Gravitational wave astrophysics: a new window on the Universe

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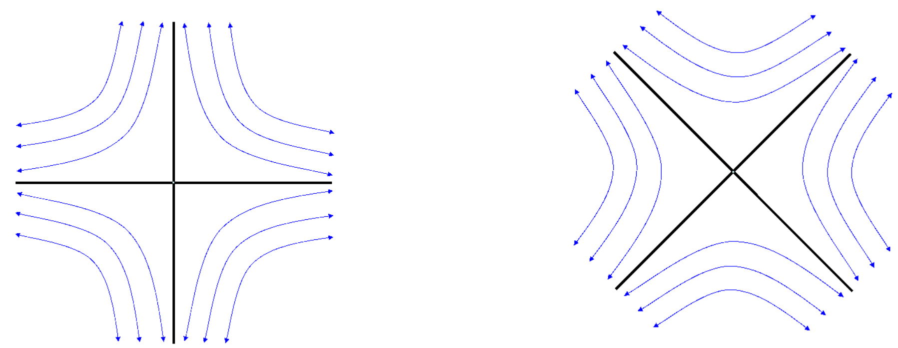
LIGO Scientific Collaboration and Virgo Collaboration

LIGO-G1701157

“Recent developments in Neutrino Physics and Astrophysics”, LNGS, 9/4/2017

Gravitational Waves: Einstein's Messengers

$$h(t,z) = h_{\mu\nu} e^{i(\omega t - kz)} = h_+(t - z/c) + h_\times(t - z/c)$$



$$h_{\mu\nu} = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & h_+ & h_\times & 0 \\ 0 & h_\times & -h_+ & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}$$

Dimensionless strain:

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

I = mass quadrupole moment of the source

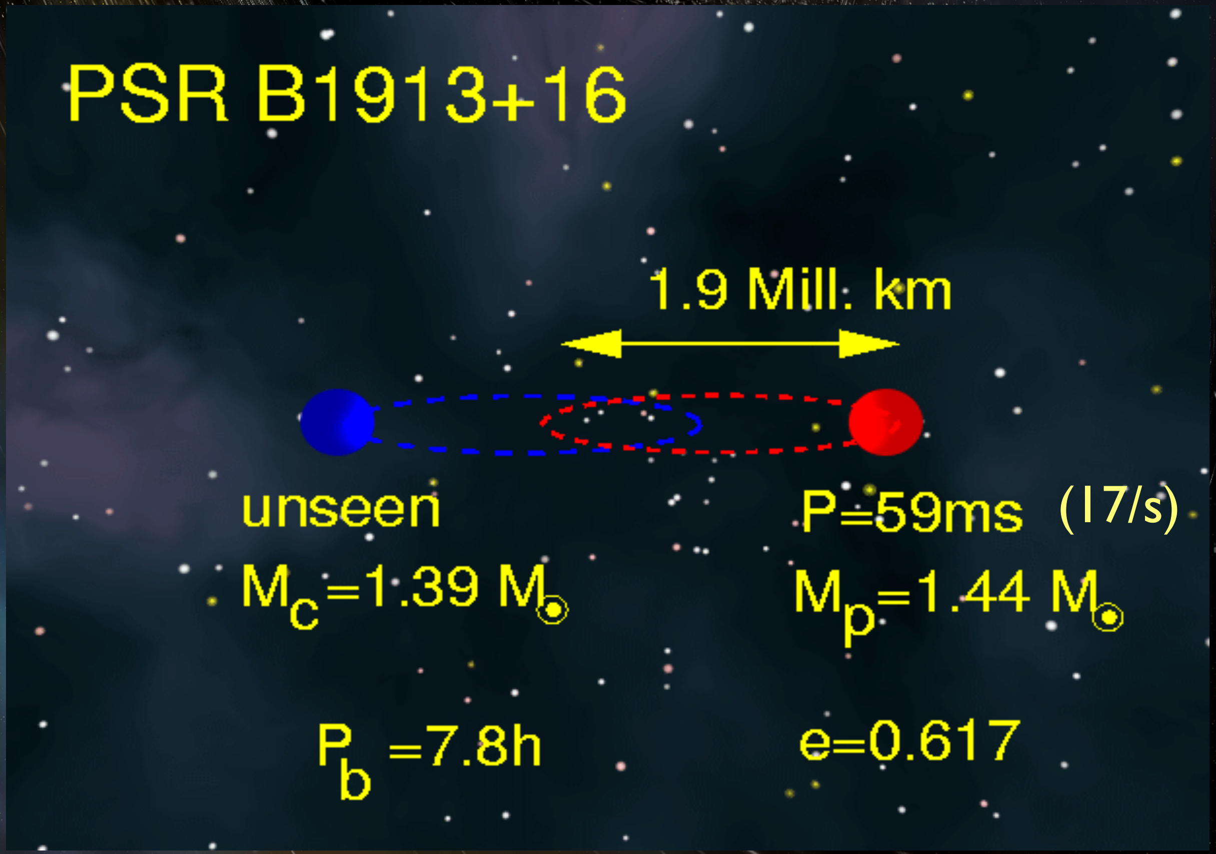
R = source distance

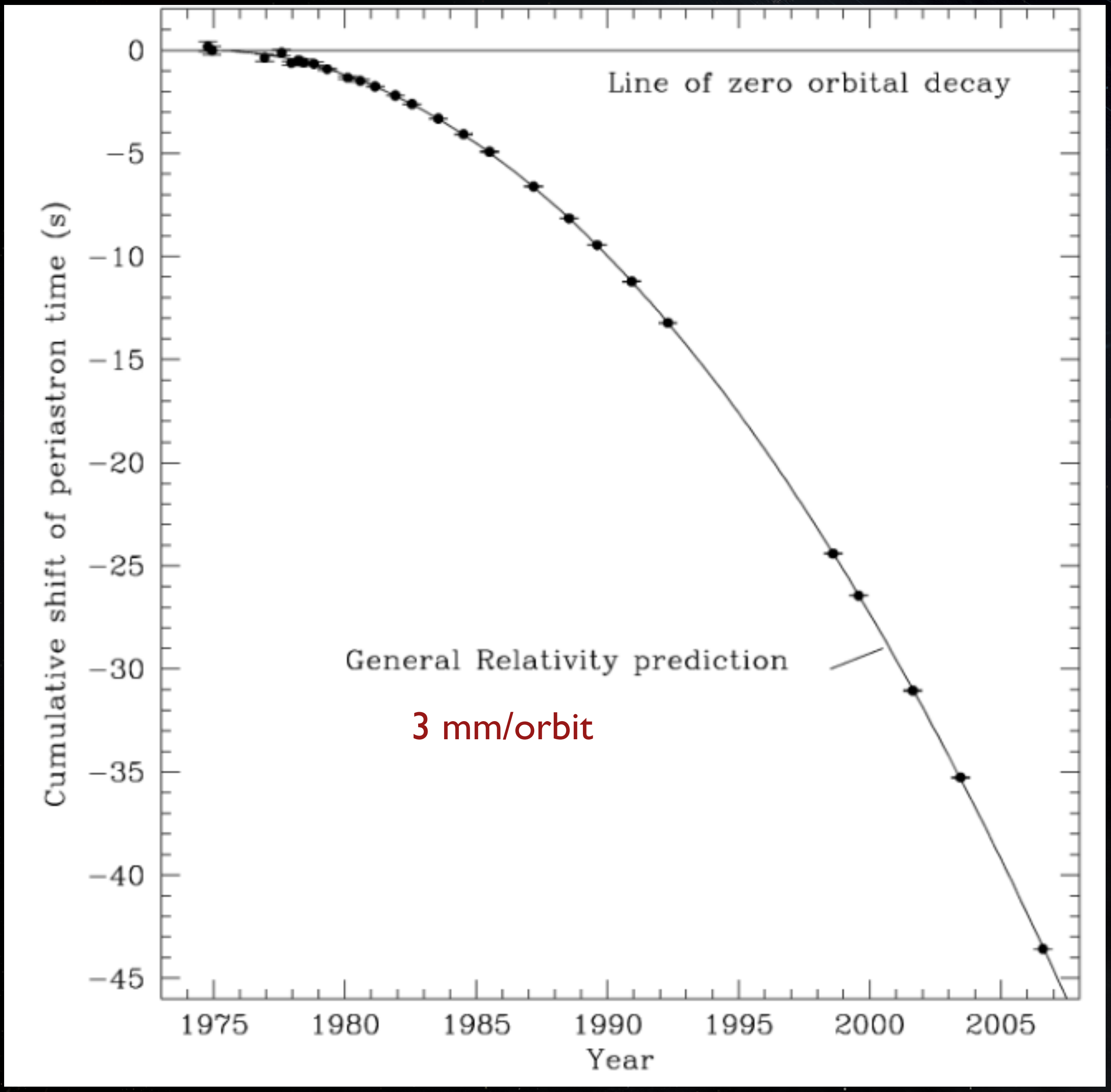
Prior Evidence for GW

Joseph Taylor

Russell Hulse

Joel Weisberg

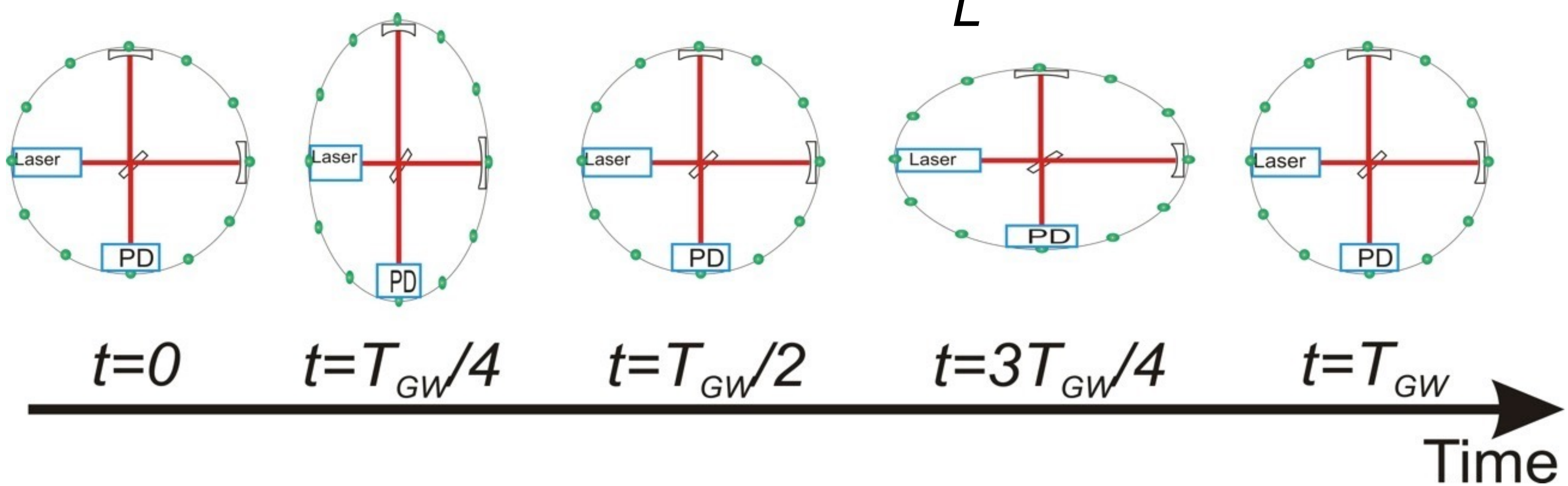




Collision expected in 300 million years

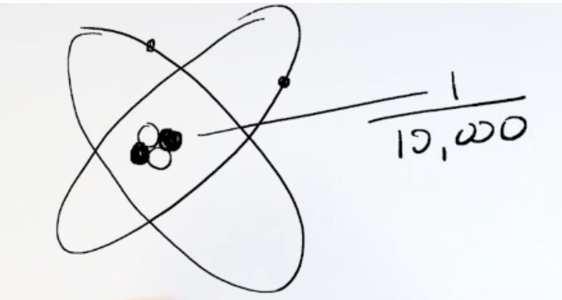
How to Detect Gravitational Waves

Physically, gravitational waves are strains $\frac{\Delta L}{L} \sim 10^{-22}$



On Earth: if L=1km, $\Delta L = 10^{-19}$m

ΔL = 0.0000000000000000001 m



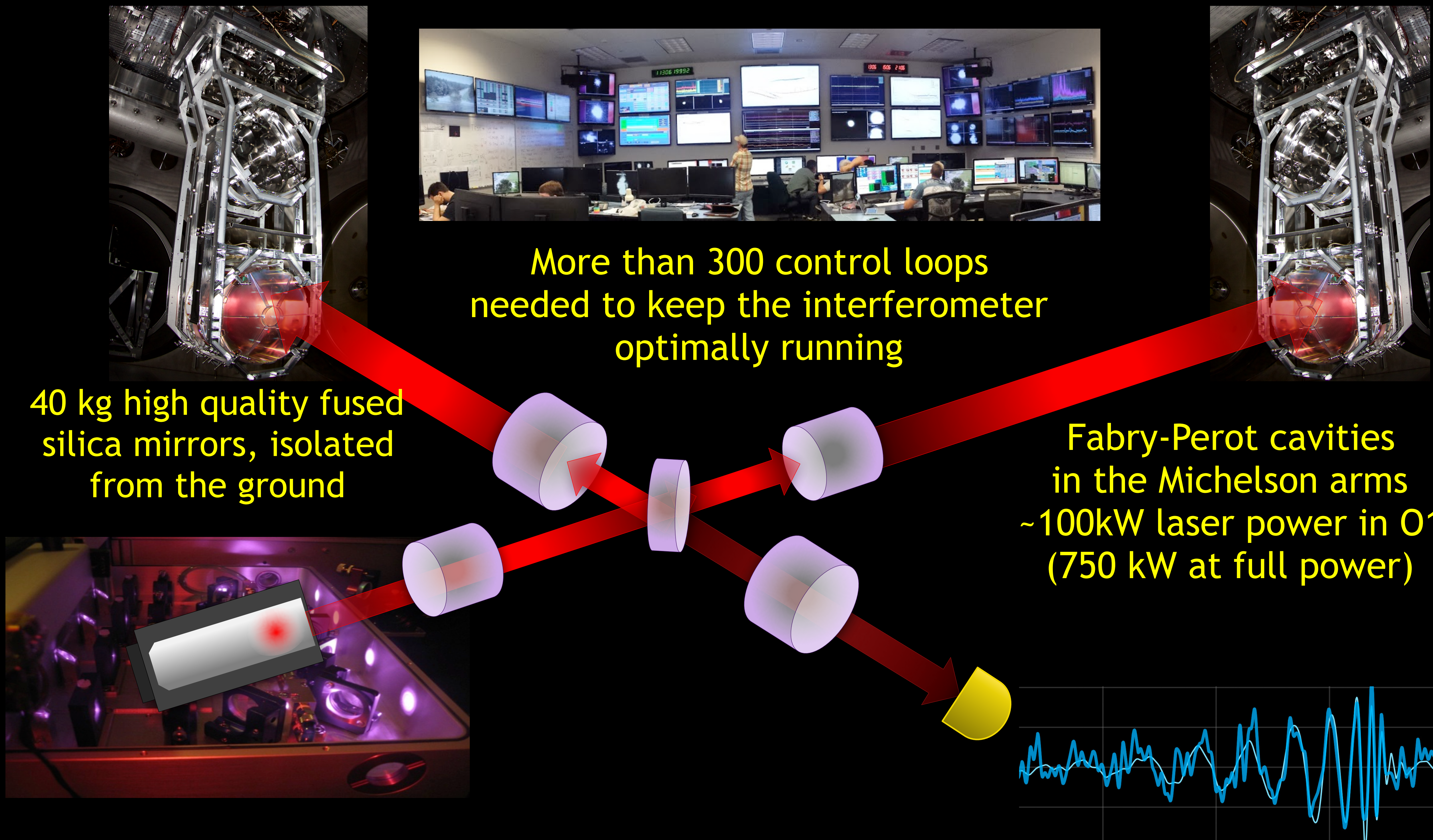
LIGO: Laser Interferometer Gravitational-wave Observatory

Hanford, WA

Livingston, LA

- LIGO Observatories constructed from 1994-2000
- Initial LIGO operated from 2002-2010
- Advanced LIGO 2015

The Advanced LIGO detectors



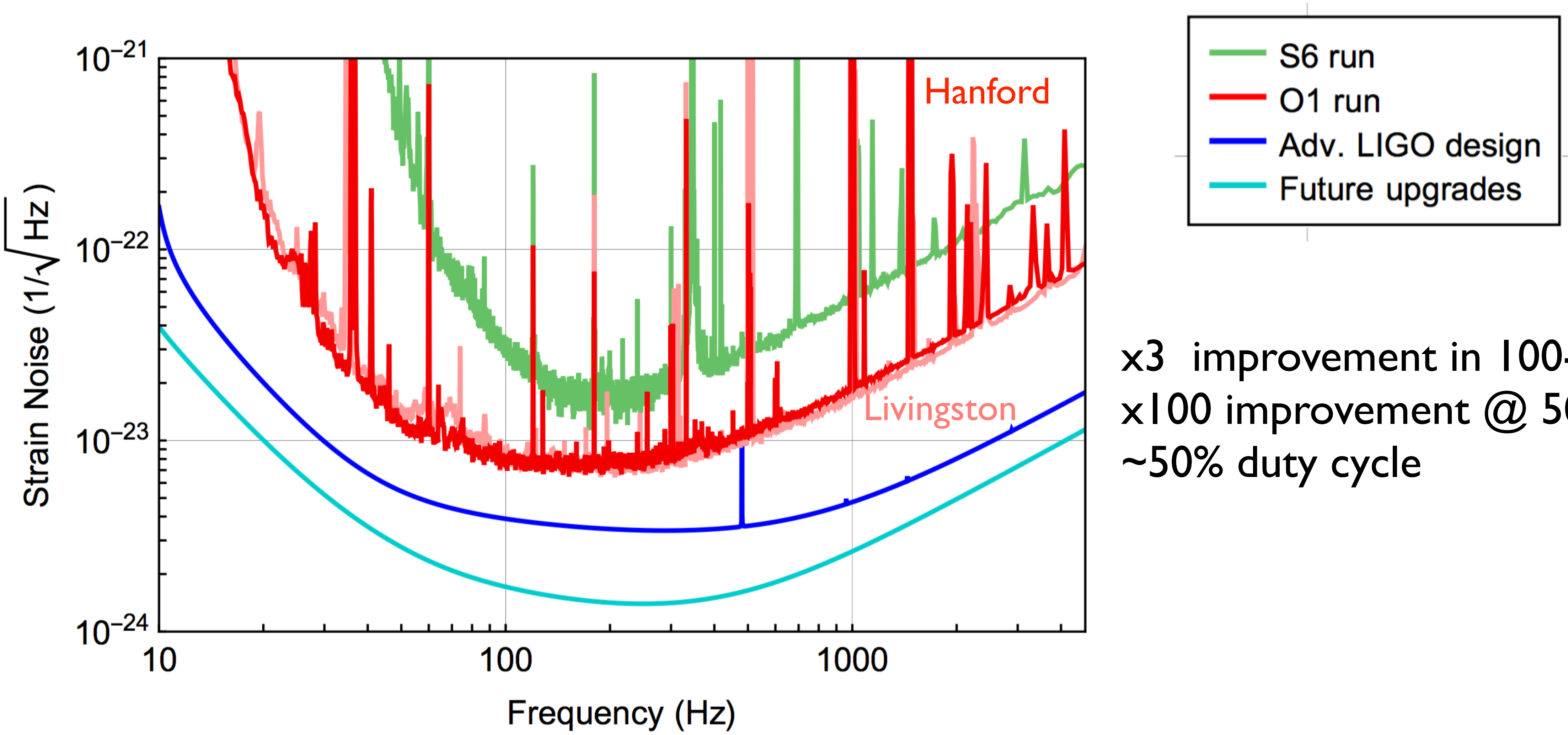
LIGO Scientific Collaboration

~ 1000 members ~ 90 institutions, 16 countries

Advanced LIGO First Science Run

Sept 12, 2015 - Jan 12, 2016

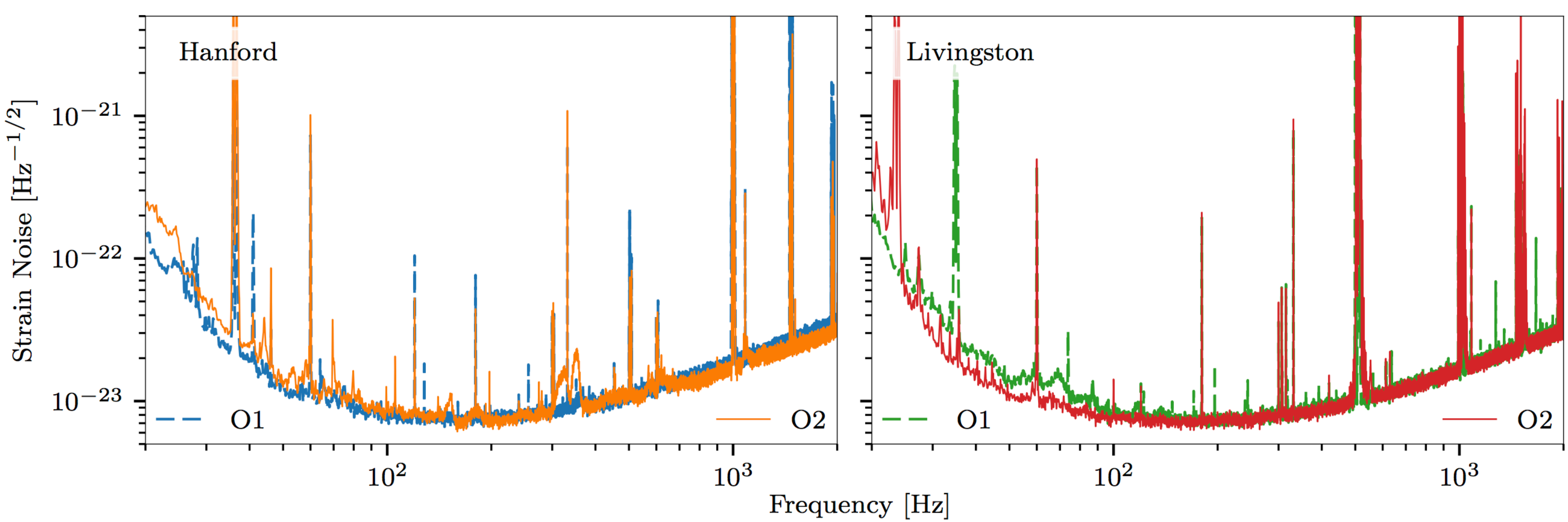
PRL 116, 131103 (2016)



x3 improvement in 100-300 Hz
x100 improvement @ 50 Hz
~50% duty cycle

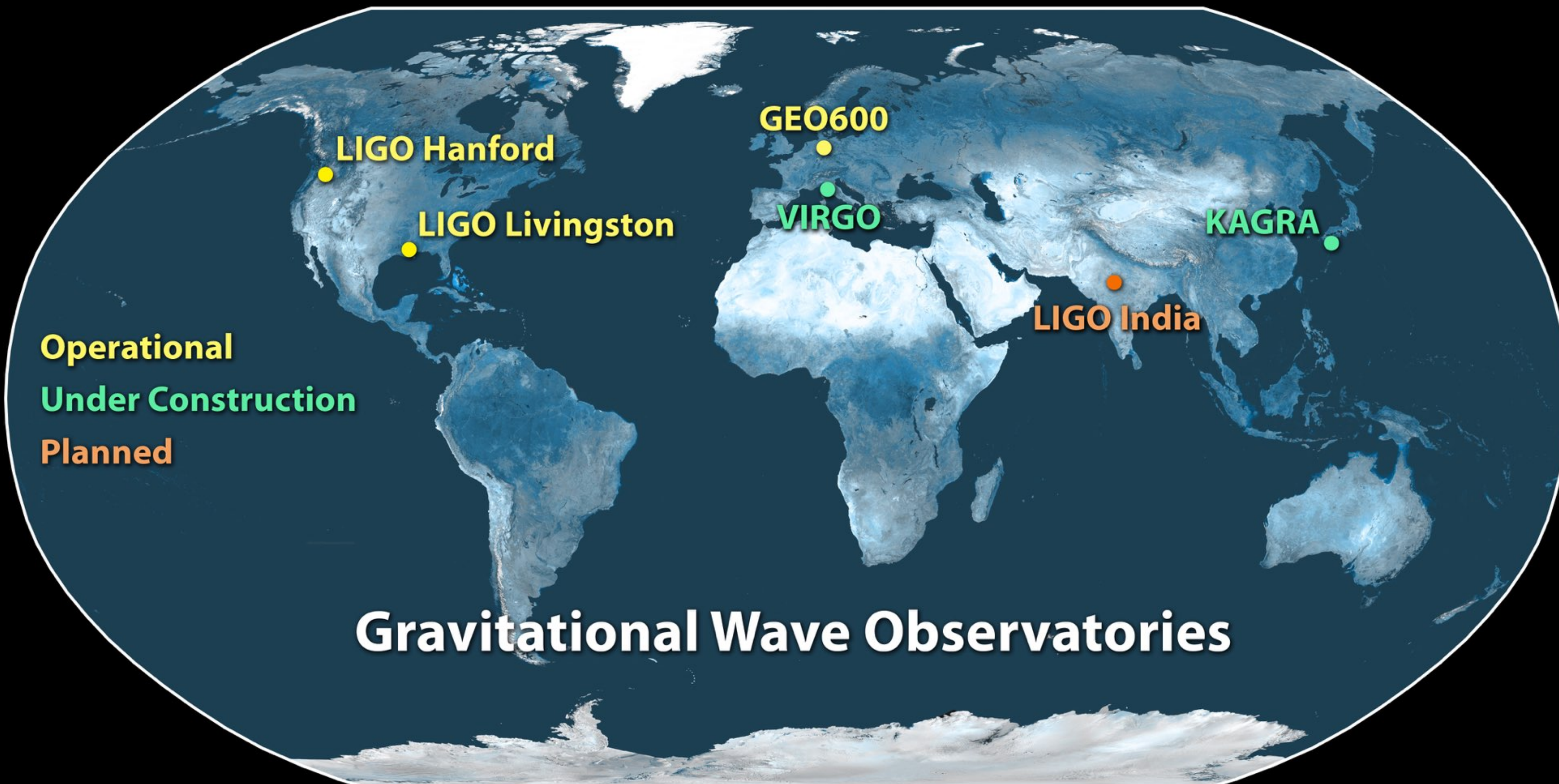
Second Science Run

Nov 30, 2016 - Aug 25, 2017



PRL 118, 221101 (2017) Suppl

A Global Quest



Advanced Virgo

Virgo is a European collaboration with about 280 members

Advanced Virgo (AdV): upgrade of the Virgo interferometric detector

Participation by scientists from France, Hungary, Italy, Poland, Spain, and The Netherlands

- 20 laboratories represented in VSC, about 280 authors
  - APC Paris
  - ARTEMIS Nice
  - EGO Cascina
  - INFN Firenze-Urbino
  - INFN Genova
  - INFN Napoli
  - INFN Perugia
  - INFN Pisa
  - INFN Roma La Sapienza
  - INFN Roma Tor Vergata
  - INFN Trento-Padova
  - LAL Orsay – ESPCI Paris
  - LAPP Annecy
  - LKB Paris
  - LMA Lyon
  - Nikhef Amsterdam
  - POLGRAW(Poland)
  - RADBOUD Uni. Nijmegen
  - RMKI Budapest
  - Univ. of Valencia

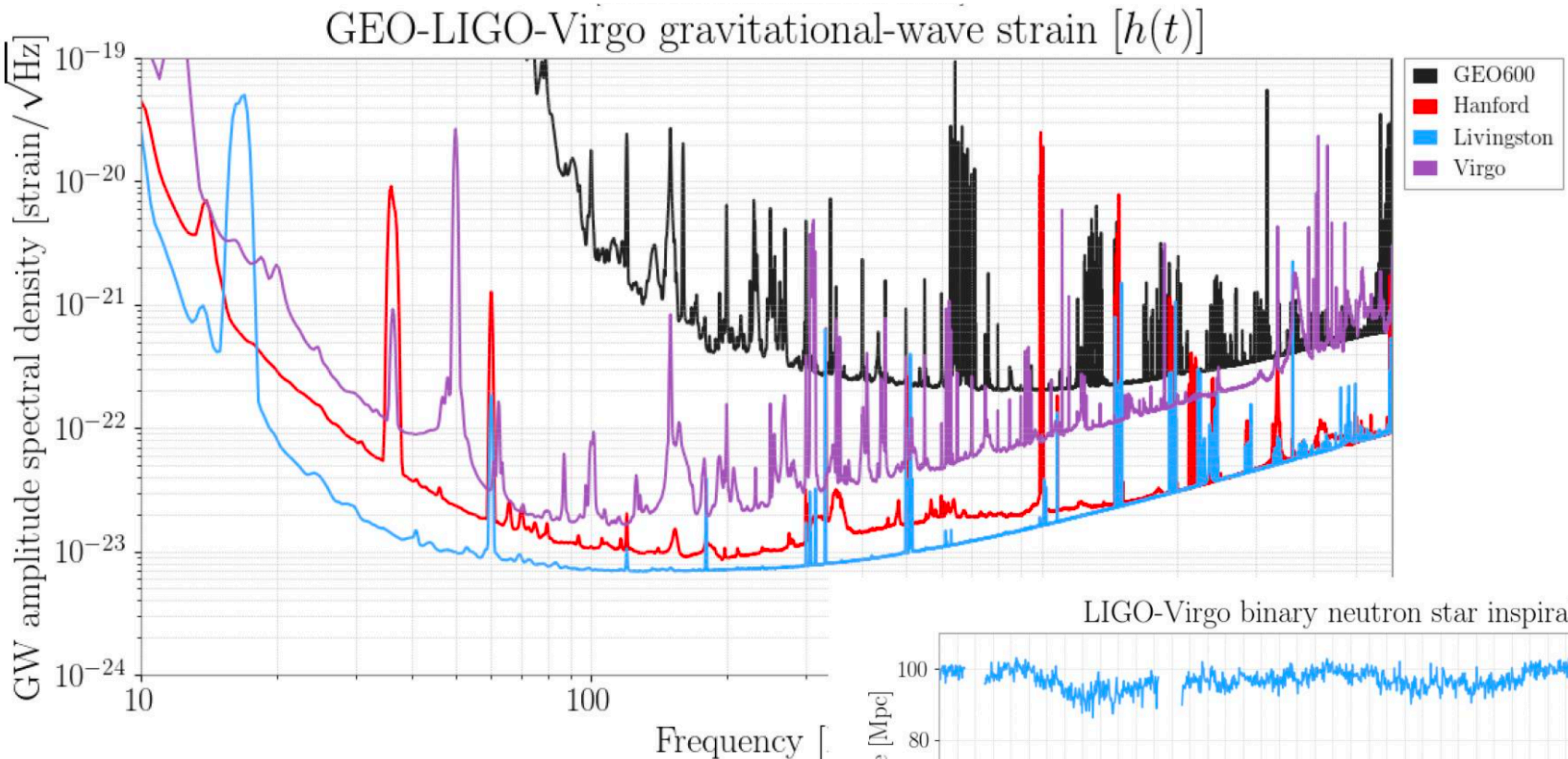
Advanced Virgo project has been formally completed on July 31, 2017

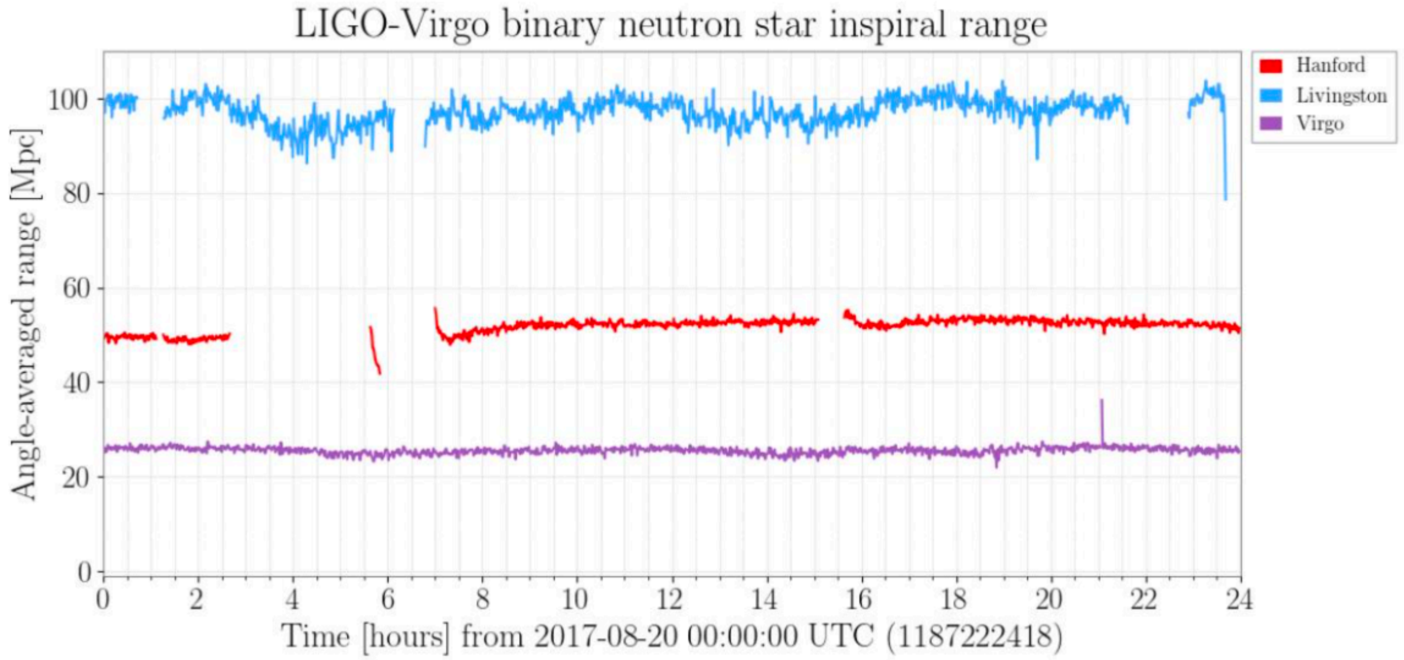
Part of the international network of 2nd generation detectors

Joined the O2 run on August 1, 2017

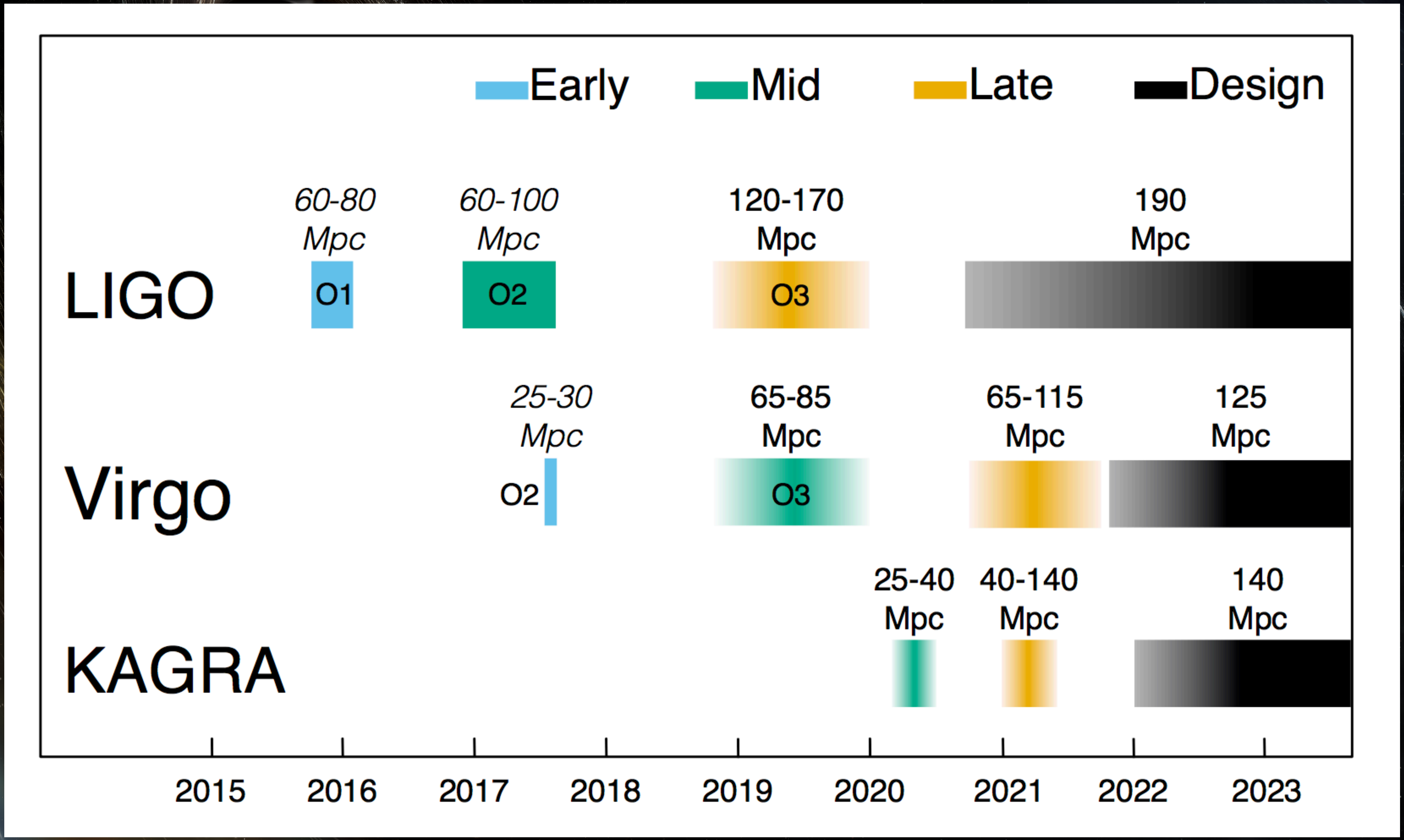
6 European countries

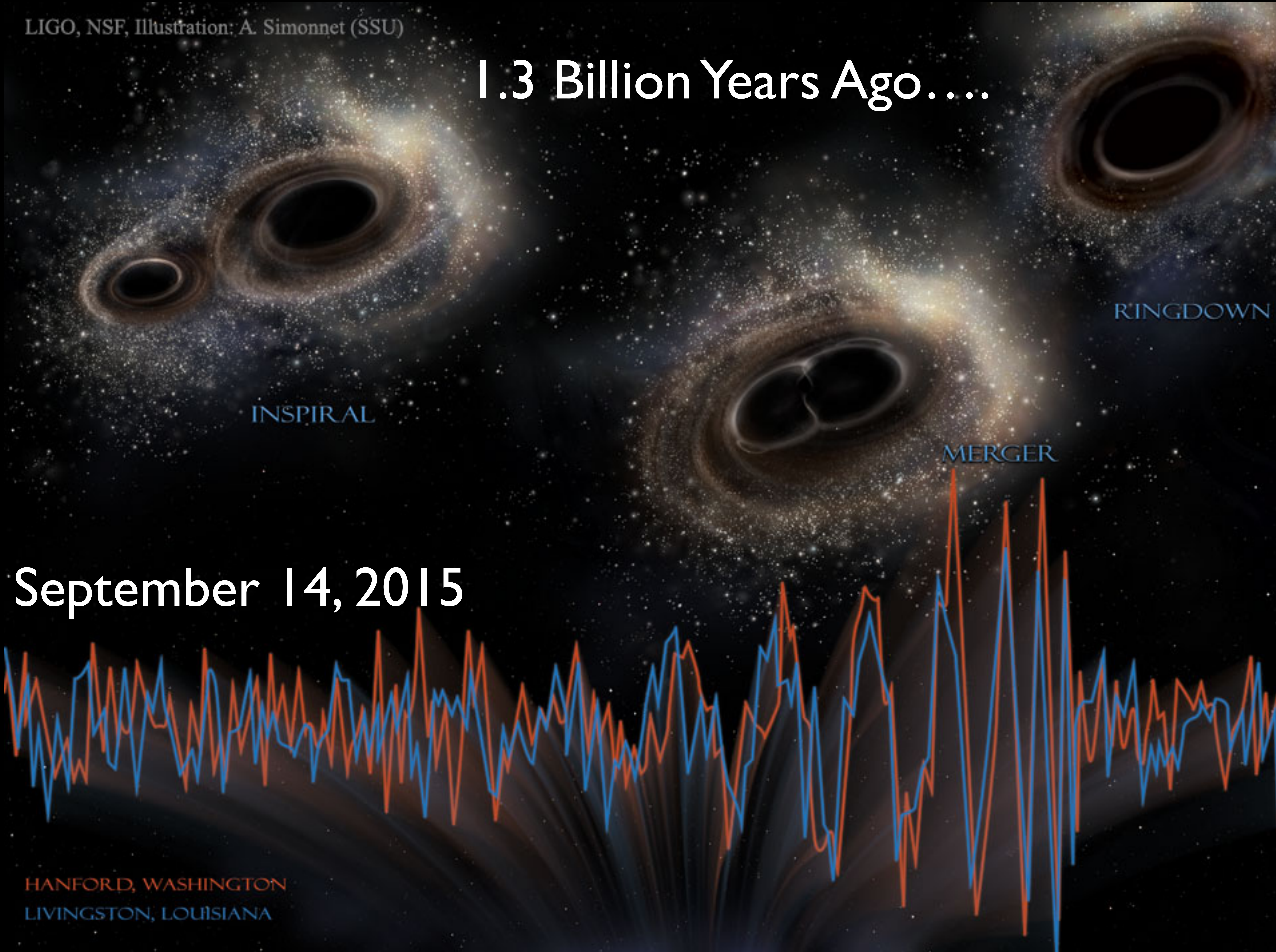
Advanced Virgo





Observing Scenario




LIGO, NSF, Illustration: A. Simonnet (SSU)
1.3 Billion Years Ago….
INSPIRAL
MERGER
RINGDOWN
September 14, 2015
HANFORD, WASHINGTON
LIVINGSTON, LOUISIANA

GW150914

$36+29 \rightarrow 62M_\odot$, SNR=24

FAR<1/1Myr (>5sigma)

d=420Mpc (z=0.09)

LVT151012

$23+13 \rightarrow 35M_\odot$, SNR=10

FAR=1/4y (1.7 sigma)

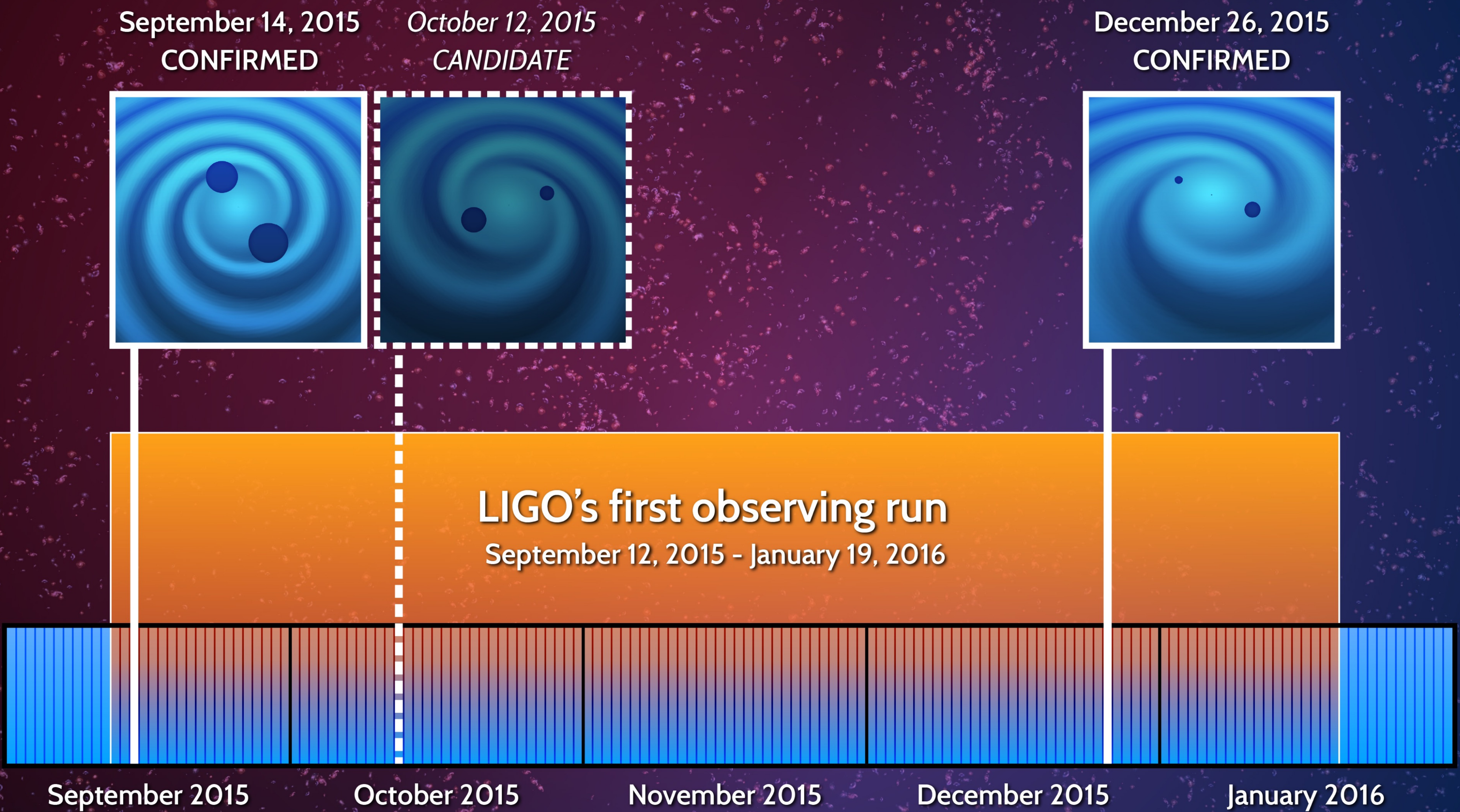
d=1000Mpc (z=0.2)

GW151226

$14+7.5 \rightarrow 21M_\odot$, SNR=13

FAR<1/1Myr (>5sigma)

d=440Mpc (z=0.09)

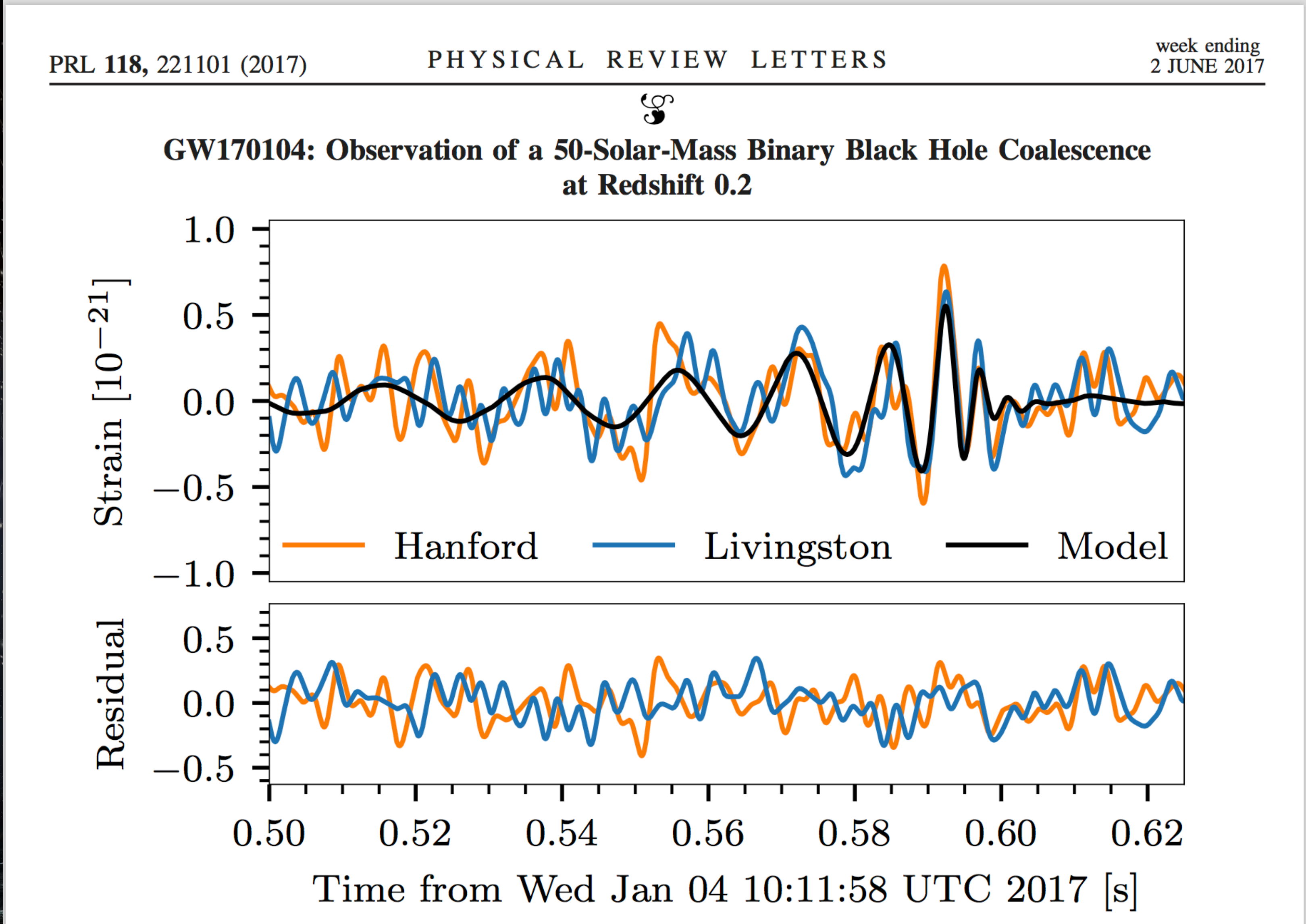


Credit: LIGO

Announced in June

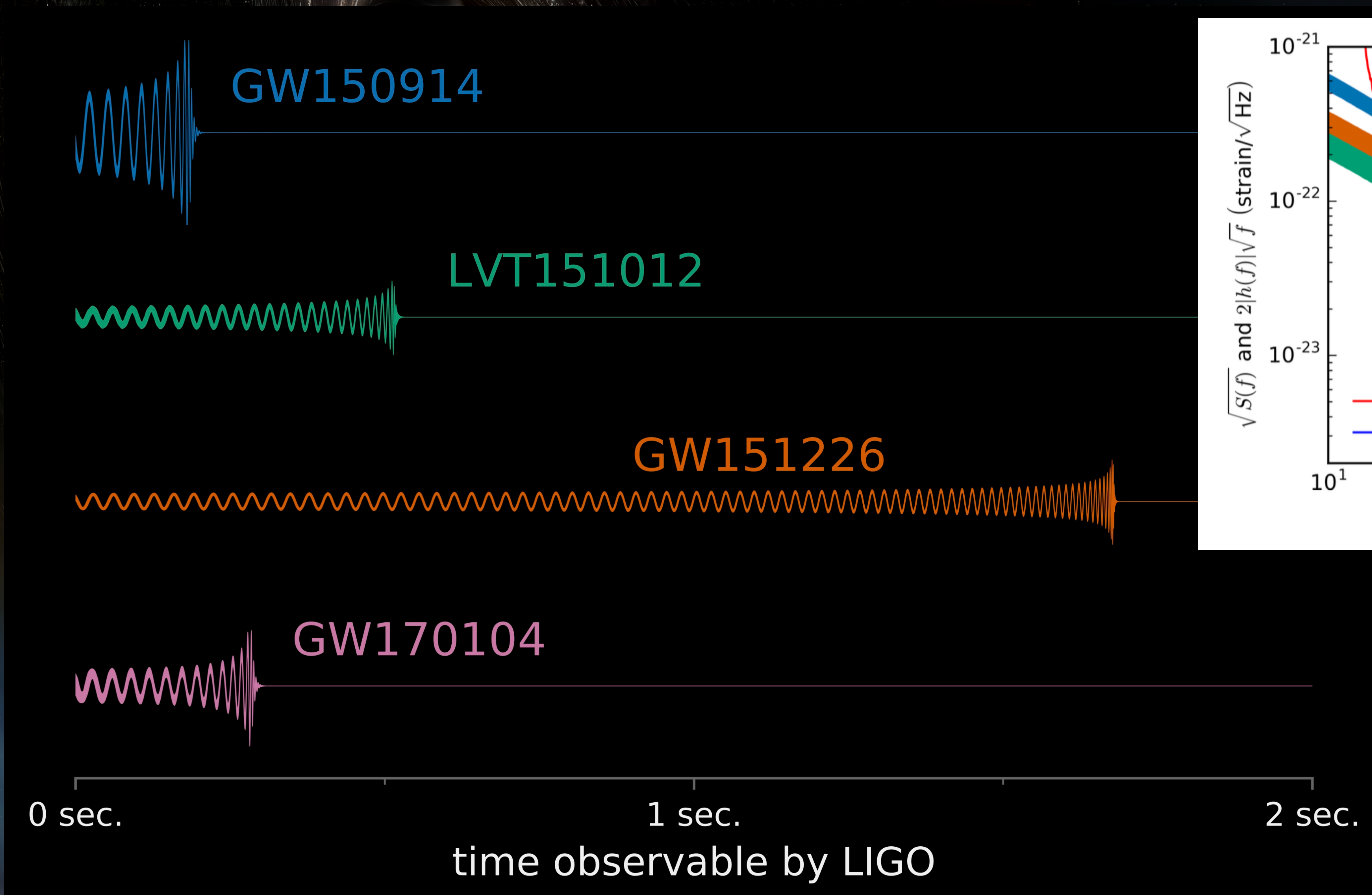
GW170104

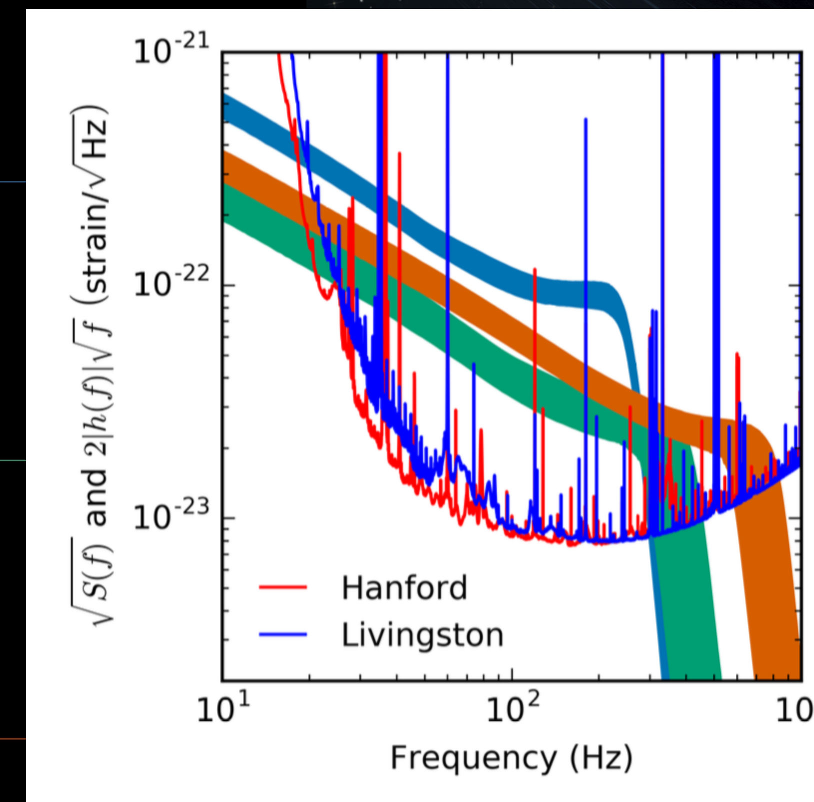
31+19→51M$_\odot$, SNR=13
FAR<1/70,000 yr
d=880Mpc (z=0.18)



Abbott+ PRL, 118, 221101 (2017)

Binary Black Hole Signals





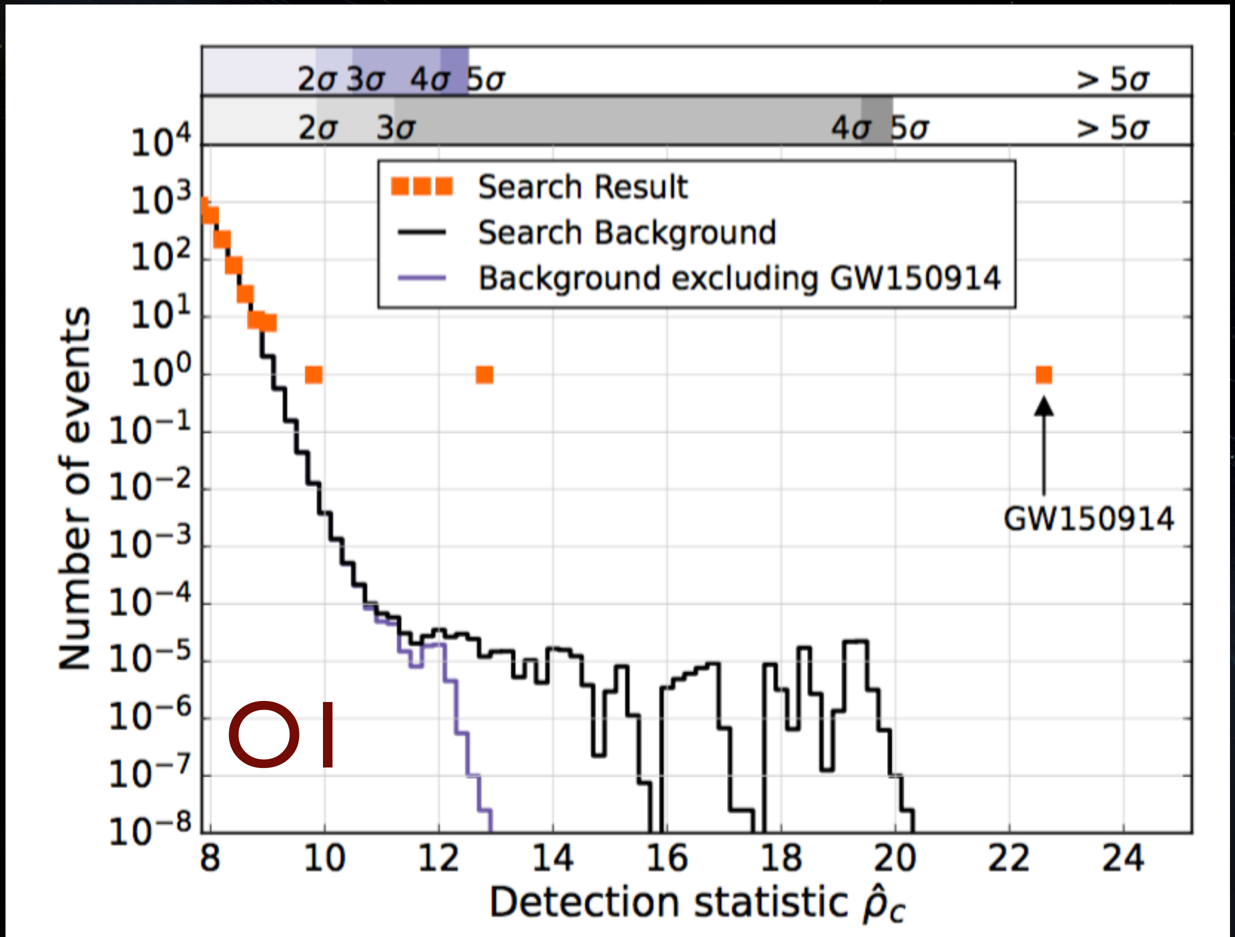
PRX 6, 041015 (2016)

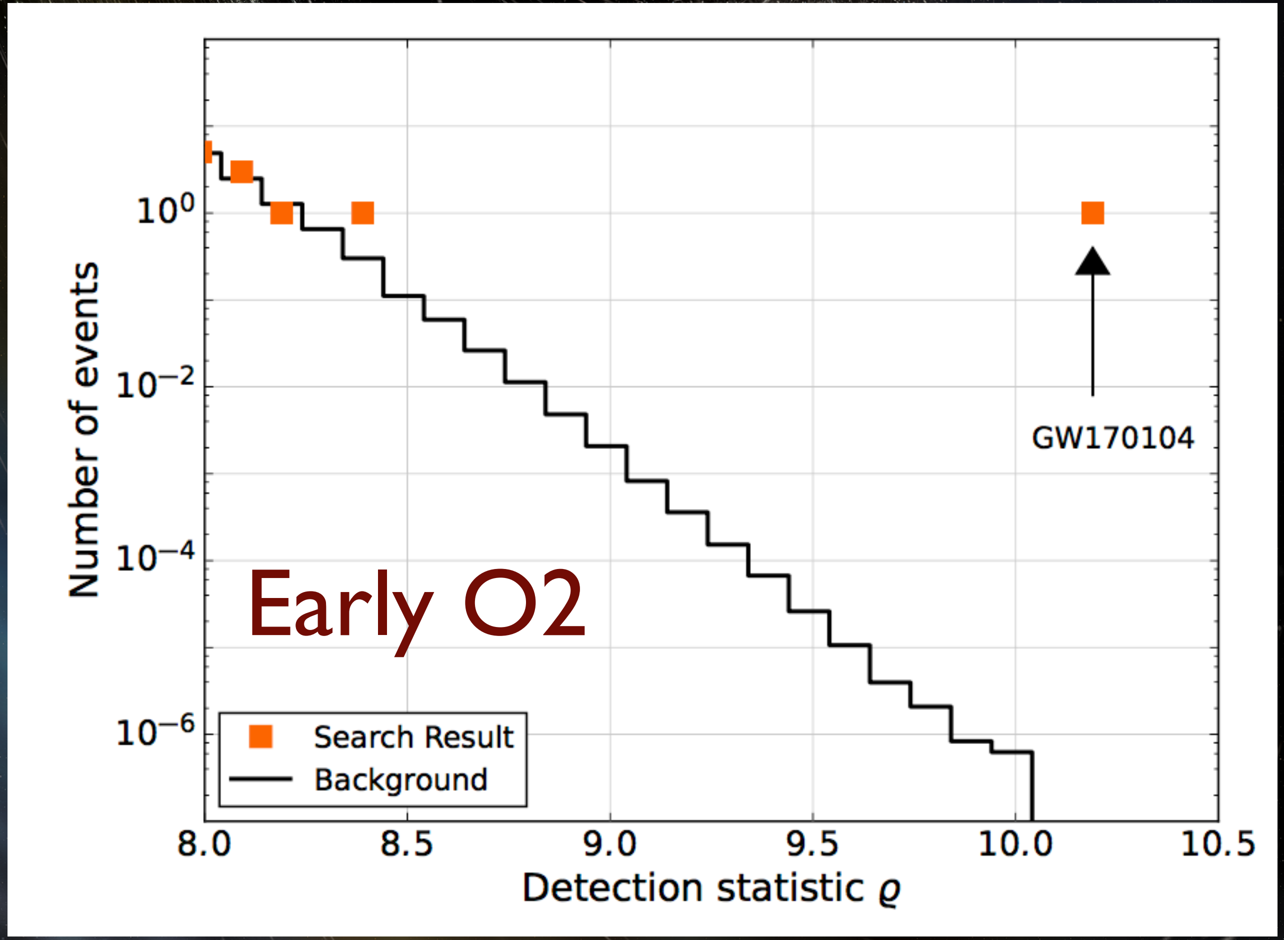
Image credit: LIGO/Caltech/MIT/U. of Chicago (B. Farr)

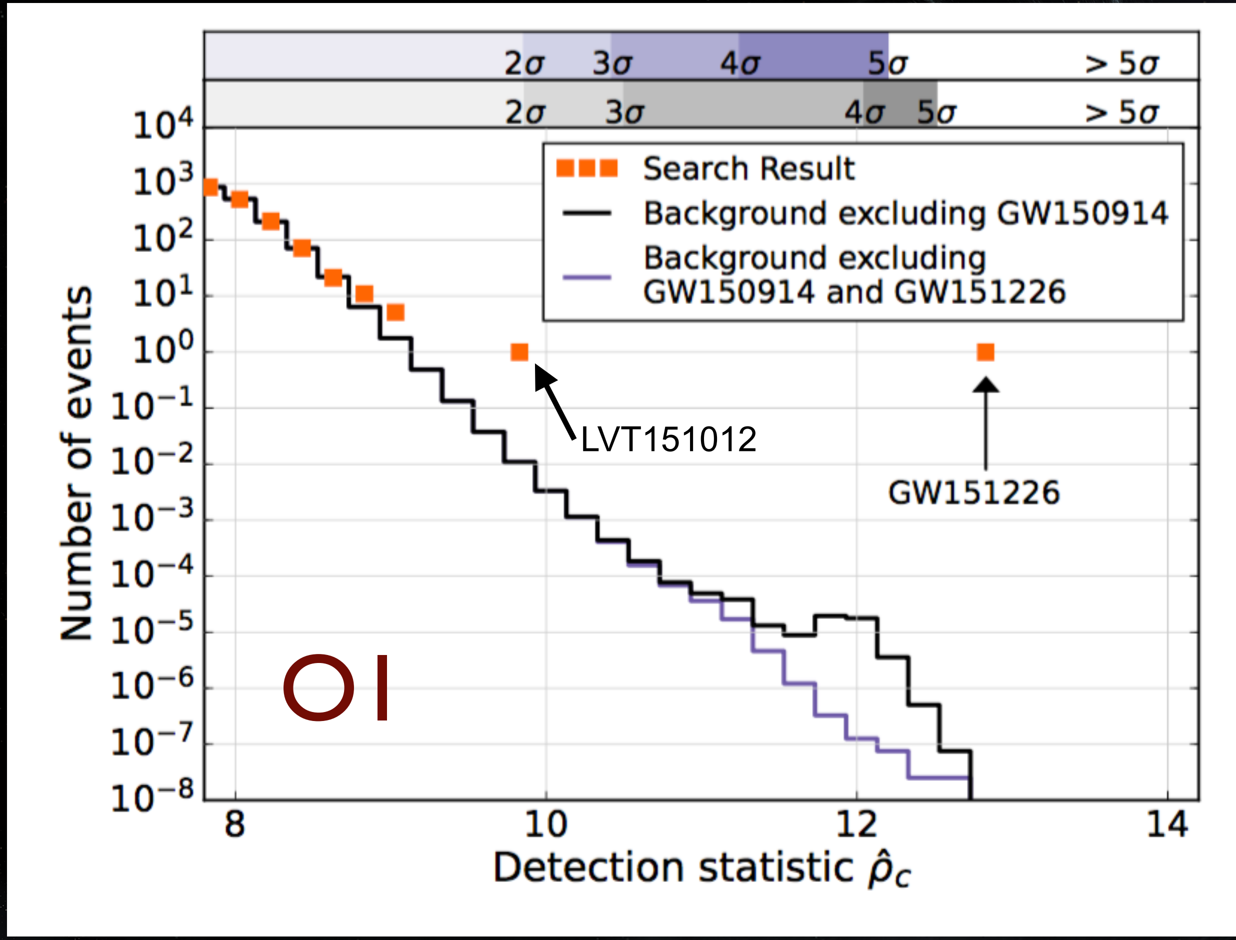
Detection Confidence

PRX 6, 041015 (2016)

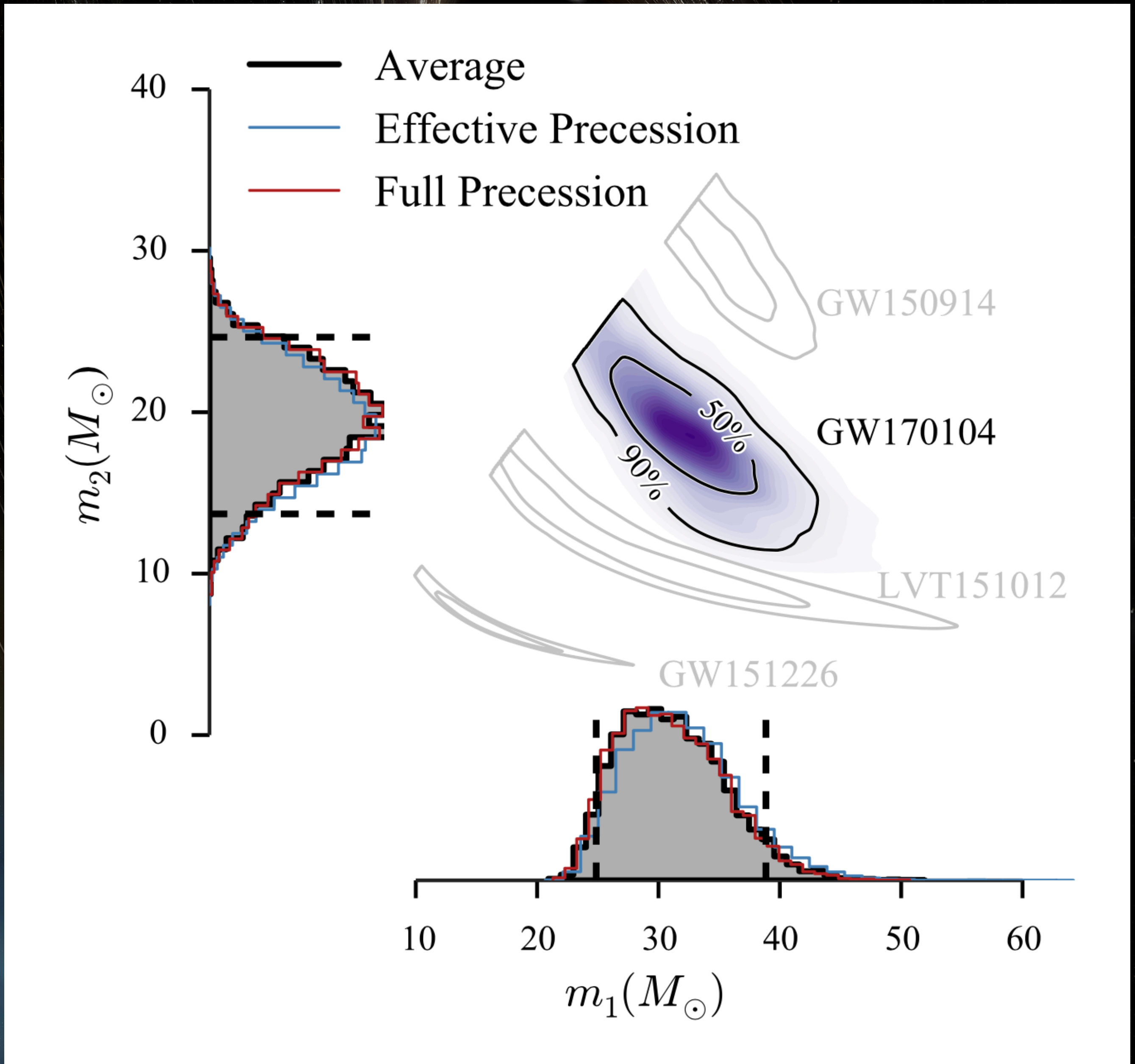
PRL 118, 221101 (2016)







Black Hole Masses



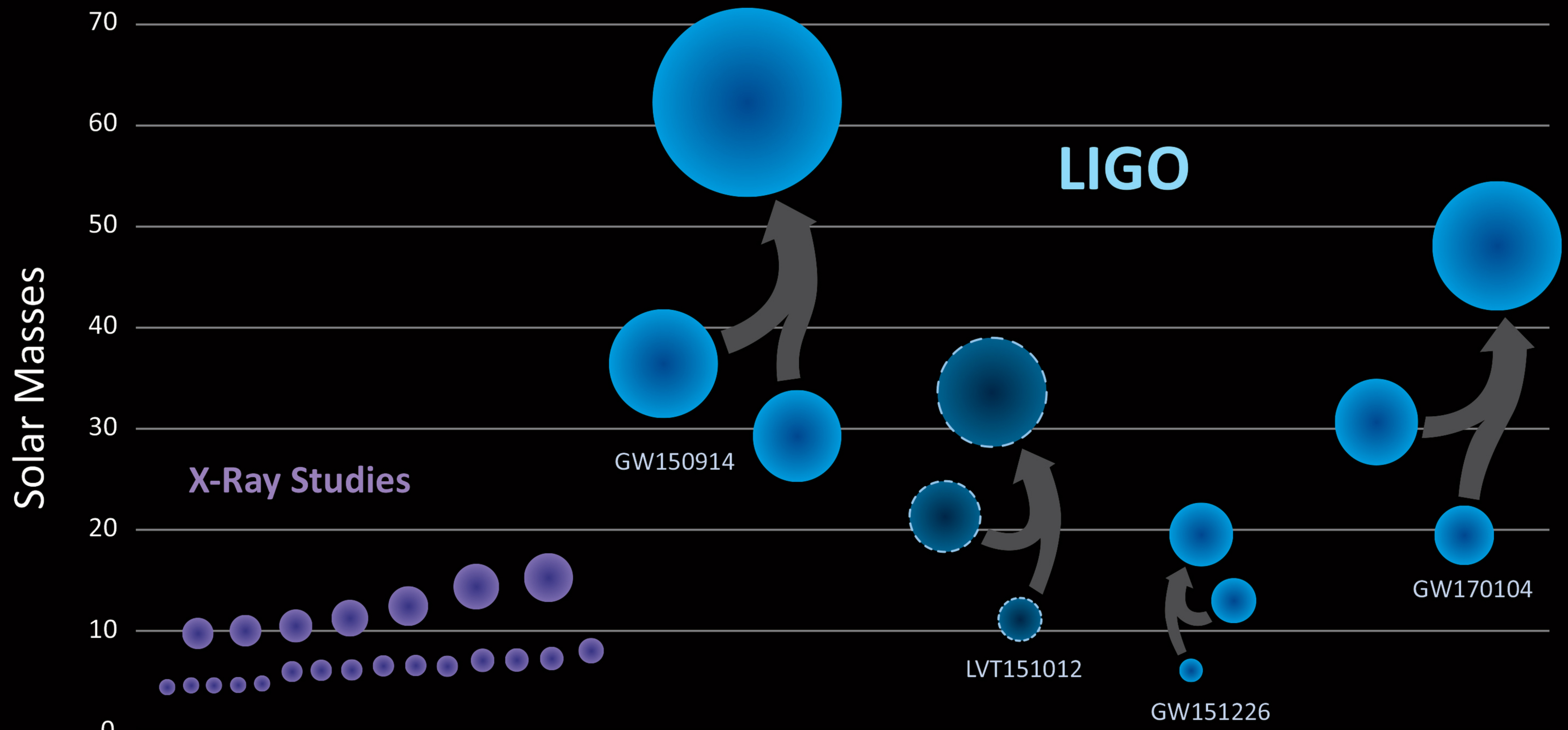
PRL 118, 221101 (2016)

Most robust evidence for the existence of 'heavy' stellar mass BHs (> 20 $M_\odot$)

BBH most likely formed in a low-metallicity environment: < ½ $Z_\odot$

Merger rate of stellar mass BBHs: 12 – 213/Gpc^3/yr

"Solar Mass" Black Holes

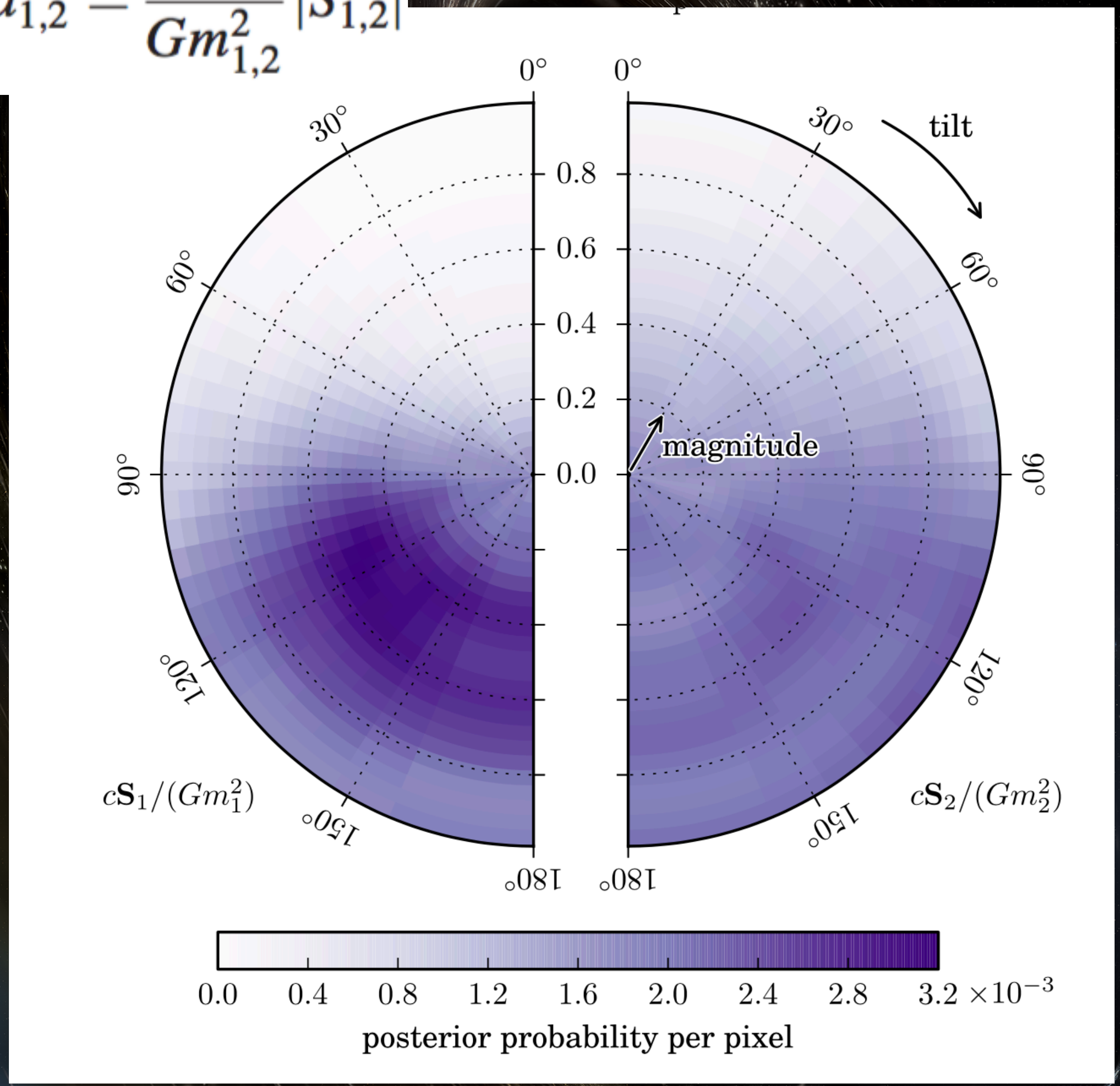


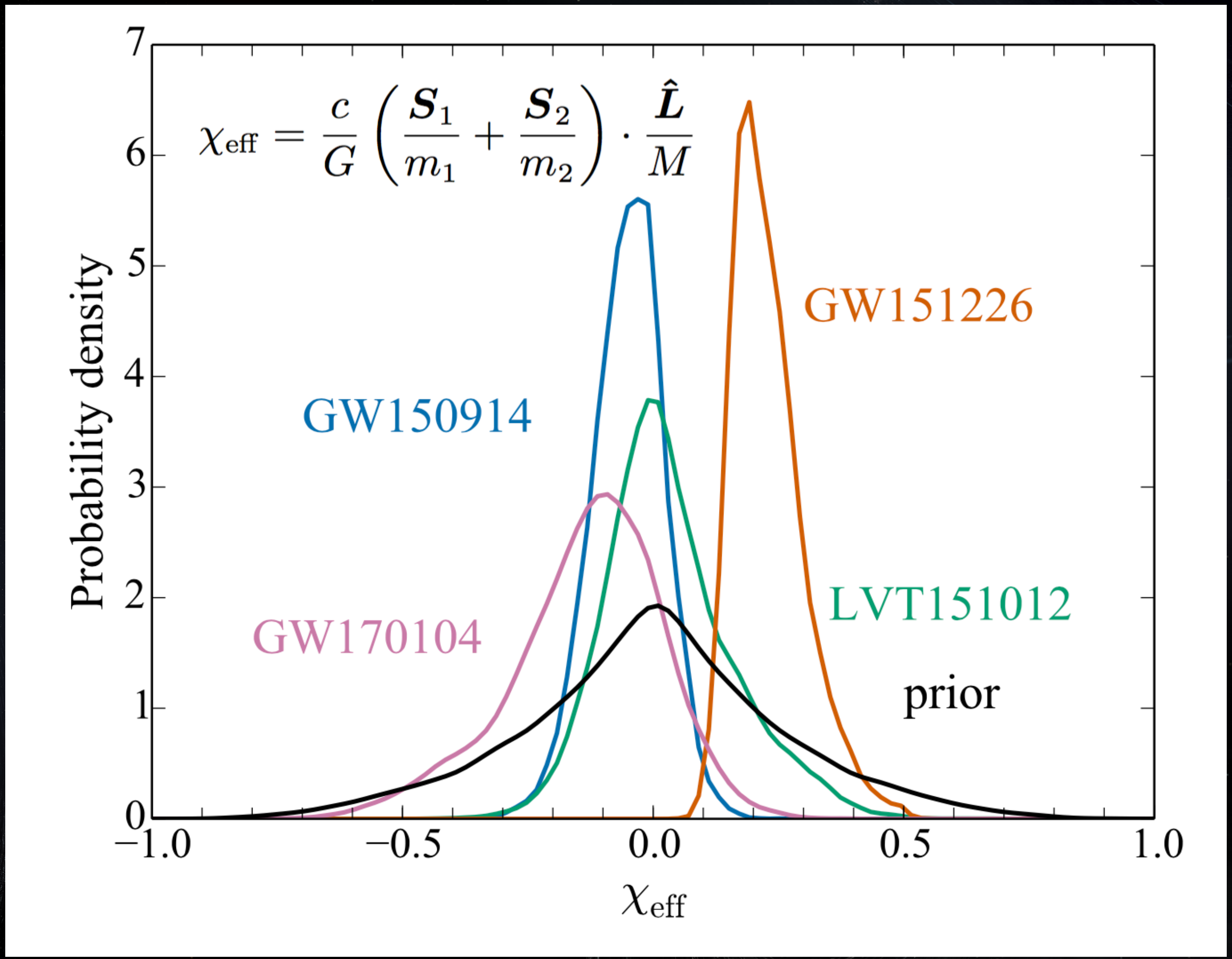
Credit: LIGO/Sonoma State (Simonnet)

Black Holes Spin

PRL 118, 221101 (2016)

$$a_{1,2} = \frac{c}{Gm_{1,2}^2}|S_{1,2}|$$

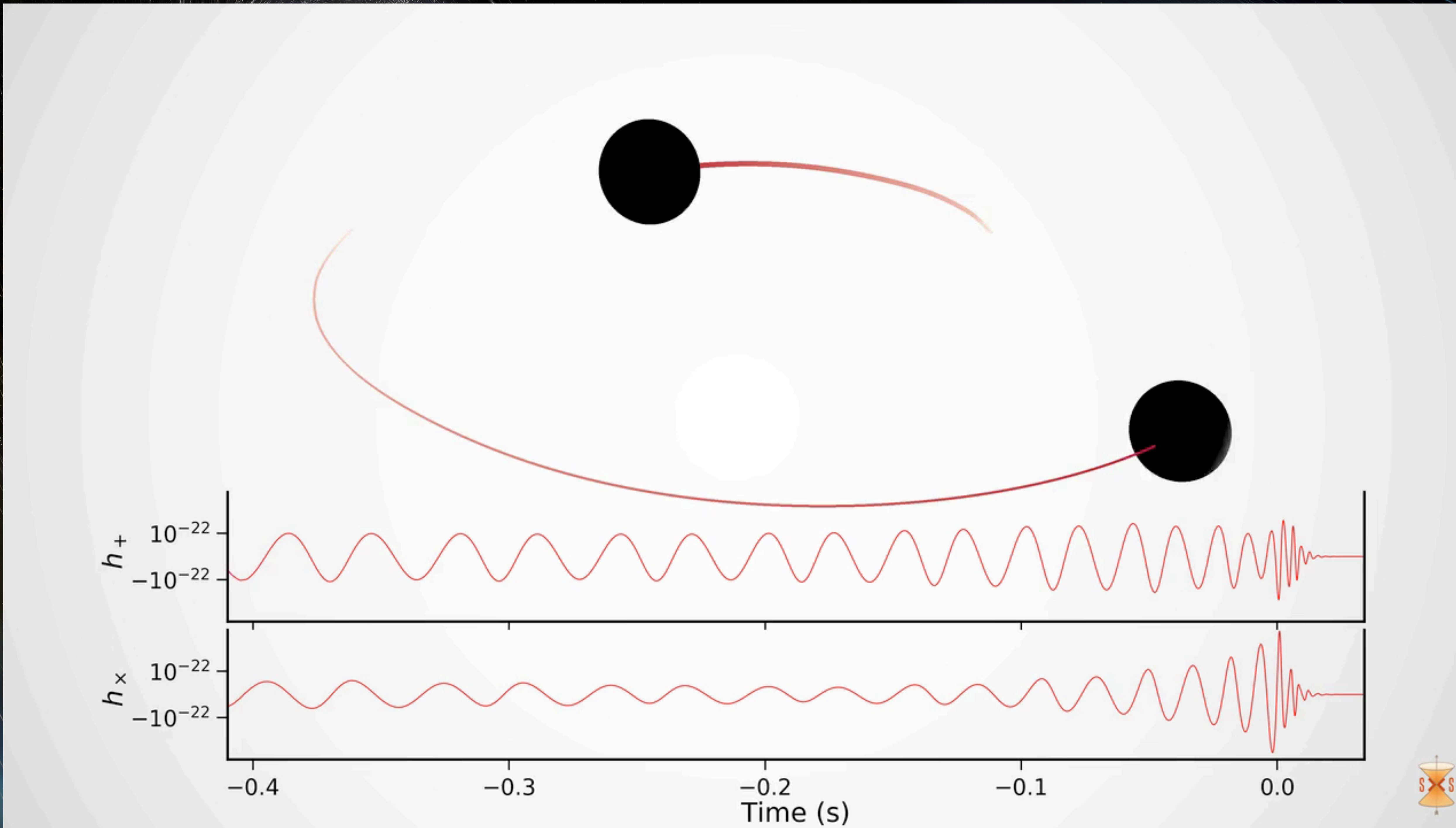




GW170104: evidence for spin-orbit misalignment

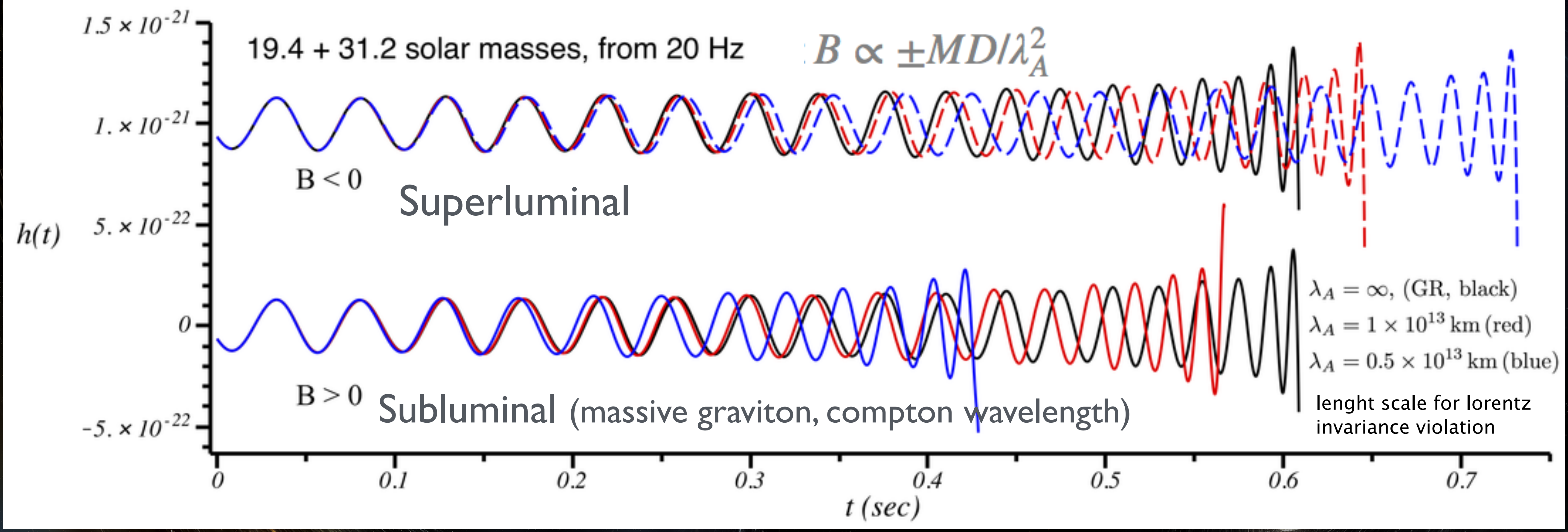
Beginning to inform formation models:
isolated binary evolution vs dynamical formation in dense clusters

Numerical Simulations



Credit: A. Babul/H. Pfeiffer/CITA/SXS

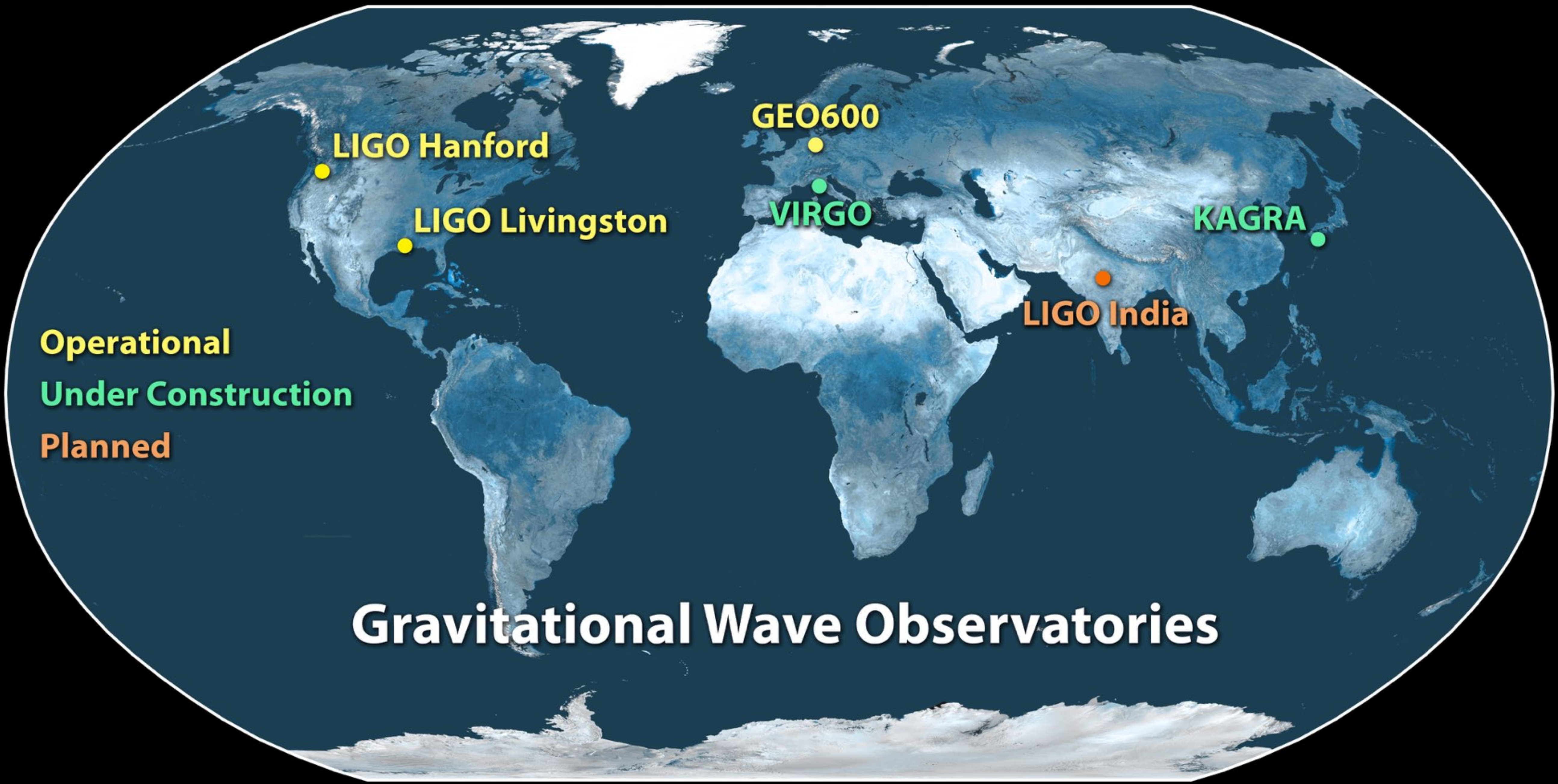
Testing General Relativity: Lorentz Invariance



Credit: Littenberg

- With GW170104 we could test for generic dispersion relation for gravitational waves
- We found no evidence for dispersion of gravitational waves

A Global Quest



Sky Locations of Gravitational-wave Events GW150914, GW151226, GW170104 and Candidate LVT151012

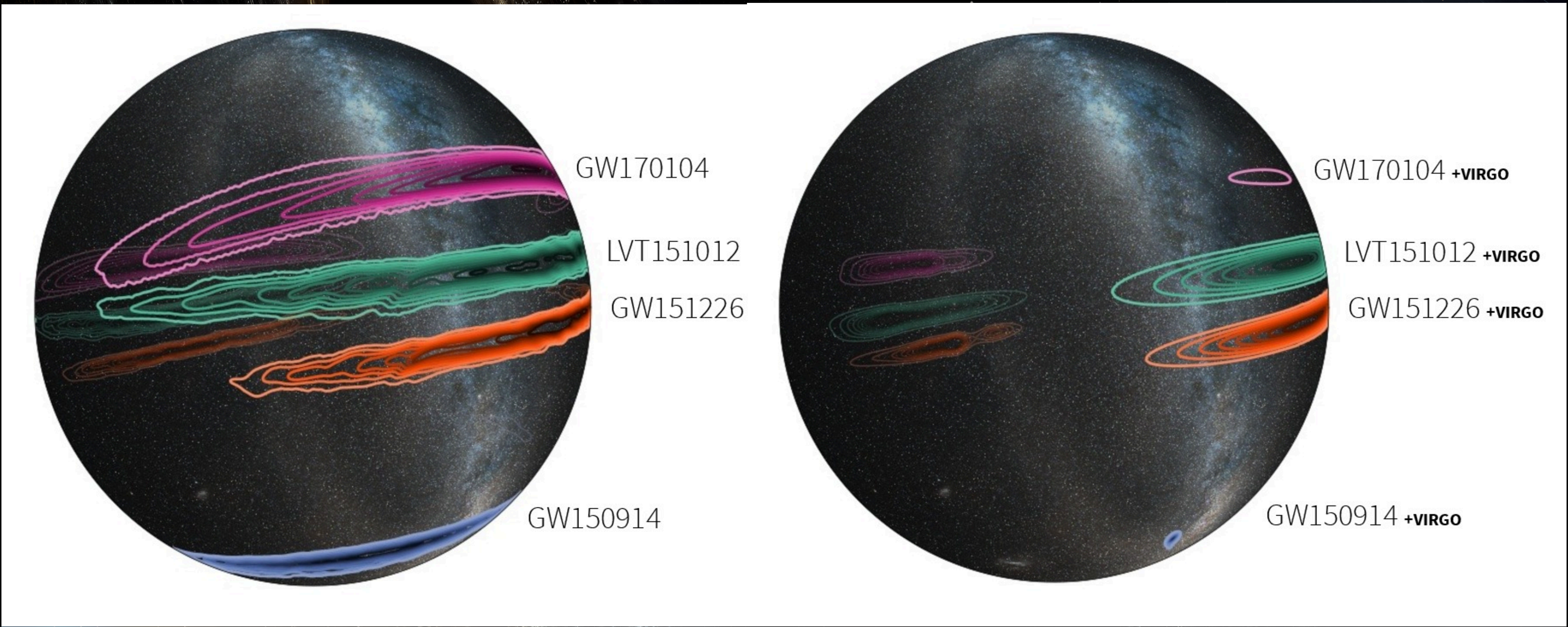
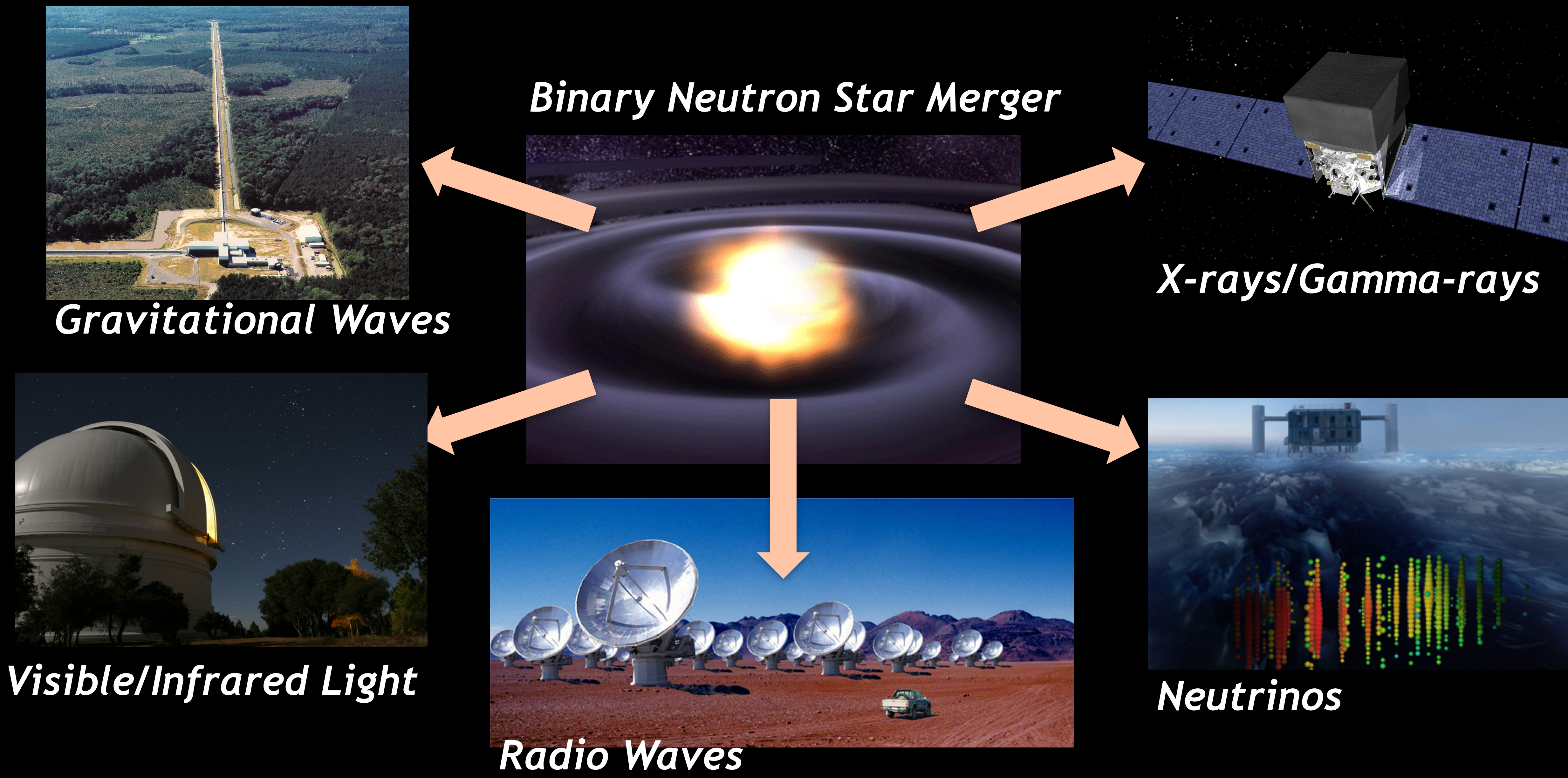


Image Credit: LSC/Singer (Milky Way image: Axel Mellinger)

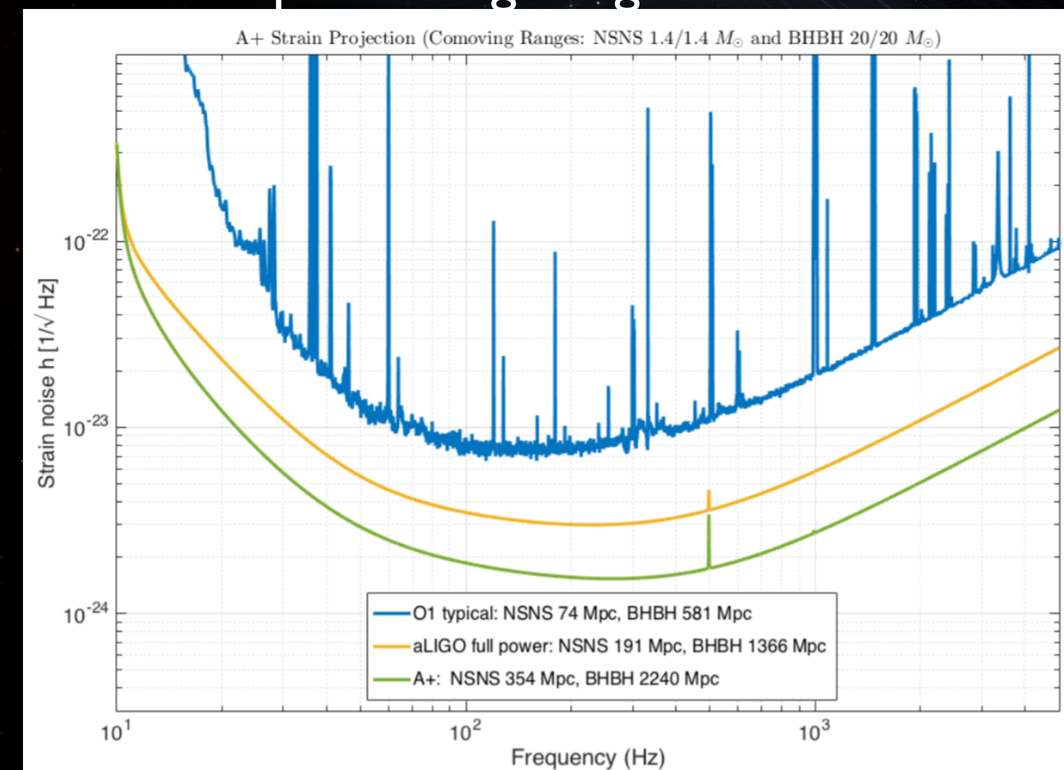
Multi-messenger Astronomy with Gravitational Waves



Near Term Future: The Next Decade

Advanced LIGO Plus (A+)

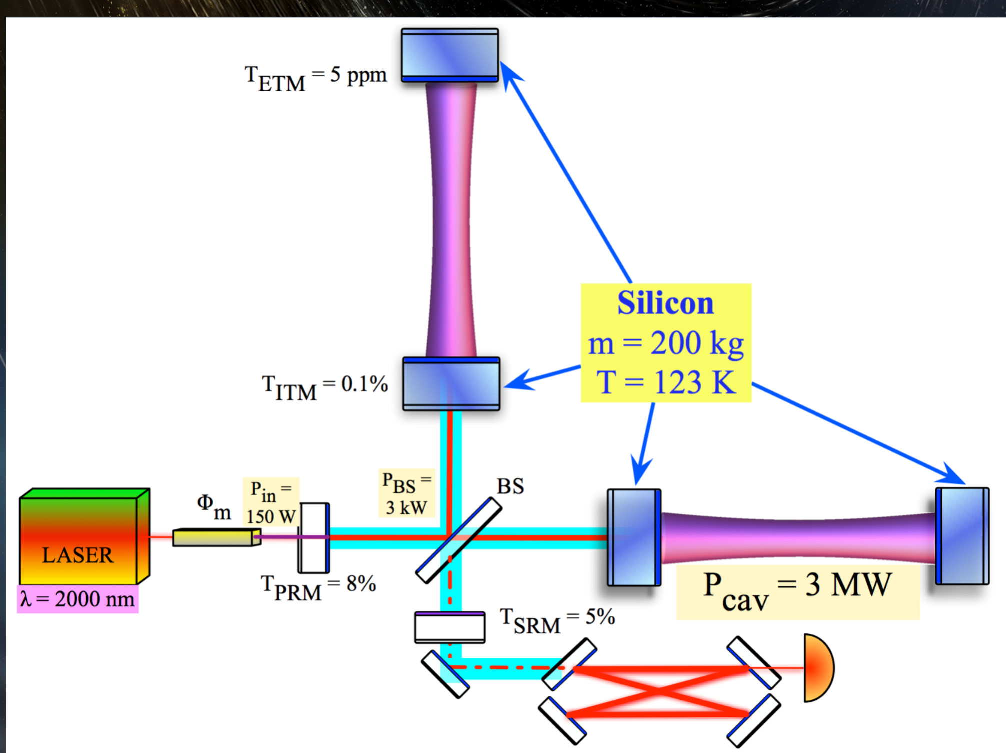
https://dcc.ligo.org/LIGO-G1600769/



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

Existing infrastructure, known technology (frequency-dependent squeezed light, improved coatings)



LIGO Voyager

additional x2 sensitivity broadband improvement, lower frequency 20Hz -> 10Hz

larger Si masses, cryogenic operation, new laser wavelength

Long Term

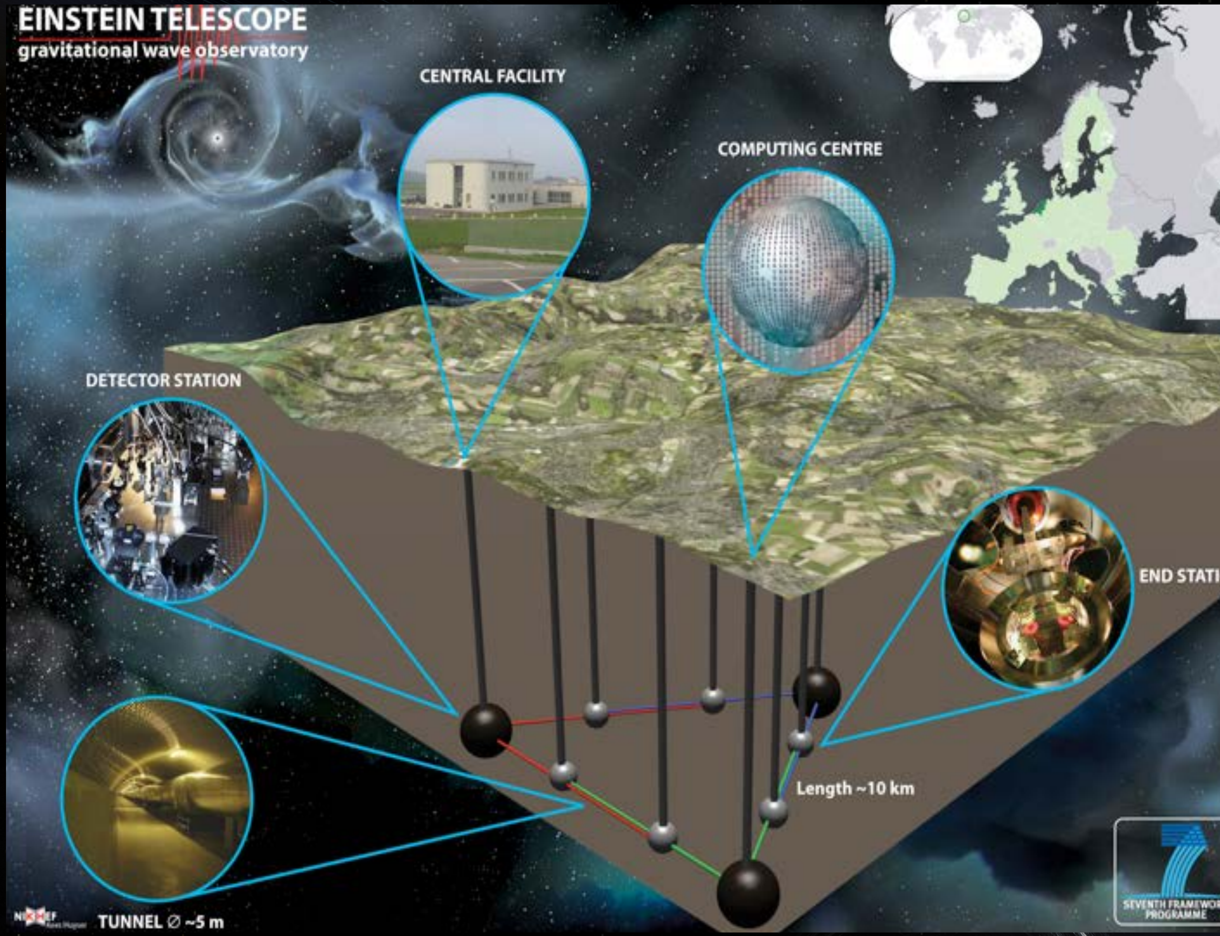
Einstein Telescope:

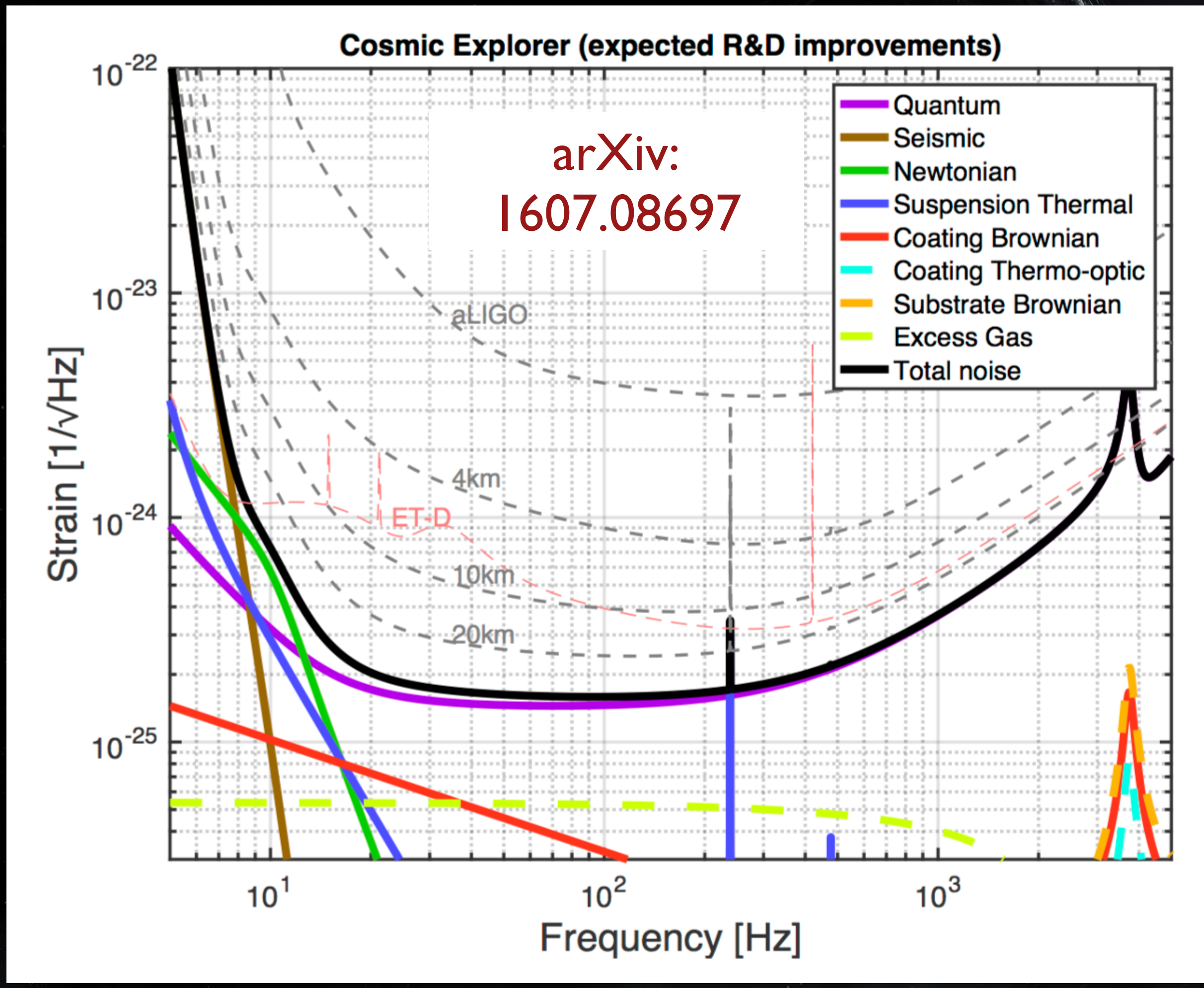
- European conceptual design study
- Multiple interferometers underground, 10 km arm length, in triangle. Assumes 10-15 year technology development.
- ~10^5 binary coalescences per year

Cosmic Explorer:

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

arXiv:1607.08697





Gravitational Wave Periods

Milliseconds	Minutes to Hours	Years to Decades	Billions of Years

LIGO	LISA	PTA	CMB polarization


Thank You