



# ***Black Holes, Neutron Stars and the Birth of Gravitational Wave Astronomy***

**Laura Cadonati, Georgia Tech  
LIGO Scientific Collaboration**

**“Colliding Neutron Stars”  
NSF/LIGO/Sonoma State  
University/A. Simonnet**

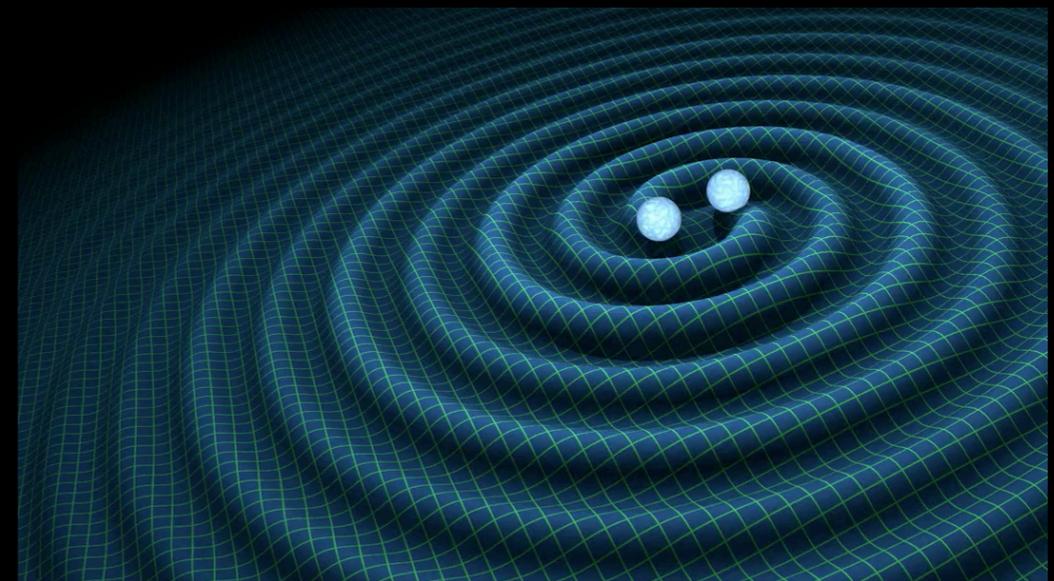
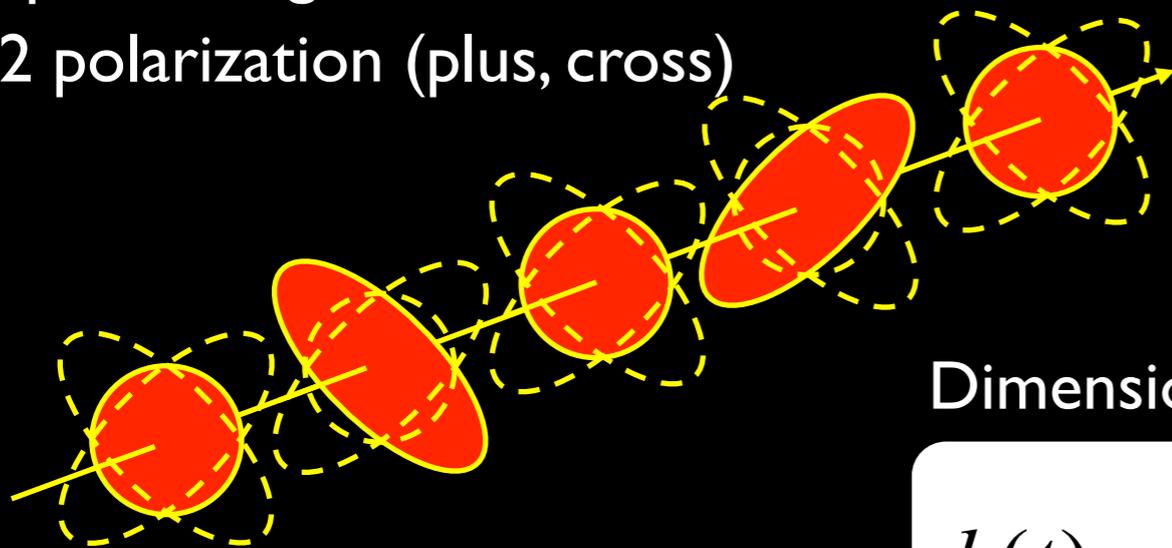
# Gravitational Waves: Einstein's Messengers



- Perturbations of the space-time metric produced by rapid changes in shape and orientation of massive objects.

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

- speed of light
- 2 polarization (plus, cross)



*Credits: R. Hurt - Caltech / JPL*

Dimensionless strain:

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

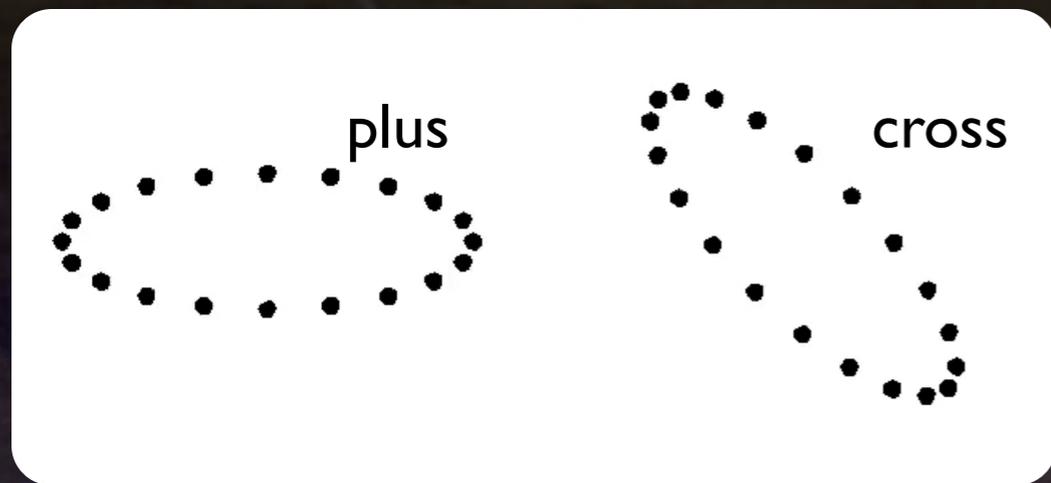
I = source mass quadrupole moment

R = source distance

**Gravitational waves carry information from the coherent, relativistic motion of large masses**

# How to Detect Gravitational Waves

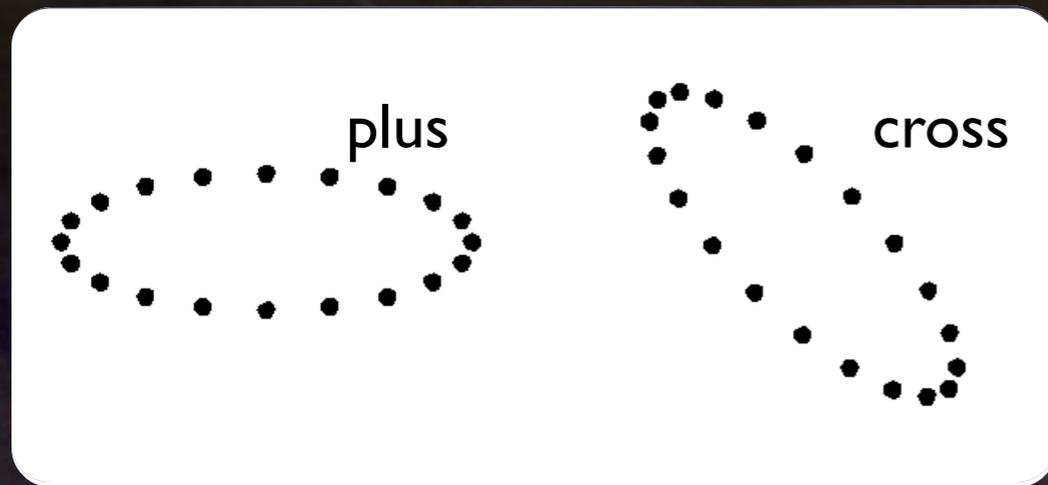
Physically, gravitational waves are strains



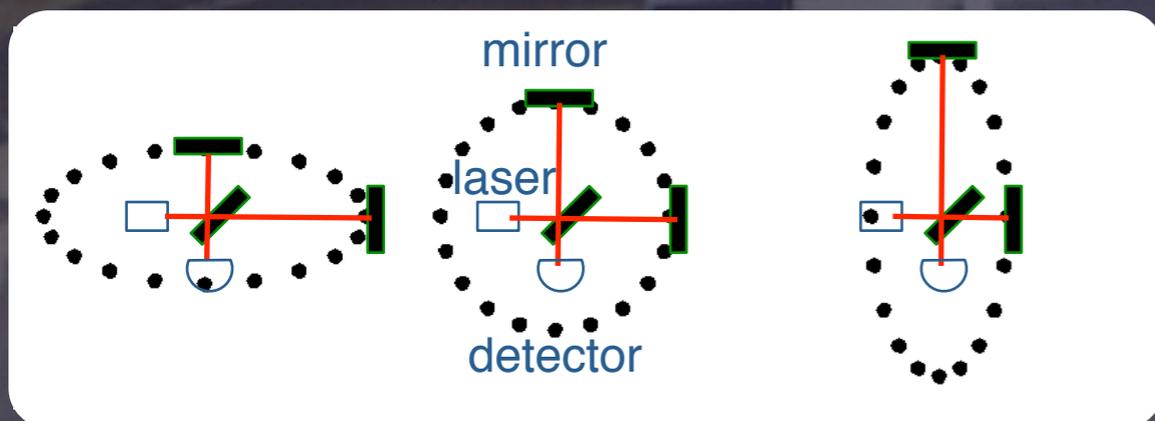
*Deformation of a ring of free-falling particles due to the + and x polarization*

# How to Detect Gravitational Waves

Physically, gravitational waves are strains

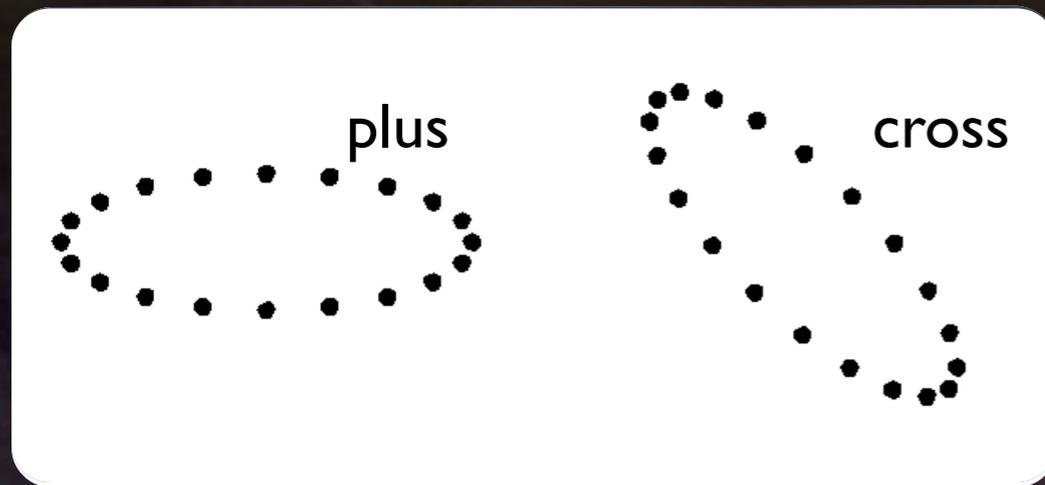


*Deformation of a ring of free-falling particles due to the + and x polarization*

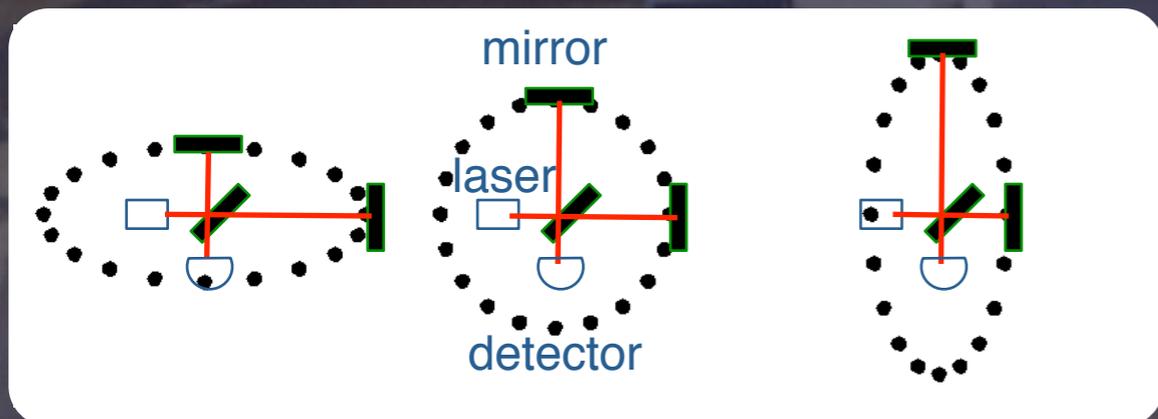


# How to Detect Gravitational Waves

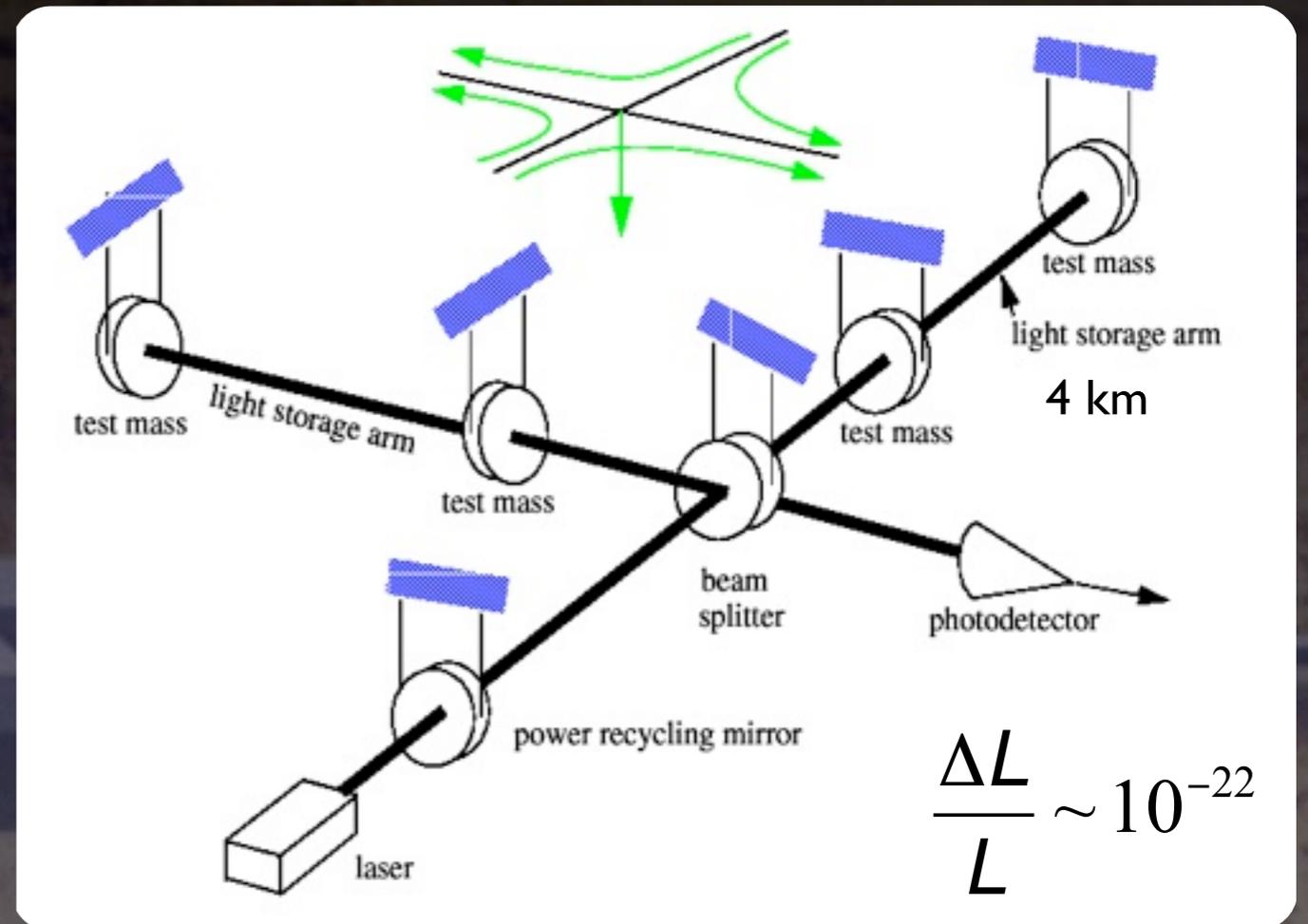
Physically, gravitational waves are strains



*Deformation of a ring of free-falling particles due to the + and x polarization*

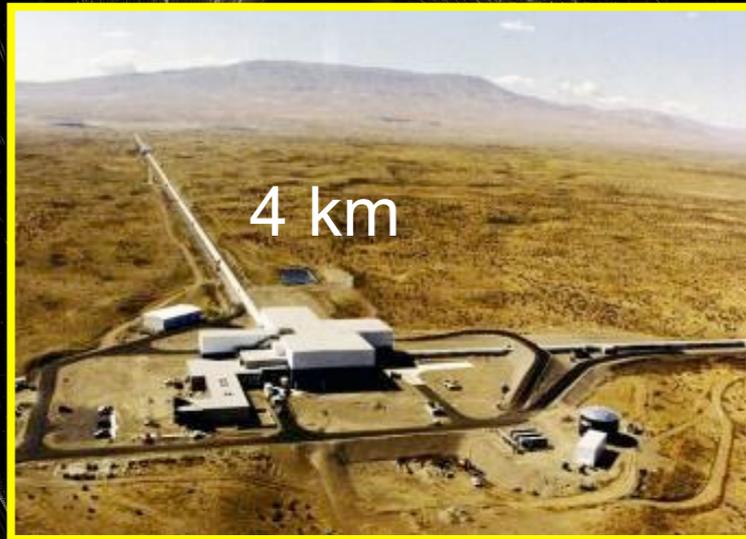


## Suspended Mirrors as Test Masses



Goal: measure difference in length to one part in  $10^{22}$ , or  $10^{-19}$  meters

# LIGO: Laser Interferometer Gravitational-wave Observatory



**Hanford, WA**

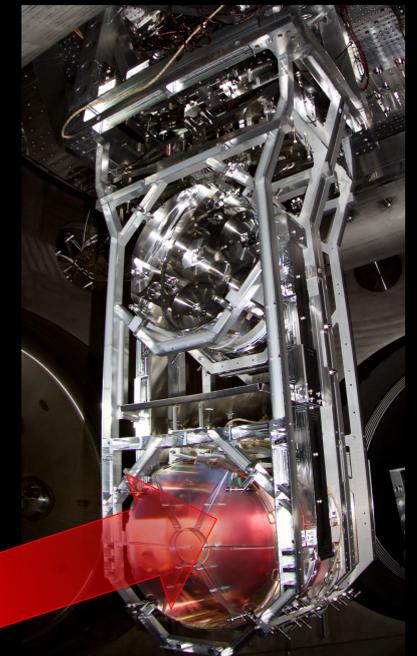
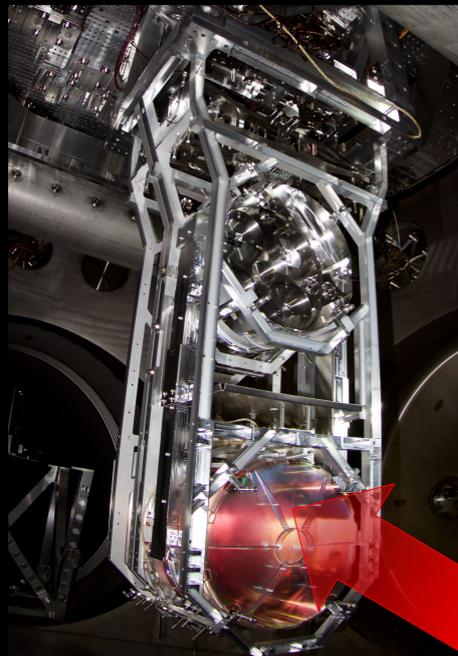


*The LIGO Laboratory is jointly operated by Caltech and MIT through a Cooperative Agreement between Caltech and NSF*

- LIGO Observatories construction: 1994-2000
- Initial LIGO operation: 2002-2010
- Advanced LIGO: 2015-now



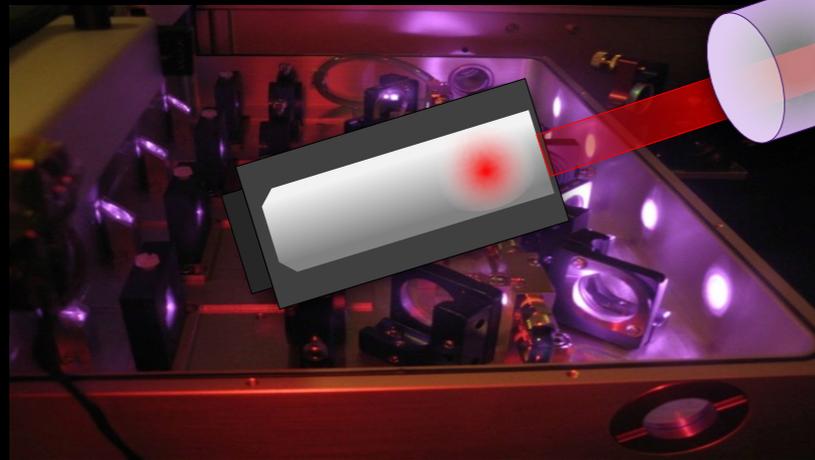
**Livingston, LA**



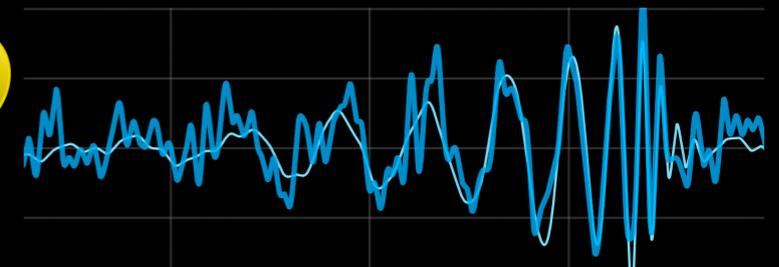
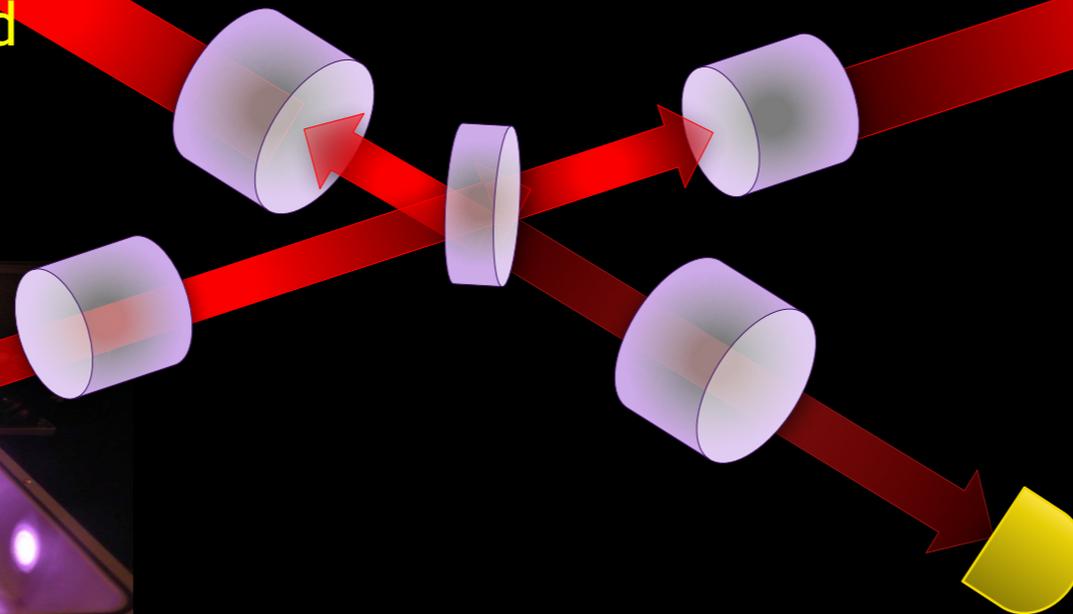
More than 300 control loops needed to keep the interferometer optimally running

40 kg high quality fused silica mirrors, isolated from the ground

Fabry-Perot cavities in the Michelson arms  
~100kW laser power in O1  
(750 kW at full power)



150W laser, 1064nm  
(20-25W during O1)



Output photodetector:  
Interferometer noise +  
gravitational wave signal

# Advanced LIGO

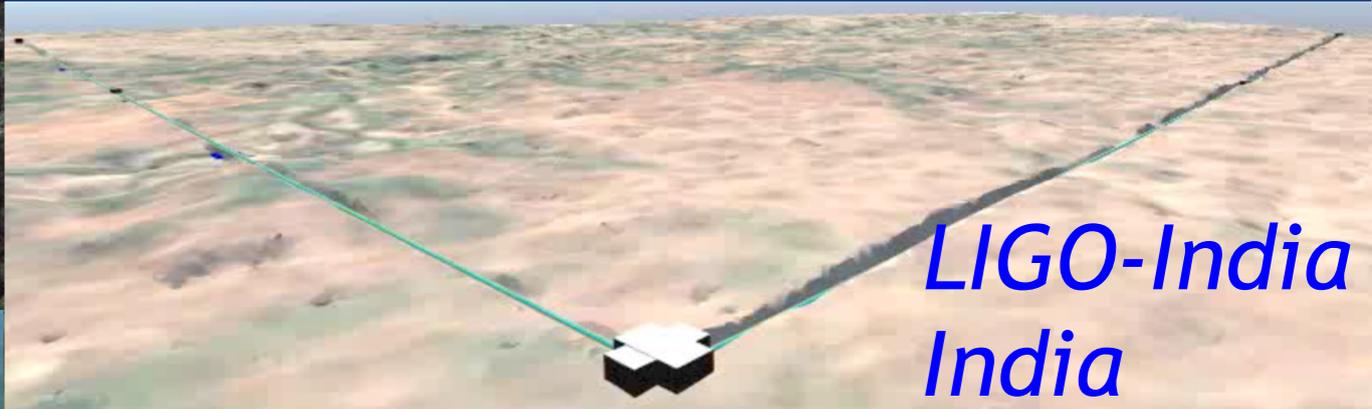
*LIGO  
Livingston  
USA*



*Virgo  
Italy*



*LIGO-India  
India*



*LIGO Hanford  
USA*



*KAGRA  
Japan*



# LIGO

# LIGO Scientific Collaboration



~ 1200 members ~ 100 institutions, 18 countries

Caltech



Andrews University

WASHINGTON STATE UNIVERSITY



CALIFORNIA STATE UNIVERSITY FULLERTON

UTRGV



SOUTHERN UNIVERSITY AND AGRICULTURAL & MECHANICAL COLLEGE



AMERICAN UNIVERSITY WASHINGTON, DC



PennState



TEXAS TECH UNIVERSITY



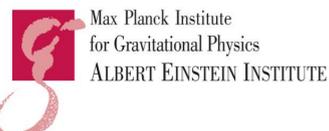
清华大学 Tsinghua University



MONTCLAIR STATE UNIVERSITY



The University of Sheffield



Max Planck Institute for Gravitational Physics ALBERT EINSTEIN INSTITUTE



INTERNATIONAL INSTITUTE OF PHYSICS



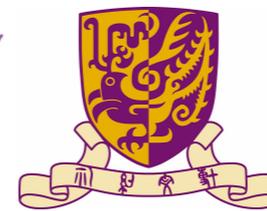
BELLEVUE COLLEGE



Universitat de les Illes Balears



UNIVERSITY OF CAMBRIDGE



UNIVERSITY OF Southampton

Université de Montréal



MONASH University

NCSA



UNIVERSITY of WISCONSIN UWMILWAUKEE



TRINITY UNIVERSITY



Australian National University

UNIVERSITY OF THE WEST OF SCOTLAND UWS



University of Glasgow



THE UNIVERSITY OF ADELAIDE AUSTRALIA

W BOTHELL



COLUMBIA UNIVERSITY IN THE CITY OF NEW YORK



LOMONOSOV MOSCOW STATE UNIVERSITY



THE UNIVERSITY OF CHICAGO

WHITMAN COLLEGE

MONTANA STATE UNIVERSITY

SONOMA STATE UNIVERSITY

UNIVERSITY OF WASHINGTON



LSU LOUISIANA STATE UNIVERSITY



CARDIFF UNIVERSITY PRIFYSGOL CAERDYDD



UNIVERSITY OF BIRMINGHAM

KING'S COLLEGE LONDON



LSU LOUISIANA STATE UNIVERSITY



CHARLES STURT UNIVERSITY



Marshall Space Flight Center



UNIVERSITY OF STRATHCLYDE



東京大学 THE UNIVERSITY OF TOKYO



Georgia Institute of Technology



Korean Gravitational Wave Group



Universität Hamburg DER FORSCHUNG | DER LEHRE | DER BILDUNG



THE UNIVERSITY OF MELBOURNE

MONASH University

Northwestern

UF UNIVERSITY of FLORIDA



Science & Technology Facilities Council Rutherford Appleton Laboratory



EMBRY-RIDDLE AERONAUTICAL UNIVERSITY

1102 1004

Leibniz Universität Hannover

SWINBURNE SWINBURNE UNIVERSITY OF TECHNOLOGY

CITA I CAT Canadian Institute for Theoretical Astrophysics Institut Canadien d'astrophysique théorique



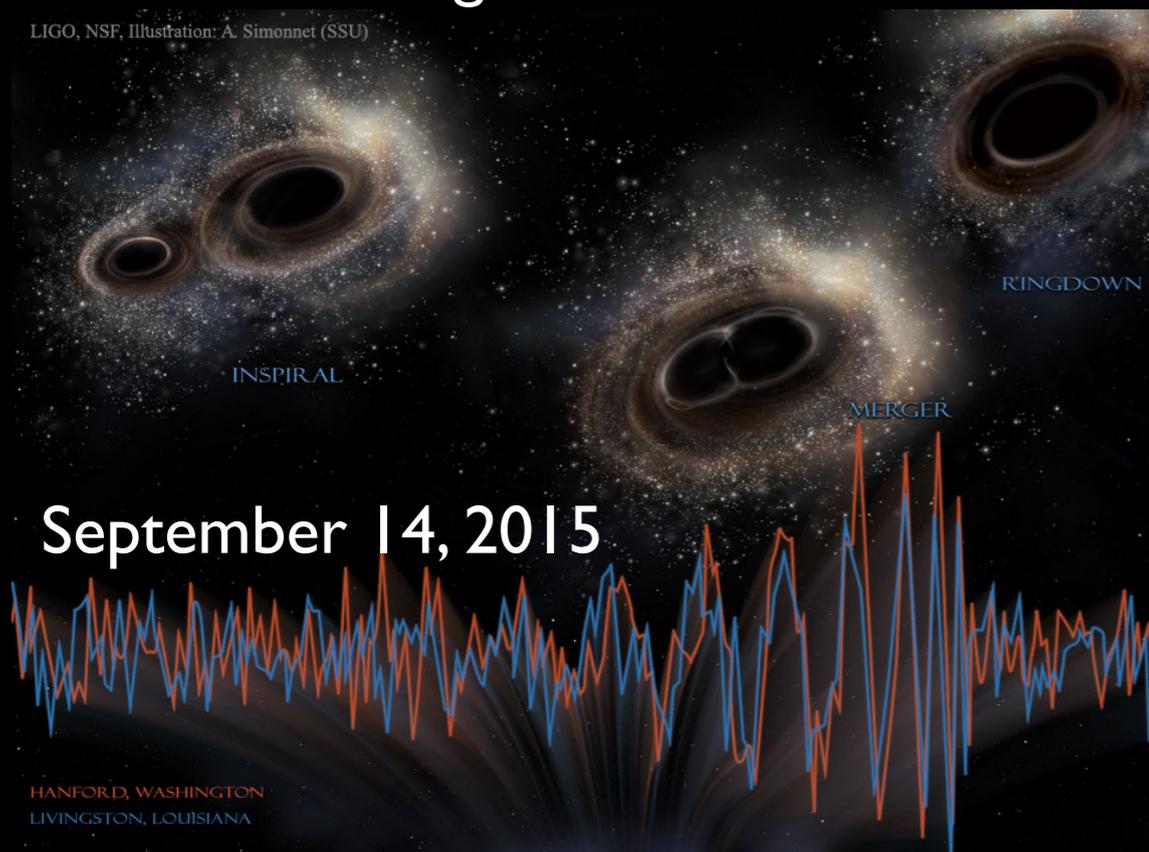
THE UNIVERSITY of MISSISSIPPI



Goddard SPACE FLIGHT CENTER

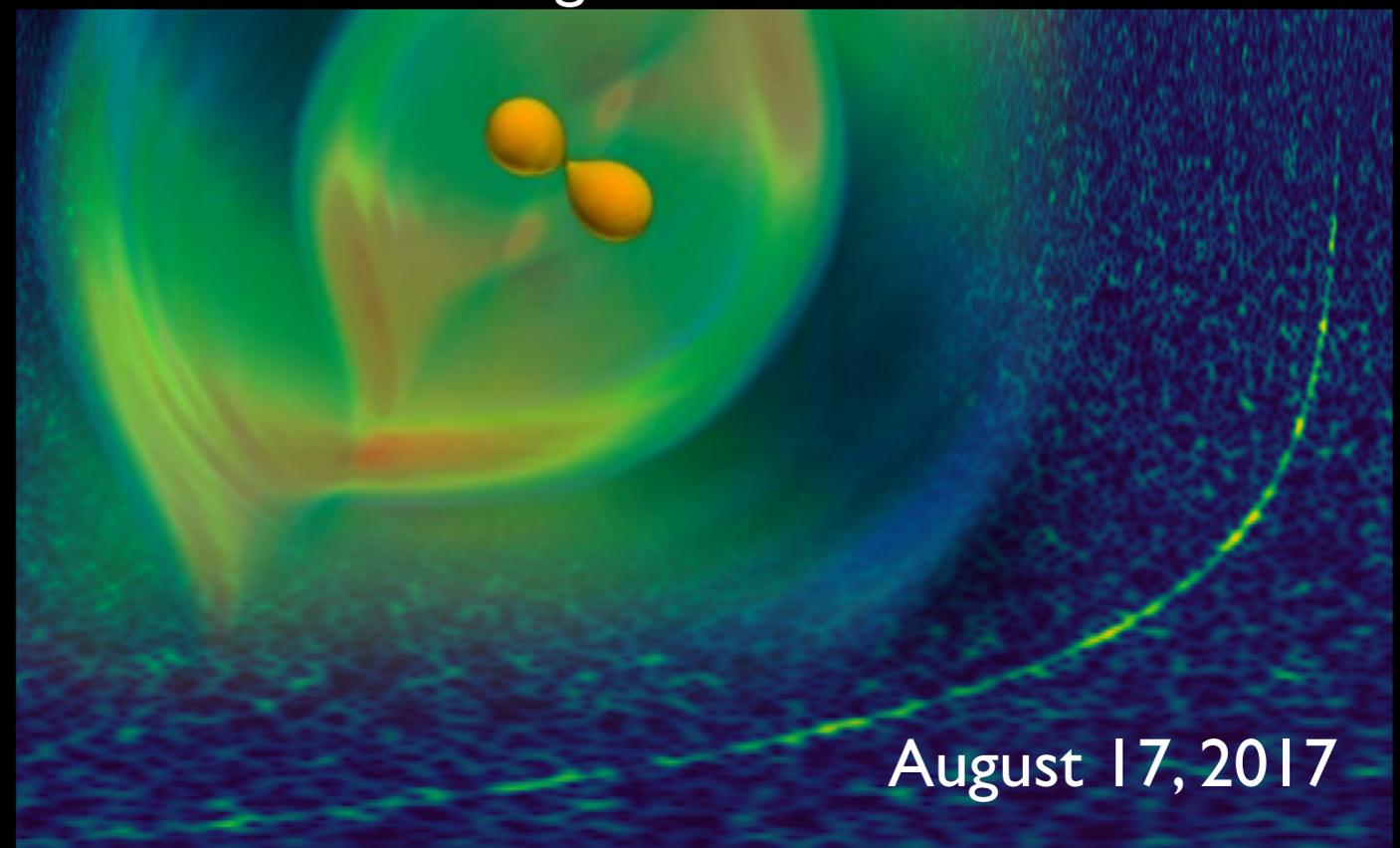
# GW150914 and GW170817: Two ground-breaking discoveries that opened a new era in Gravitational Wave Astrophysics

1.3 Billion Years Ago....



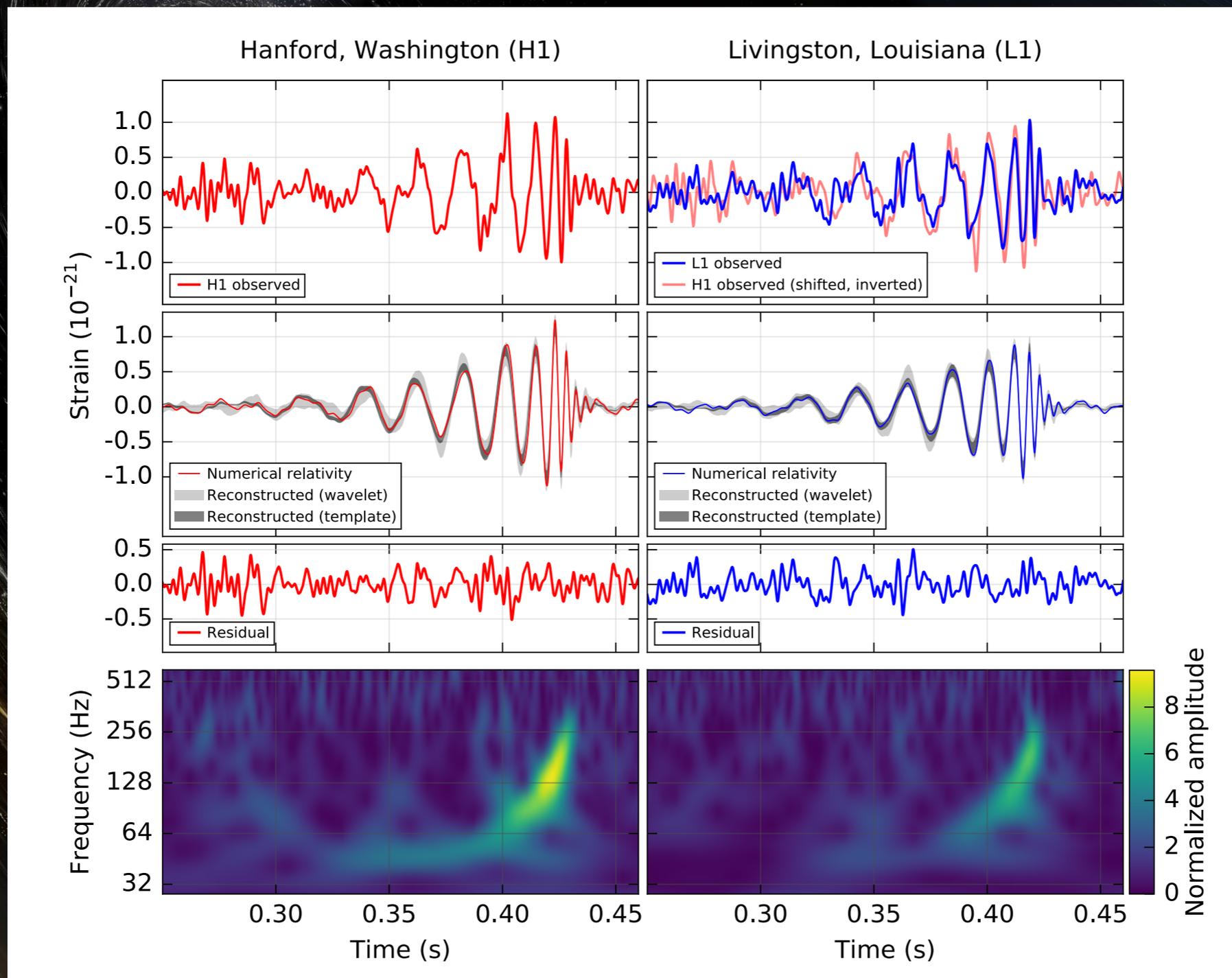
Binary Black Hole Coalescence

135 Million Years Ago....



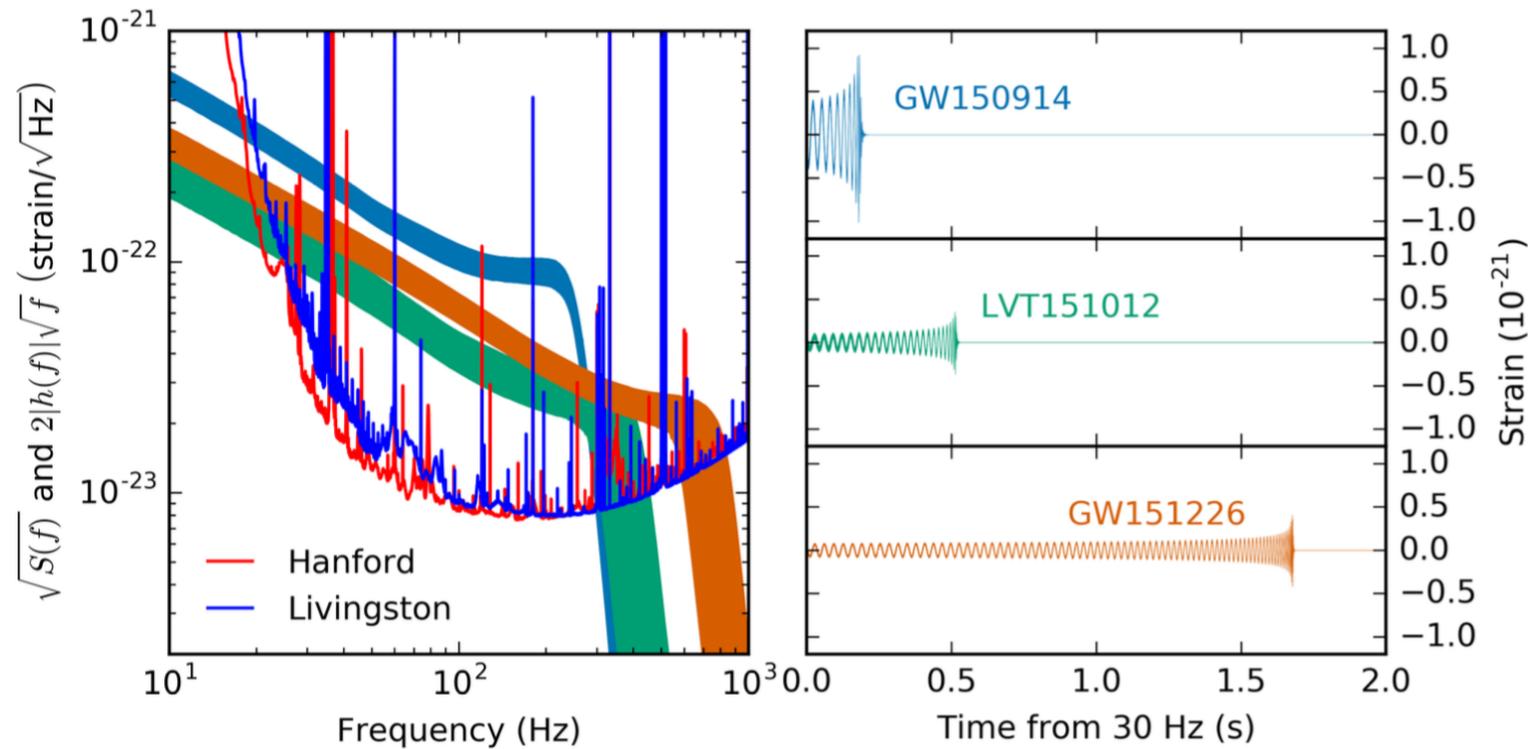
Binary Neutron Star Coalescence

# First Discovery: GW150914

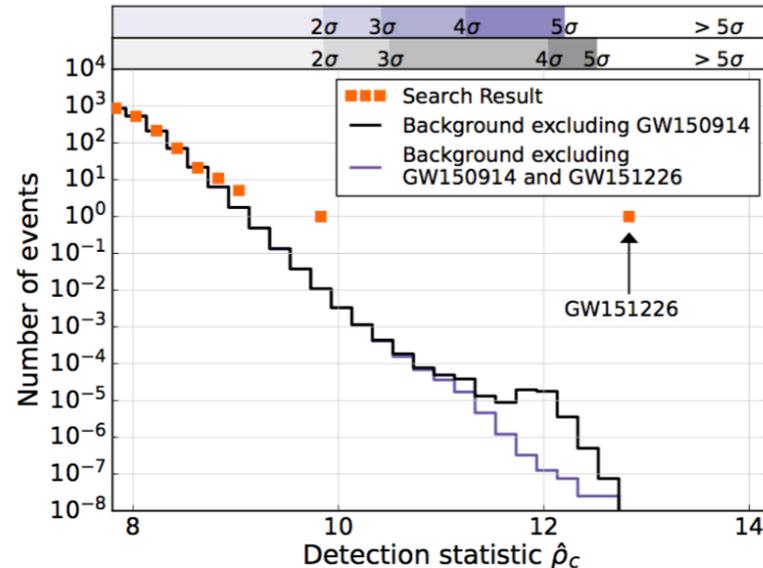
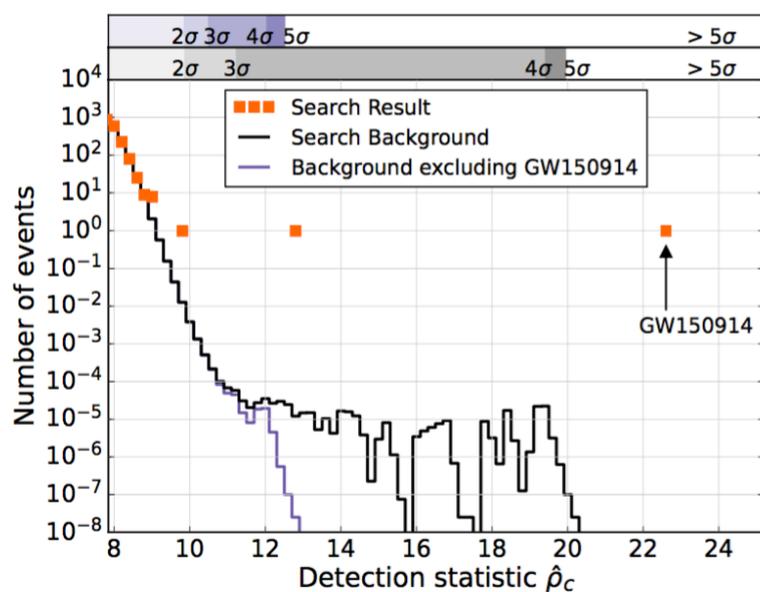


*Observation of Gravitational Waves from a Binary Black Hole Merger*  
Phys. Rev. Lett., 116:061102, 2016

# Binary Black Hole Signals in LIGO's First Science Run

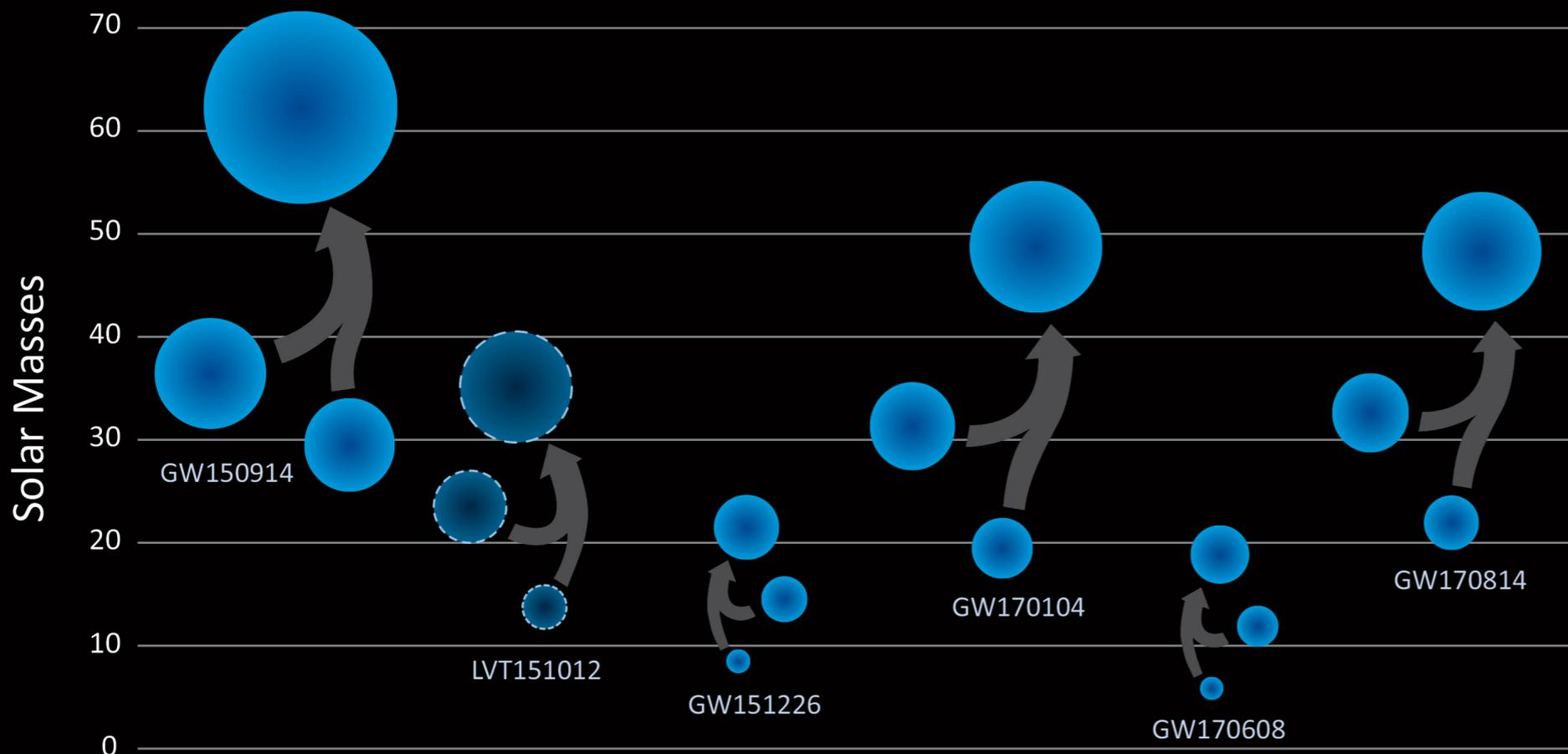


*Binary Black Hole Mergers in the first Advanced LIGO Observing Run*  
Phys. Rev. X, 6: 041015, 2016



approximately 250,000 templates  
False Alarm Rate < 1 in 203000 yr

# “Solar Mass” Black Holes



Most robust evidence for existence of ‘heavy’ stellar mass BHs ( $> 20 M_{\odot}$ )

BBH most likely formed in a low-metallicity environment:  $< \frac{1}{2} Z_{\odot}$

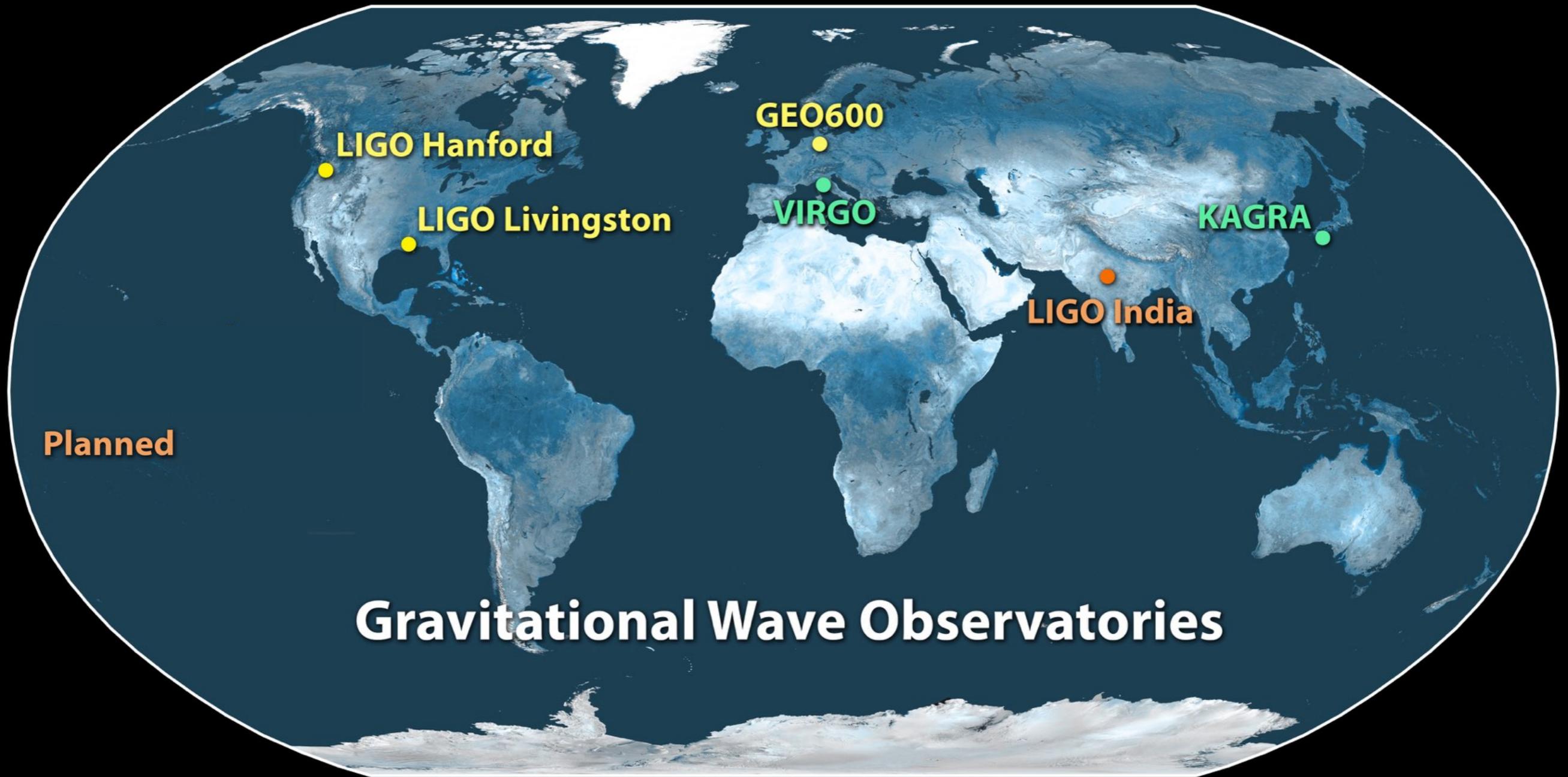
Merger rate of stellar mass BBHs:  
 $12 - 213/\text{Gpc}^3/\text{yr}$

Credits: LIGO/Caltech/Sonoma State (Simonnet)

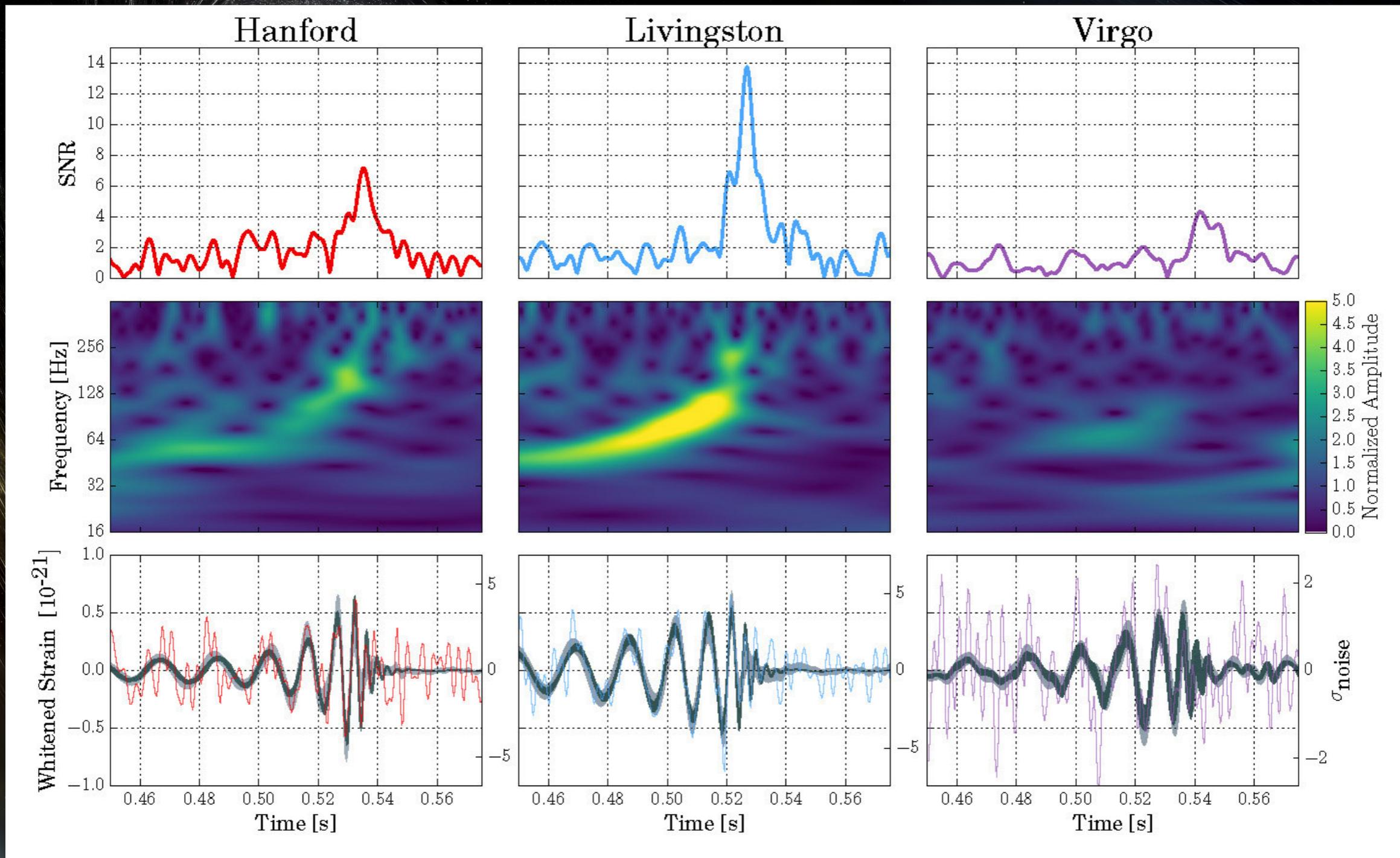
LIGO/VIRGO

BH spin distributions beginning to inform formation models:  
isolated binary evolution vs dynamical formation in dense clusters

# A Global Quest



# Three detectors: GW170814



*A Three-Detector Observation of Gravitational Waves from a Binary Black Hole Coalescence*  
Phys. Rev. Lett., 119:141101, 2017

# GW170814

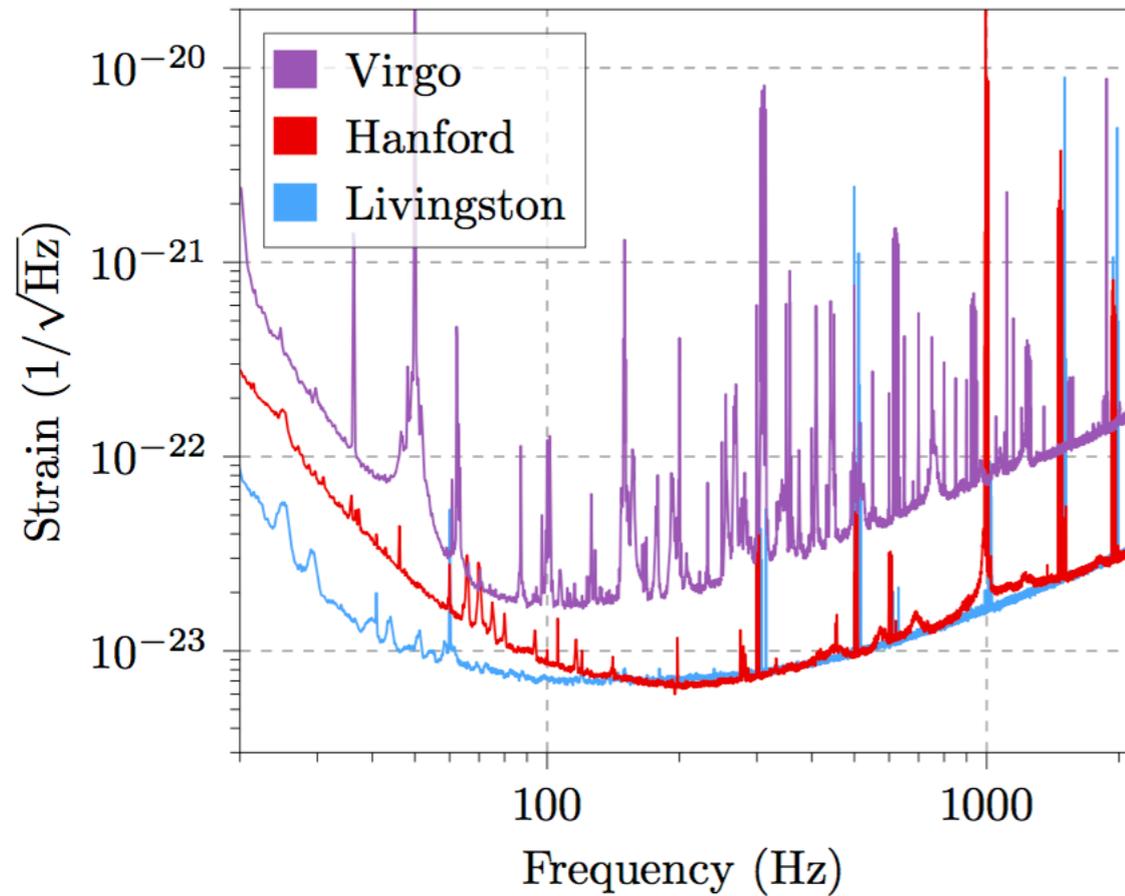


FIG. 2: Amplitude spectral density of strain sensitivity of the Advanced LIGO – Advanced Virgo network, estimated using 4096 s of data around the time of GW170814. Here, several known linearly coupled noise sources have been removed from the data.

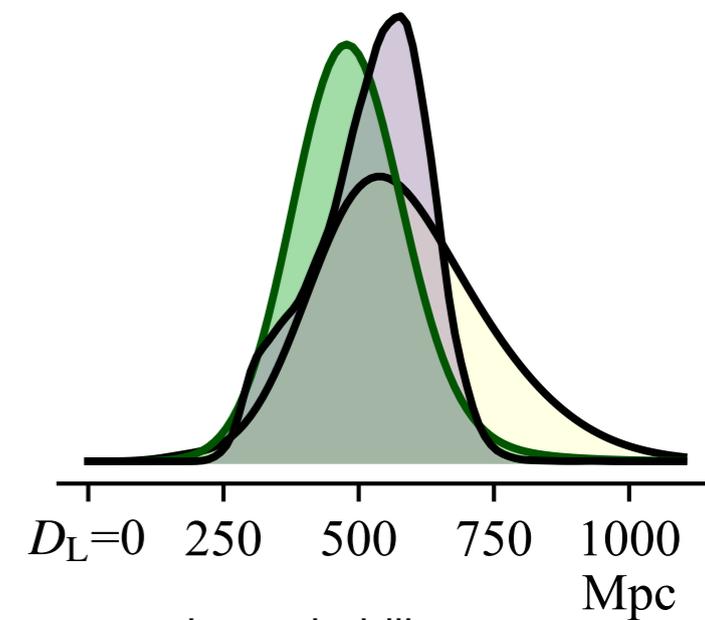
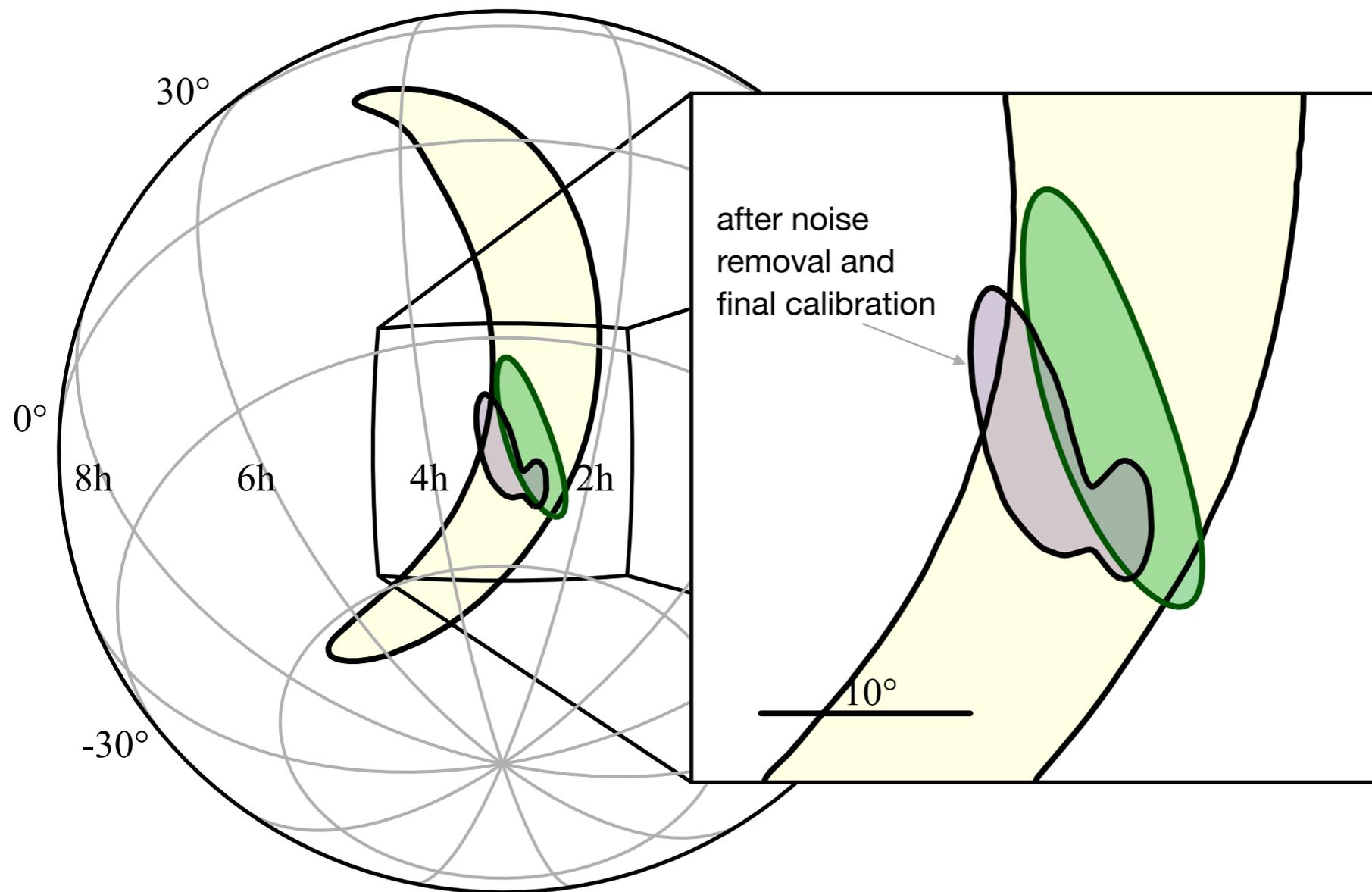
TABLE I: Source parameters for GW170814: median values with 90% credible intervals. We quote source-frame masses; to convert to the detector frame, multiply by  $(1+z)$  [127, 128]. The redshift assumes a flat cosmology with Hubble parameter  $H_0 = 67.9 \text{ km s}^{-1} \text{ Mpc}^{-1}$  and matter density parameter  $\Omega_m = 0.3065$  [129].

Primary black hole mass $m_1$	$30.5^{+5.7}_{-3.0} M_\odot$
Secondary black hole mass $m_2$	$25.3^{+2.8}_{-4.2} M_\odot$
Chirp mass $\mathcal{M}$	$24.1^{+1.4}_{-1.1} M_\odot$
Total mass $M$	$55.9^{+3.4}_{-2.7} M_\odot$
Final black hole mass $M_f$	$53.2^{+3.2}_{-2.5} M_\odot$
Radiated energy $E_{\text{rad}}$	$2.7^{+0.4}_{-0.3} M_\odot c^2$
Peak luminosity $\ell_{\text{peak}}$	$3.7^{+0.5}_{-0.5} \times 10^{56} \text{ erg s}^{-1}$
Effective inspiral spin parameter $\chi_{\text{eff}}$	$0.06^{+0.12}_{-0.12}$
Final black hole spin $a_f$	$0.70^{+0.07}_{-0.05}$
Luminosity distance $D_L$	$540^{+130}_{-210} \text{ Mpc}$
Source redshift $z$	$0.11^{+0.03}_{-0.04}$

# Sky Localization

The inclusion of Virgo improves the sky localization from  $1160 \text{ deg}^2$  to  $60 \text{ deg}^2$

Plausible volume ( $\Rightarrow$  number of possible host galaxies) decreases from  $71$  to  $2.1 \times 10^6 \text{ Mpc}^3$



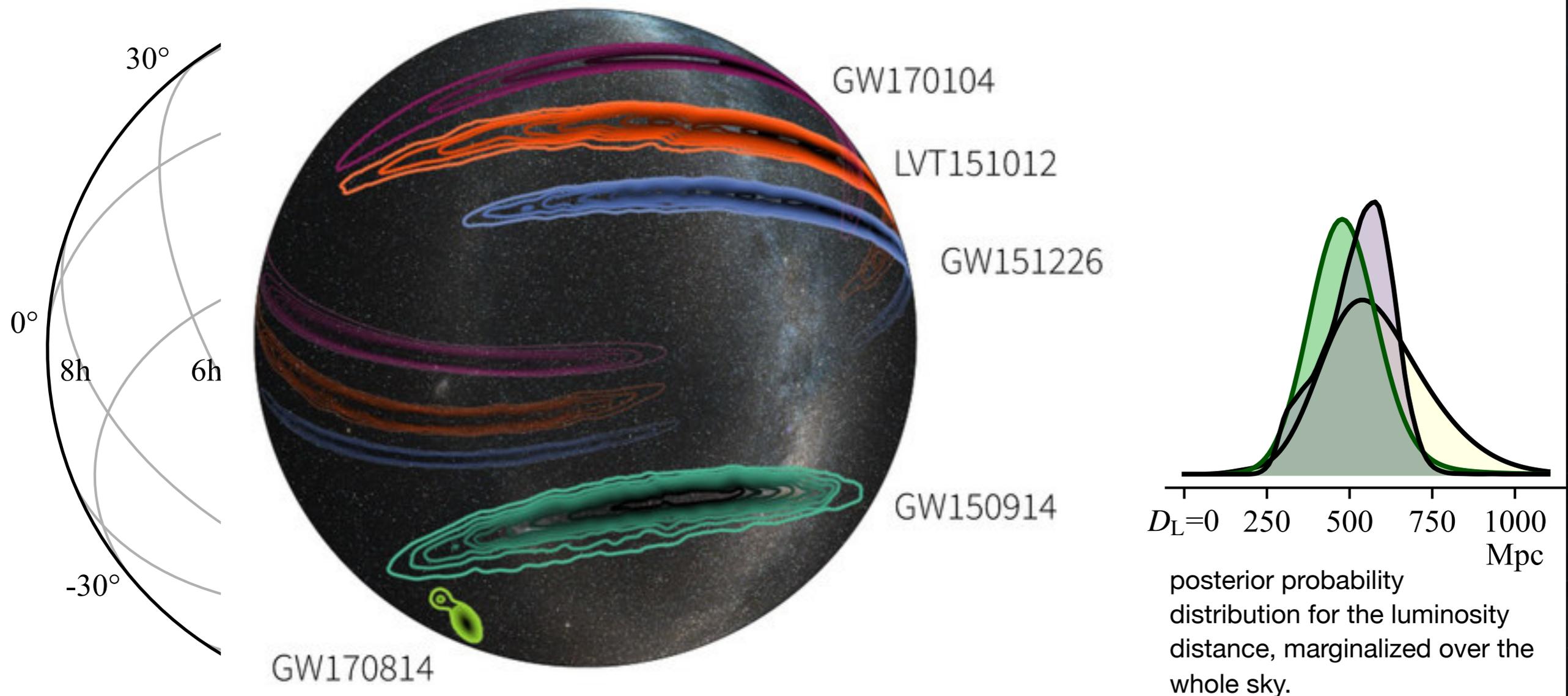
posterior probability distribution for the luminosity distance, marginalized over the whole sky.

*A Three-Detector Observation of Gravitational Waves from a Binary Black Hole Coalescence*  
Phys. Rev. Lett., 119:141101, 2017

# Sky Localization

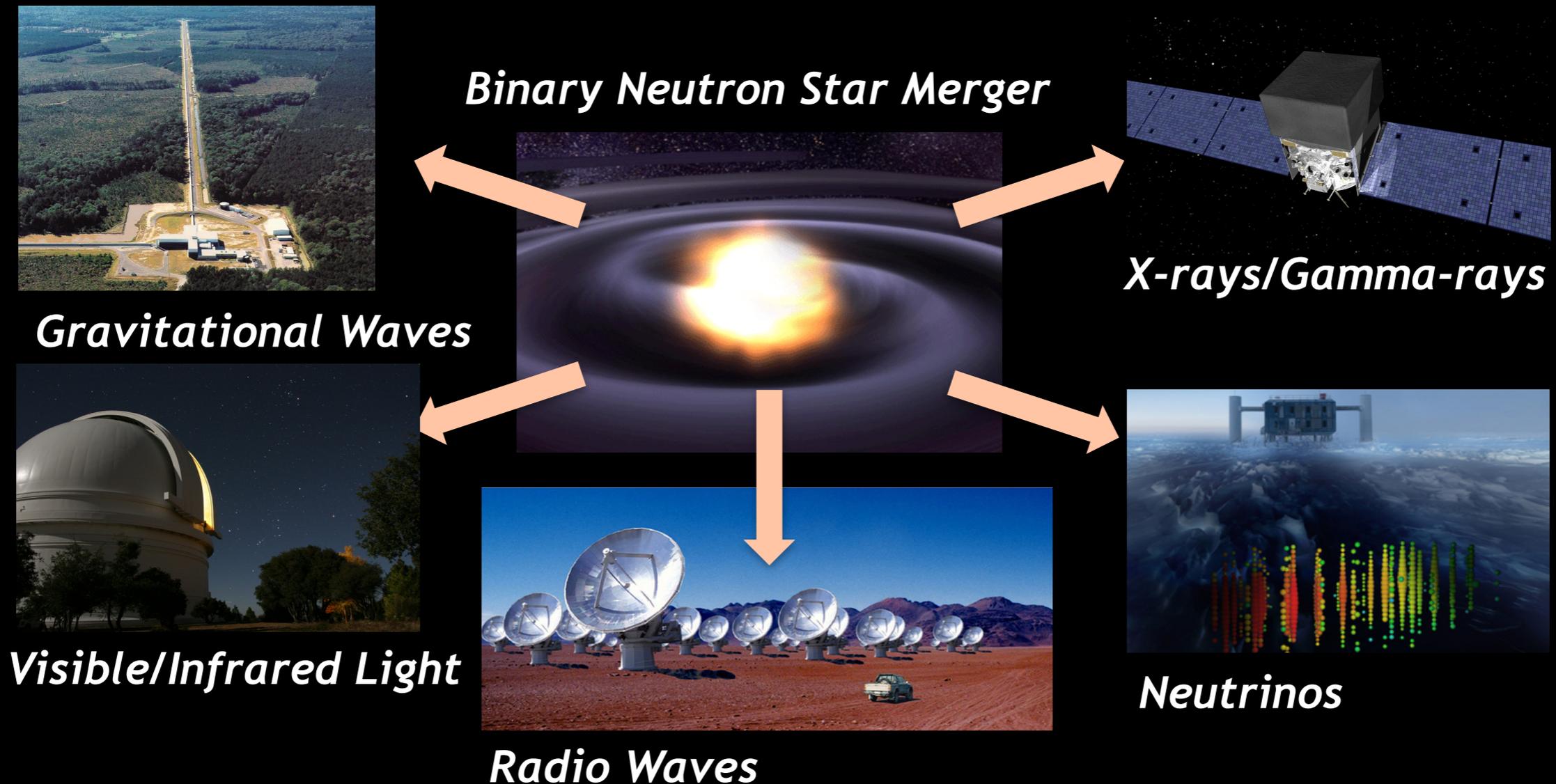
The inclusion of Virgo improves the sky localization from  $1160 \text{ deg}^2$  to  $60 \text{ deg}^2$

Plausible volume ( $\Rightarrow$  number of possible host galaxies) decreases from 71 to  $2.1 \times 10^6 \text{ Mpc}^3$



*A Three-Detector Observation of Gravitational Waves from a Binary Black Hole Coalescence*  
Phys. Rev. Lett., 119:141101, 2017

# Multi-messenger Astronomy with Gravitational Waves

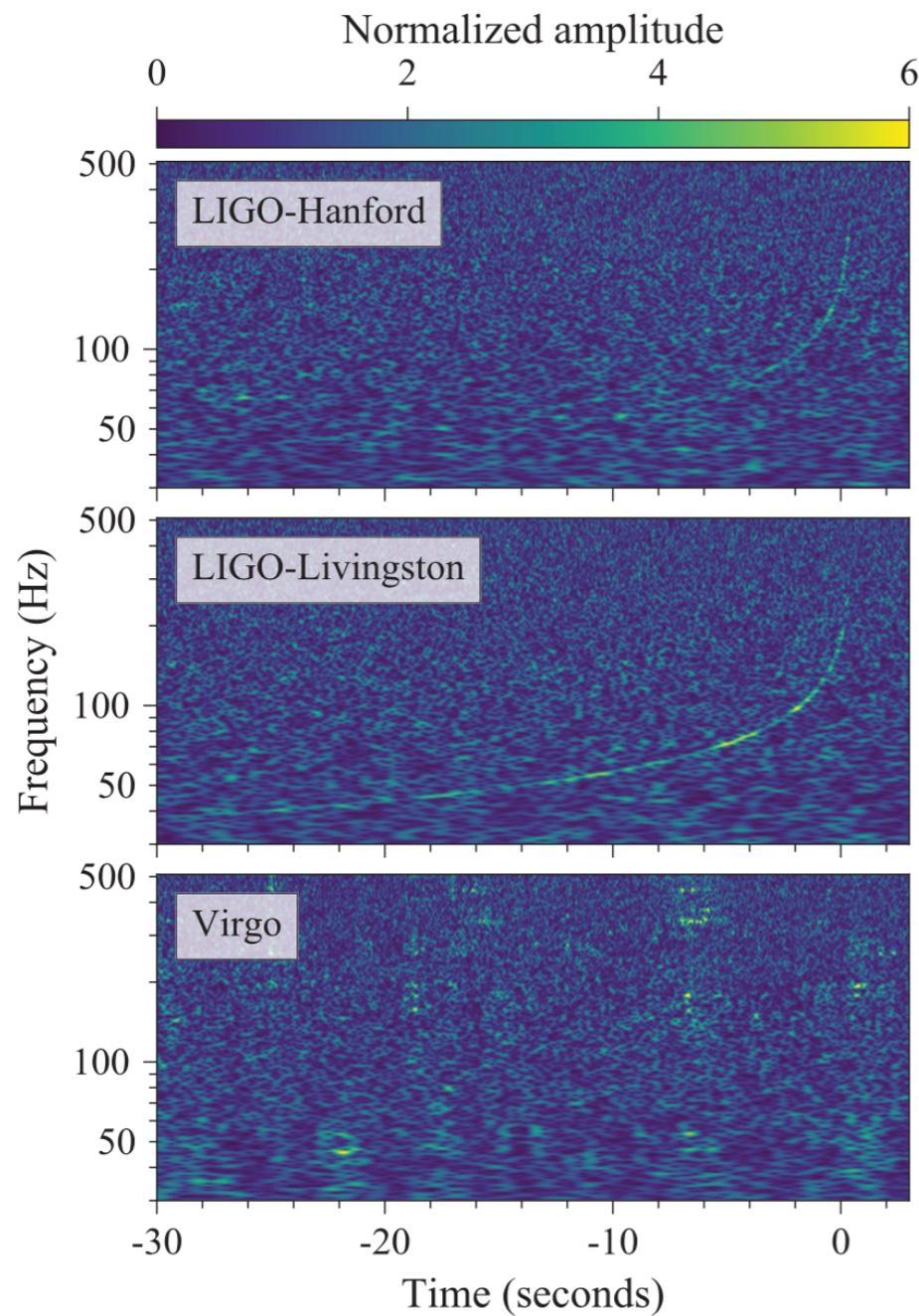


**LIGO and Virgo signed agreements with 95 groups for EM/neutrino followup of GW events**

- ~200 EM instruments - satellites and ground based telescopes covering the full spectrum from radio to very high-energy gamma-rays
- Worldwide astronomical institutions, agencies and large/small teams of astronomers

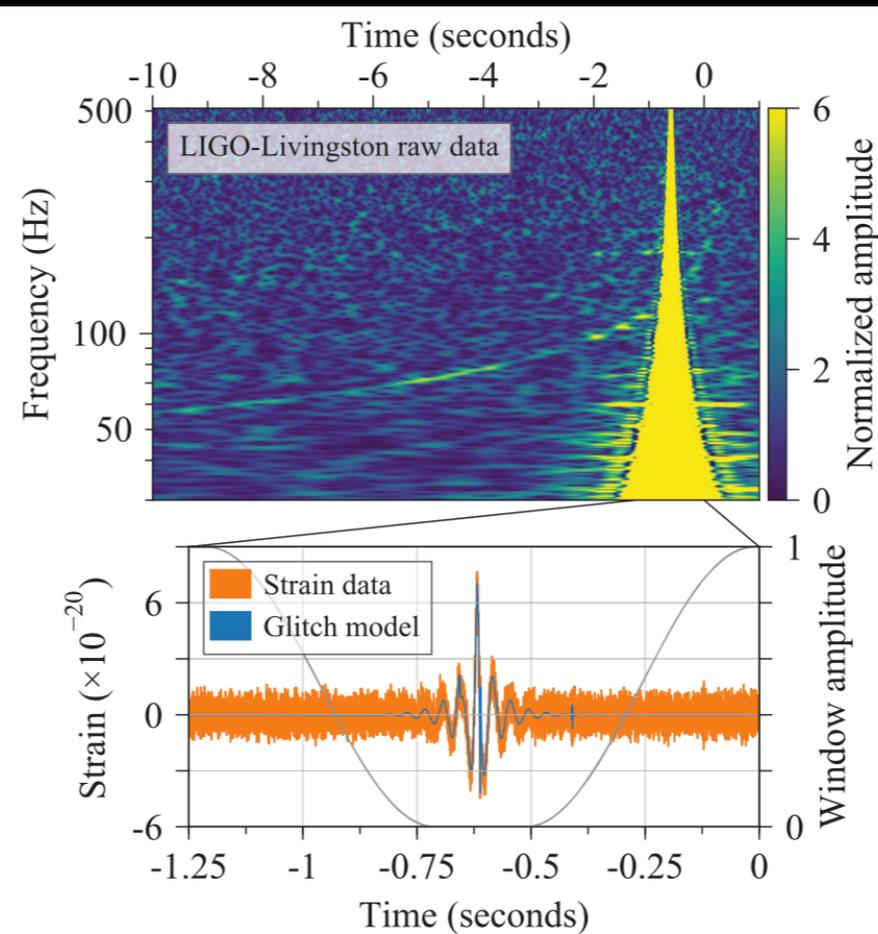
# Discovery of a Binary Neutron Star

August 17, 2017 - 12:41:04.4 UTC



GW170817 swept through the detectors' sensitive band in  $\sim 100$ s ( $f_{\text{start}} = 24$ Hz)

Loudest (network SNR of 32.4), closest and best localized signal ever observed by LIGO/Virgo



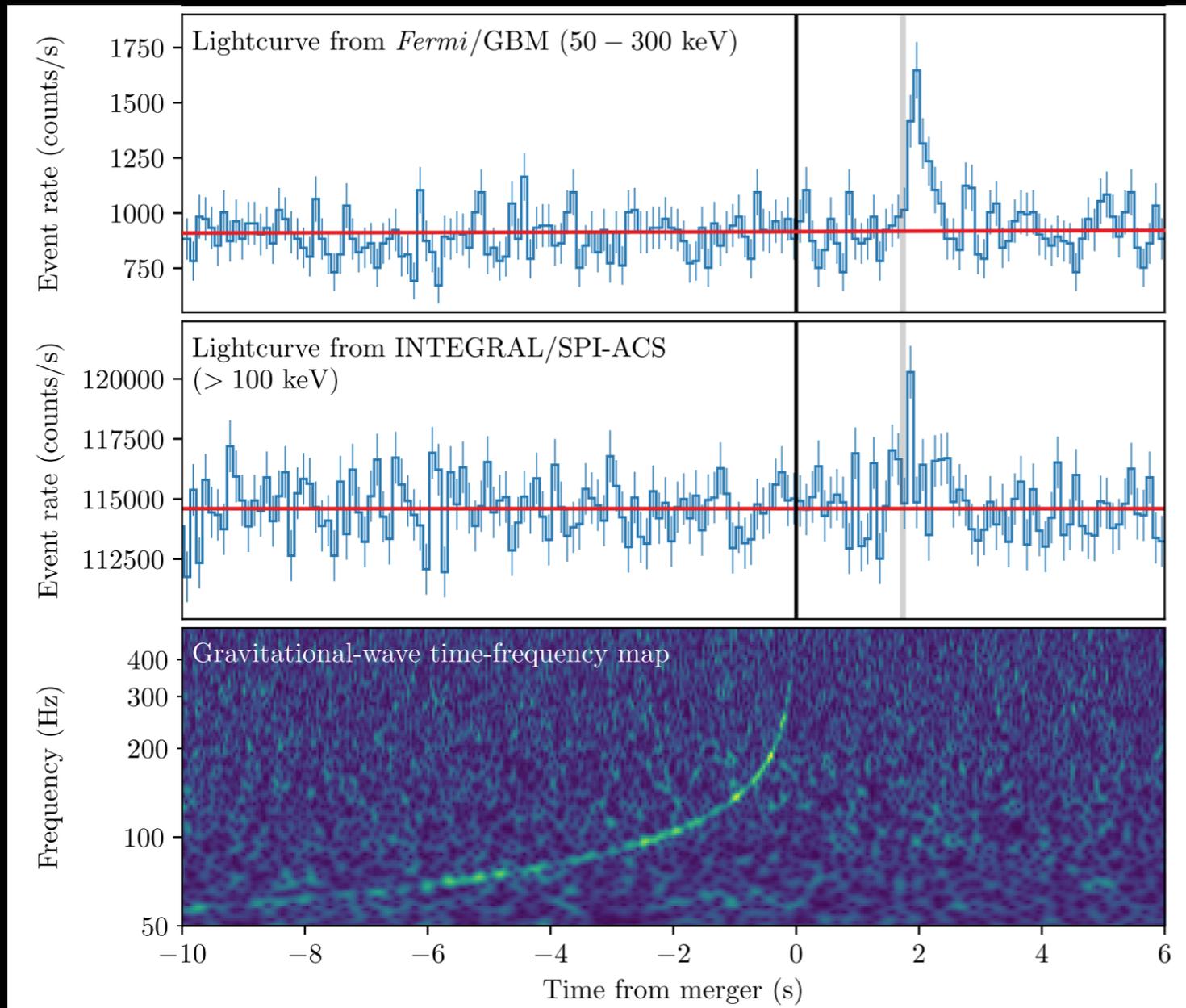
Glitch in L1 1.1 seconds before the coalescence

Similar noise transients are registered roughly once every few hours in each of the LIGO detectors - no temporal correlation between the LIGO sites

glitch cleaning

*GW170817: Observation of Gravitational Waves from a Binary Neutron Star Inspiral*  
Phys. Rev. Lett., 119:161101, 2017

# A Coincident Gamma Ray Burst: GRB-170817A



GRB 170817A occurs ( $1.74 \pm 0.05$ ) seconds after GW170817

It was autonomously detected in-orbit by **Fermi-GBM** (GCN was issued 14s after GRB) and in the routine untargeted search for short transients by **INTEGRAL SPI-ACS**

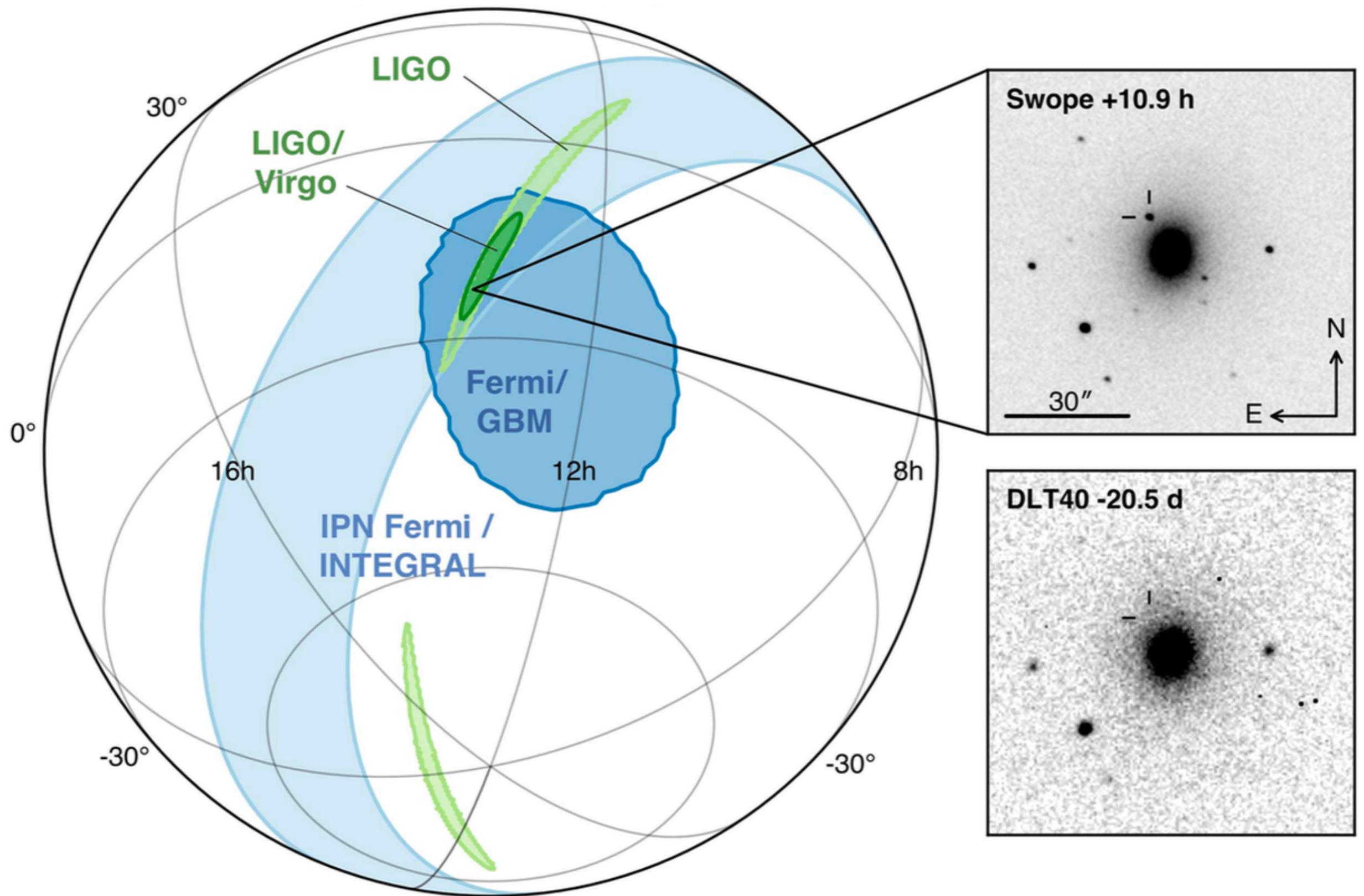
GRB 170817A is **3 times** more likely to be a short GRB than a long GRB

Probability that GW170817 and GRB 170817A occurred this close in time and with location agreement by chance is  $5.0 \times 10^{-8}$  (Gaussian equivalent significance of  $5.3\sigma$ )

*Gravitational Waves and Gamma Rays from a Binary Neutron Star Merger: GW170817 and GRB 170817A*

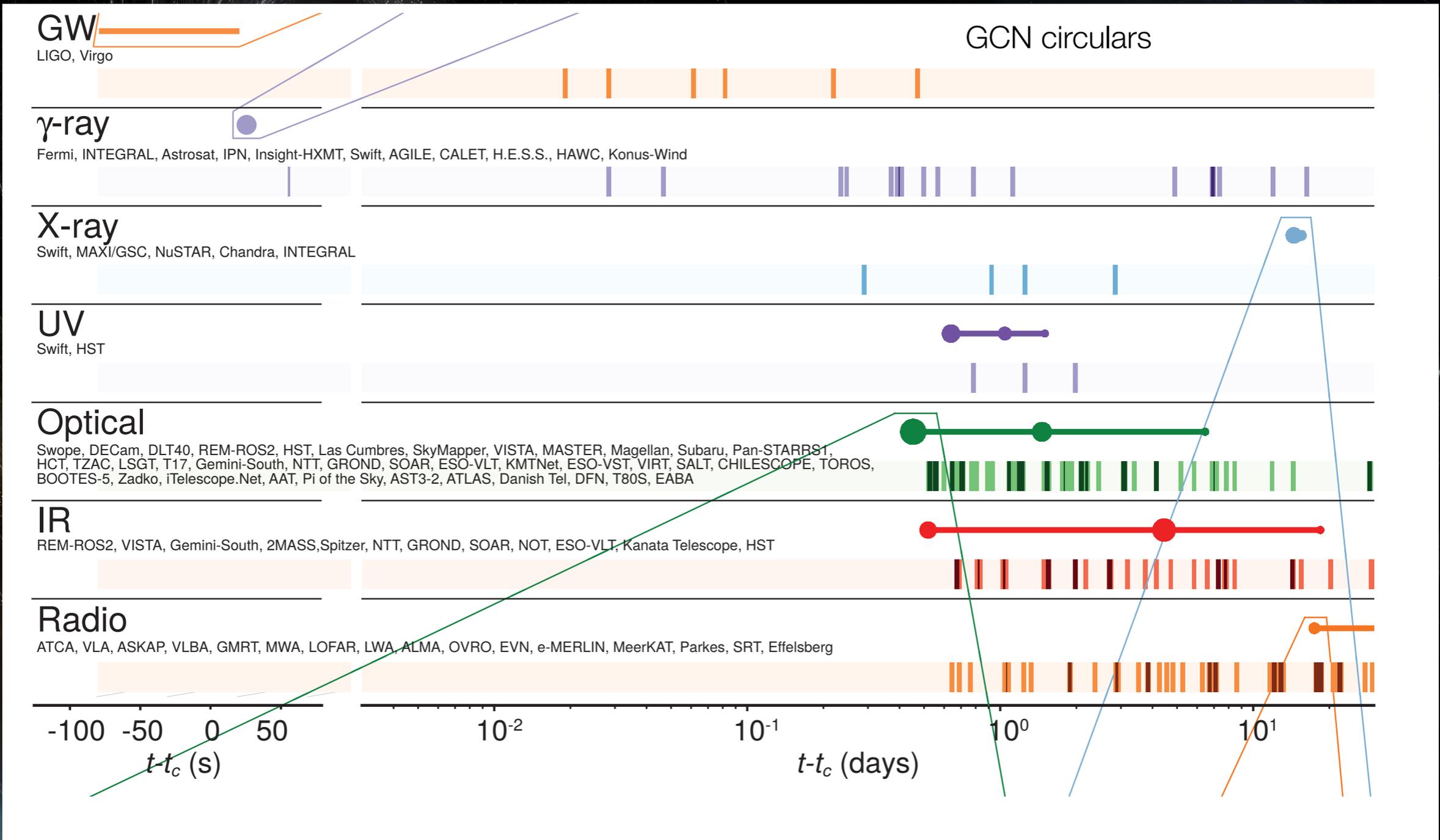
The Astrophysical Journal Letters, 848:L13, 2017

**BNS mergers are progenitors of (at least some) SGRBs, and GWs travel at speed of light**



*Multi-messenger Observations of a Binary Neutron Star Merger*  
 The Astrophysical Journal Letters, 848:L12, 2017

# EM Followup Campaign



*Multi-messenger Observations of a Binary Neutron Star Merger*  
The Astrophysical Journal Letters, 848:L12, 2017

# Kilonova

SSS17a

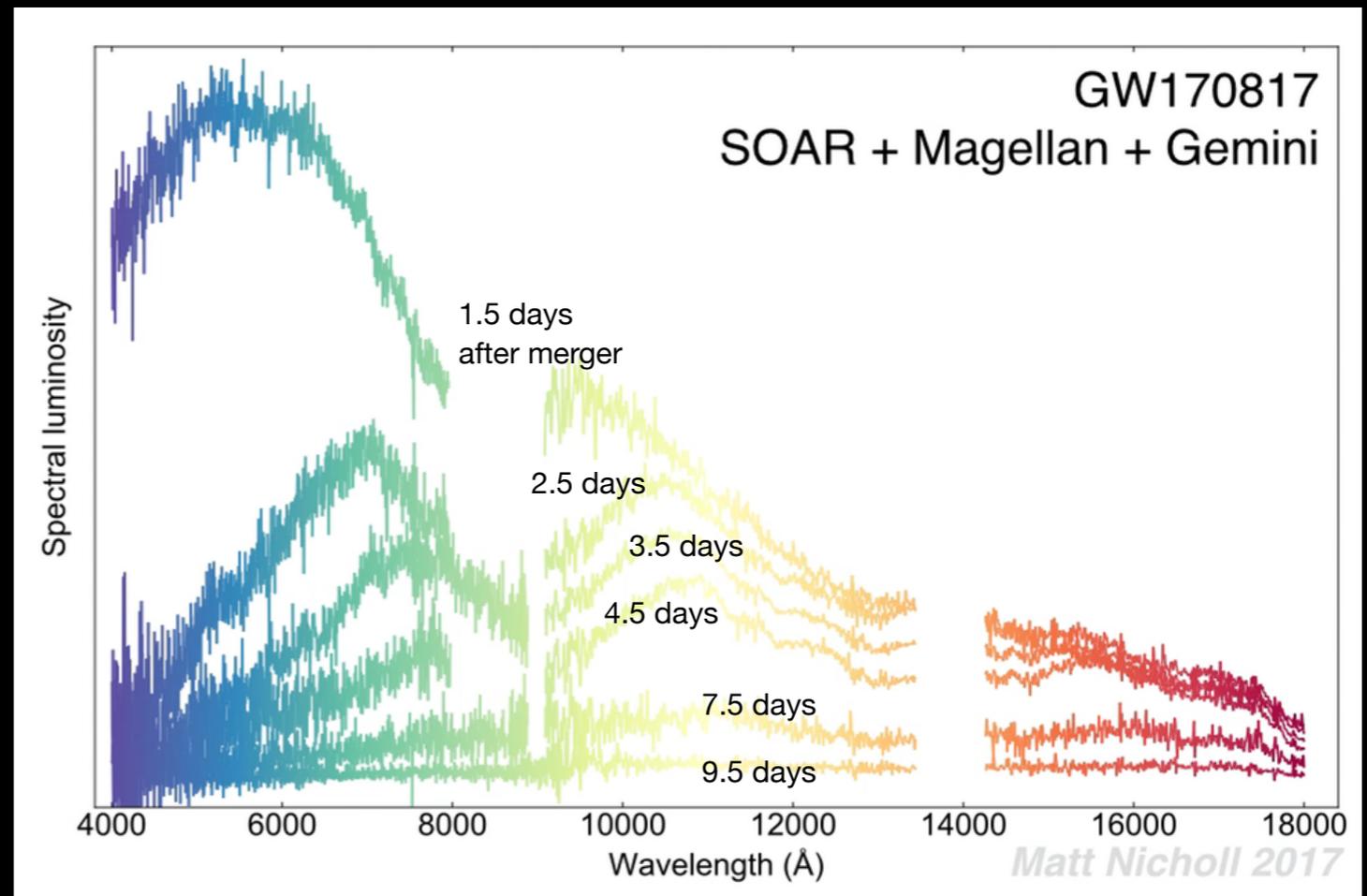


August 17, 2017



August 21, 2017

Swope & Magellan Telescopes



### Element Origins

Jennifer Johnson/SDSS, CC BY

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														

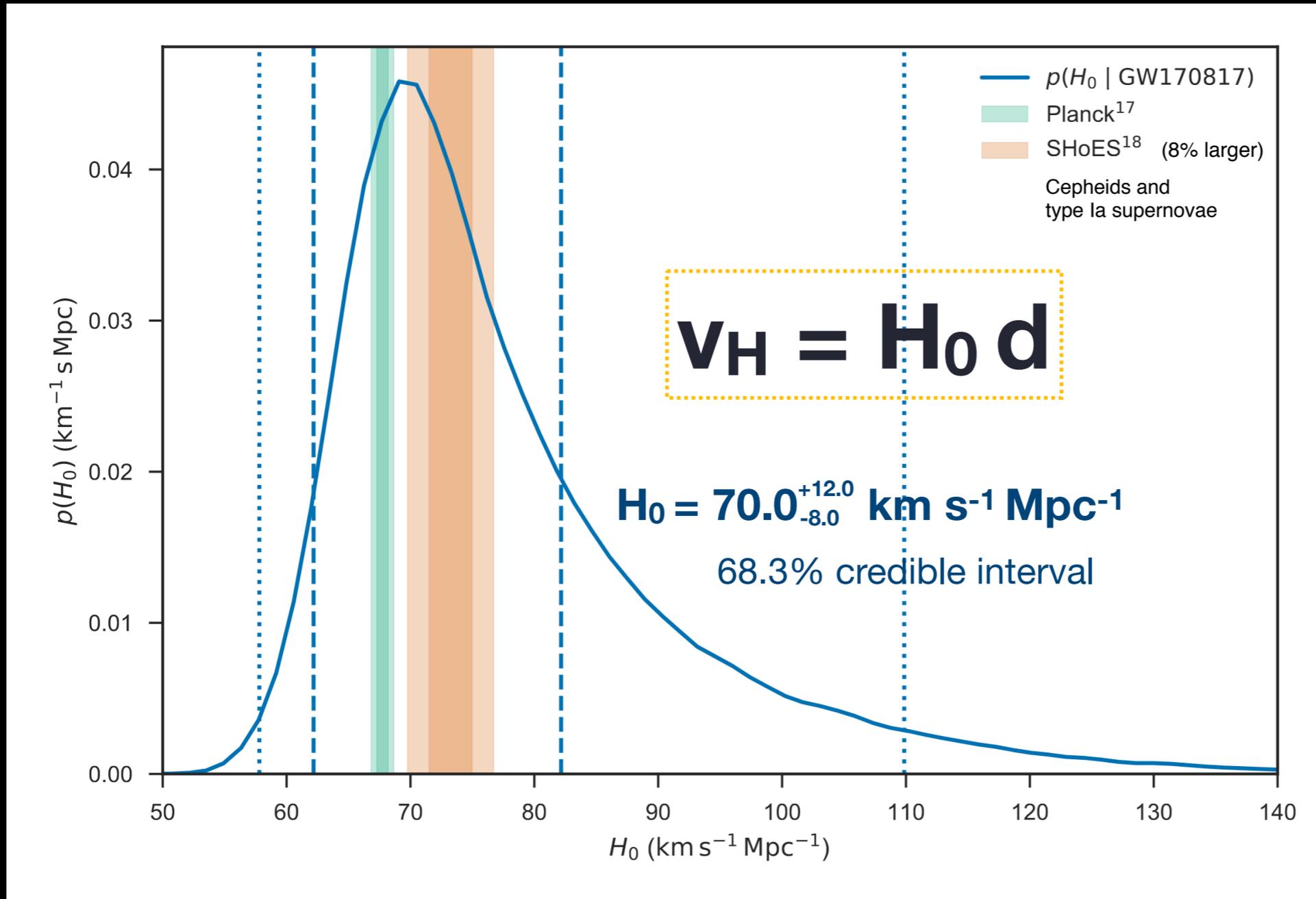
Merging Neutron Stars  
Dying Low Mass Stars

Exploding Massive Stars  
Exploding White Dwarfs

Big Bang  
Cosmic Ray Fission

Based on graphic created by Jennil

# BNS as Standard Sirens



## Gravitational wave cosmology:

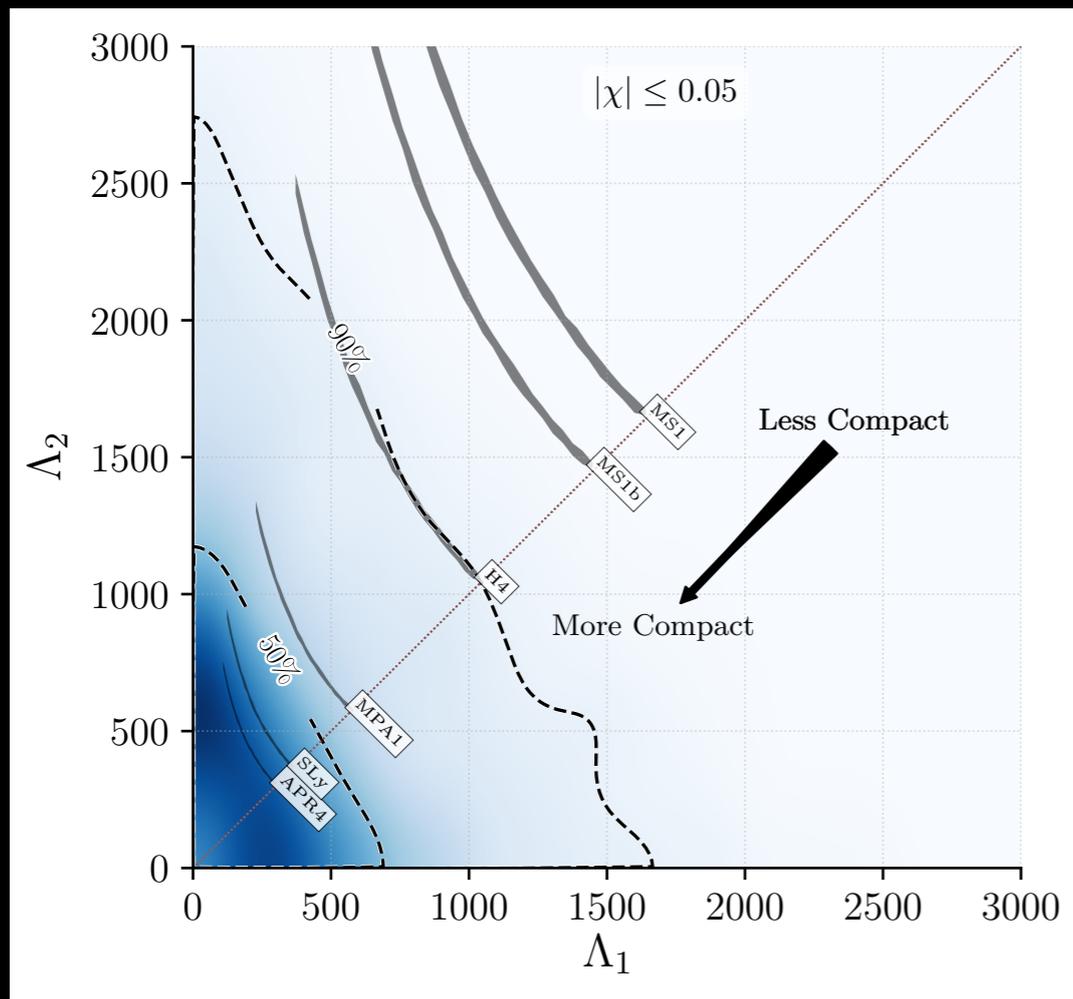
BNS as standard sirens to measure the rate of expansion of the Universe

$v_H$  - local “Hubble flow” velocity of the source - Use optical identification of the host galaxy NGC 4993

$d$  - distance to the source - Use the GW distance estimate

*A gravitational-wave standard siren measurement of the Hubble constant*  
Nature, 551:85, 2017

# Nuclear Physics with GWs and BNS



Constraining properties of nuclear matter via neutron star equation of state and tidal disruption, which is encoded in the BNS gravitational waveform

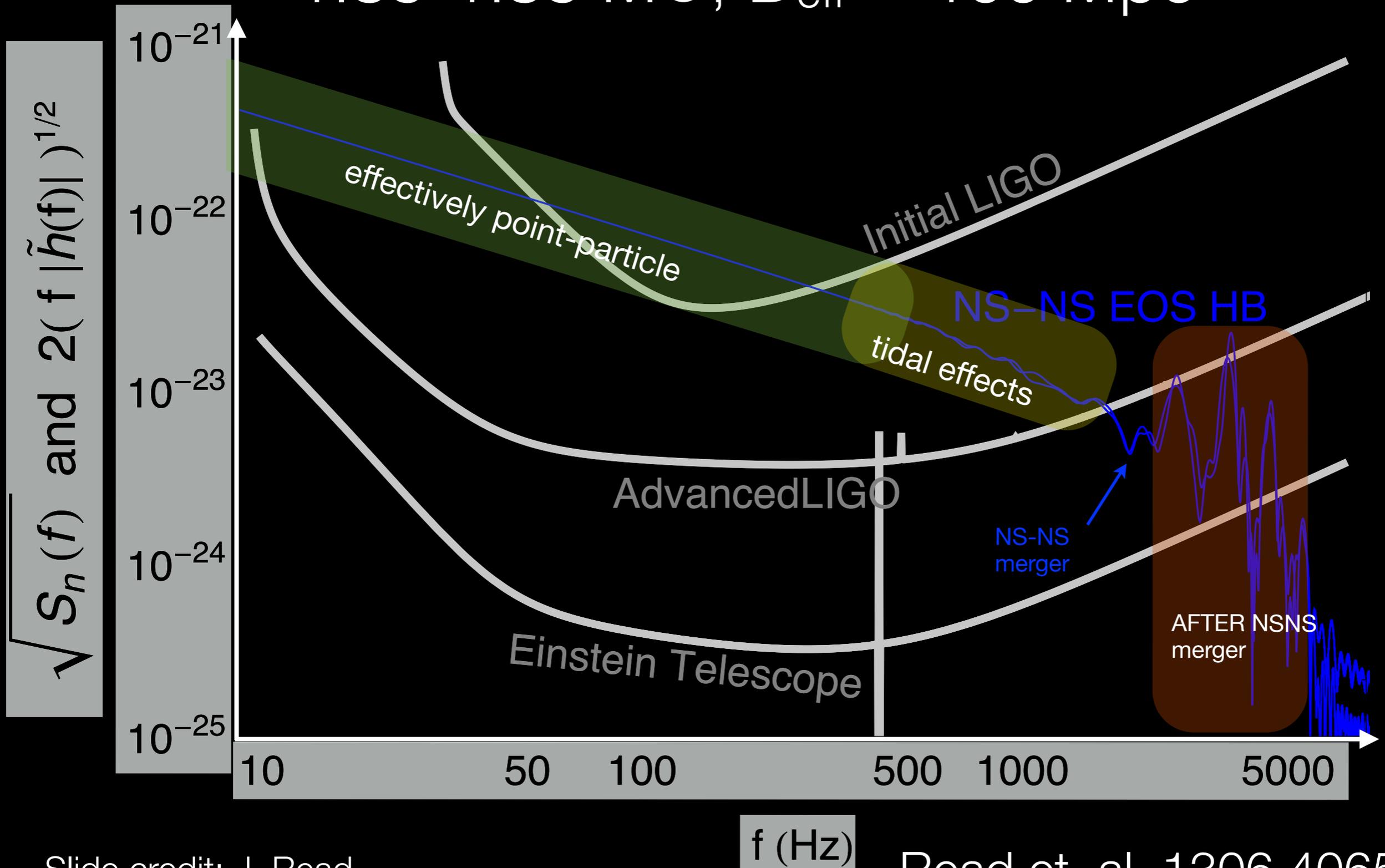
tidal deformability parameter  $\Lambda \sim k_2 (R/m)^5$   
 $k_2$  - second Love number  
 $R, m$  = radius, mass of the neutron star

*GW170817: Observation of Gravitational Waves from a Binary Neutron Star Inspiral*  
Phys. Rev. Lett., 119:161101, 2017

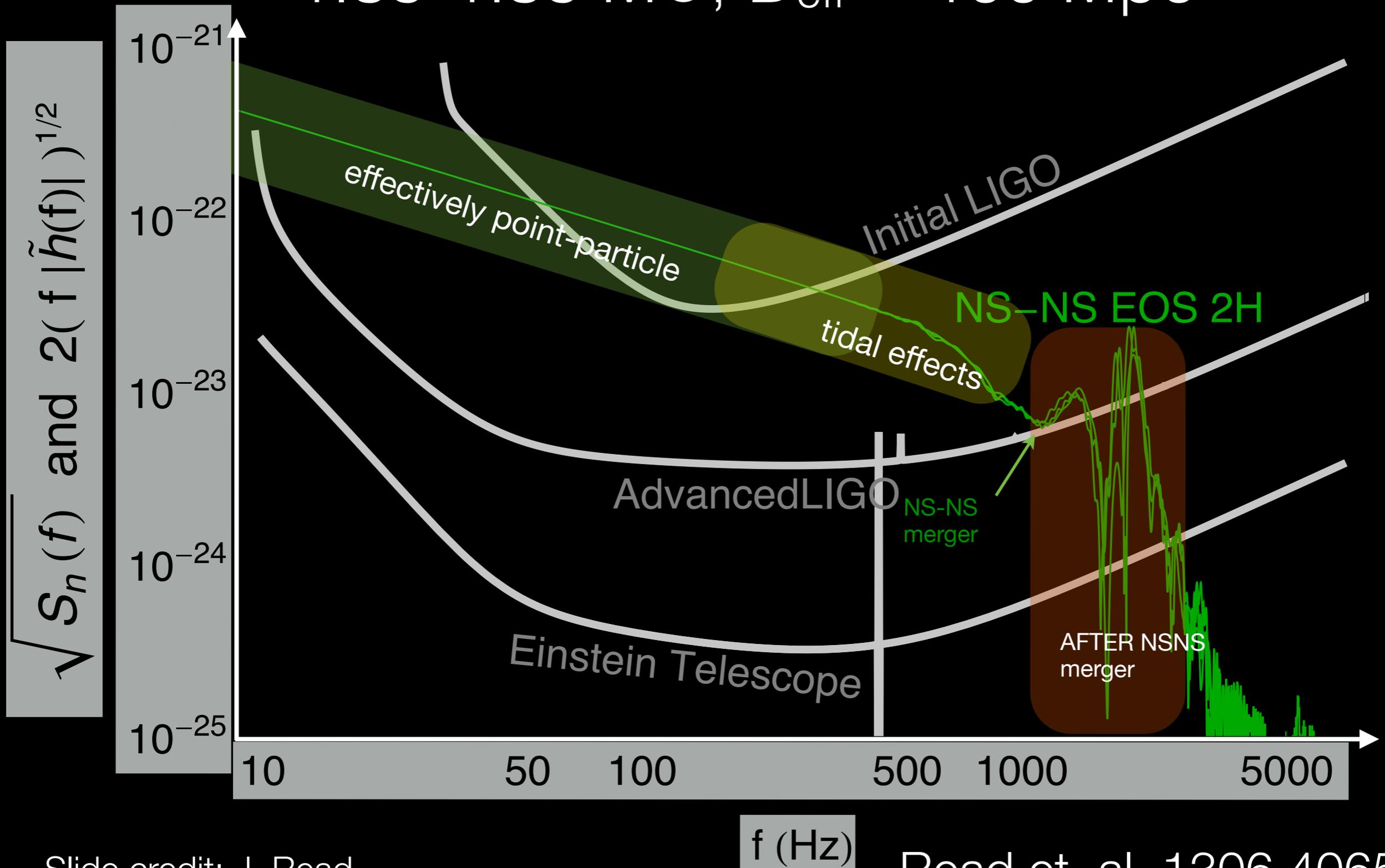
Also, the outcome of a BNS merger depends on the progenitor masses and also on the NS equation of state - searches for post-merger oscillations are still limited by sensitivity

*Search for post-merger gravitational waves from the remnant of the binary neutron star merger GW170817*  
ApJ Lett., 851:16, 2017

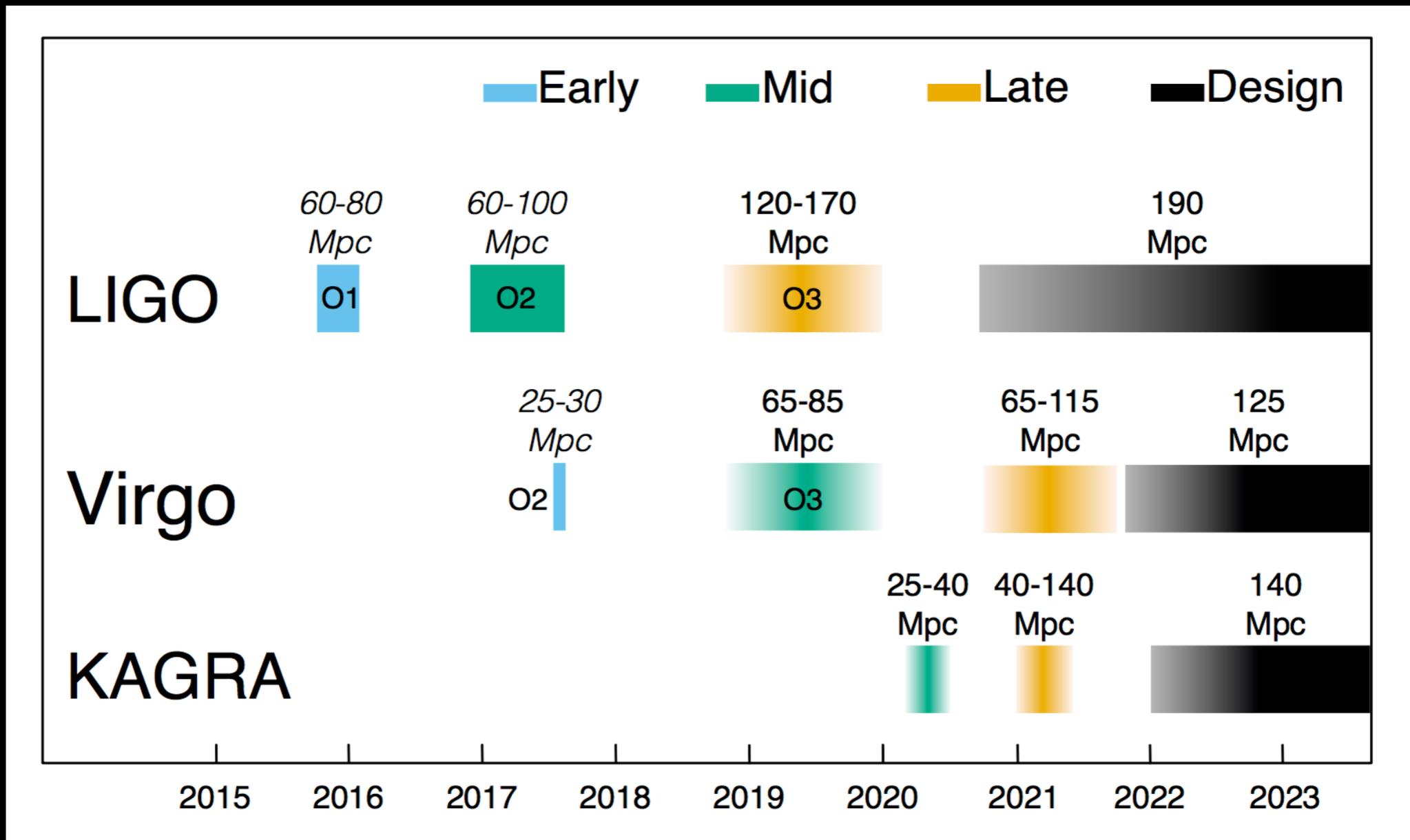
# EOS impact on BNS Spectrum: 1.35-1.35 $M_{\odot}$ , $D_{\text{eff}} = 100$ Mpc



# EOS impact on BNS Spectrum: 1.35-1.35 $M_{\odot}$ , $D_{\text{eff}} = 100$ Mpc



# Observing Scenarios



*Prospects for Observing and Localizing Gravitational-Wave Transients with Advanced LIGO and Advanced Virgo and KAGRA*

<https://dcc.ligo.org/LIGO-P1200087/public>

# Near Term Future: The Next Decade

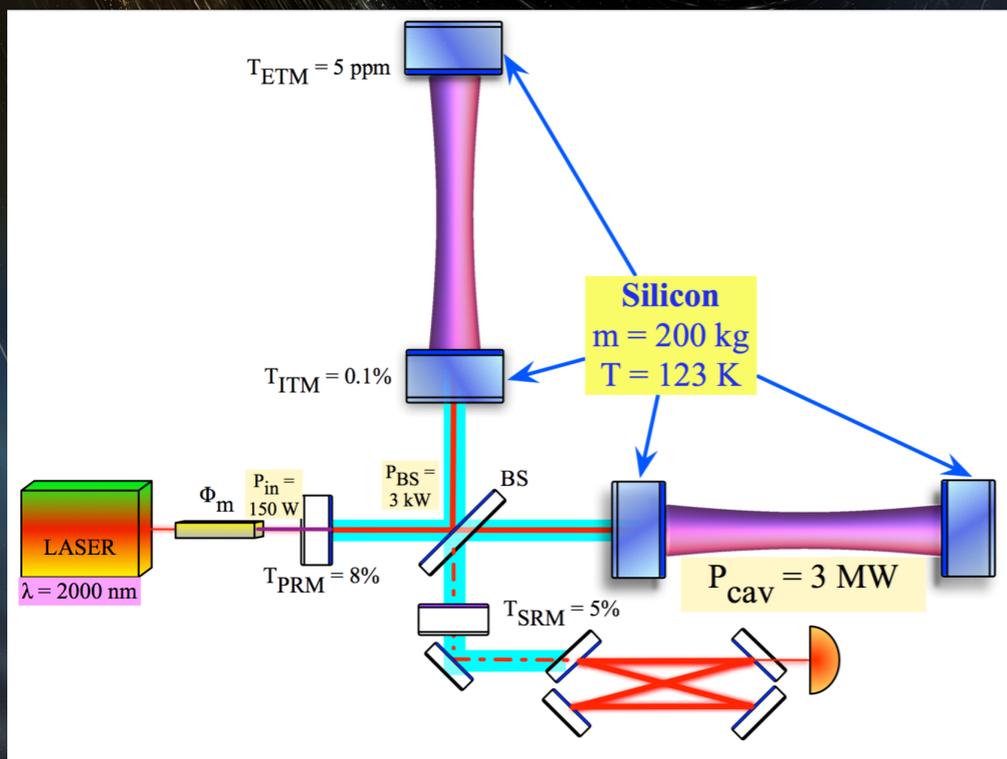
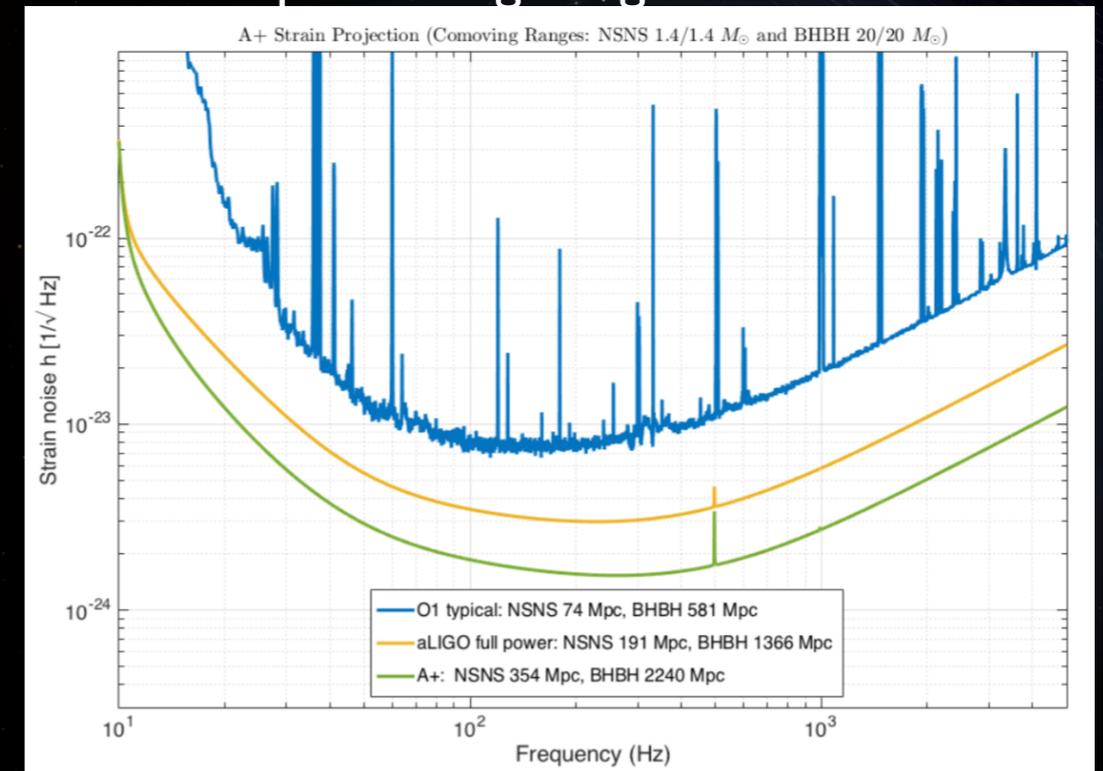
## Advanced LIGO Plus (A+)

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

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

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



## LIGO Voyager

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

larger Si masses, cryogenic operation, new laser wavelength

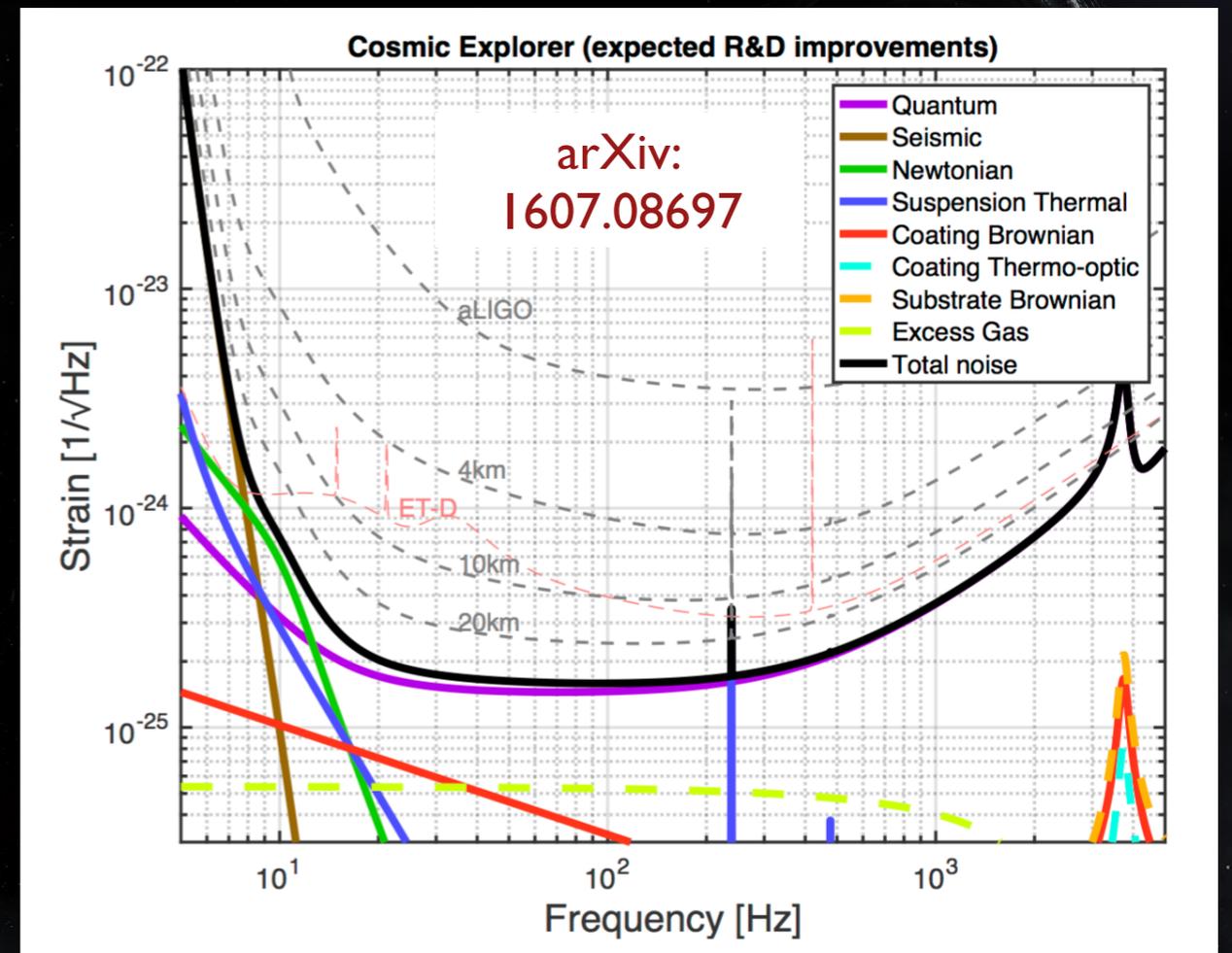
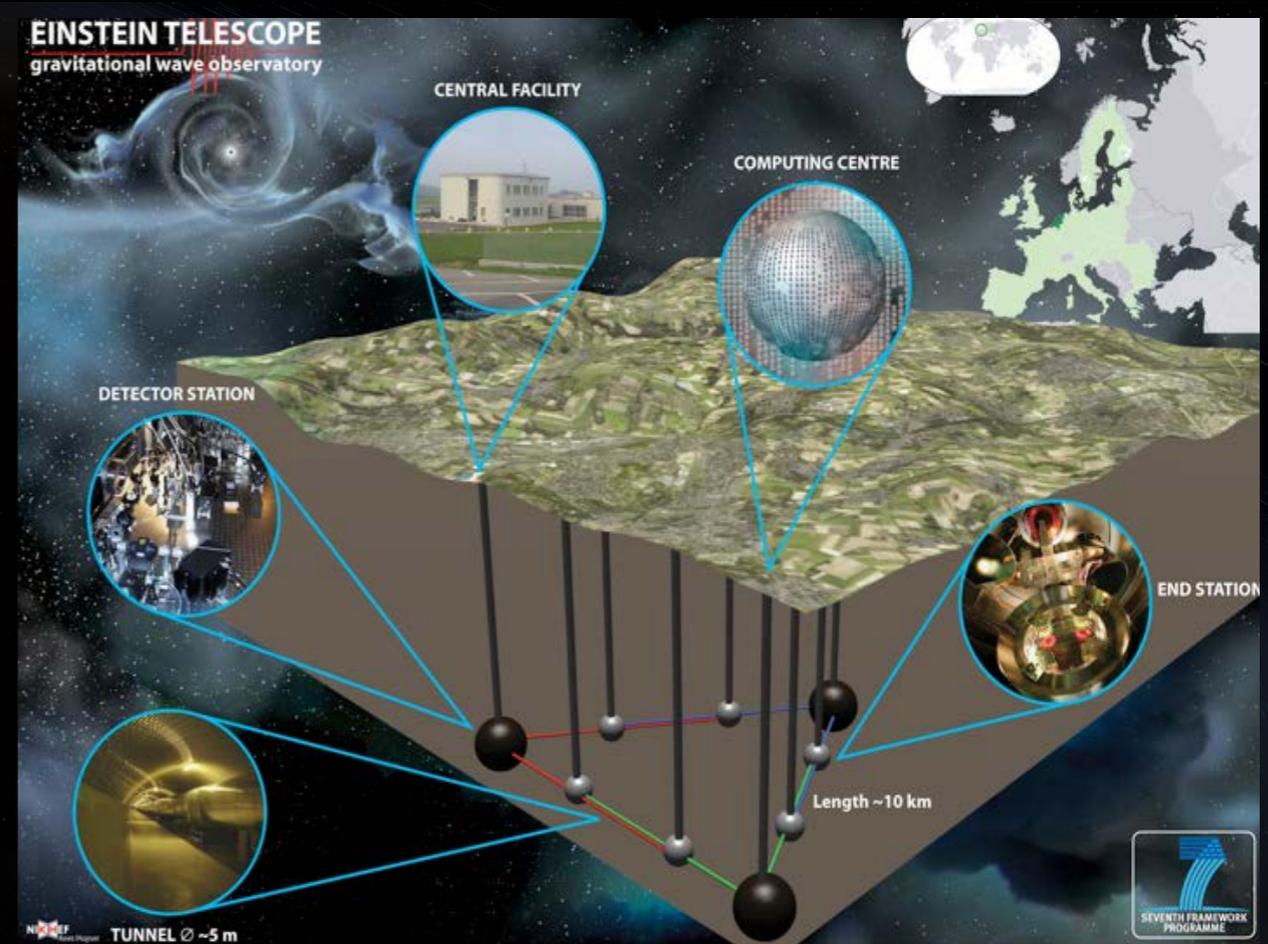
# 3G detectors

## Einstein Telescope

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

## Cosmic Explorer

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



# Gravitational Wave Periods

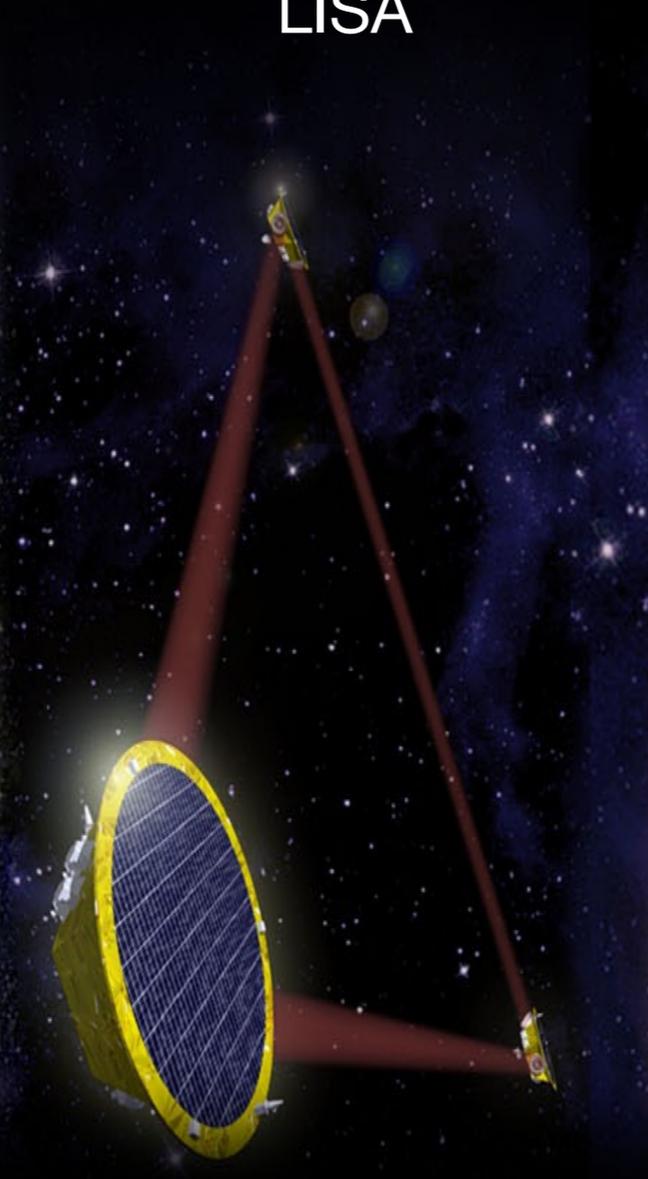
**Milliseconds**

LIGO/Virgo



**Minutes  
to Hours**

LISA



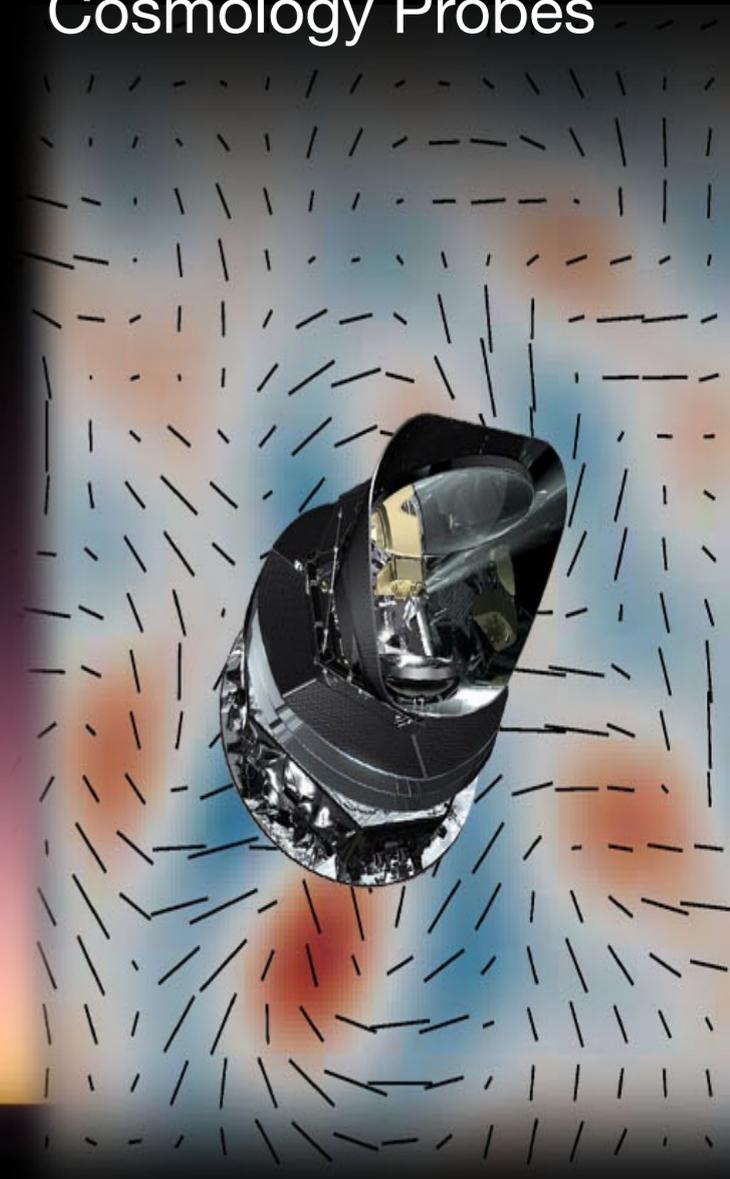
**Years  
to Decades**

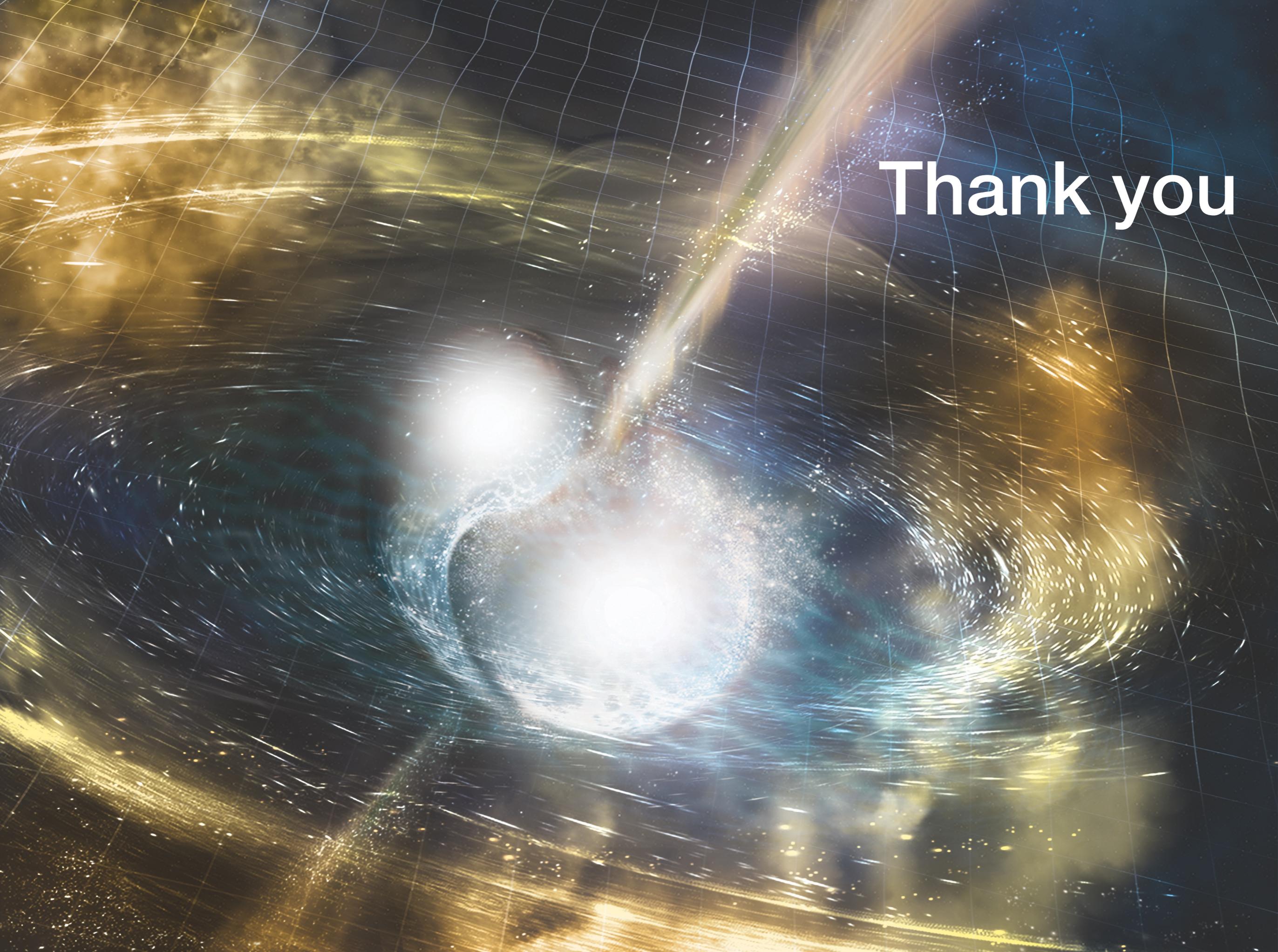
Pulsar Timing Array



**Billions  
of Years**

Cosmology Probes



The background is a complex, futuristic visualization. It features a central, bright white and blue core that appears to be a source of energy or light. This core is surrounded by swirling, golden and blue light trails that create a sense of motion and depth. A grid of thin, white lines is overlaid on the scene, giving it a technical or digital feel. The overall color palette is dominated by blues, whites, and golds, with a dark, almost black background that makes the light elements stand out.

**Thank you**