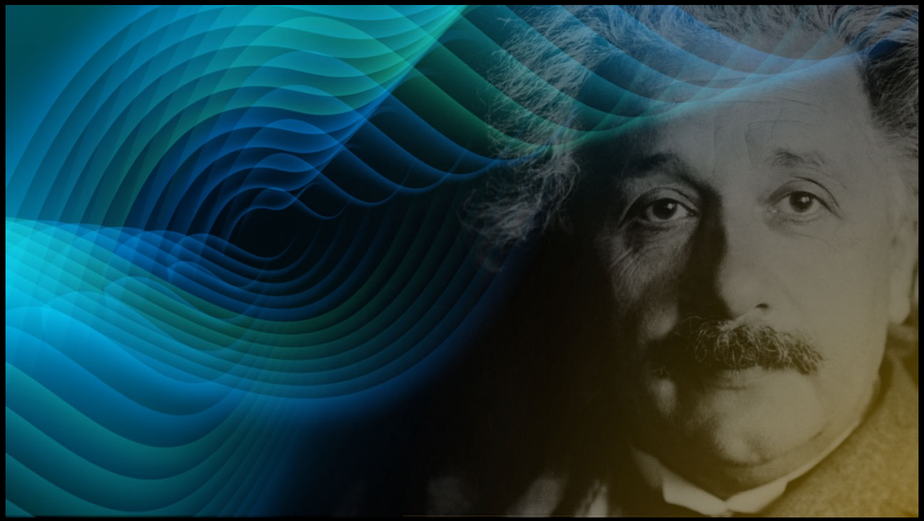
Black Holes, Neutron Stars and the Birth of Gravitational Wave Astronomy

Laura Cadonati, Georgia Tech
LIGO Scientific Collaboration

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

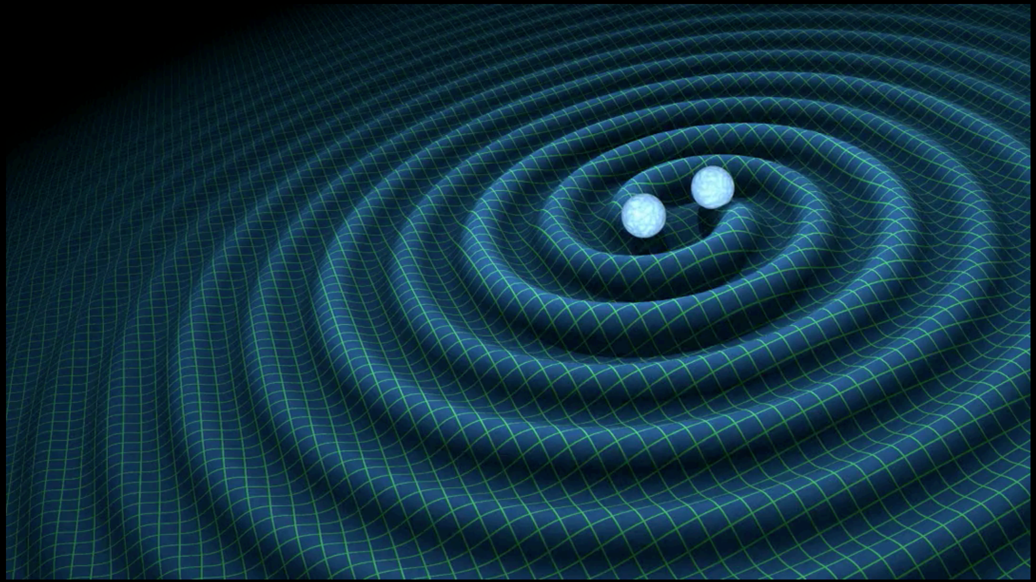
LIGO-G1800119

Gravitational Waves: Einstein's Messengers



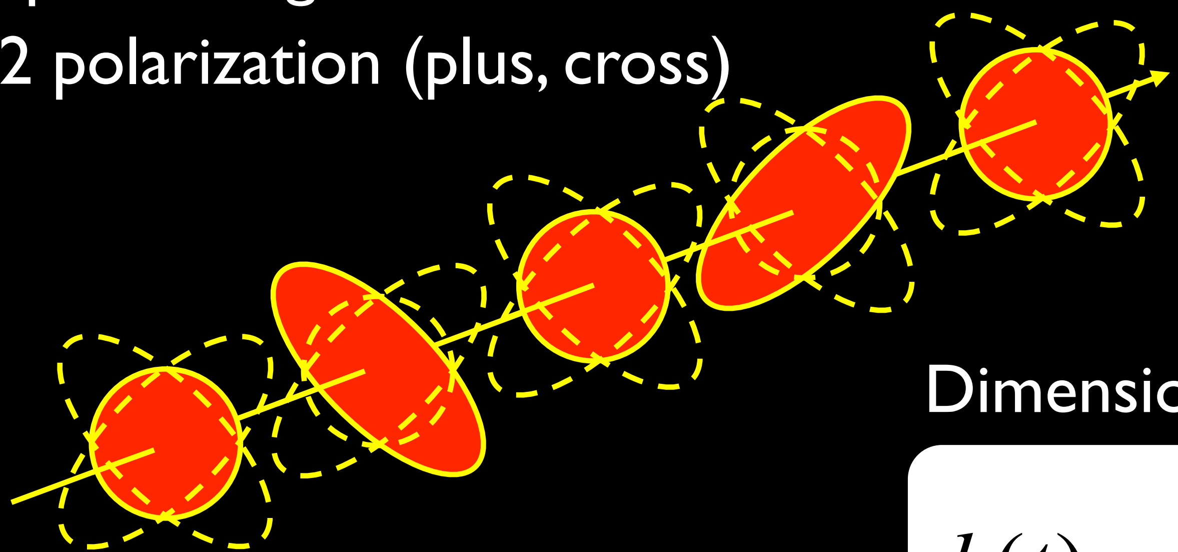
- Perturbations of the space-time metric produced by rapid changes in shape and orientation of massive objects.

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



Credits: *R. Hurt - Caltech / JPL*

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



Dimensionless strain:

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

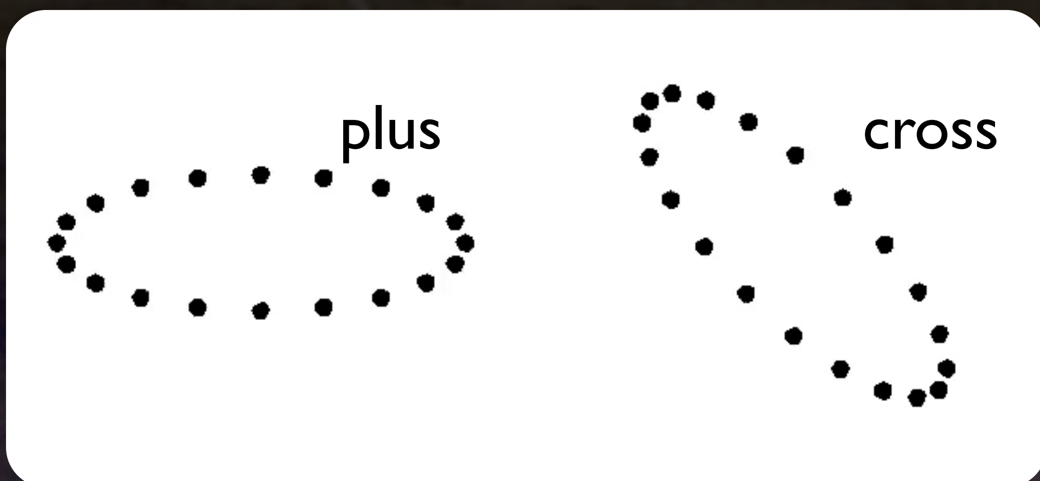
I = source mass quadrupole moment

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

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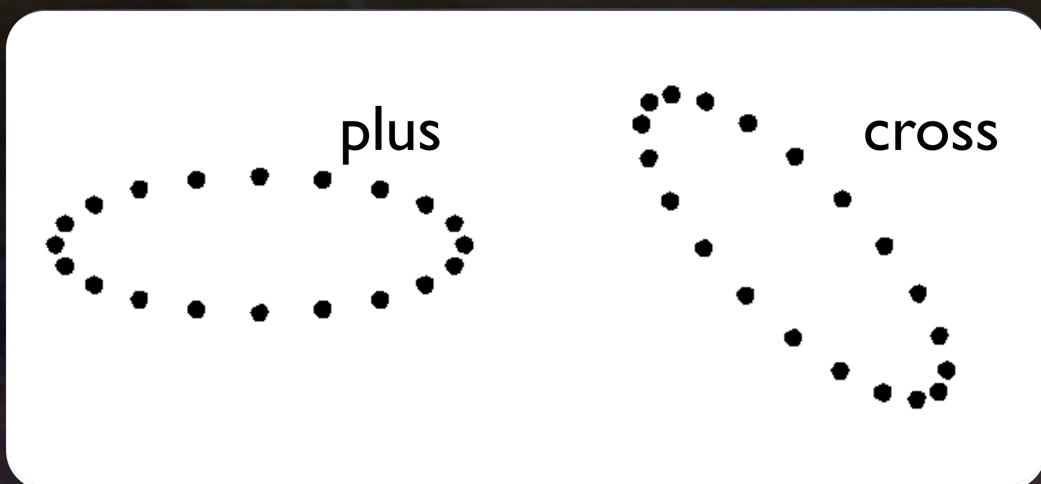

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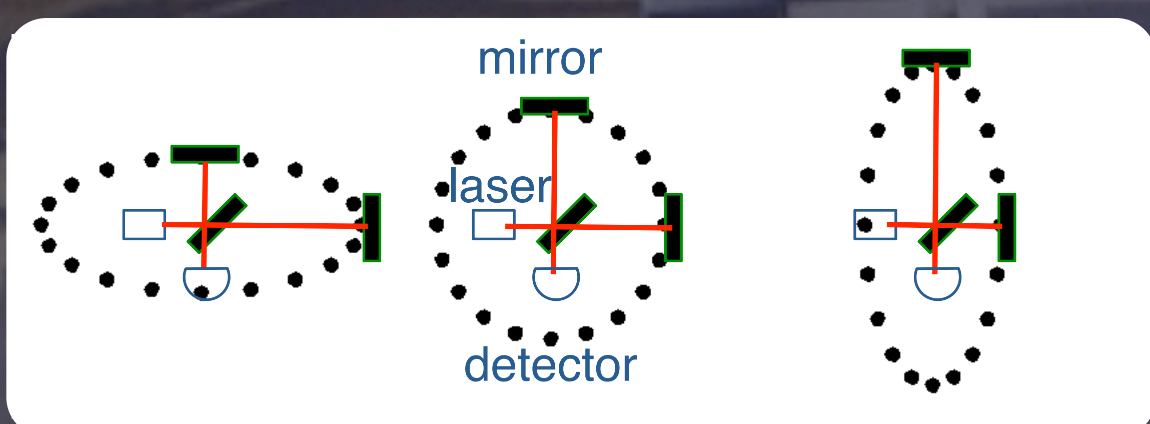
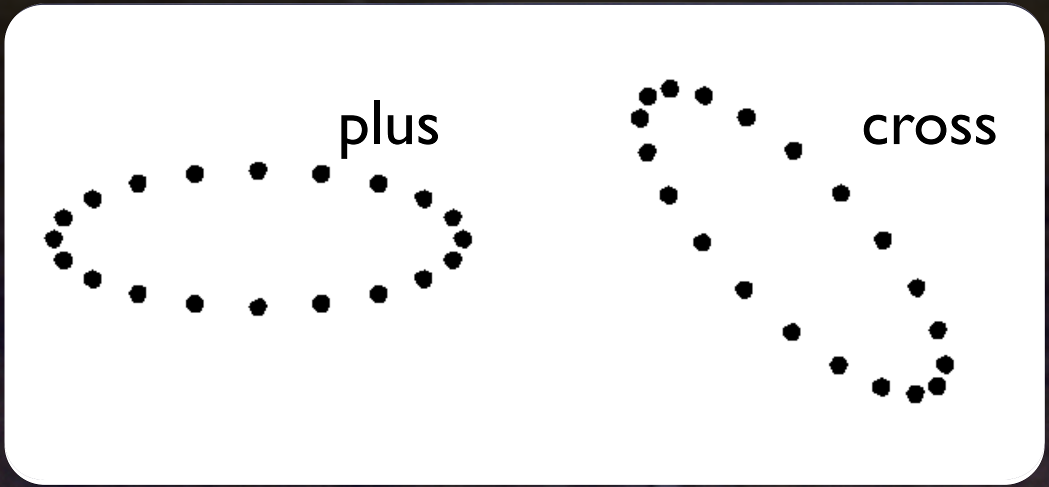
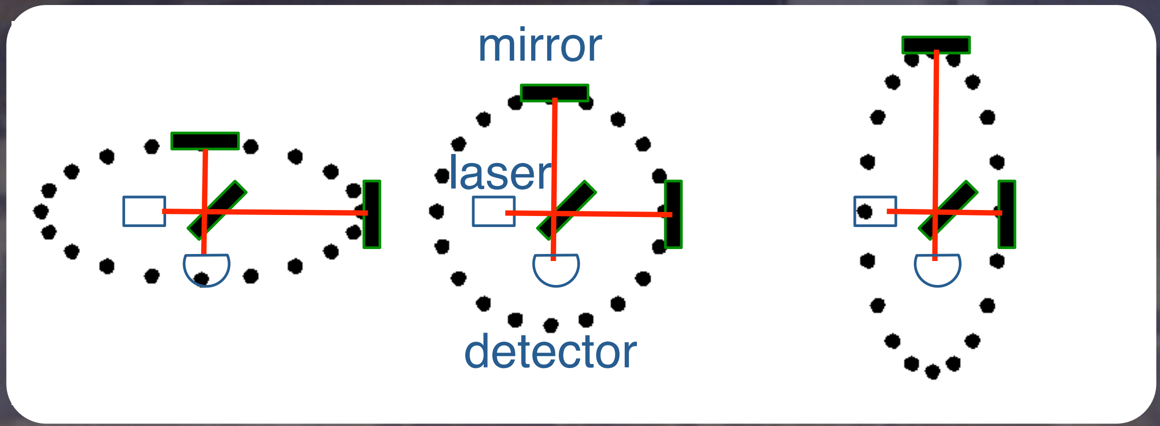


How to Detect Gravitational Waves

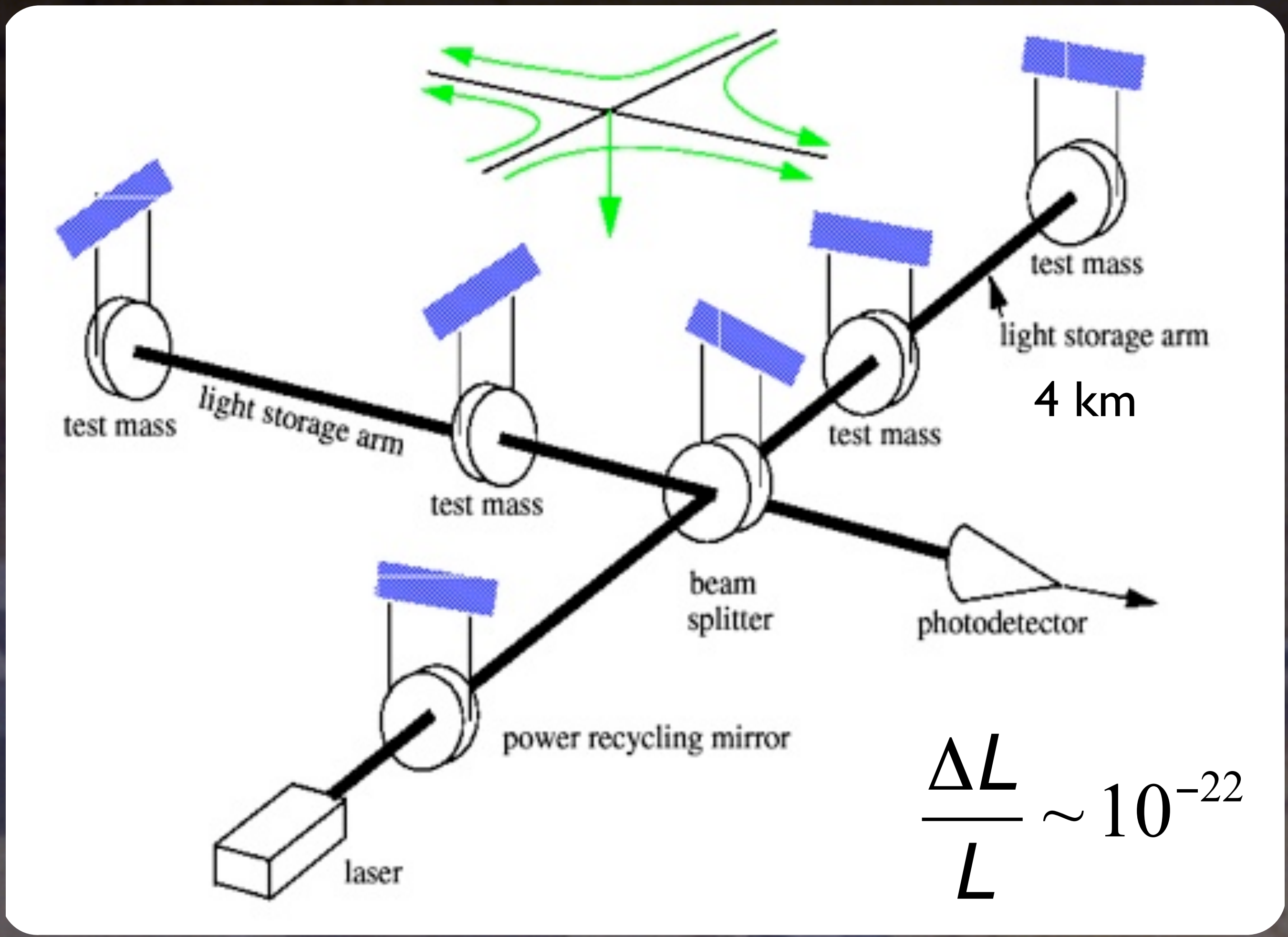
Physically, gravitational waves are strains



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



Suspended Mirrors as Test Masses



$$\frac{\Delta L}{L} \sim 10^{-22}$$

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

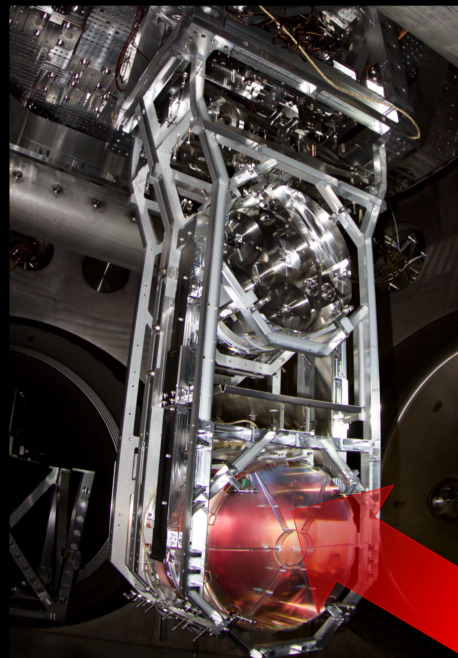
LIGO: Laser Interferometer Gravitational-wave Observatory

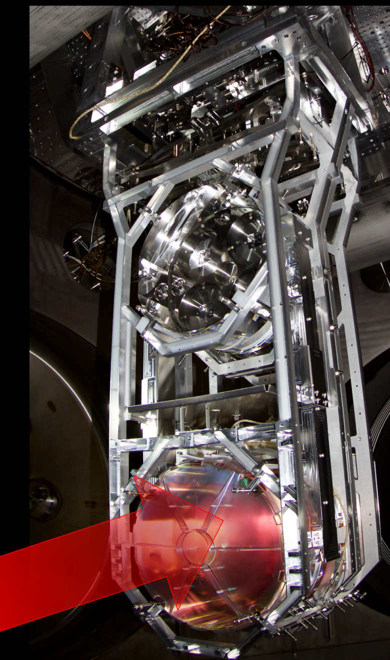
Hanford, WA

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

Livingston, LA

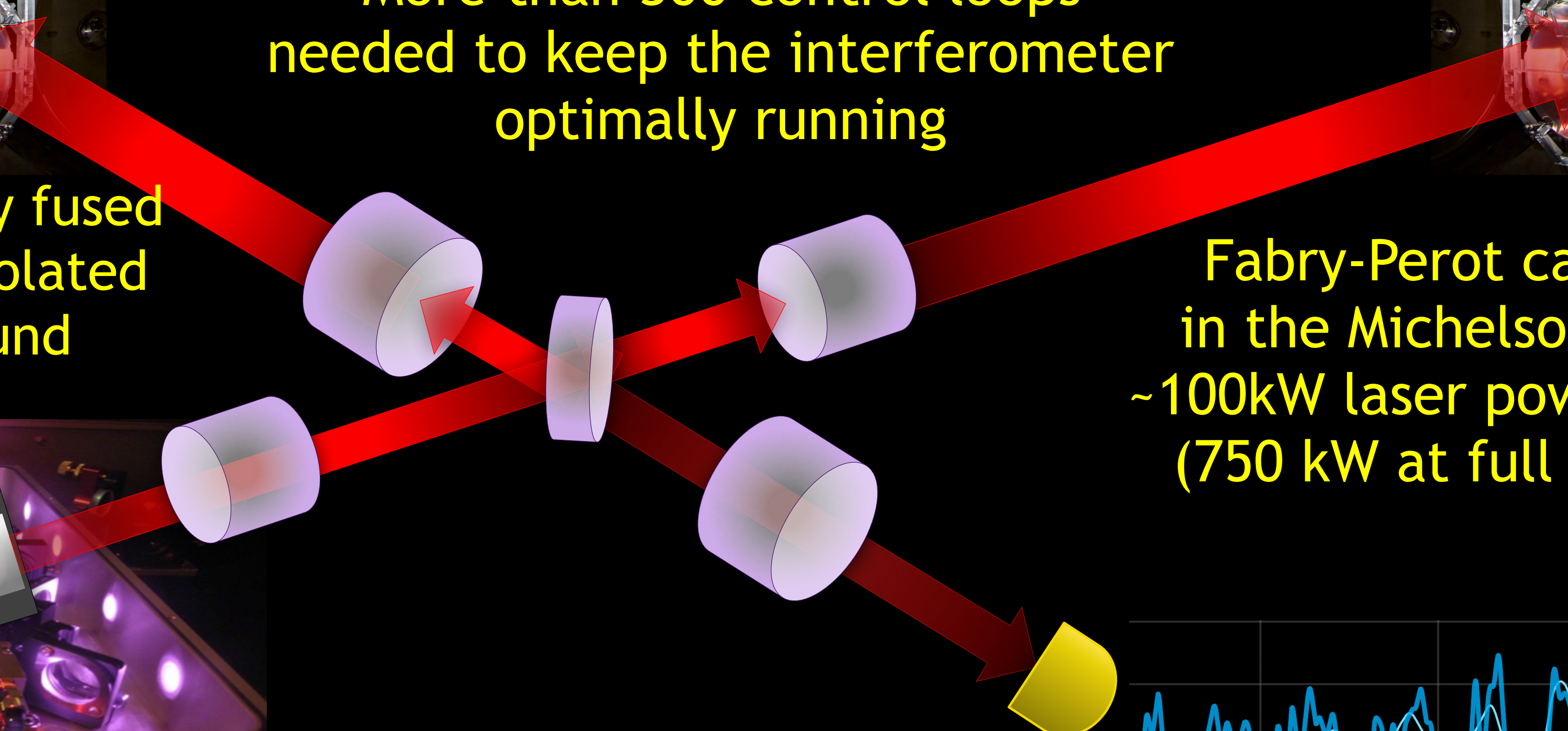
- LIGO Observatories construction: 1994-2000
- Initial LIGO operation: 2002-2010
- Advanced LIGO: 2015-now



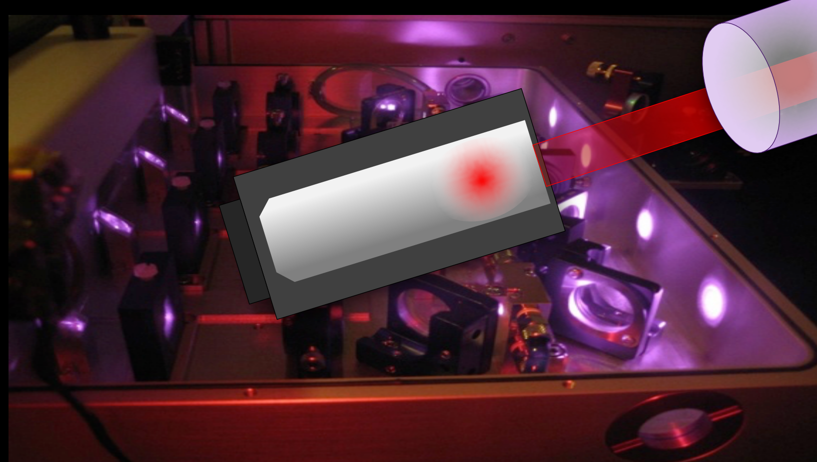


More than 300 control loops needed to keep the interferometer optimally running

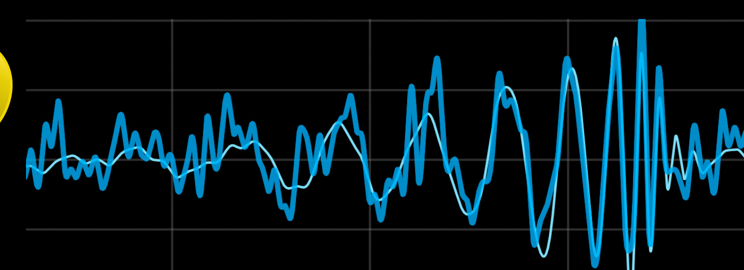
40 kg high quality fused silica mirrors, isolated from the ground



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

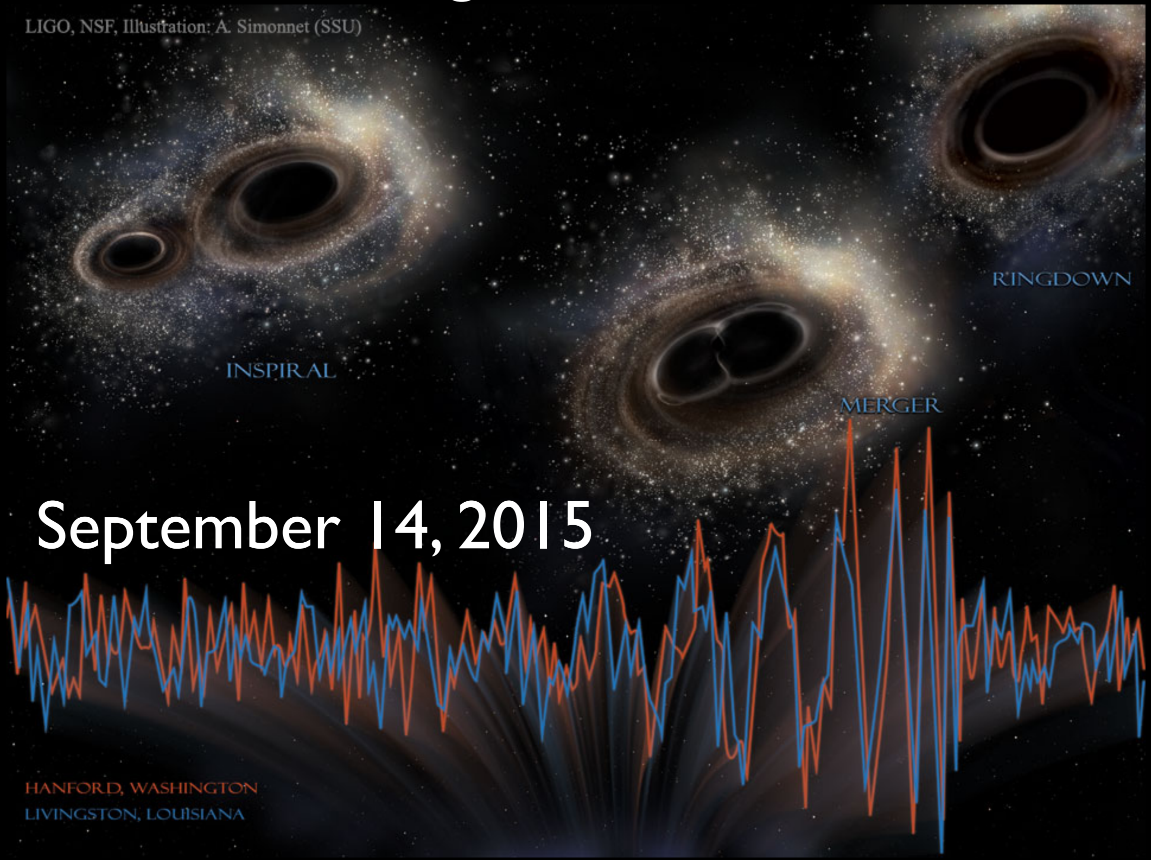
KAGRA
Japan

LIGO Scientific Collaboration

~ 1200 members ~ 100 institutions, 18 countries

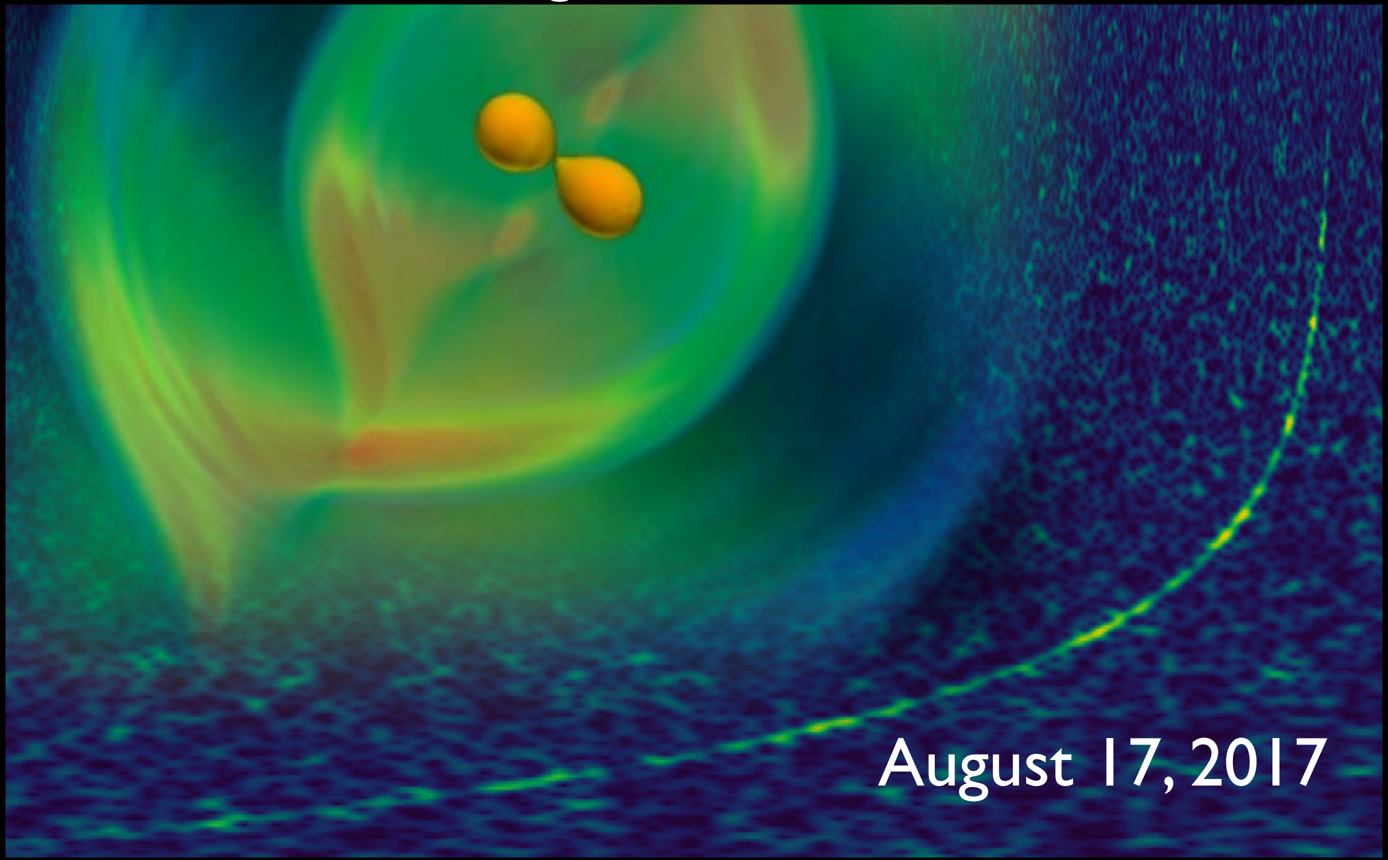
GW150914 and GW170817: Two ground-breaking discoveries that opened a new era in Gravitational Wave Astrophysics

1.3 Billion Years Ago….



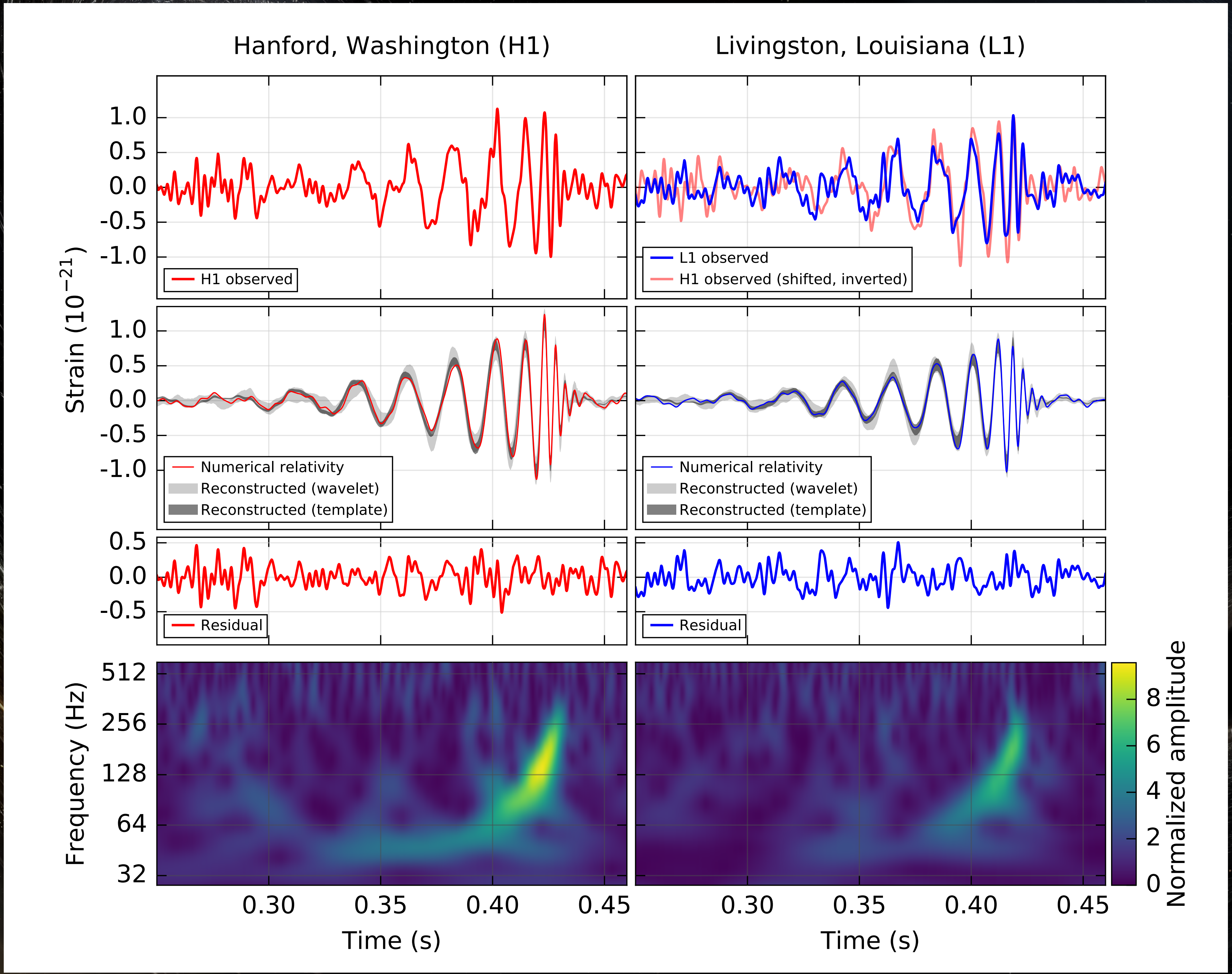
Binary Black Hole Coalescence

135 Million Years Ago….



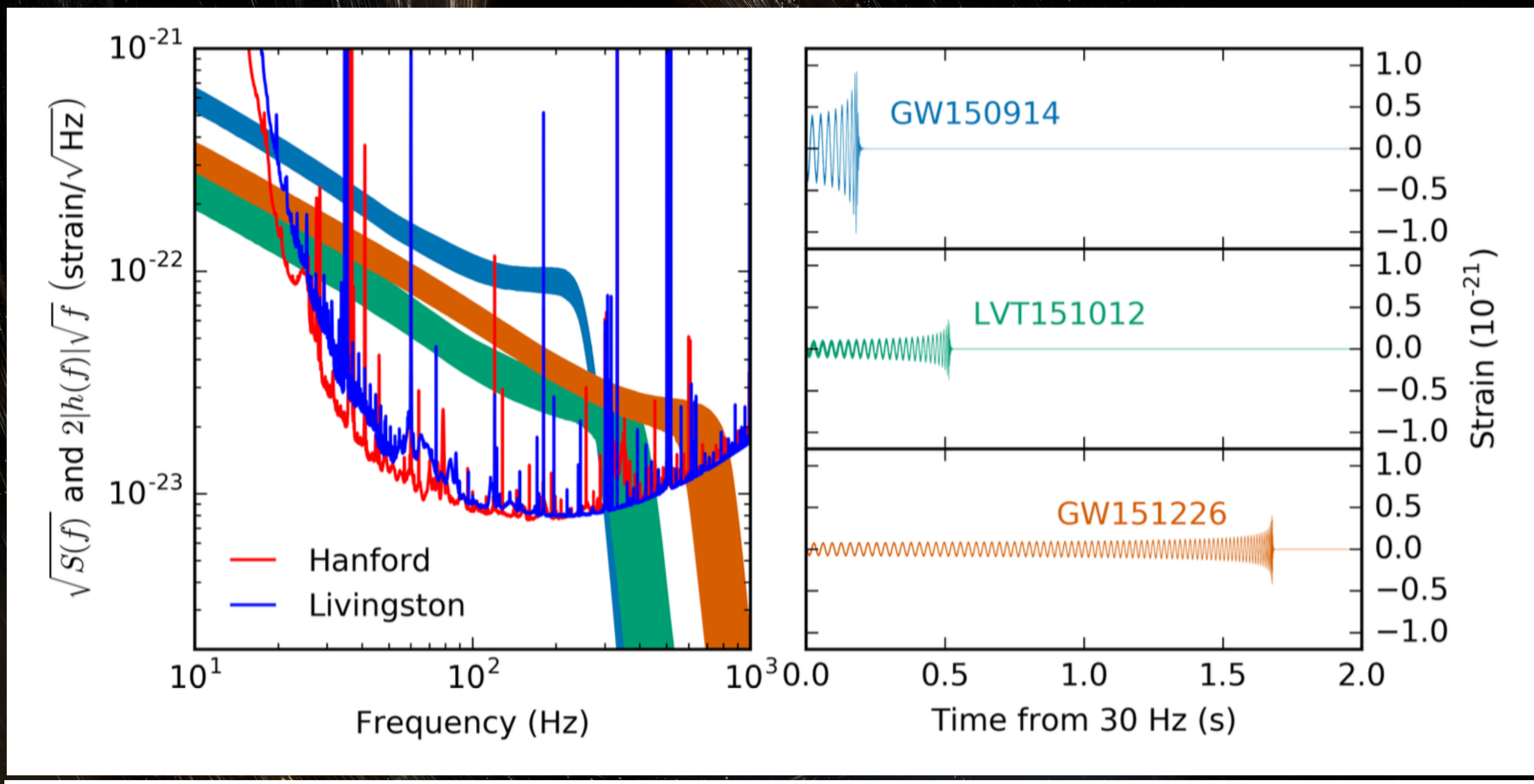
Binary Neutron Star Coalescence

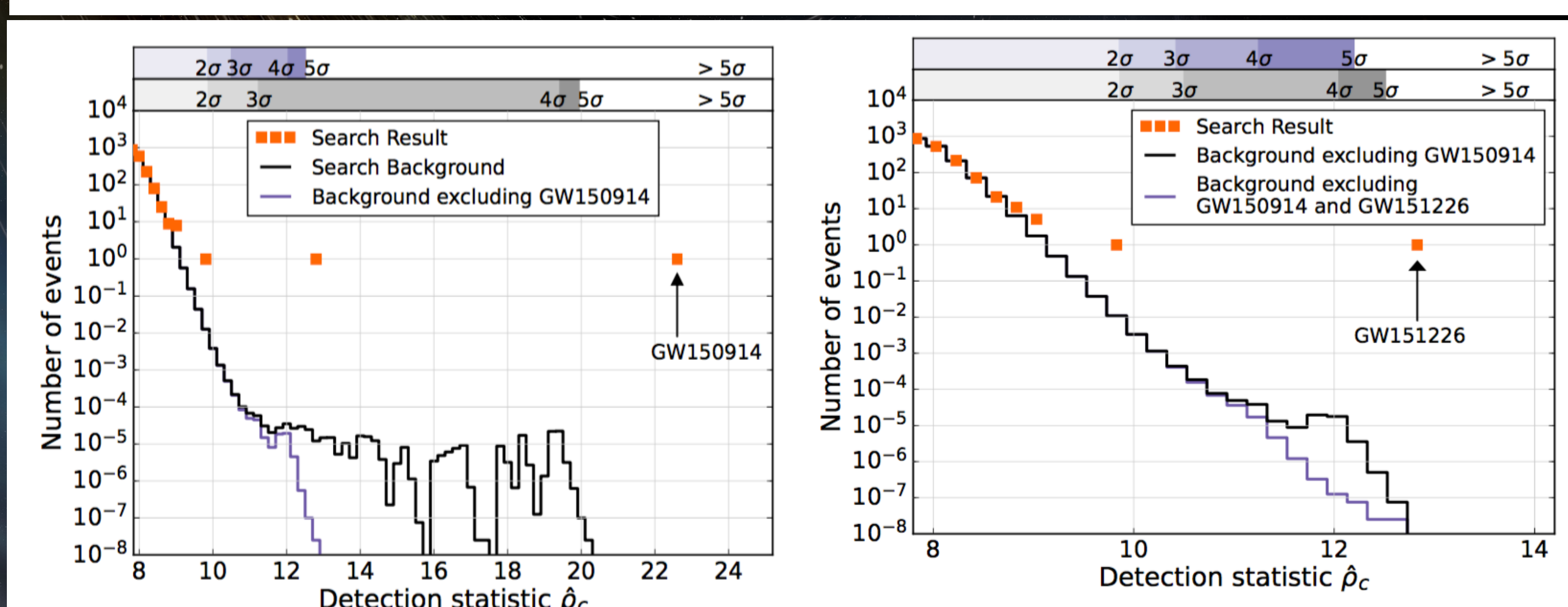
First Discovery: GW150914



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



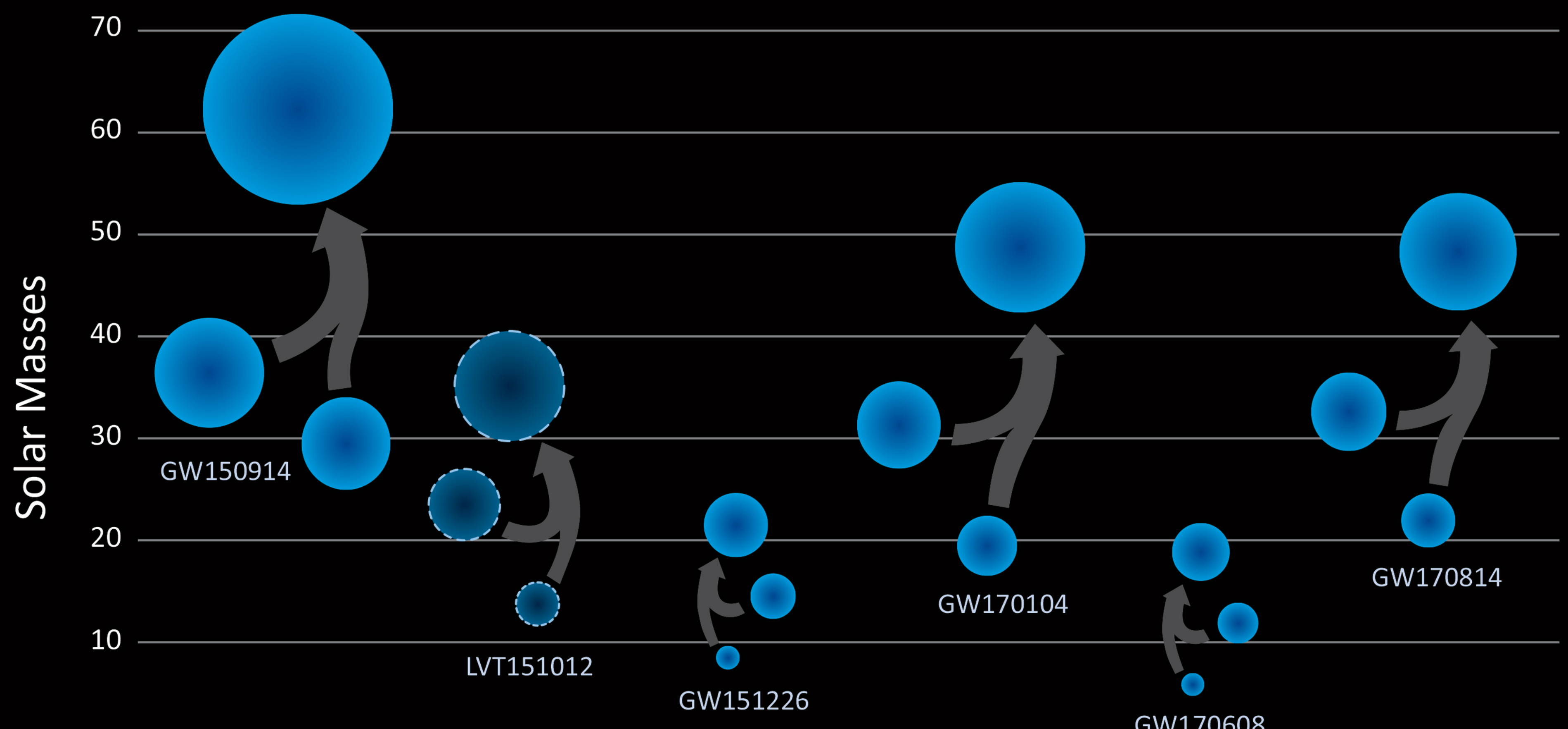


Binary Black Hole Mergers in the first Advanced LIGO Observing Run
Phys. Rev. X, 6: 041015, 2016

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: < ½ $Z_\odot$

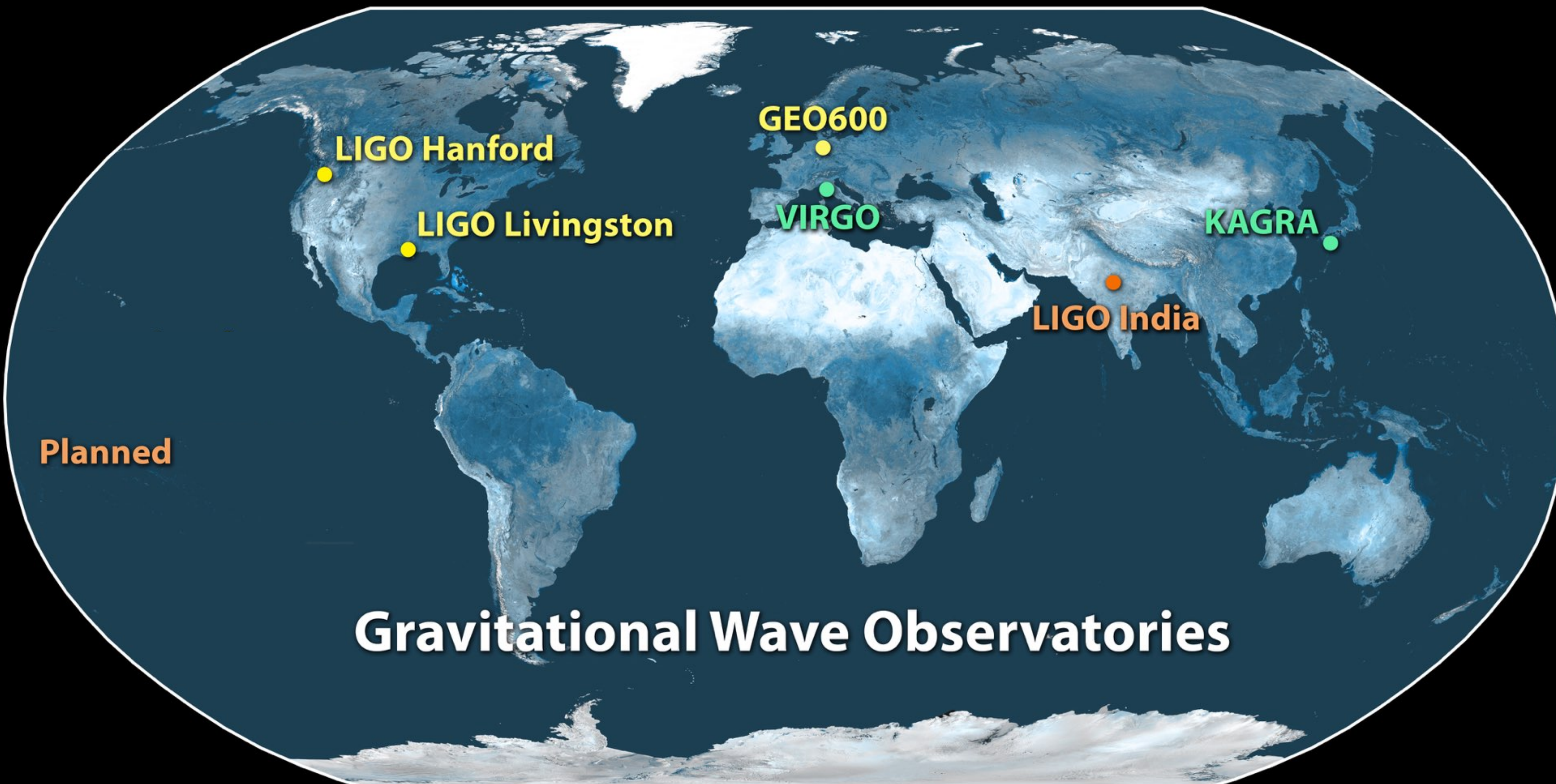
Merger rate of stellar mass BBHs:
12 — 213/Gpc^3/yr

Credits: LIGO/Caltech/Sonoma State (Simonnet)

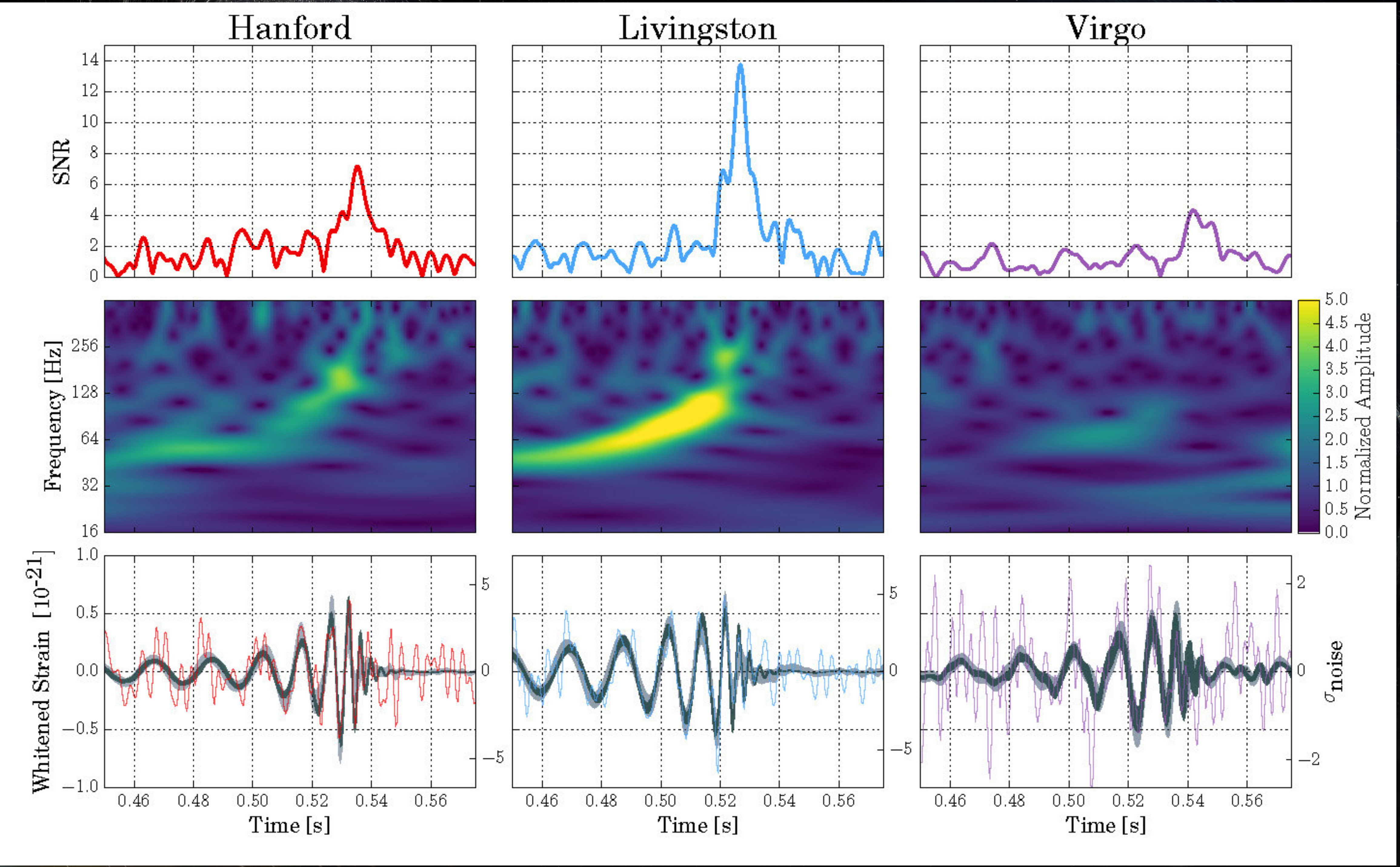
LIGO/VIRGO

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

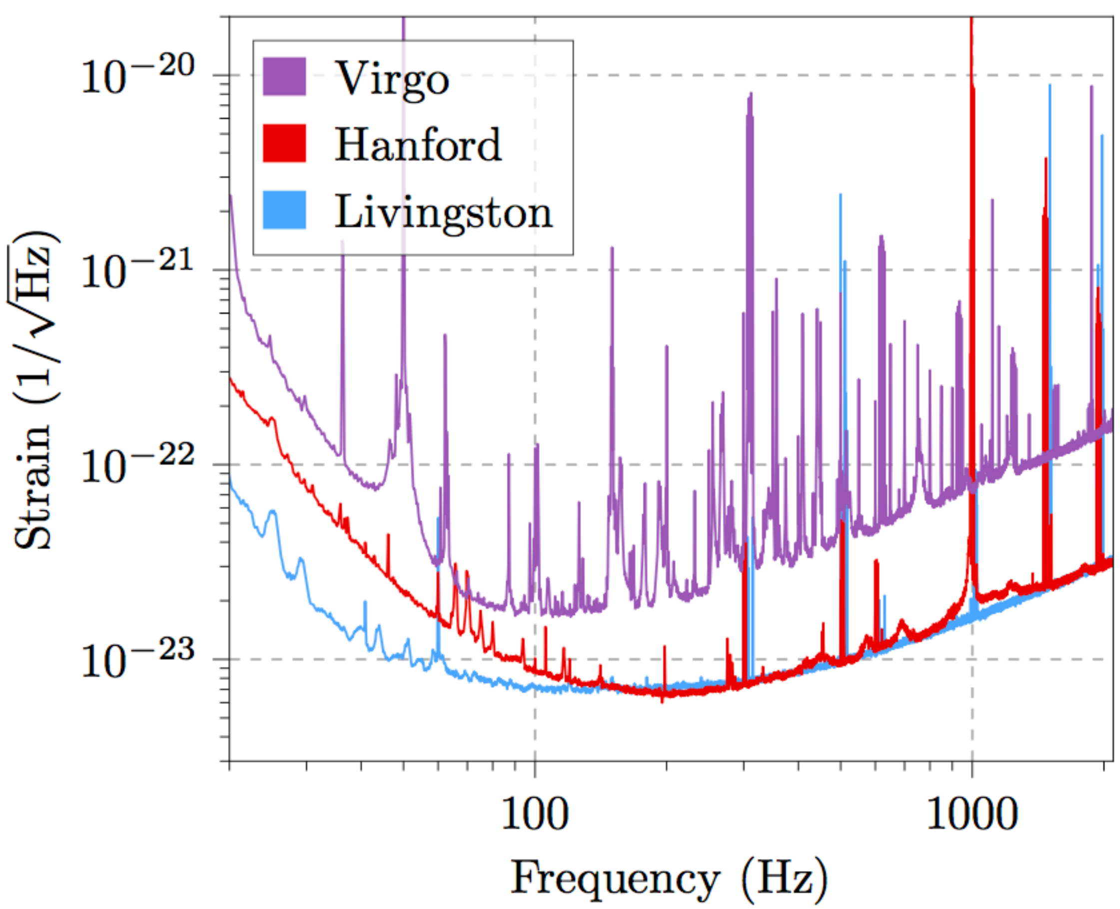


FIG. 2: Amplitude spectral density of strain sensitivity of the Advanced LIGO – Advanced Virgo network, estimated using 4096 s of data around the time of GW170814. Here, several known linearly coupled noise sources have been removed from the data.

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

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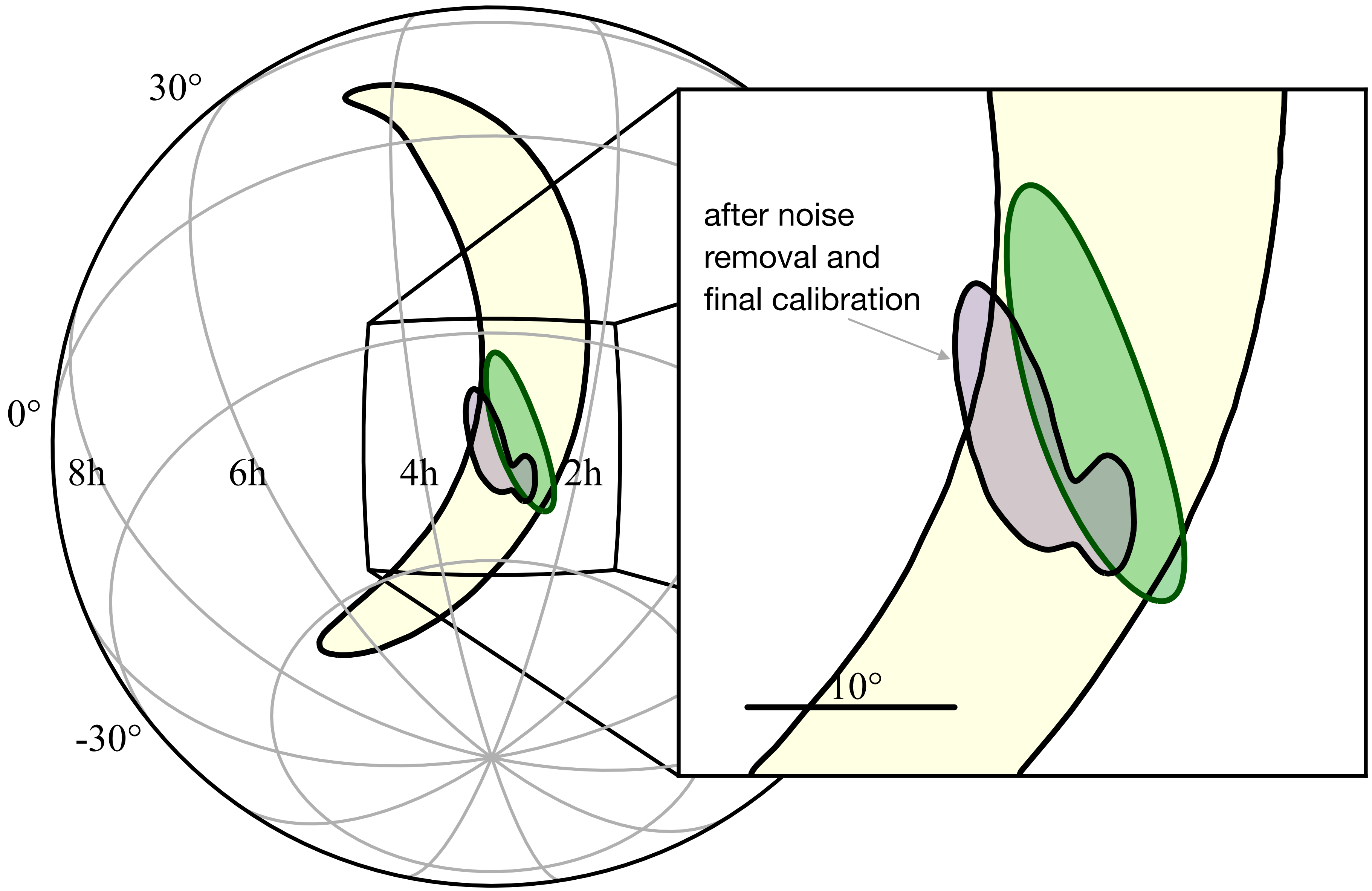
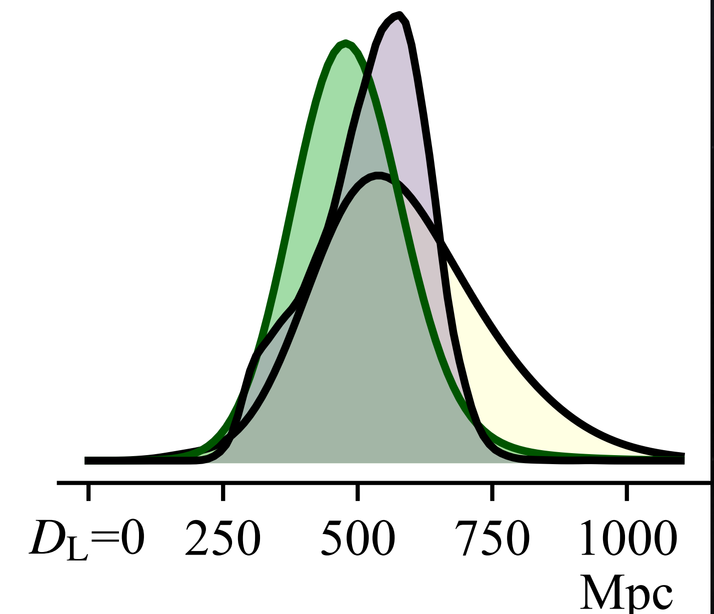
Phys. Rev. Lett., 119:141101, 2017

Sky Localization

The inclusion of Virgo improves the sky localization from 1160 deg^2 to 60 deg^2

Plausible volume (==> number of possible host galaxies) decreases from 71 to 2.1 $\times 10^6$ Mpc^3





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

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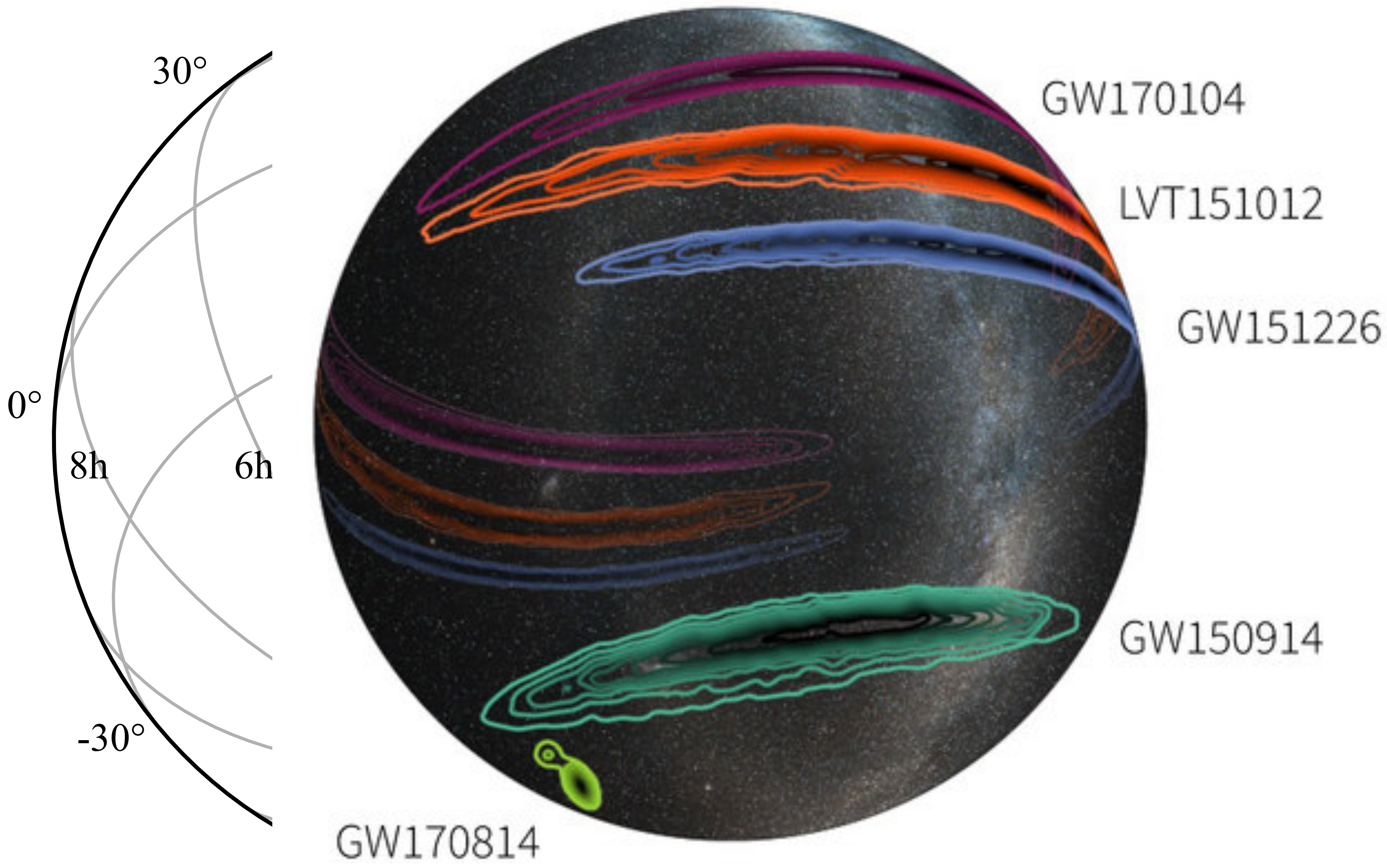

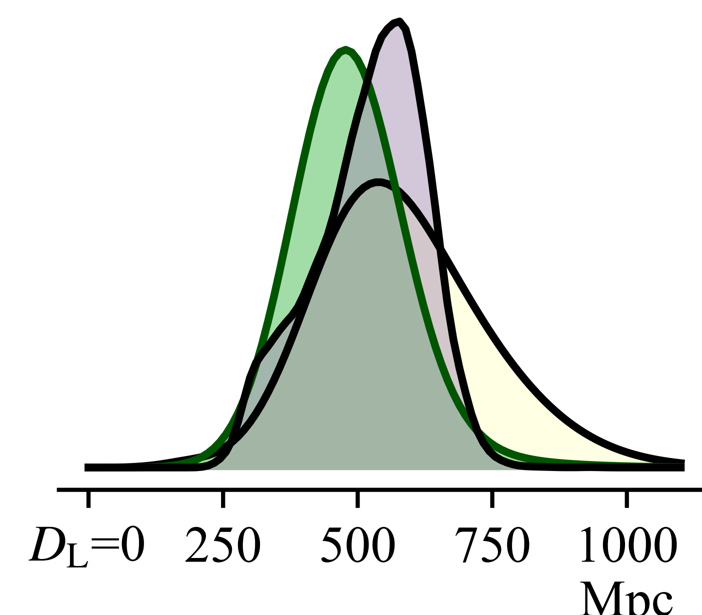

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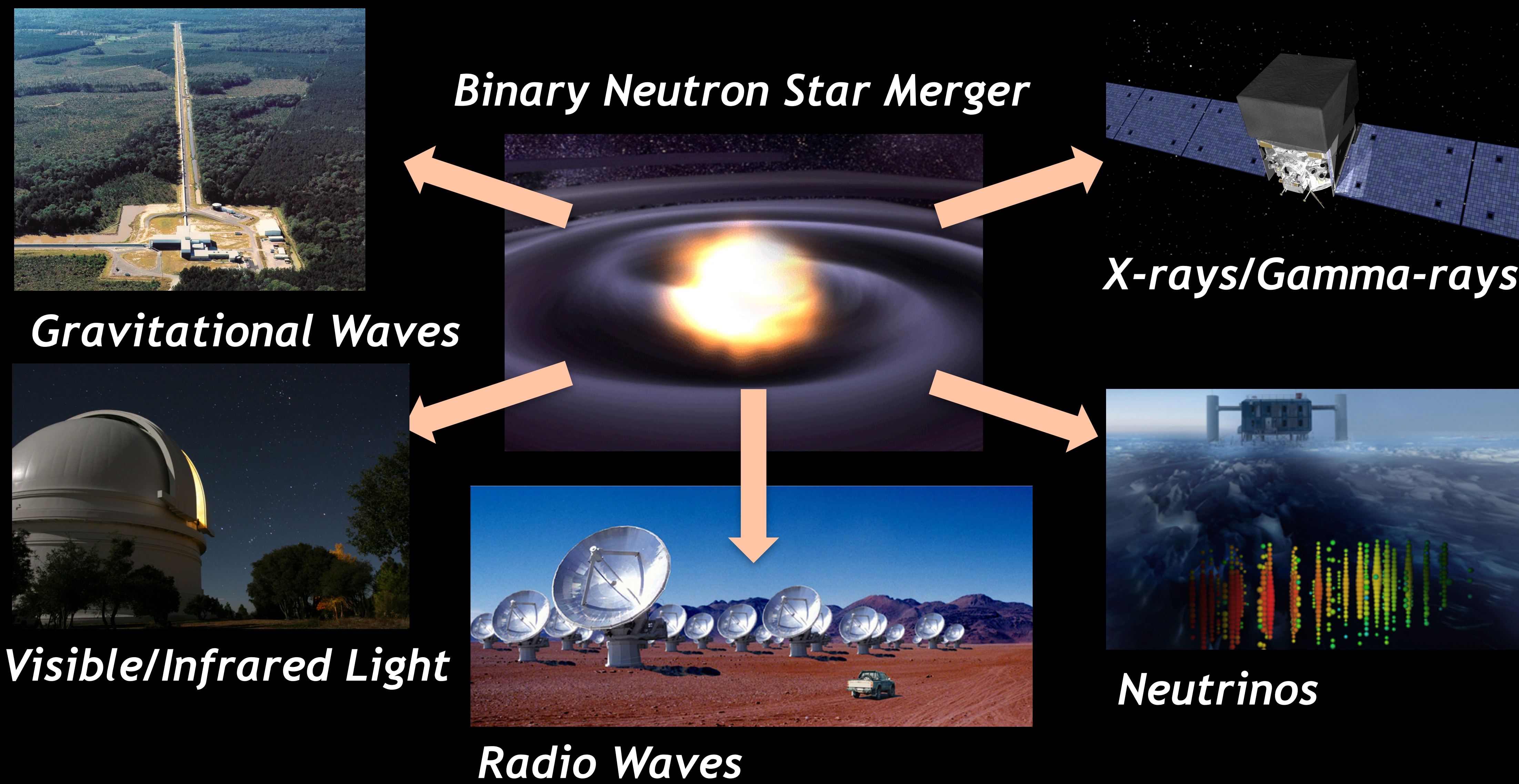
A Three-Detector Observation of Gravitational Waves from a Binary Black Hole Coalescence
Phys. Rev. Lett., 119:141101, 2017

Multi-messenger Astronomy with Gravitational Waves

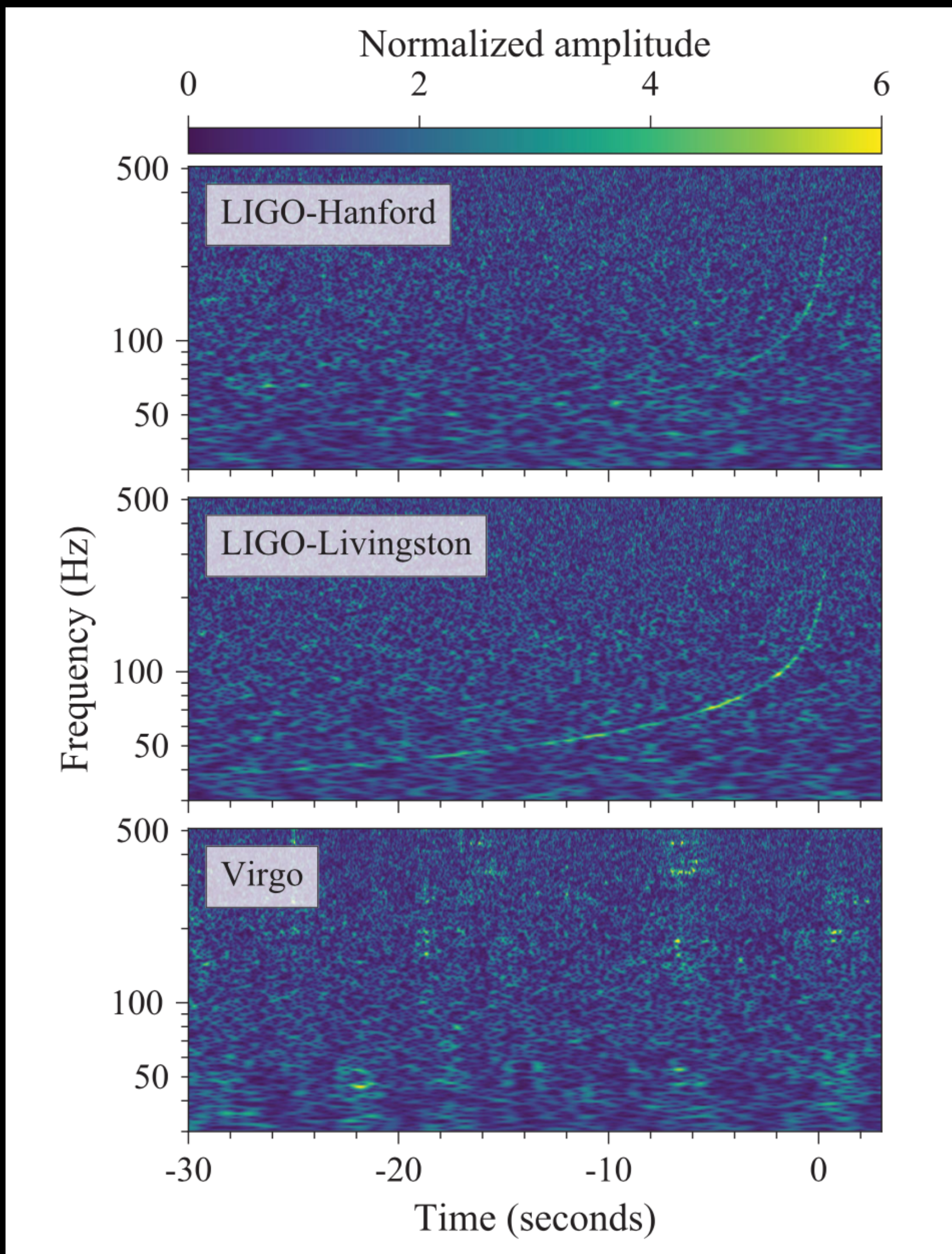


LIGO and Virgo signed agreements with 95 groups for EM/neutrino followup of GW events

- ~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

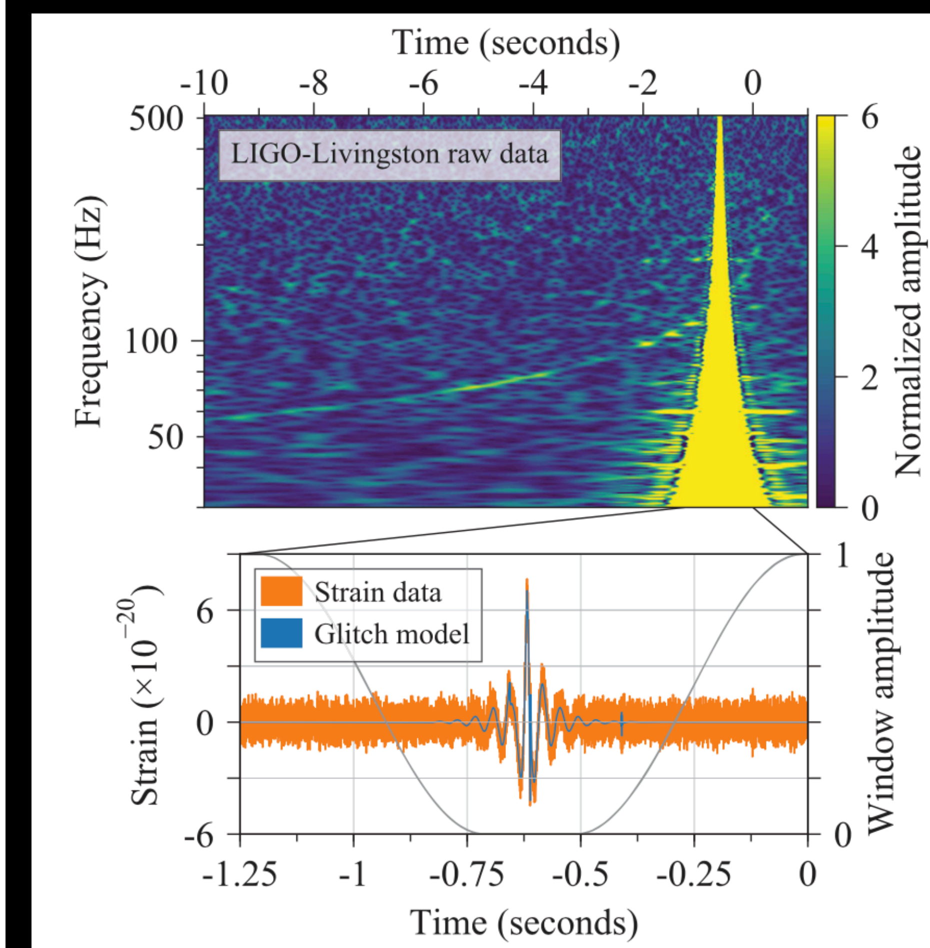
Discovery of a Binary Neutron Star

August 17, 2017 - 12:41:04.4 UTC



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

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



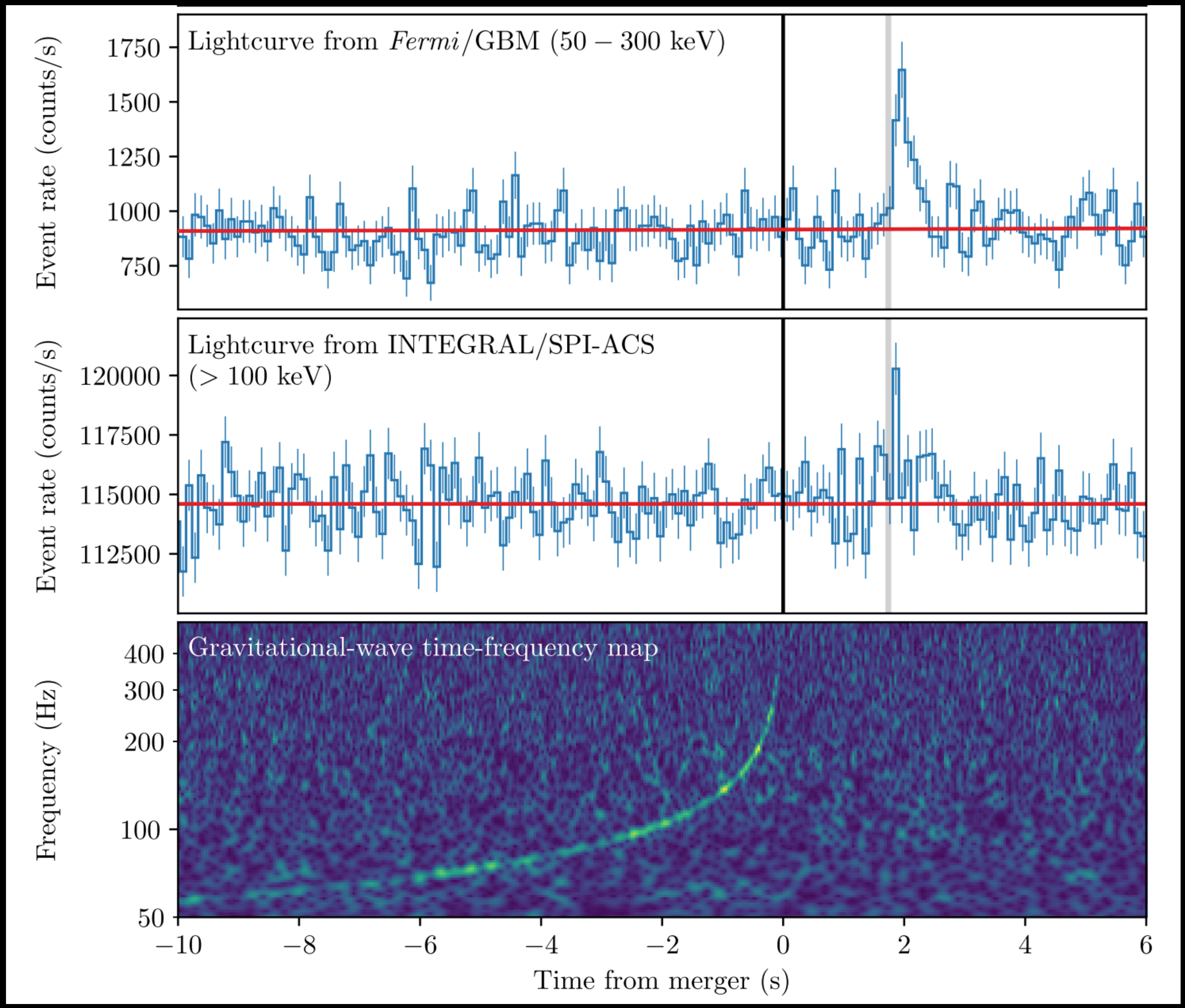
Glitch in L1 1.1 seconds before the coalescence

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



Gravitational Waves and Gamma Rays from a Binary Neutron Star Merger: GW170817 and GRB 170817A
The Astrophysical Journal Letters, 848:L13, 2017

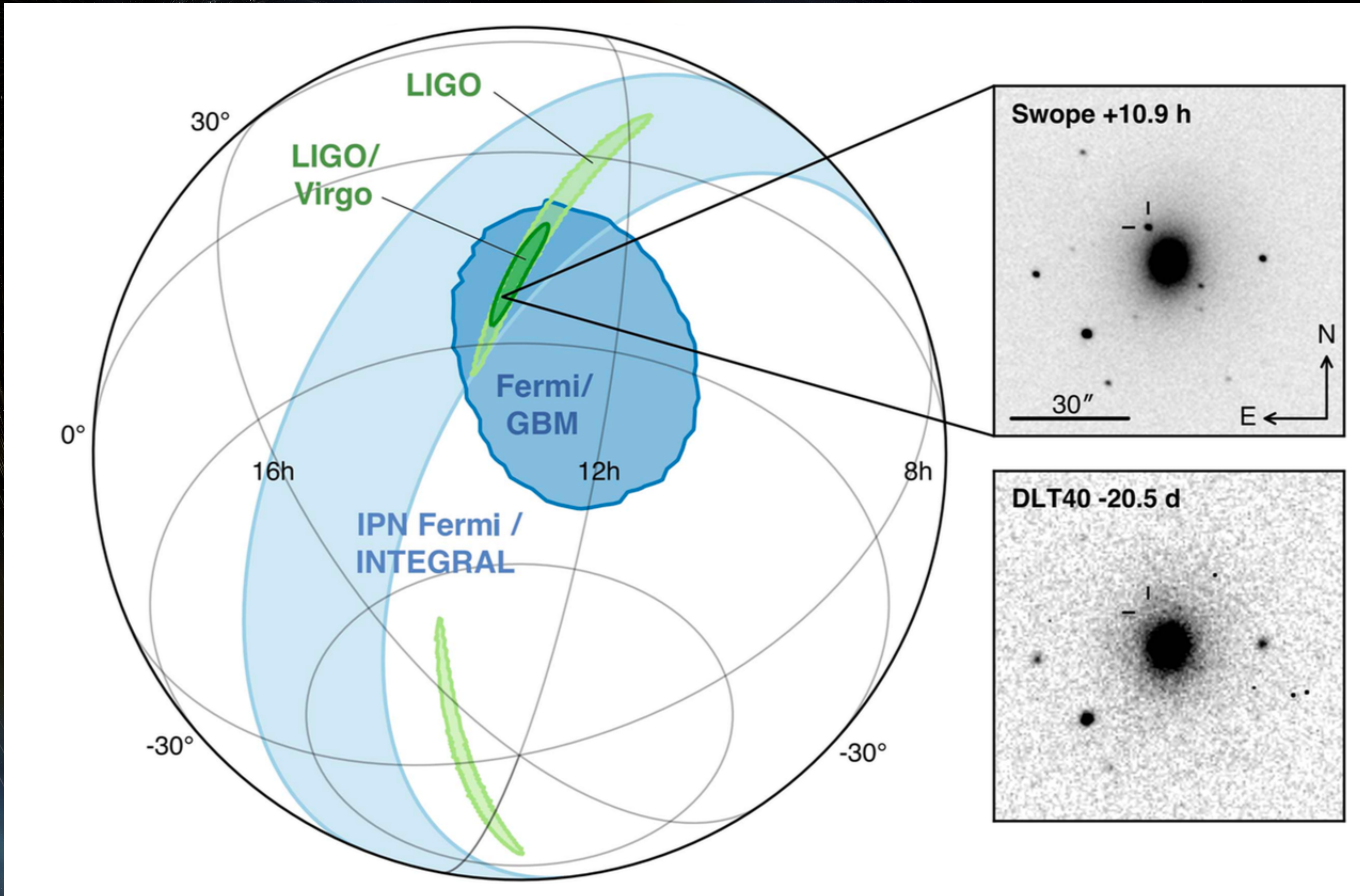
GRB 170817A occurs (1.74 ± 0.05) seconds after GW170817

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

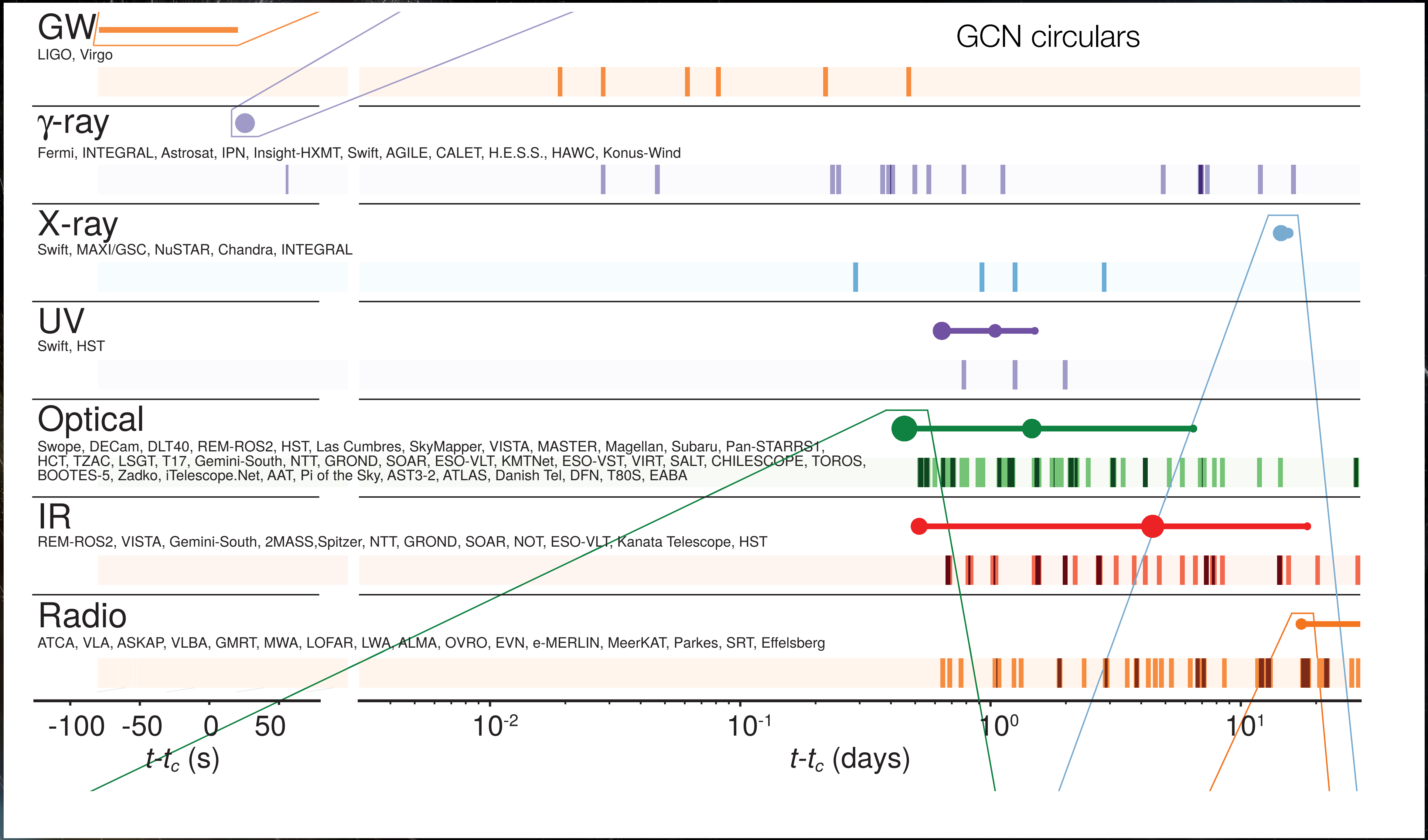
Probability that GW170817 and GRB 170817A occurred this close in time and with location agreement by chance is 5.0×10^{-8} (Gaussian equivalent significance of 5.3σ)

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

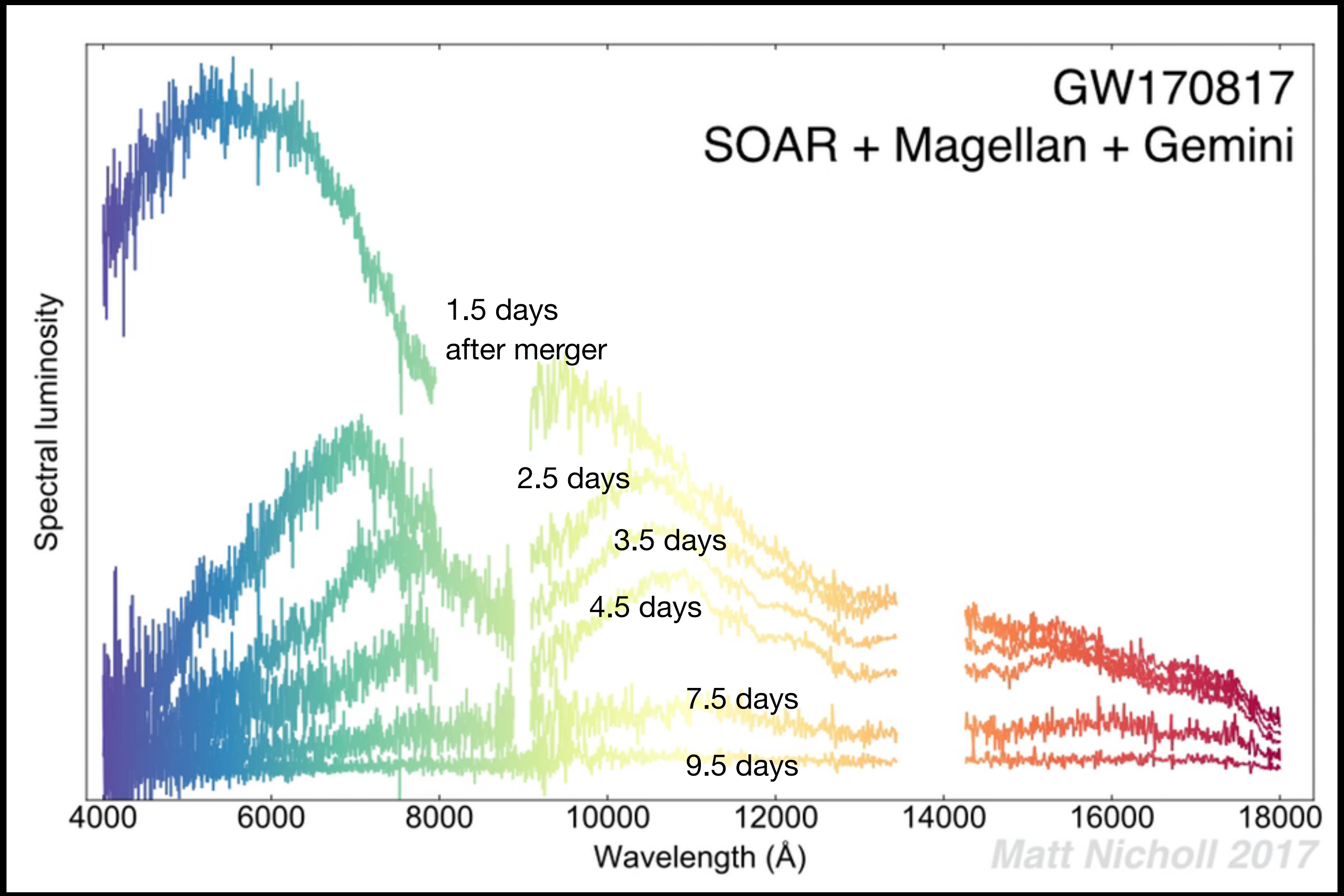
Kilonova

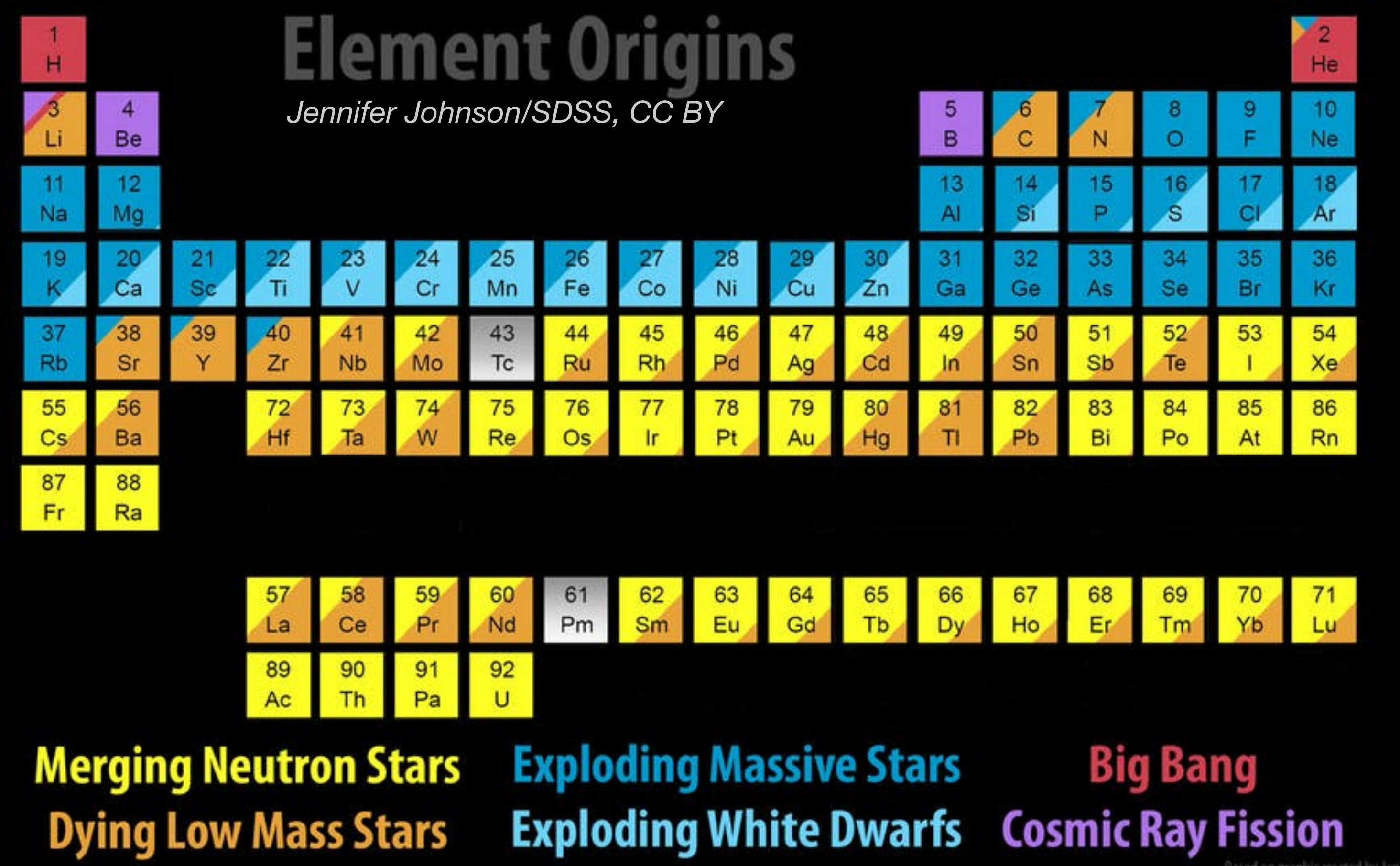
SSS17a

August 17, 2017

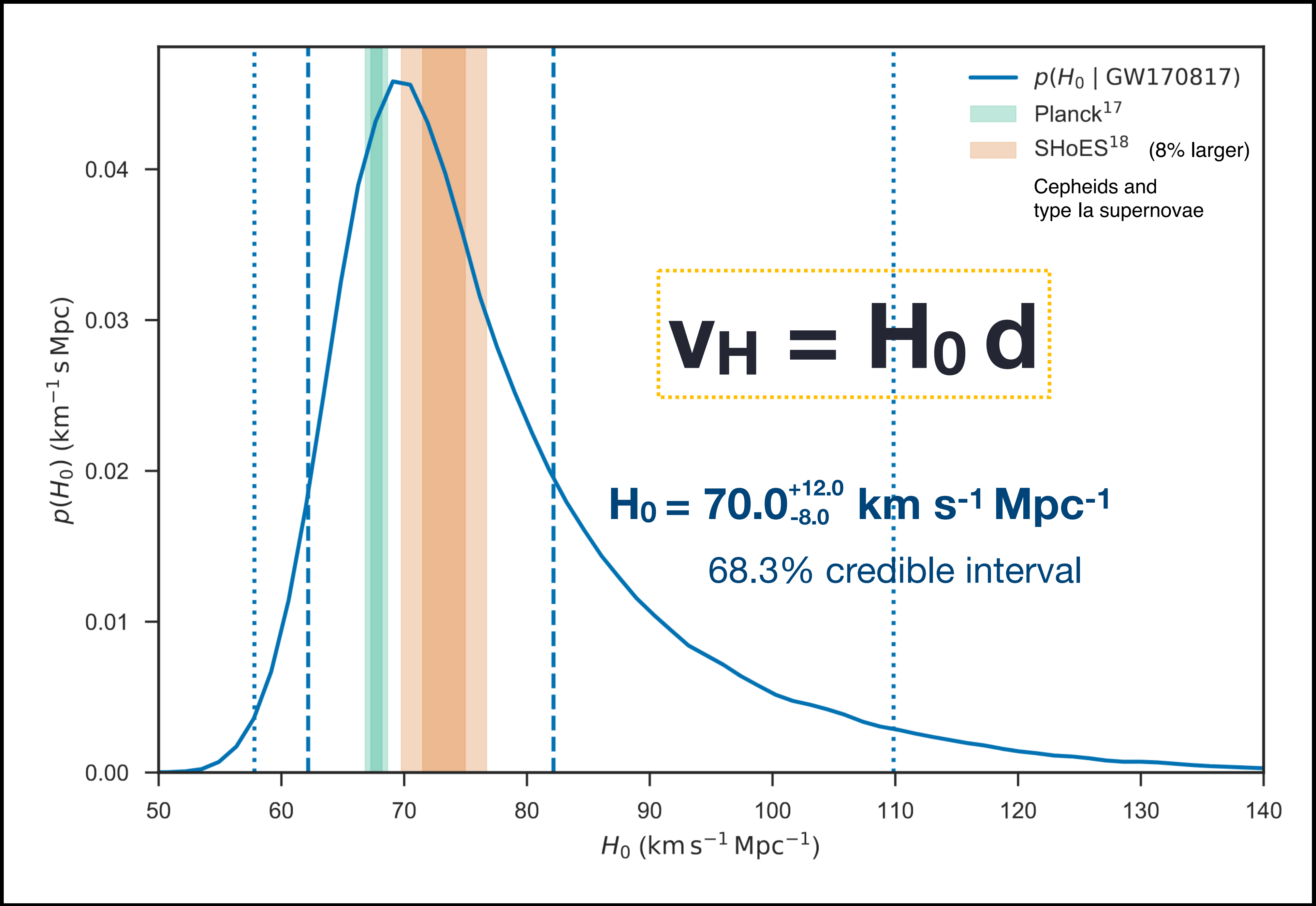
August 21, 2017

Swope & Magellan Telescopes





BNS as Standard Sirens



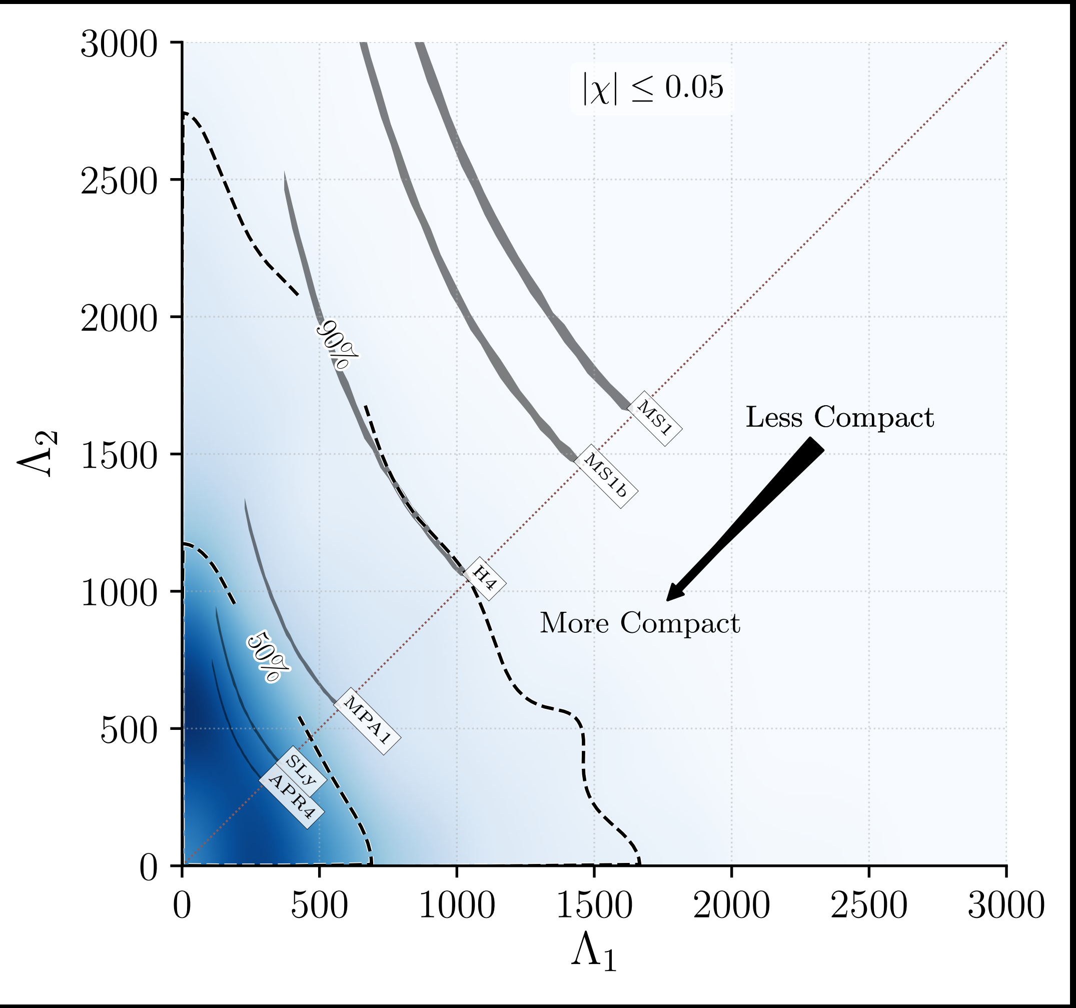
A gravitational-wave standard siren measurement of the Hubble constant
Nature, 551:85, 2017

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

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

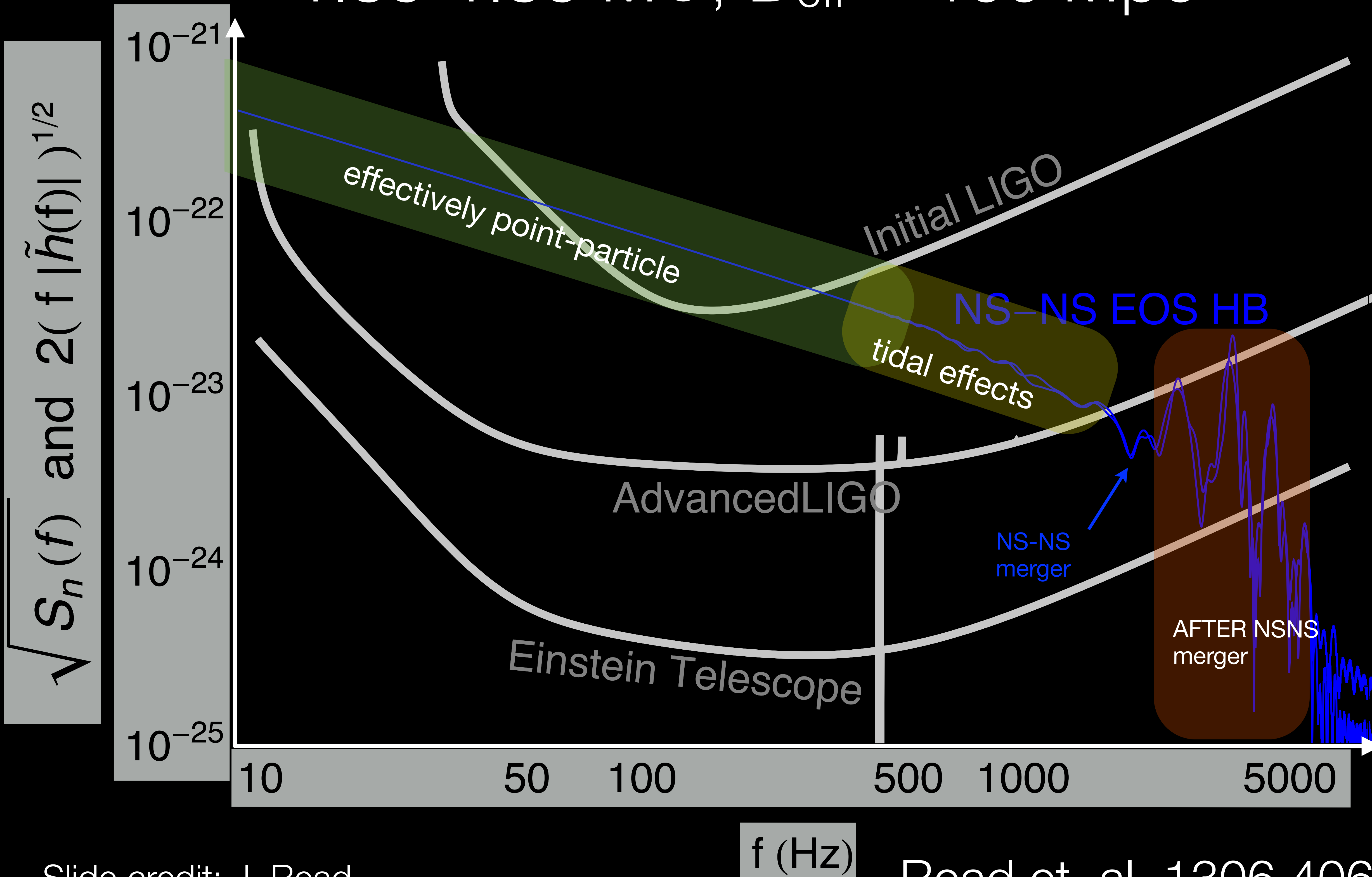
GW170817: Observation of Gravitational Waves from a Binary Neutron Star Inspiral
Phys. Rev. Lett., 119:161101, 2017

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⊙, D_{eff} = 100 Mpc



Slide credit: J. Read

Read et. al. 1306.4065

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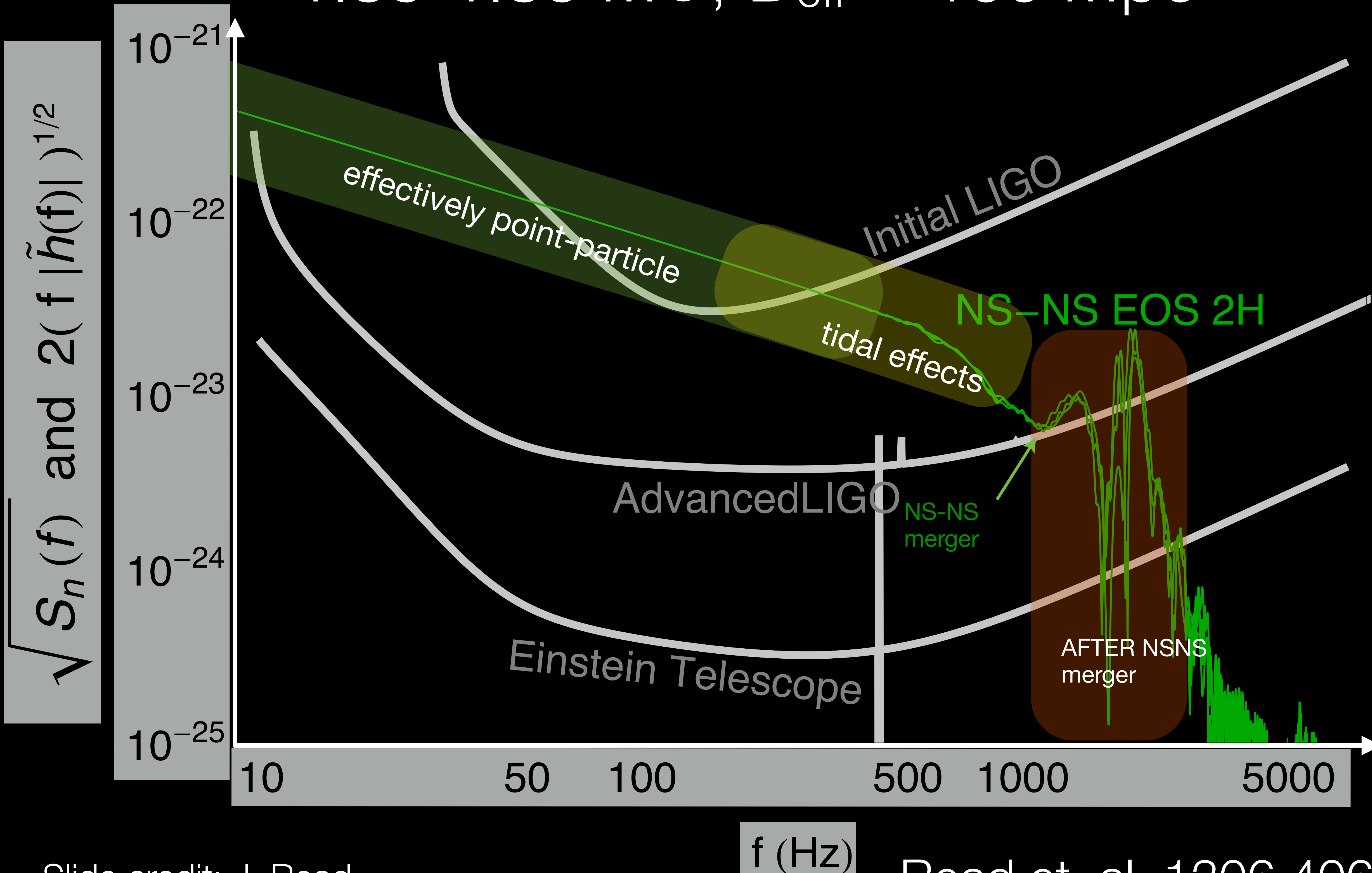
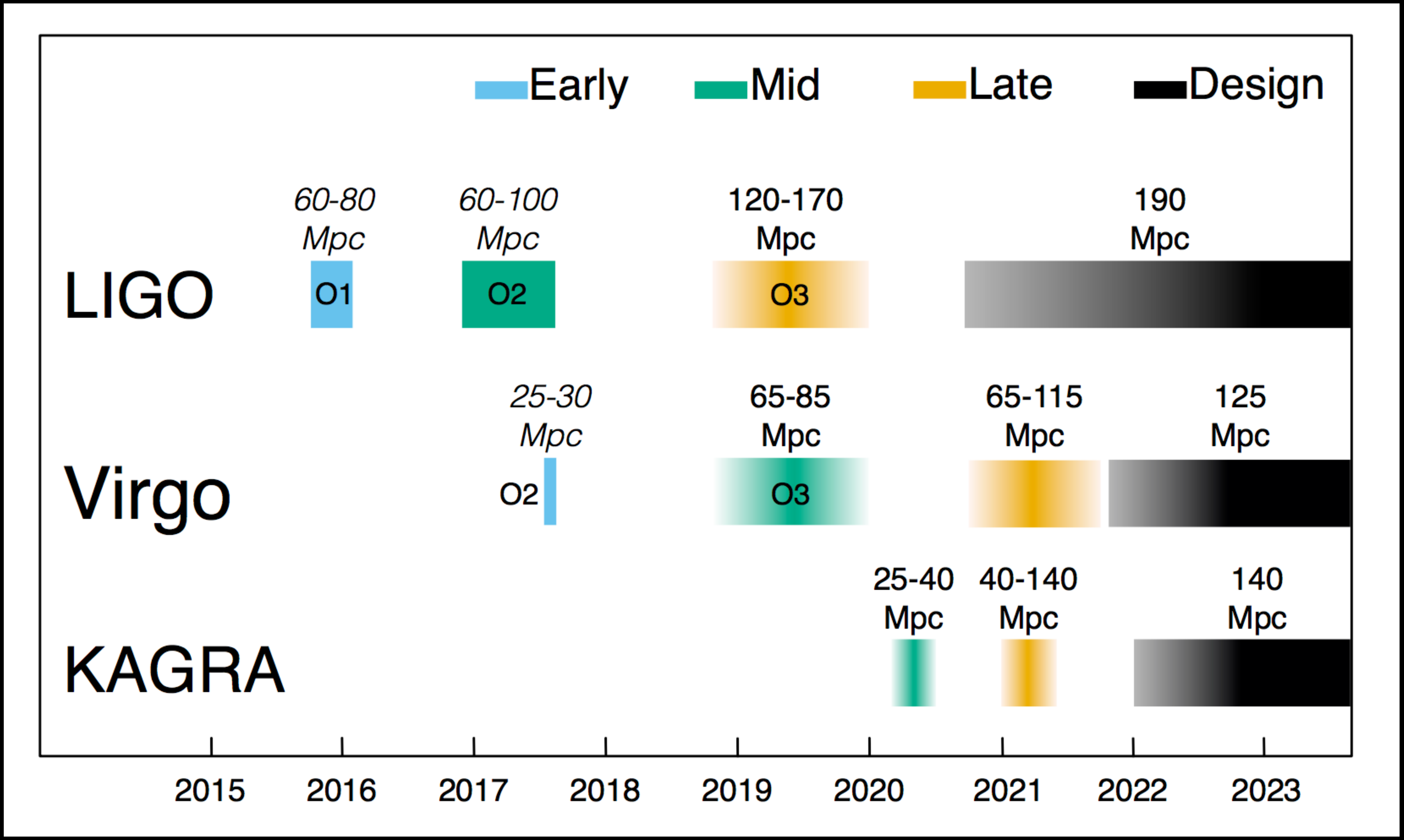


Slide credit: J. Read

Read et. al. 1306.4065

Observing Scenarios

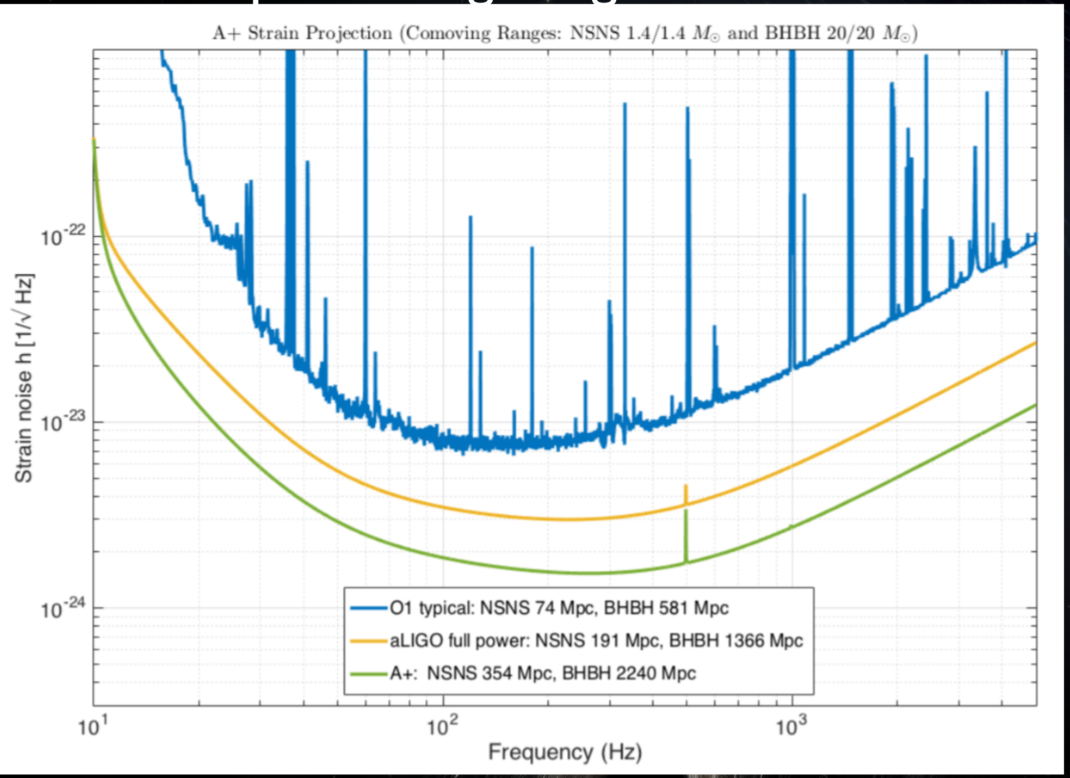


Prospects for Observing and Localizing Gravitational-Wave Transients with Advanced LIGO and Advanced Virgo and KAGRA
https://dcc.ligo.org/LIGO-P1200087/public

Near Term Future: The Next Decade

Advanced LIGO Plus (A+)

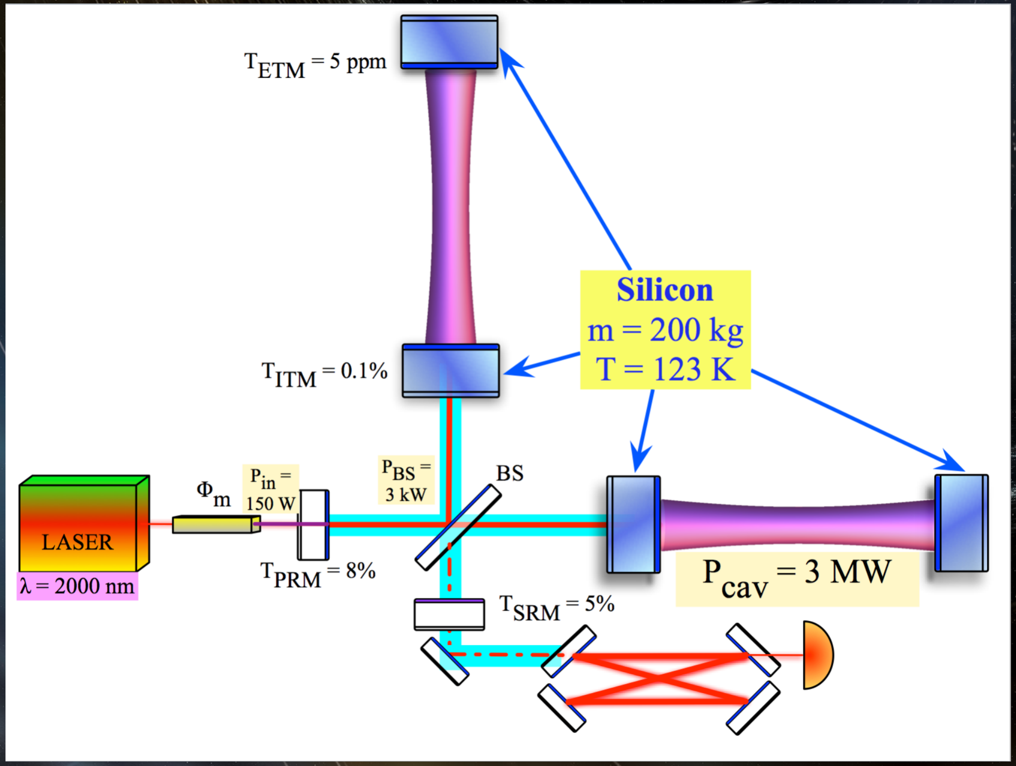
https://dcc.ligo.org/LIGO-G1600769/



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

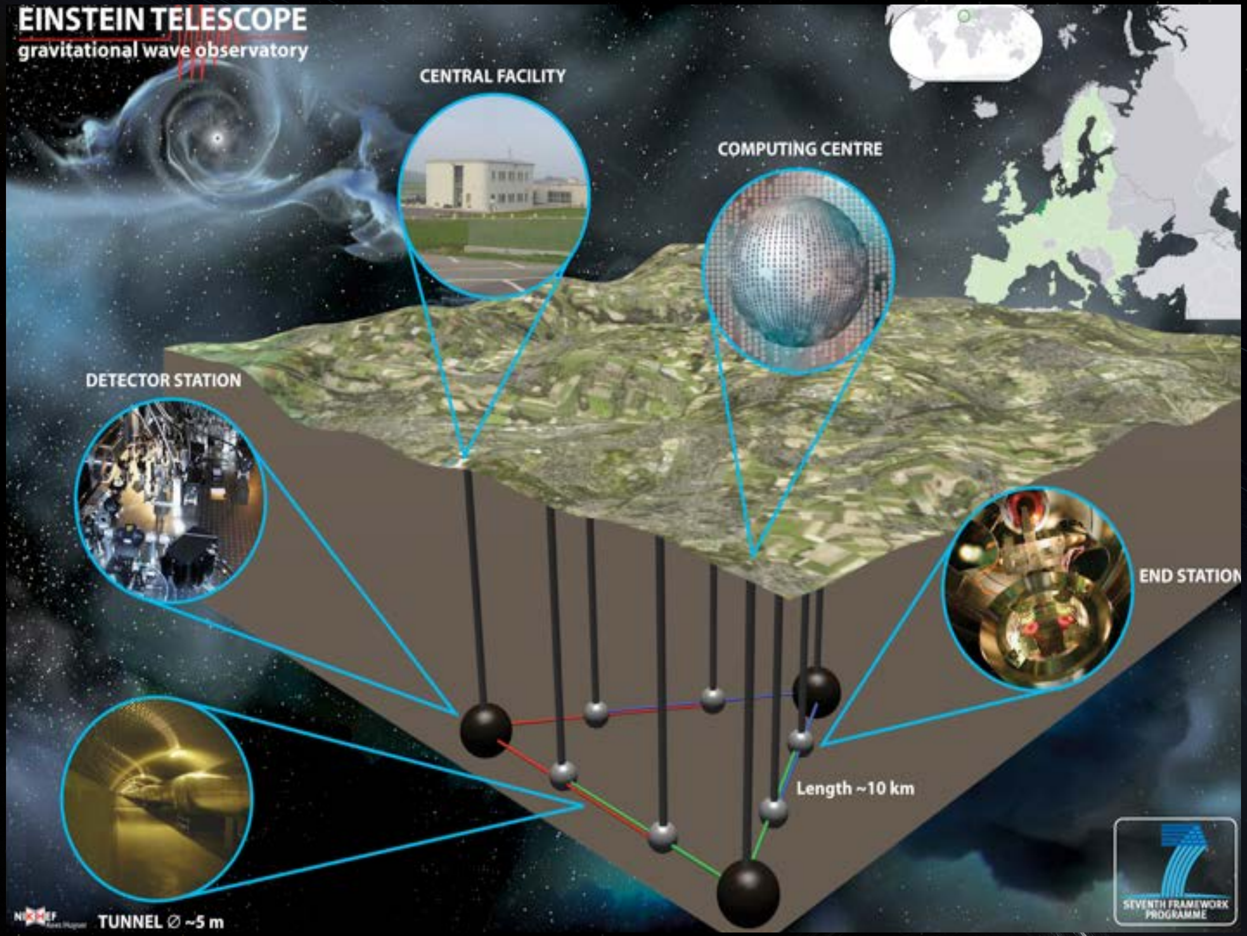
3G detectors

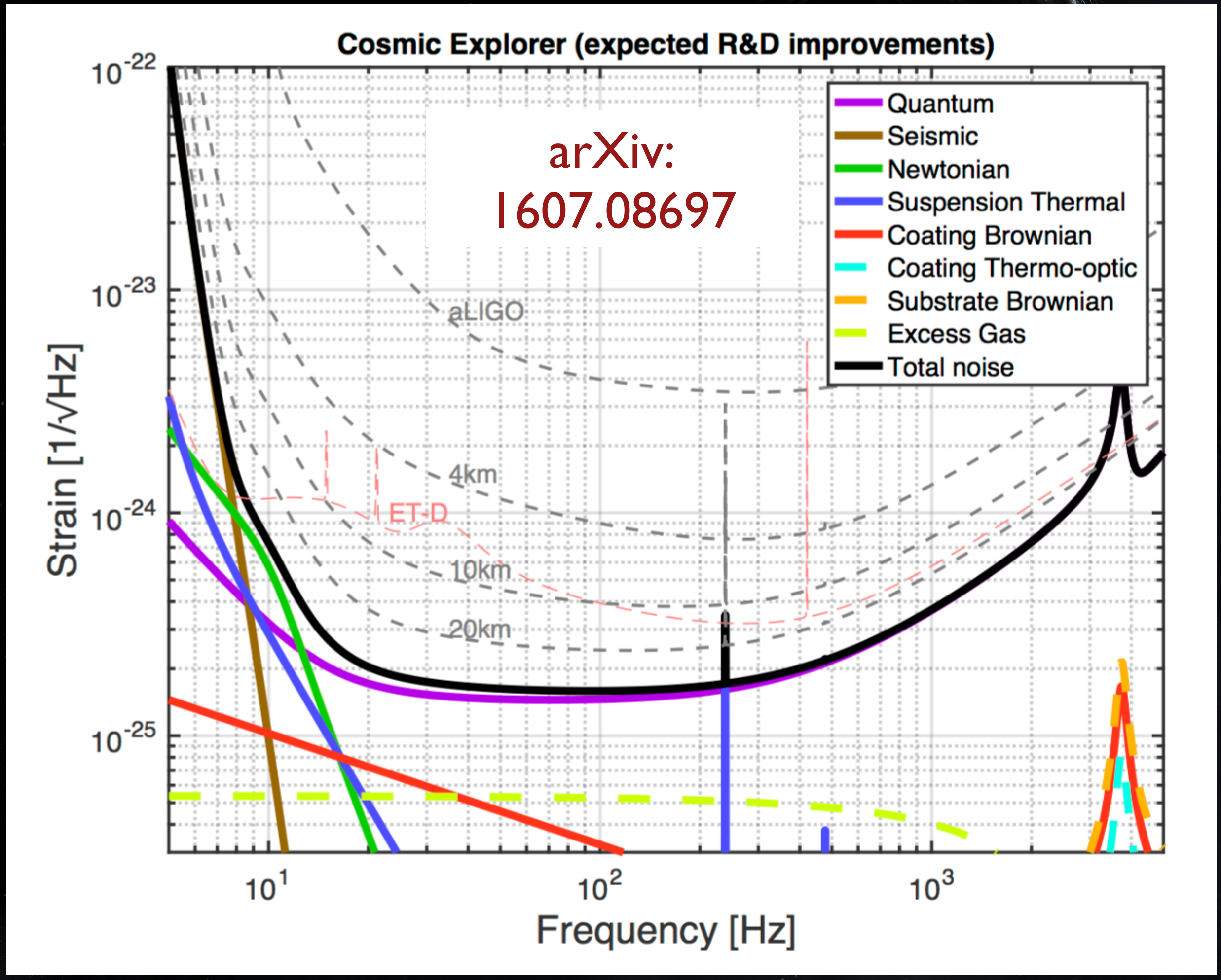
Einstein Telescope

- 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

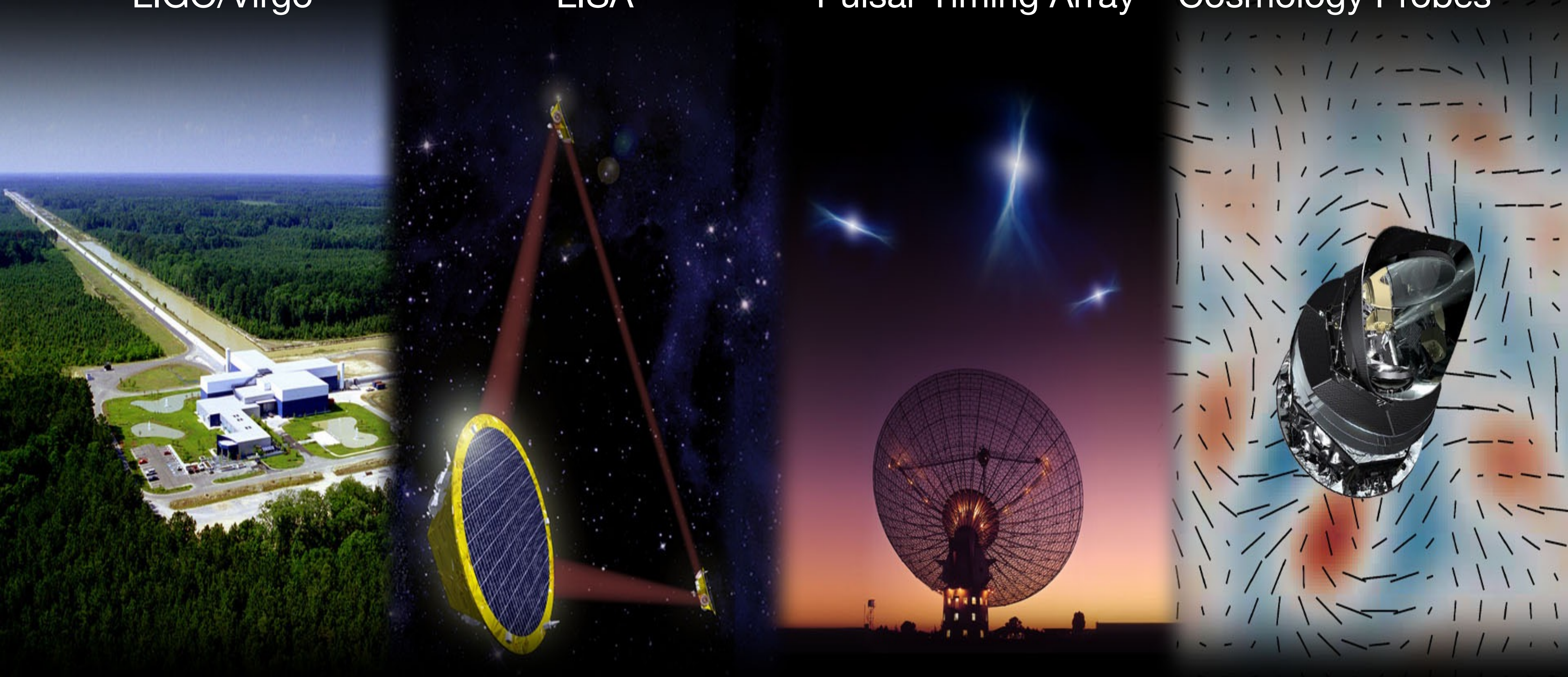
- US-based design just starting
- Based on LIGO Voyager technology, expanded to 40 km arms.

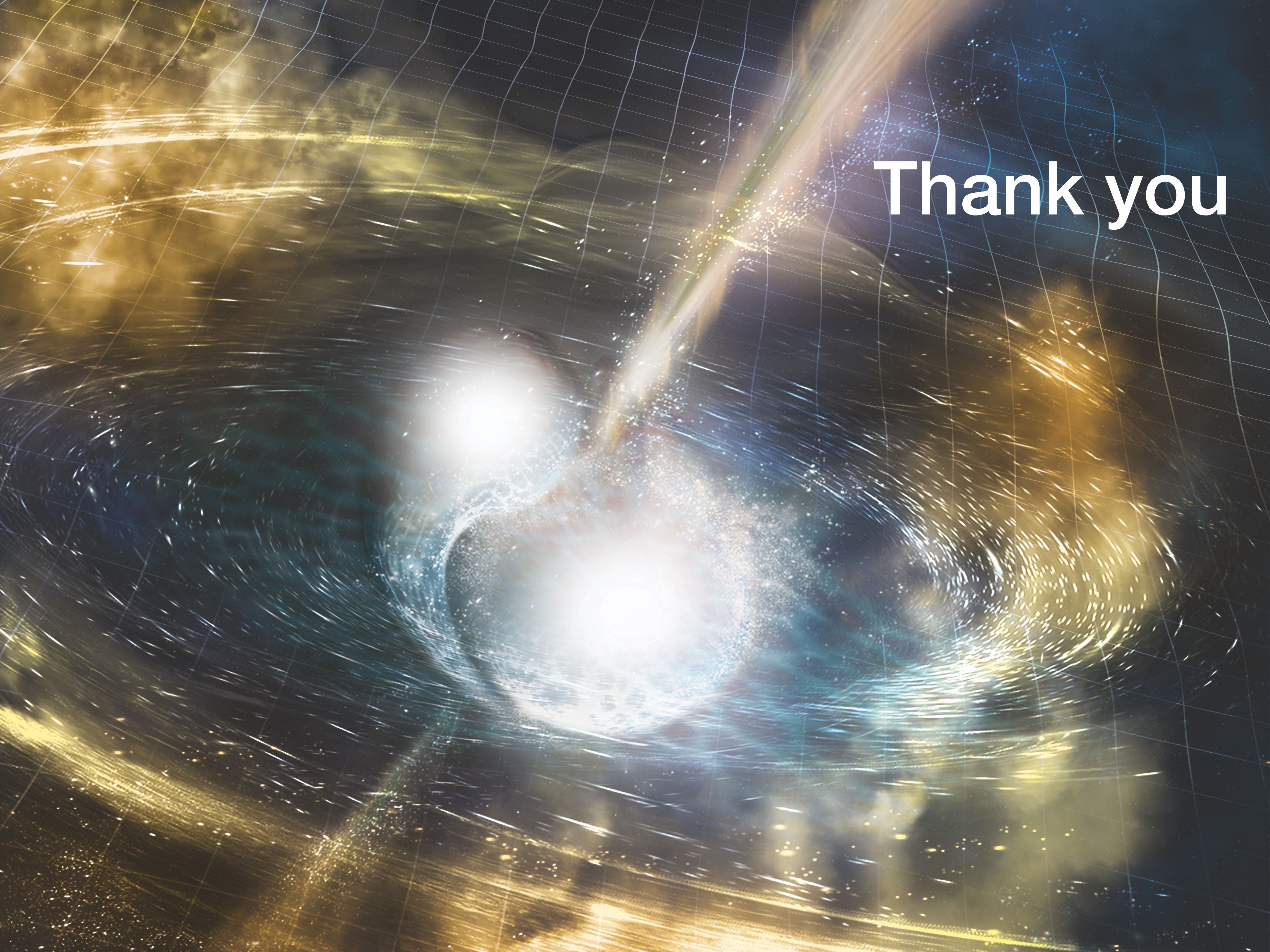




Gravitational Wave Periods

Milliseconds	Minutes to Hours	Years to Decades	Billions of Years
LIGO/Virgo	LISA	Pulsar Timing Array	Cosmology Probes




Thank you