New Directions in Theoretical Physics: Gravitational Waves

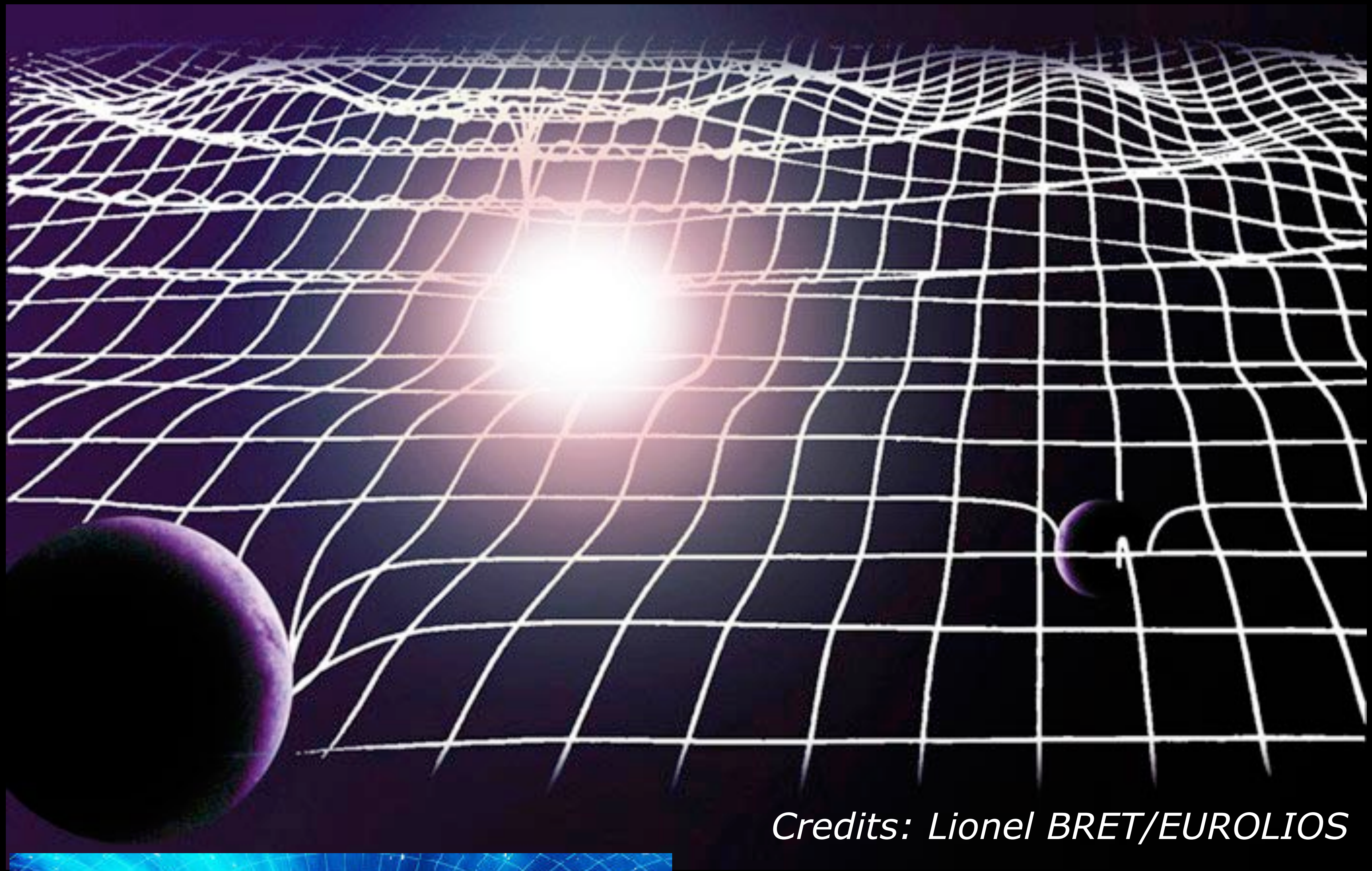
Laura Cadonati, Georgia Tech

New Directions in Theoretical Physics - Edinburgh, Jan 10-12 2023

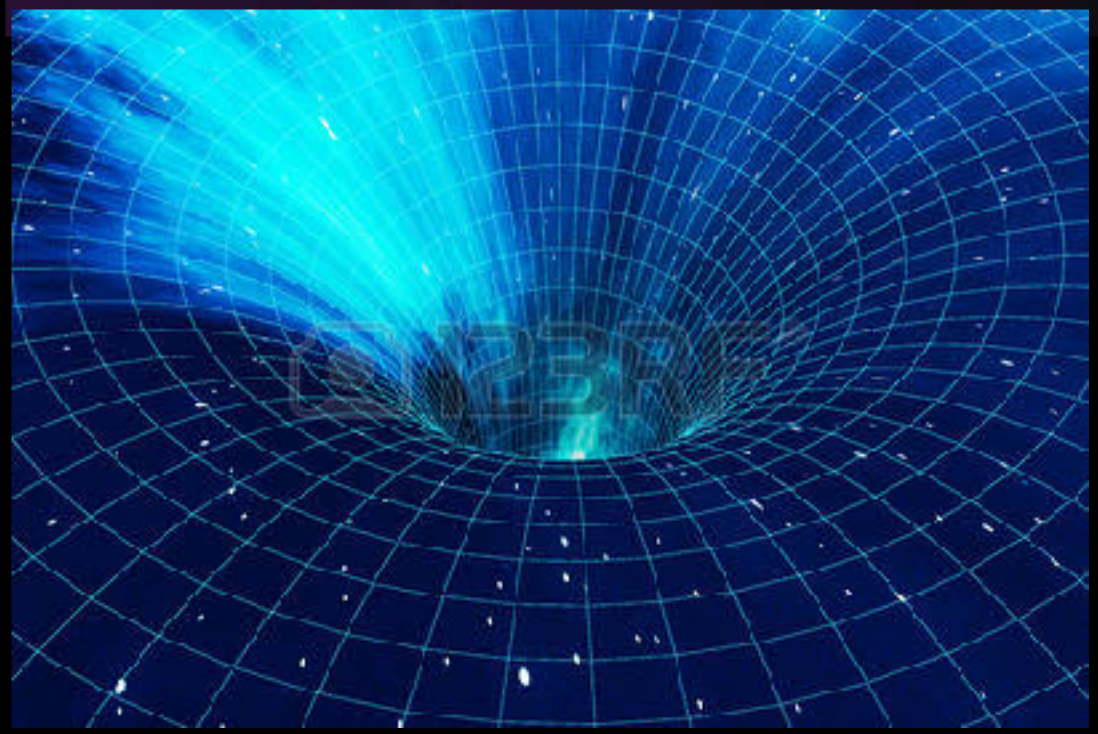
The EM sky

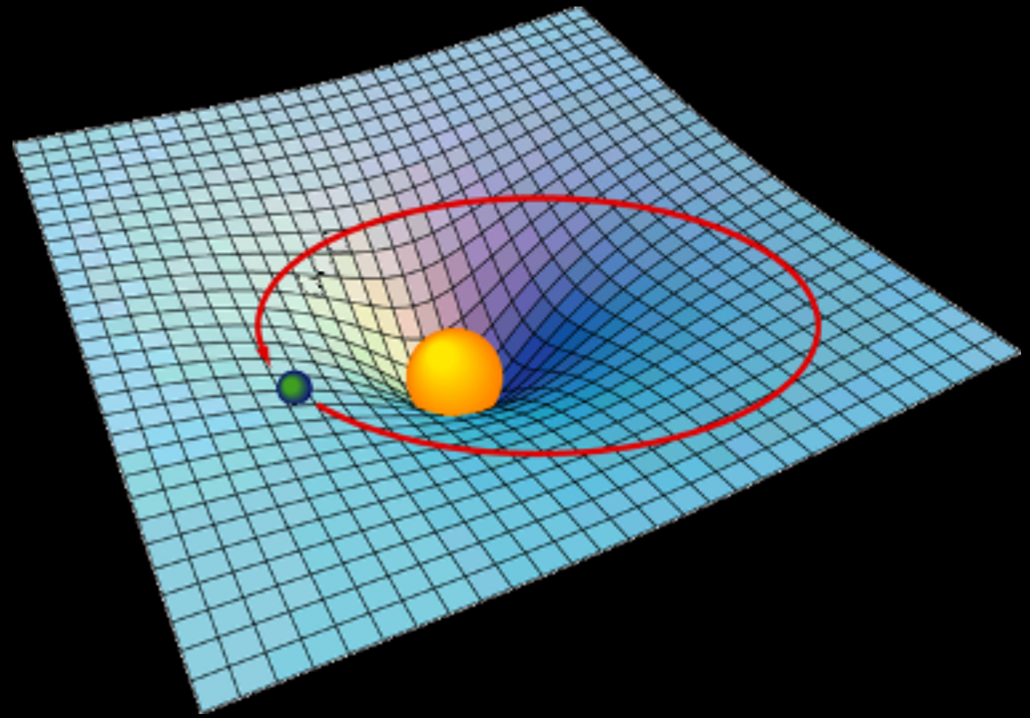
James Webb Space Telescope First Deep Field, galaxy cluster SMACS 0723 - Credits: NASA, ESA, CSA, STScI

The GR sky

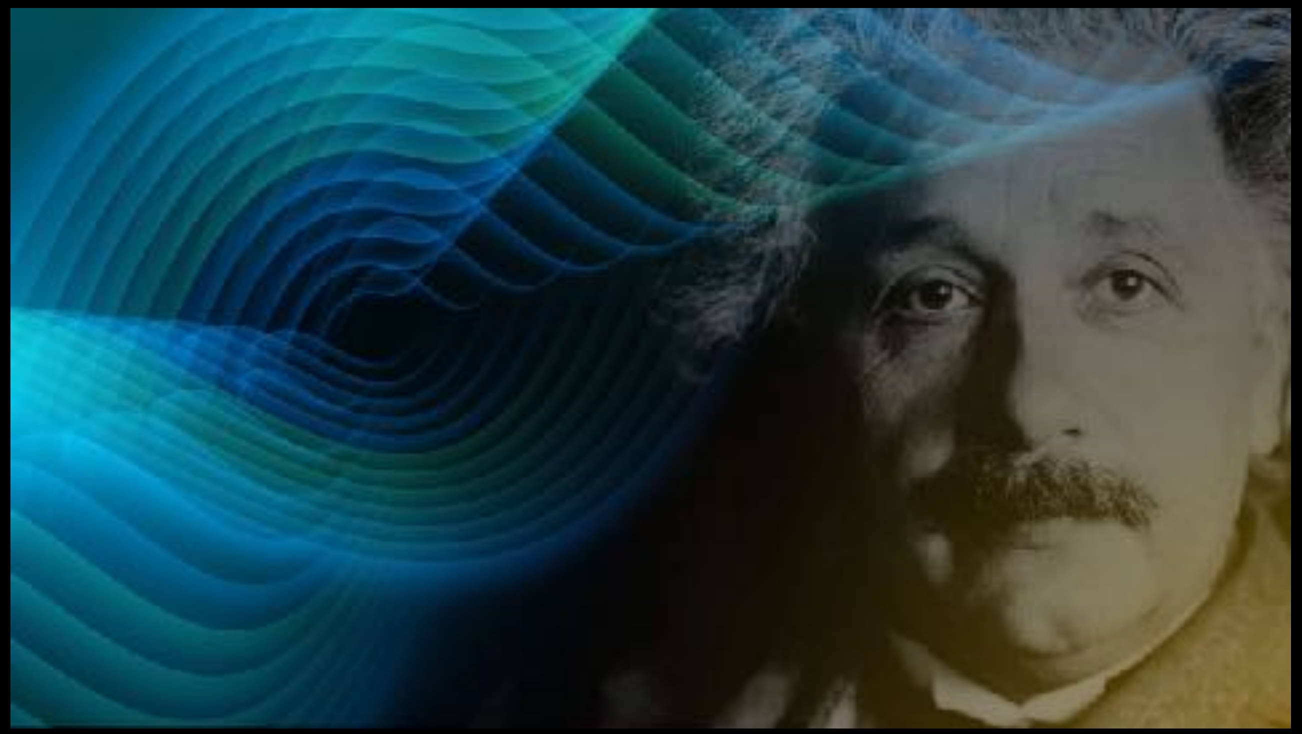


Credits: Lionel BRET/EUROLIOS





Gravitational Waves: Ripples in Space-Time

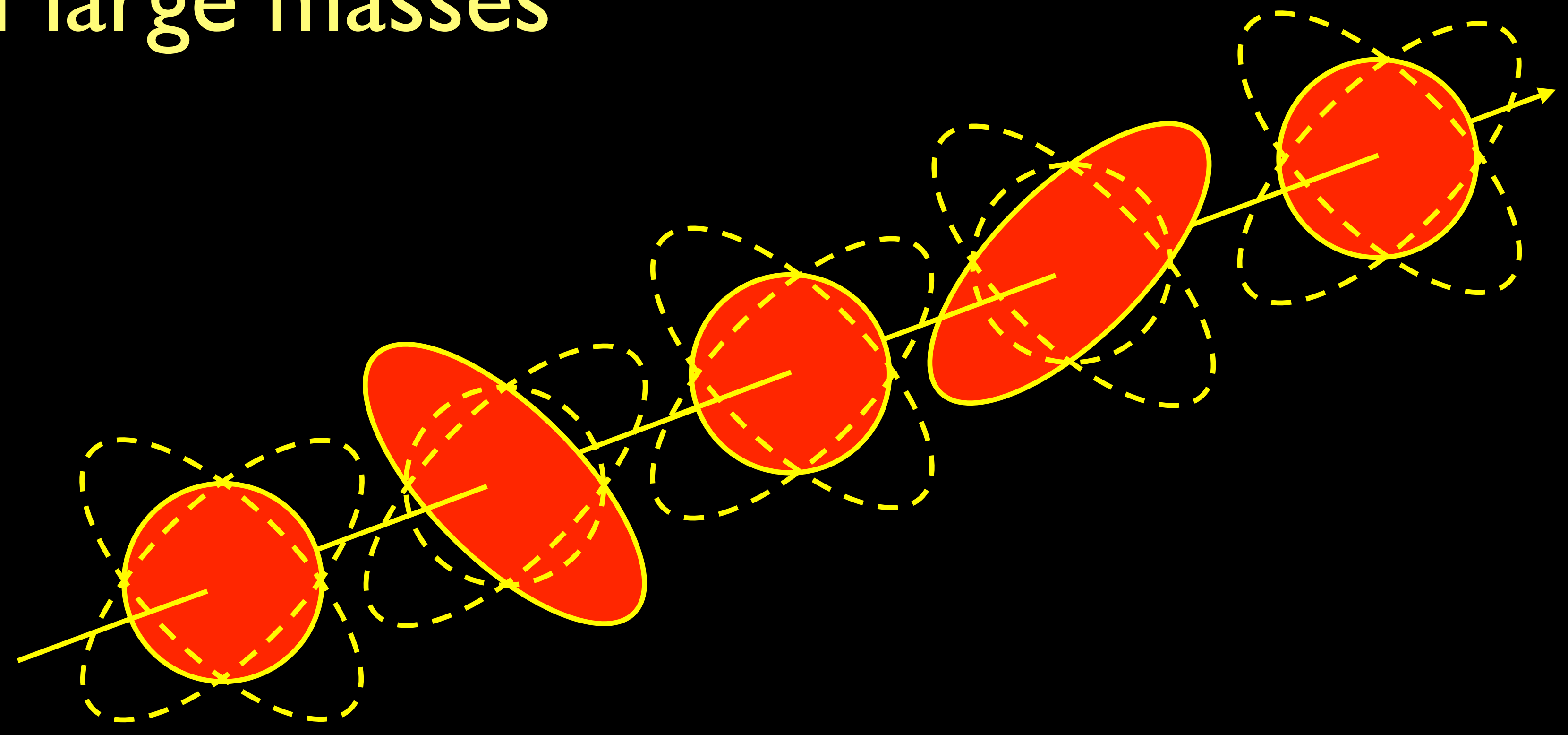


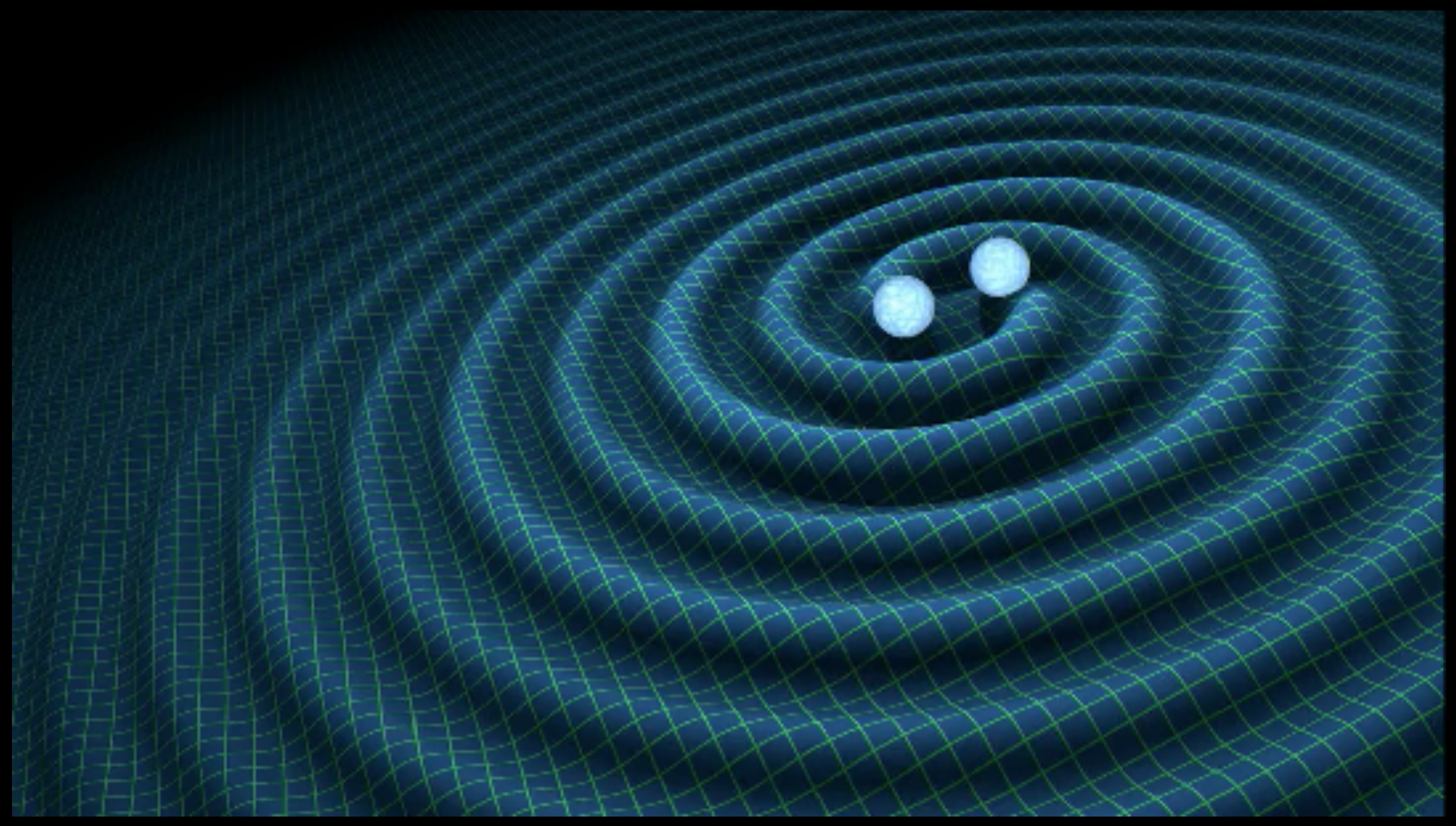
Perturbations of the space-time metric produced by rapid changes in shape and orientation of massive objects.

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

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

- Propagate at speed of light
- Transverse waves
- 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

A New Probe for the Universe

Some of the questions gravitational waves can help answer:

Physics

- Is General Relativity the correct theory of gravity?
- How does matter behave under extreme gravity?
- What is the equation of state of neutron stars?

Astrophysics & Astronomy

- What powers short gamma ray bursts, the brightest events in the universe?
- How do stars explode?
- How many stellar mass black holes are there in the universe?
- Do intermediate mass black holes exist?

Cosmology

- Can we detect primordial gravitational waves?
- What is the value of the Hubble constant?
- Do primordial black holes exist?

Black Hole Merger and Ringdown

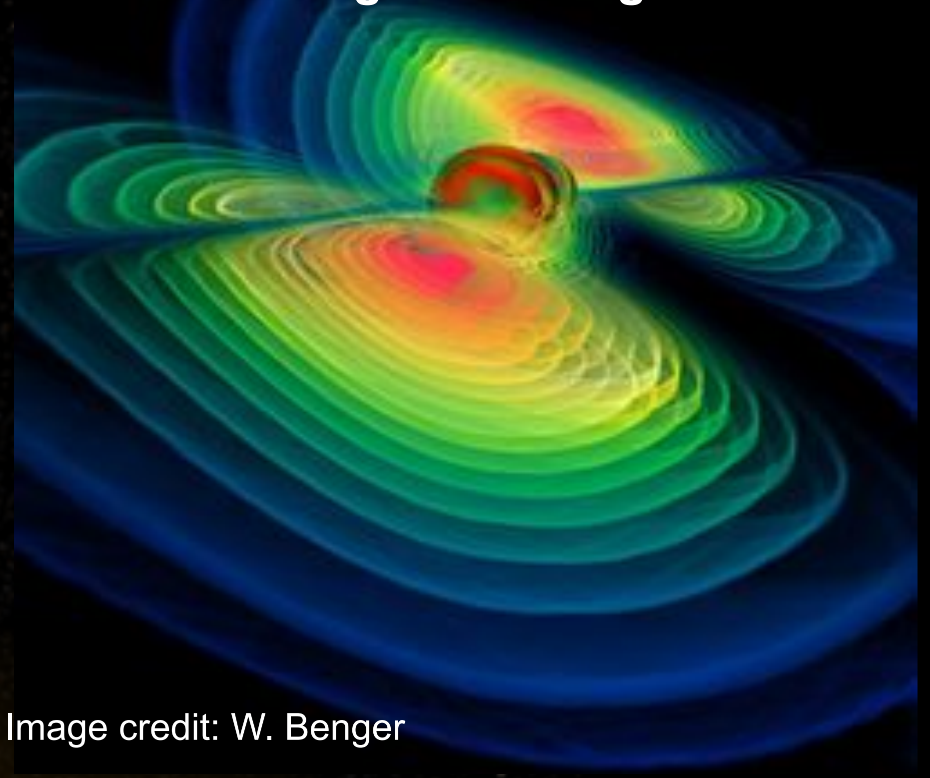


Image credit: W. Benger

Image credit: NASA

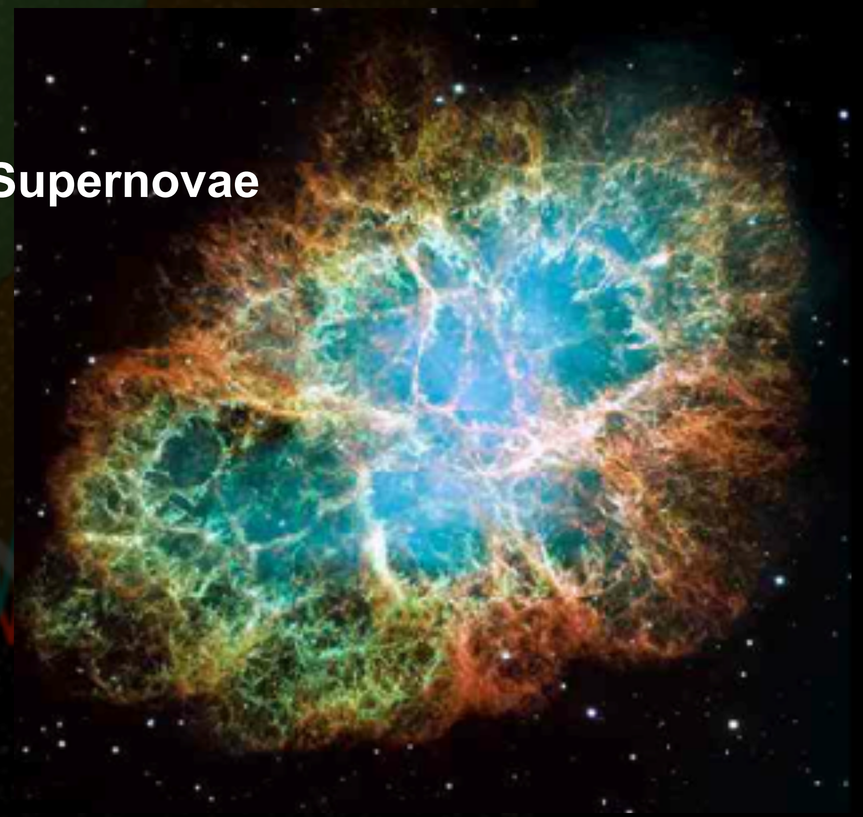
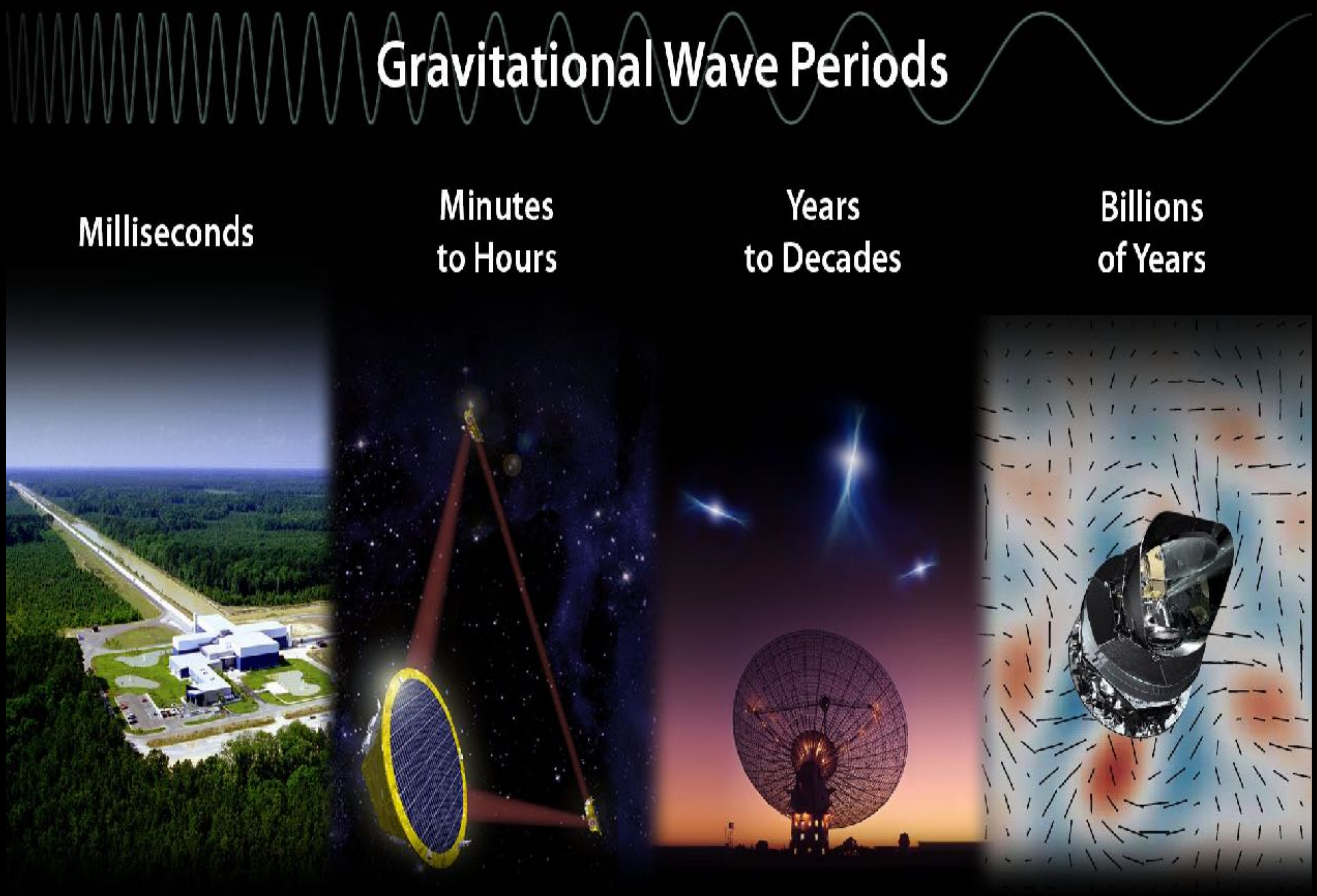


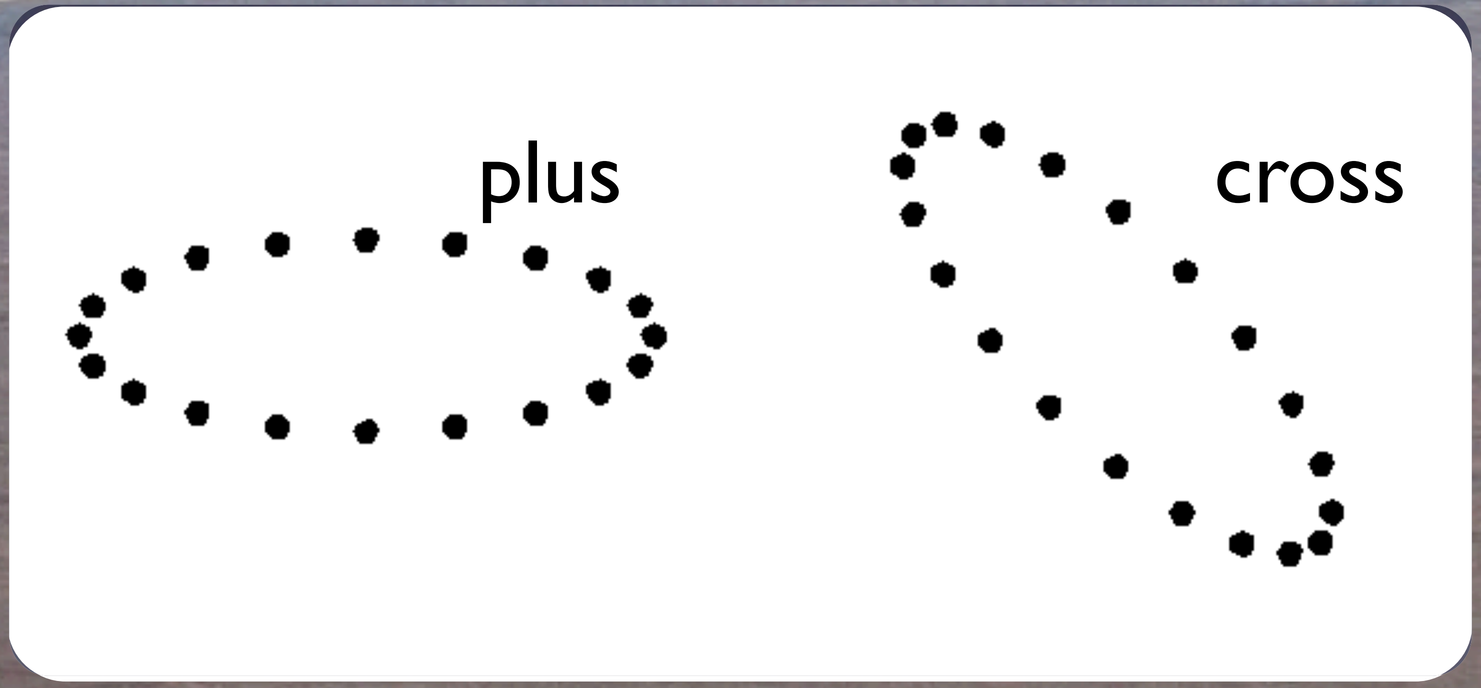
Image credit: Hubble



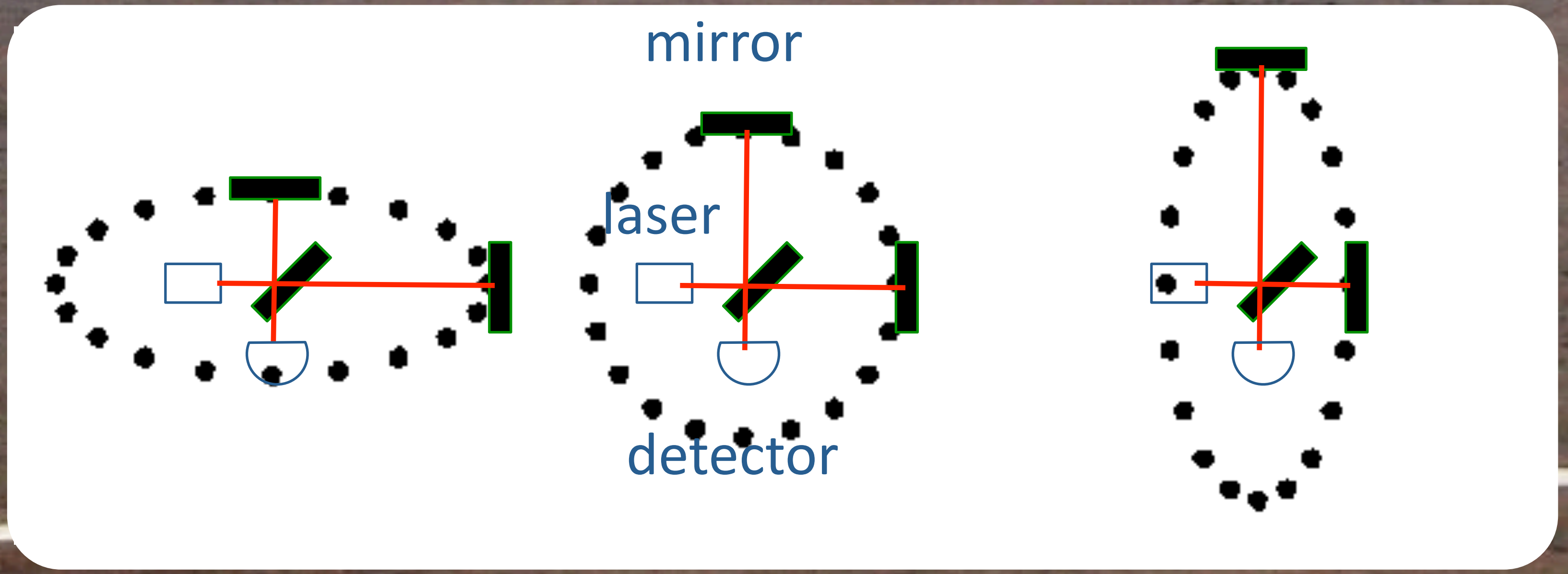
LIGO/Virgo LISA Pulsar Timing Array Cosmology Probes

How to Detect Gravitational Waves

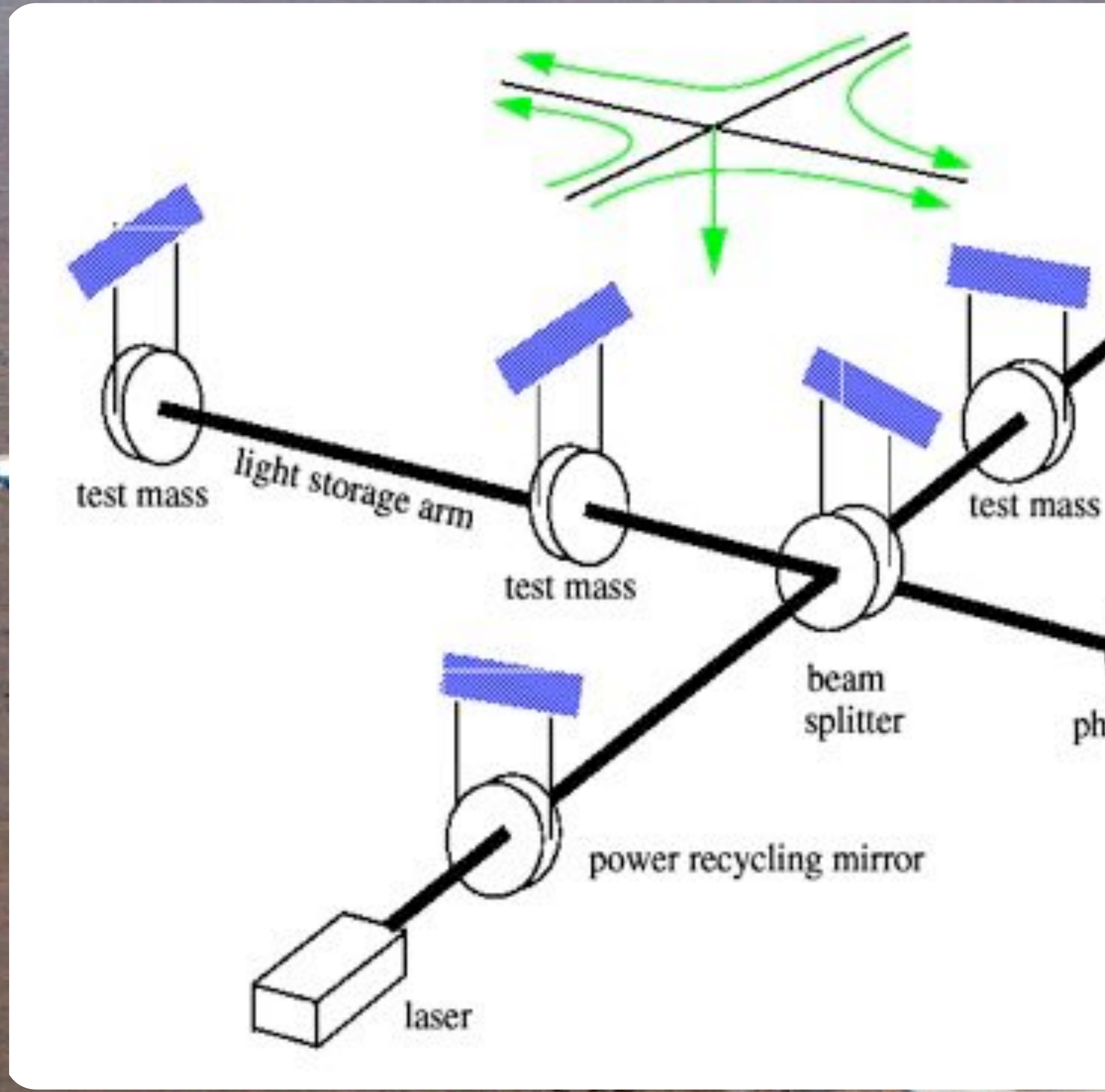
Physically, gravitational waves are strains



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



Suspended Mirrors as Test Masses

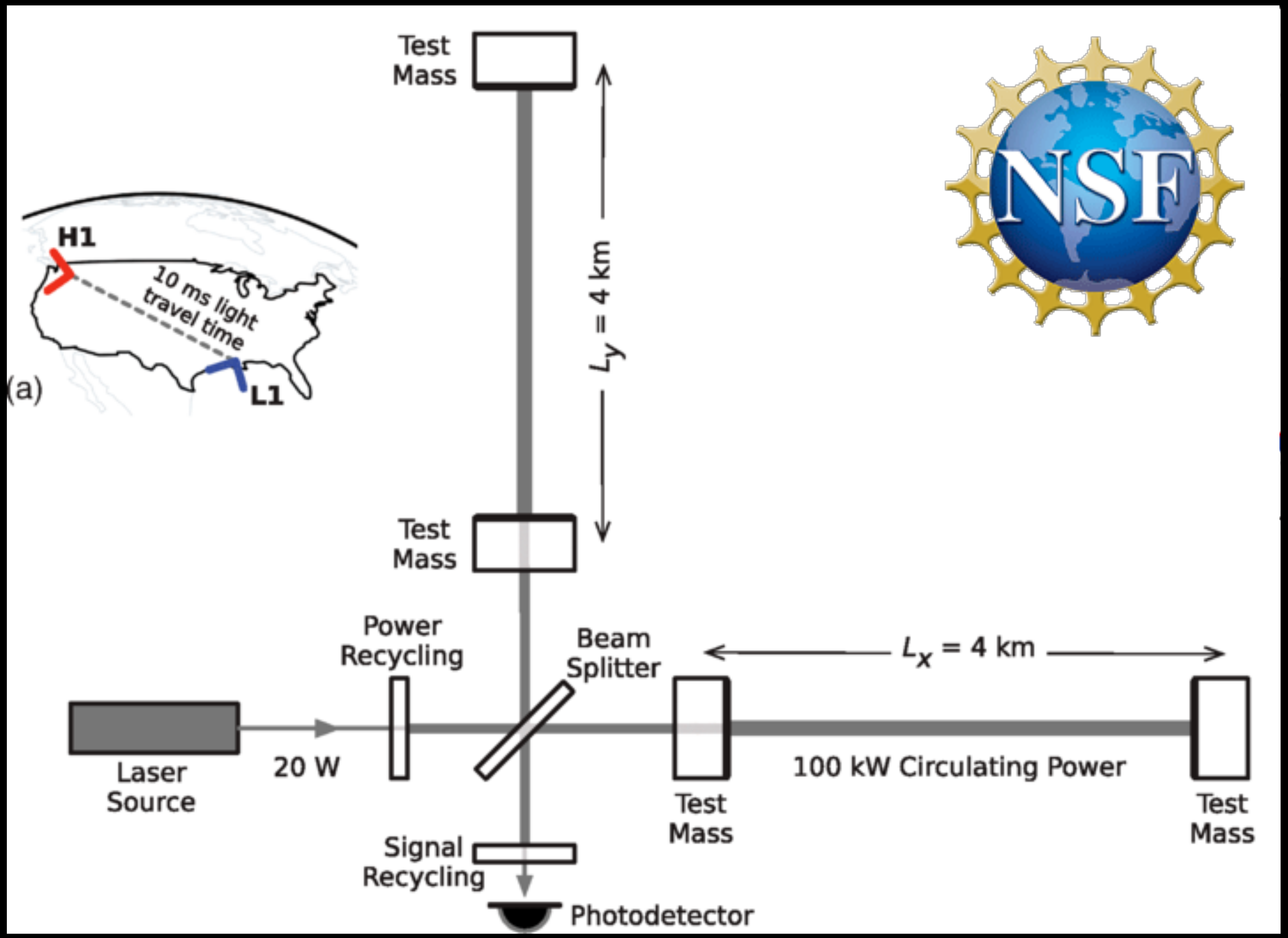


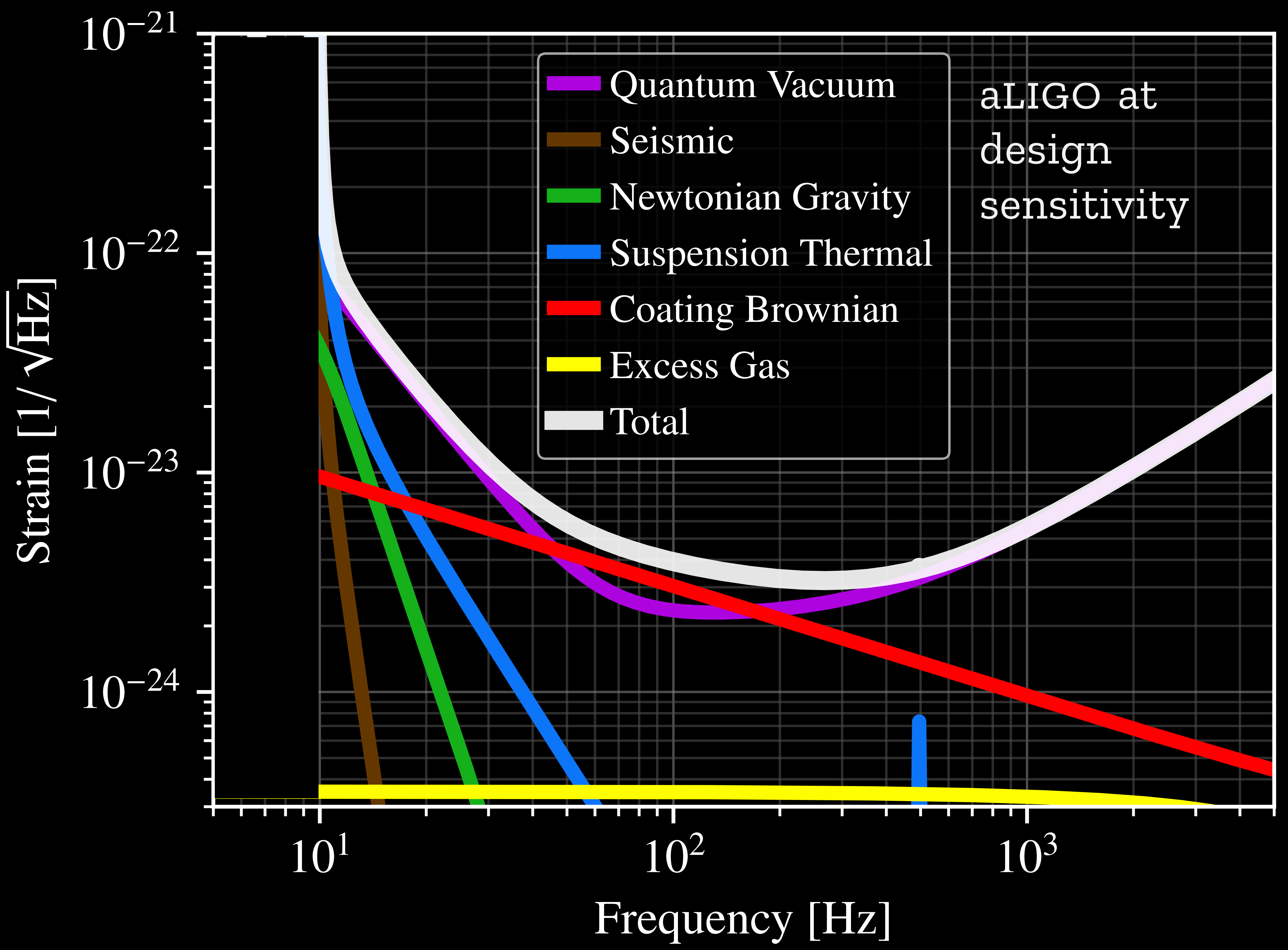
$$\frac{\Delta L}{L} \sim 10^{-22}$$

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

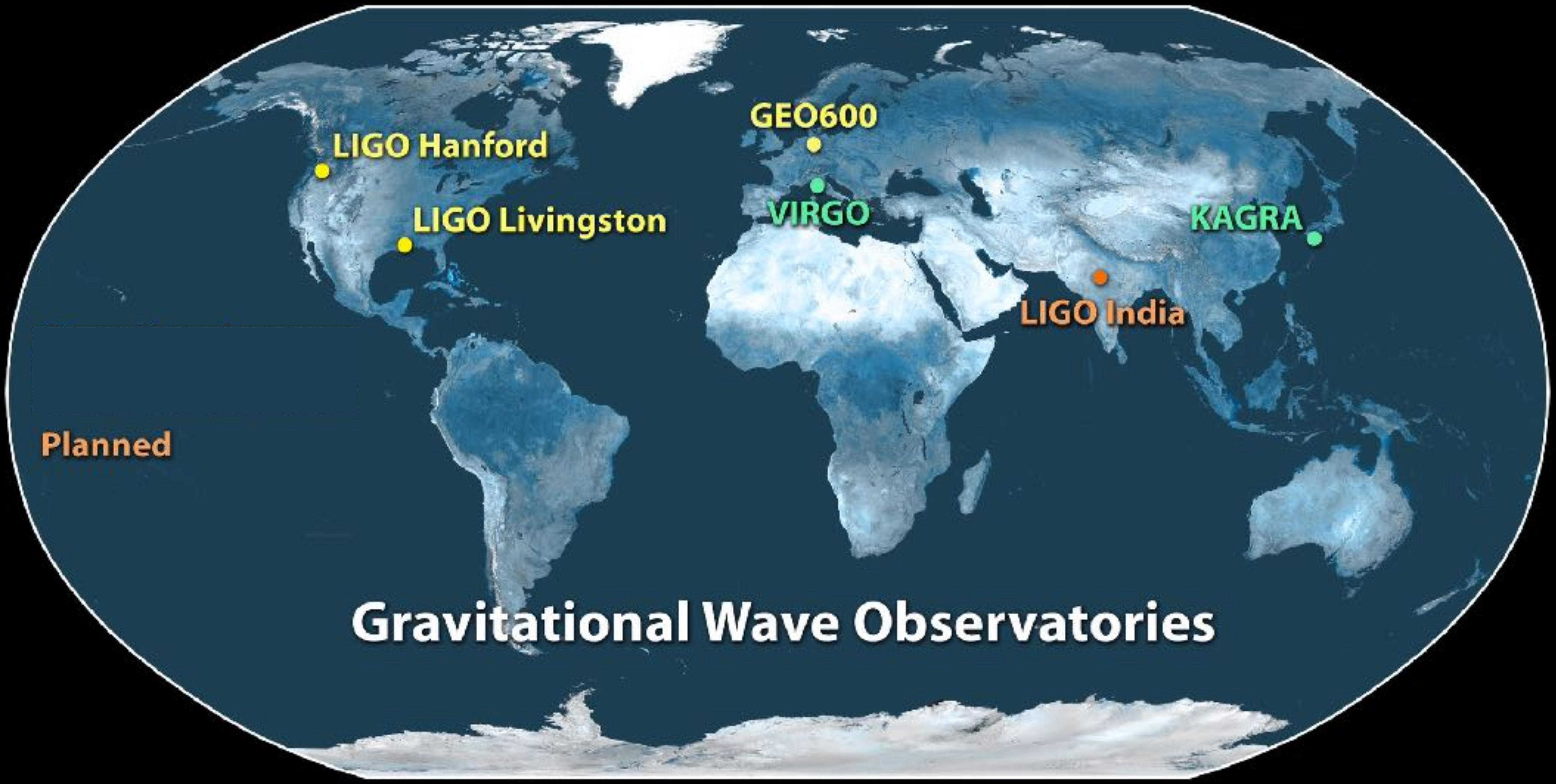
LIGO

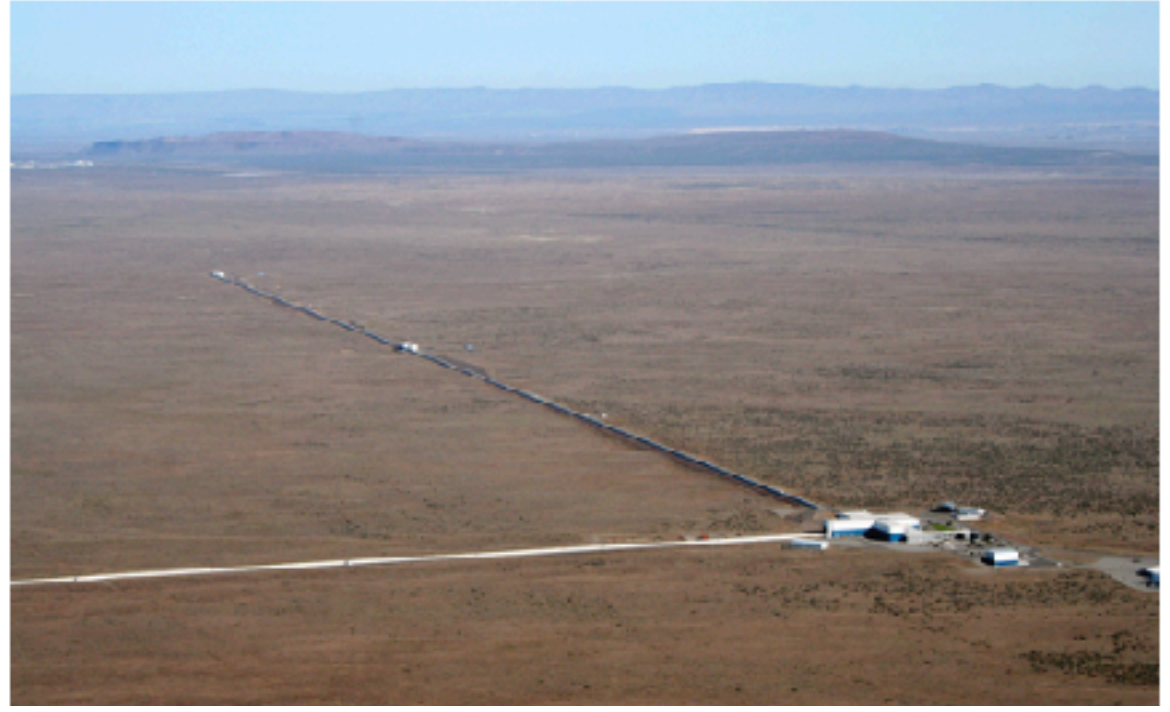
Laser Interferometer Gravitational-Wave Observatory





An International Gravitational Wave observatory Network





LIGO Hanford (WA)

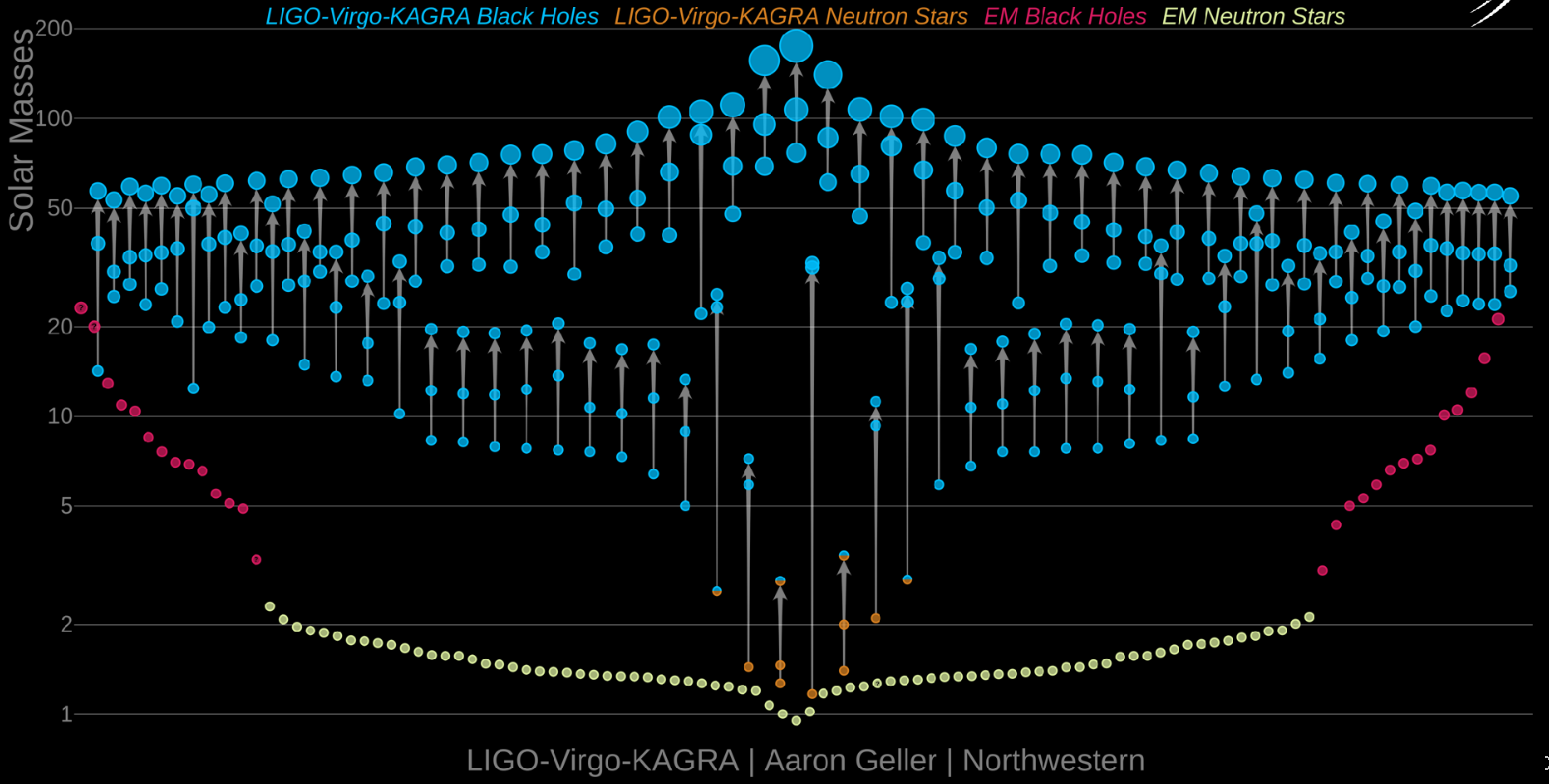
LIGO Livingston (LA)

Virgo, Pisa (Italy)

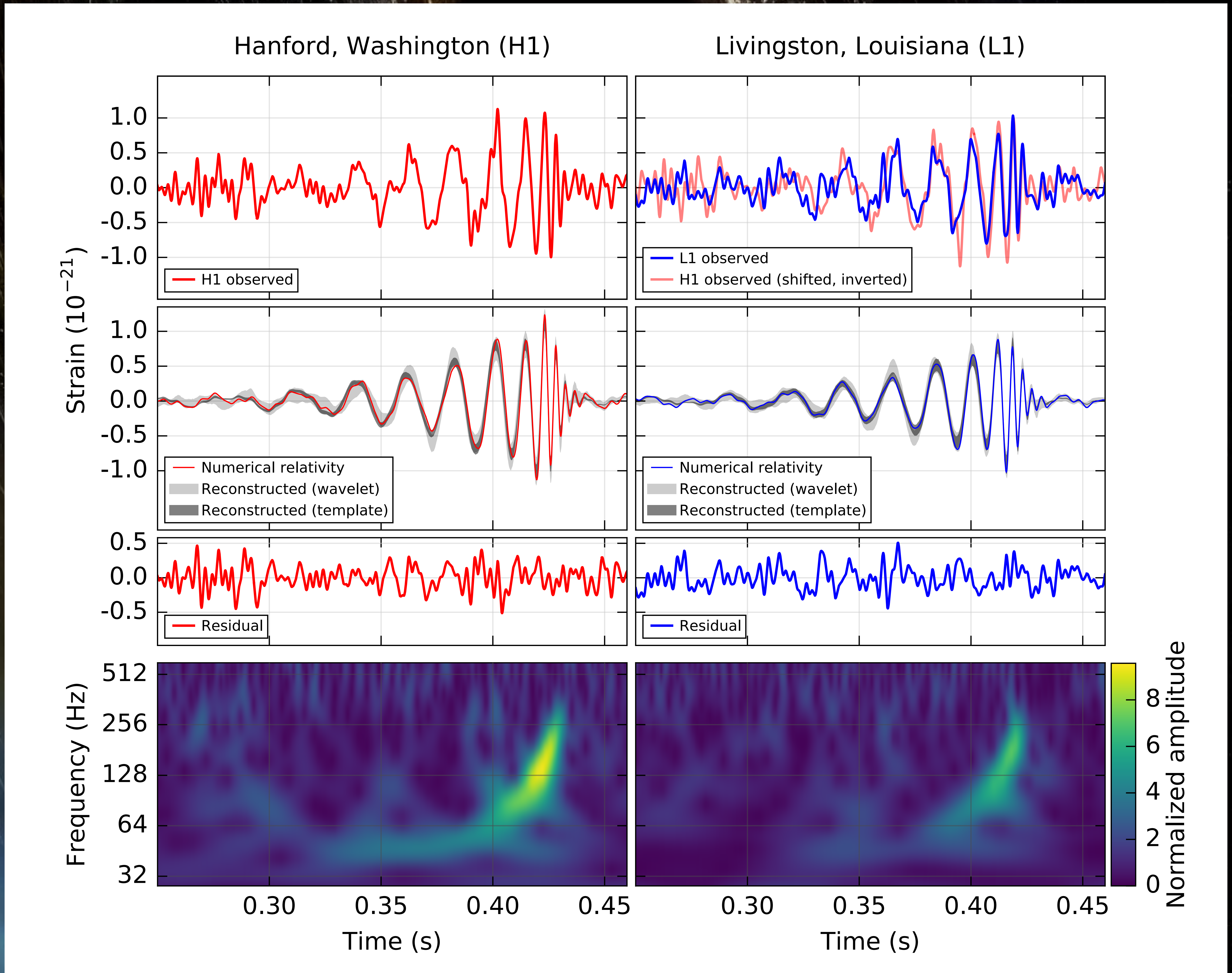
GEO600, Hannover (Germany)

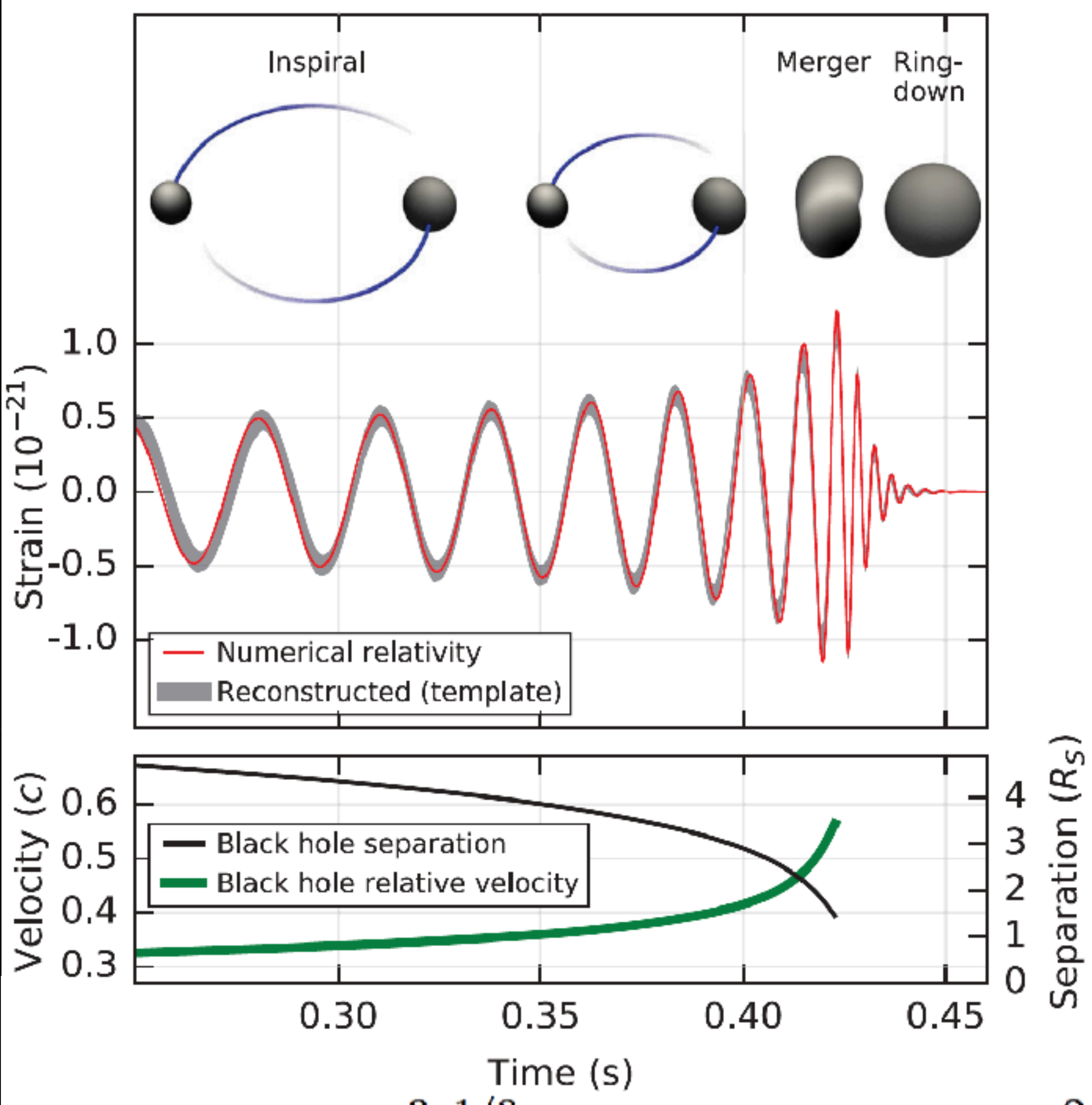
Ground-Based Observations from the Current Detectors

Masses in the Stellar Graveyard



The First Black Holes: GW150914





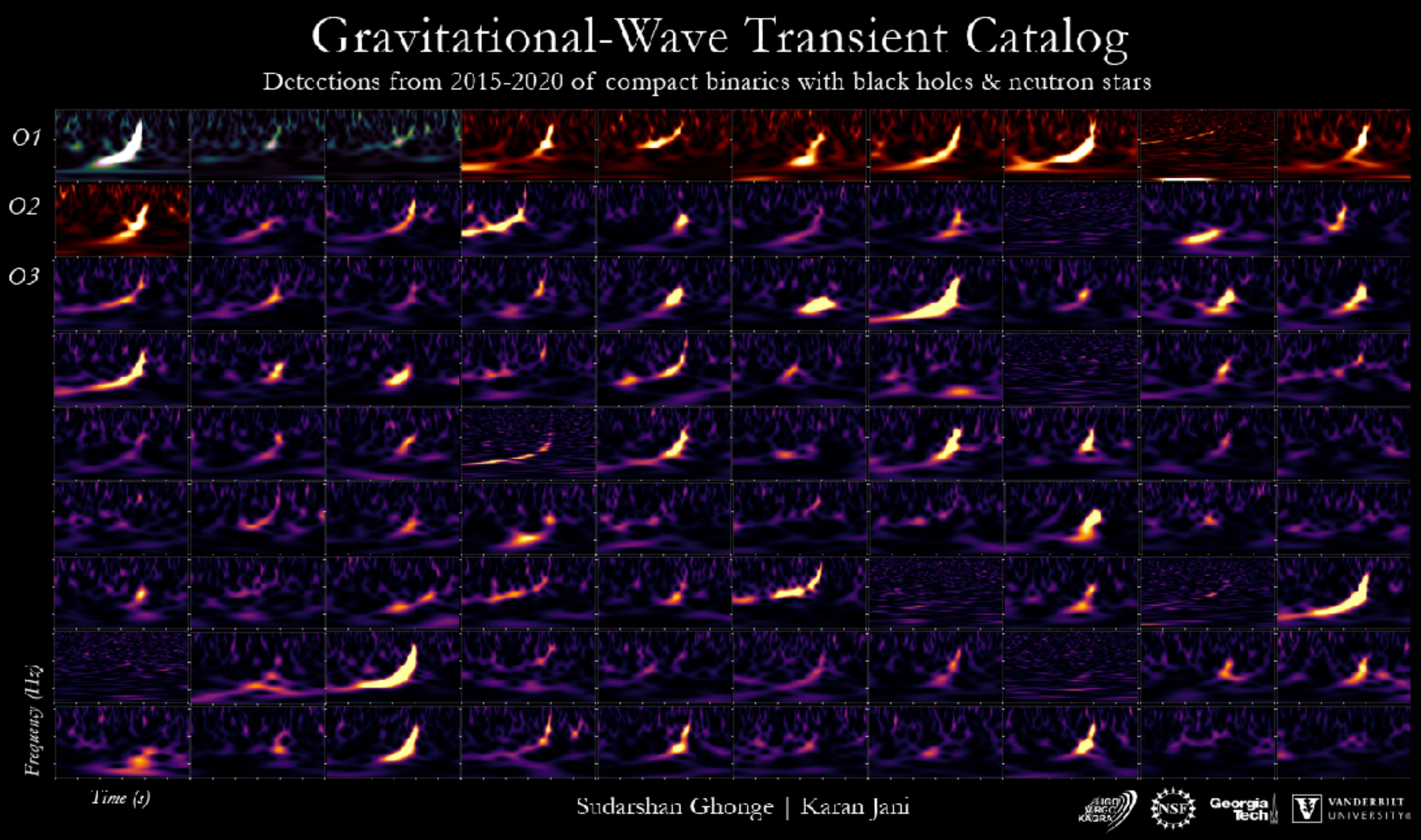
$$v/c = (GM\pi f/c^3)^{1/3}$$

$$R_S = 2GM/c^2$$

R_S~200km

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

GWTC-3



GWTC-3: Compact Binary Coalescences Observed by LIGO and Virgo During the Second Part of the Third Observing Run arXiv:2111.0360

Masses: 1-100 $M_\odot$

- Lower Mass gap (between NS and BH): 3-5 $M_\odot$
- Upper Mass gap (pulsation pair instability supernovae): 50-120 $M_\odot$

Spin orientation

- Expect align spins for isolated binary evolution
- Negative effective spin could point to dynamical formation

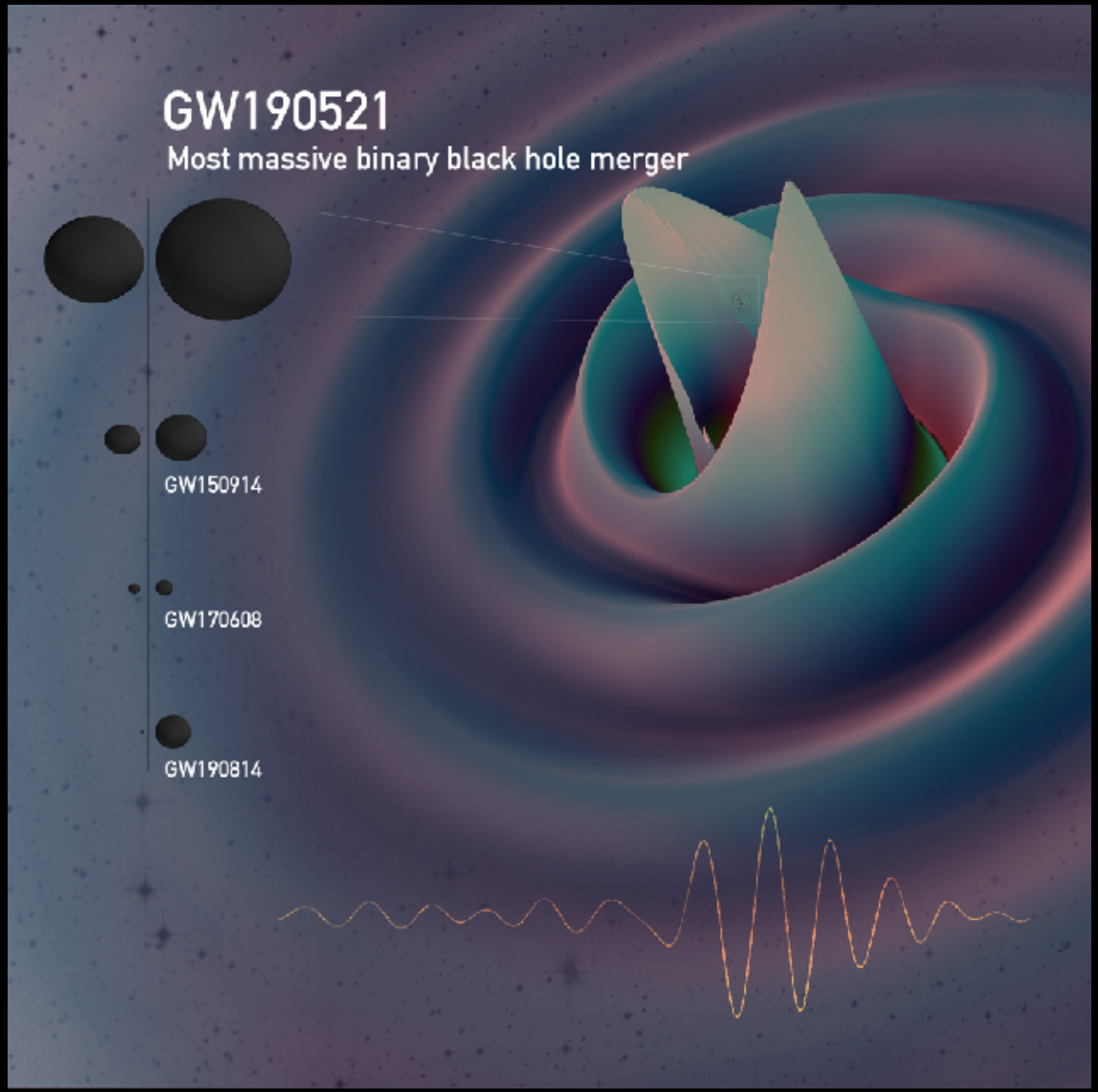
Distance/redshift

- probe star formation rate at different points in the Universe evolution
- Probe of relative element abundance (a star's composition affects its evolution)

GW190521

PRL 125, 101102 (2020)

The most massive black hole collision observed to date (~142 $M_\odot$)



[Image credit: D. Ferguson, K. Jani, D. Shoemaker, P. Laguna, Georgia Tech, MAYA Collaboration]

The extraordinarily large masses of the black holes that produced GW190521 challenge our understanding of black hole formation and serve as a unique laboratory to understand the fundamentals of how gravity works.

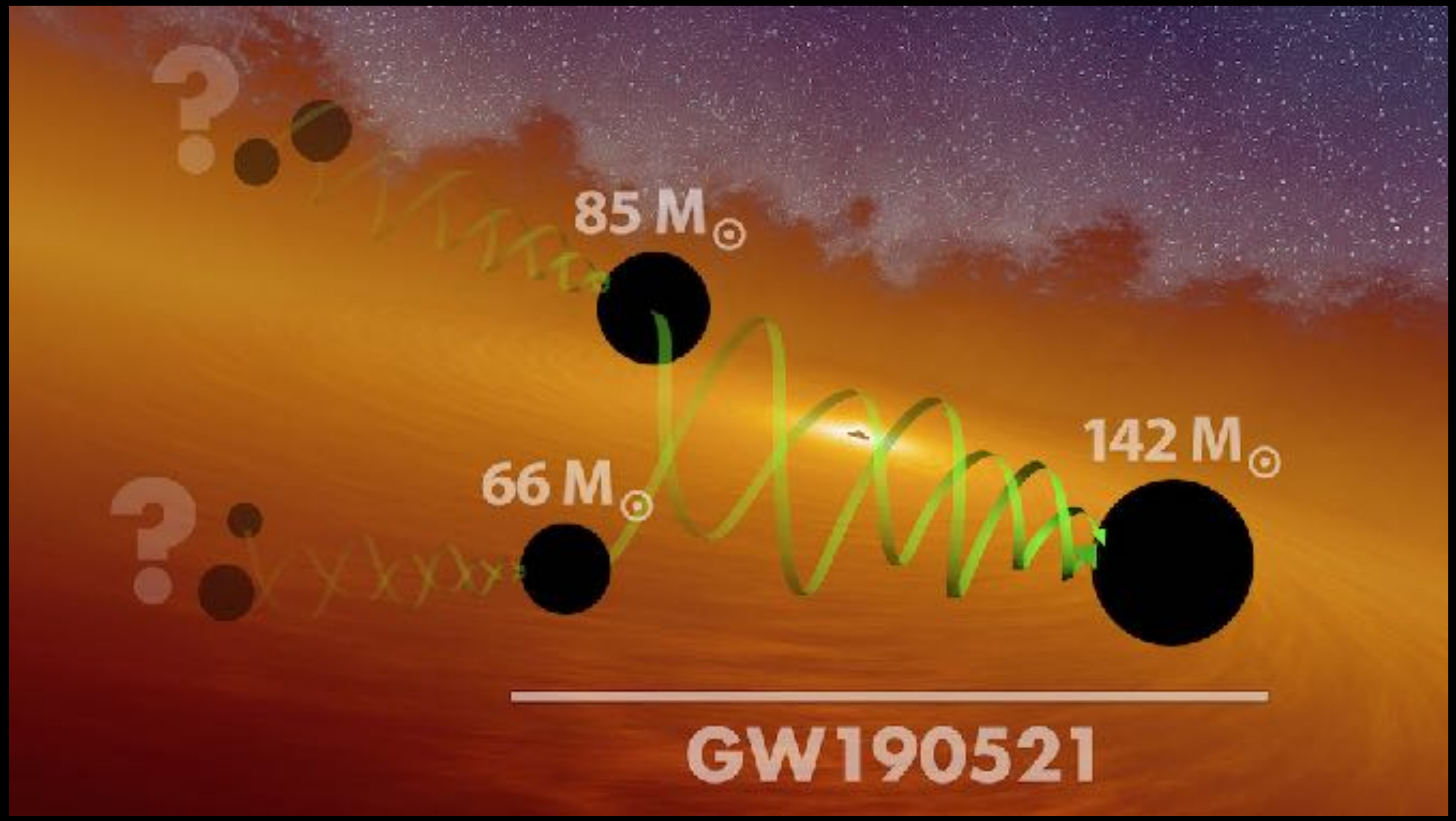
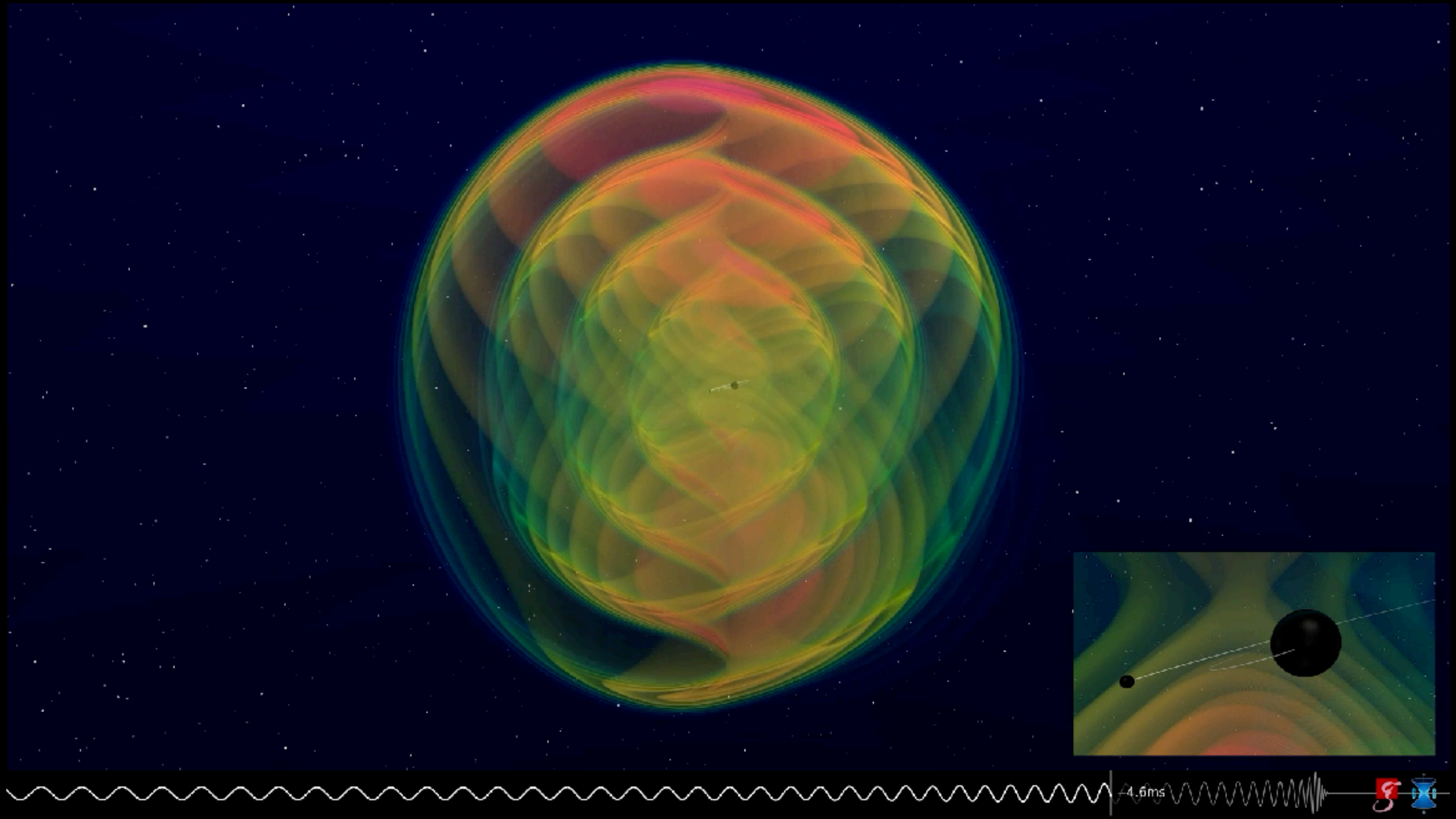


Image credit: LIGO/Caltech/MIT/R. Hurt (IPAC).

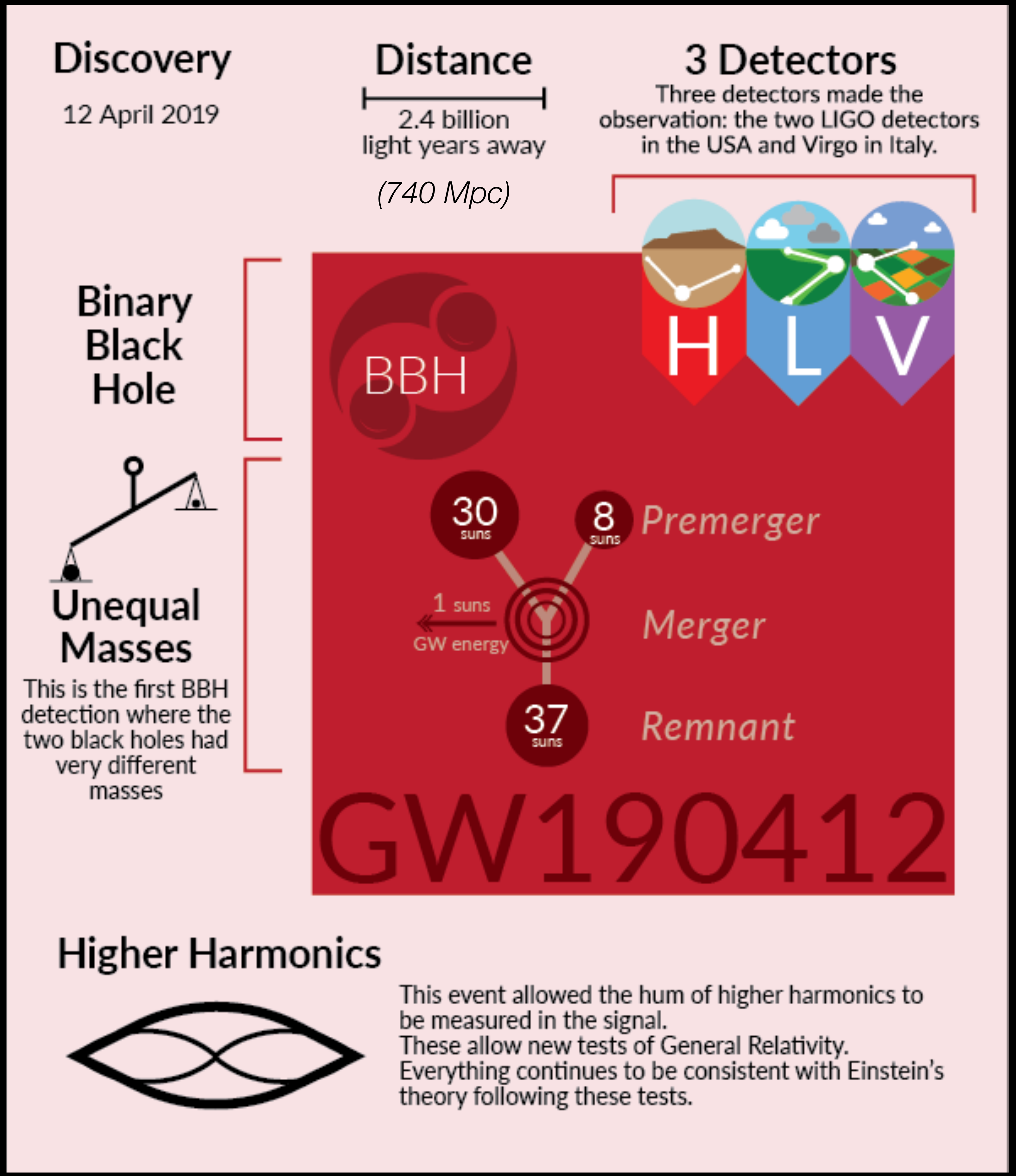
GW190412

Phys. Rev. D 102, 043015 (2020)

first GW observation from the merger of two black holes with very different masses
Shows evidence for higher harmonics; mild evidence of precession?



Credit: N. Fischer, H. Pfeiffer, A. Buonanno (Max Planck Institute for Gravitational Physics), Simulating eXtreme Spacetimes (SXS) Collaboration

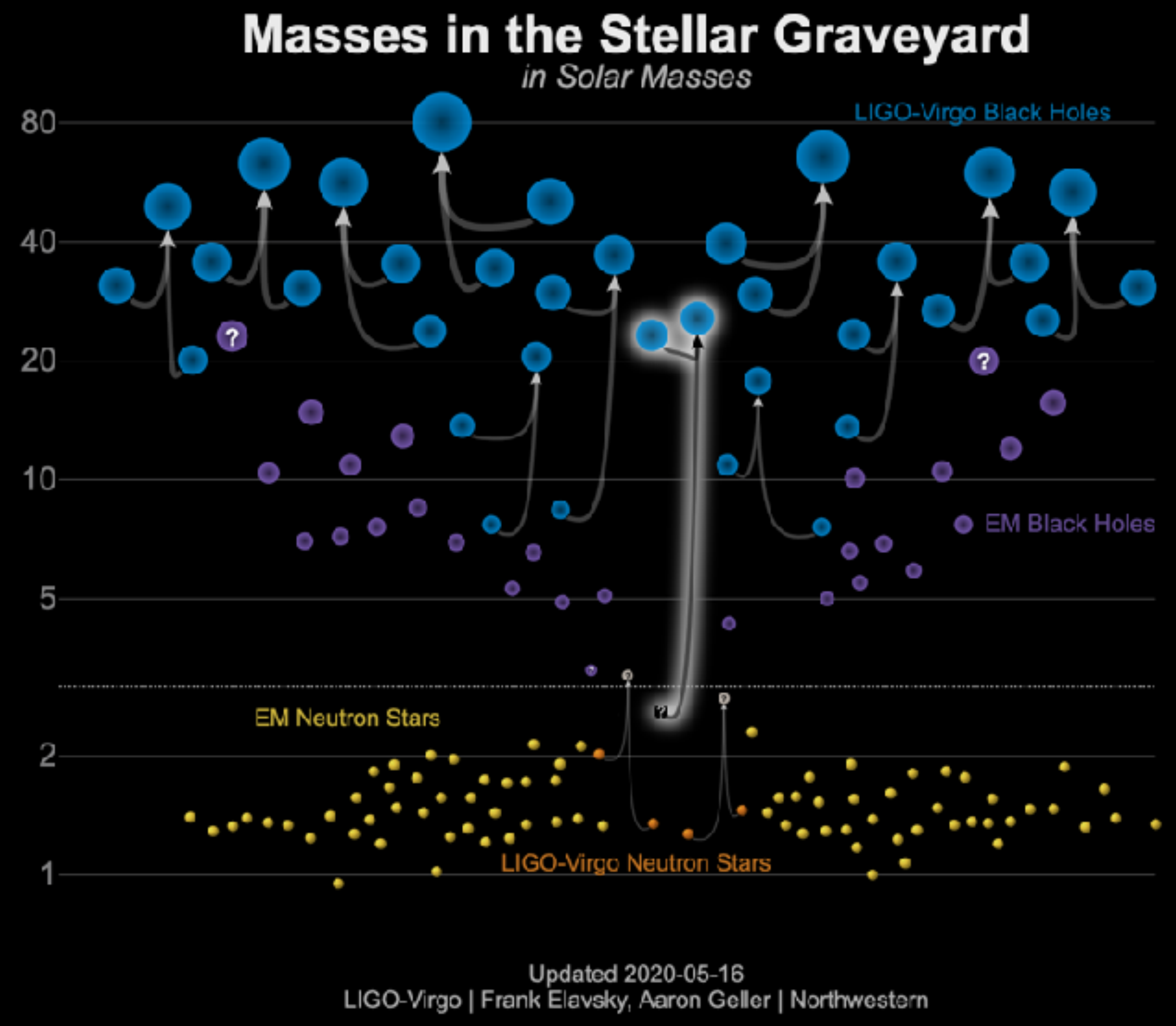


GW190814

ApJL 896 (2020) L2

A highly asymmetric system of ambiguous nature, corresponding to the merger of a 23 solar mass black hole with a 2.6 solar mass compact object, making the latter either the lightest black hole or heaviest neutron star observed in a compact binary

Artistic rendition. Credit: Carl Knox (OzGrav)



Insufficient SNR for tidal deformability analysis

No EM counterpart

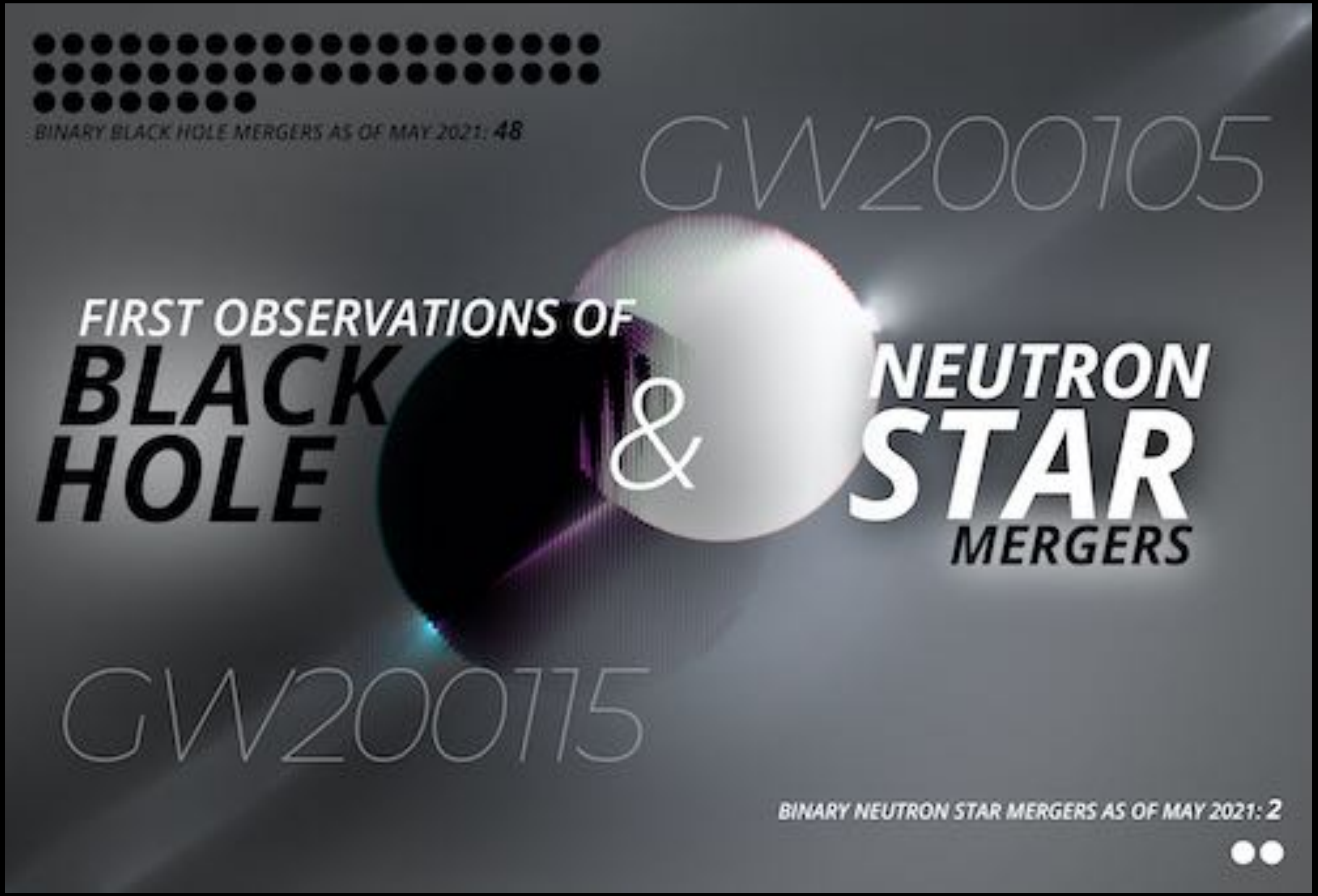
Challenges understanding of formation mechanisms

18.5 deg^2
240 Mpc
q=0.1
1-23/Gpc^3/y

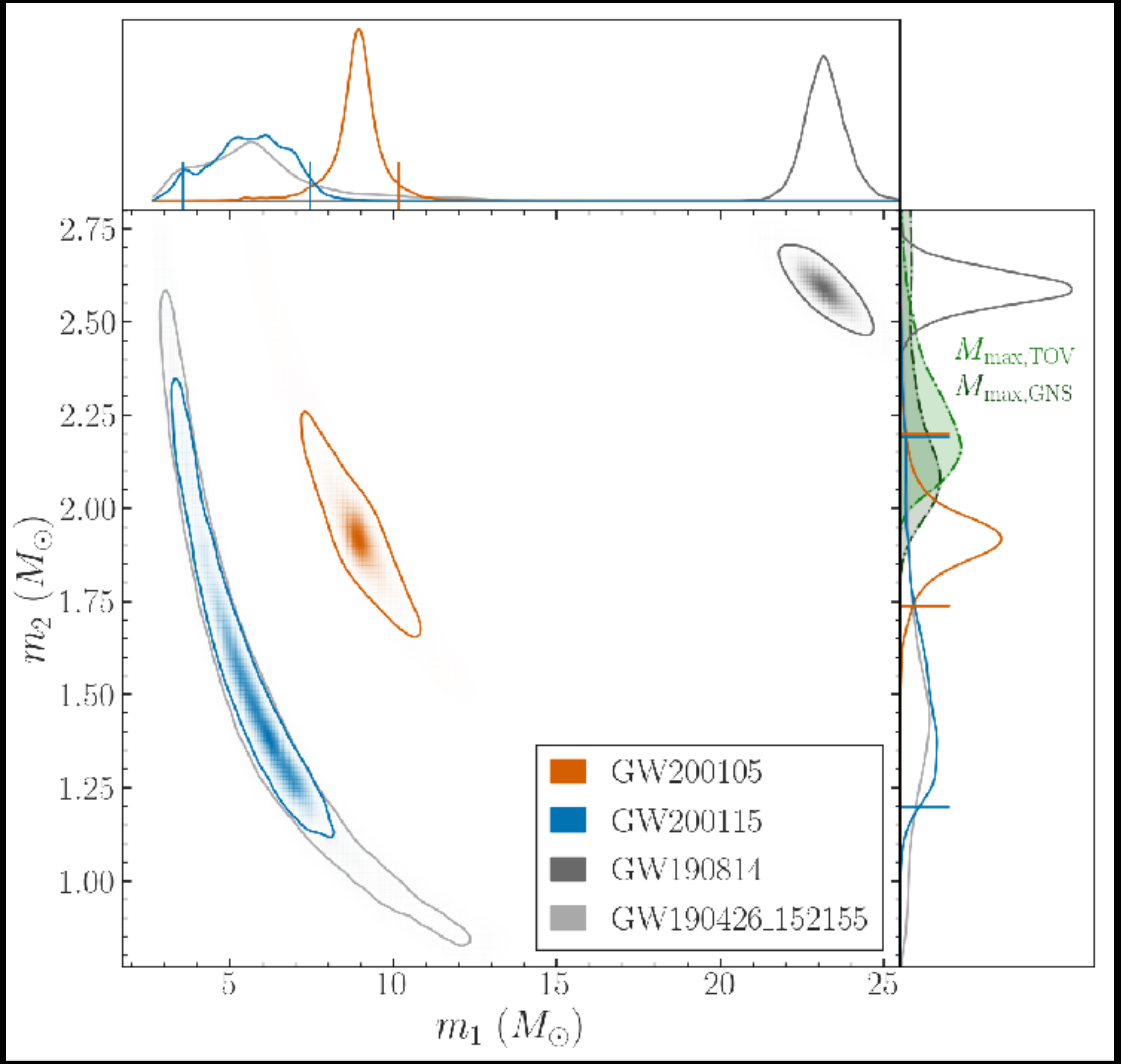
ApJL 915 (2021) L5

NSBH: GW200105 and GW200115

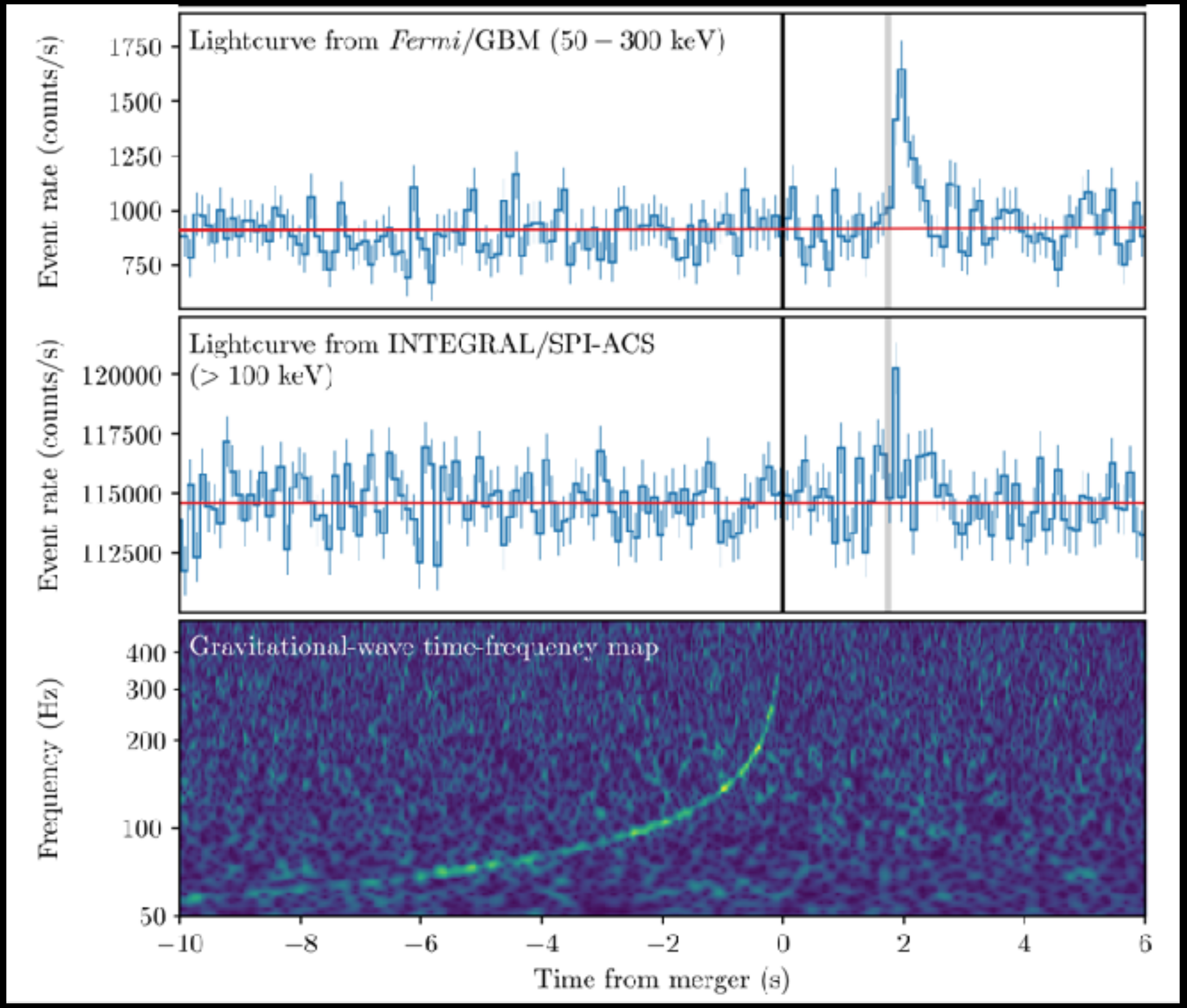
GW200105: 8.9+1.9 M⊙ GW200115: 5.7+1.5 M⊙ No EM counterpart found

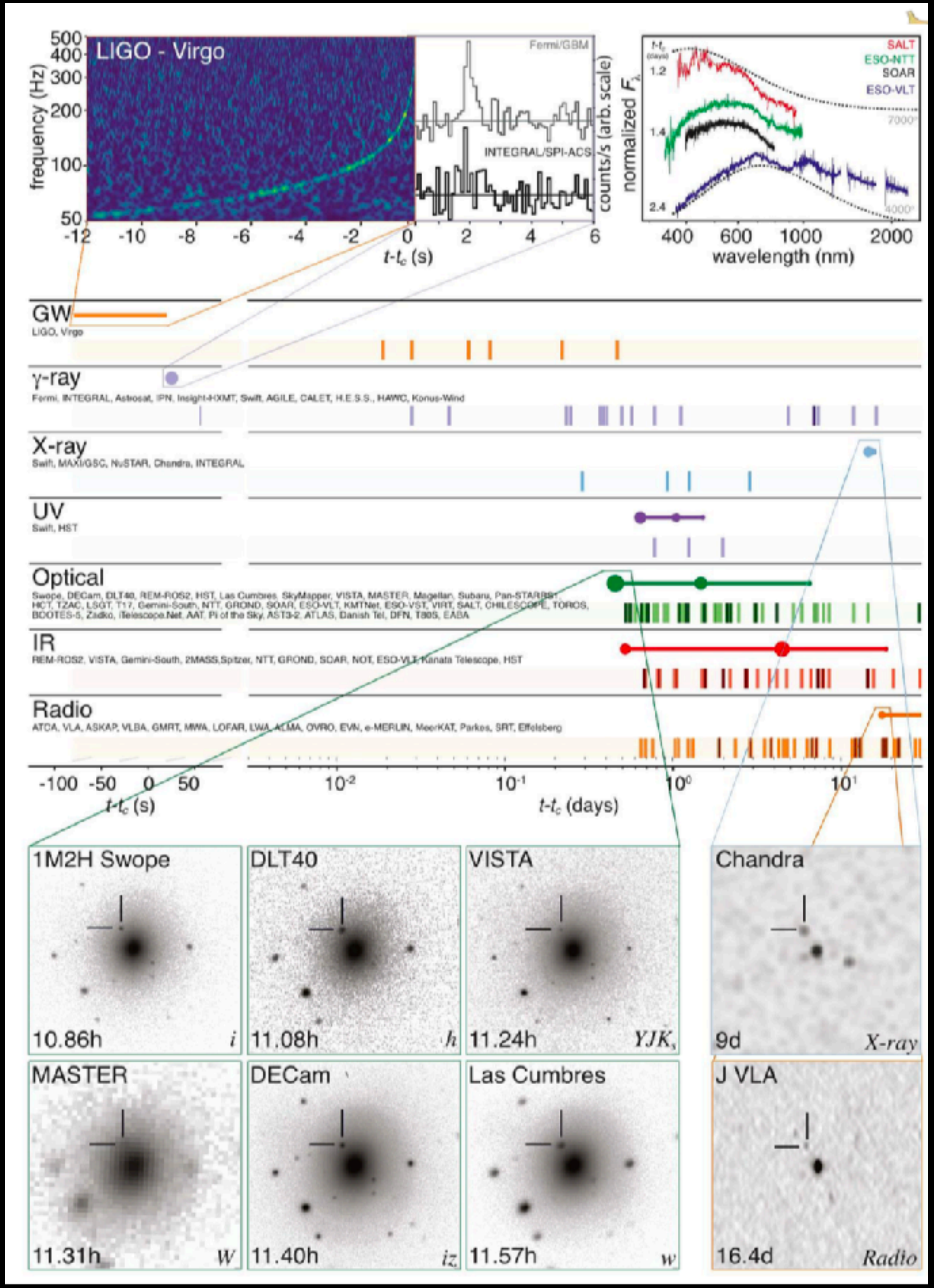


Artist's illustration of a merging black hole and neutron star.
Credit: Carl Knox, OzGrav/Swinburne University.



GW170817
Binary Neutron Star Merger



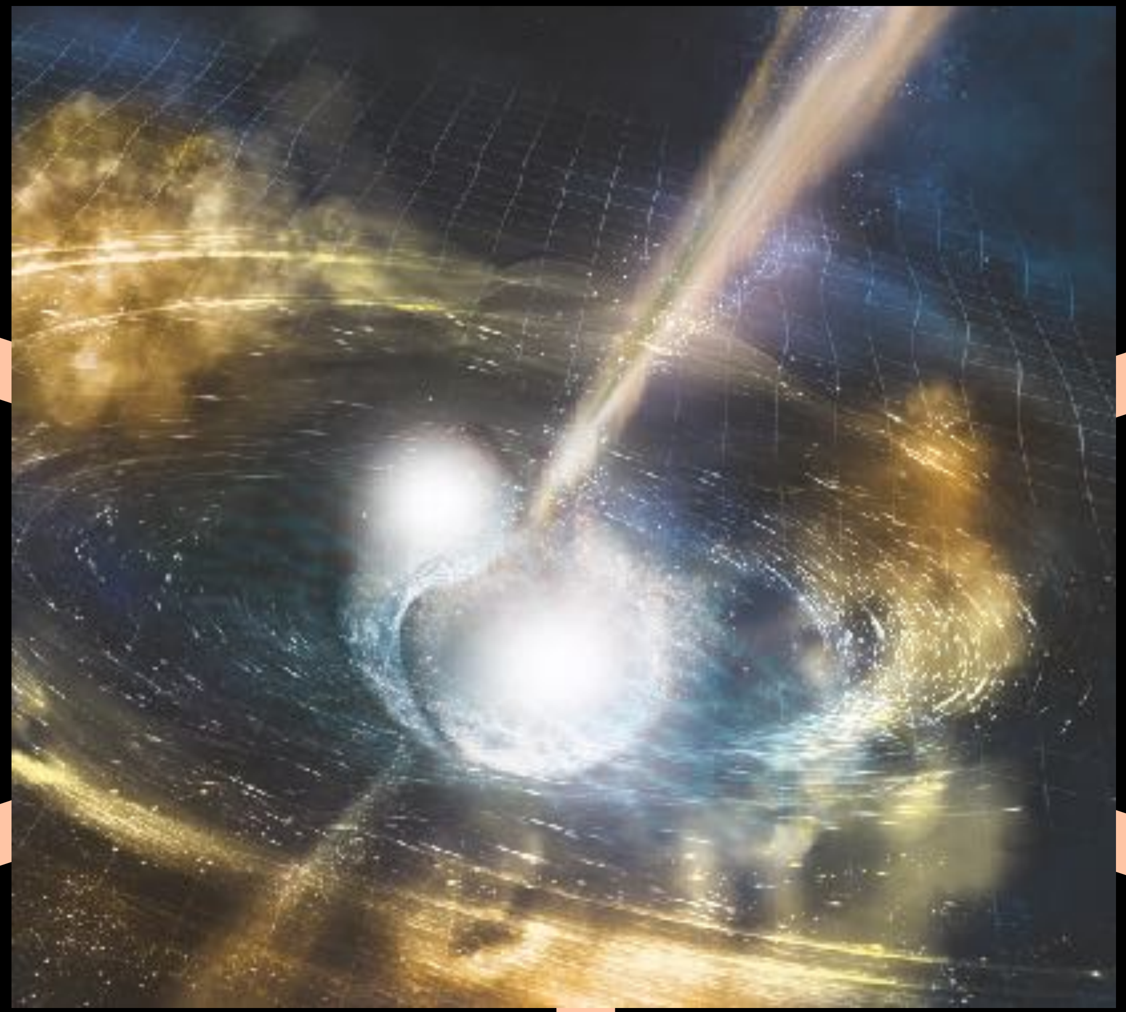


Multi-messenger Observations of a Binary Neutron Star Merger
The Astrophysical Journal Letters, 848:L12, 2017

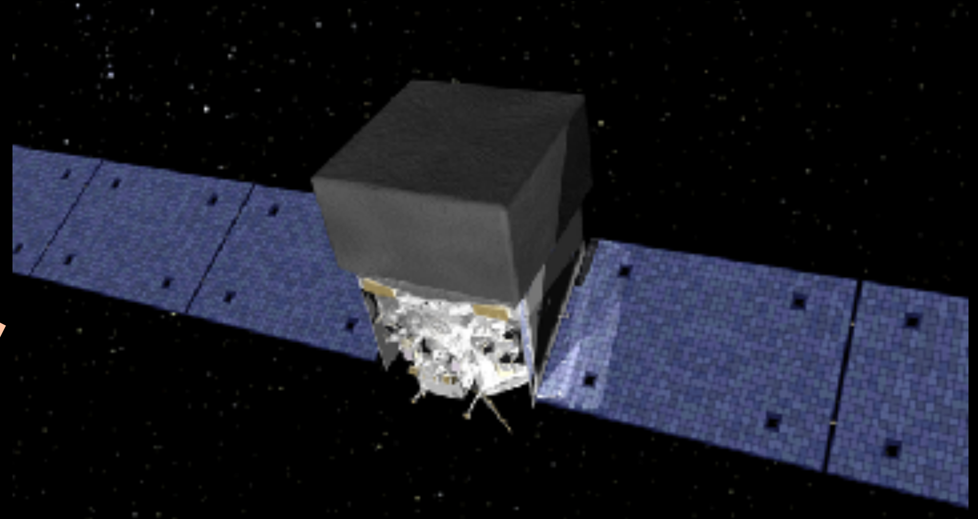
Credits: LIGO/Fermi

Multi-messenger Astronomy with Gravitational Waves

Binary Neutron Star Merger

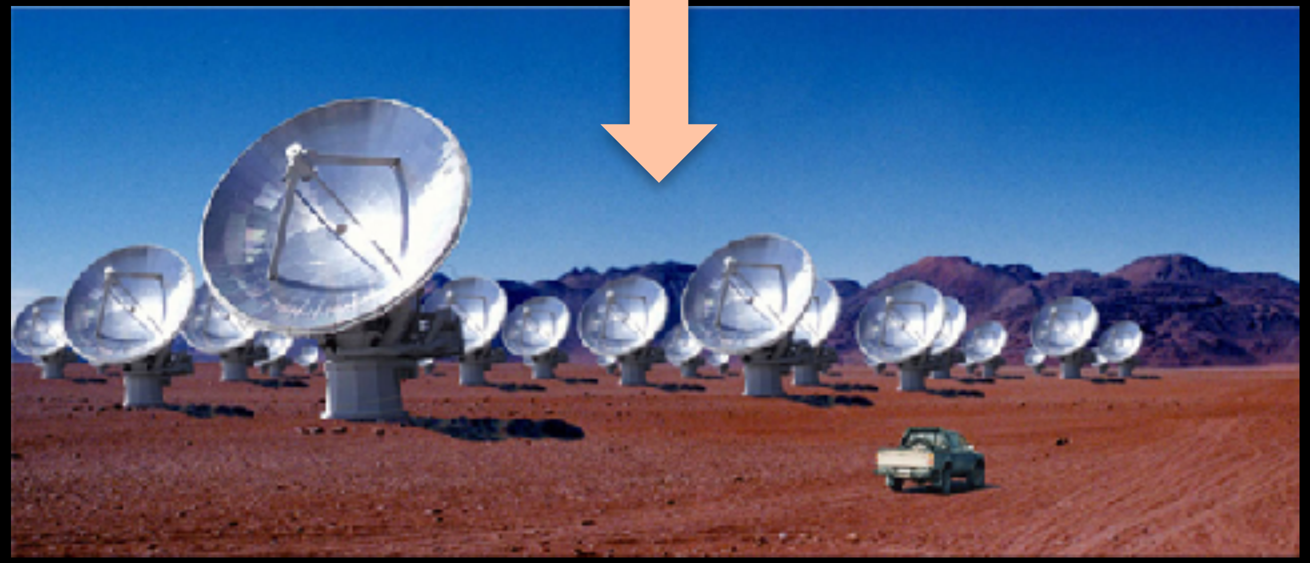


Gravitational Waves

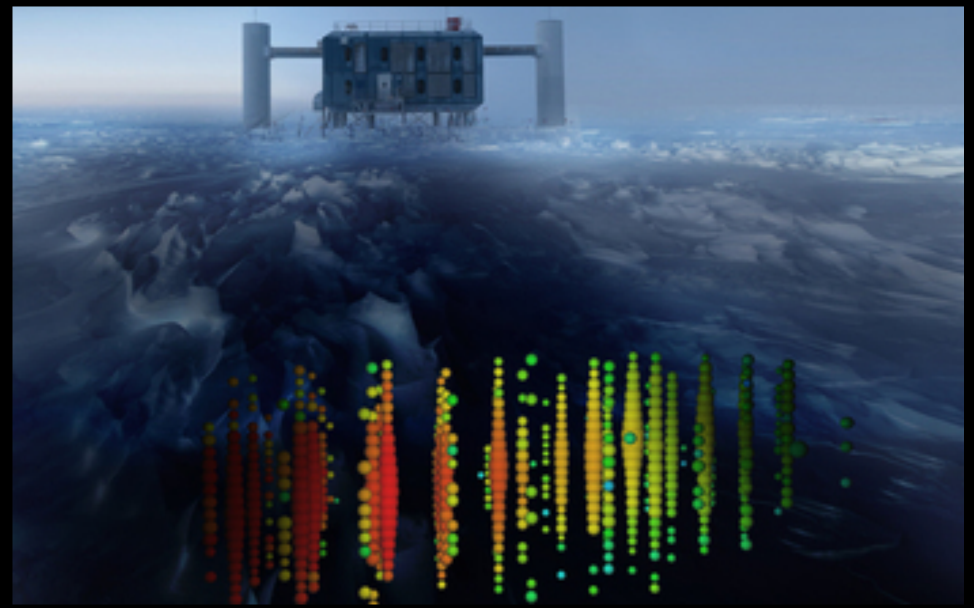


X-rays/Gamma-rays

Visible/Infrared Light

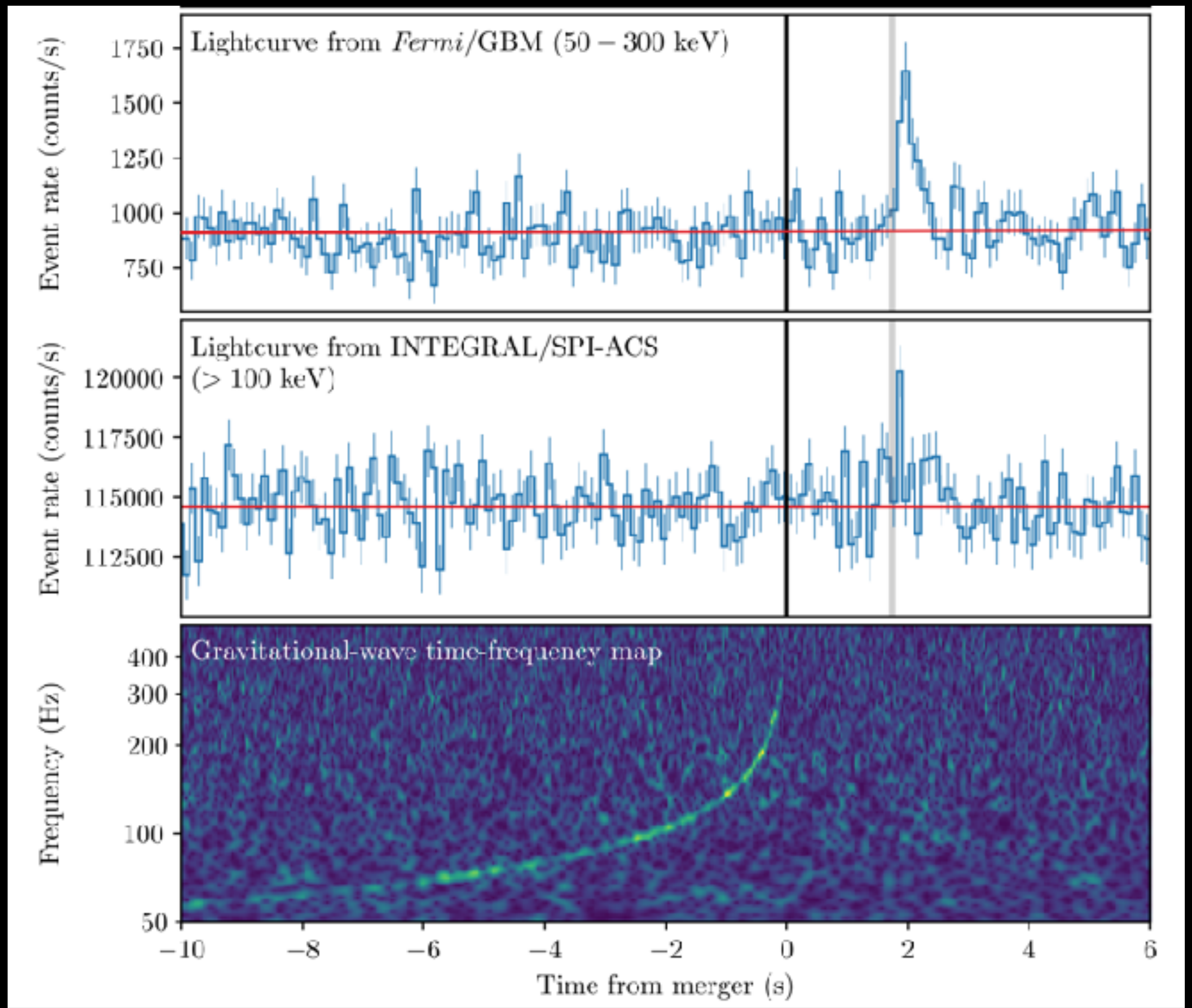


Radio Waves

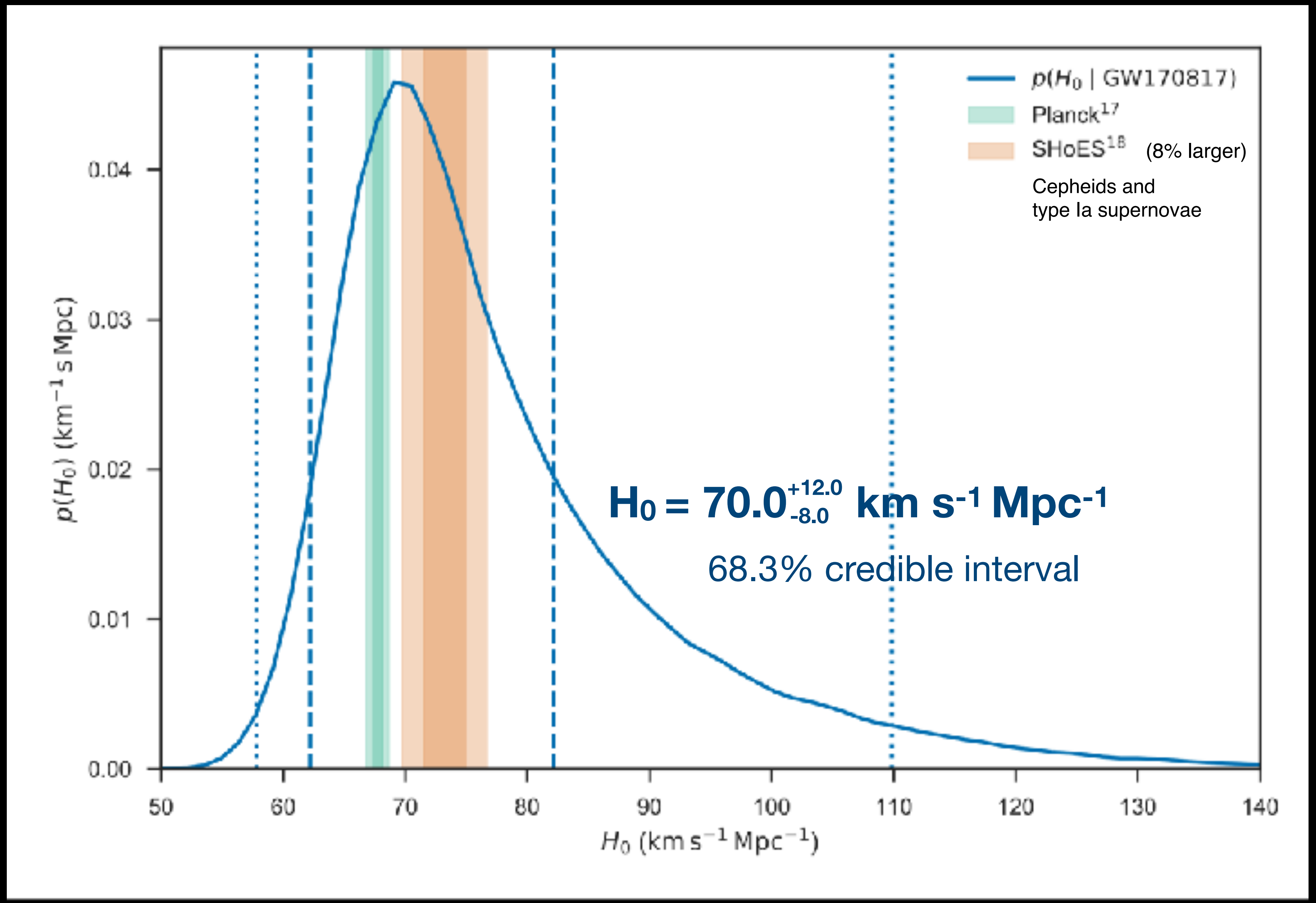


Neutrinos

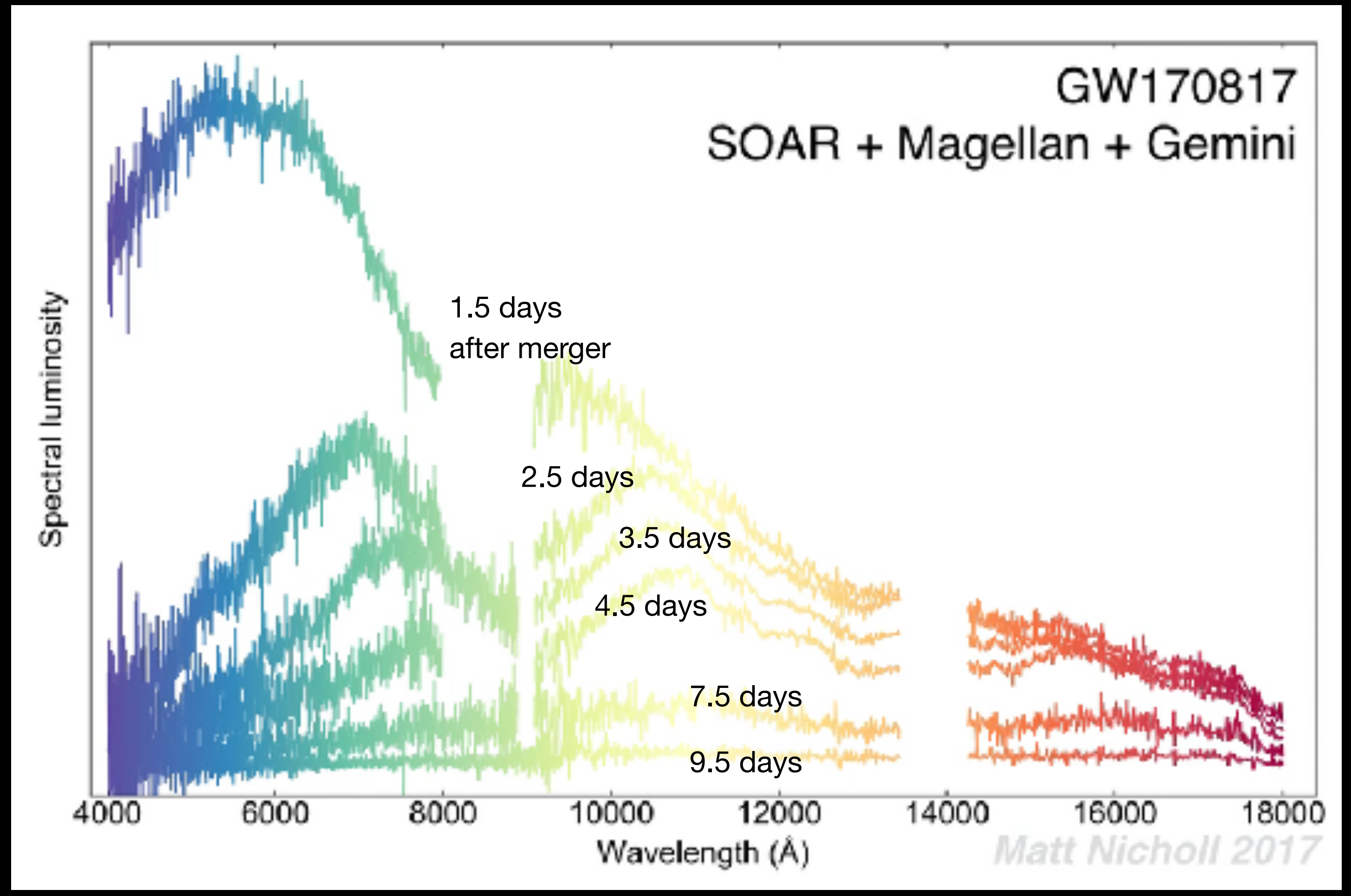
Multi-Messenger Science from GW170817

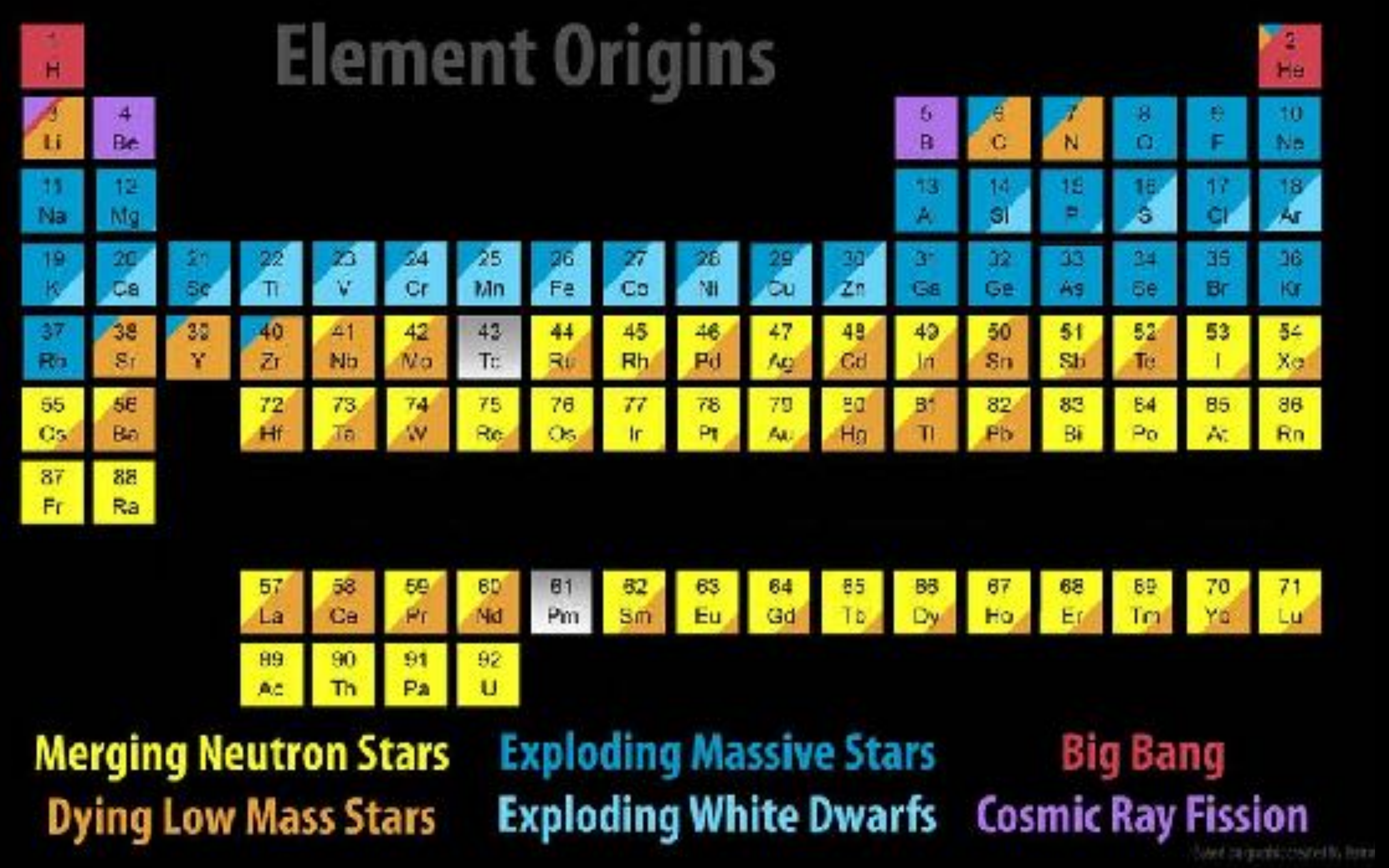


Neutron star mergers and Gamma Ray Bursts



Measuring the Hubble Constant





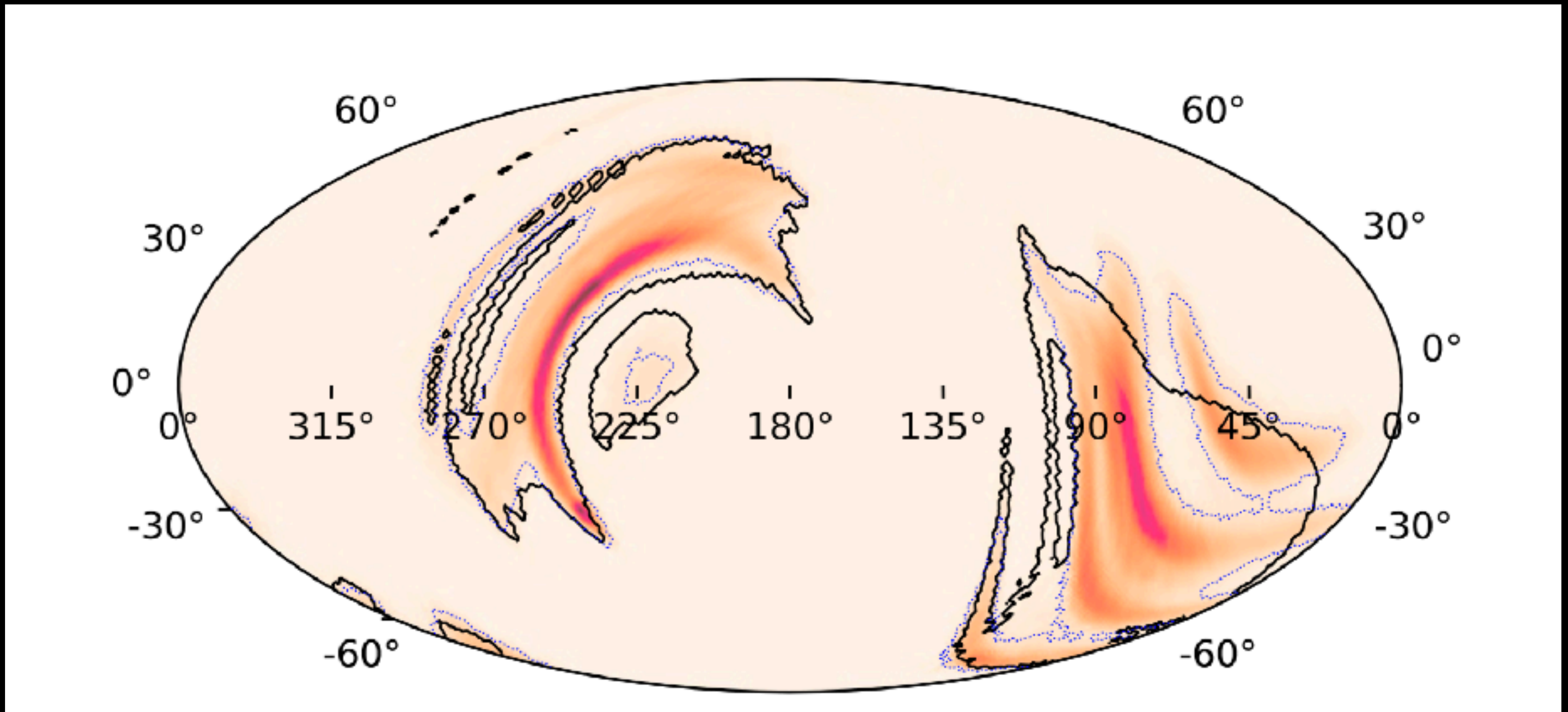
Neutron star mergers and Kilonovae

GW190425

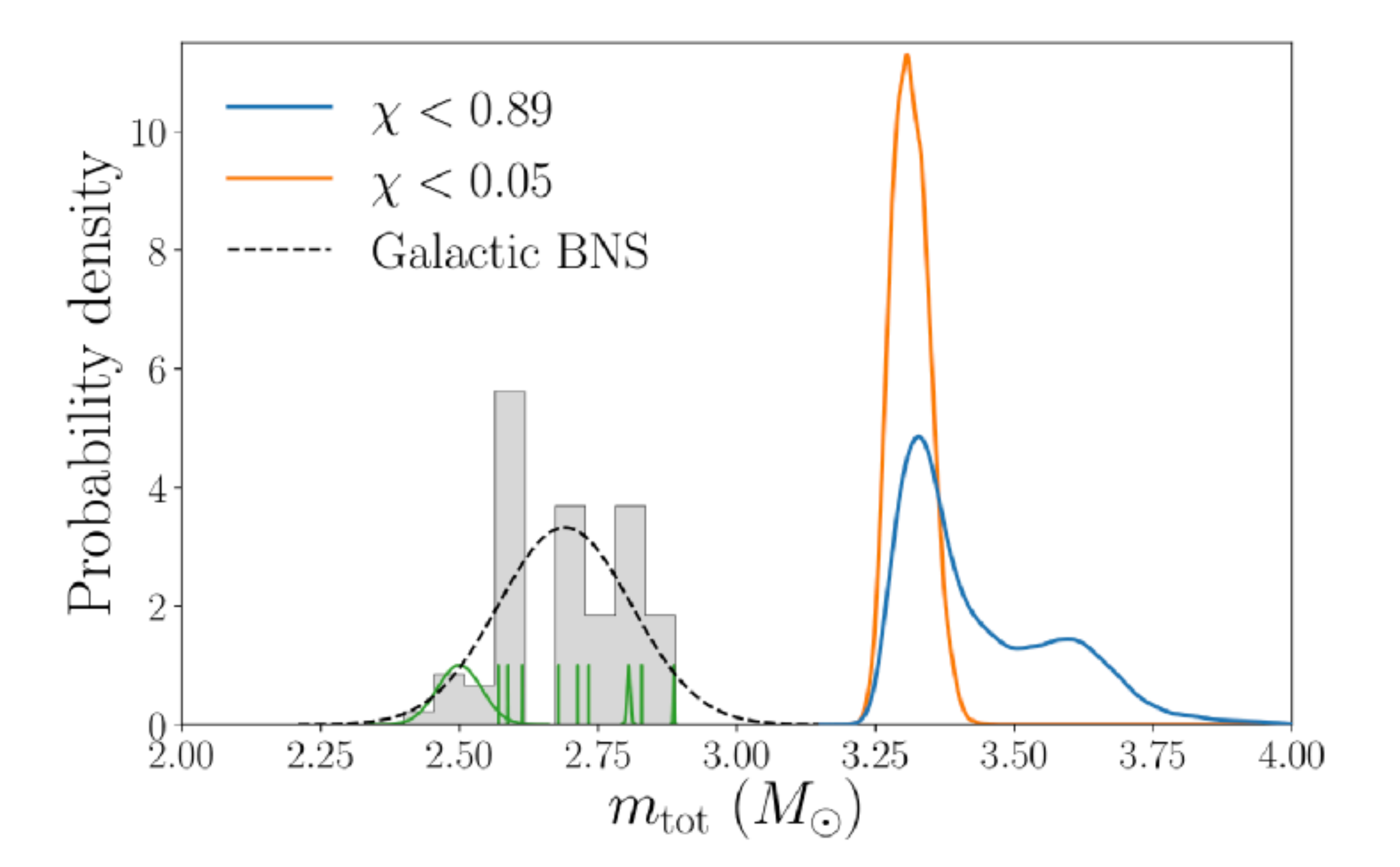
ApJL 892 (2020) L3

Observation of a compact binary coalescence with total mass ~3.4 $M_\odot$

BNS = Binary Neutron Stars



Map uses data from LIGO Livingston and Virgo



Initial Alert (solid line)

43 minute latency

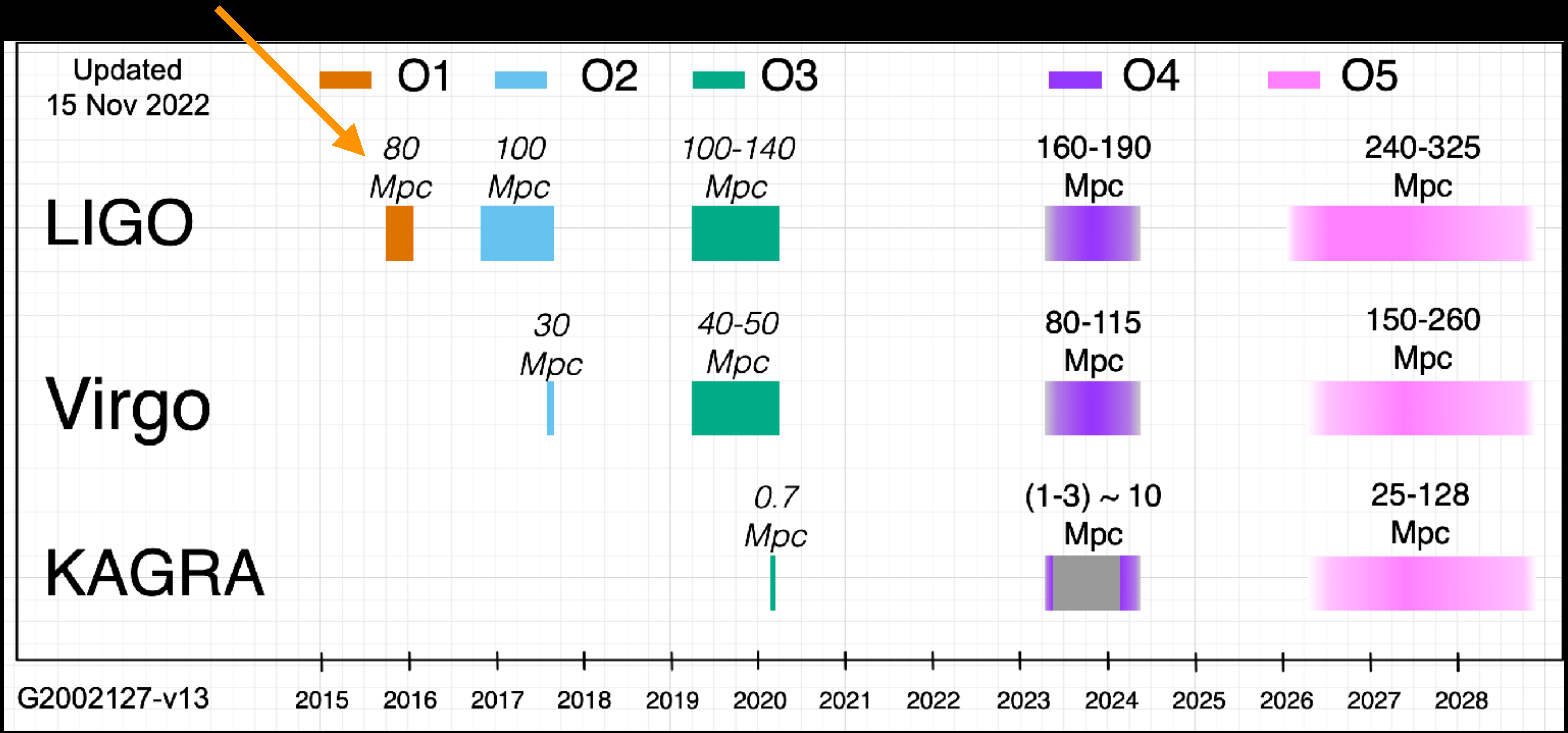
BNS w/ >99% probability

90% region: **10,200 sq. deg.**

Distance: **110 – 200 Mpc**

5-sigma outlier of observed galactic BNS population

BNS range: how far can we see a binary neutron star merger? (1 Mpc = 3 million light years)



Reach: ~ 3x O3
~500-1000 BBH/year
~10 NS-BH/year
~200-300 BNS/year

~100 BBH/year (z≲2)
~1-2 NS-BH/year
~ 10-30 BNS/year (z≲0.1)
38–44% (12–16%) events with 90% credible region smaller than 20 deg2 (5 deg^2).

https://observing.docs.ligo.org/plan/

The Next Generation
2030's

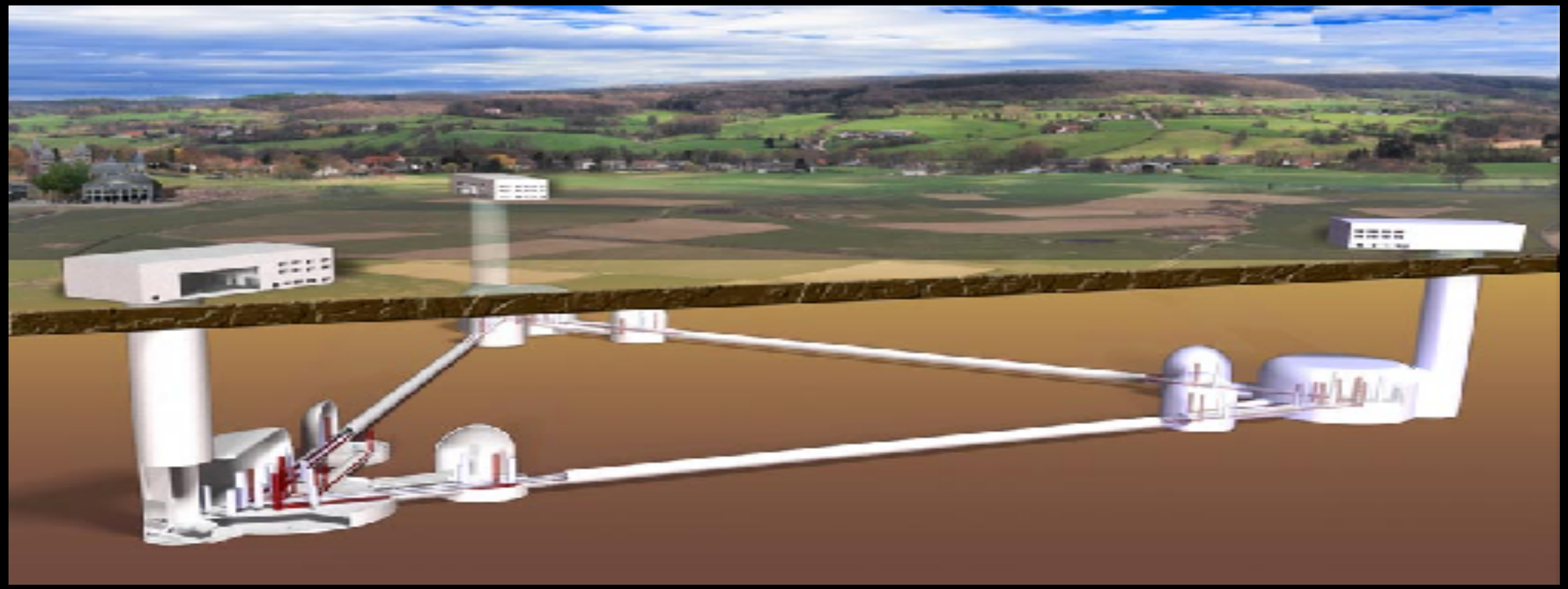
Third Generation

~10^5 binary coalescences per year (circa 2035)

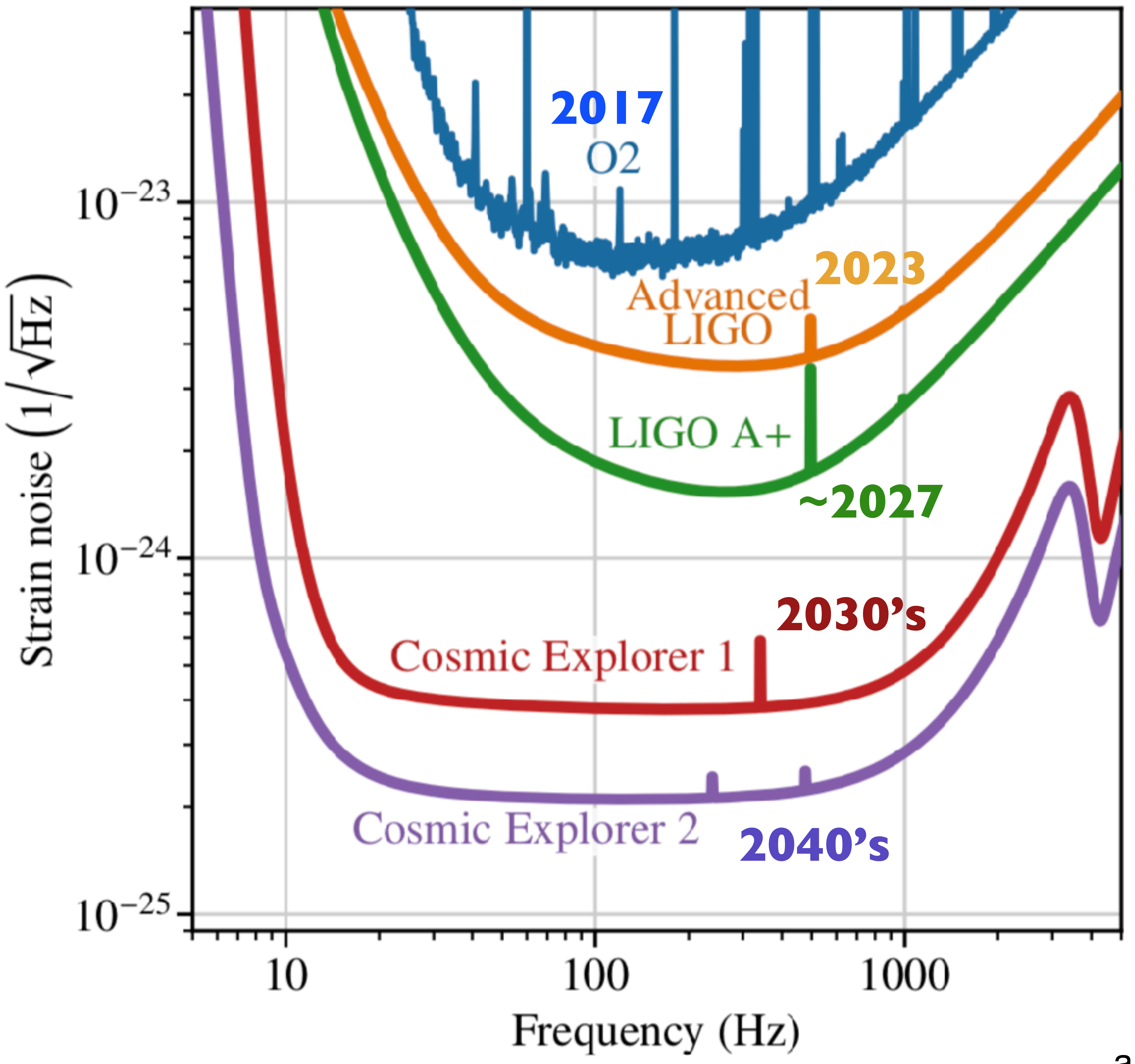
Cosmic Explorer

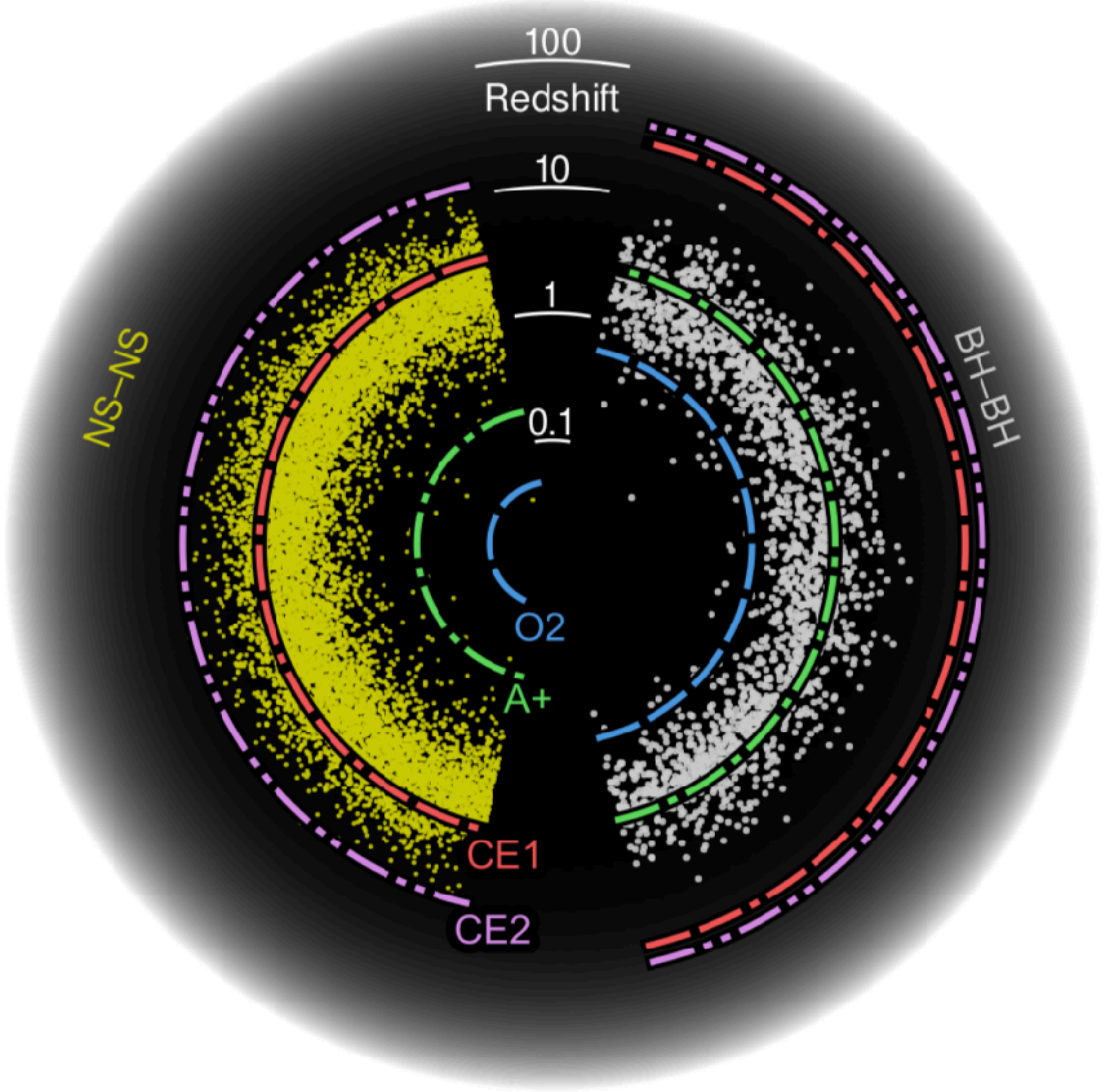
- NSF-funded US conceptual design study well under way
- 40km surface Observatory baseline
- Signal grows with length – not most noise sources
- Stage 1(~2035) Extension of A+ technologies
- Stage 2 (~2045) Cryogenics, new material for test masses and coatings

Einstein Telescope



- European conceptual design study
- Multiple instruments in xylophone configuration
- underground to reduce newtonian background
- 10 km arm length, in triangle
- Site selection ~2023





arXiv:1903.04615

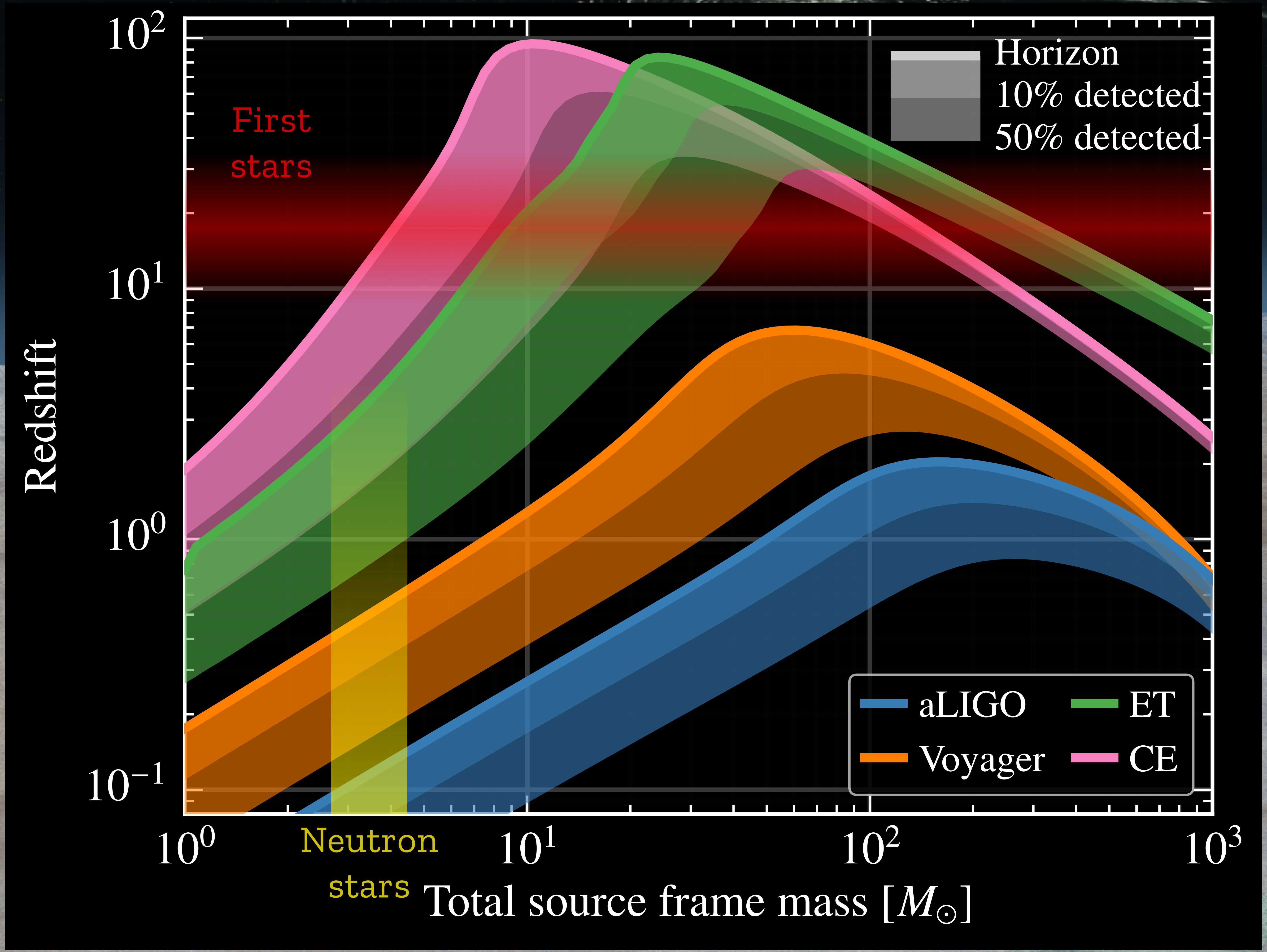


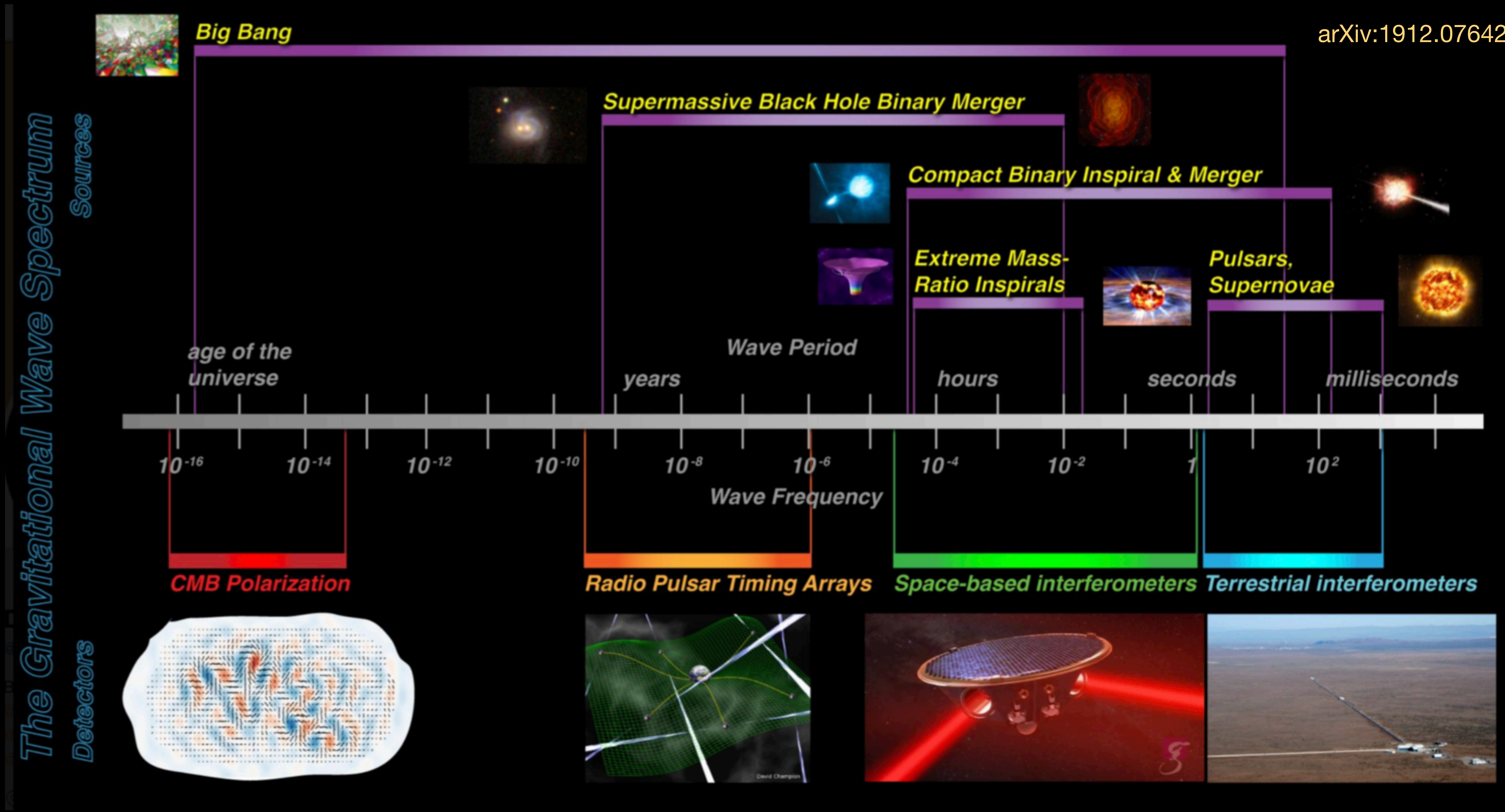
Table 1: Expected detections per year (N), number detected with a resolution of < 1, < 10 and < 100 sq. deg. (N_1, N_{10} and N_{100}, respectively) and median localization error (M in sq. deg.), in a network consisting of LIGO-Hanford, LIGO-Livingston and Virgo (HLV), HLV plus KAGRA and LIGO-India (HLVKI) and 1 Einstein Telescope and 2 Cosmic Explorer detectors (1ET+2CE).

Network	N	N_1	N_{10}	N_{100}	M
HLV	48	0	16	48	19
HLVKI	48	0	48	48	7
1ET+2CE	990k	14k	410k	970k	12

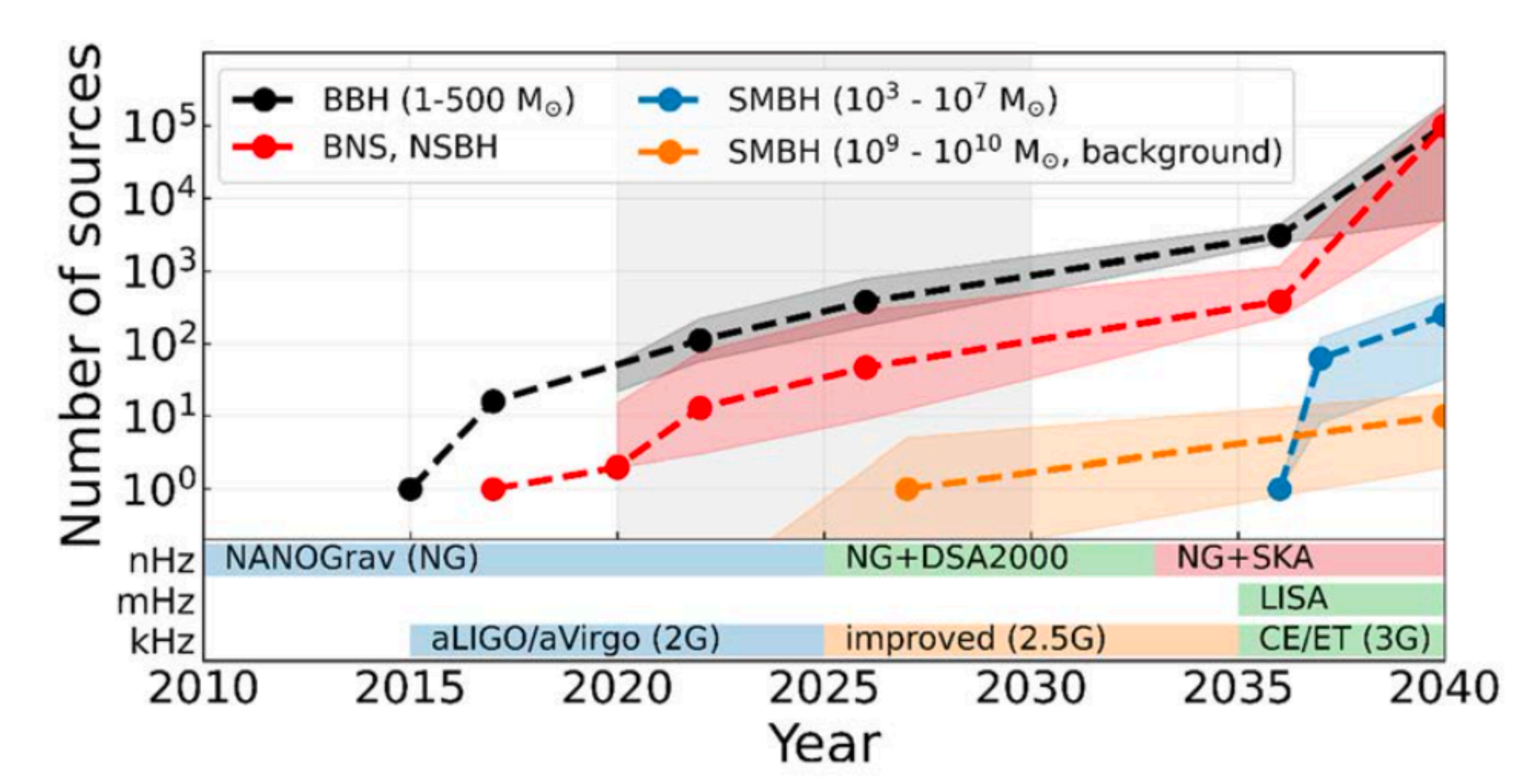
arXiv:1903.09277

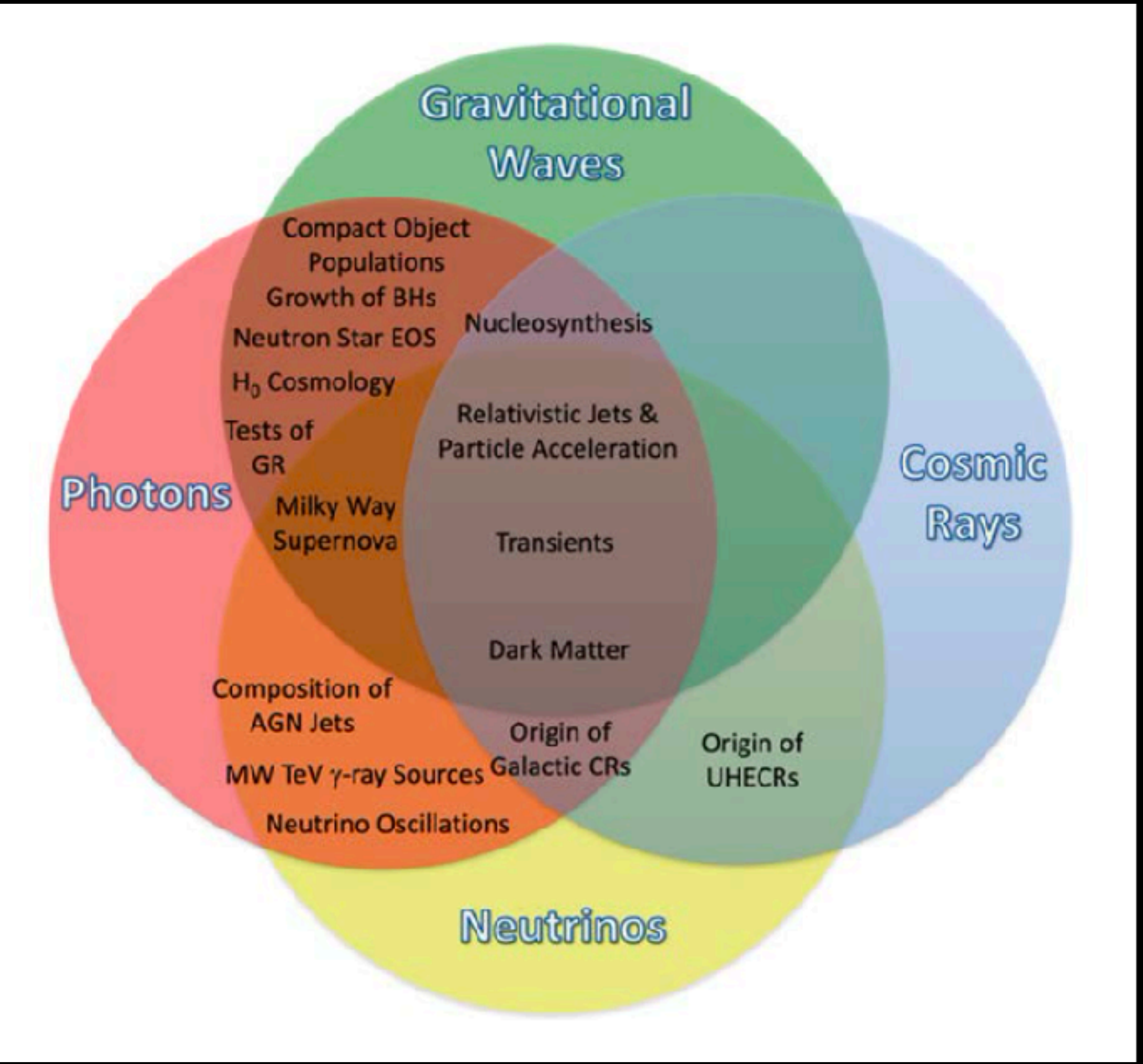
Formation and evolution of compact binaries
Heavy element nucleosynthesis
Jet physics
Cosmology
Multi-band gravitational wave astronomy

arXiv:1912.07642



Pathways To Discovery





ASTRO2020 Decadal Survey: Pathways to Discovery in Astronomy and Astrophysics for the 2020s - PAG report , pp 440-463 (2021)