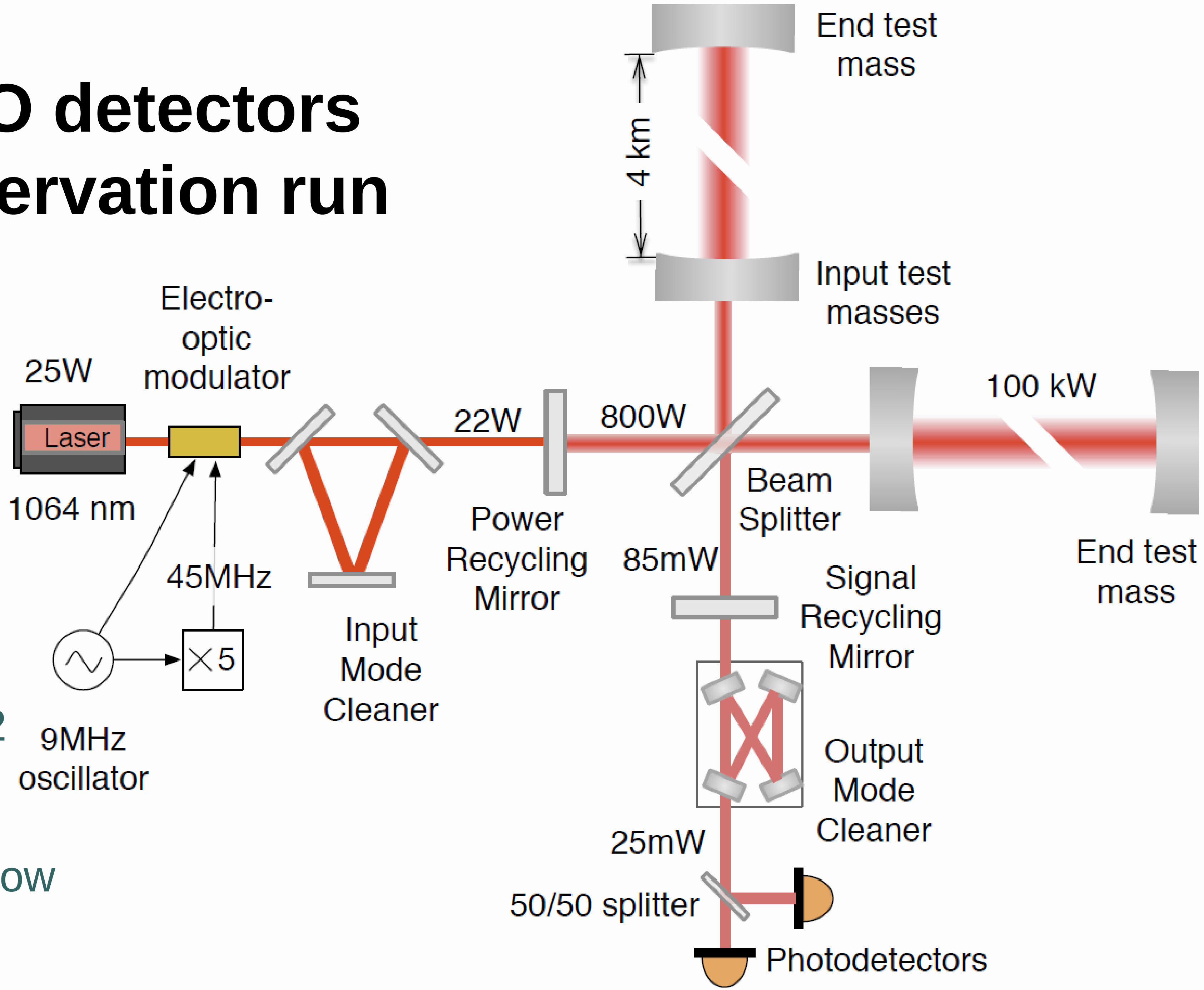
Livingston Observatory

Virgo Detector

Hanford Observatory



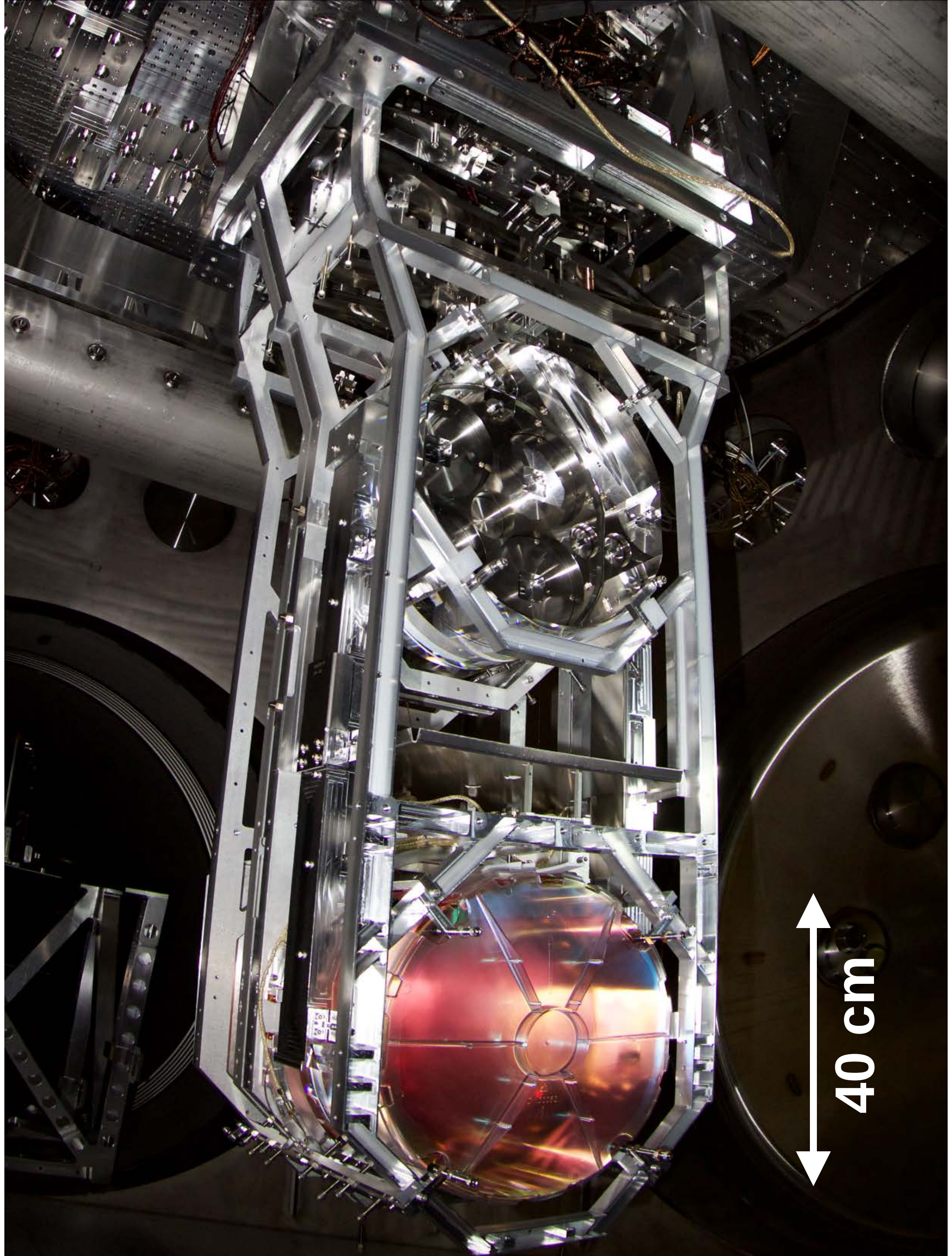
Advanced LIGO detectors during first observation run

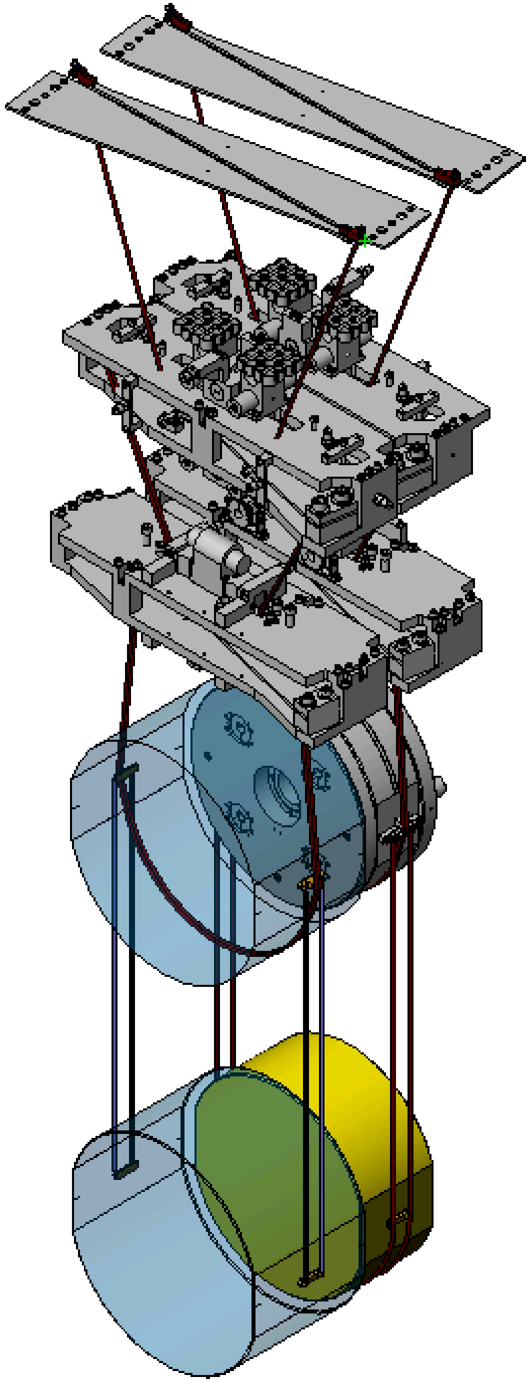


Timeline:

- Funding 1984-1992
- Construction 1992-2002
- Initial LIGO 2002-2010
- Advanced LIGO 2008-now

Test Mass Suspension

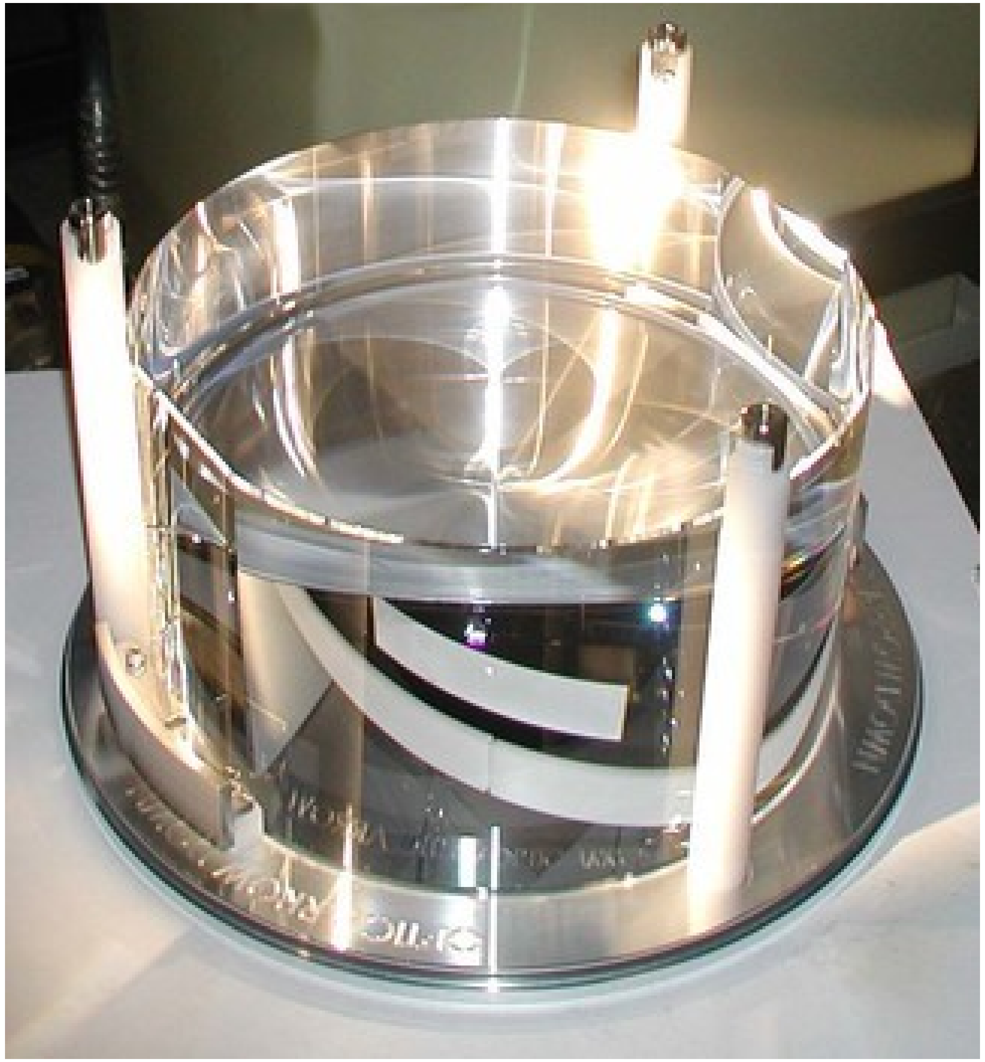




Large Test Mass Optics

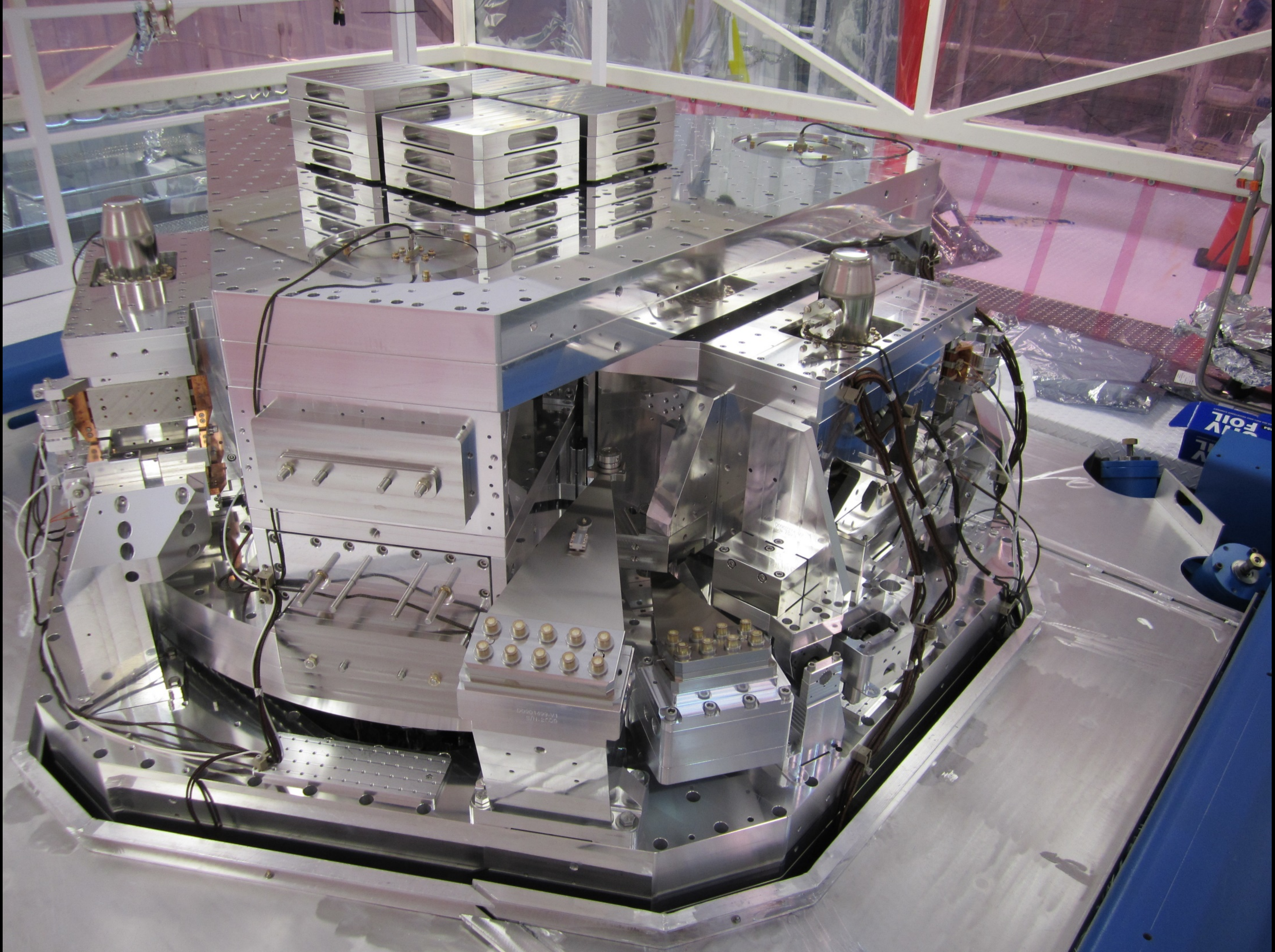
Specifications:

- Diameter: 340 mm
- Thickness: 200 mm
- Mass: 39.6 kg
- ROC: 2250 m / 1940 m
- Figure: <1 nm rms
- Scatter: ~10 ppm
- Surface absorption: ~0.3 ppm
- Bulk absorption: ~0.2 ppm/cm
- HR transmission: ~4 ppm
- AR reflectivity: ~200 ppm

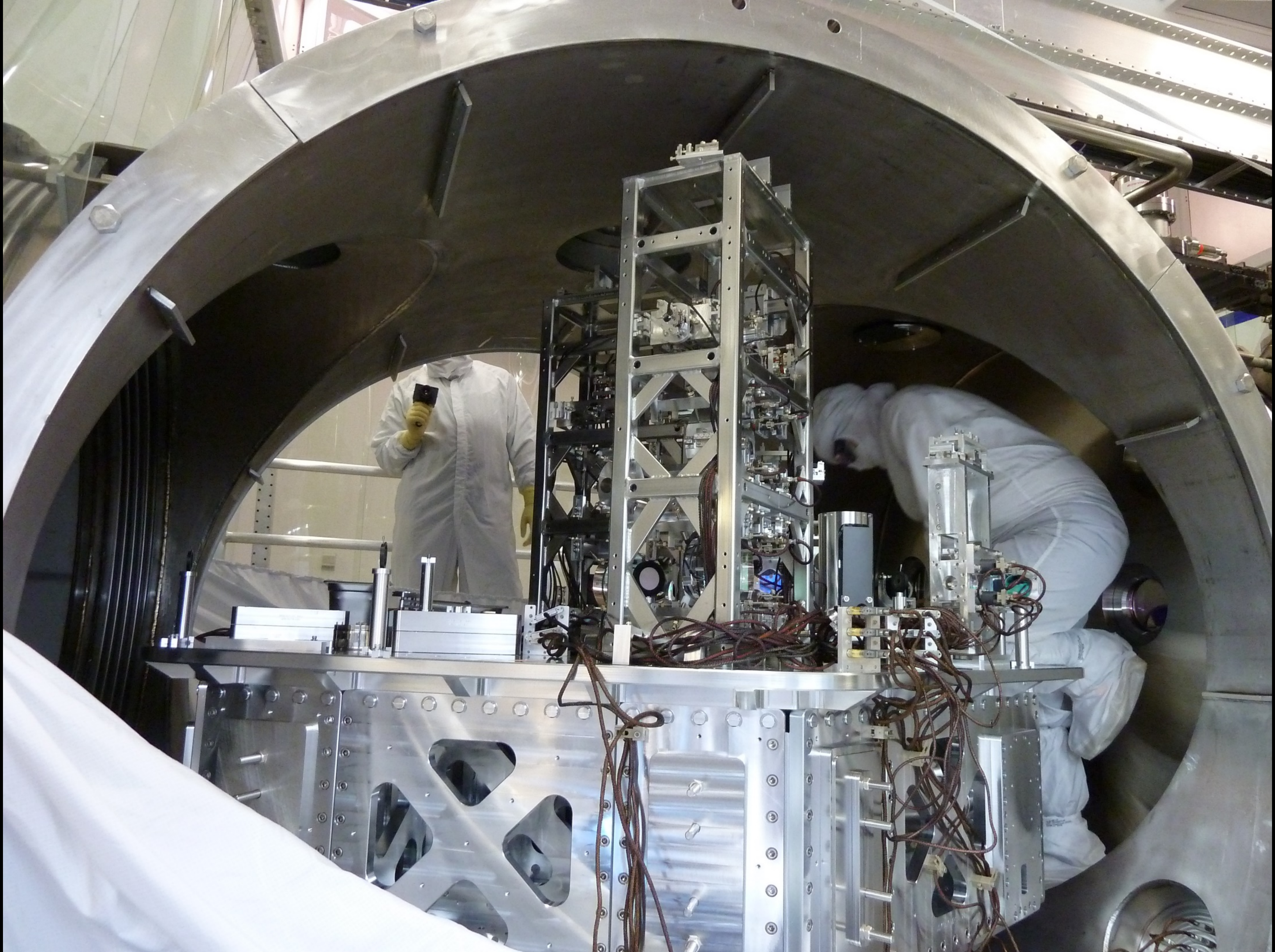


Vacuum System Vertex

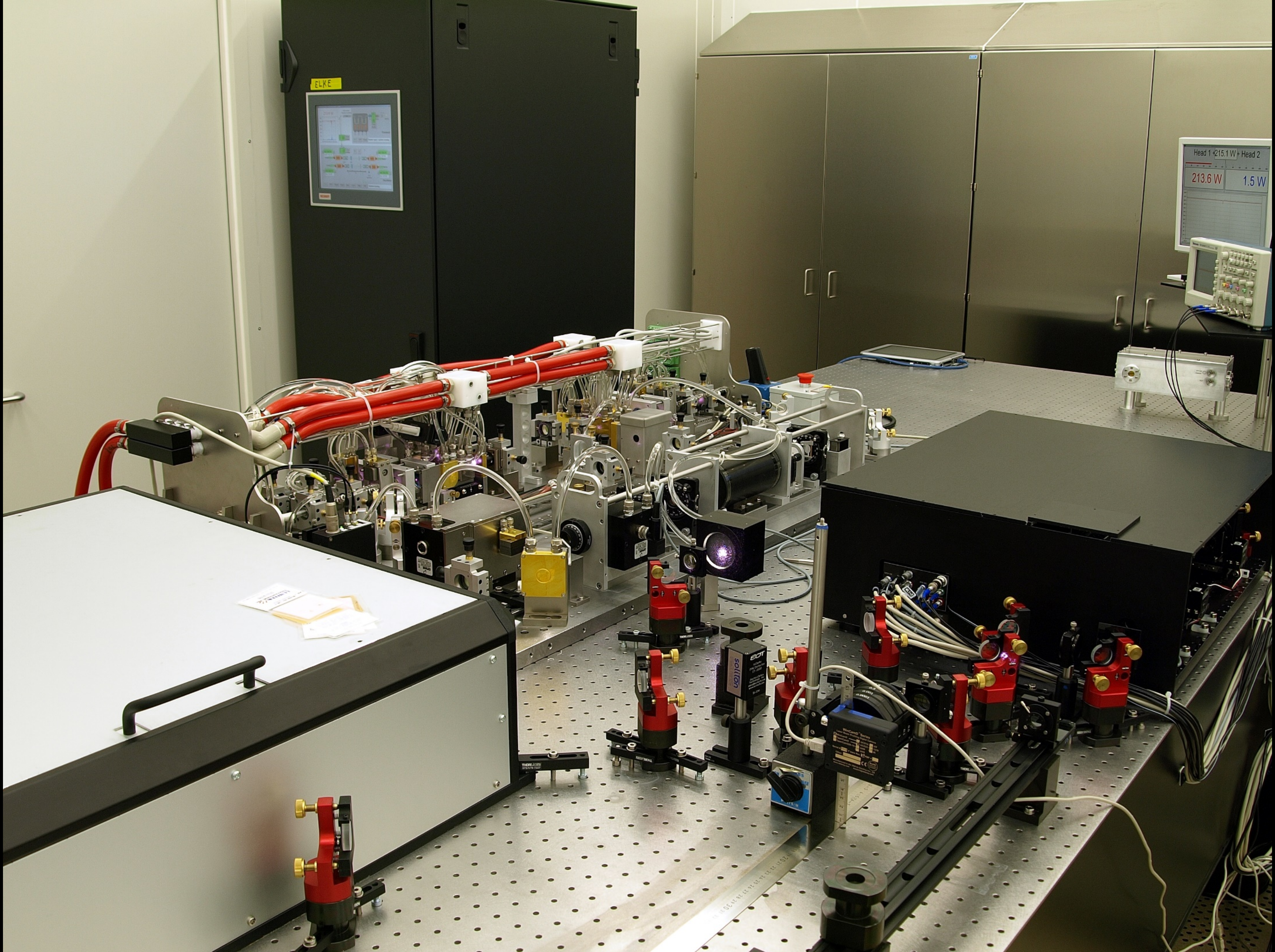
Seismic Isolation Platform



Input Optics Table

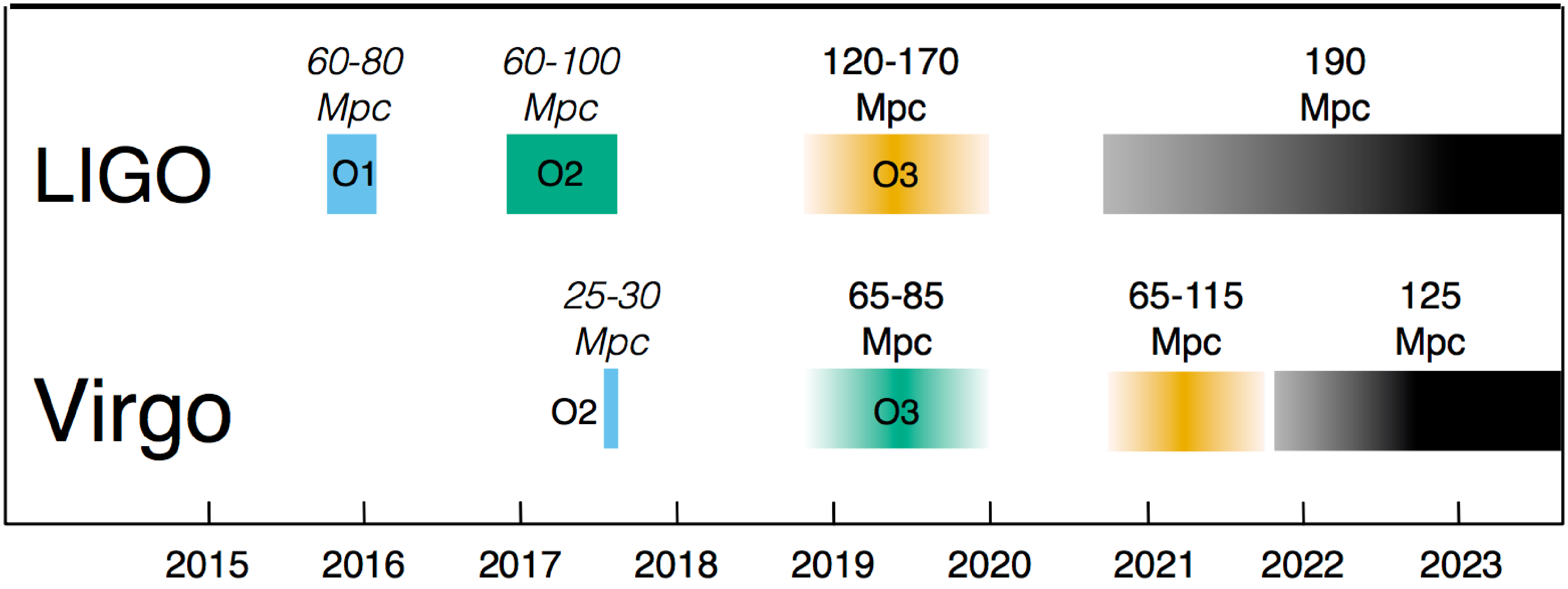


200W Pre-Stabilized Laser

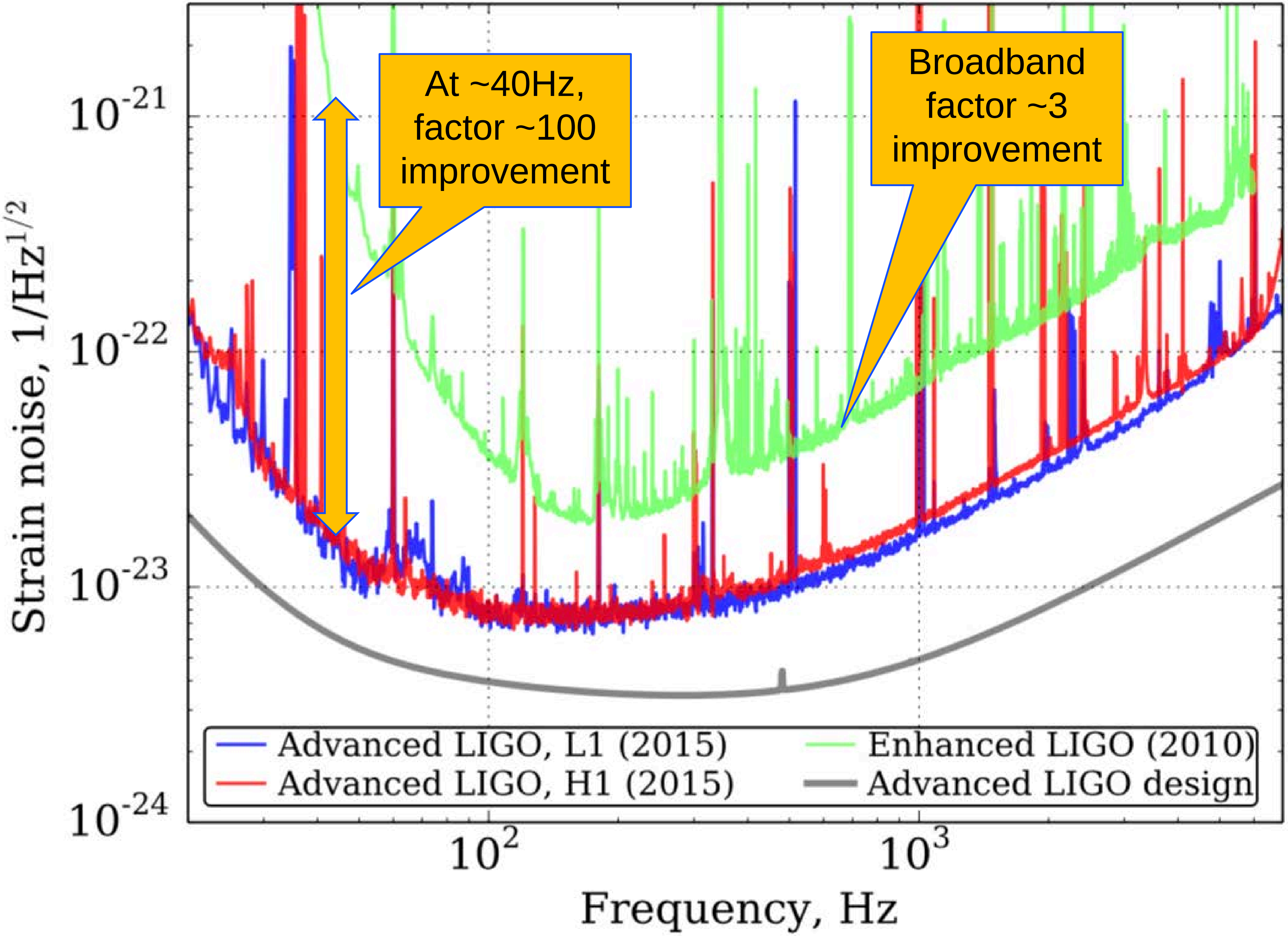


Control Room

Observation Runs

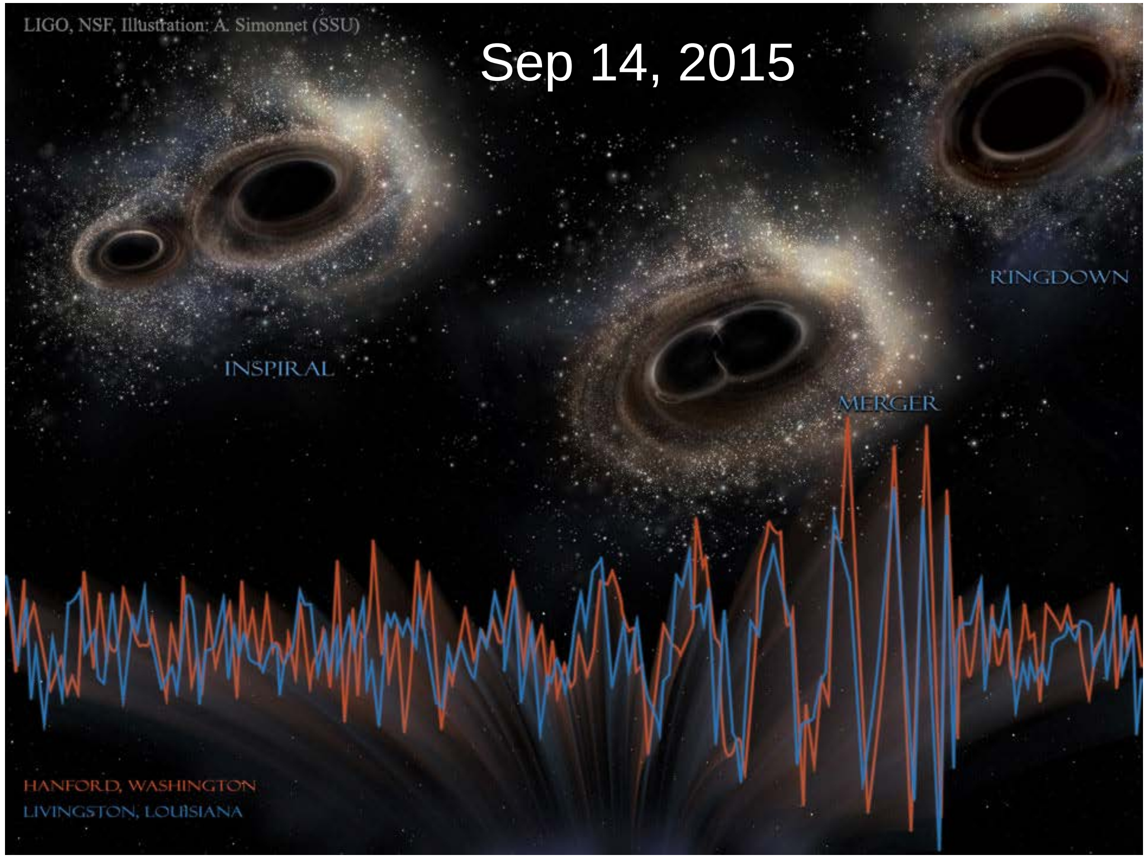


Detector Sensitivity
First Observation Run



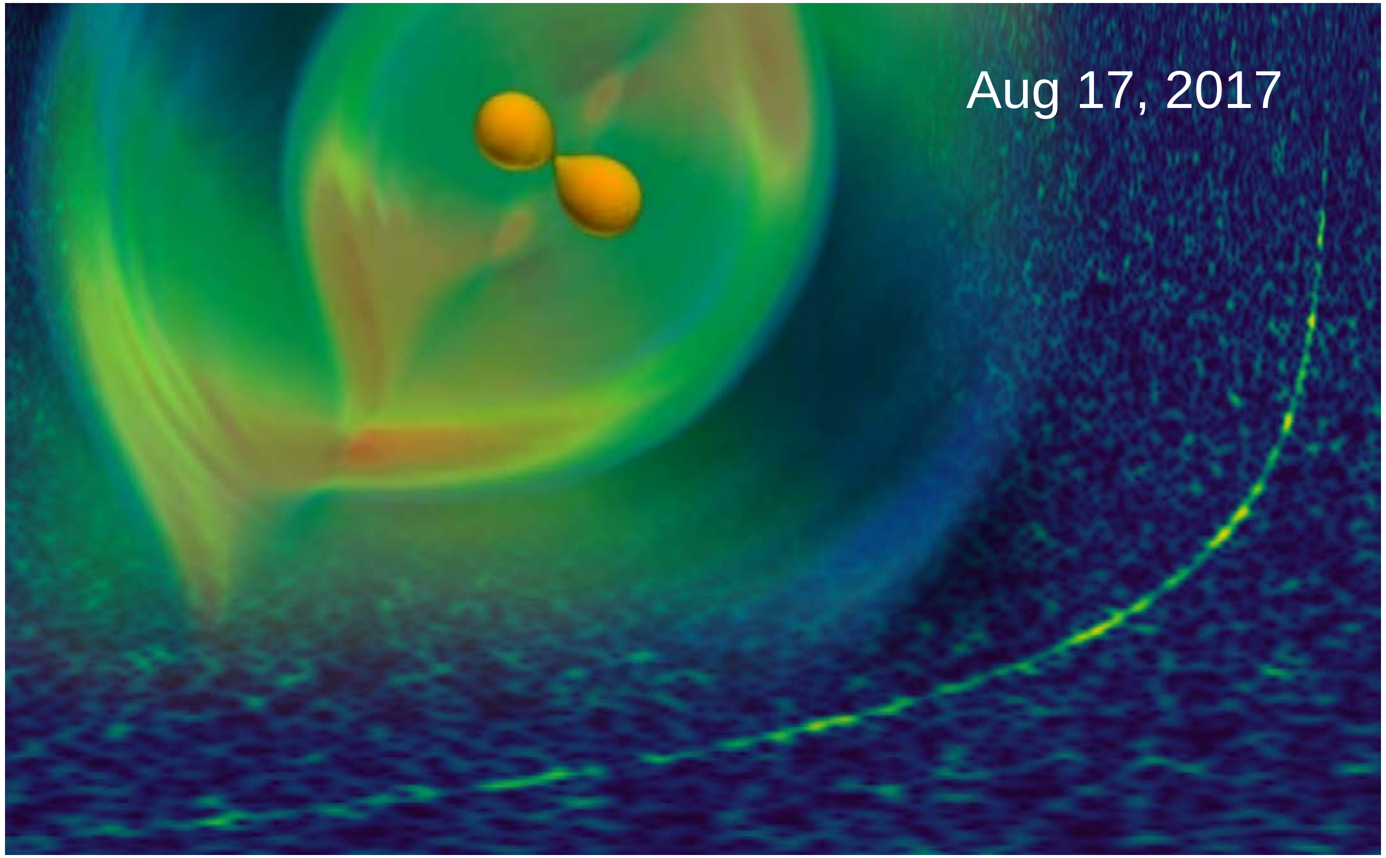
GW150914 and GW170817: Two discoveries that launched gravitational wave astrophysics

1.3 billion years ago



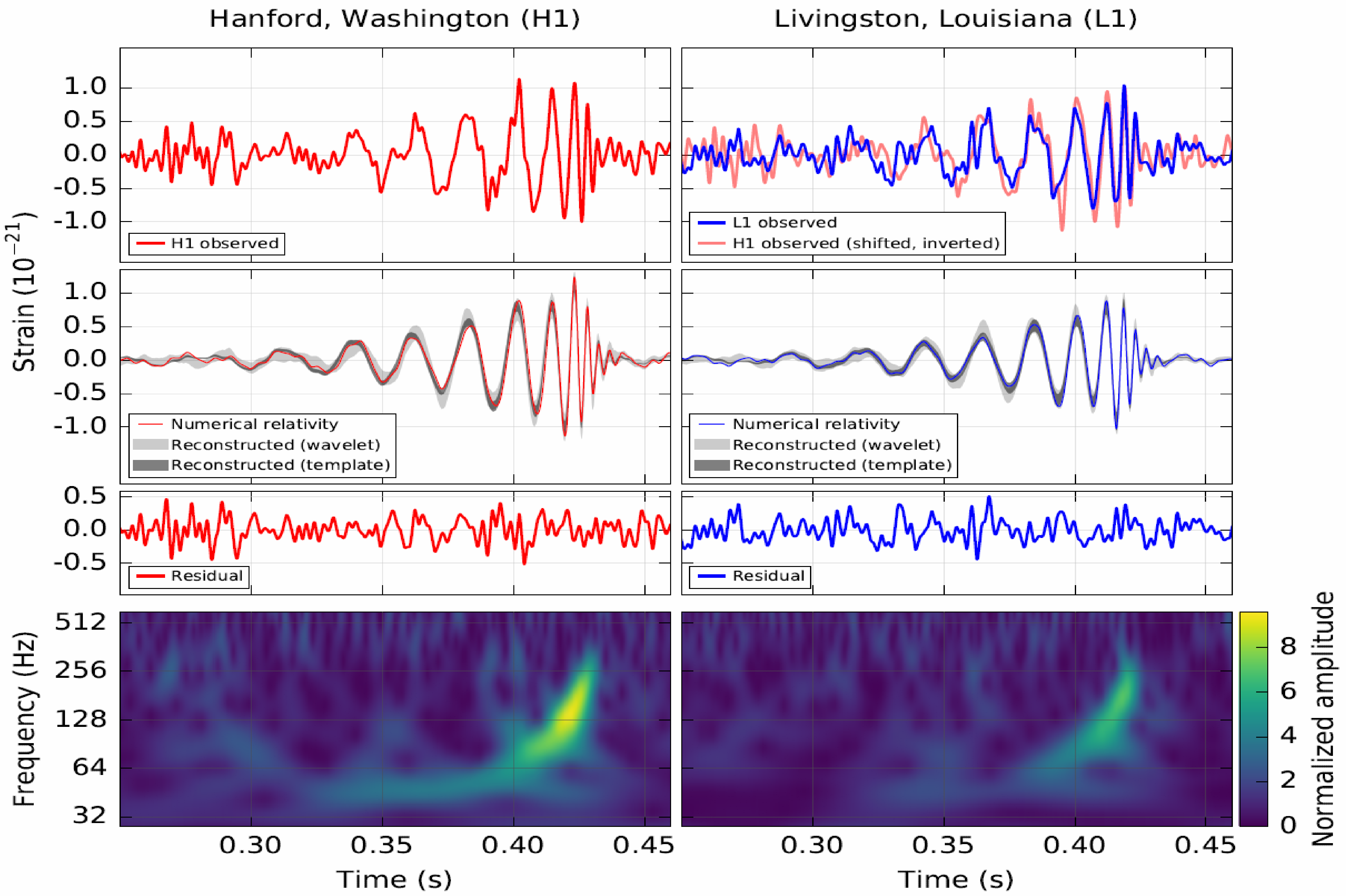
Binary Black Hole Mergers

135 million years ago



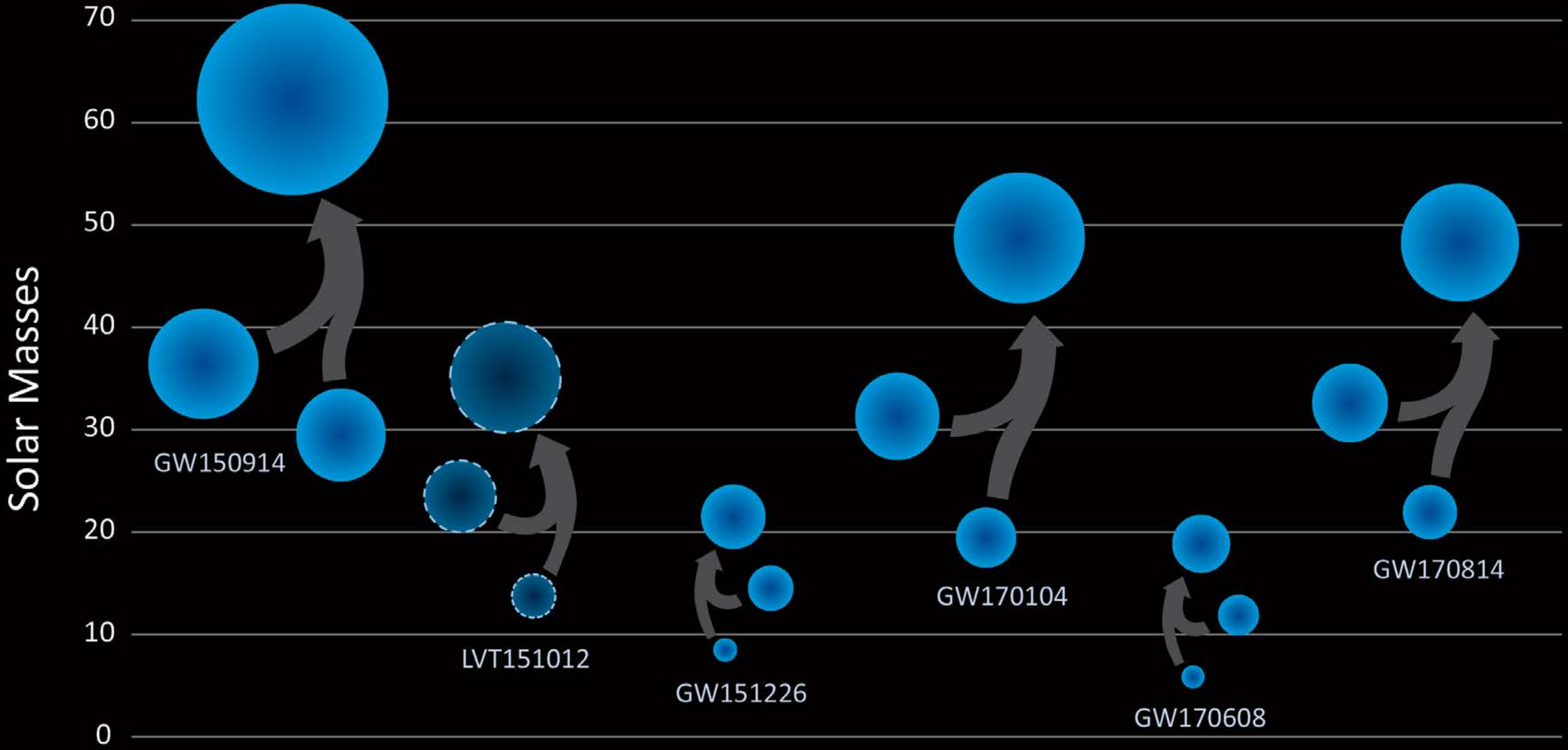
Binary Neutron Star Coalescence

GW150914



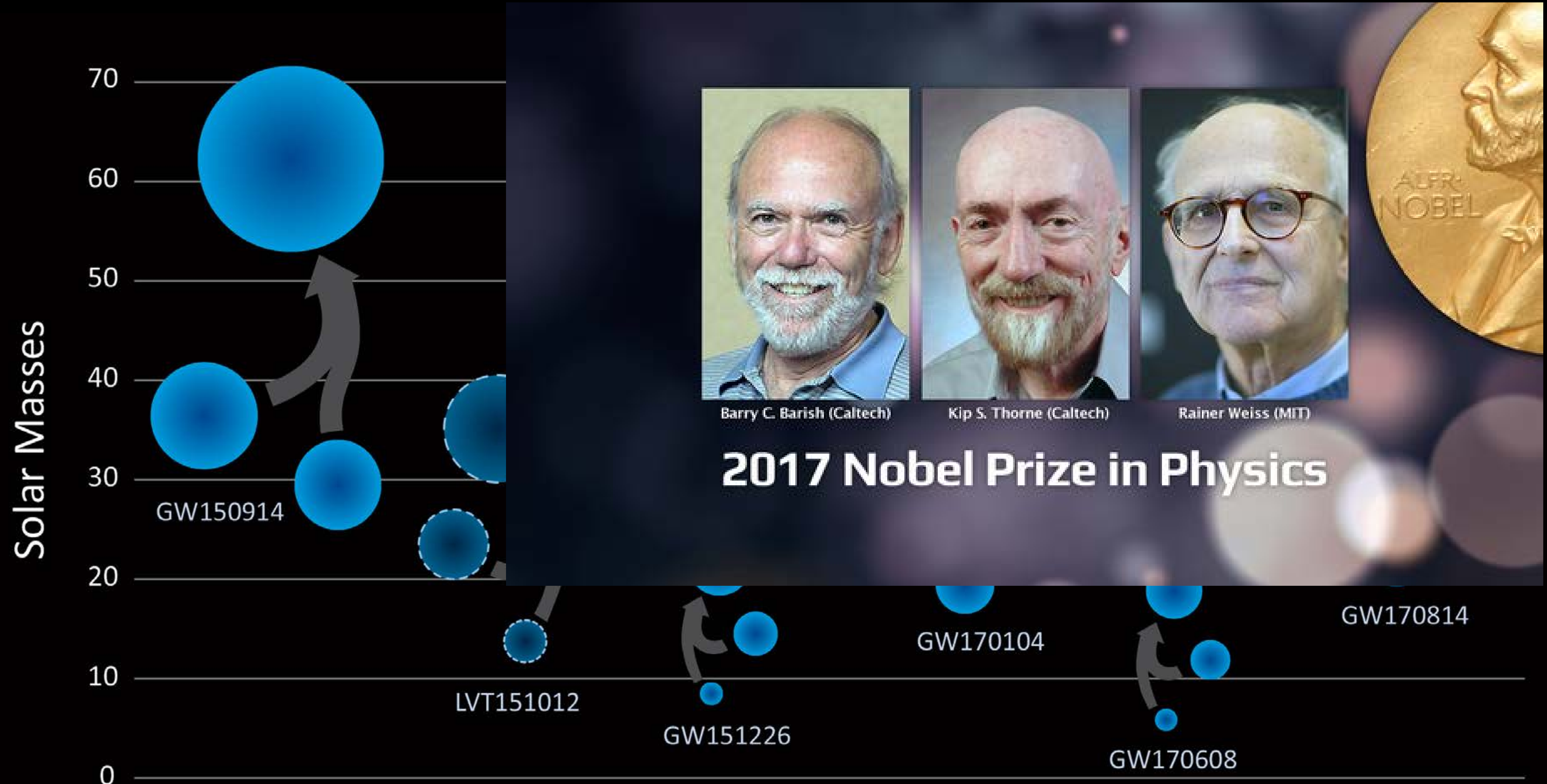
Hanford, Washington (H1)
Livingston, Louisiana (L1)
Strain (10^{-21})
1.0
0.5
0.0
-0.5
-1.0
H1 observed
L1 observed
H1 observed (shifted, inverted)
Numerical relativity
Reconstructed (wavelet)
Reconstructed (template)
Residual
Frequency (Hz)
512
256
128
64
32
0.30
0.35
0.40
0.45
Time (s)
Normalized amplitude
8
6
4
2
0

Solar Mass Black Holes



LIGO/VIRGO

Solar Mass Black Holes

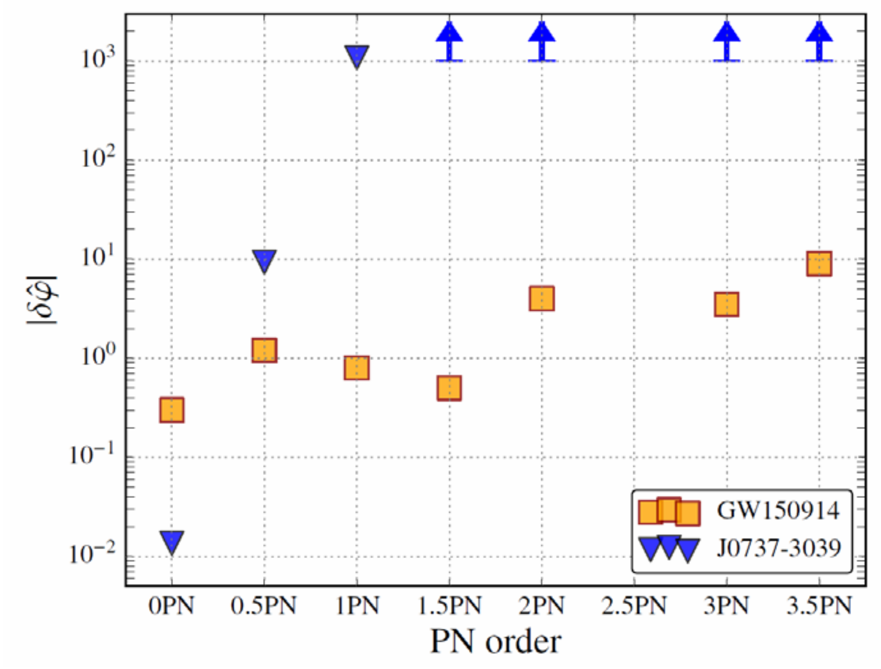


LIGO/VIRGO

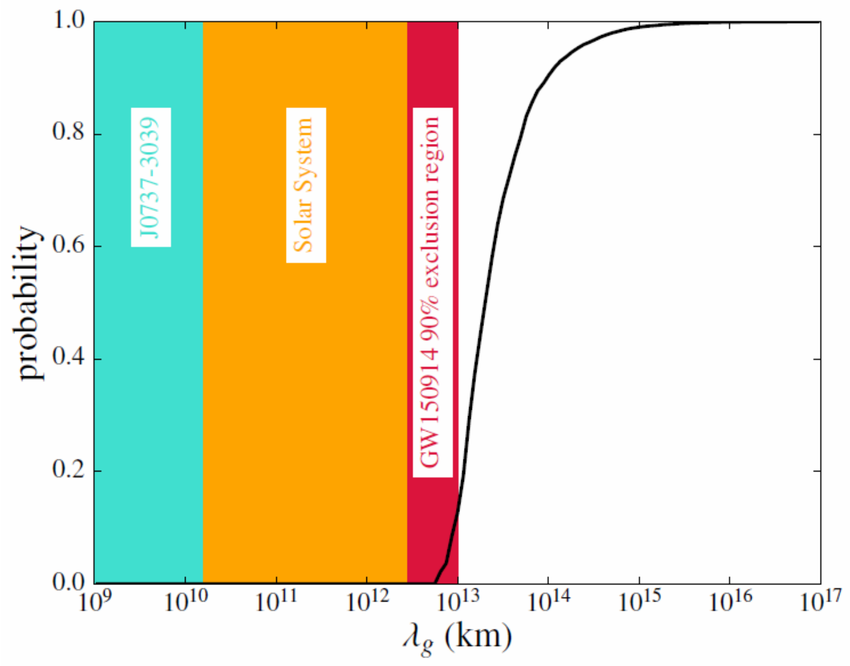
General Relativity Tests

Binary black hole mergers are the
best test of GR in the strong field, nonlinear regime

Post Newtonian Approximation

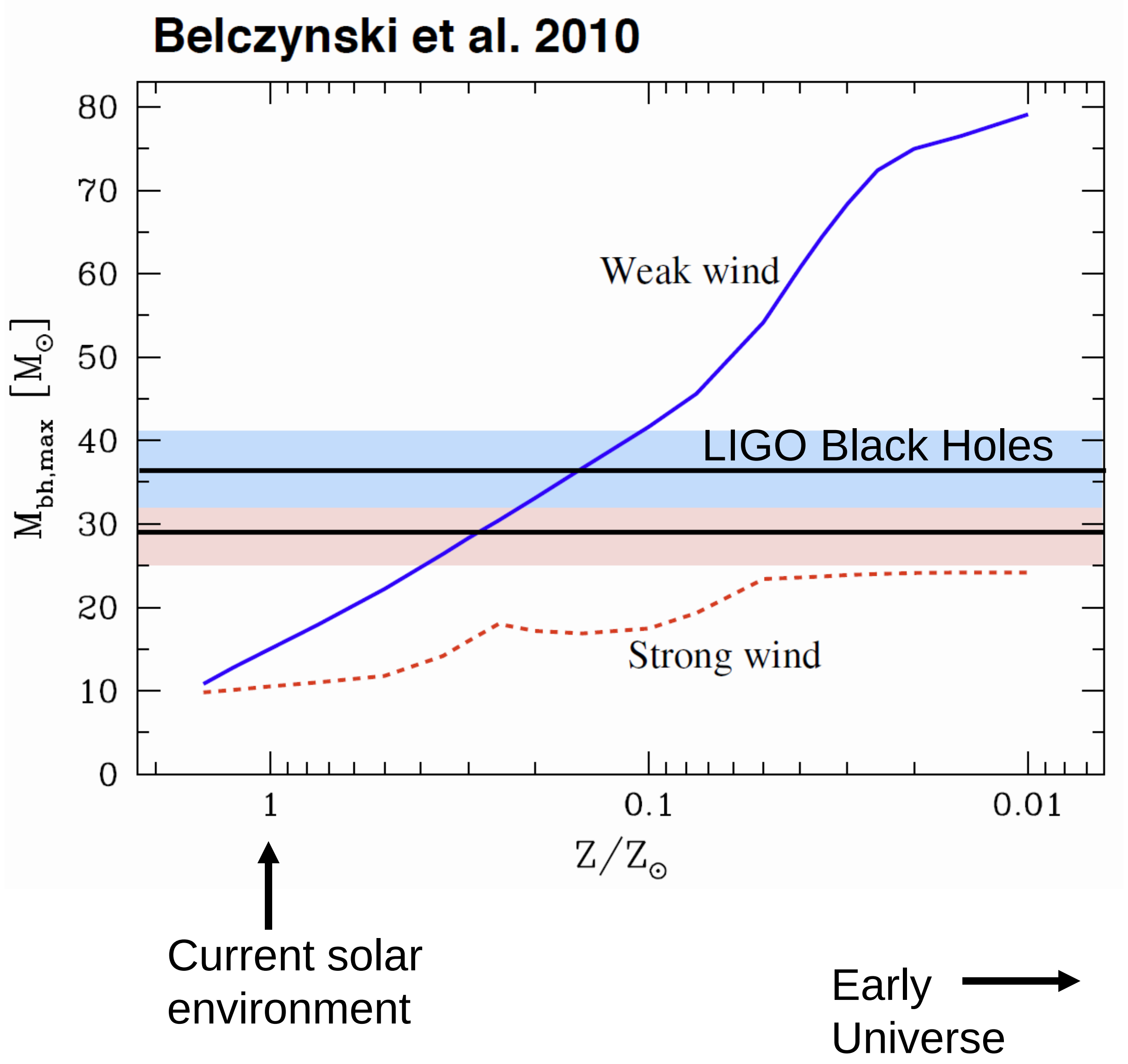


Graviton Mass / Compton Wavelength



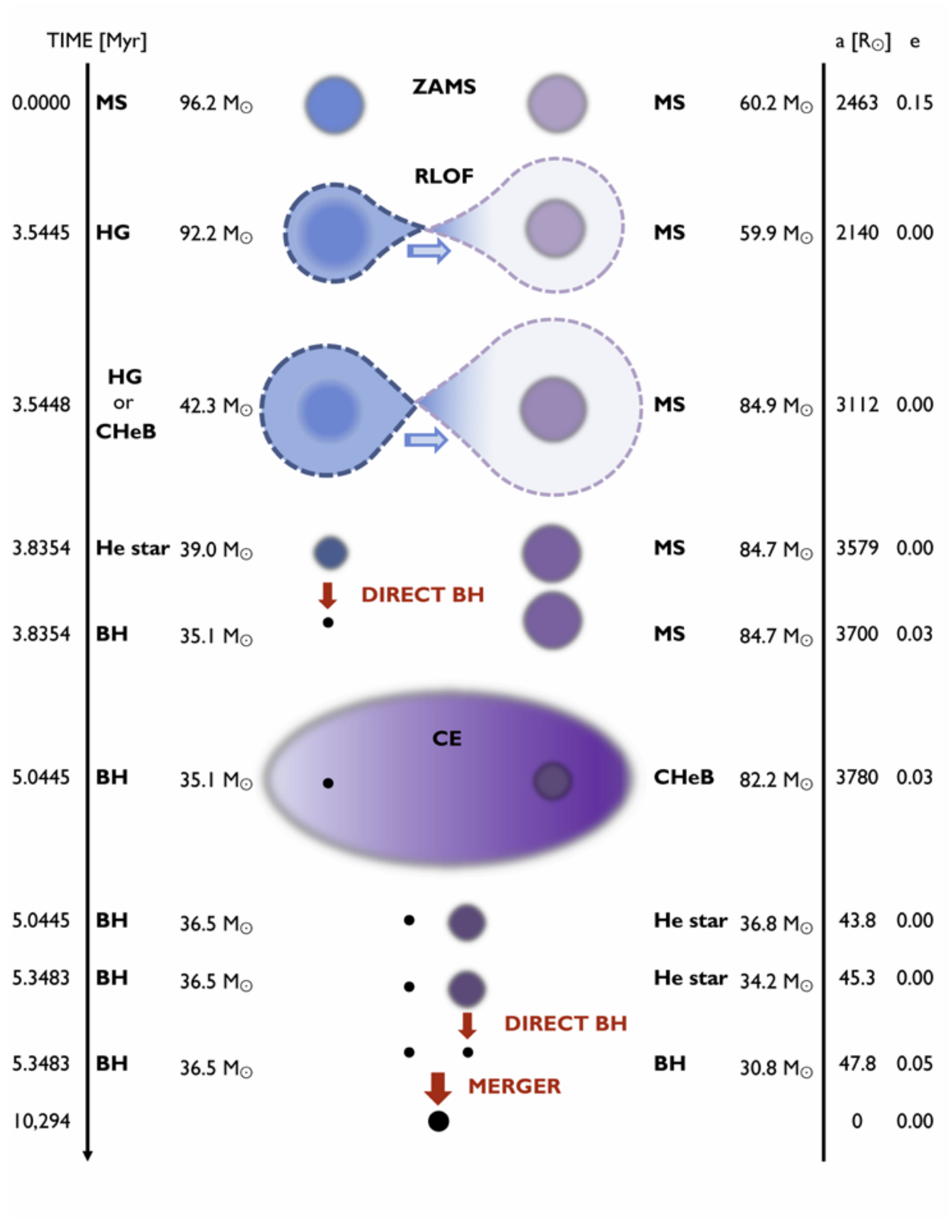
Astrophysical Implications

- Early in the Universe monster stars can form out of Hydrogen only
- Stars produce metals (meaning anything heavier than Helium)
- 30 solar mass black holes can not be formed with core collapses in the current solar environment

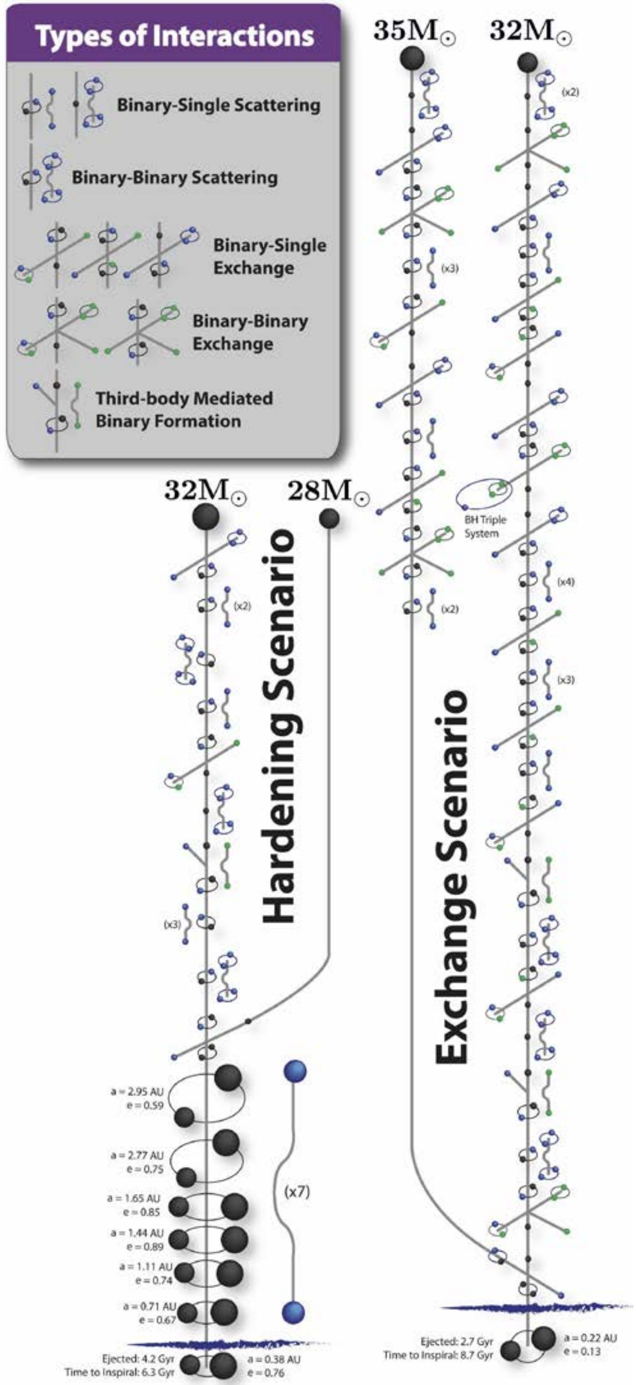


Binary Black Hole Formation

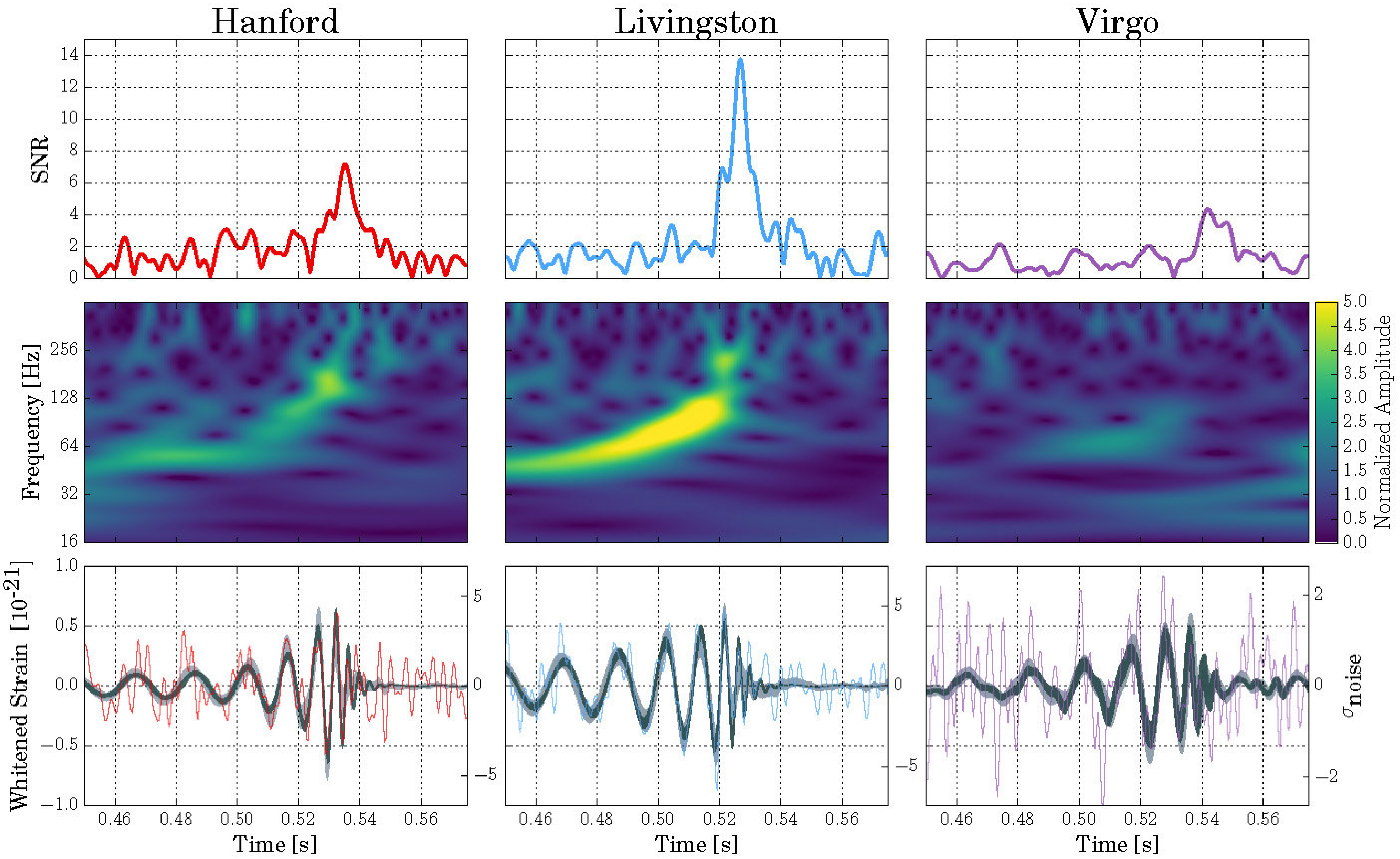
From isolated stars



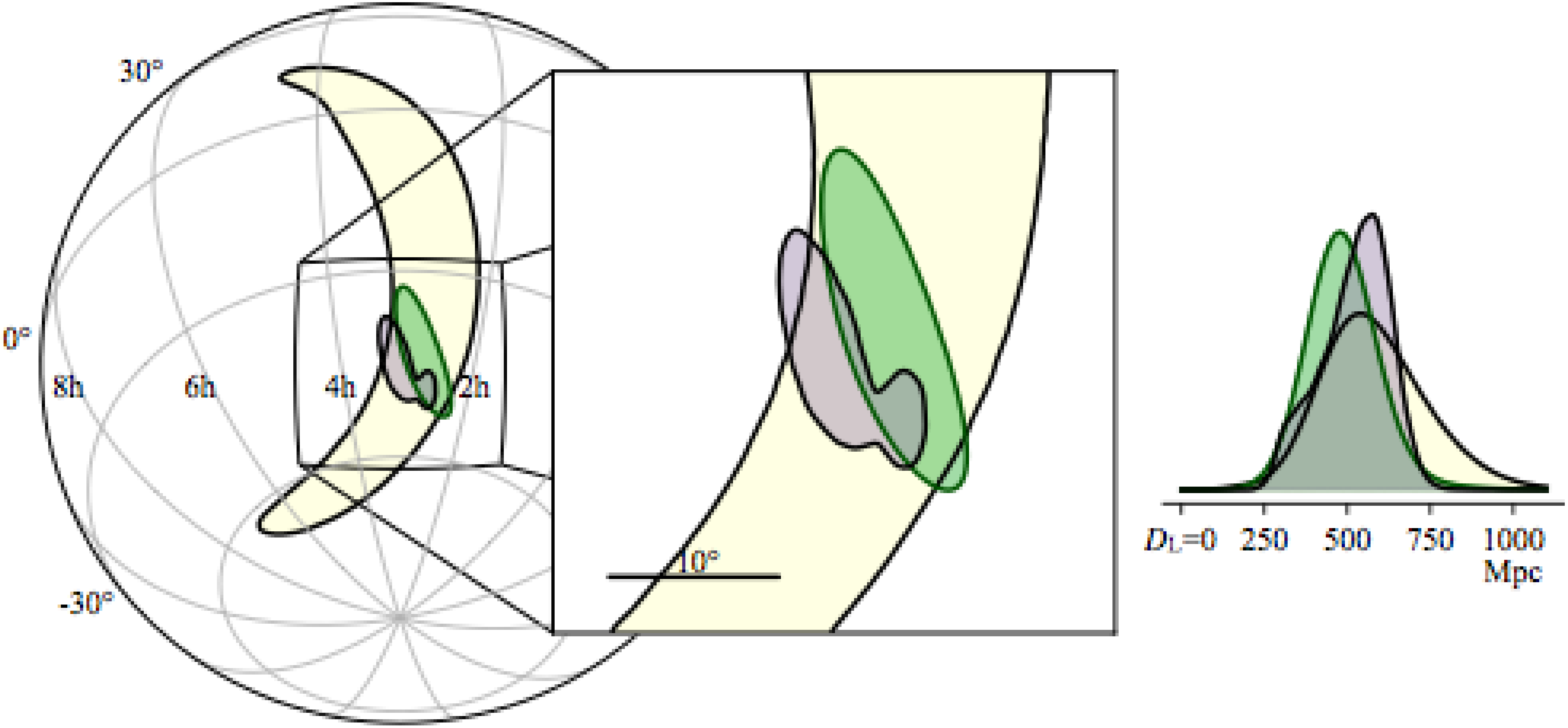
Inside globular clusters



GW170814: 3x Coincidence



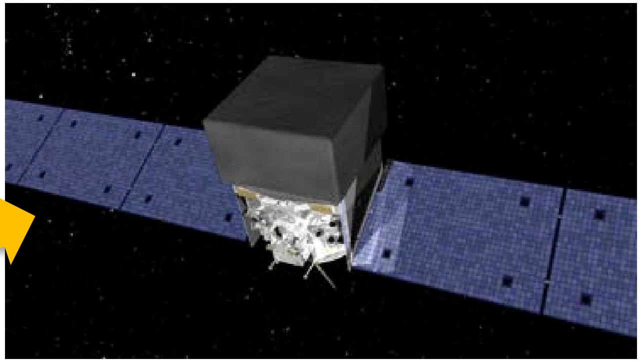
Sky Localization



Multi-messenger Astronomy with Gravitational Waves

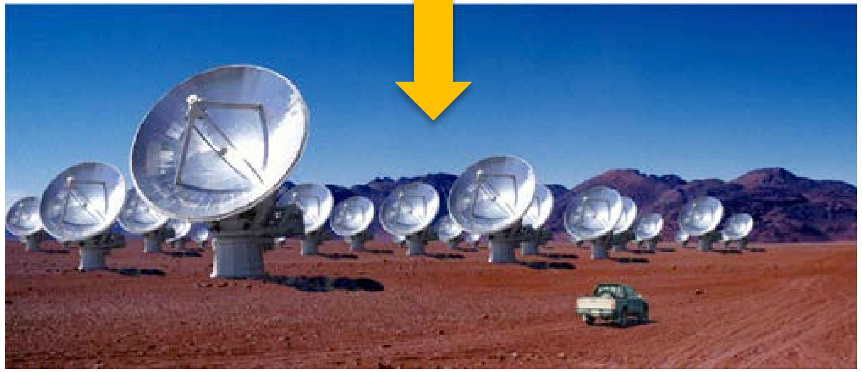
Binary Neutron Star Merger

Gravitational Waves

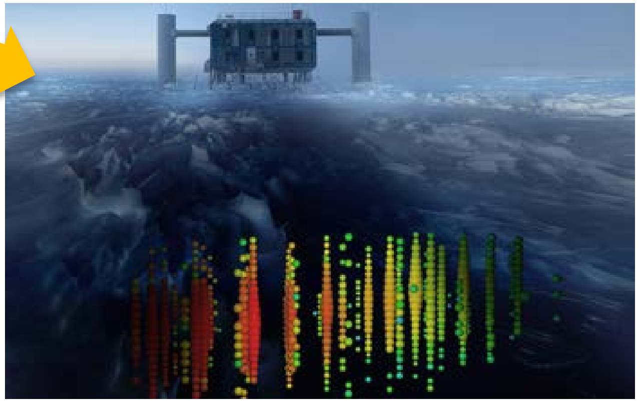


X-rays/Gamma-rays

Visible/Infrared Light

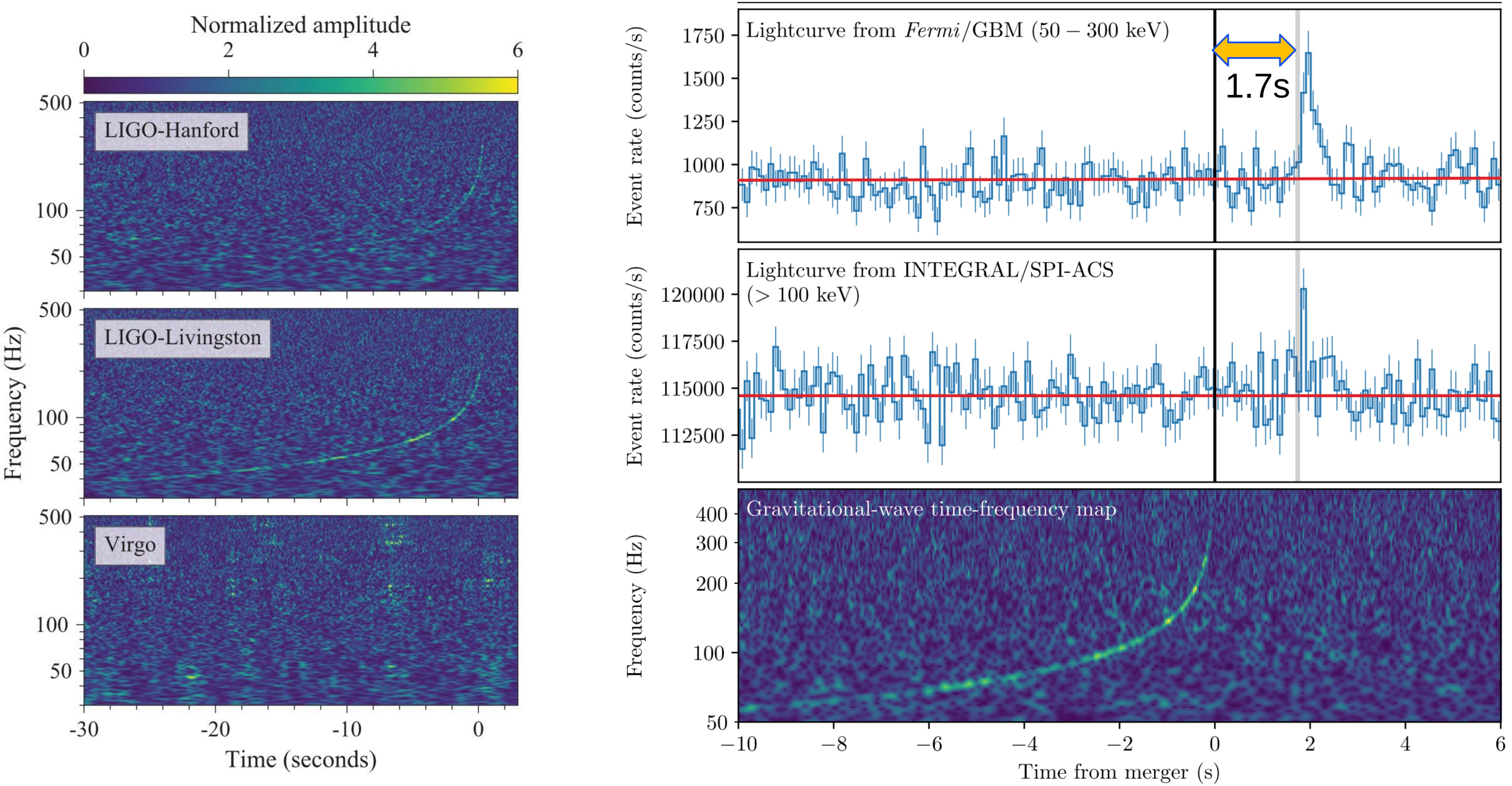


Radio Waves

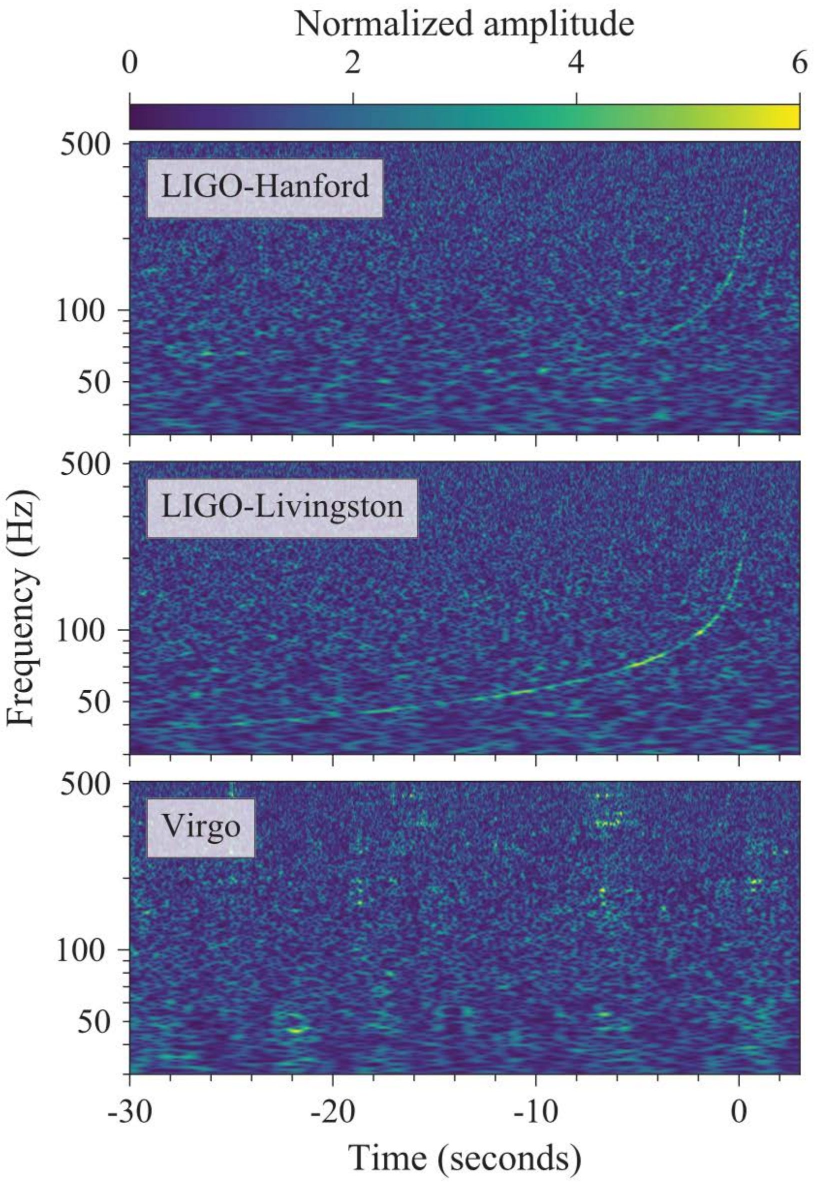


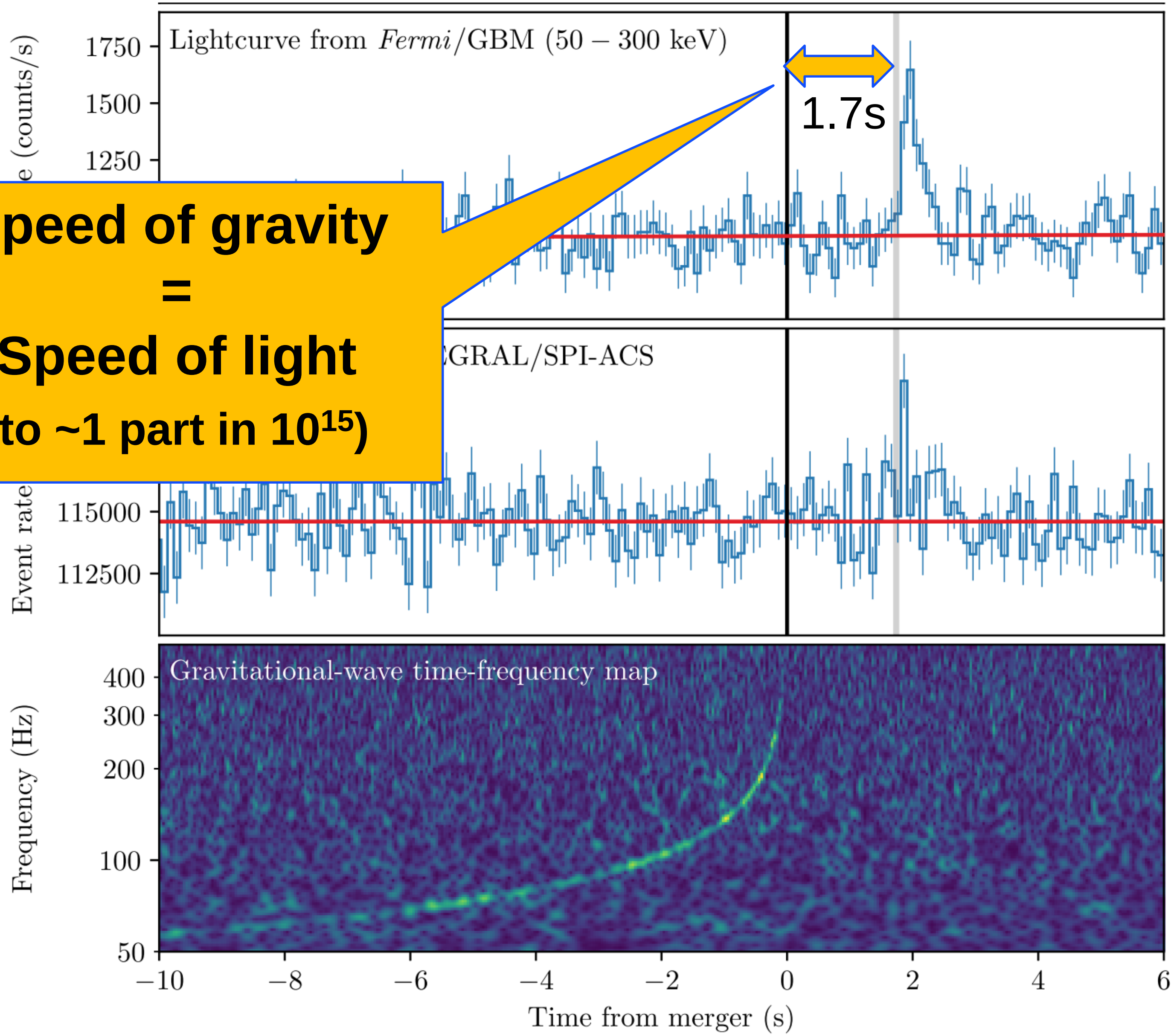
Neutrinos

Neutron Star Merger: GW170817



Neutron Star Merger: GW170817

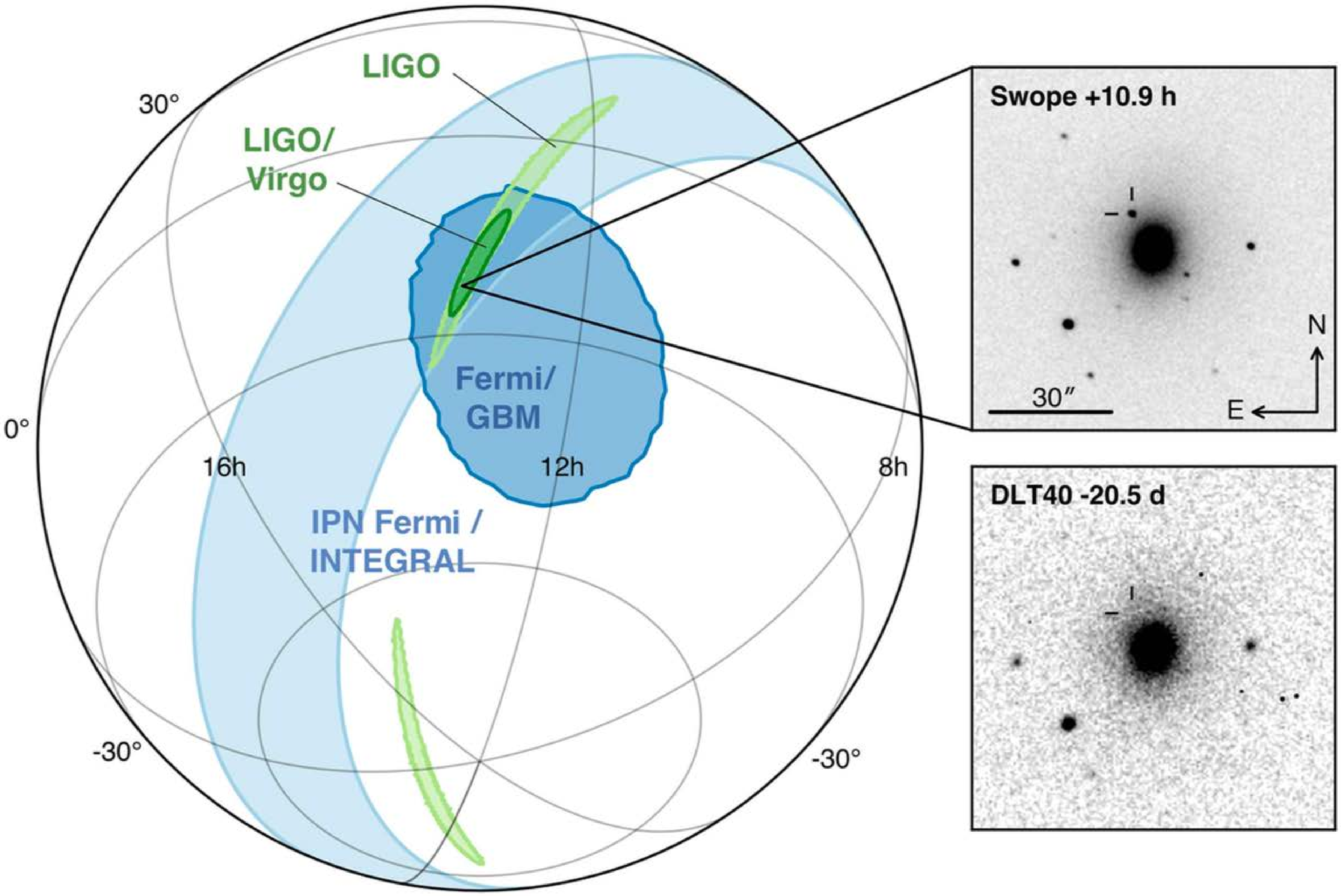




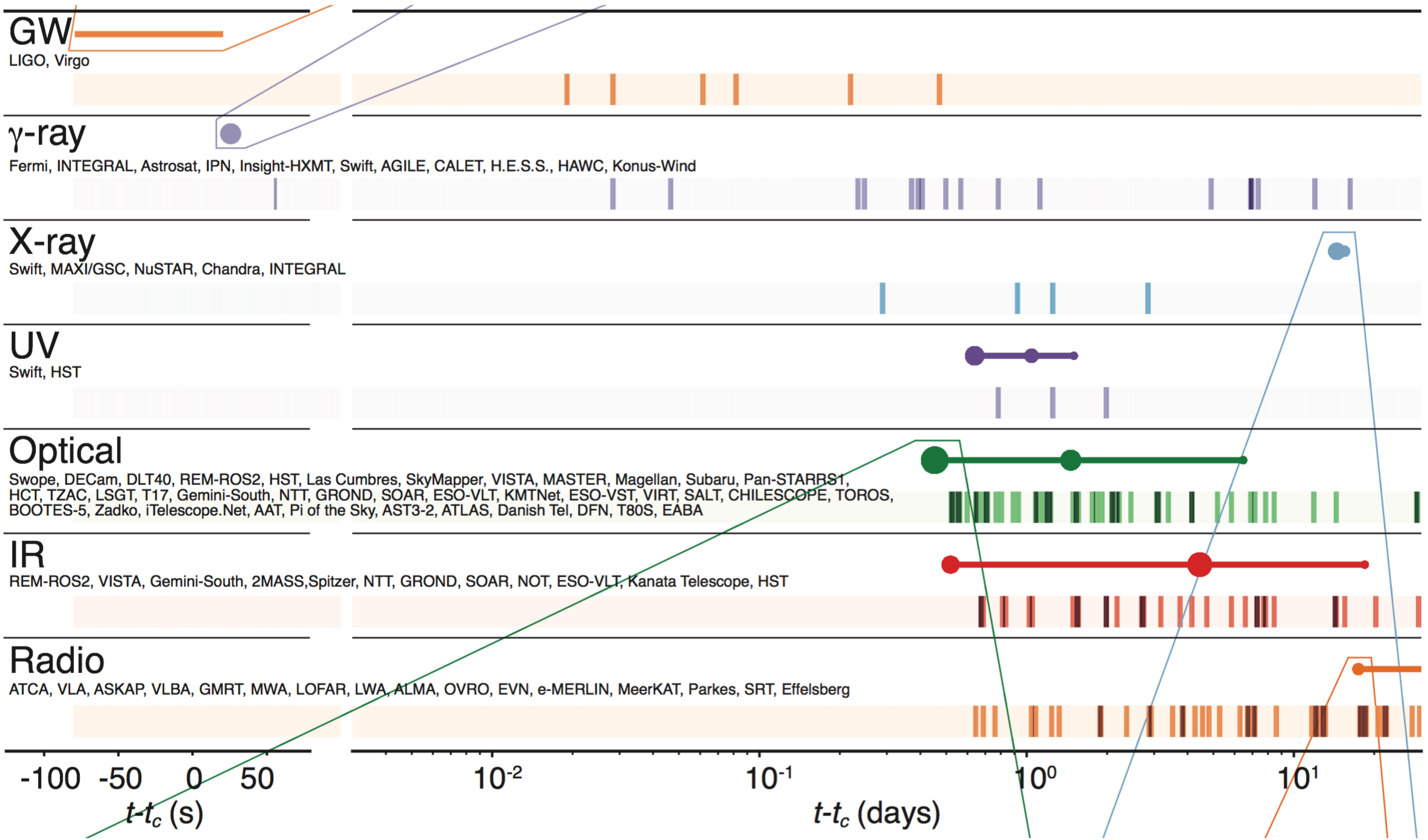
Speed of gravity
=
Speed of light
(to ~1 part in 10^{15})

Multi-messenger Observations

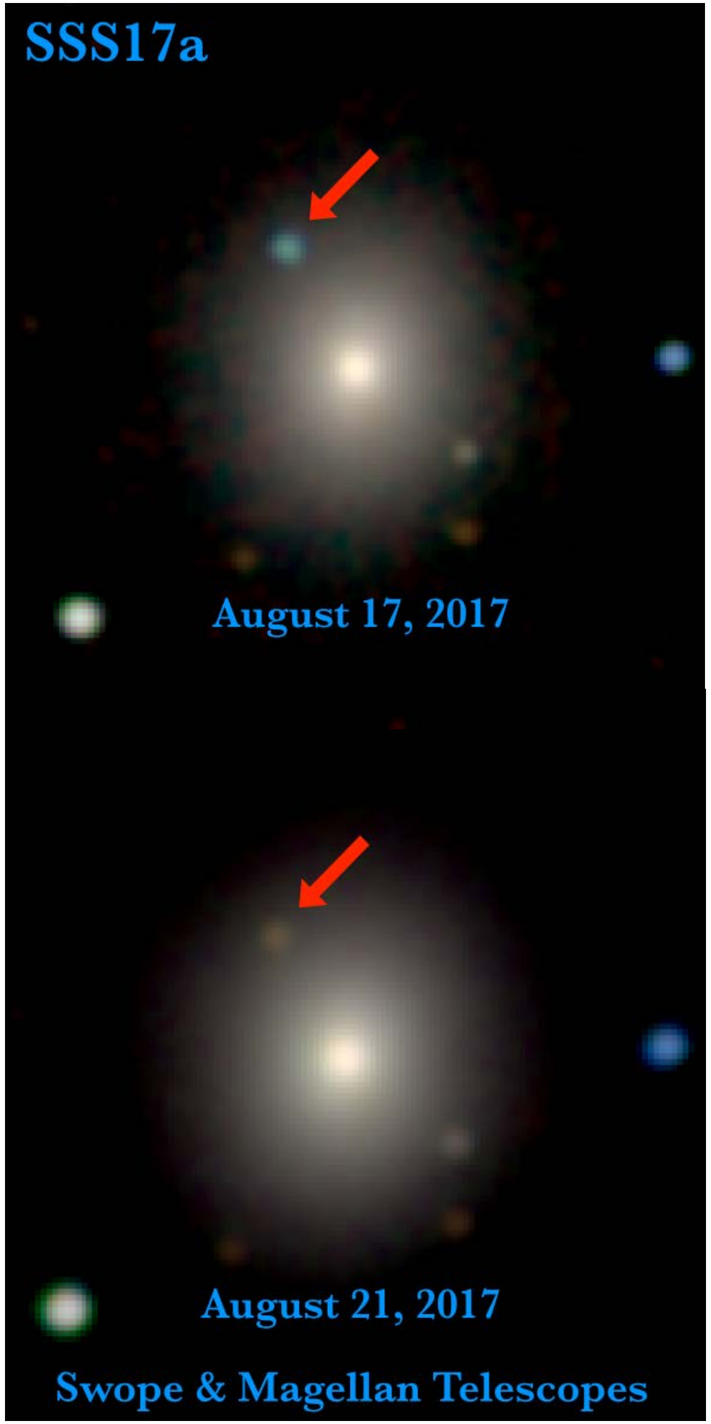
The Astrophysical Journal Letters, 848:L12, 2017



EM Follow-up Campaign



Kilonova



GW170817

Binary neutron star merger

A LIGO / Virgo gravitational wave detection with associated electromagnetic events observed by over 70 observatories.

H L V

Distance
130 million light years

Discovered
17 August 2017

Type
Neutron star merger

12:41:04 UTC
A gravitational wave from a binary neutron star merger is detected.

gravitational wave signal
Two neutron stars, each the size of a city but with at least the mass of the sun, collided with each other.

gamma ray burst
A short gamma ray burst is an intense beam of gamma ray radiation which is produced just after the merger.

+ 2 seconds
A gamma ray burst is detected.

GW170817 allows us to measure the expansion rate of the universe directly using gravitational waves for the first time.

Detecting gravitational waves from a neutron star merger allows us to find out more about the structure of these unusual objects.

This multimessenger event provides confirmation that neutron star mergers can produce short gamma ray bursts.

Au

The observation of a kilonova allowed us to show that neutron star mergers could be responsible for the production of most of the heavy elements, like gold, in the universe.

Observing both electromagnetic and gravitational waves from the event provides compelling evidence that gravitational waves travel at the same speed as light.

kilonova
Decaying neutron-rich material creates a glowing kilonova, producing heavy metals like gold and platinum.

+10 hours 52 minutes
A new bright source of optical light is detected in a galaxy called NGC 4993, in the constellation of Hydra.

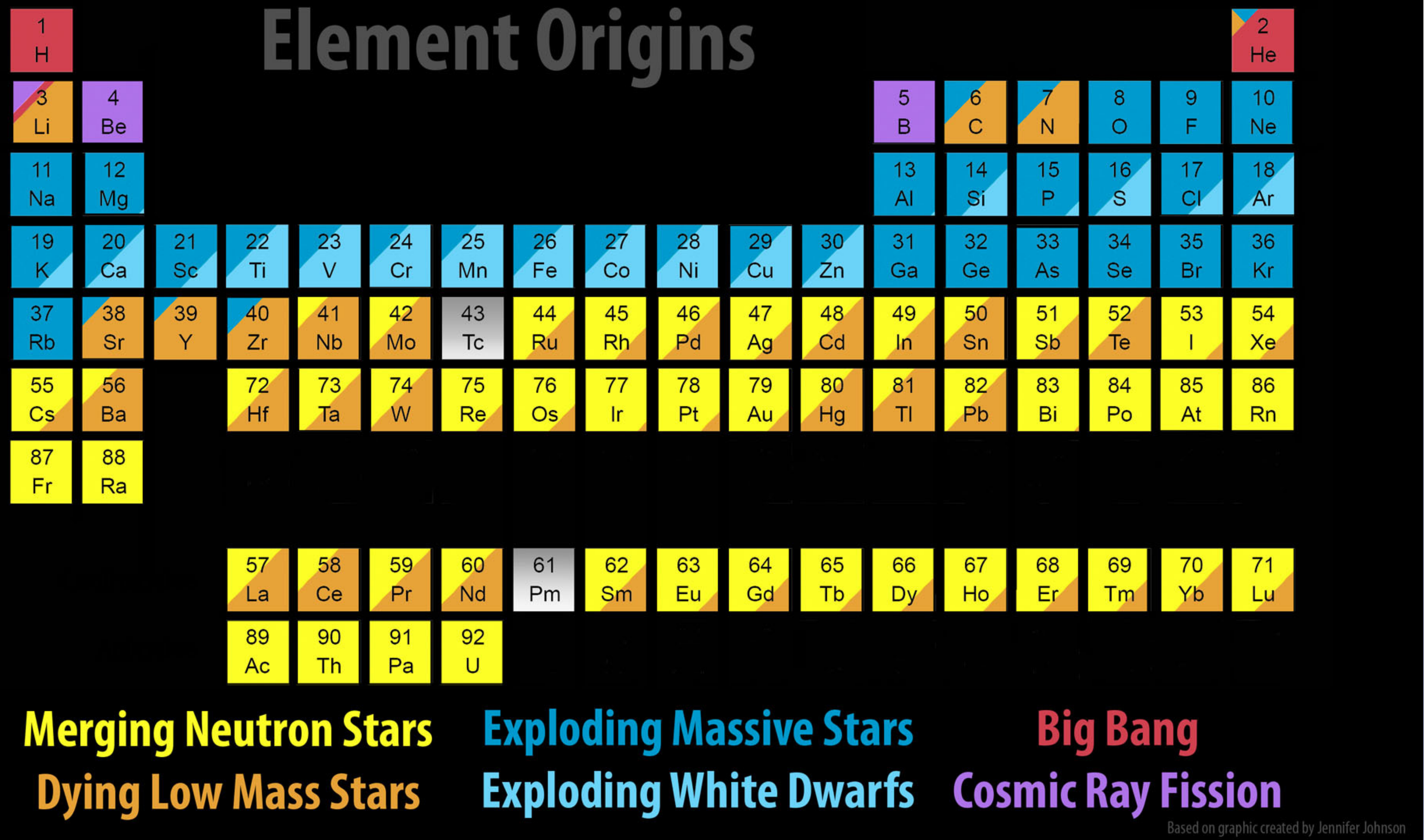
+11 hours 36 minutes
Infrared emission observed.

+15 hours
Bright ultraviolet emission detected.

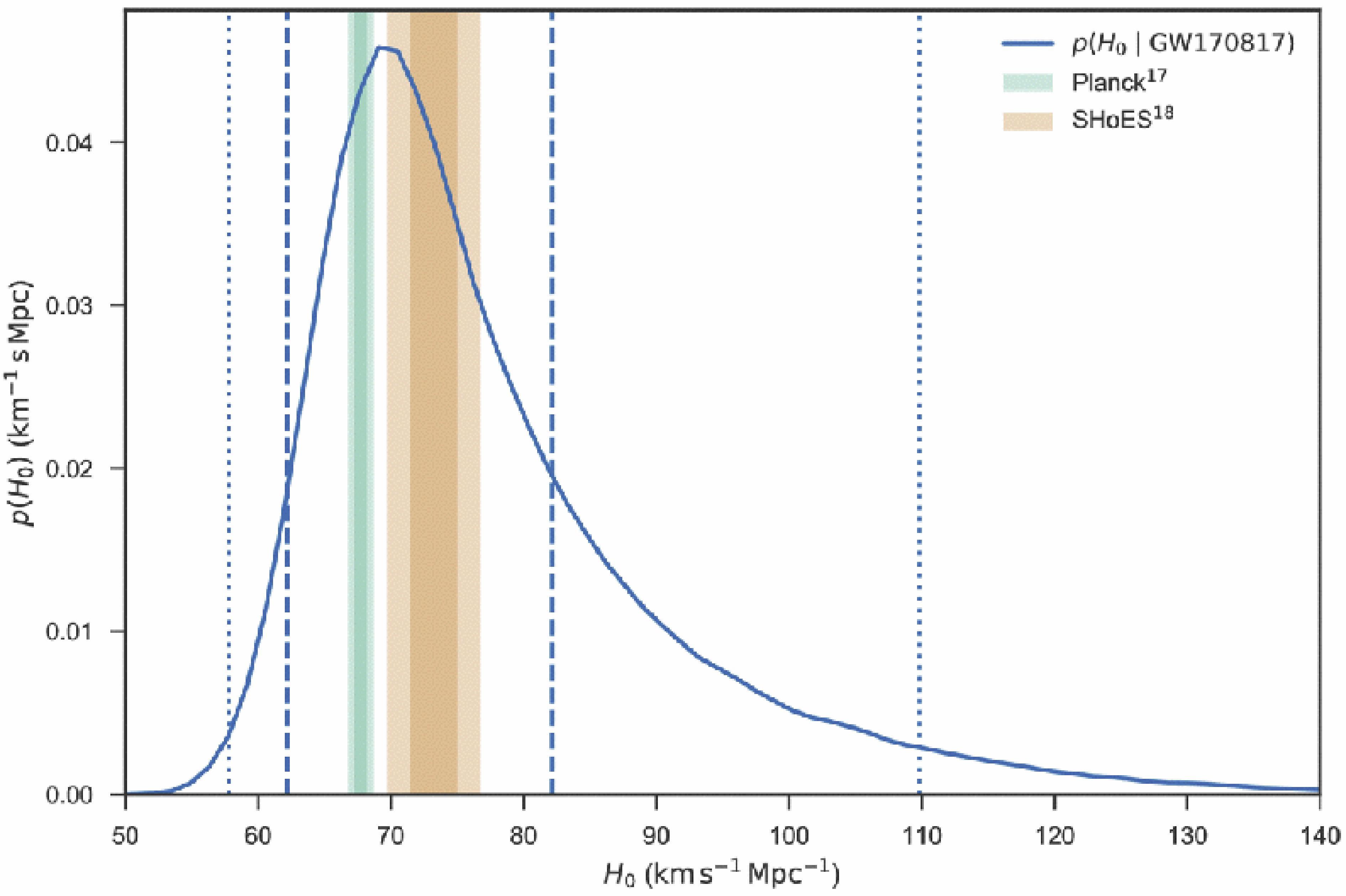
+9 days
X-ray emission detected.

radio remnant
As material moves away from the merger it produces a shockwave in the interstellar medium - the tenuous material between stars. This produces emission which can last for years.

+16 days
Radio emission detected.


Element Origins
1 H
2 He
3 Li
4 Be
5 B
6 C
7 N
8 O
9 F
10 Ne
11 Na
12 Mg
13 Al
14 Si
15 P
16 S
17 Cl
18 Ar
19 K
20 Ca
21 Sc
22 Ti
23 V
24 Cr
25 Mn
26 Fe
27 Co
28 Ni
29 Cu
30 Zn
31 Ga
32 Ge
33 As
34 Se
35 Br
36 Kr
37 Rb
38 Sr
39 Y
40 Zr
41 Nb
42 Mo
43 Tc
44 Ru
45 Rh
46 Pd
47 Ag
48 Cd
49 In
50 Sn
51 Sb
52 Te
53 I
54 Xe
55 Cs
56 Ba
72 Hf
73 Ta
74 W
75 Re
76 Os
77 Ir
78 Pt
79 Au
80 Hg
81 Tl
82 Pb
83 Bi
84 Po
85 At
86 Rn
87 Fr
88 Ra
57 La
58 Ce
59 Pr
60 Nd
61 Pm
62 Sm
63 Eu
64 Gd
65 Tb
66 Dy
67 Ho
68 Er
69 Tm
70 Yb
71 Lu
89 Ac
90 Th
91 Pa
92 U
Merging Neutron Stars
Exploding Massive Stars
Big Bang
Dying Low Mass Stars
Exploding White Dwarfs
Cosmic Ray Fission
Based on graphic created by Jennifer Johnson

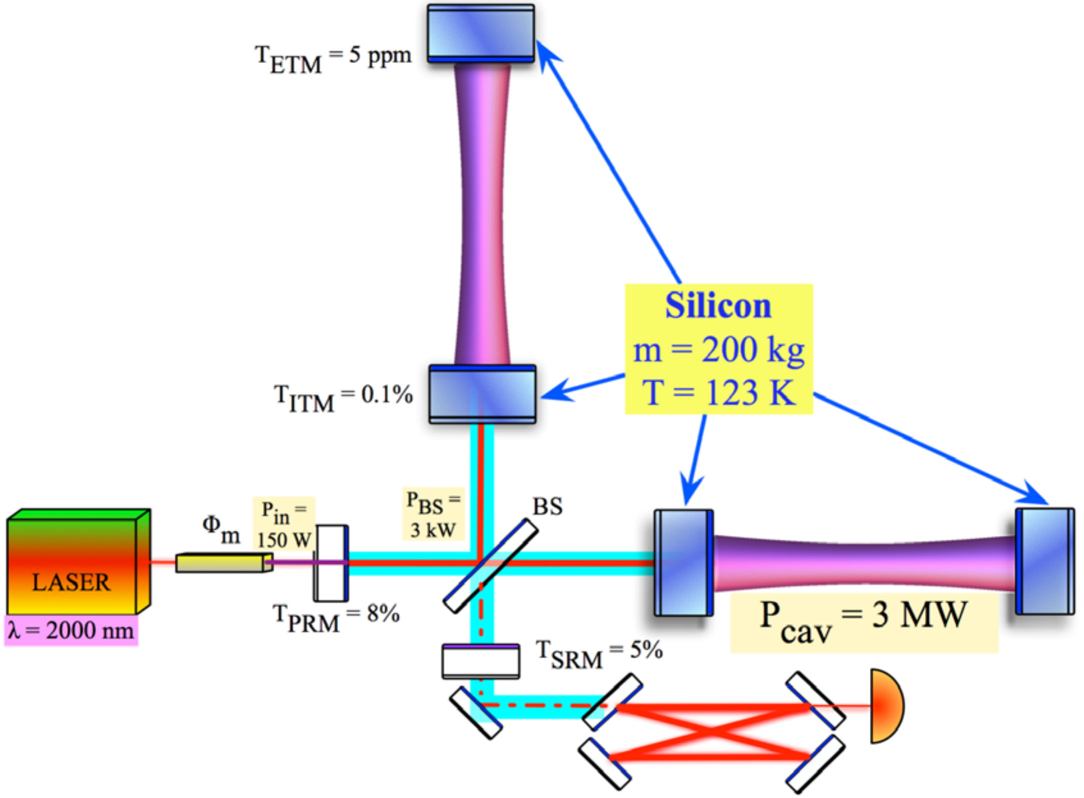
Cosmology without Distance Ladder

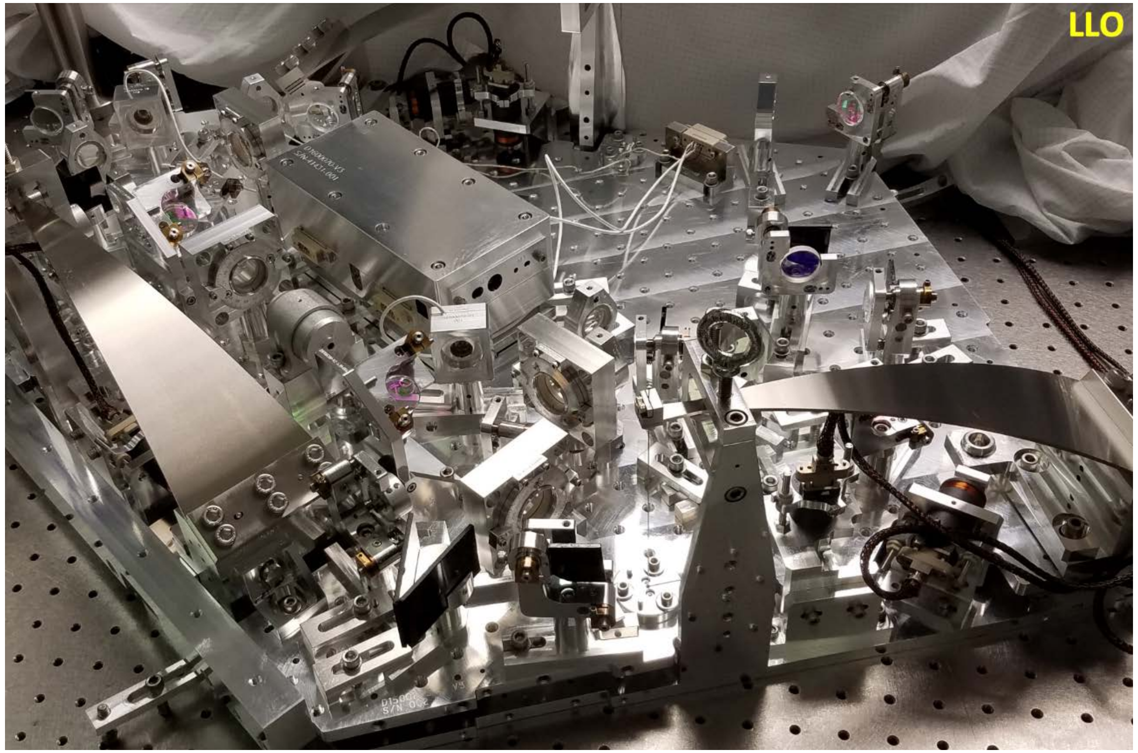


The Next Decade

Advanced LIGO Plus (A+)

- An incremental upgrade to aLIGO that leverages existing technology and infrastructure, with minimal new investment and moderate risk
- Target: x1.7 increase in range over aLIGO x5 greater event rate





LIGO Voyager

- Additional x2 sensitivity broadband improvement,
  lower frequency 20Hz → 10Hz
- Larger Si masses, cryogenic operation, new laser wavelength

Next Generation Gravitational Wave Detectors

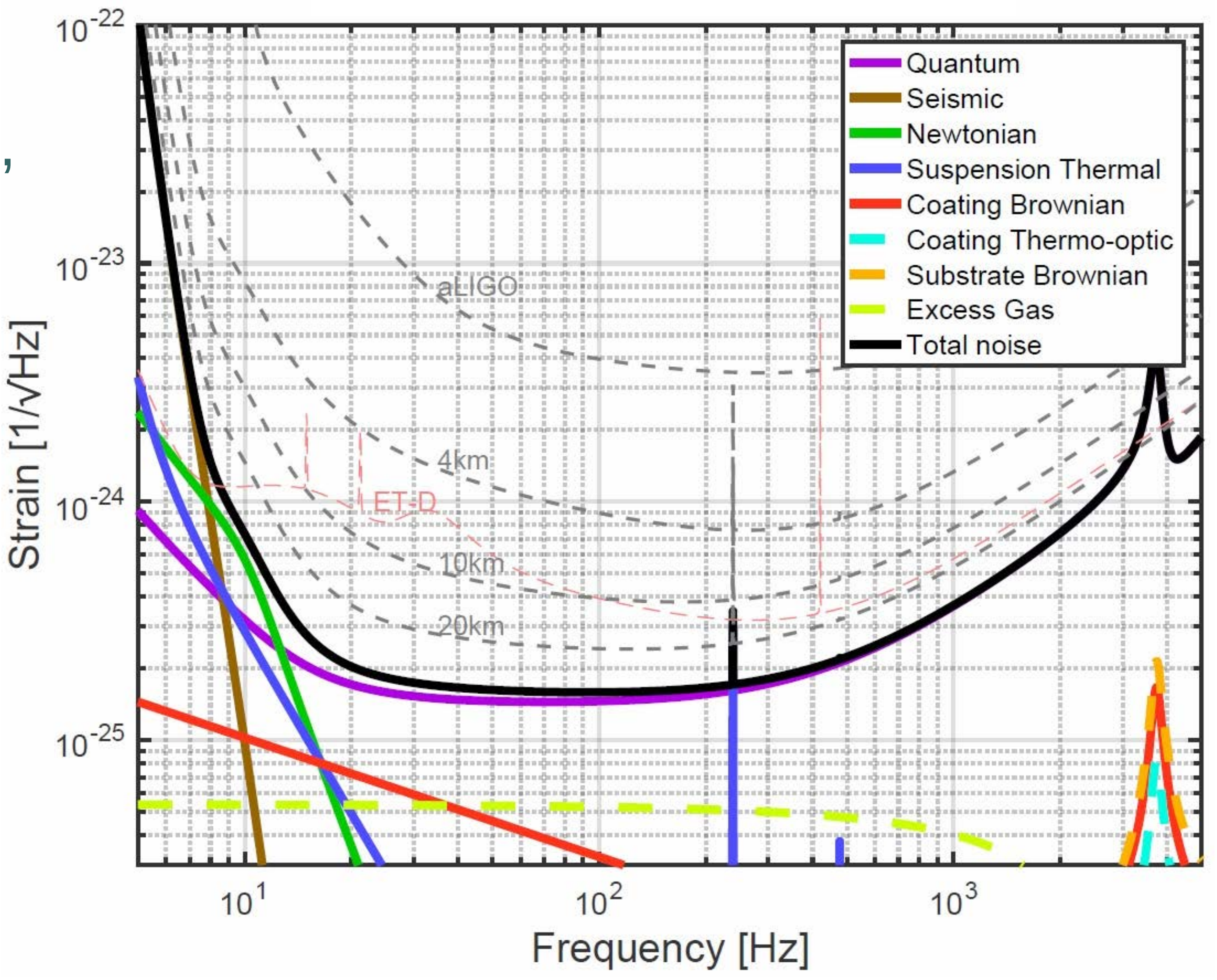
Einstein Telescope (10 km)

- European conceptual design study
- Multiple interferometers underground, 10 km arm length, in triangle. 10-15 year technology development
- ~10^5 binary coalescences per year

Cosmic Explorer (40 km)

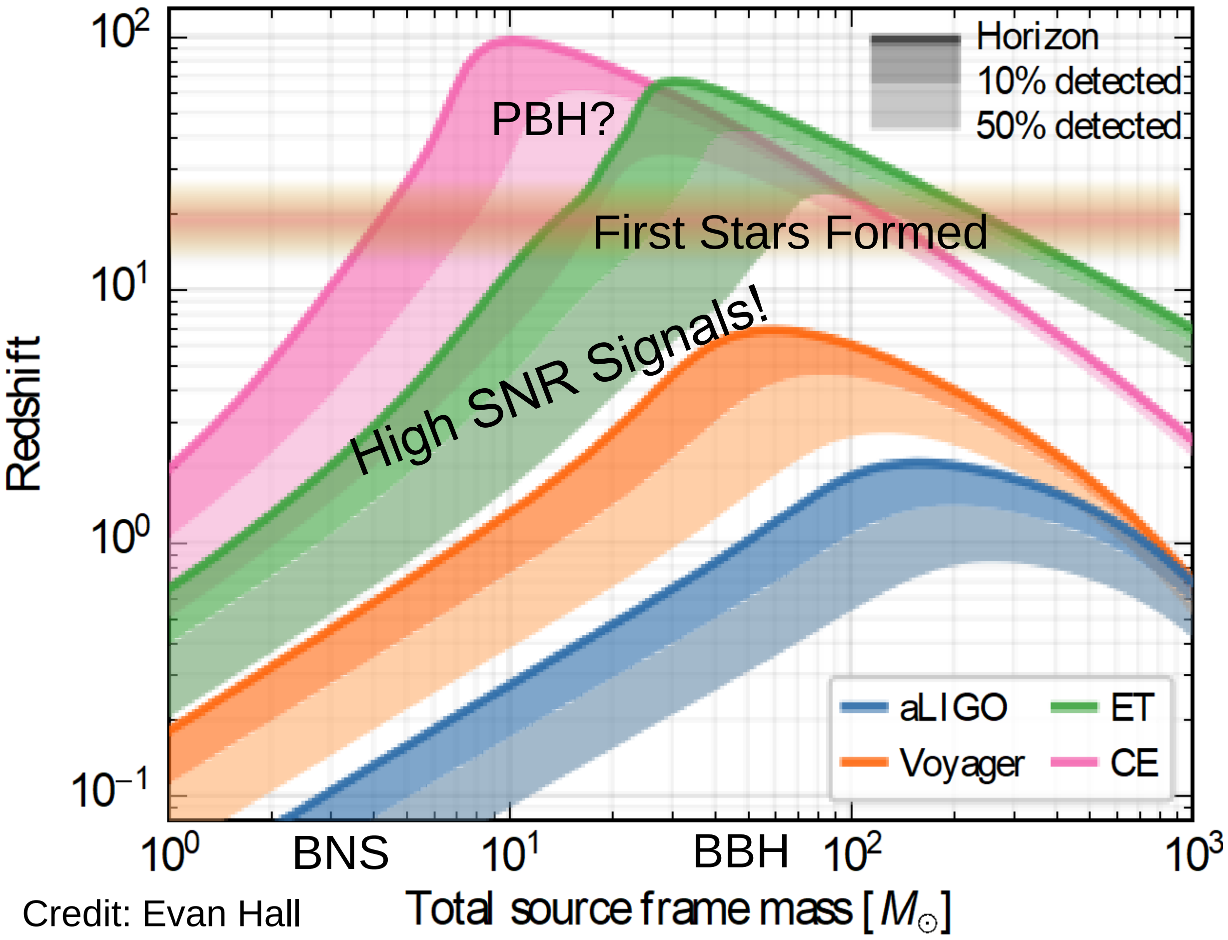
- US-based design, just starting
- Based on LIGO Voyager technology, expanded to 40 km arms.

20 Years+: New Facilities Needed



Where do we go from here?

- Mergers at cosmological distance
  - H0, dark energy EOS
- Black hole ring down
- Binary black hole formation channels
- Neutron star equation of state
- Tests of general relativity

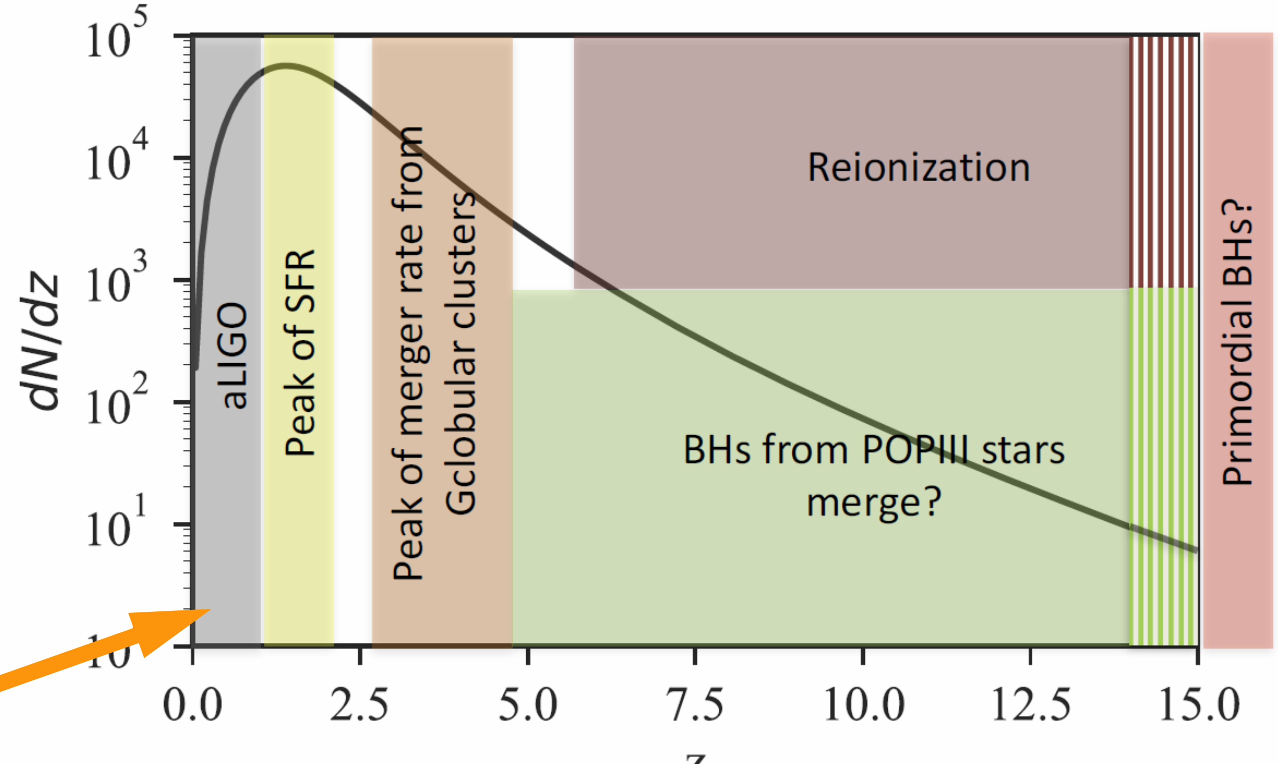


Credit: Evan Hall

Next generation detectors will detect:

$\sim 10^5$ Binary black mergers
Everywhere in the Universe!

$\sim 10^6$ Binary neutron star mergers



We are here

Advanced LIGO/Virgo and the Dawn of Gravitational-waves Physics and Astronomy

- ***Merging binary black hole and neutron star systems have been observed for the first time***
  - ***‘a scientific revolution’***

- ***Future increases in sensitivity will increase the rate of detections***
  - ***Daily Binary Black Hole Mergers, weekly binary neutron star mergers***

- ***The future looks bright!***

Stay Tuned…

Thanks to:

ligo.caltech.edu

LIGO
LASER INTERFEROMETER GRAVITATIONAL-WAVE OBSERVATORY

www.ligo.org

Support: National Science Foundation