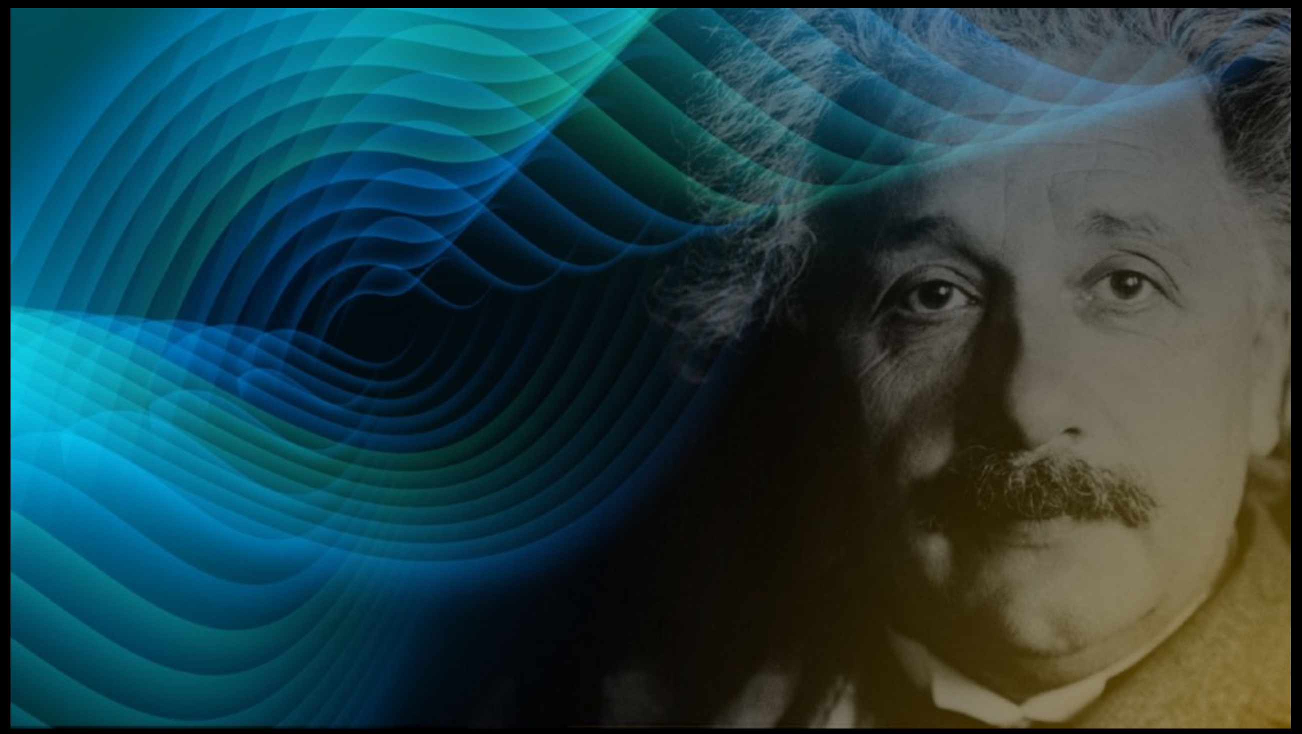
Gravitational Waves: status and prospects

Laura Cadonati, Georgia Tech
LIGO Scientific Collaboration

EDSU-2018, Guadeloupe - June 25, 2018

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

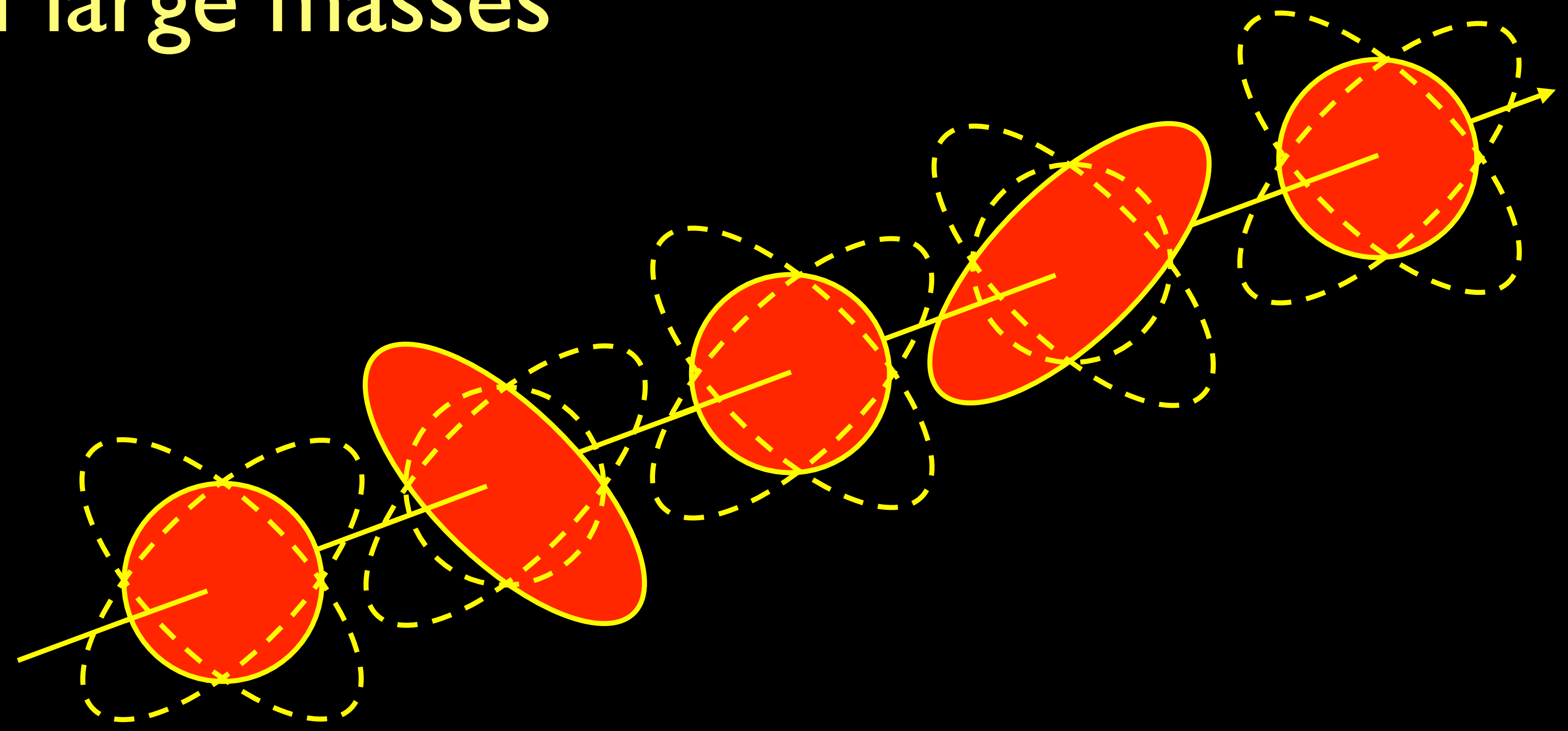
Gravitational Waves: Einstein's Messengers



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

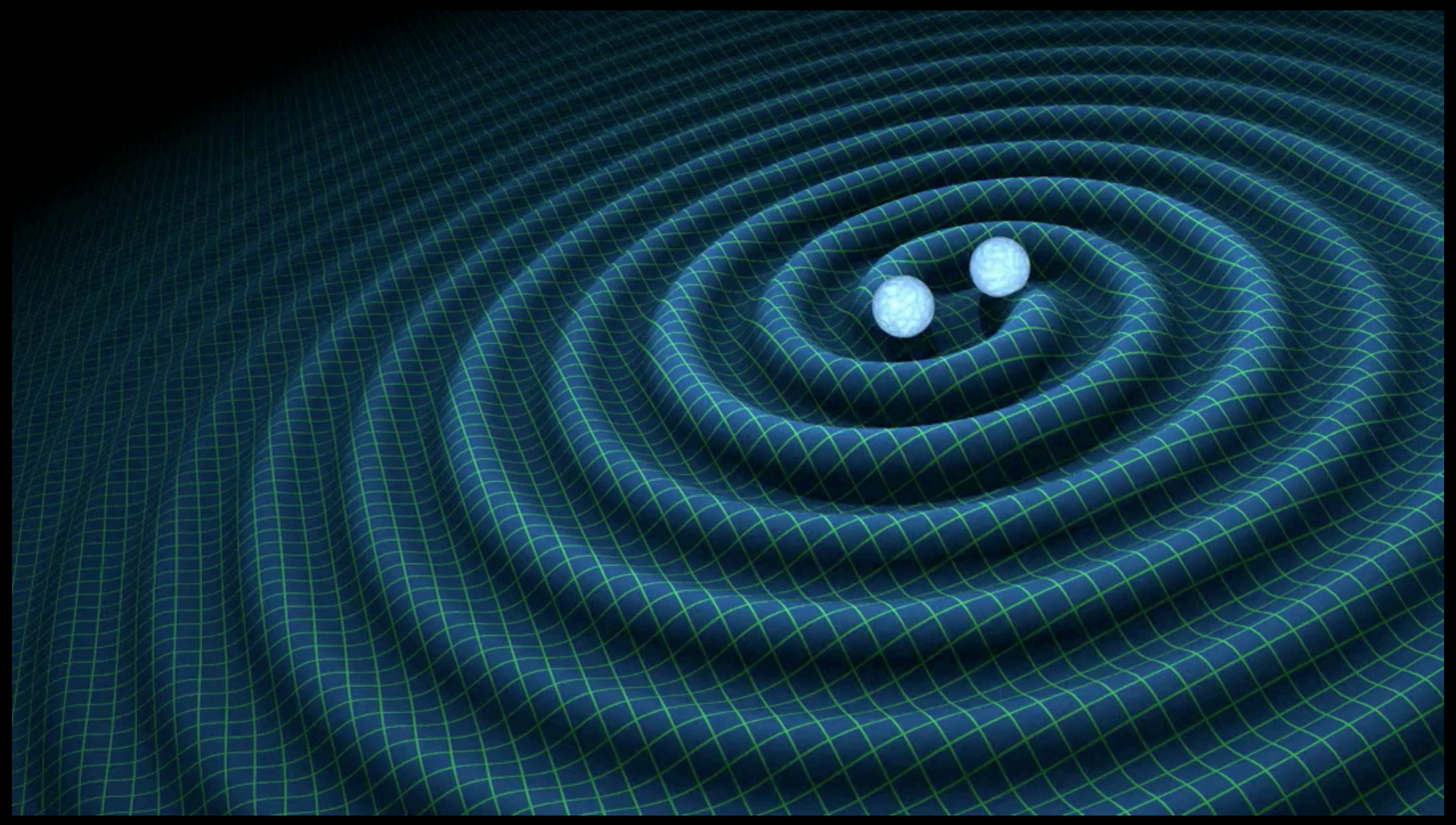
$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$$

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



speed of light

2 polarizations (plus, cross)



Credits: R. Hurt - Caltech / JPL

Dimensionless strain:

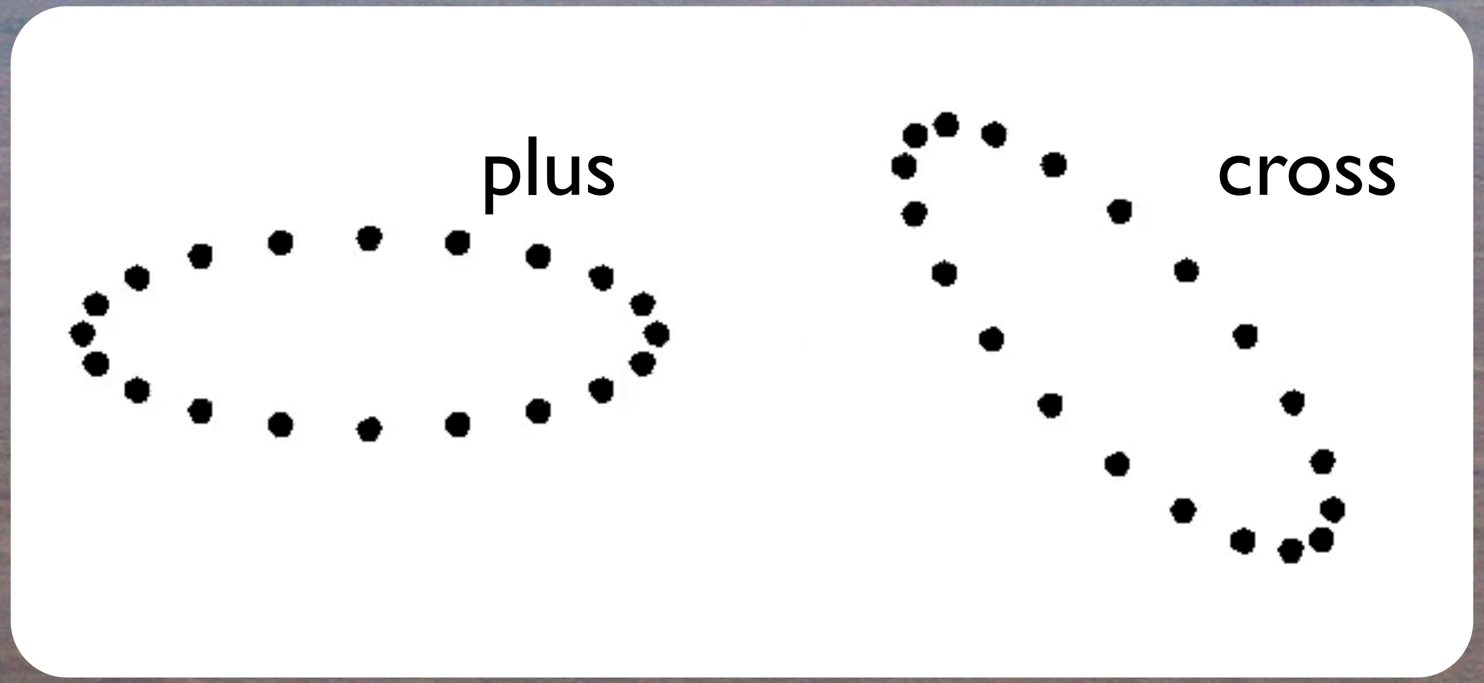
$$h(t) = \frac{1}{R}\frac{2G}{c^4}\ddot{I}(t)$$

I = source mass quadrupole moment

R = source distance

How to Detect Gravitational Waves

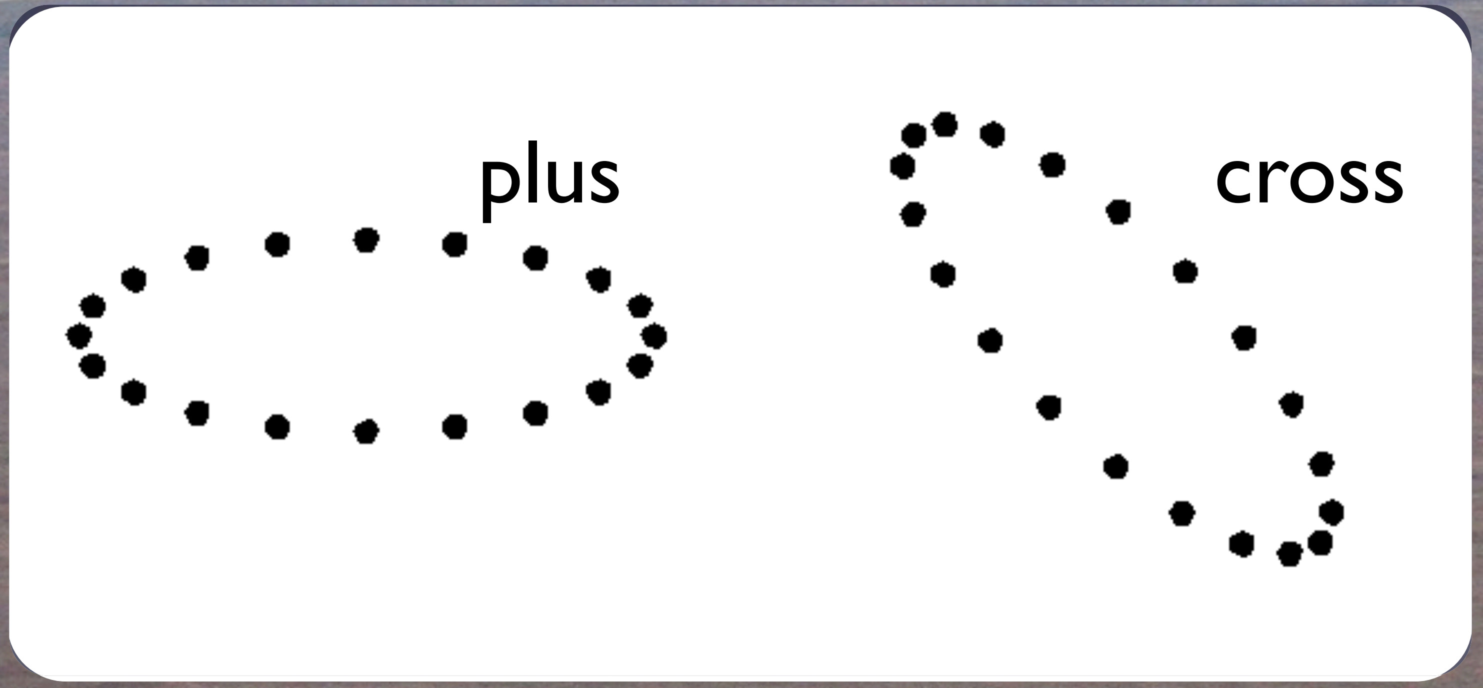
Physically, gravitational waves are strains



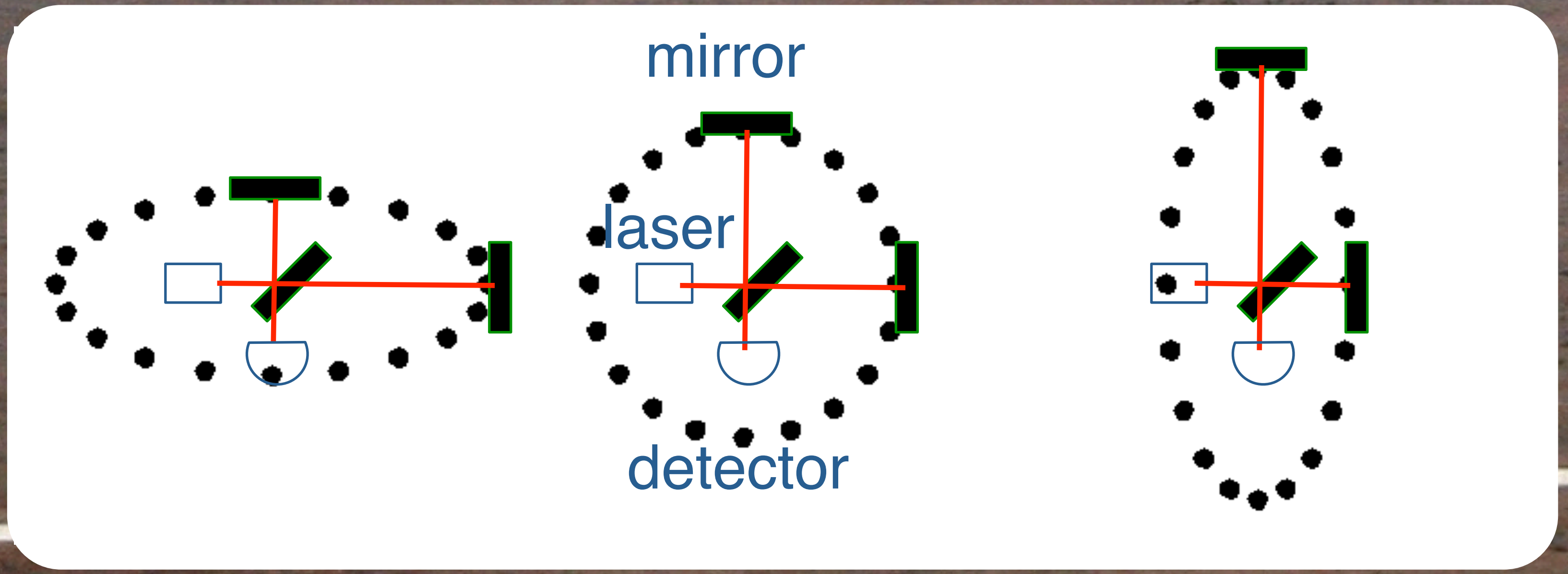
Deformation of a ring of free-falling particles due to the + and x polarization

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

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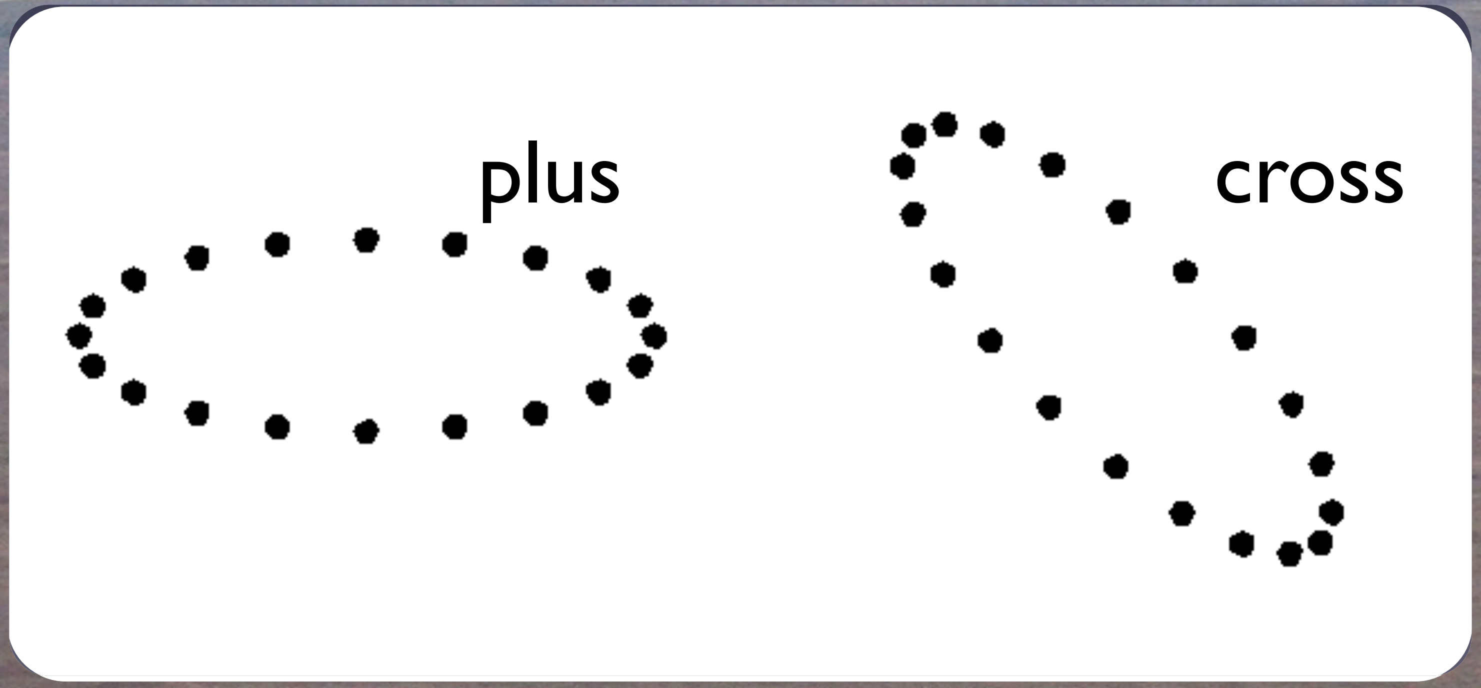

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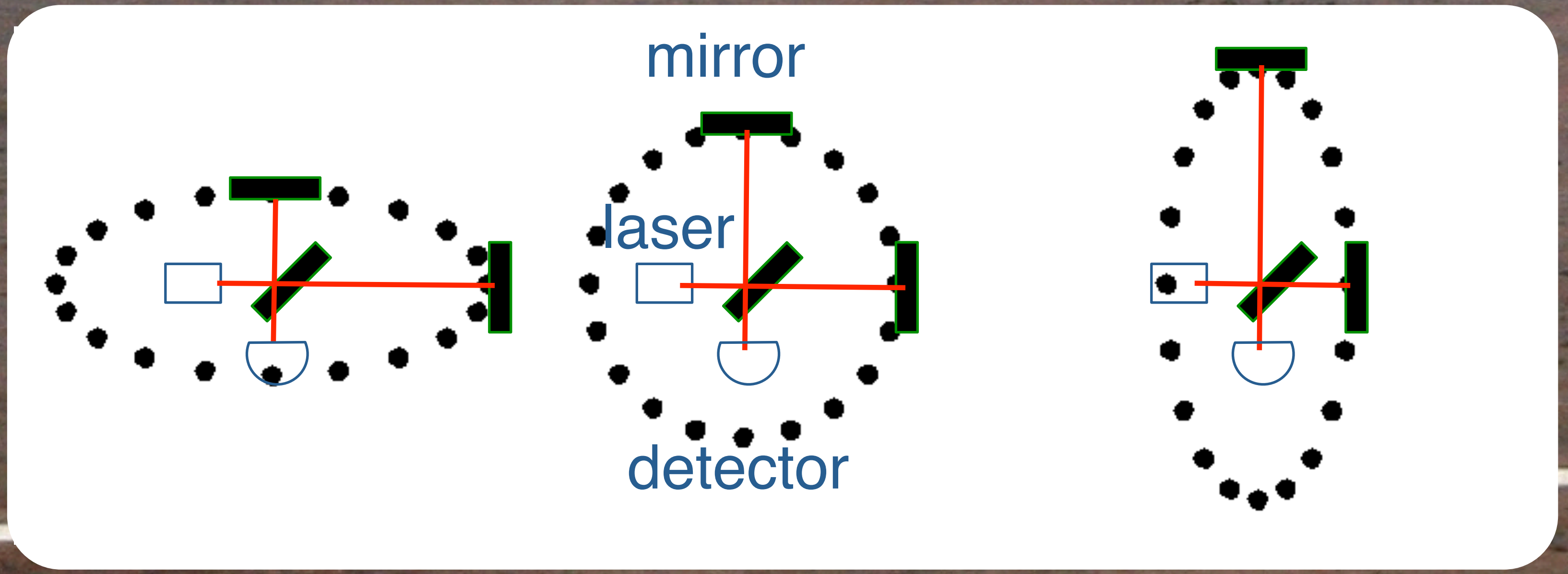
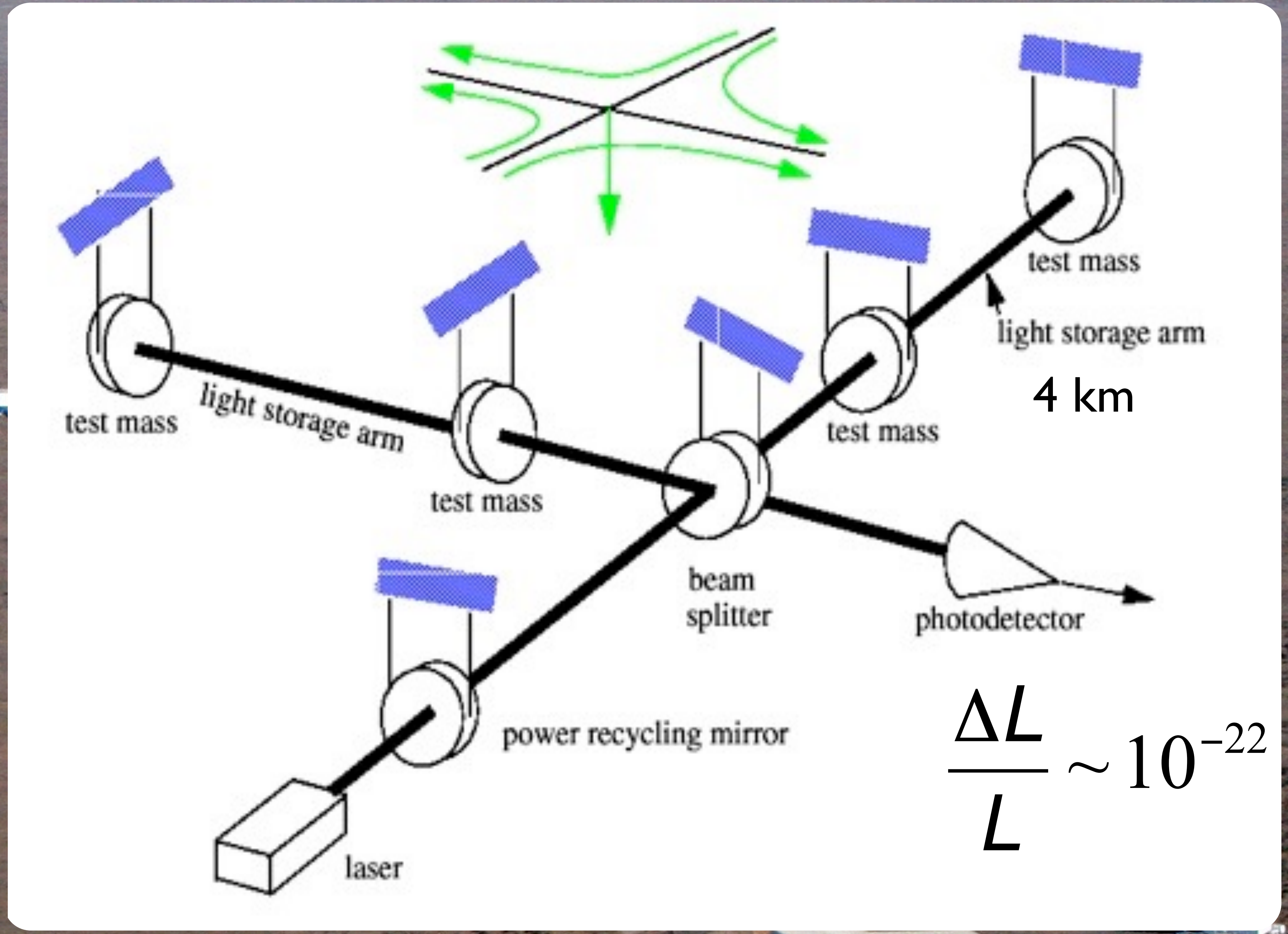


Suspended Mirrors as Test Masses



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

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

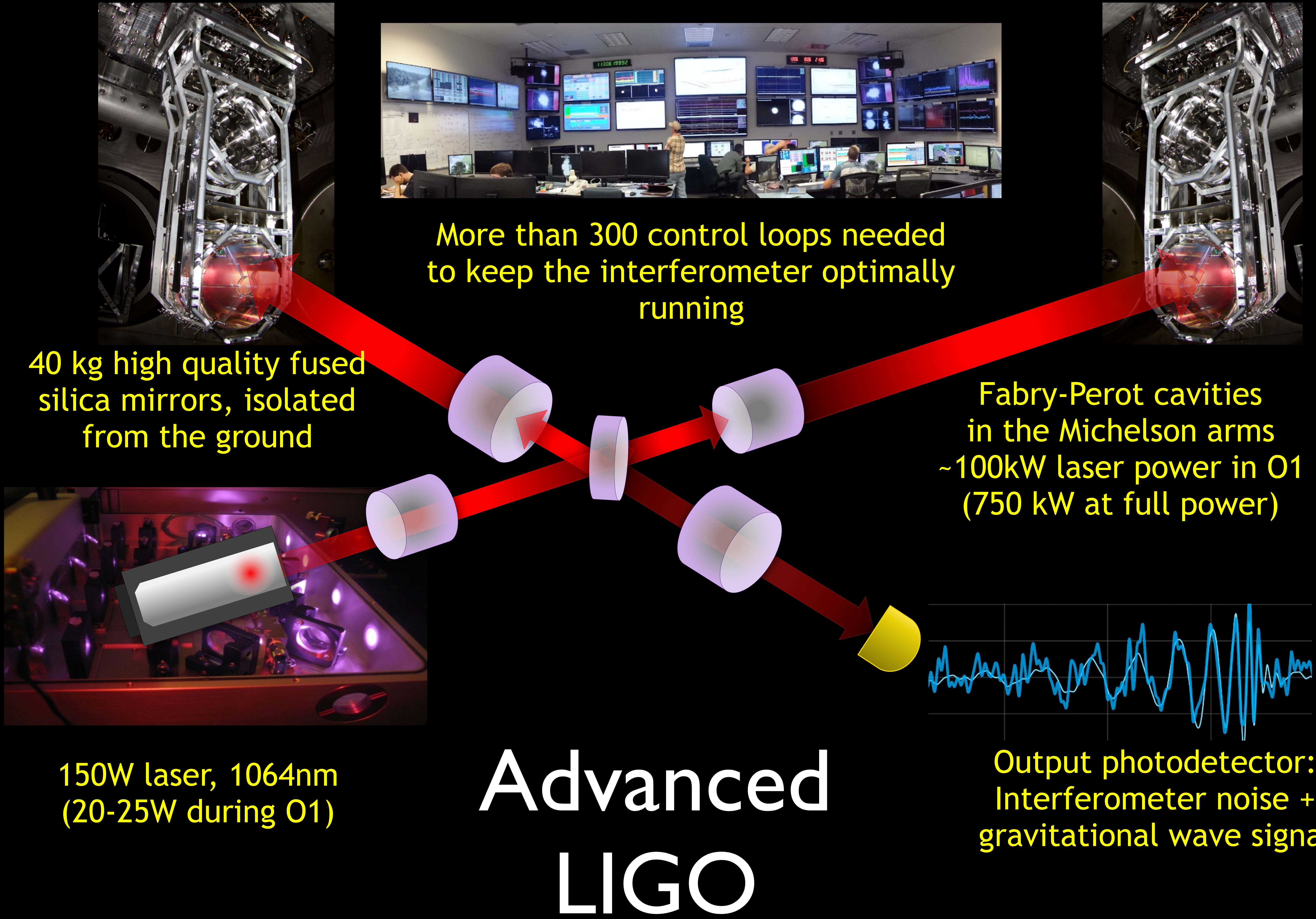
LIGO: Laser Interferometer Gravitational-wave Observatory

Hanford, WA

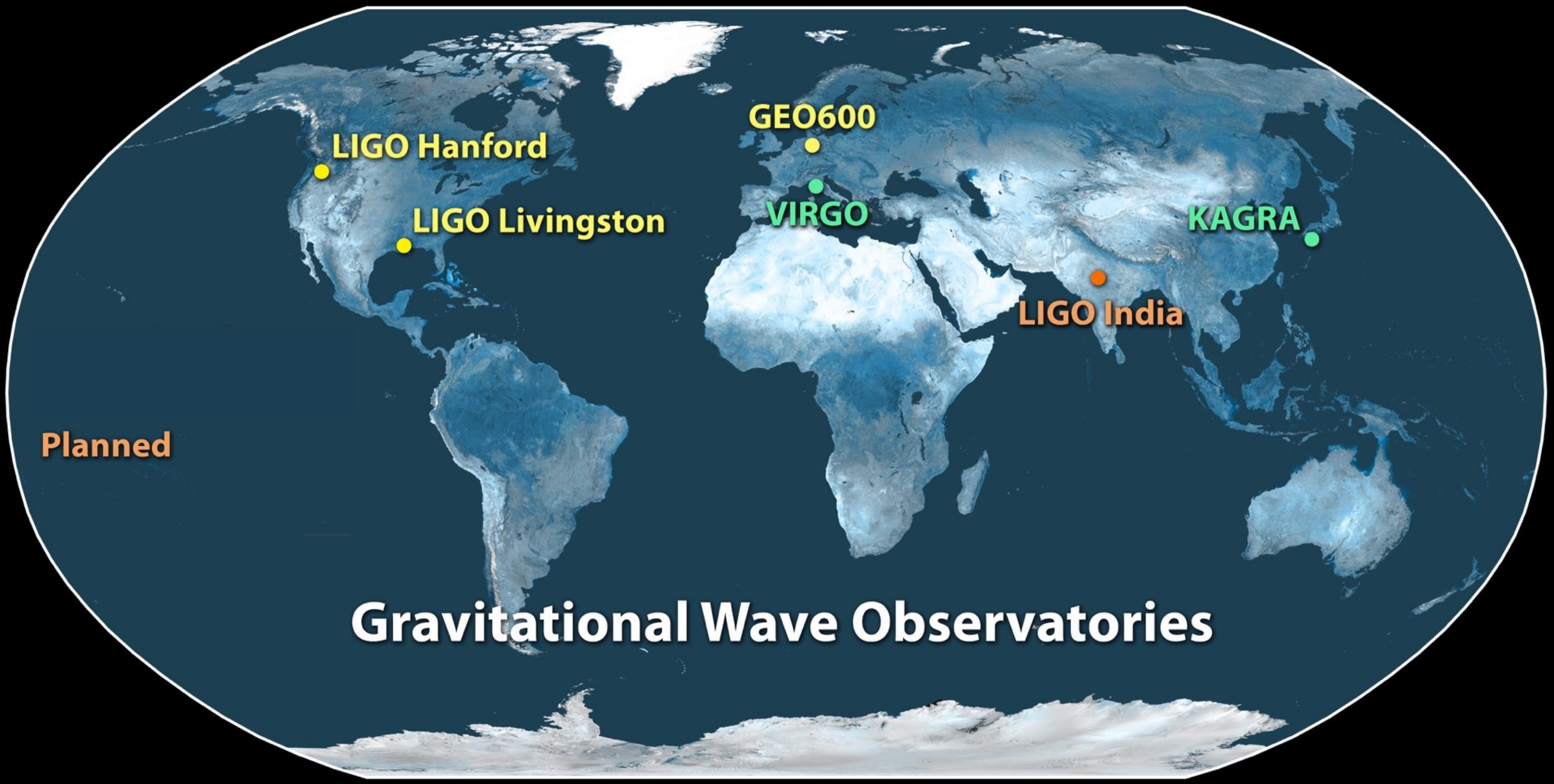
Livingston, LA

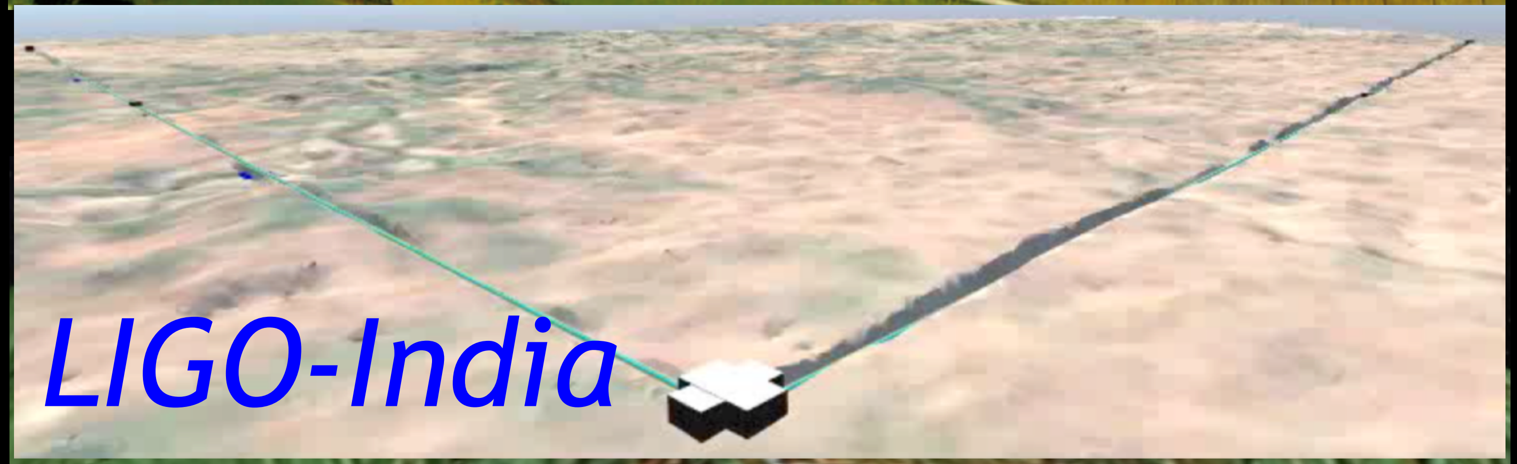
The LIGO Laboratory is jointly operated by Caltech and MIT through a Cooperative Agreement between Caltech and the National Science Foundation

- LIGO Observatories construction: 1994-2000
- Initial LIGO operation: 2002-2010
- Advanced LIGO:
  - O1: Sept 12, 2015 - Jan 12, 2016
  - O2: Dec 1, 2016 - Aug 25, 2017


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)
Advanced LIGO
Output photodetector: Interferometer noise + gravitational wave signal

A Global Quest





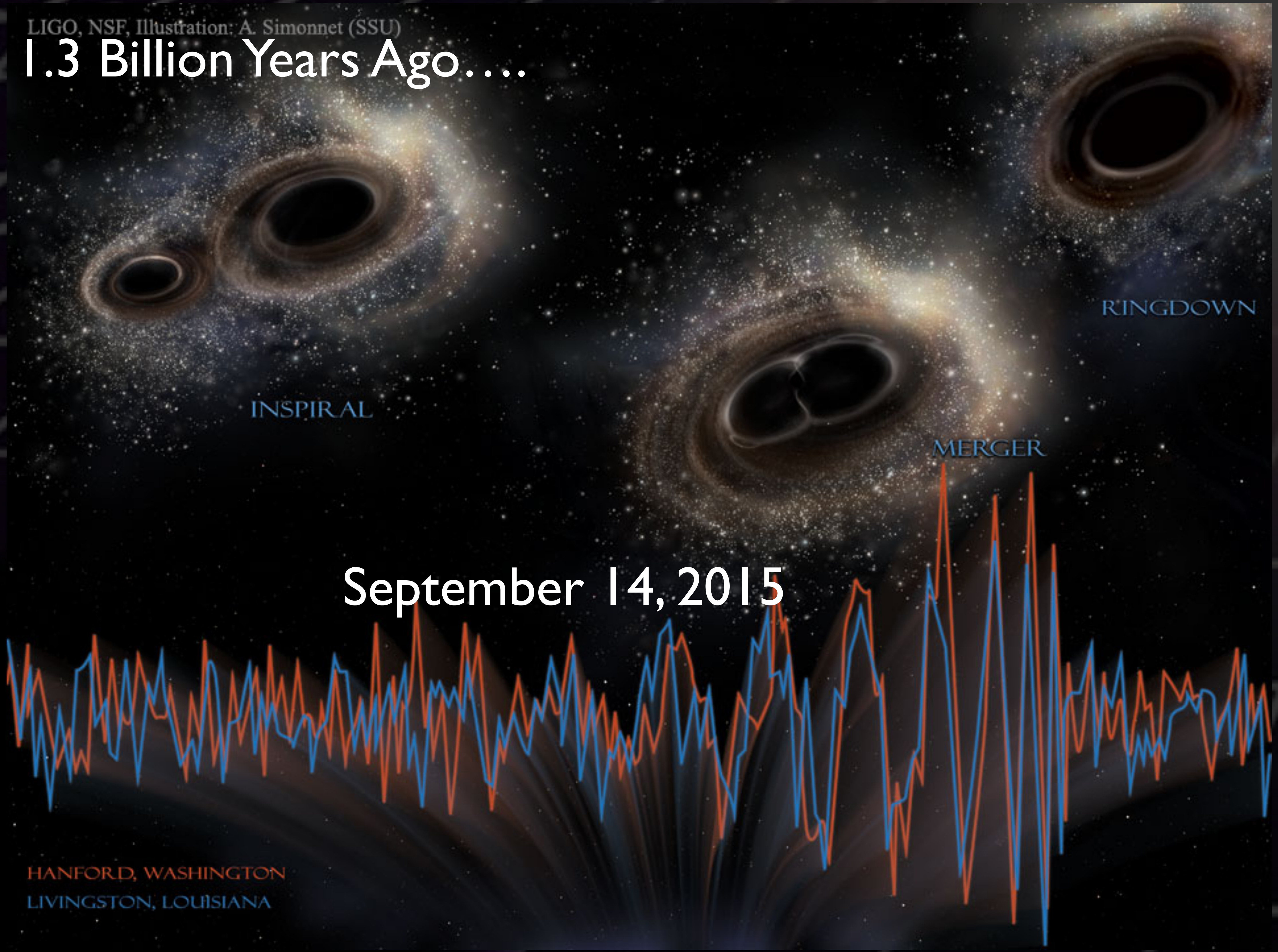
LIGO Scientific Collaboration

LIGO LSC

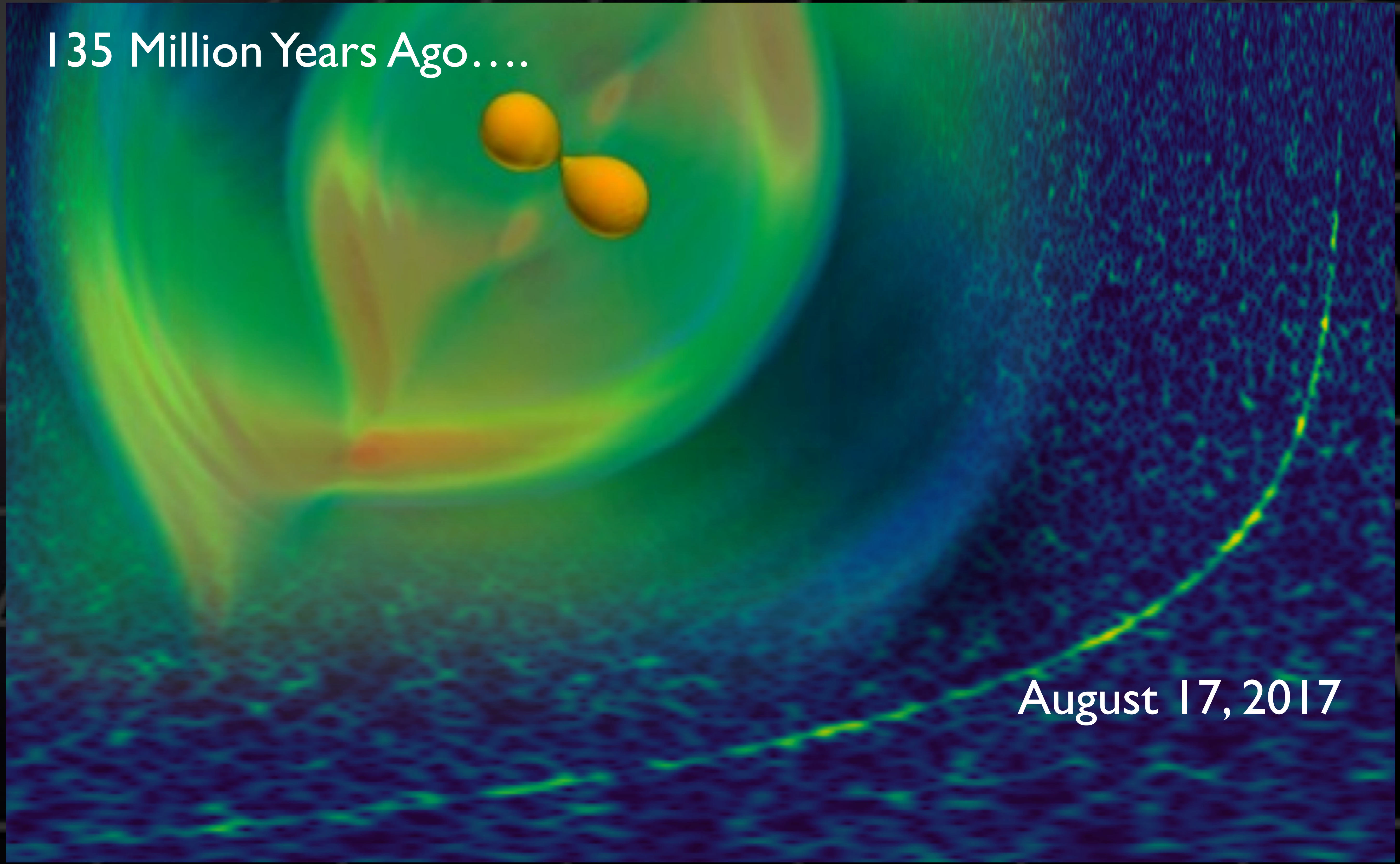
~ 1200 members ~ 100 institutions, 18 countries

Caltech
American University Washington, DC
Andrews University
Washington State University
California State University Fullerton
UTRGV
Southern University and Agricultural & Mechanical College
The University of Mississippi
Massachusetts Institute of Technology
Leland Stanford Junior University
The University Of Sheffield.
University of Maryland
indigo
INPE
PennState
Montclair State University
Monash University
清華大学 Tsinghua University
University of Minnesota
Australian National University
Max Planck Institute for Gravitational Physics Albert Einstein Institute
International Institute of Physics
Cal State LA
Bellevue College
UIB Universitat de les Illes Balears
University of Cambridge
Université de Montréal
Polytechnique Montréal
Carleton
Lomonosov Moscow State University
University of Southampton
The University of Western Australia
The University of Chicago
NCSA
Texas Tech University
University of the West of Scotland UWS
Sonoma State University
University of Glasgow
Columbia University in the City of New York
CITA ICAT
The University of Adelaide Australia
LSU Louisiana State University
Syracuse University
OzGrav
NASA
W Bothell
R·I·T
University of Strathclyde
Michigan
Whitman College
University of Washington
UW Milwaukee
Marshall Space Flight Center
Hillsdale College
Universitas Budapestinensis de Rolando Eötvös nominata
Università degli Studi del Sannio
University of Birmingham
University of Zurich
Cardiff University Prifysgol Caerdydd
King's College London
Colorado State University
東京大学 The University of Tokyo
Montana State University
Georgia Institute of Technology
Korean Gravitational-Wave Group
ACIGA
Universität Hamburg Der Forschung | Der Lehre | Der Bildung
The University of Melbourne
Northwestern
UF University of Florida
GEO 600
Charles Sturt University
Leibniz Universität Hannover
Swinburne University of Technology
Trinity University
NASA Goddard Space Flight Center
Embry-Riddle Aeronautical University

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

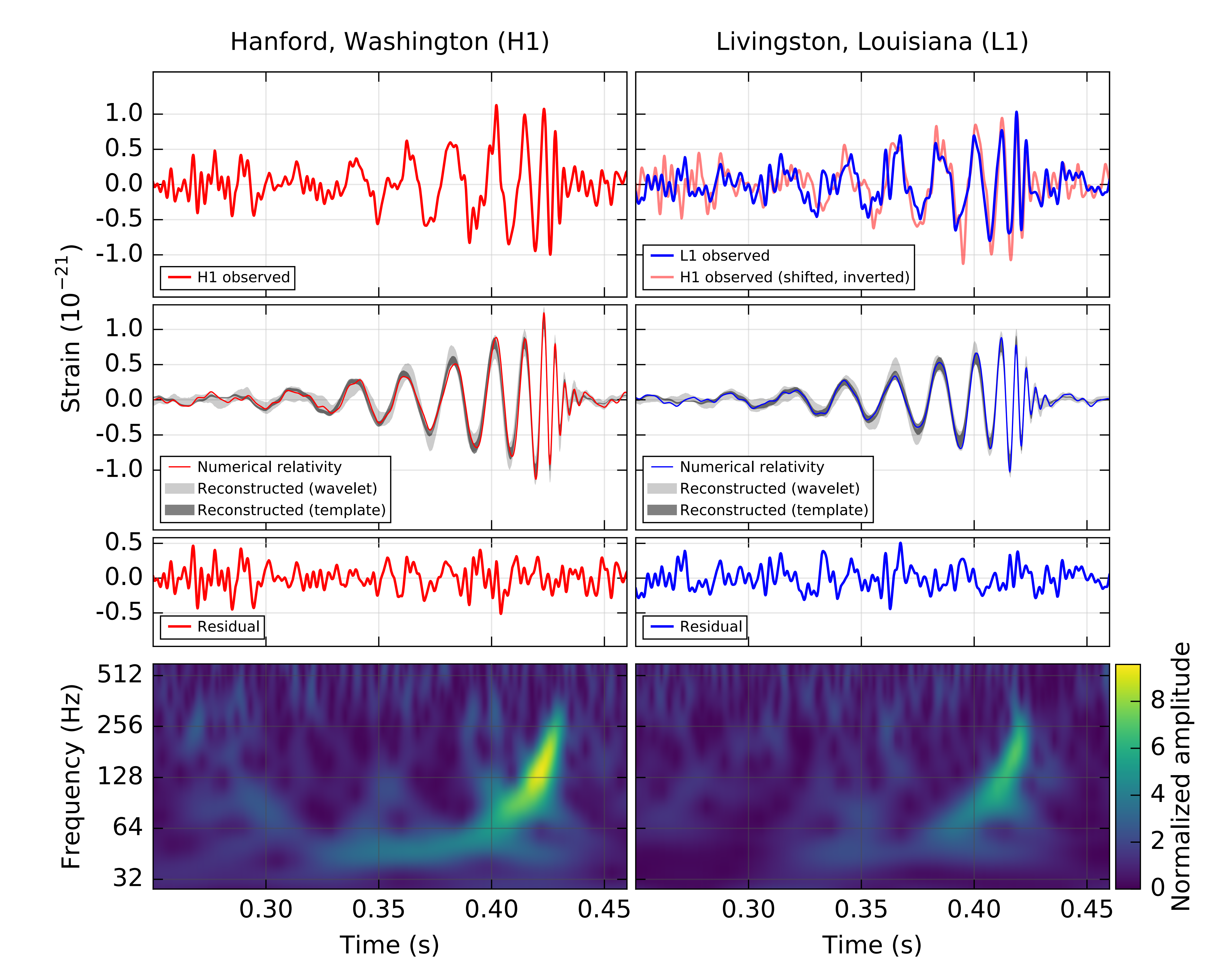


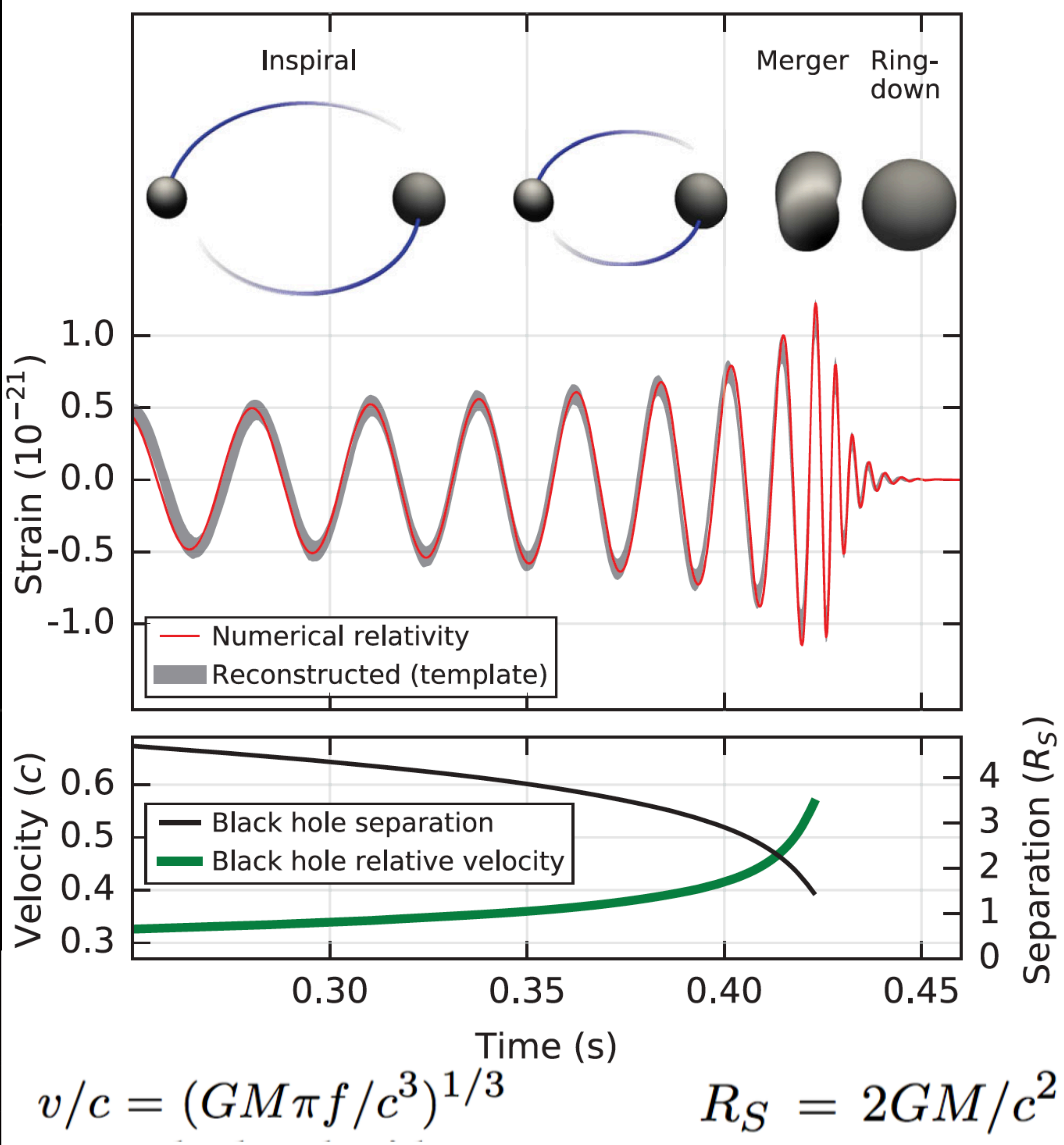
Binary Black Hole Coalescence



Binary Neutron Star Coalescence

First Discovery: GW150914

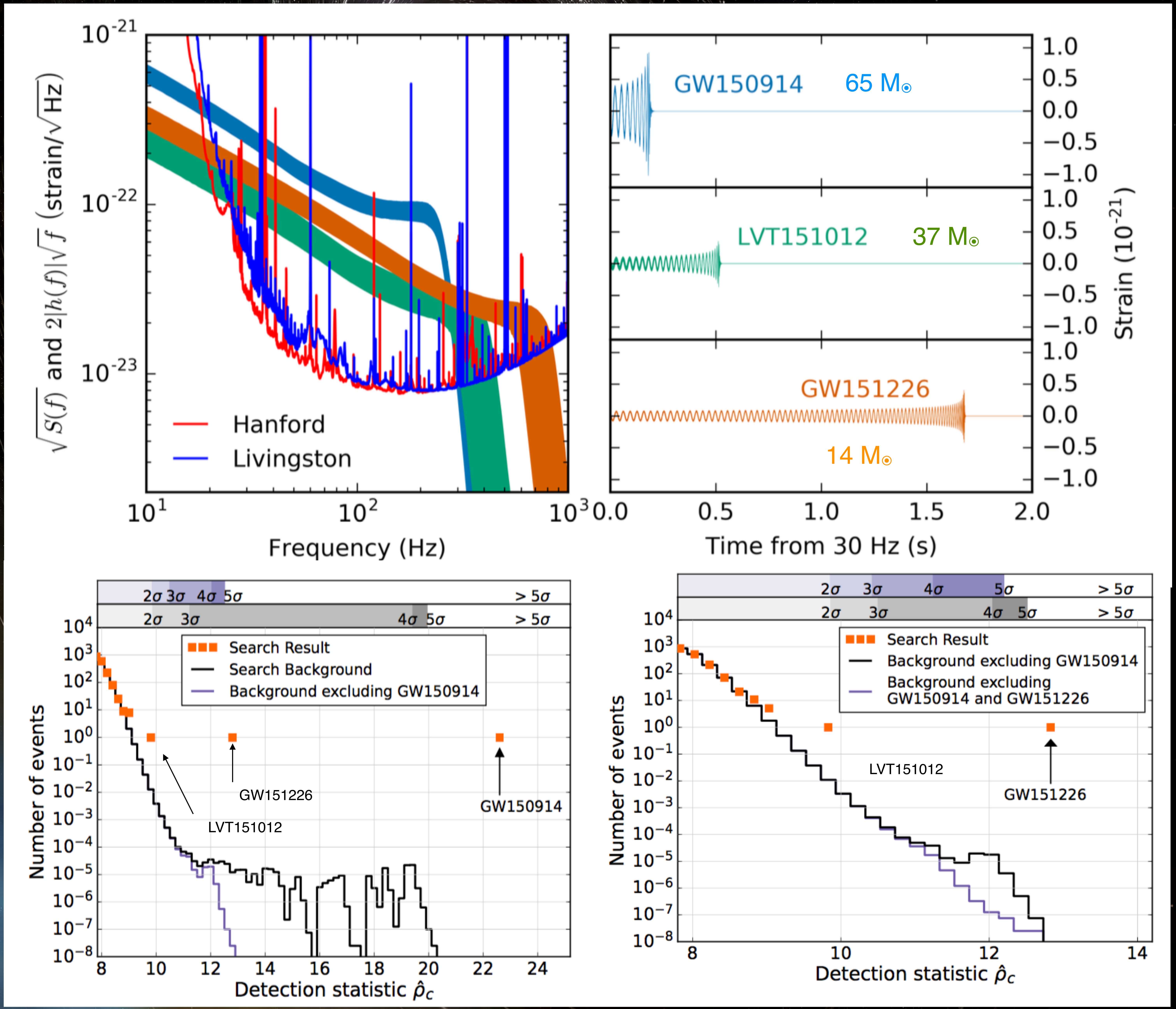




R_S~200km

Observation of Gravitational Waves from a Binary Black Hole Merger — PRL 116:061102, 2016

Binary Black Hole Mergers in LIGO's First Science Run



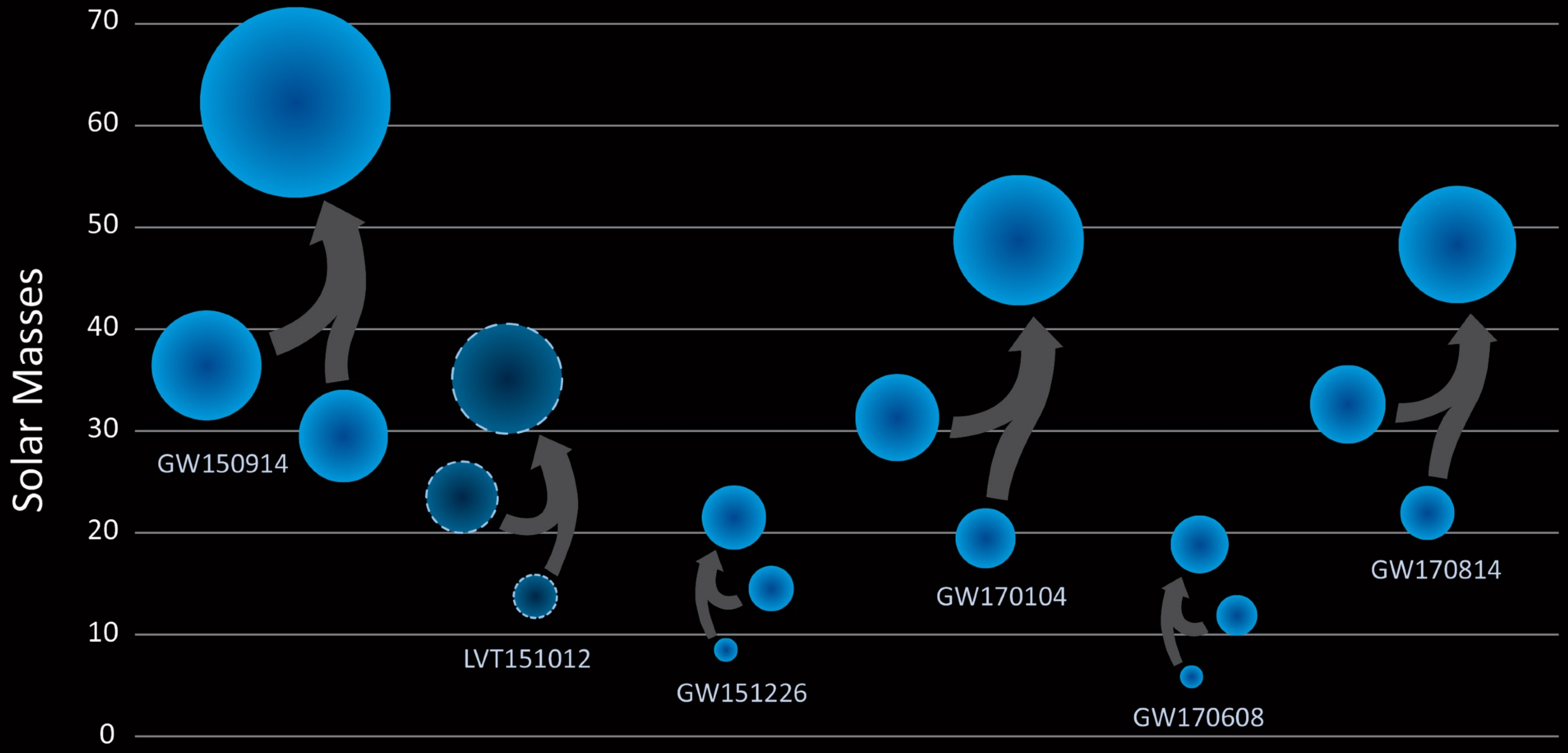
~ 250,000 templates

16 million time lags

False Alarm Rate < 1 in 203,000 yr

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

Black Hole Masses



Credits: LIGO/Caltech/Sonoma State (Simonnet)

LIGO/VIRGO

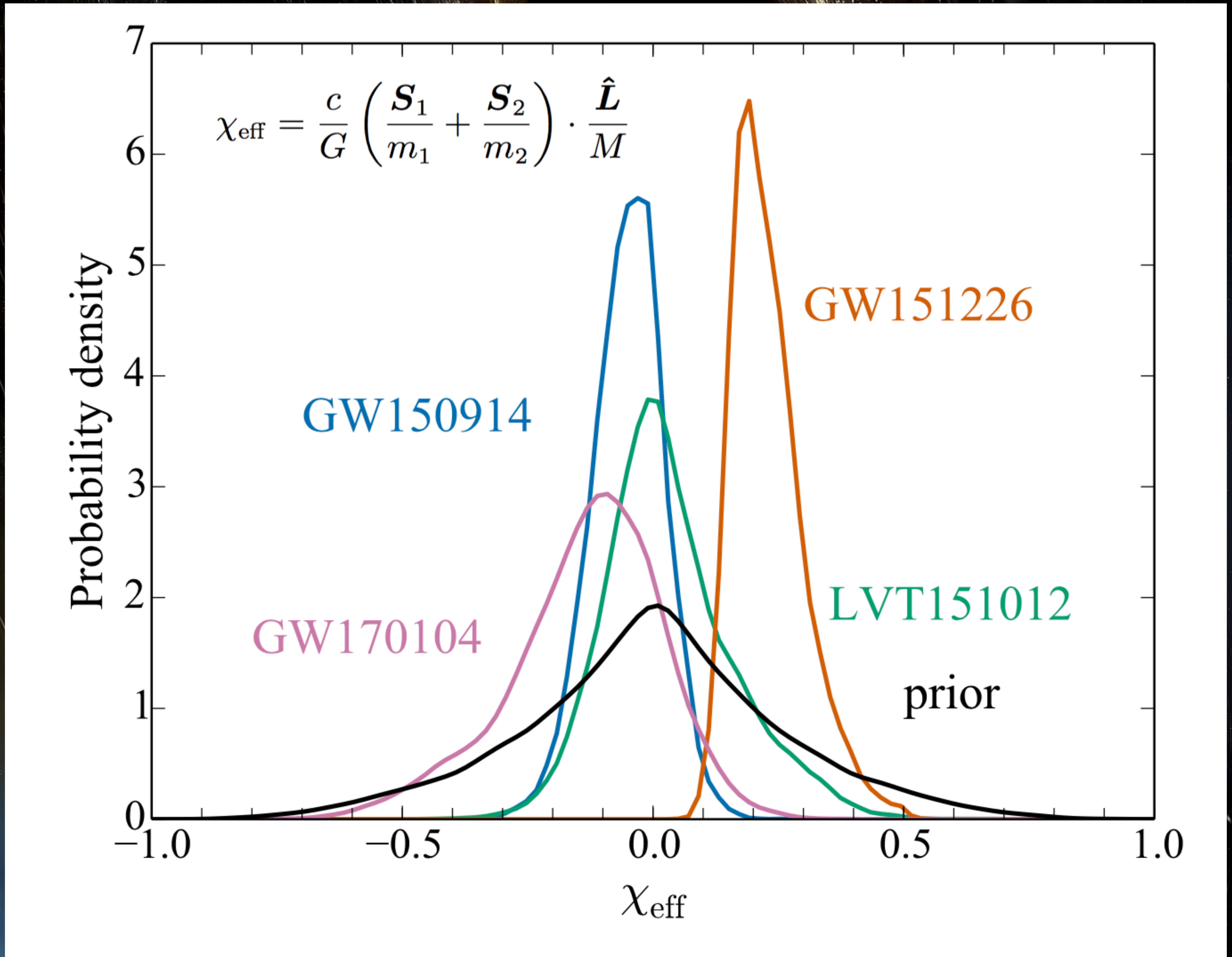
Most robust evidence for existence of 'heavy' stellar mass BHs (> 20 $M_\odot$)

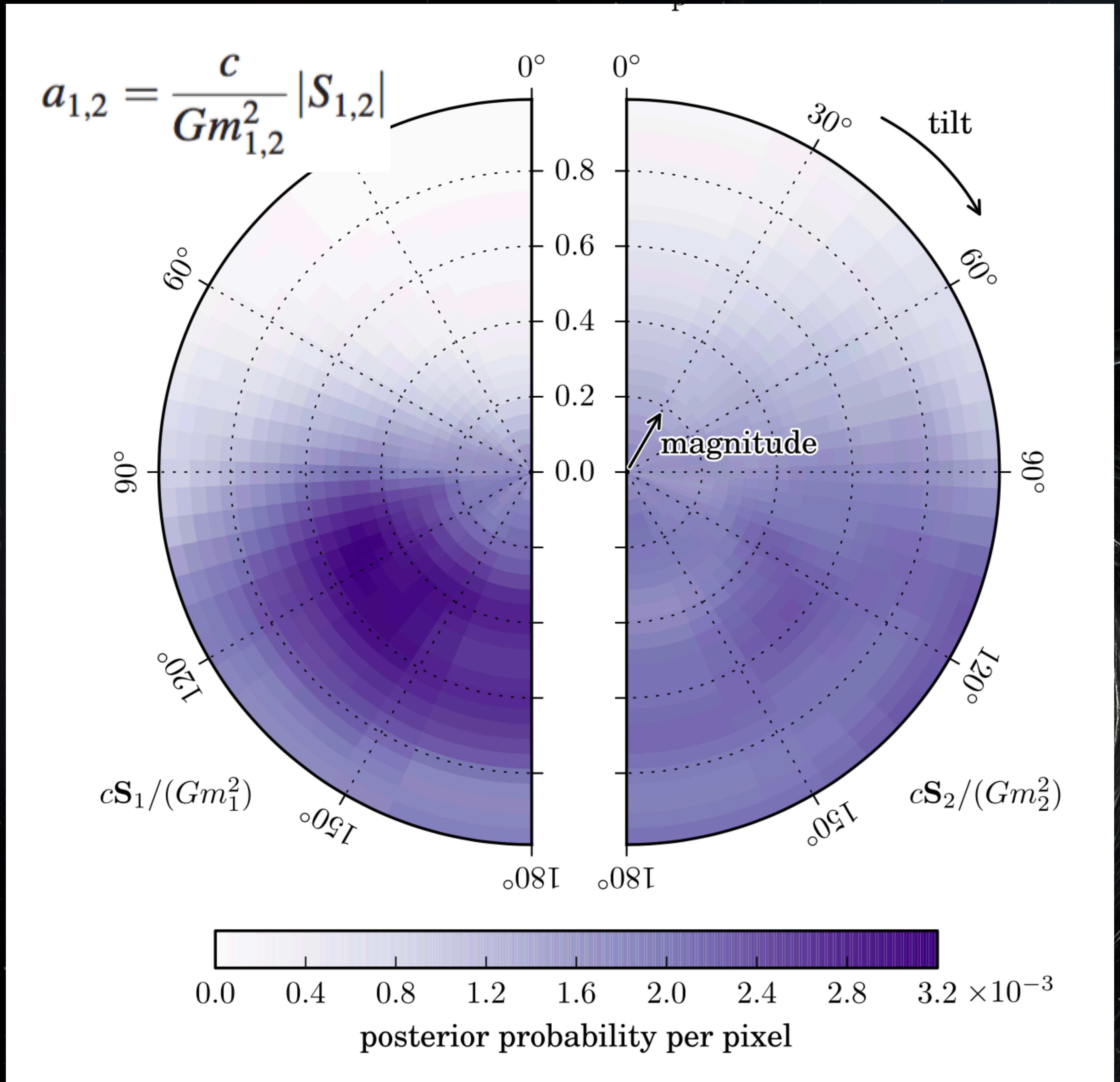
BBH most likely formed in a low-metallicity environment: < ½ $Z_\odot$

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

Black Hole Spins

PRL 118, 221101 (2016)

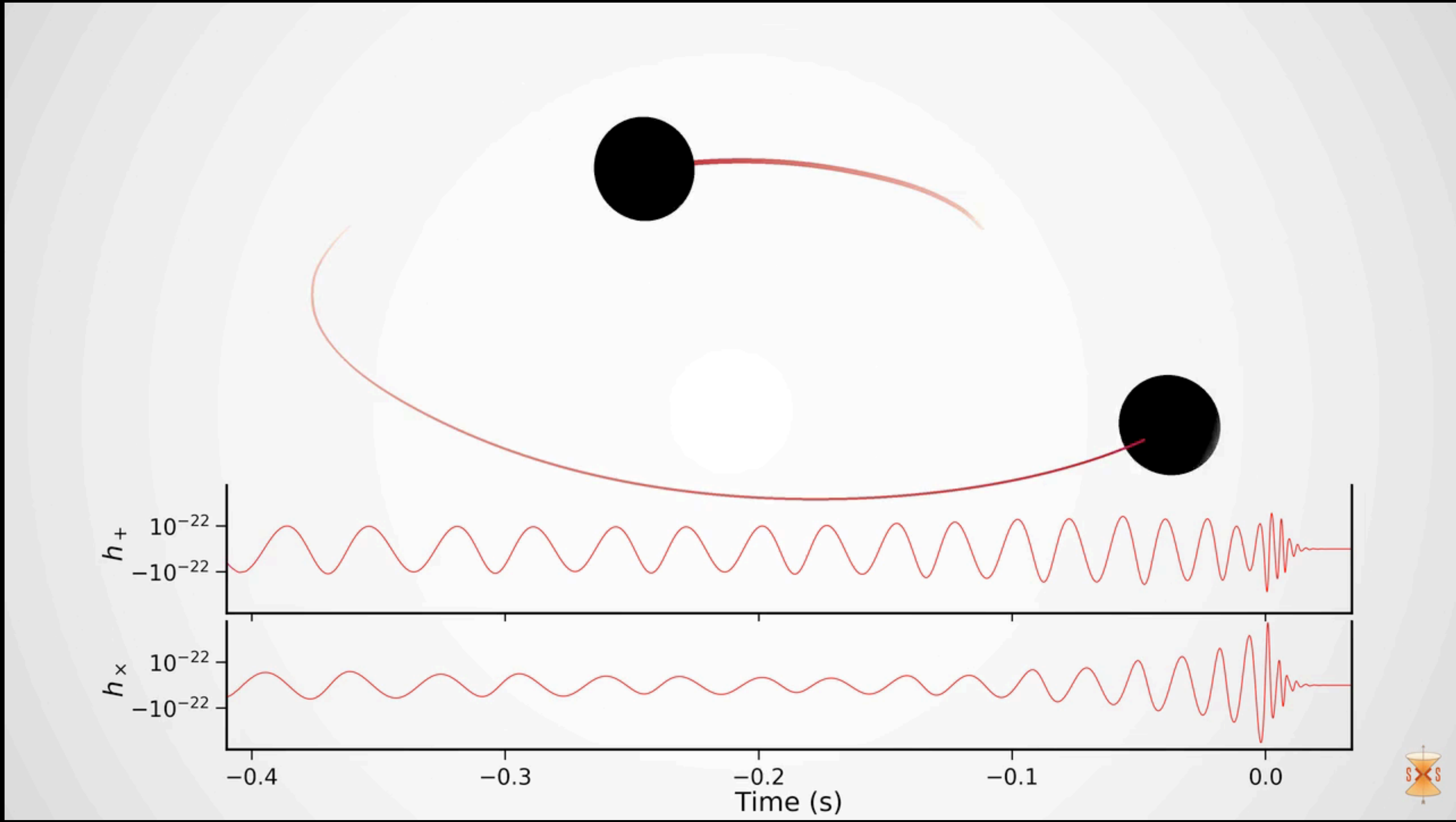




GW170104: evidence for spin-orbit misalignment

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

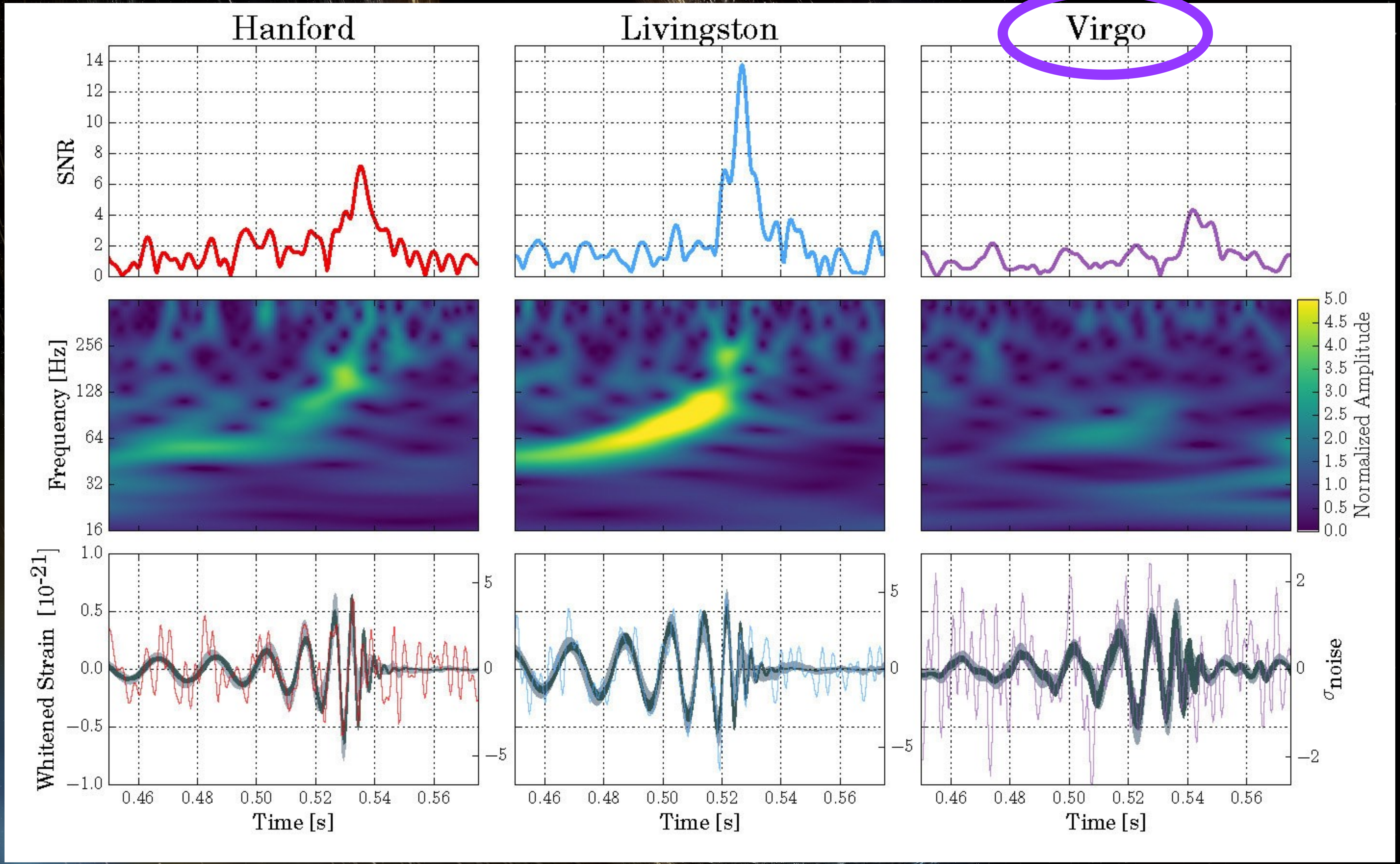
Spin, Orientation and Polarization

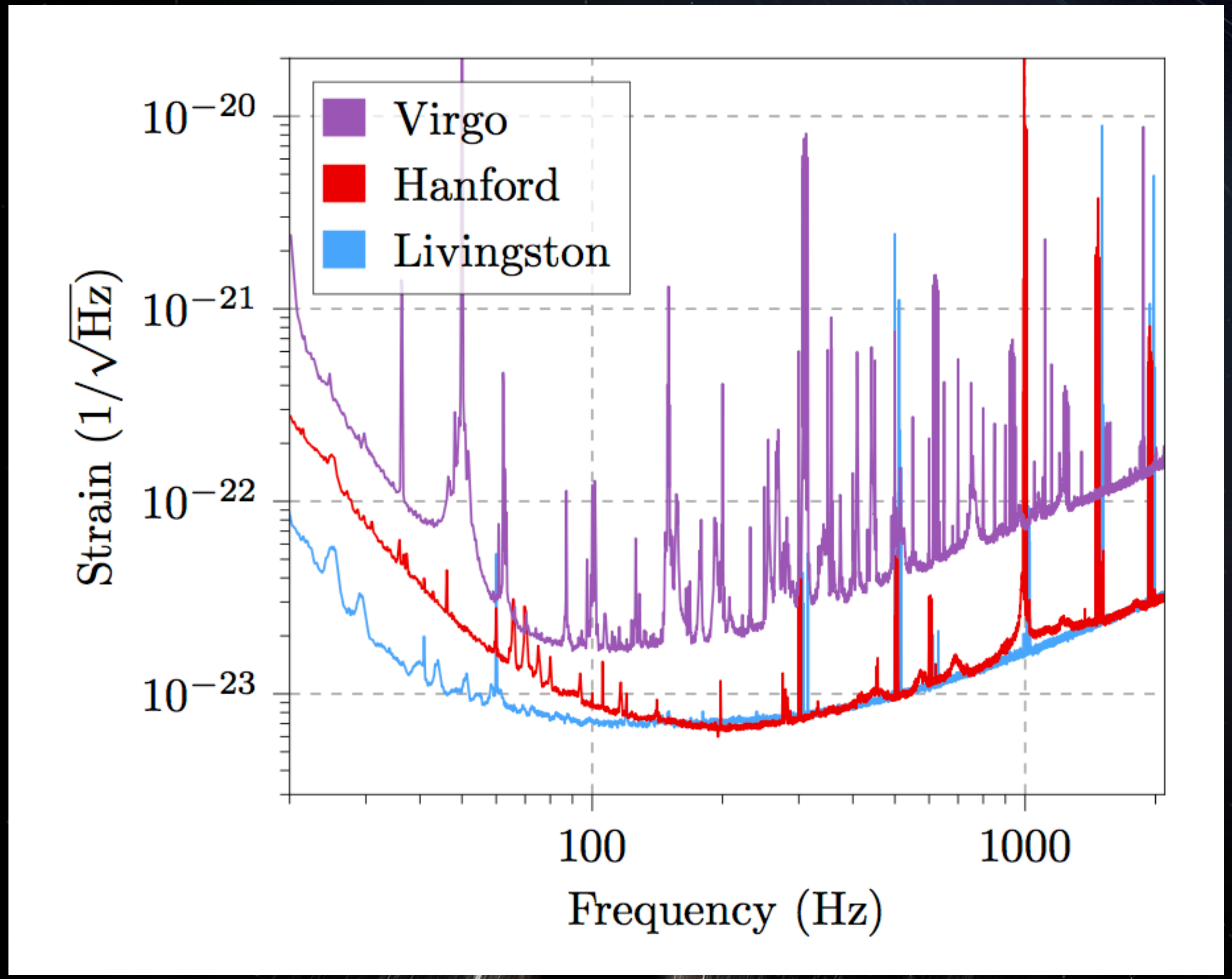


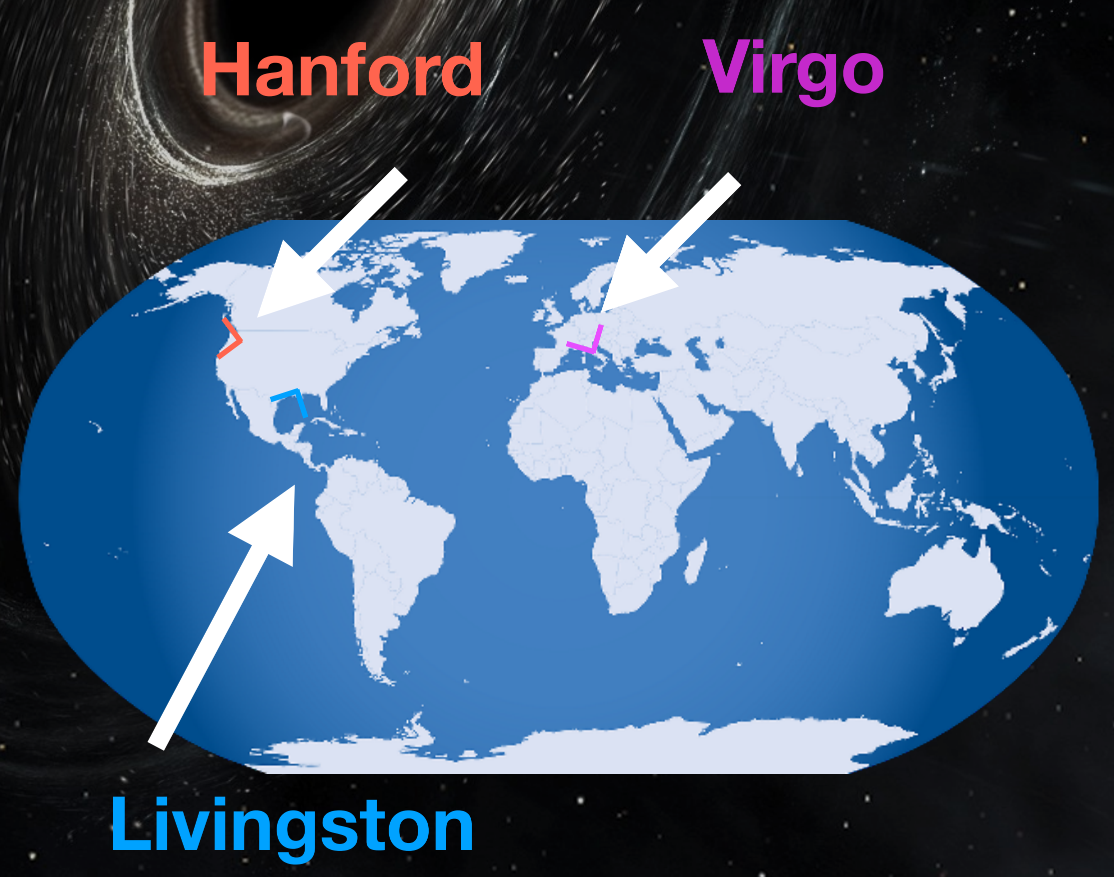
Credit: A. Babul/H. Pfeiffer/CITA/SXS

LIGO alone can only measure one of the polarizations and therefore obtains only limited information about the orientation of the binary. More than 2 locations are needed to disentangle polarization.

The LIGO-Virgo Network: GW170814





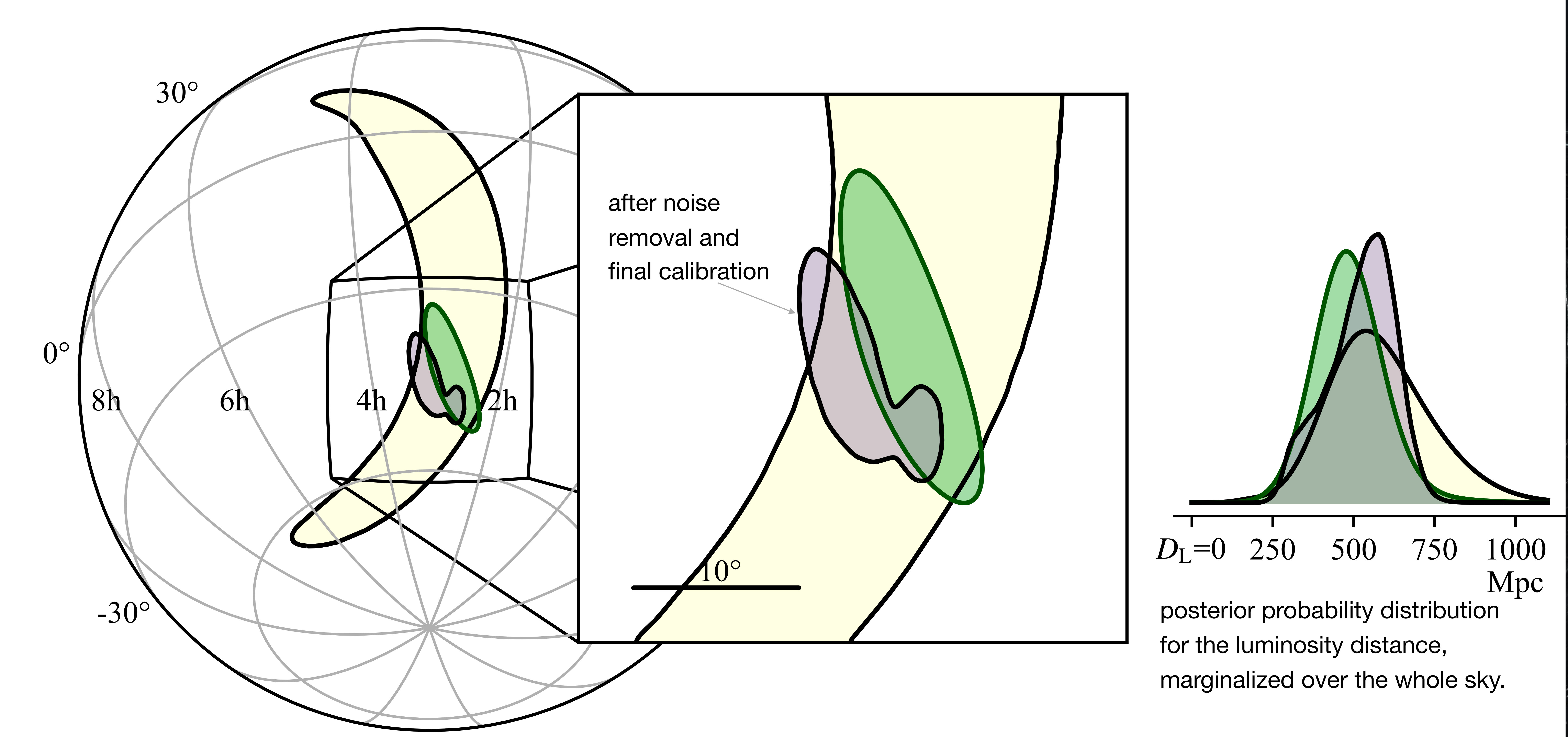


A Three-Detector Observation of Gravitational Waves from a Binary Black Hole Coalescence
Phys. Rev. Lett., 119:141101, 2017

Sky Localization

The inclusion of Virgo improves the sky localization from 1160 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.

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 deg² to 60 deg²

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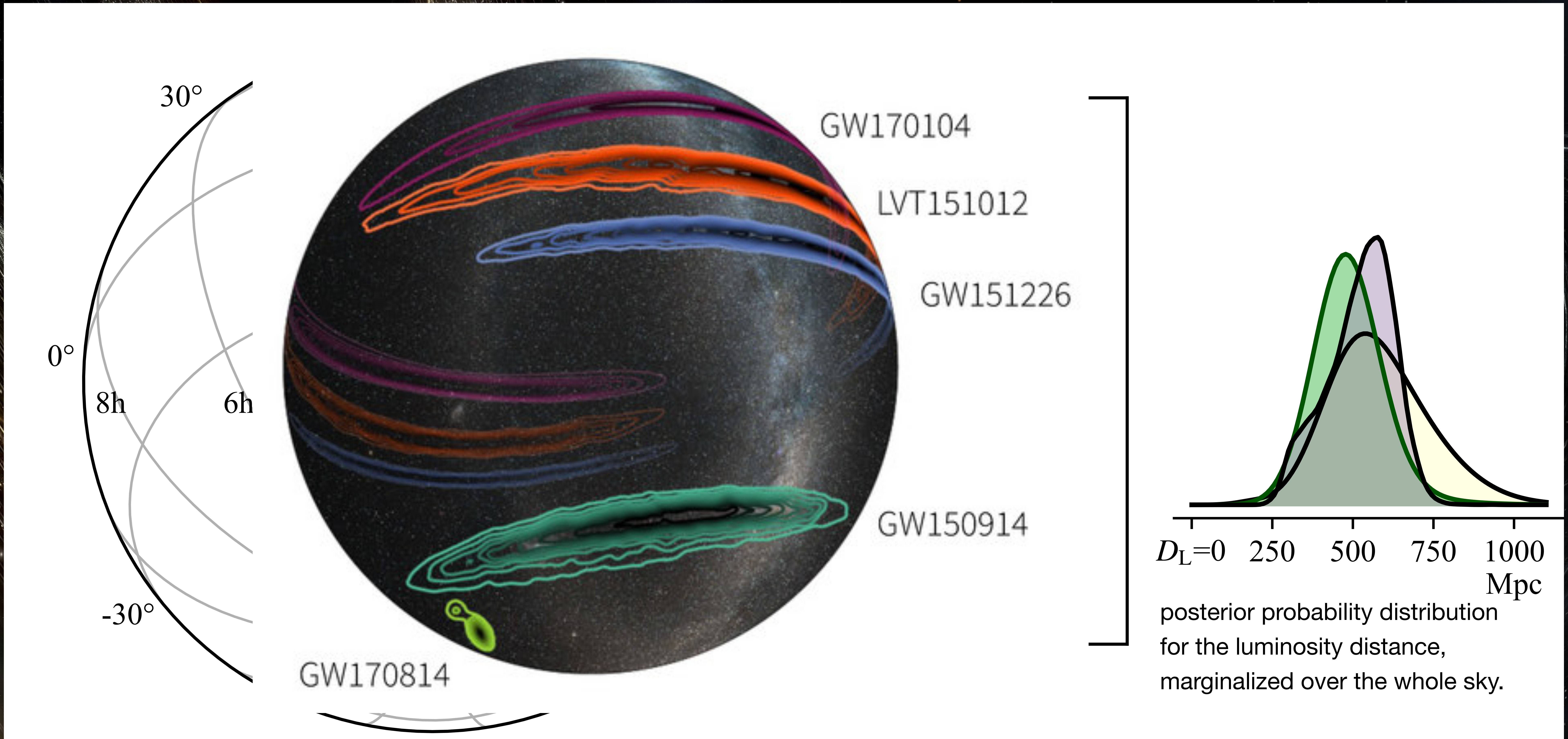
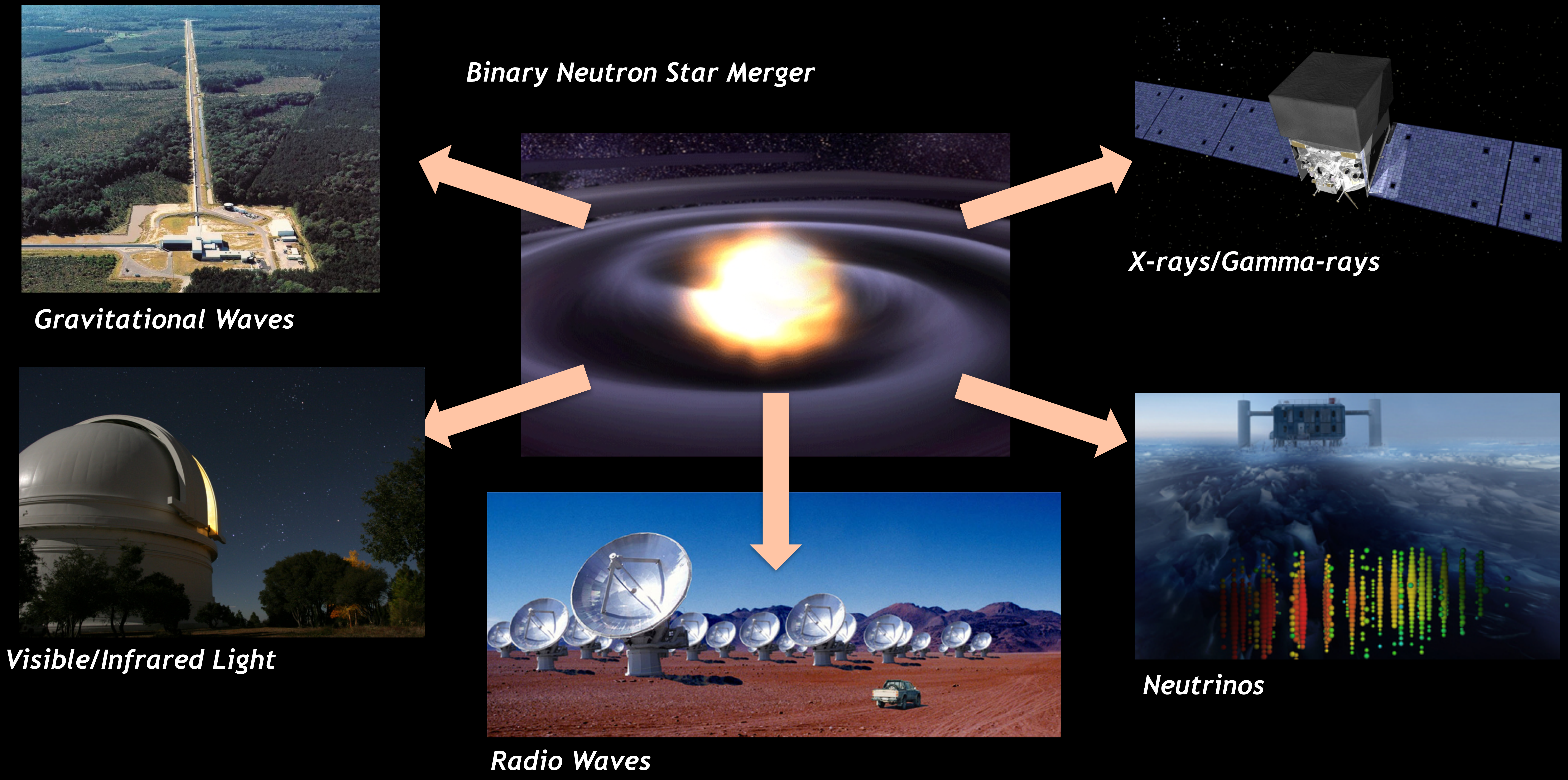


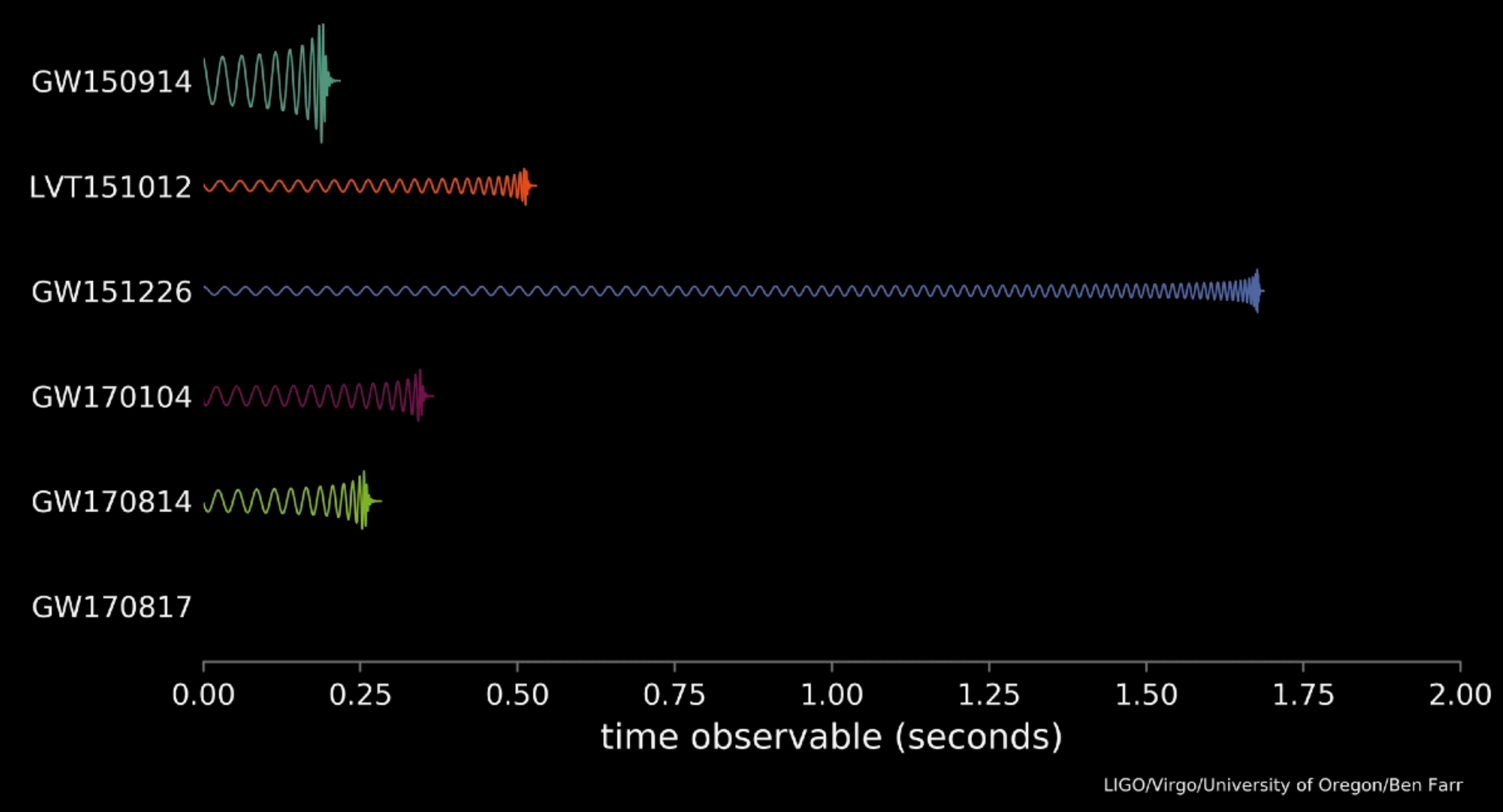
A Three-Detector Observation of Gravitational Waves from a Binary Black Hole Coalescence
Phys. Rev. Lett., 119:141101, 2017

Multi-messenger Astronomy with Gravitational Waves



Leading to O1, LIGO and Virgo signed agreements with 95 groups for EM/neutrino followup of GW events

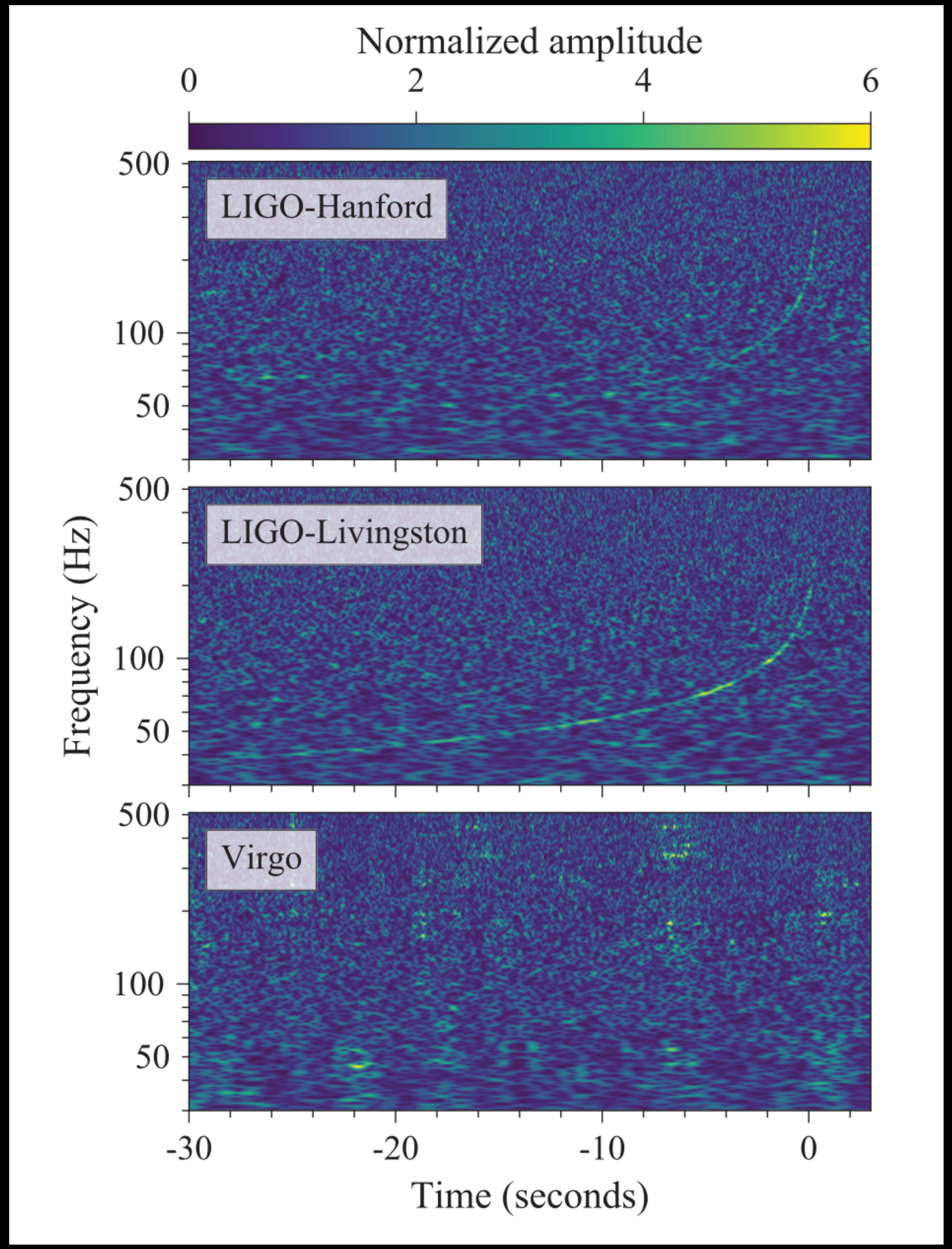
- ~200 EM instruments - satellites and ground based telescopes covering the full spectrum from radio to very high-energy gamma-rays
- Worldwide astronomical institutions, agencies and large/small teams of astronomers



Discovery of a Binary Neutron Star Merger

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

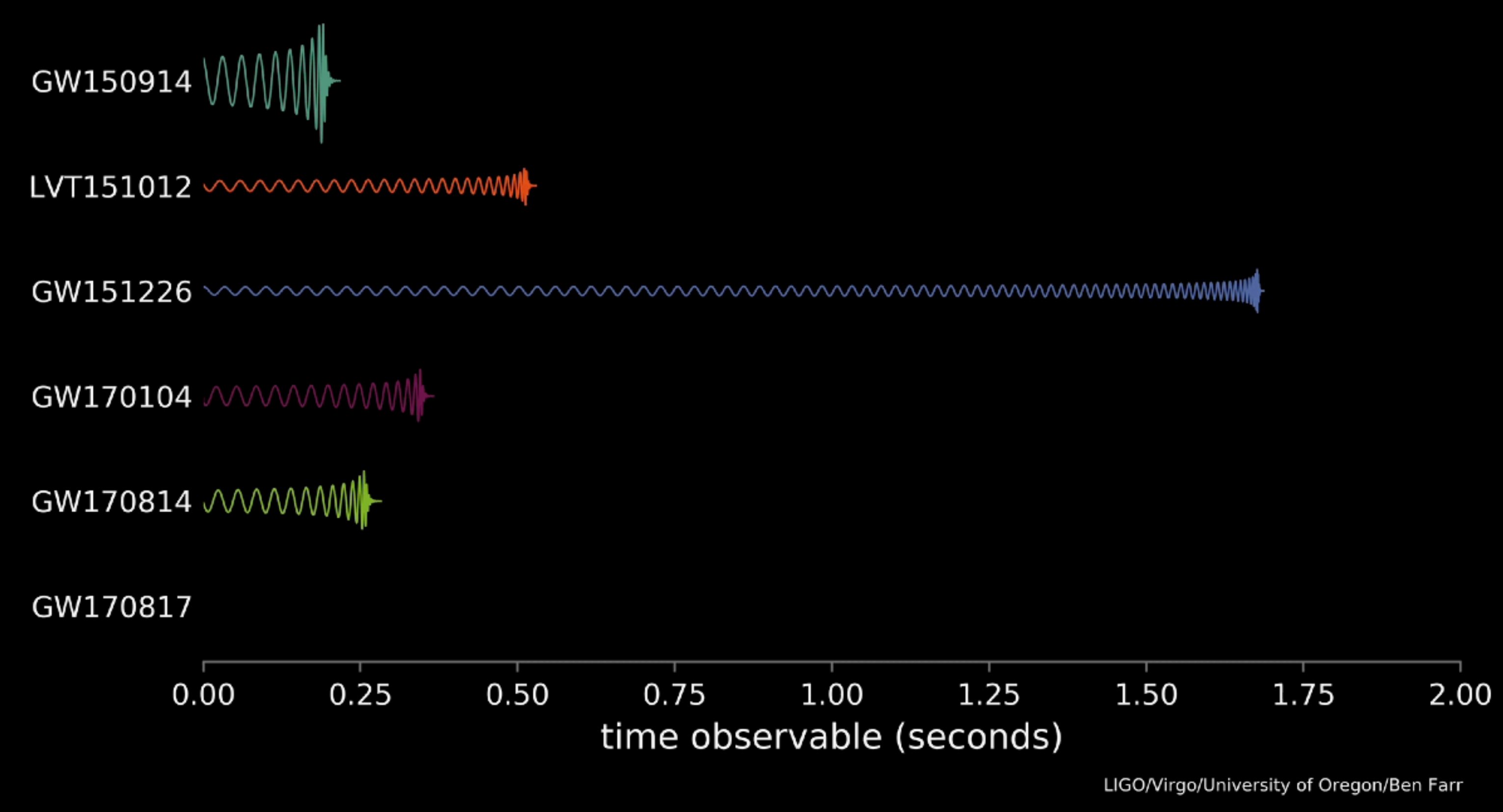
August 17, 2017 - 12:41:04.4 UTC



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

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

Discovery of a Binary Neutron Star Merger



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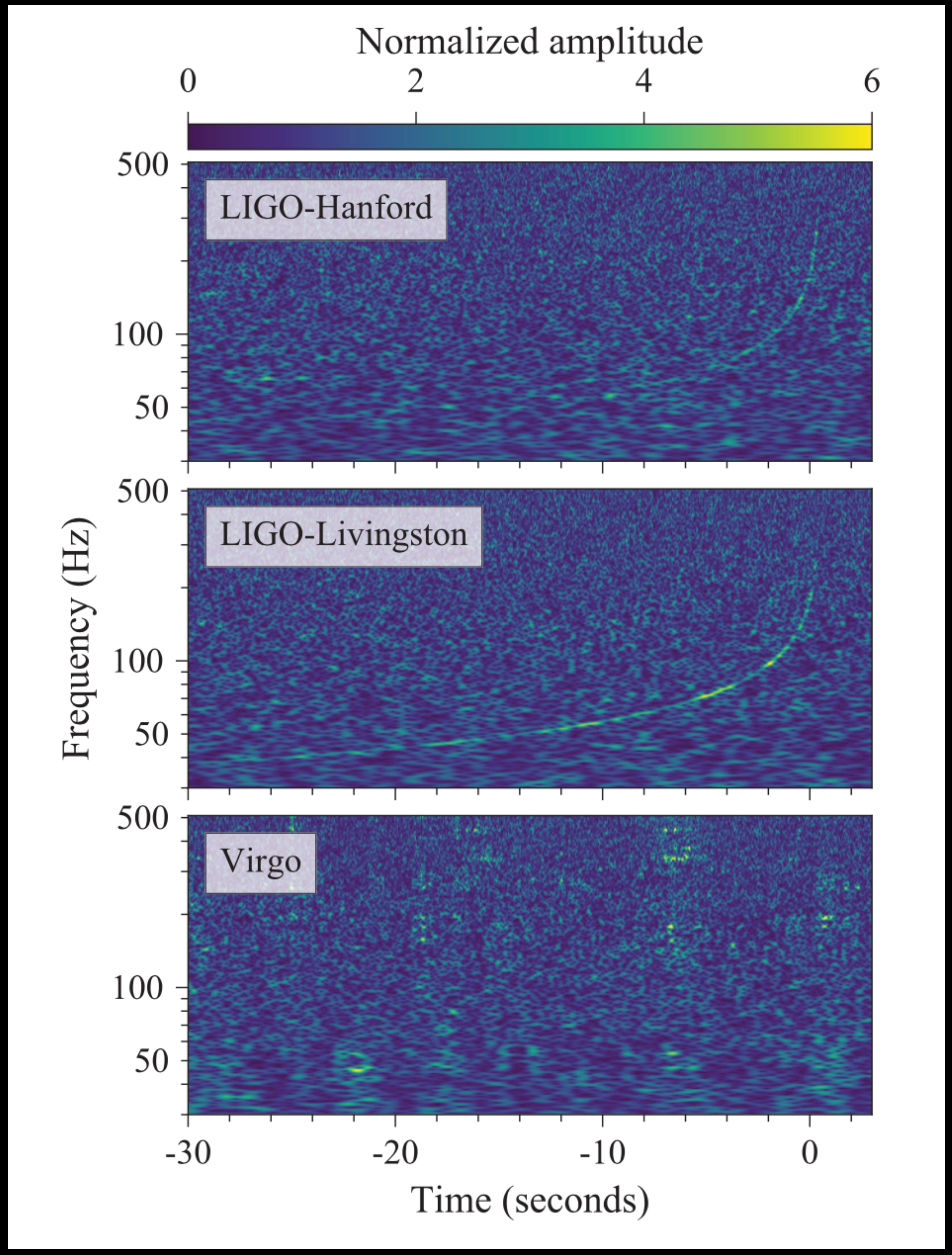

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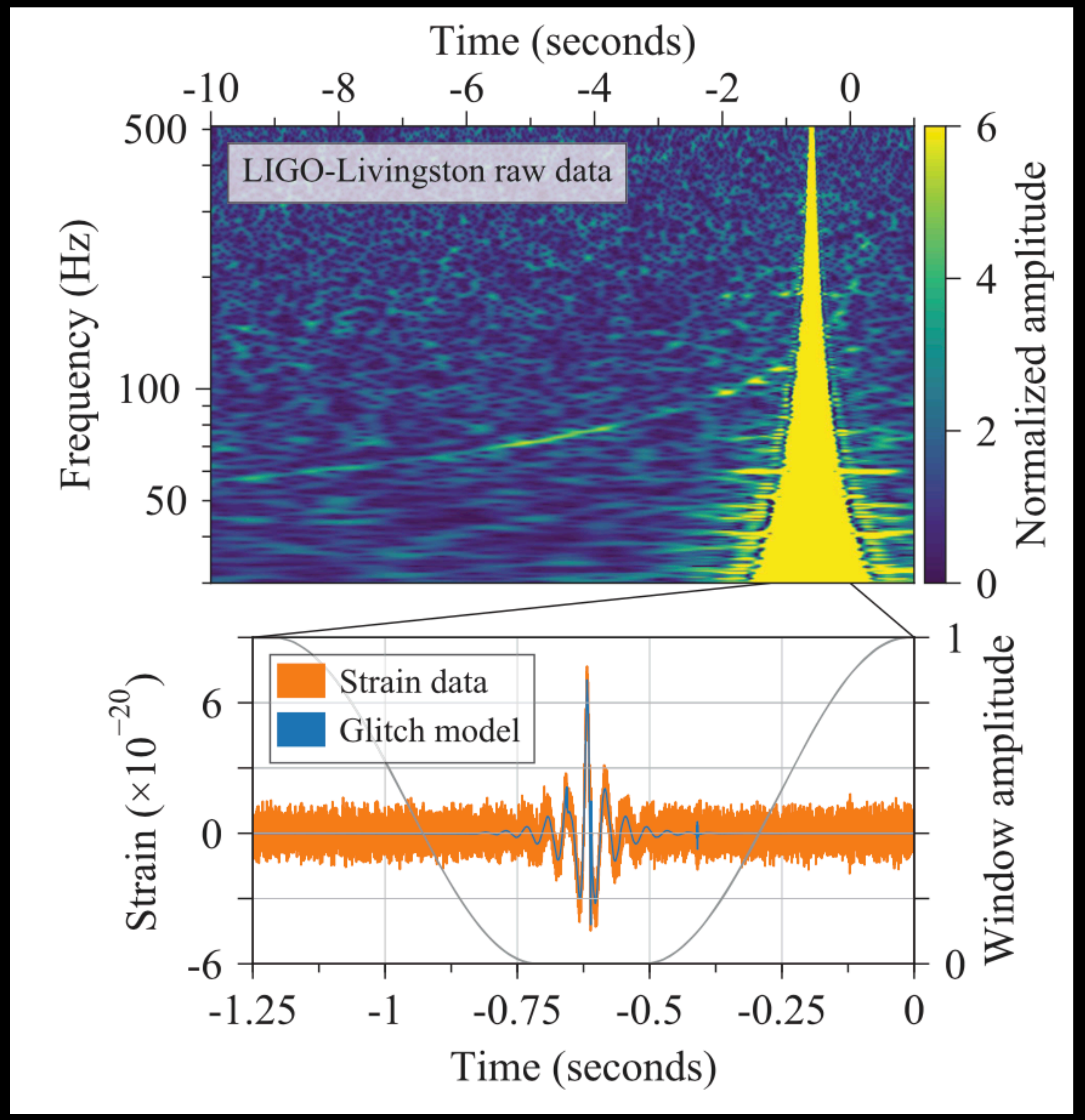
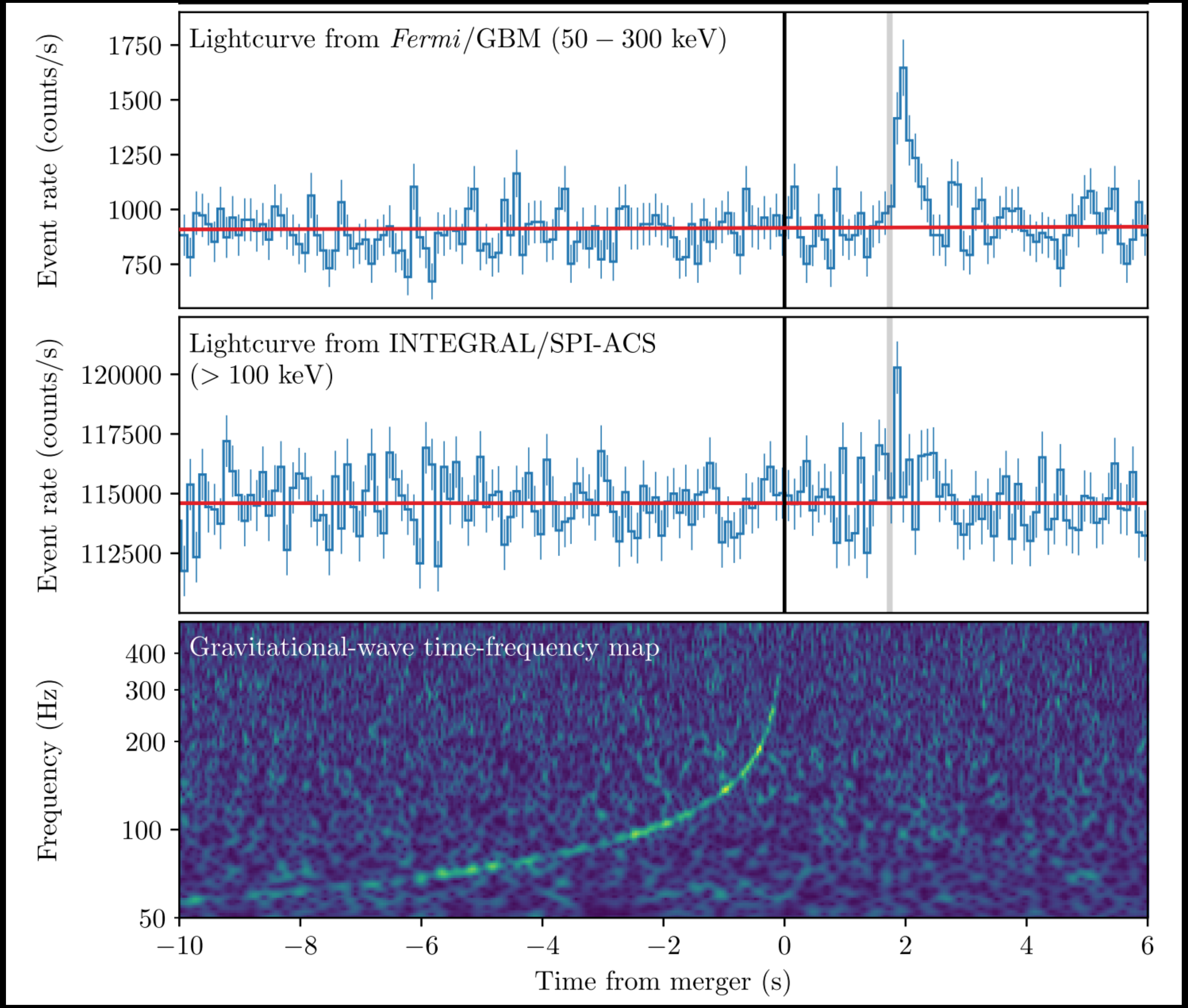


Glitch in L1 1.1 seconds before the coalescence

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

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

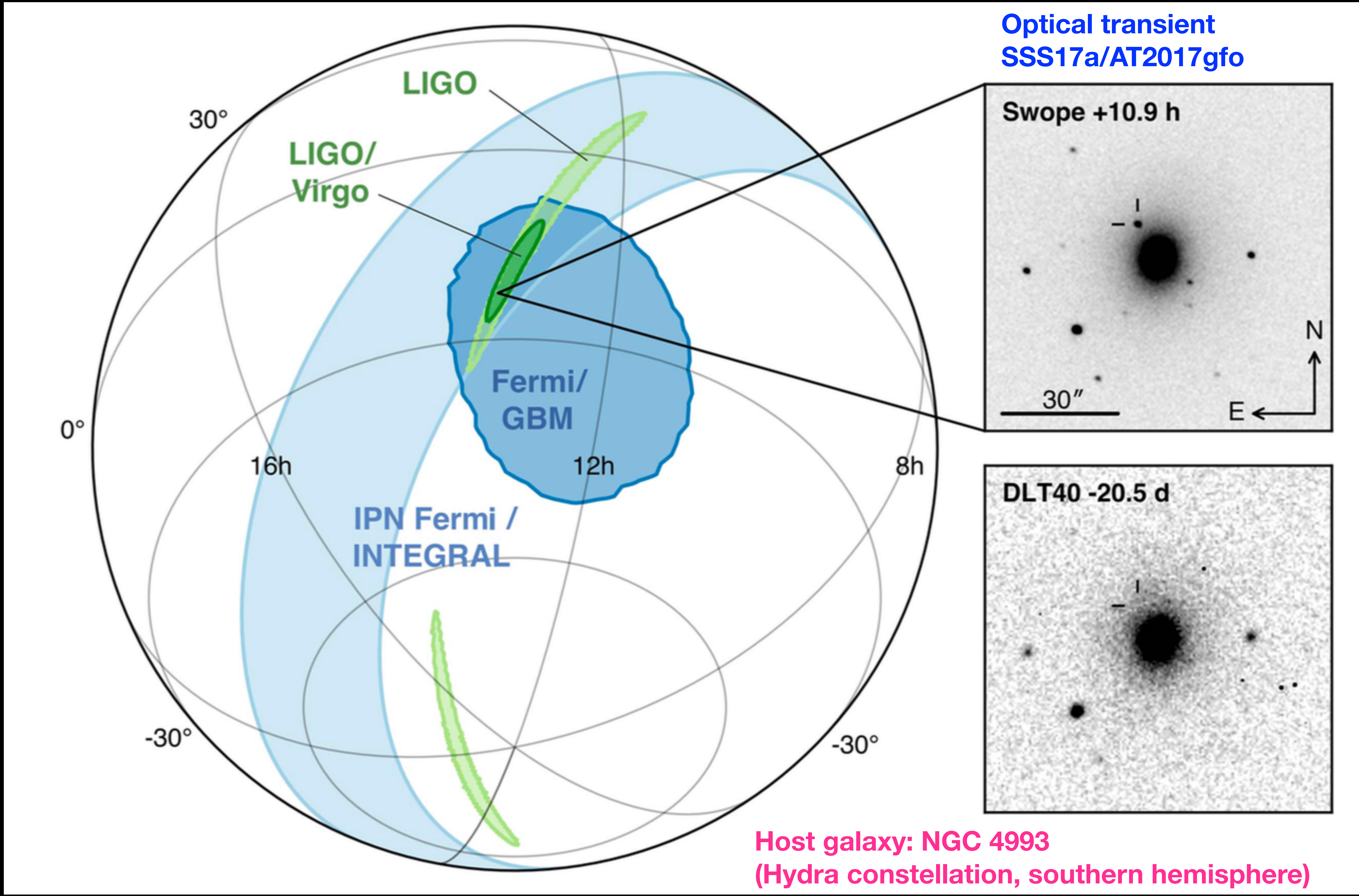
GRB 170817A occurs (1.74 ± 0.05) seconds after GW170817

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

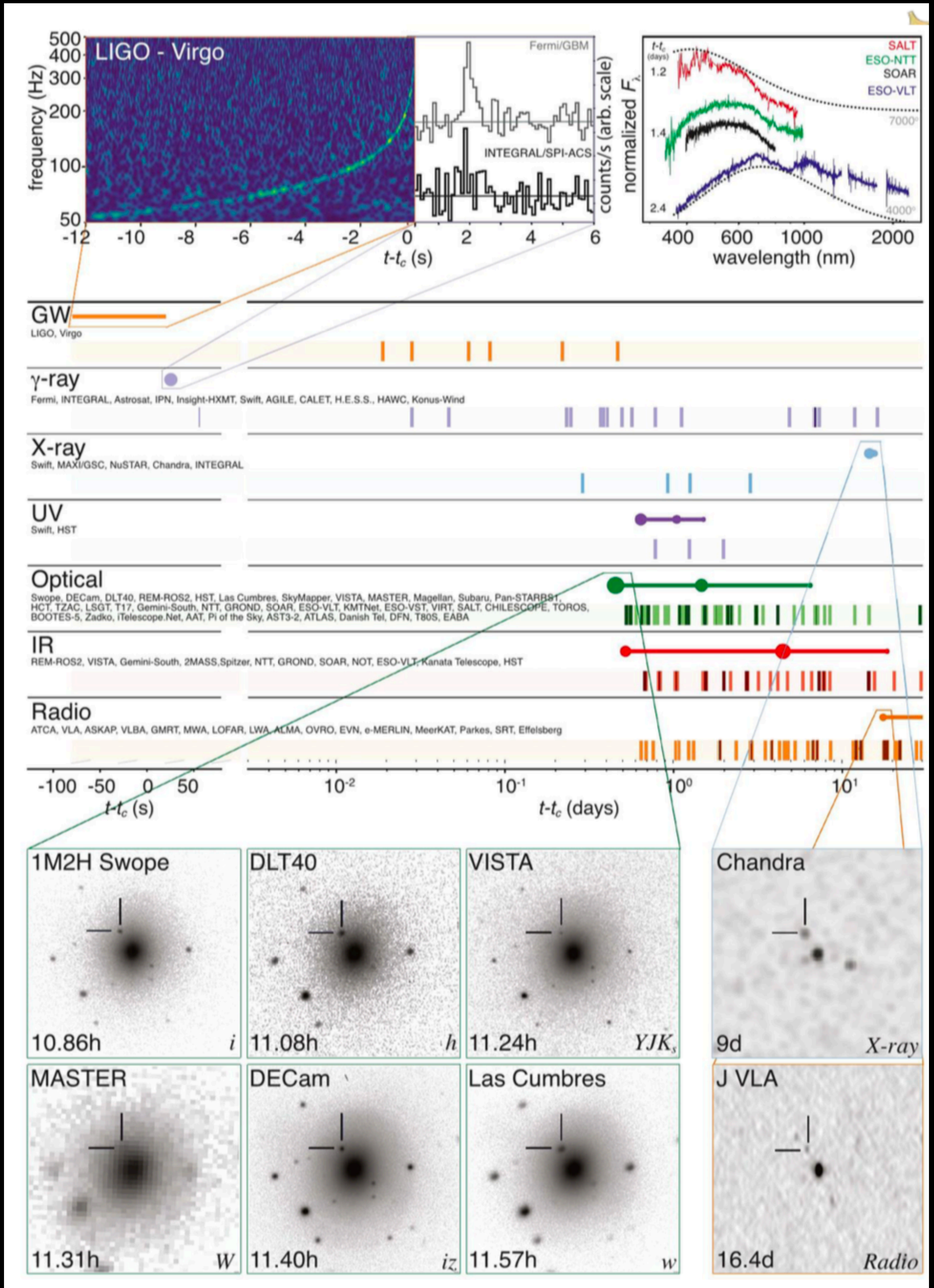
Probability that GW170817 and GRB 170817A occurred this close in time and with location agreement by chance is 5.0×10^{-8} (Gaussian equivalent significance of 5.3σ)

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 and discovery of a Kilonova



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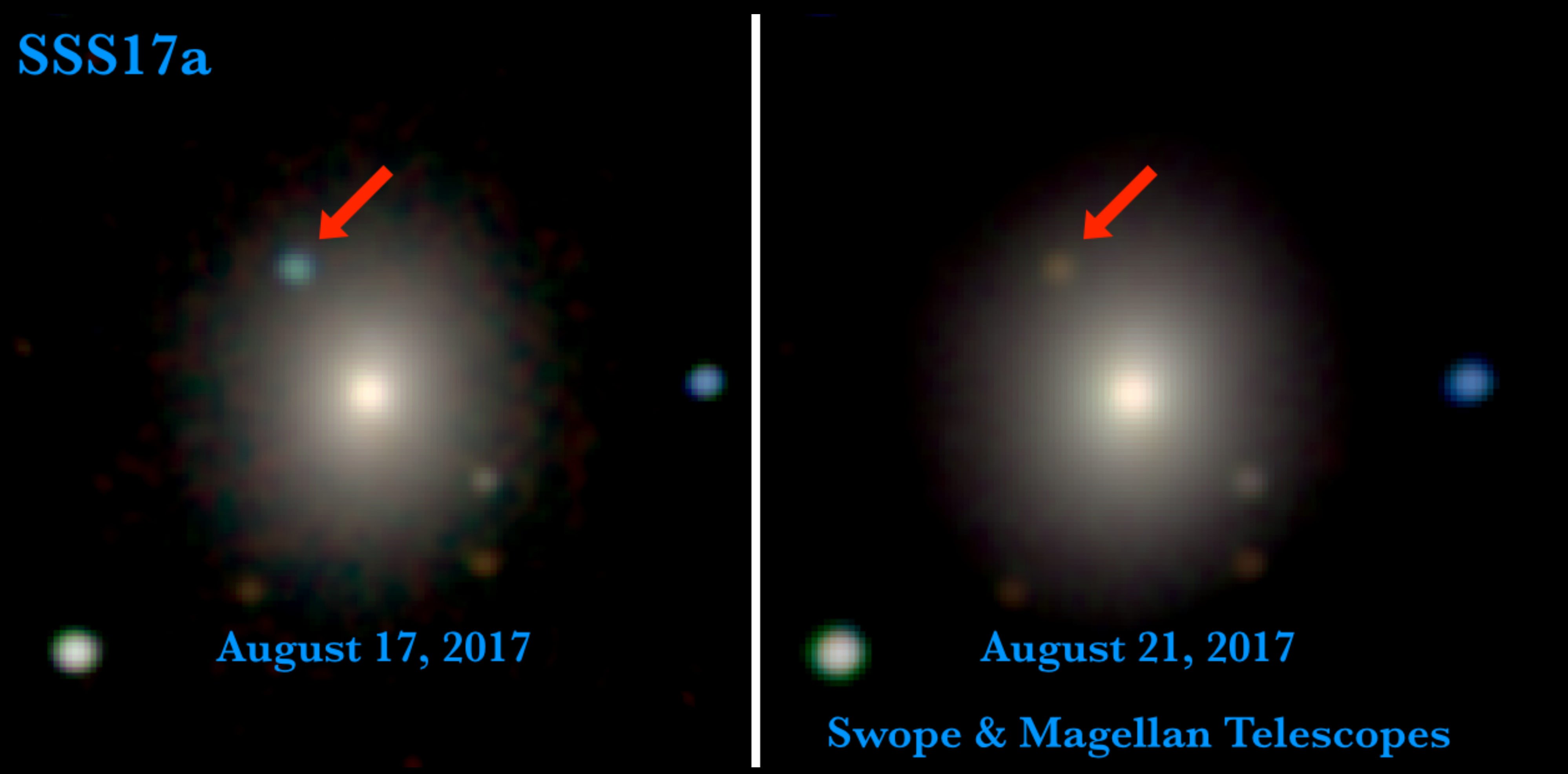
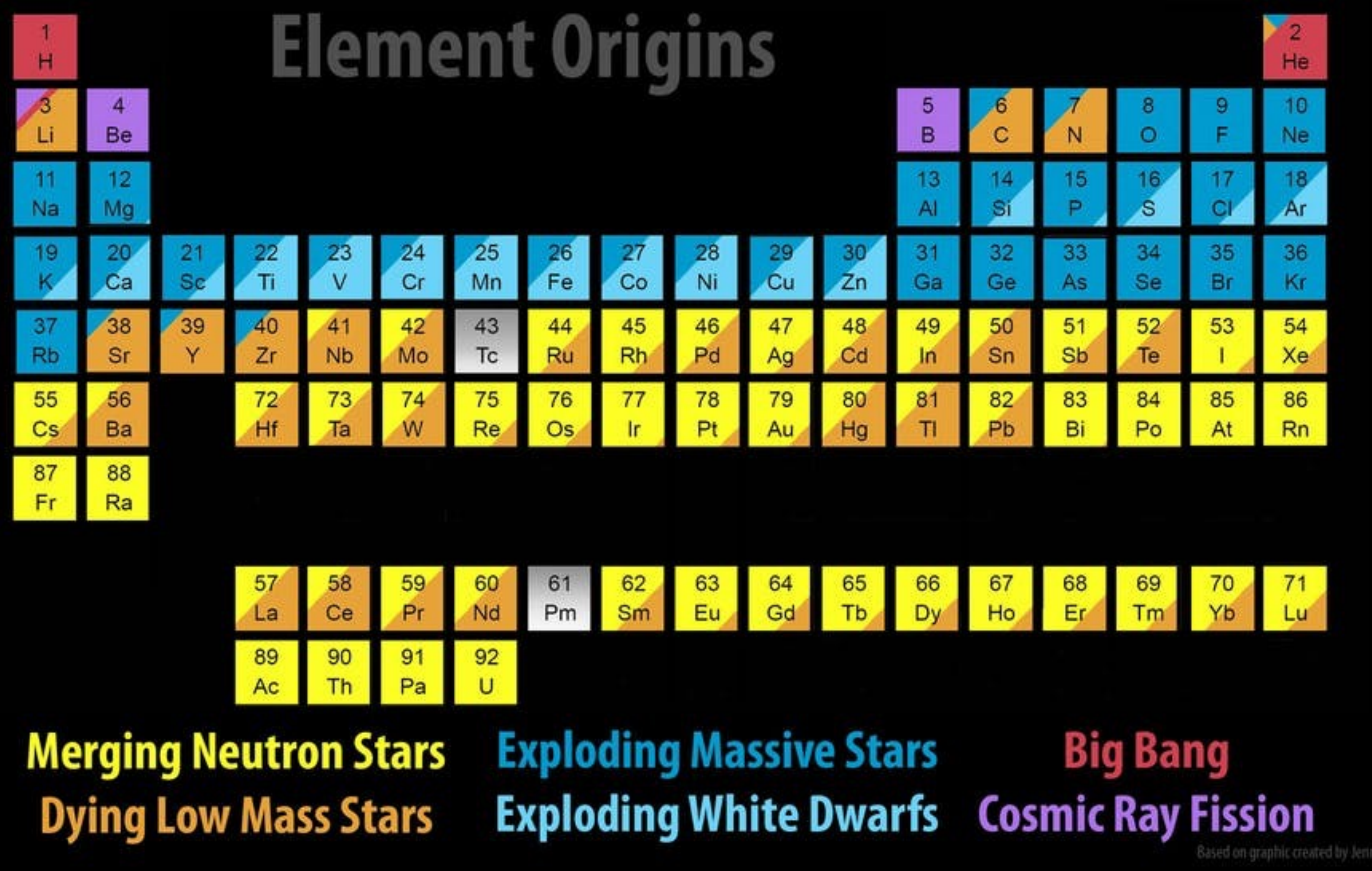
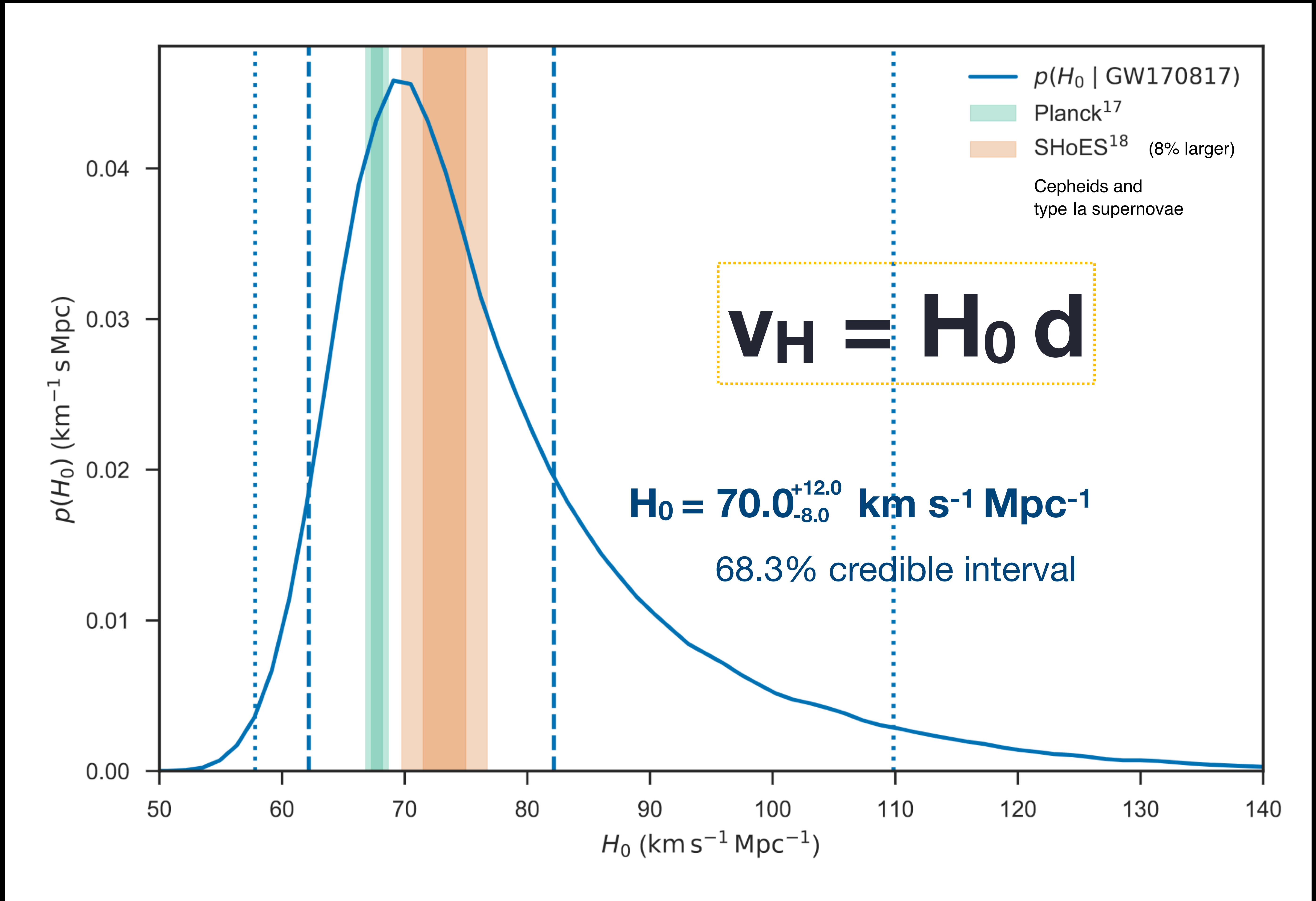
The Astrophysical Journal Letters, 848:L12, 2017





BNS as Standard Sirens



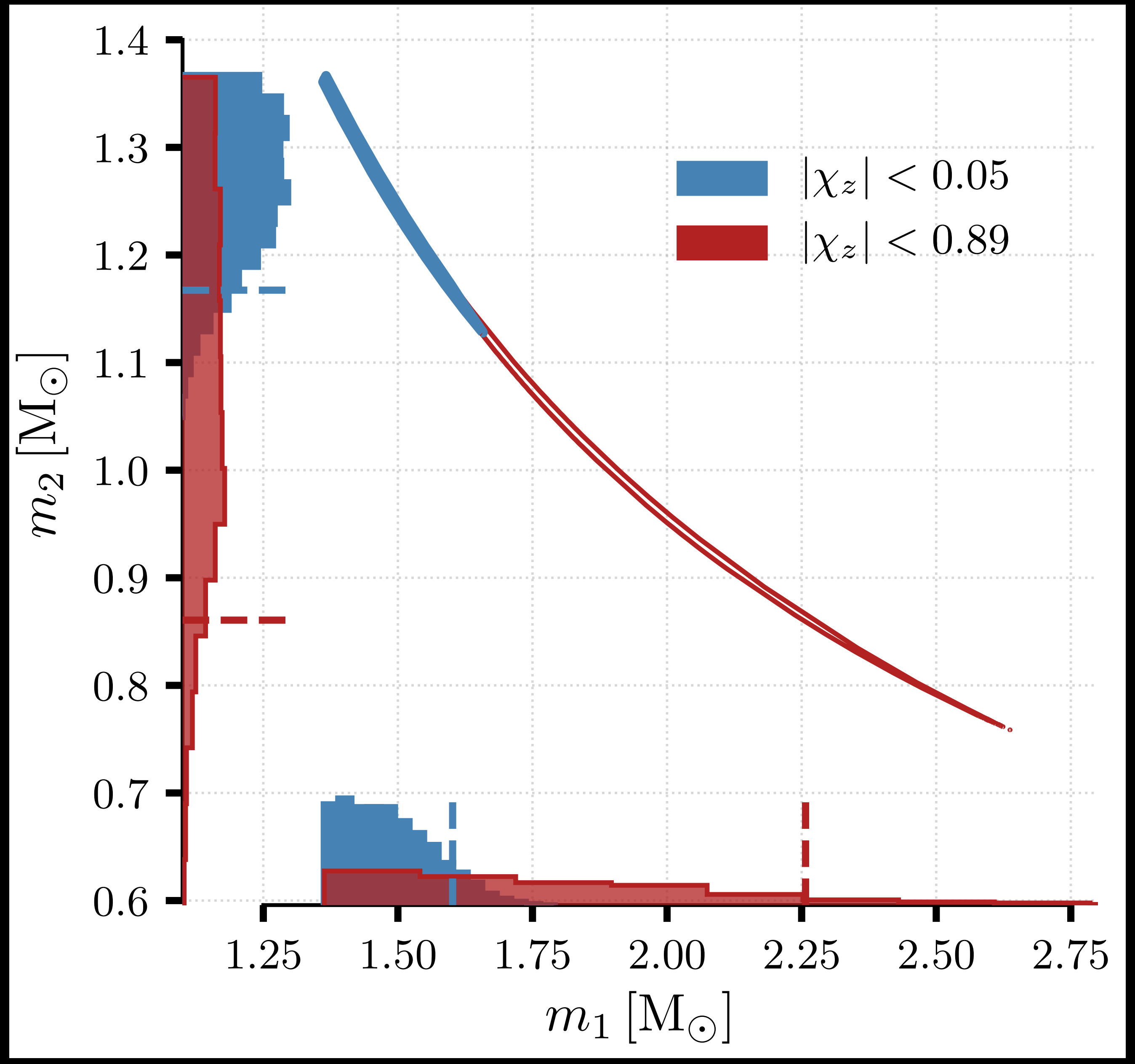
A gravitational-wave standard siren measurement of the Hubble constant
Nature, 551:85, 2017

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

BNS properties



PRL 119, 161101, 2017

The properties of gravitational-wave sources are inferred by matching the data with predicted waveforms

For low orbital and gravitational-wave frequencies the evolution of the frequency is dominated by chirp mass

$$\mathcal{M} = \frac{(m_1 m_2)^{3/5}}{(m_1 + m_2)^{1/5}}$$

As orbit shrinks the gravitational-wave phase is increasing influenced by relativistic effects related to the mass ratio

Component masses are affected by the degeneracy between mass ratio and the aligned spin components χ_{1z} and χ_{2z}

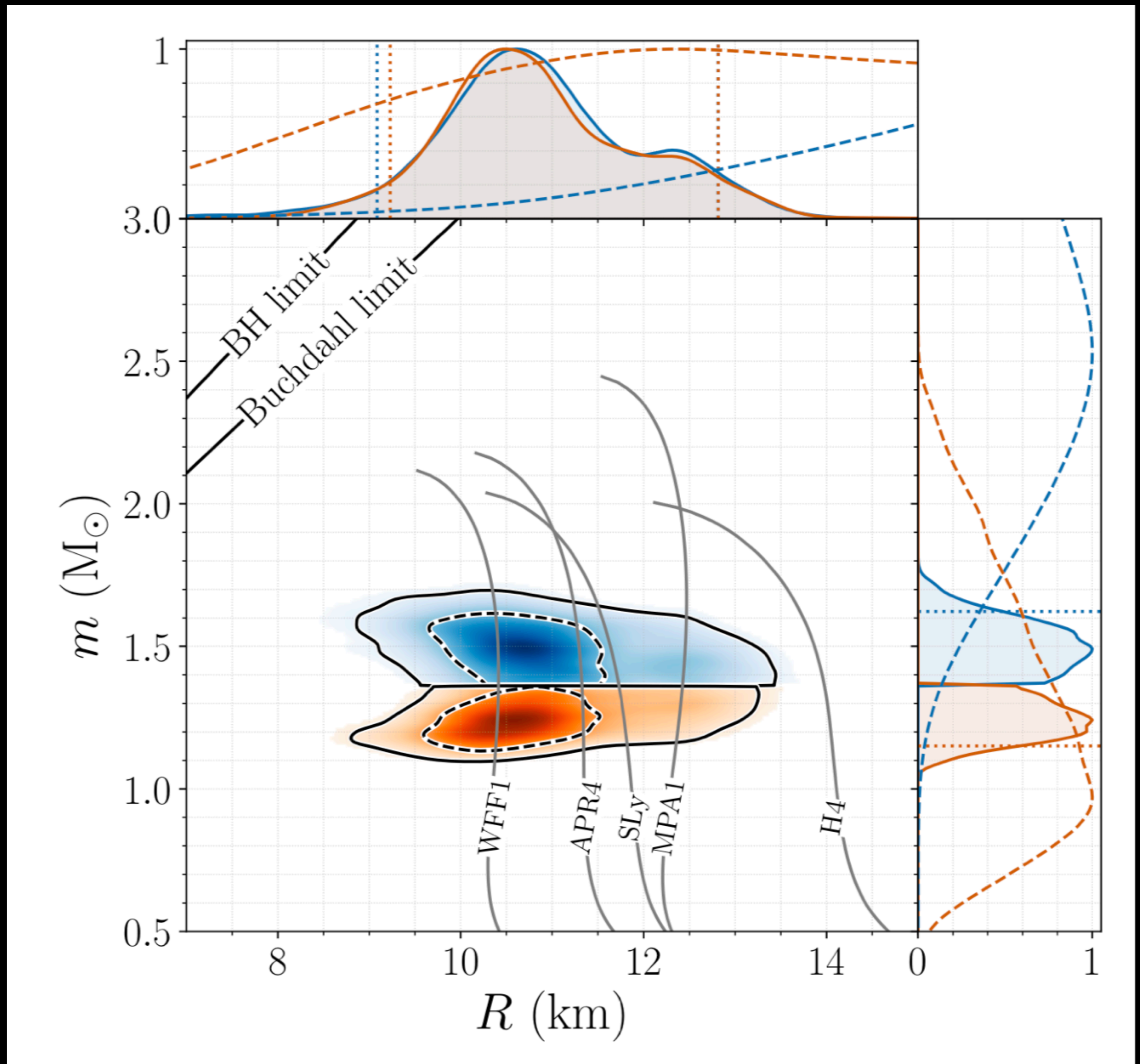
Early estimates now improved using known source location, improved waveform modeling, and re-calibrated Virgo data.

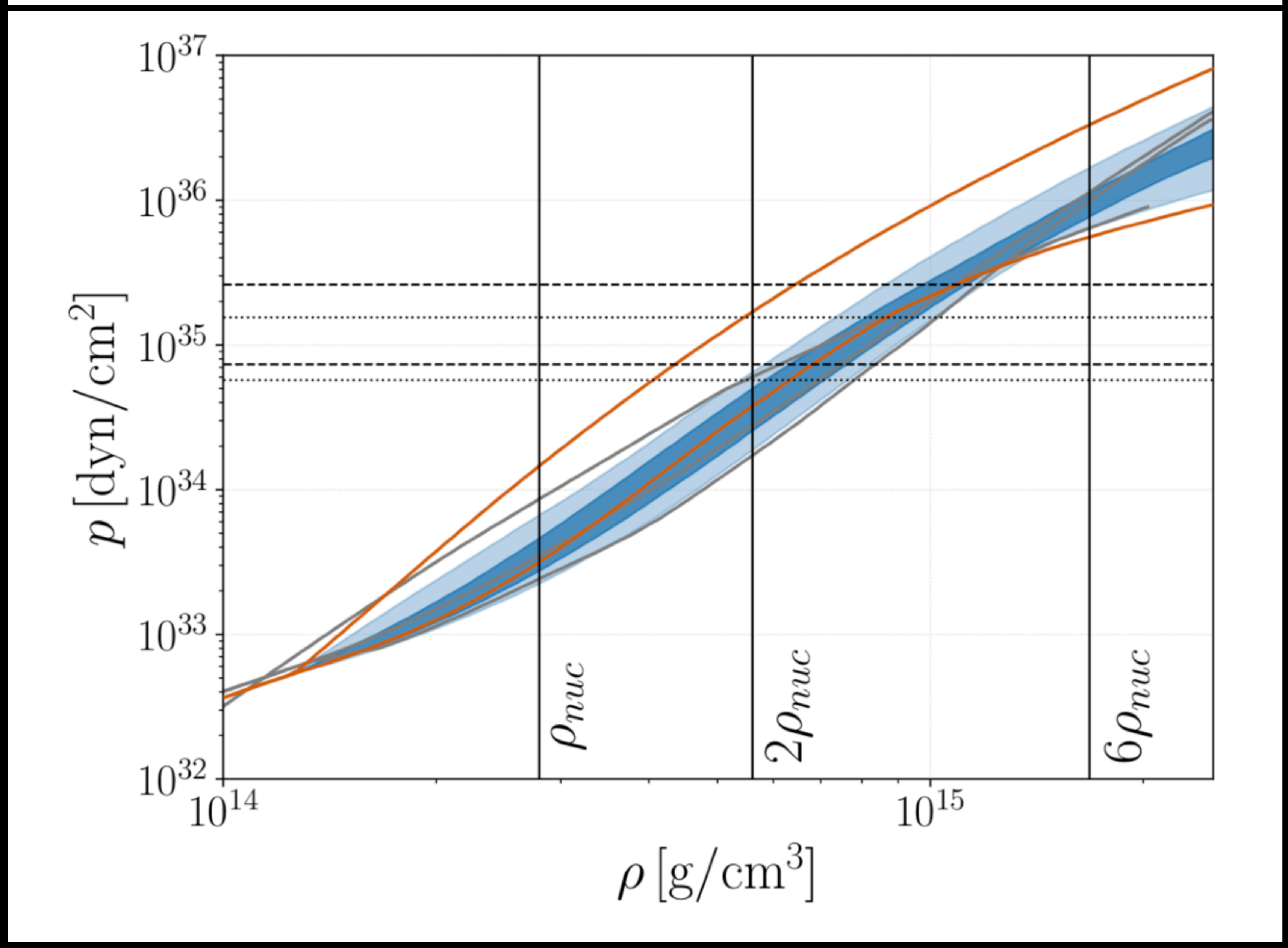
Properties of the binary neutron star merger GW170817 - arXiv:1805.11579

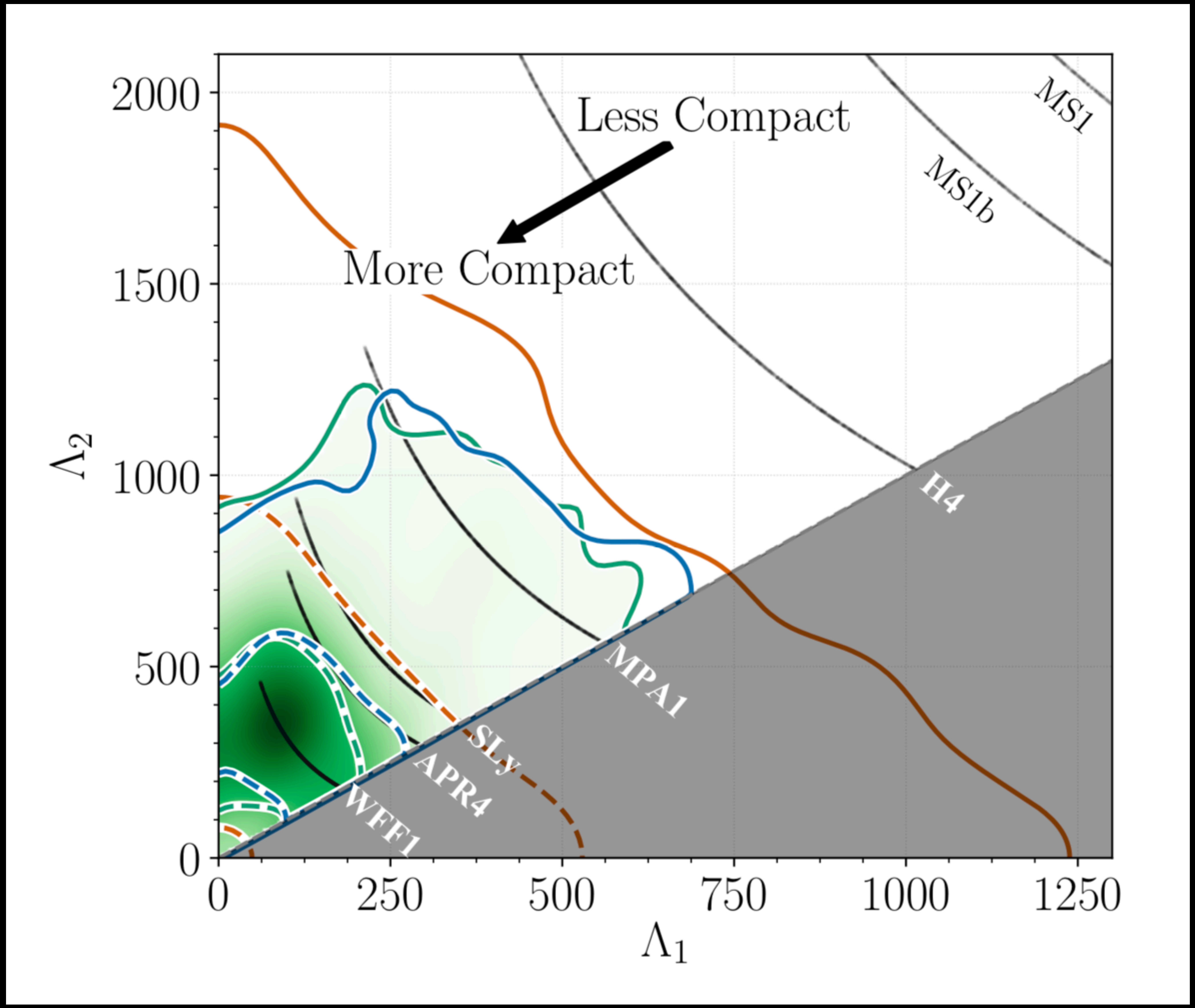
Neutron Star Structure

Properties of the binary neutron star merger GW170817 - arXiv:1805.11579

GW170817: Measurements of neutron star radii and equation of state arXiv:1805.11581



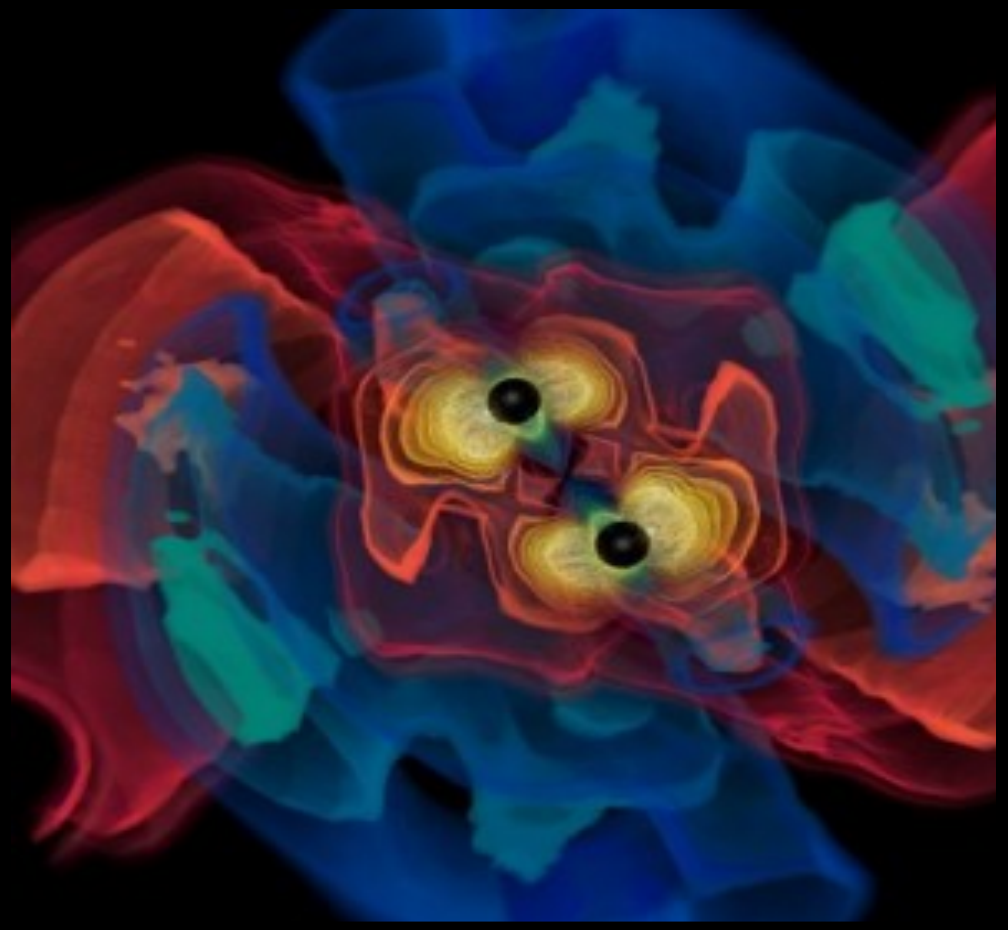




Constraining properties of nuclear matter via neutron star equation of state and tidal disruption, which is encoded in the BNS gravitational waveform

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

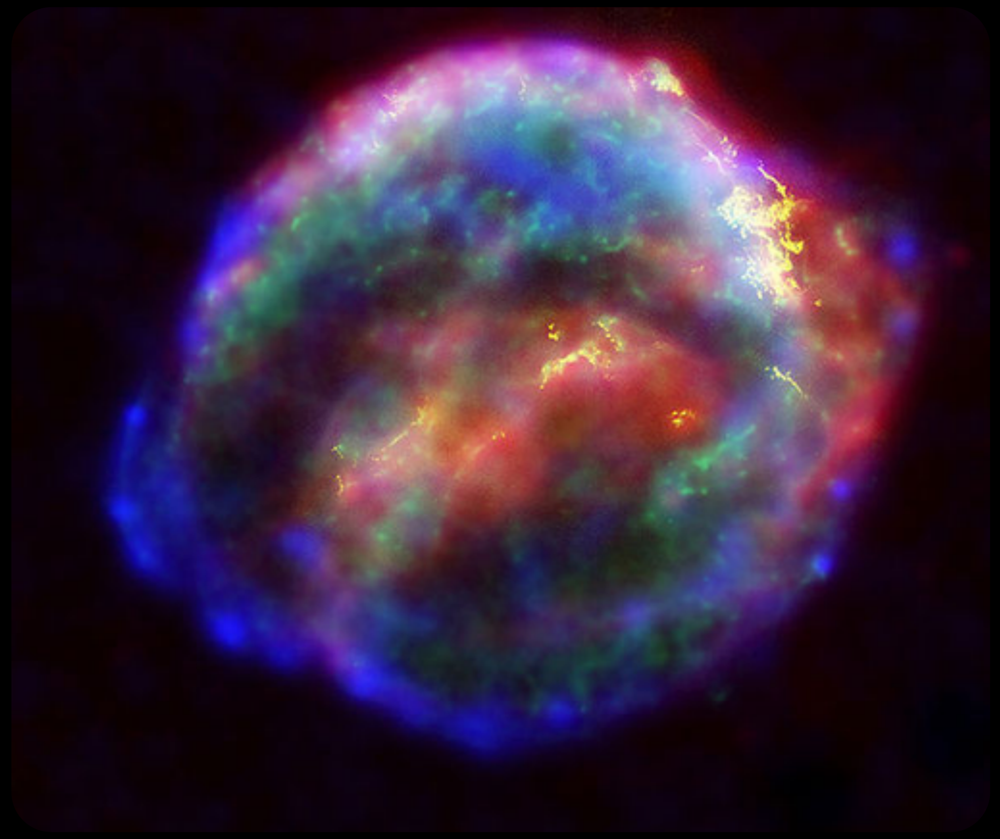
Gravitational Wave Astrophysics



Credit: AEI, CCT, LSU

Coalescing Binary Systems

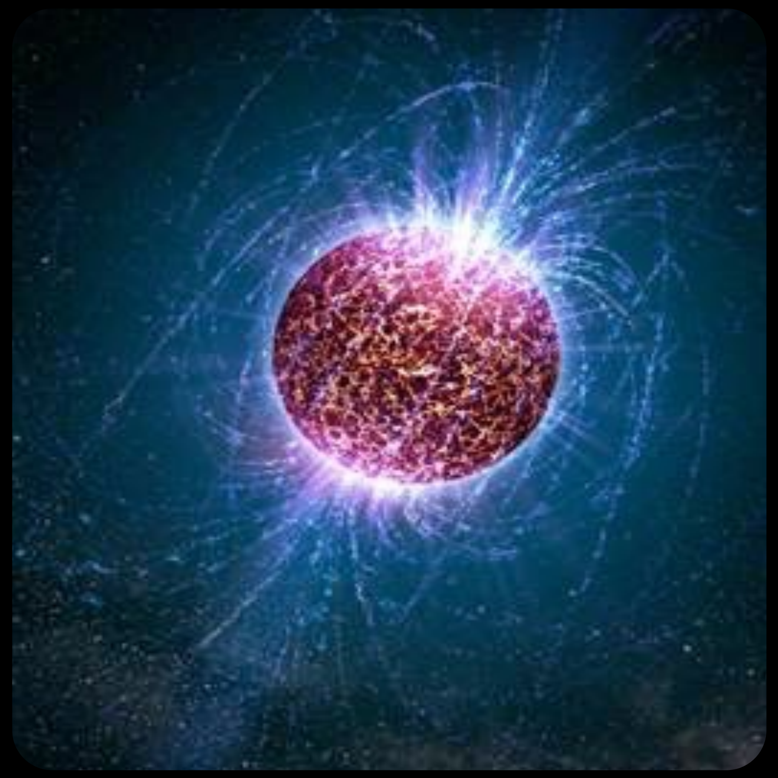
Neutron Stars,
Black Holes



Credit: Chandra X-ray Observatory

'Bursts'

asymmetric core collapse supernovae
cosmic strings
Postmerger
???

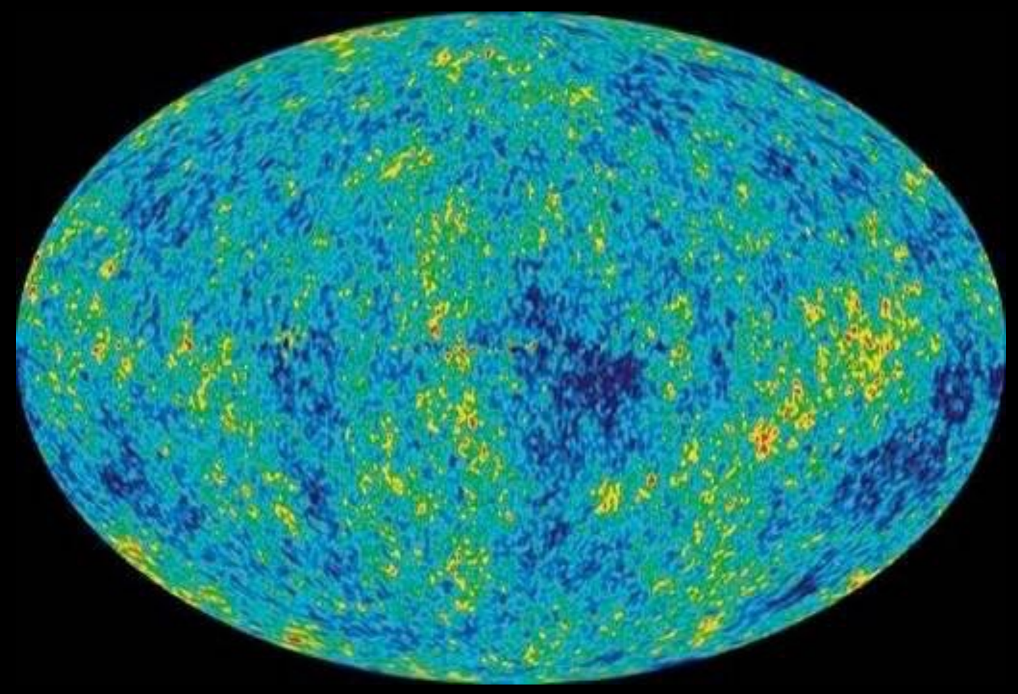


Casey Reed, Penn State

Continuous Sources

Spinning neutron stars

crustal deformations,
accretion

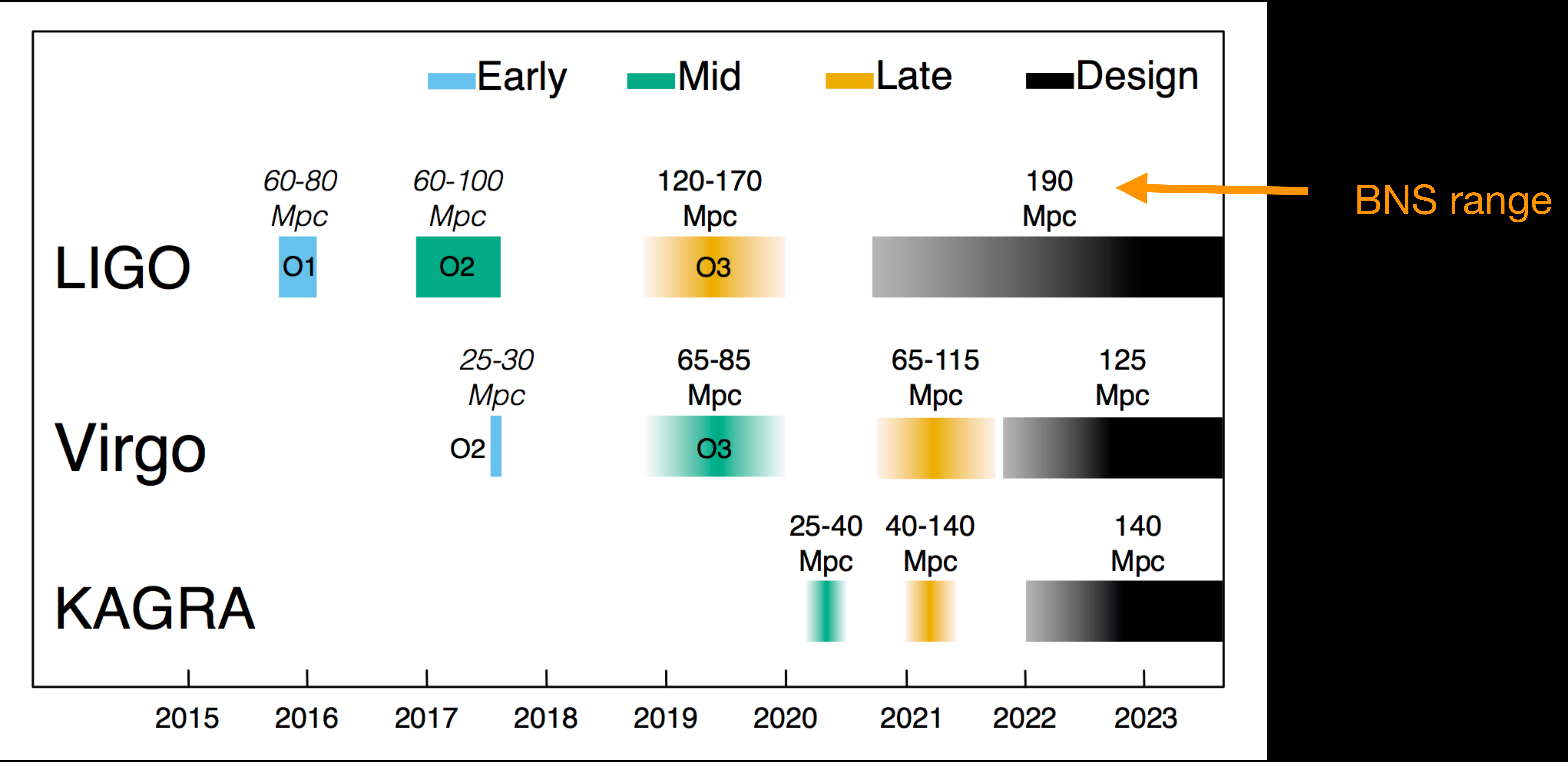


NASA/WMAP Science Team

Cosmic GW background

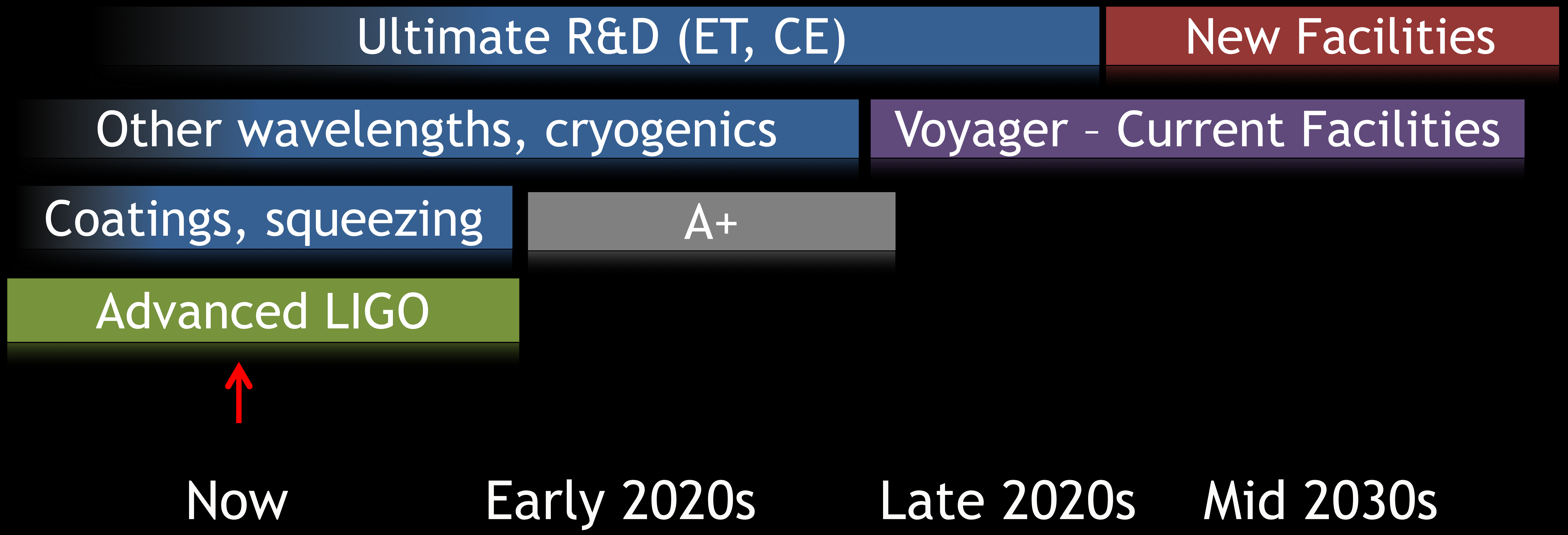
stochastic,
incoherent
background

Observing Scenarios



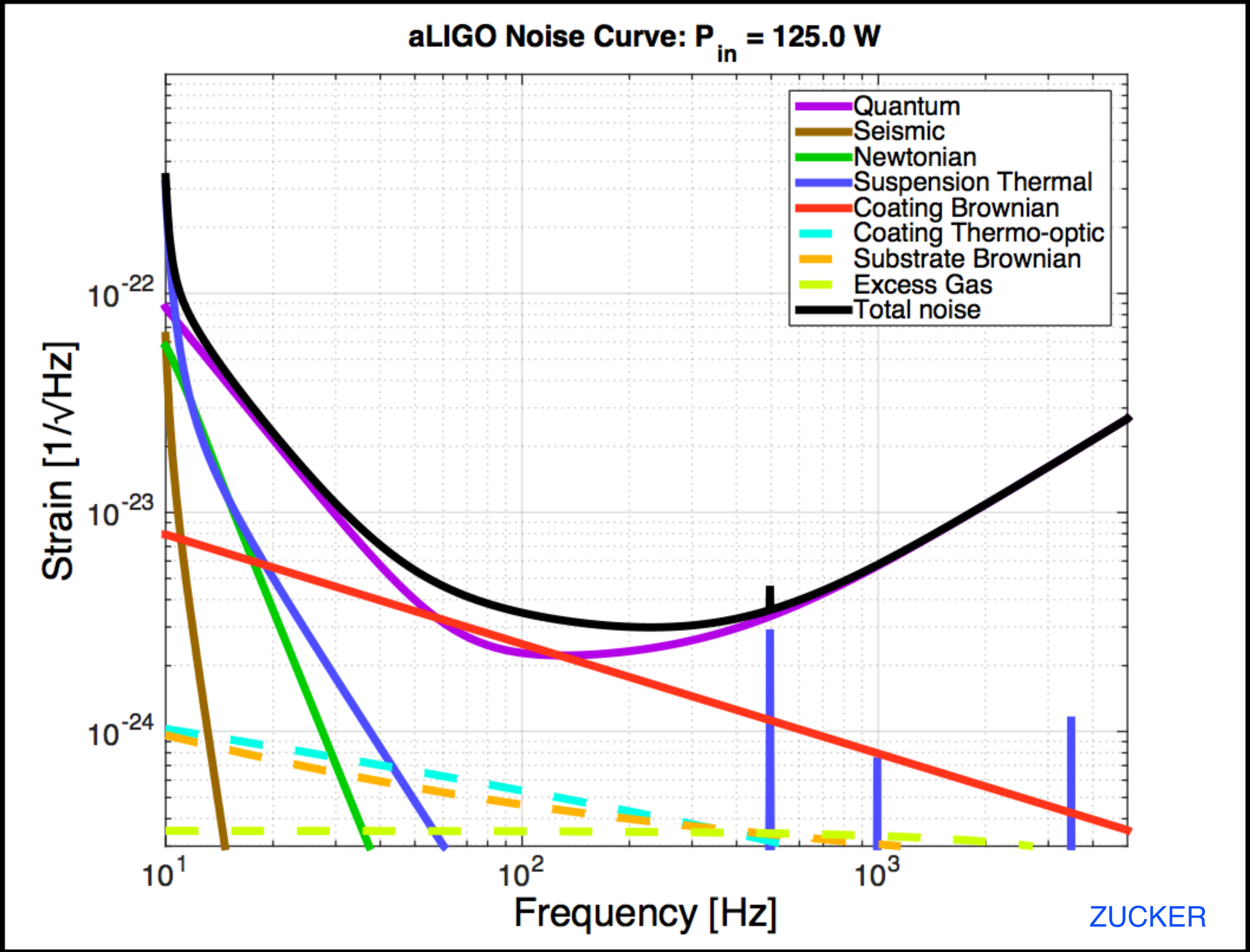
Prospects for Observing and Localizing Gravitational-Wave Transients with Advanced LIGO and Advanced Virgo and KAGRA — https://dcc.ligo.org/LIGO-P1200087/public

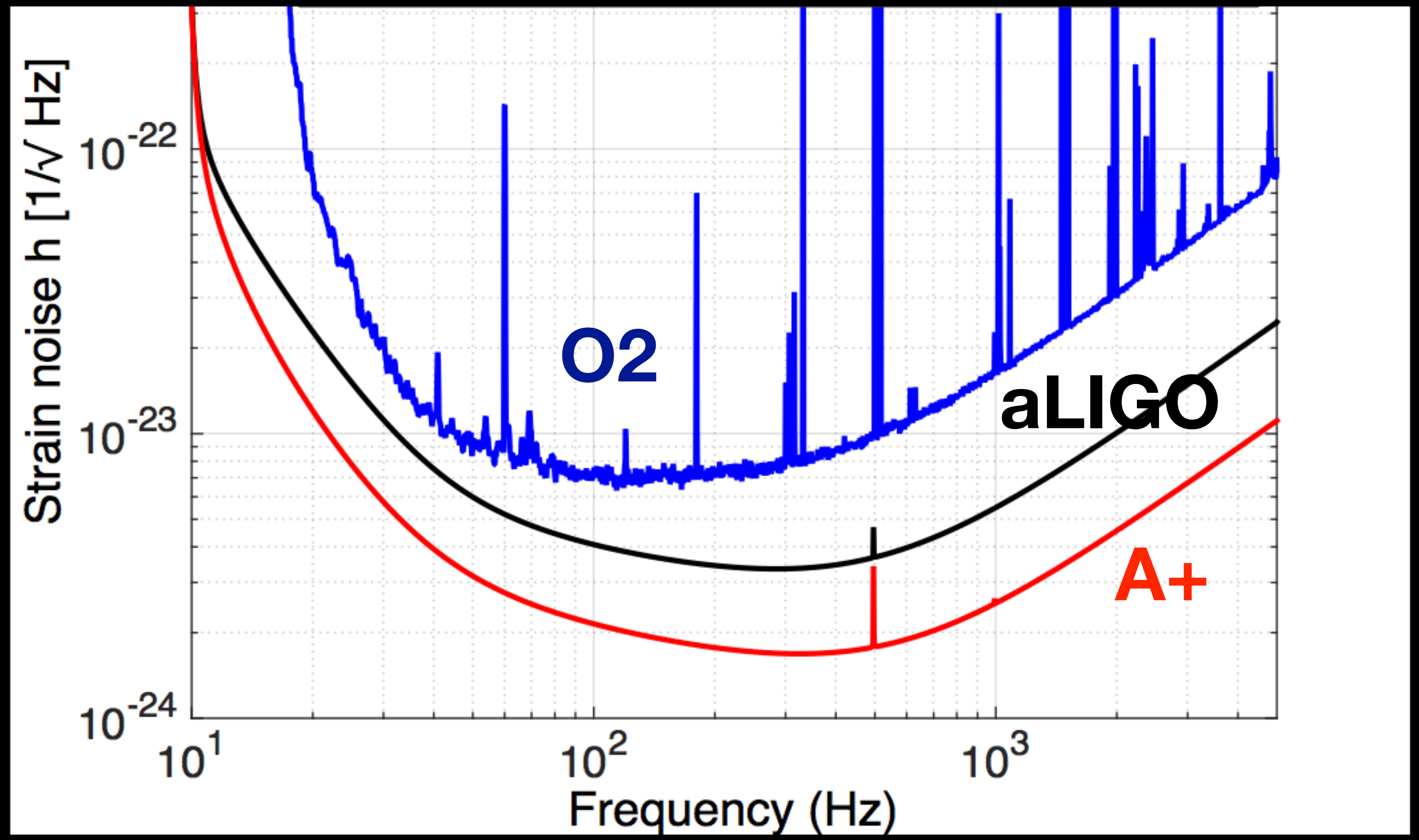
LIGO Concept Roadmap



Near-term Future: aLIGO target

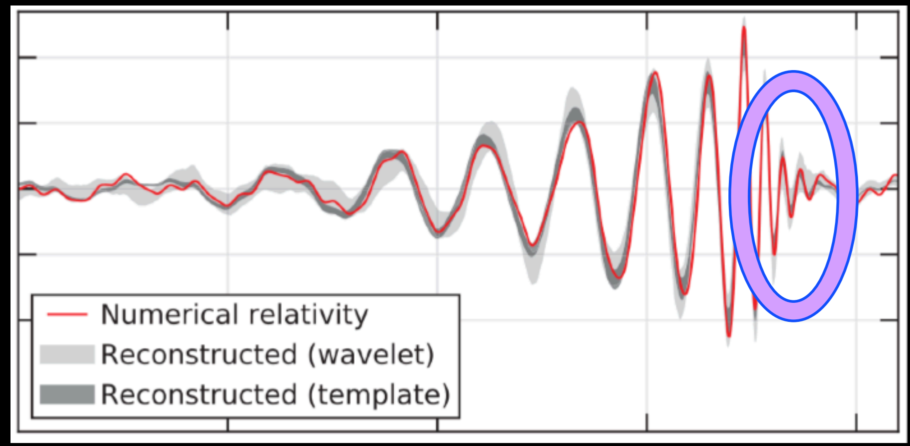
~10^2 binary coalescences per year (2020)





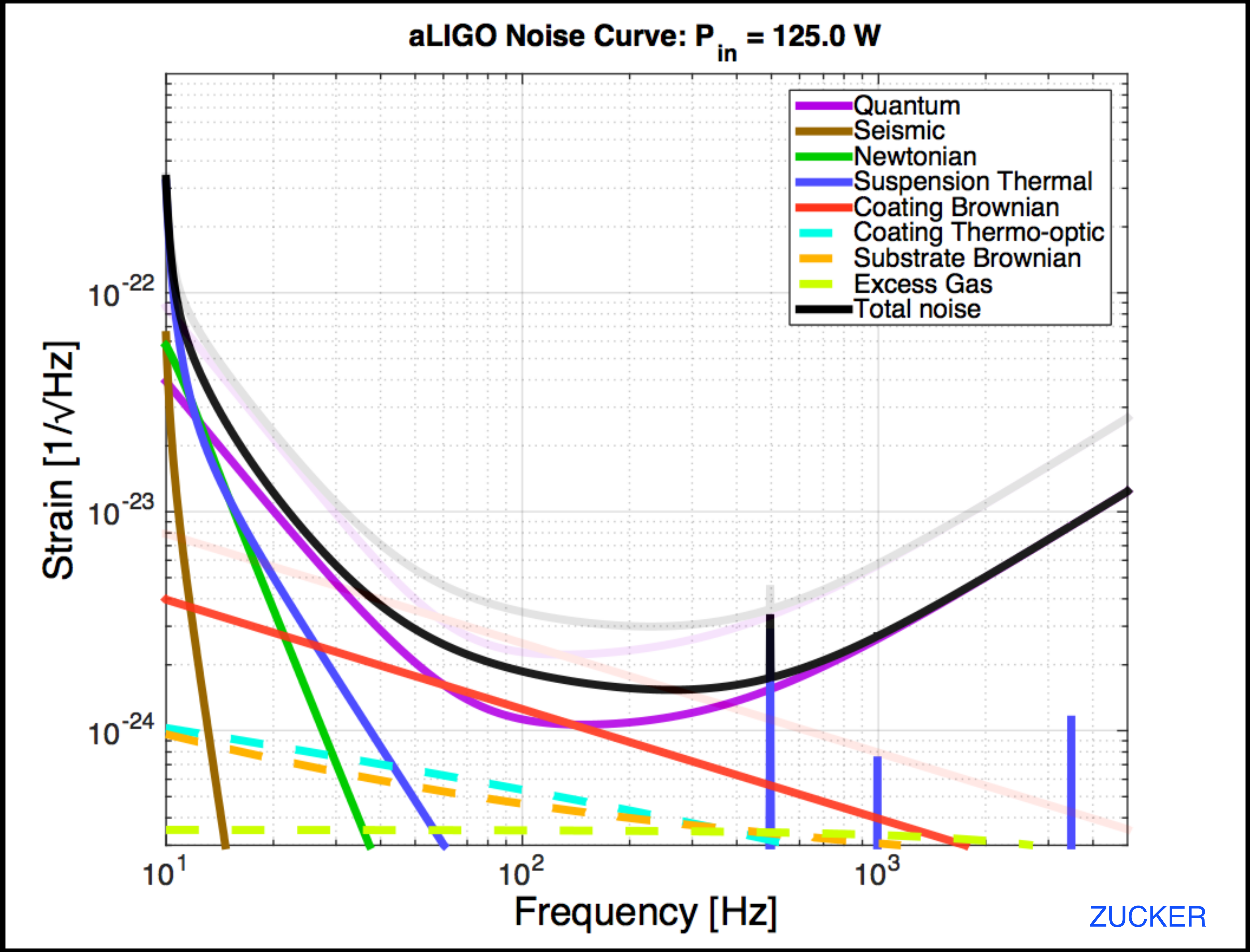
after additional commissioning
Reach: ~ 2x O2
~100 BBH/year
~1-2 NS-BH/year
~20-30 BNS/year

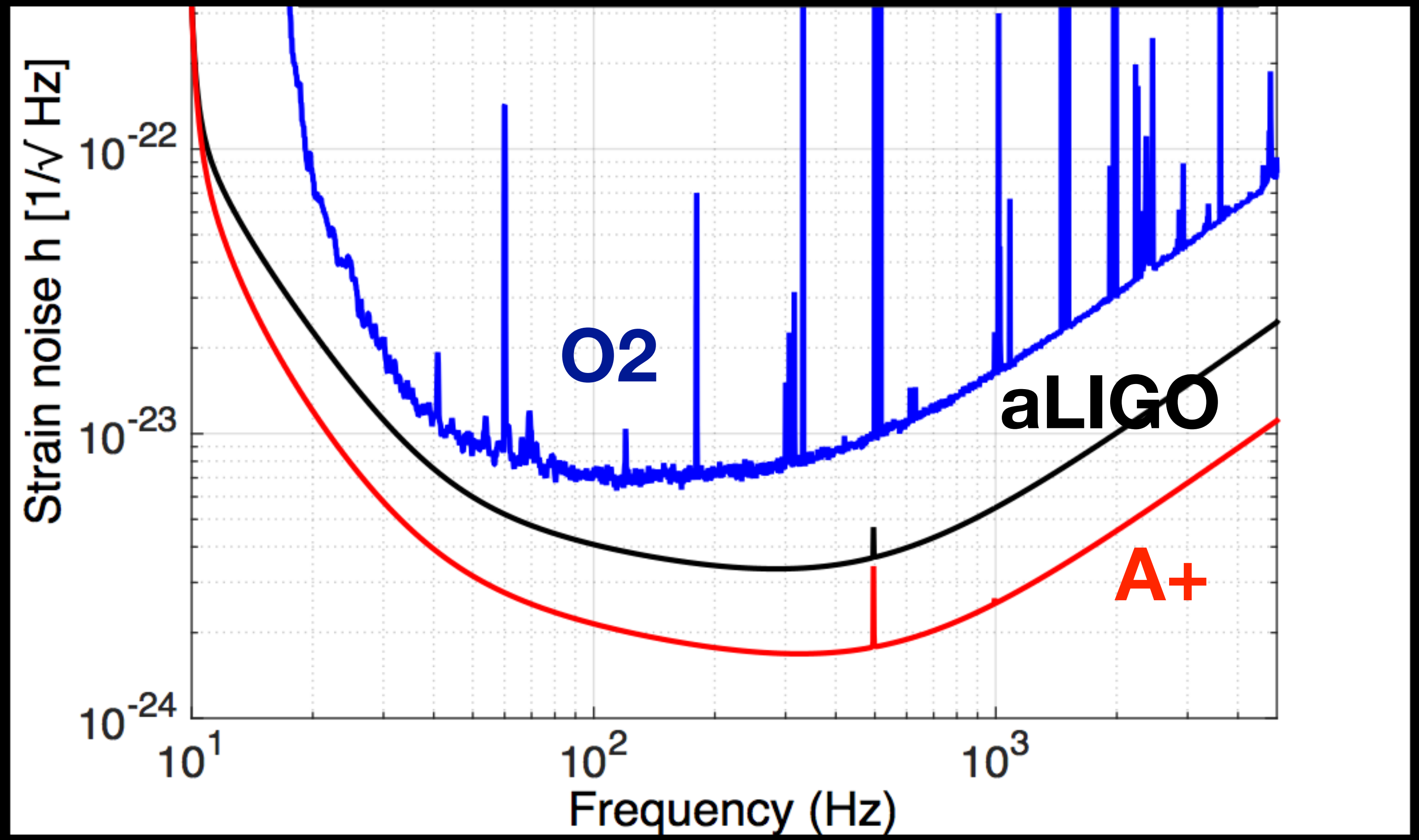
QNM SNR ~20 for an event like GW150914



Medium-term Future: A+

~10^3 binary coalescences per year (early 2020s)





aLIGO with frequency-dependent squeezing and lower optical coating thermal noise

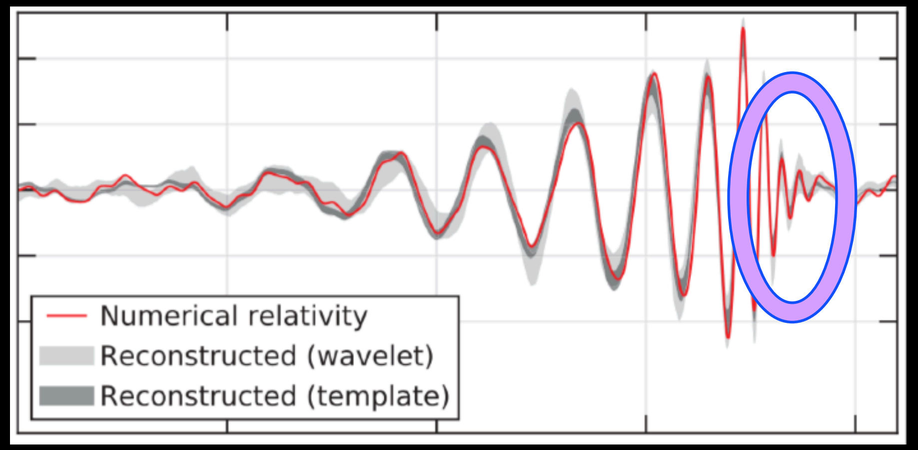
Reach: ~ 3x O2

~500-1000 BBH/year

~10 NS-BH/year

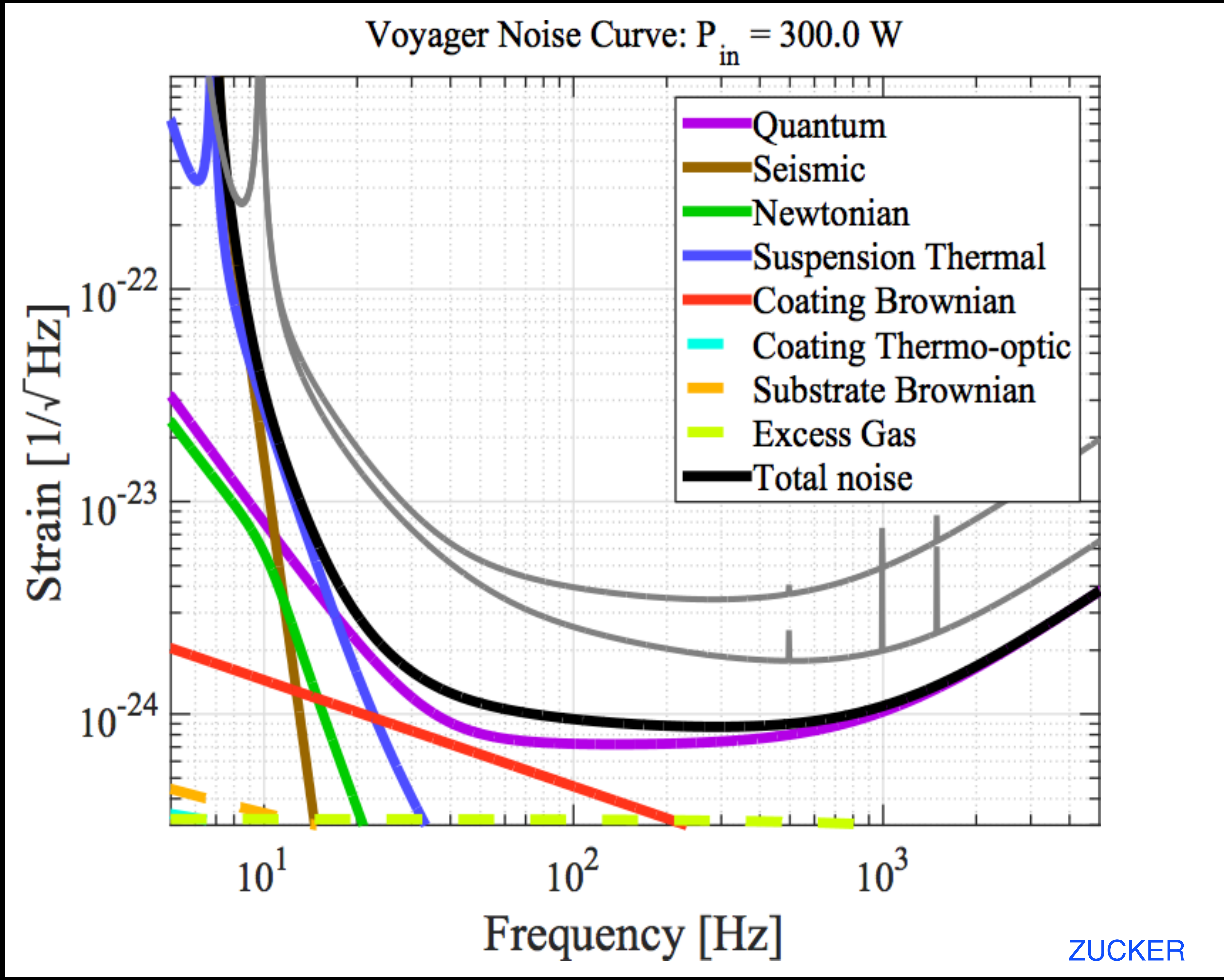
~200-300 BNS/year

QNM SNR ~35 for an event like GW150914



Long-term Future for current facilities: Voyager

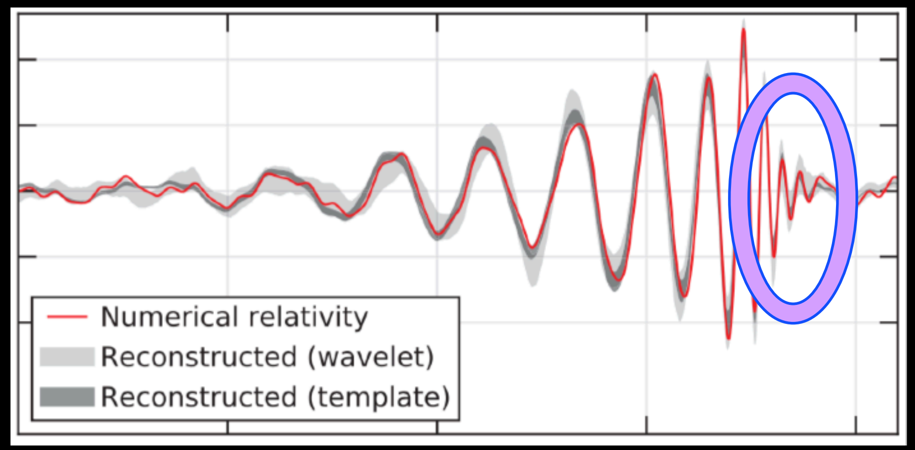
~10^4 binary coalescences per year (late 2020s)



aLIGO with:
Si optics, > 100 kg;
Si or AlGaAs coatings;
'mildly' Cryogenic;
λ~2 μm, 300 W

BNS reach: ~10x O2
BBH reach: z~5

QNM SNR ~80
(for an event like GW150914)



The 3rd Generation

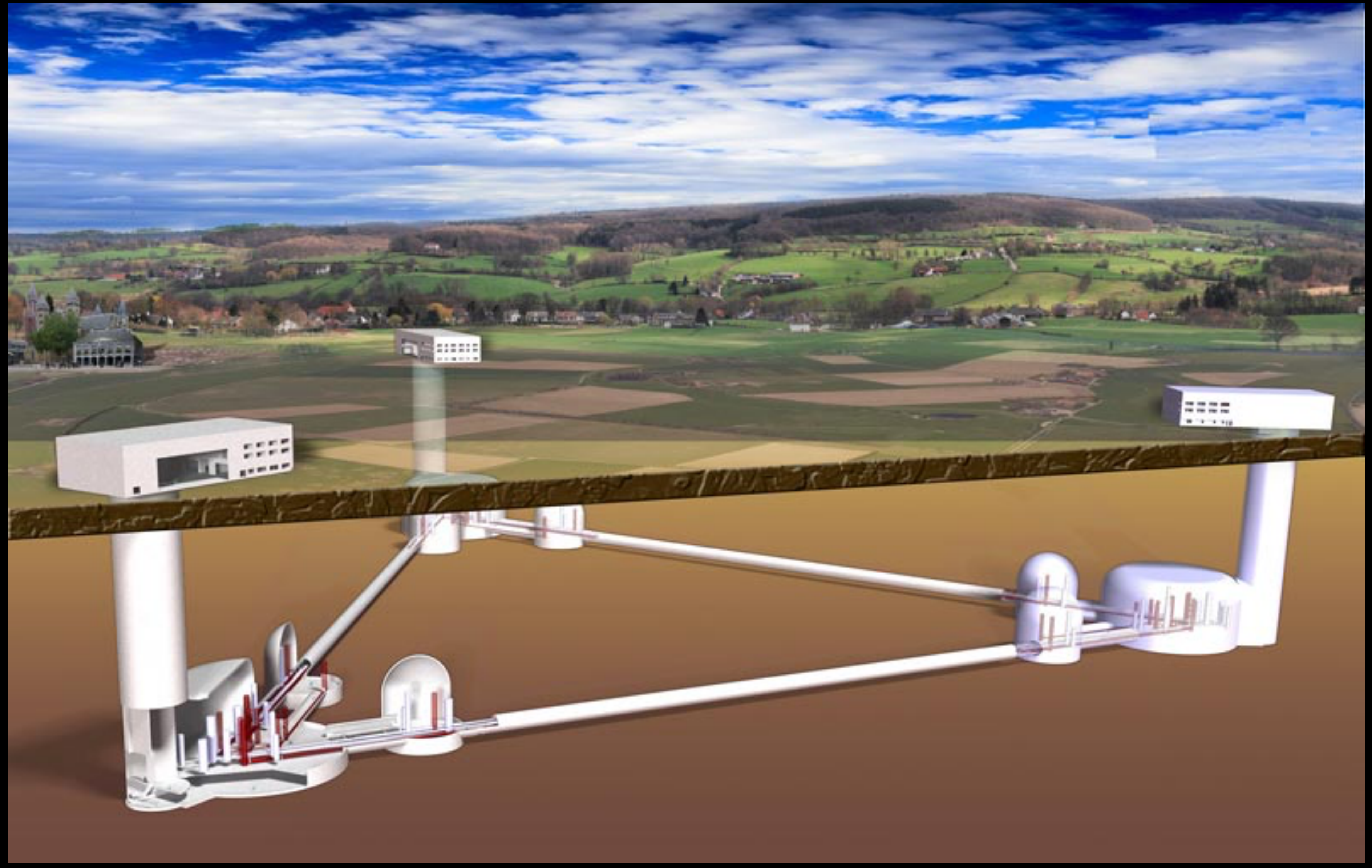
~10^5 binary coalescences per year (2030s)

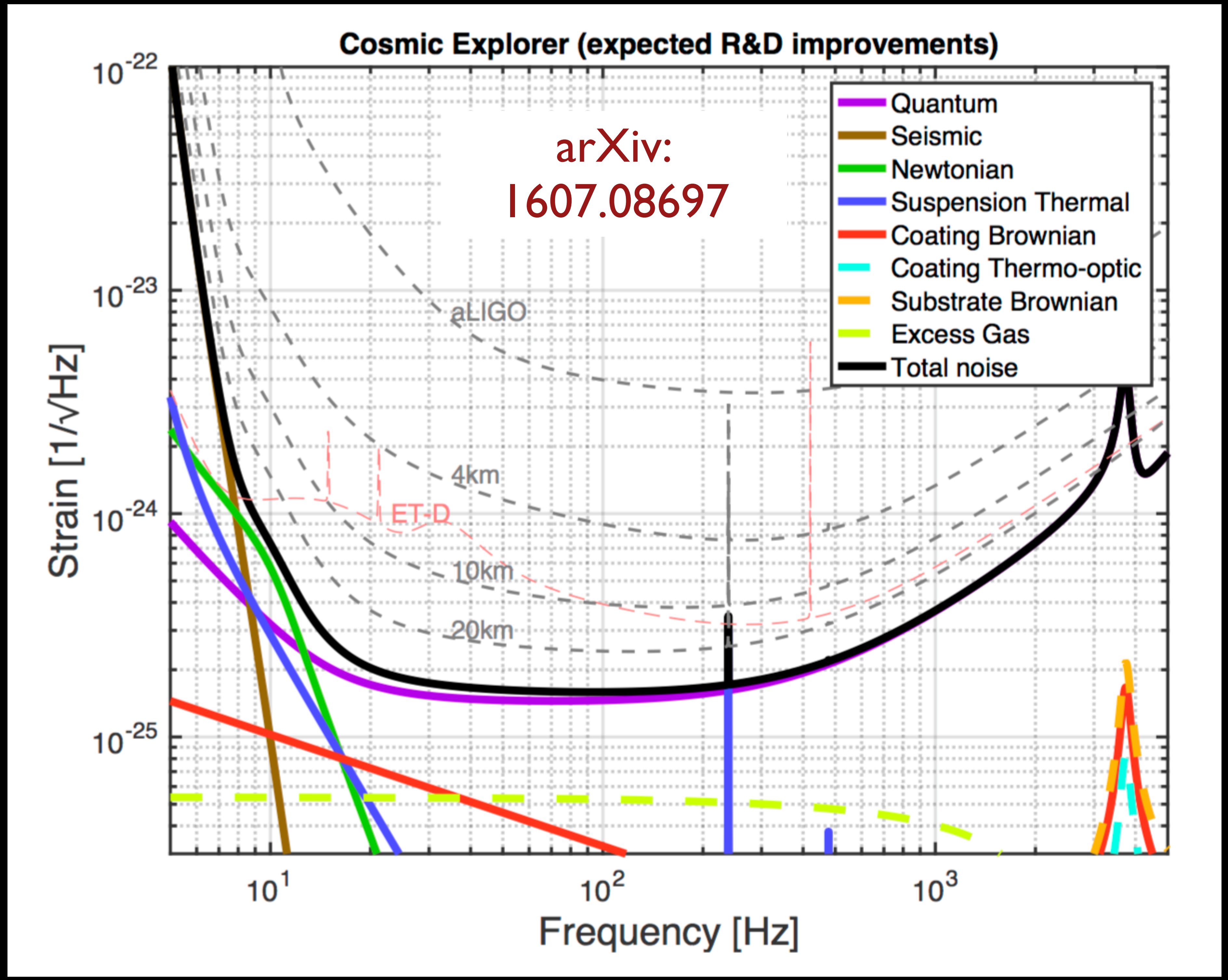
Einstein Telescope

- European conceptual design study
- Multiple instruments in xylophone configuration
- underground to reduce newtonian background
- 10 km arm length, in triangle.
- Assumes 10-15 year technology development.

Cosmic Explorer

- 40km surface Observatory baseline
- Signal grows with length – not most noise sources
- Thermal noise, radiation pressure, seismic, Newtonian unchanged; coating thermal noise improves faster than linearly with length






Thank you