

New Directions in Theoretical Physics: Gravitational Waves

Laura Cadonati, Georgia Tech

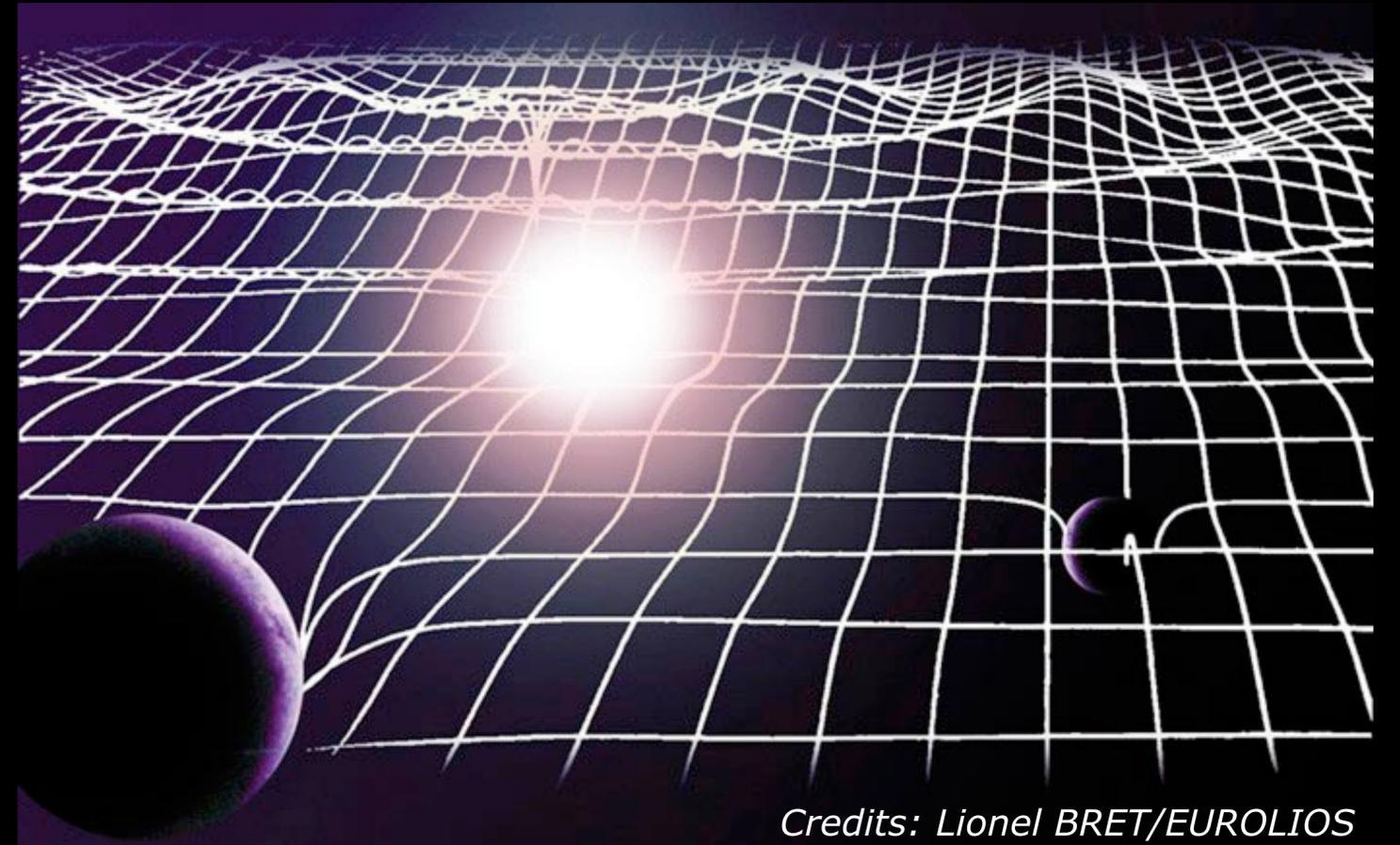


The EM sky

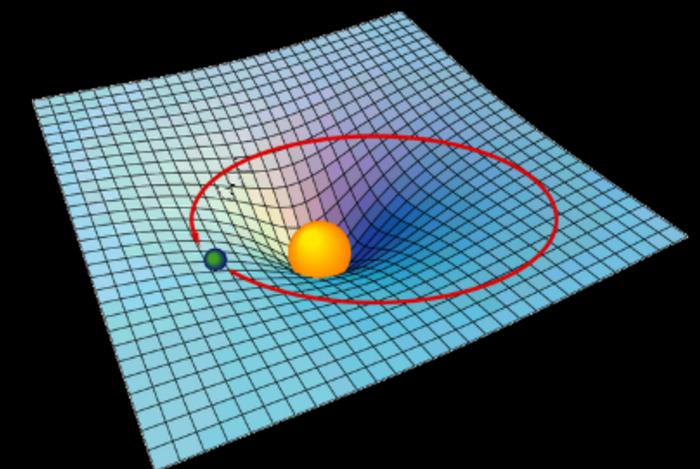
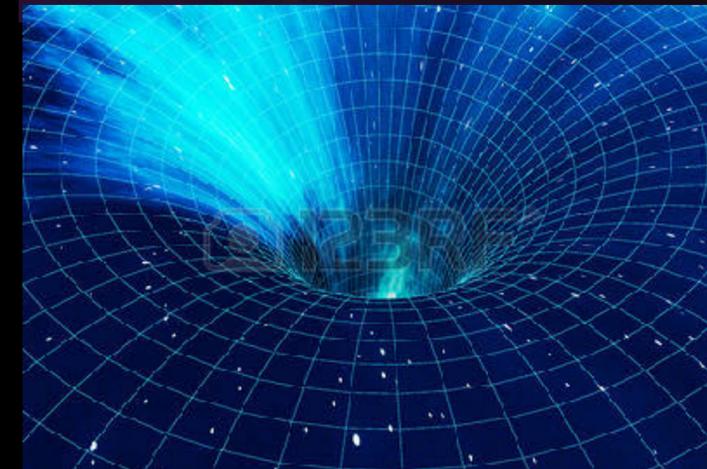


James Webb Space Telescope First Deep Field, galaxy cluster SMACS 0723 - Credits: NASA, ESA, CSA, STScI

The GR sky



Credits: Lionel BRET/EUROLIOS



Gravitational Waves: Ripples in Space-Time

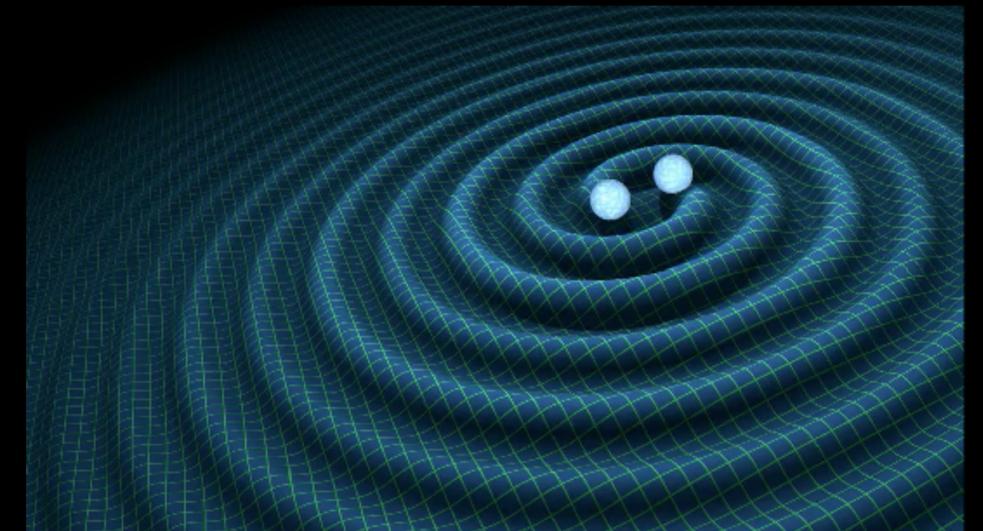
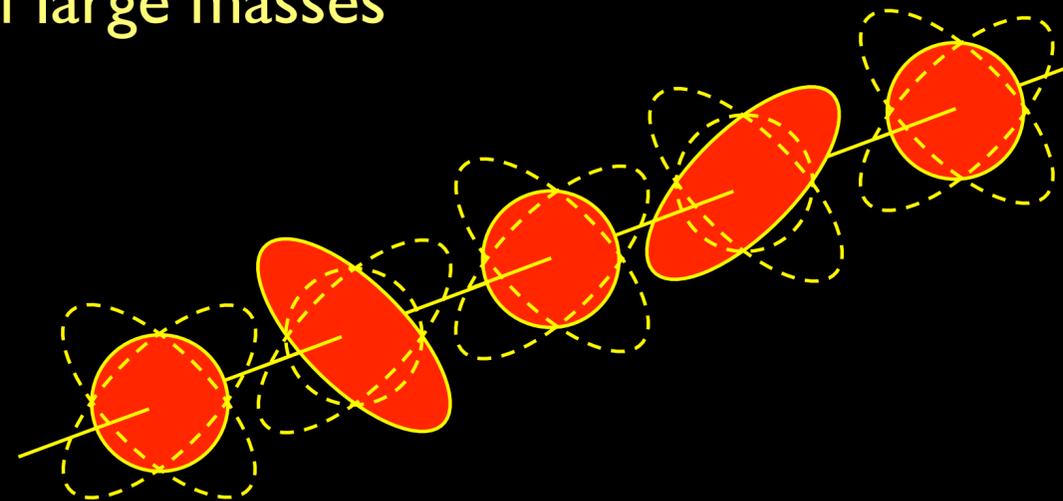


Perturbations of the space-time metric produced by rapid changes in shape and orientation of massive objects.

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

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

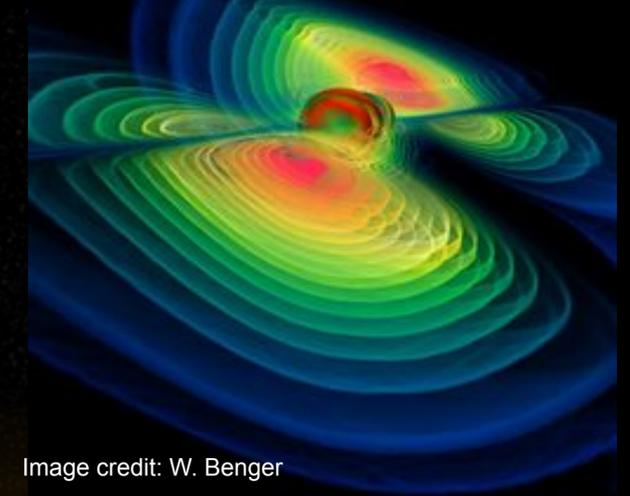


Image credit: W. Bengert

Neutron Star Formation

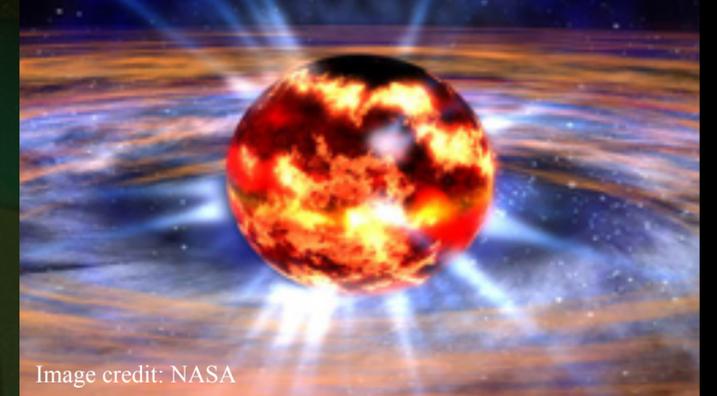


Image credit: NASA

Supernovae

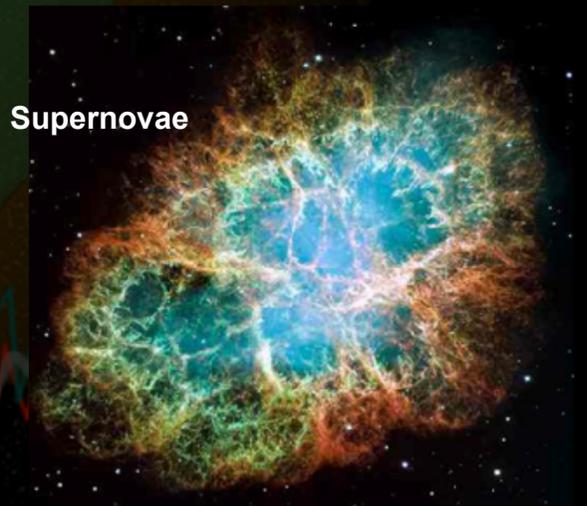


Image credit: Hubble

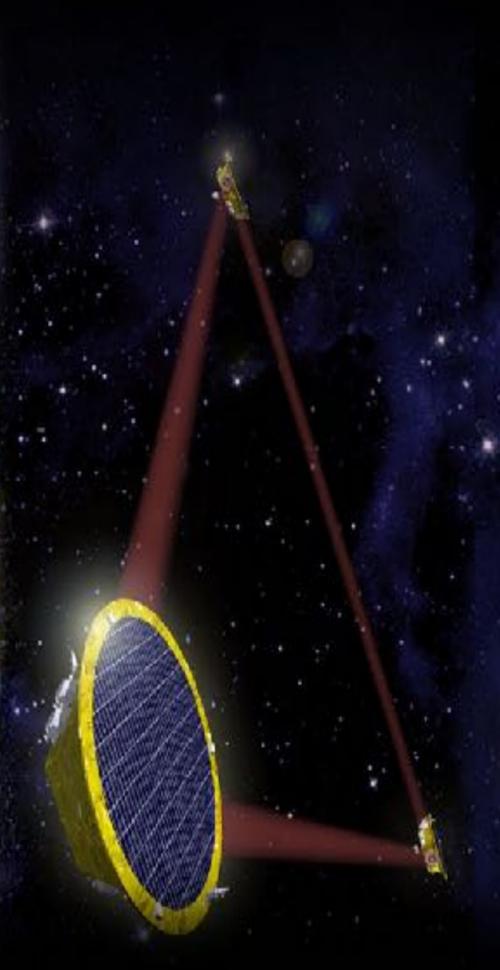
Gravitational Wave Periods

Milliseconds



LIGO/Virgo

Minutes
to Hours



LISA

Years
to Decades



Pulsar Timing Array

Billions
of Years

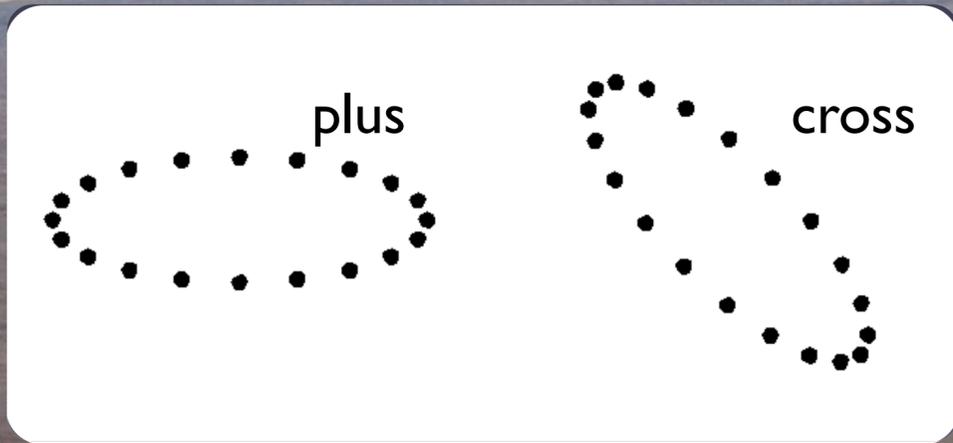


Cosmology Probes

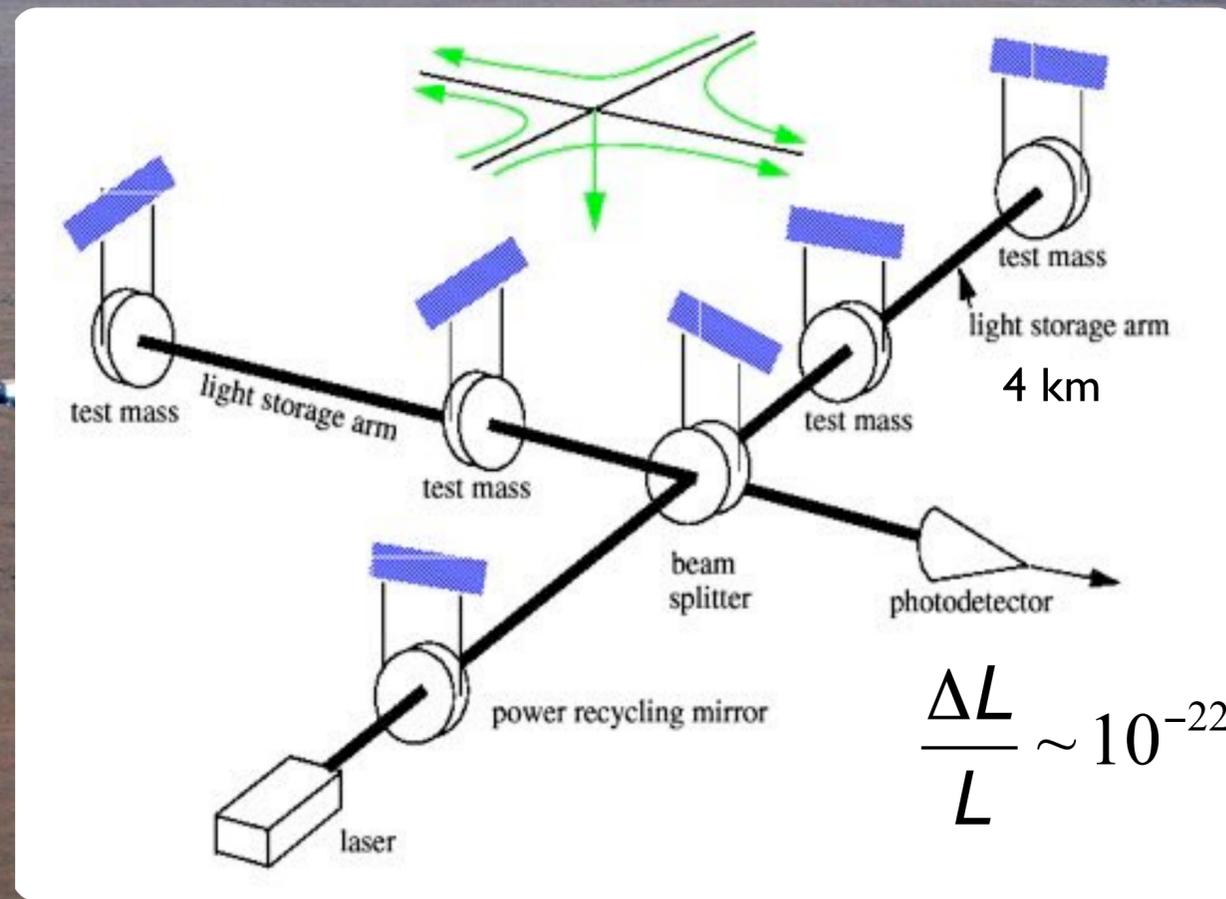
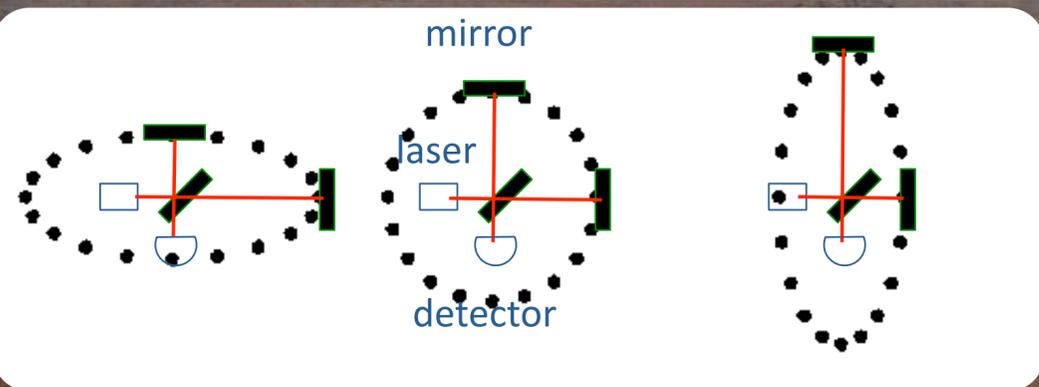
How to Detect Gravitational Waves

Physically, gravitational waves are strains

Suspended Mirrors as Test Masses

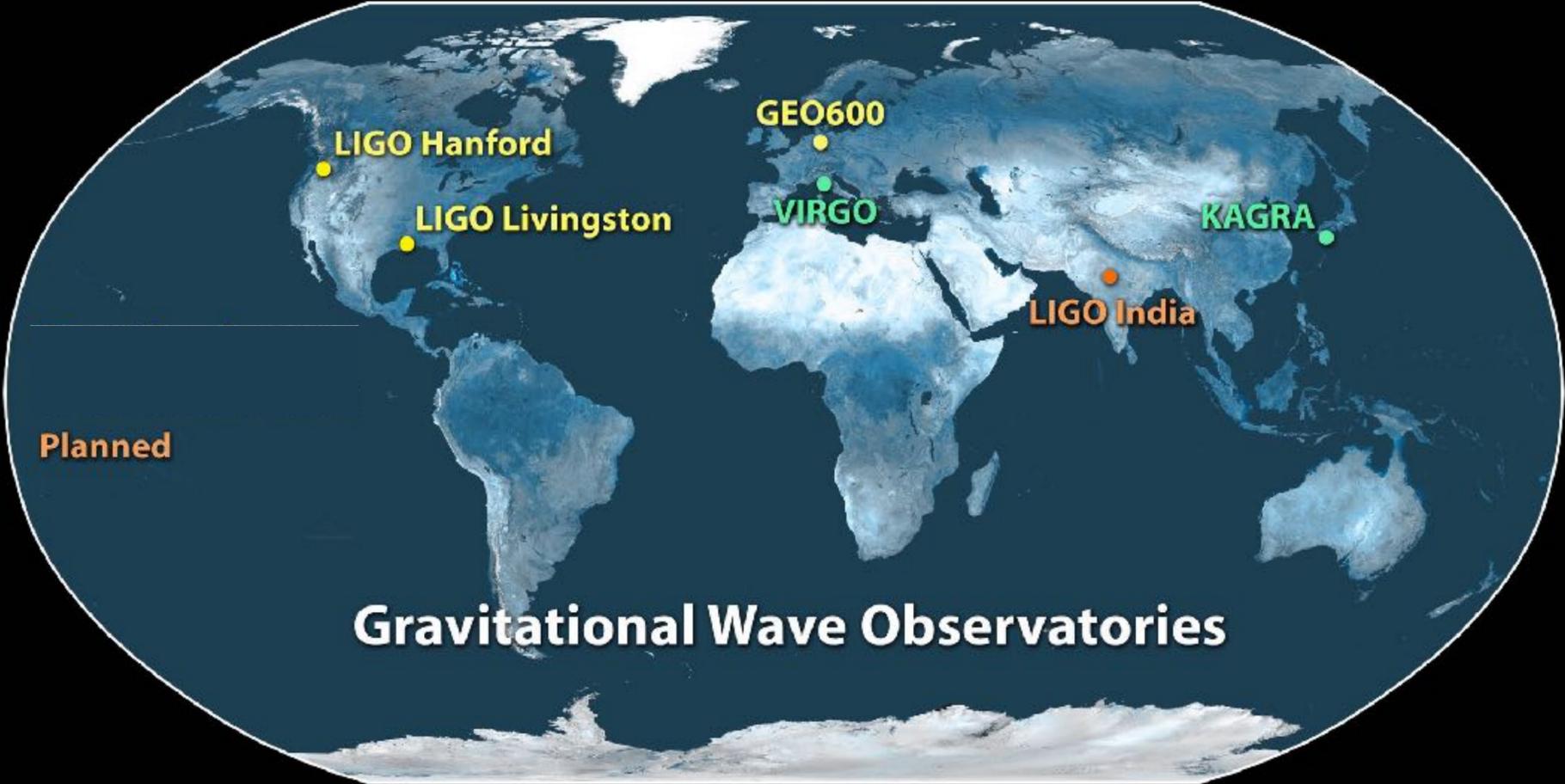


Deformation of a ring of free-falling particles due to the + and x polarization



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

An International Gravitational Wave observatory Network



LIGO Hanford (WA)



LIGO Livingston (LA)



Virgo, Pisa (Italy)



GEO600, Hannover (Germany)

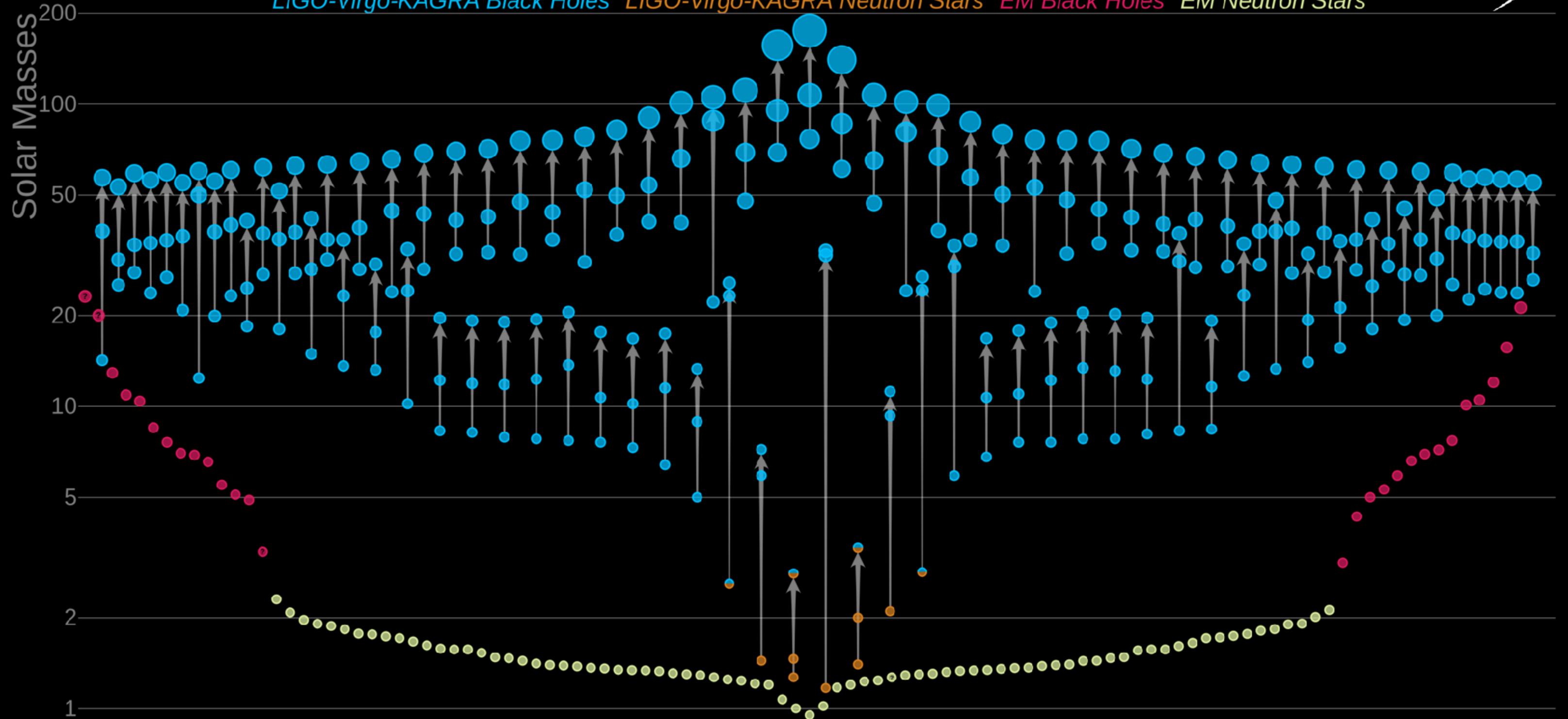
An aerial photograph of a large industrial facility, possibly a power plant or refinery, with several large buildings and a complex network of pipes and roads. The facility is situated in a flat, open area with a dense forest in the background. The sky is filled with dramatic, colorful clouds in shades of orange, yellow, and blue, suggesting a sunset or sunrise. The text "Ground-Based Observations from the Current Detectors" is overlaid in white, bold, sans-serif font across the center of the image.

Ground-Based Observations from the Current Detectors

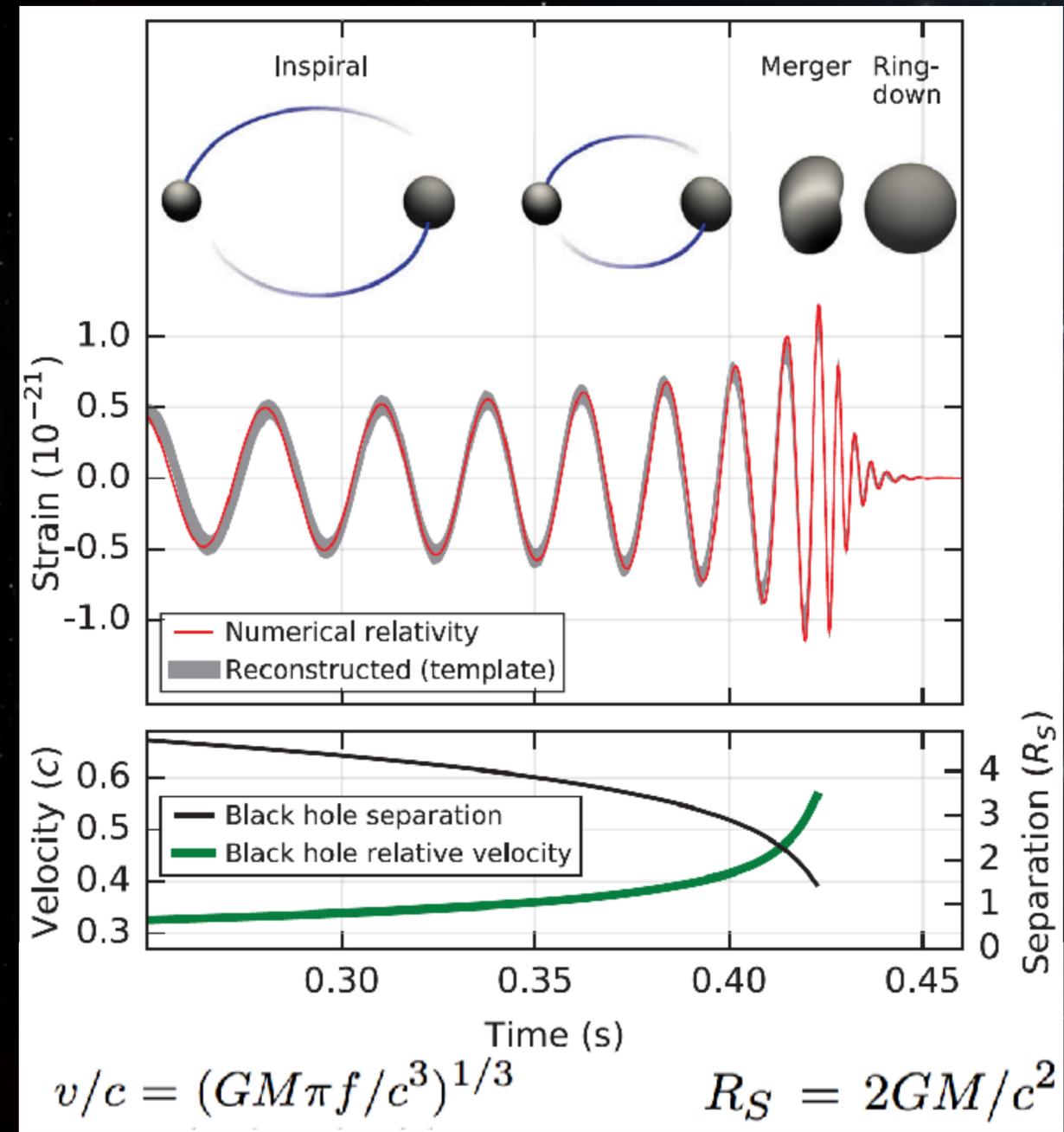
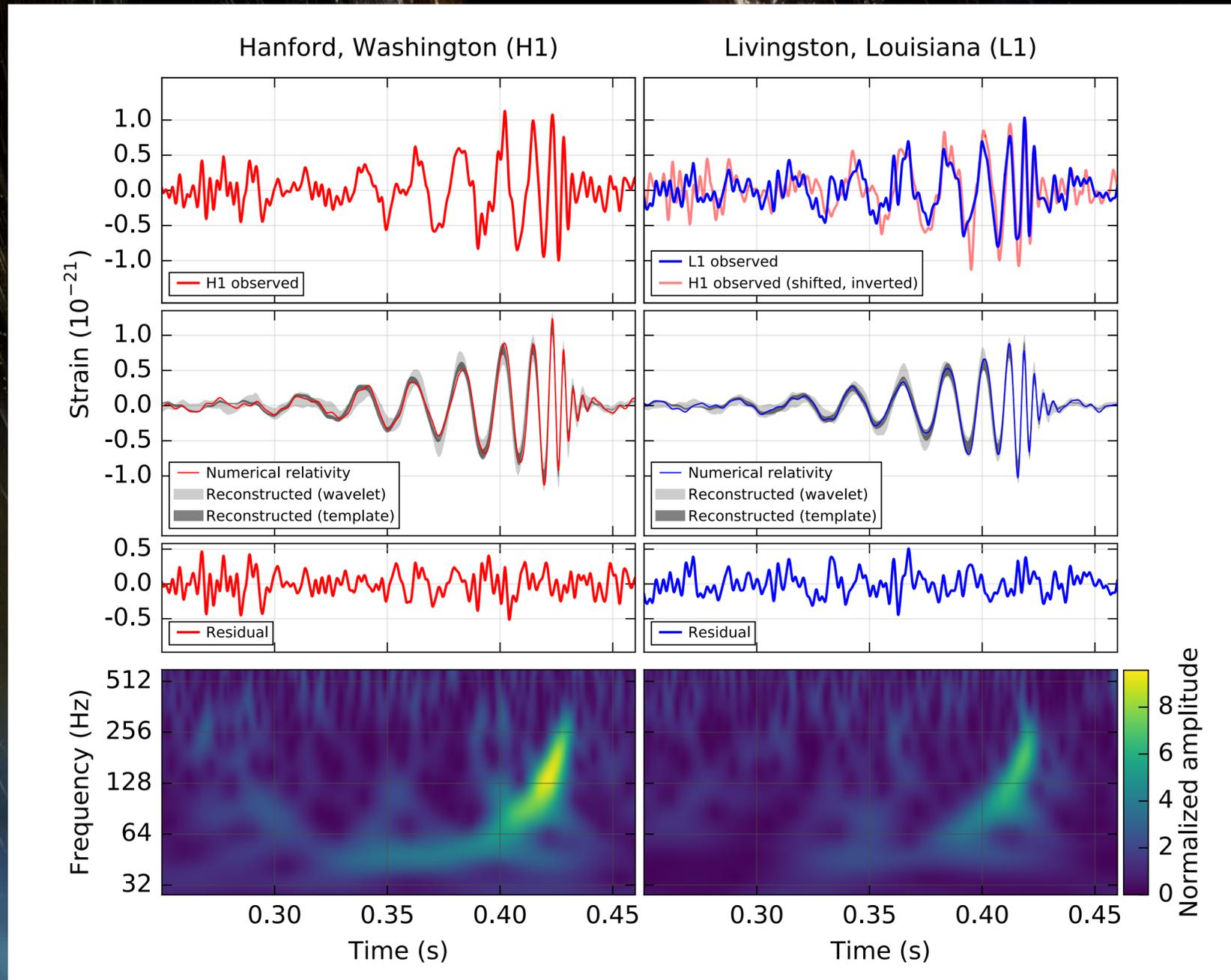
Masses in the Stellar Graveyard



LIGO-Virgo-KAGRA Black Holes LIGO-Virgo-KAGRA Neutron Stars EM Black Holes EM Neutron Stars



The First Black Holes: GW150914

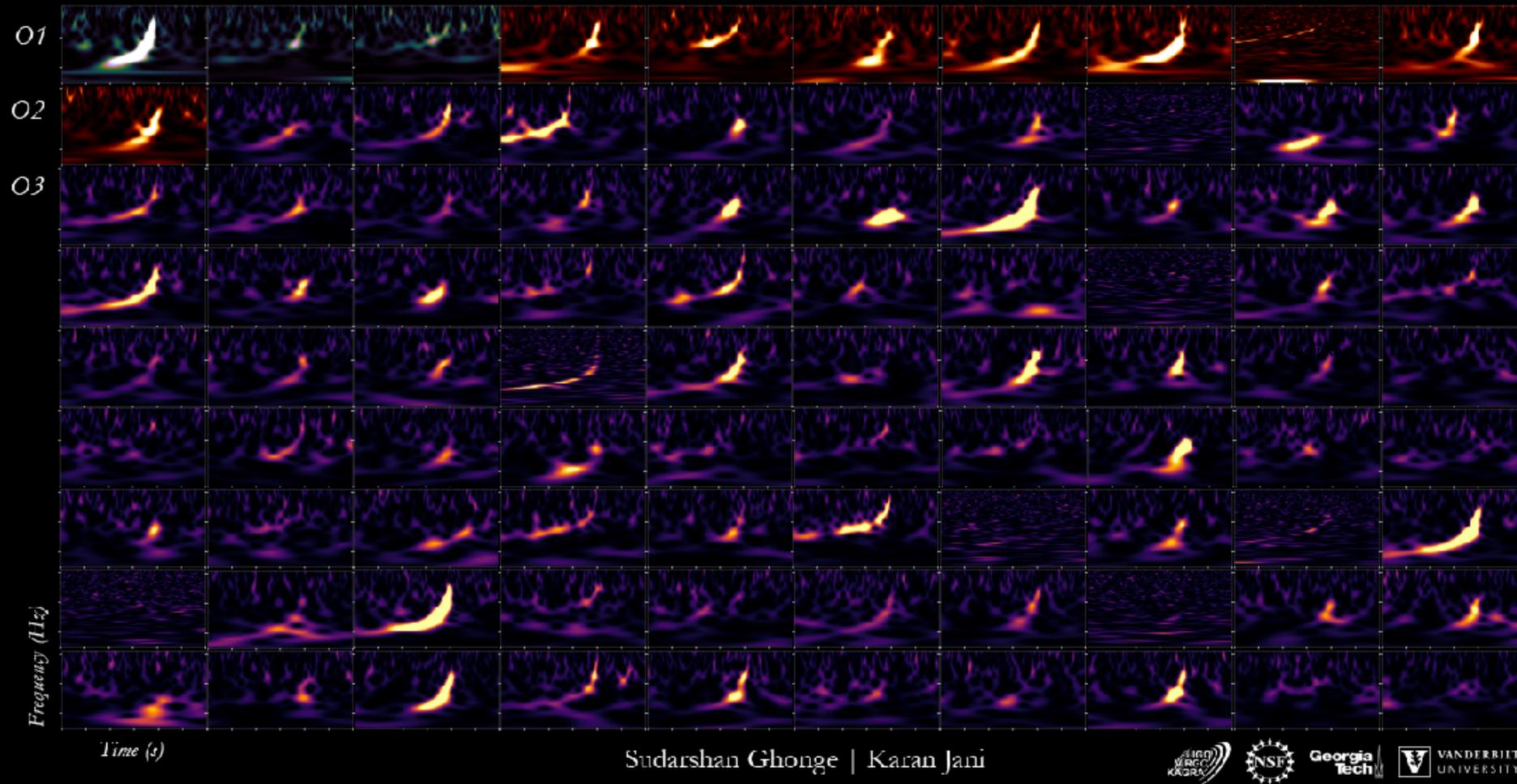


Observation of Gravitational Waves from a Binary Black Hole Merger — PRL 116:061102, 2016

GWTC-3

Gravitational-Wave Transient Catalog

Detections from 2015-2020 of compact binaries with black holes & neutron stars



*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

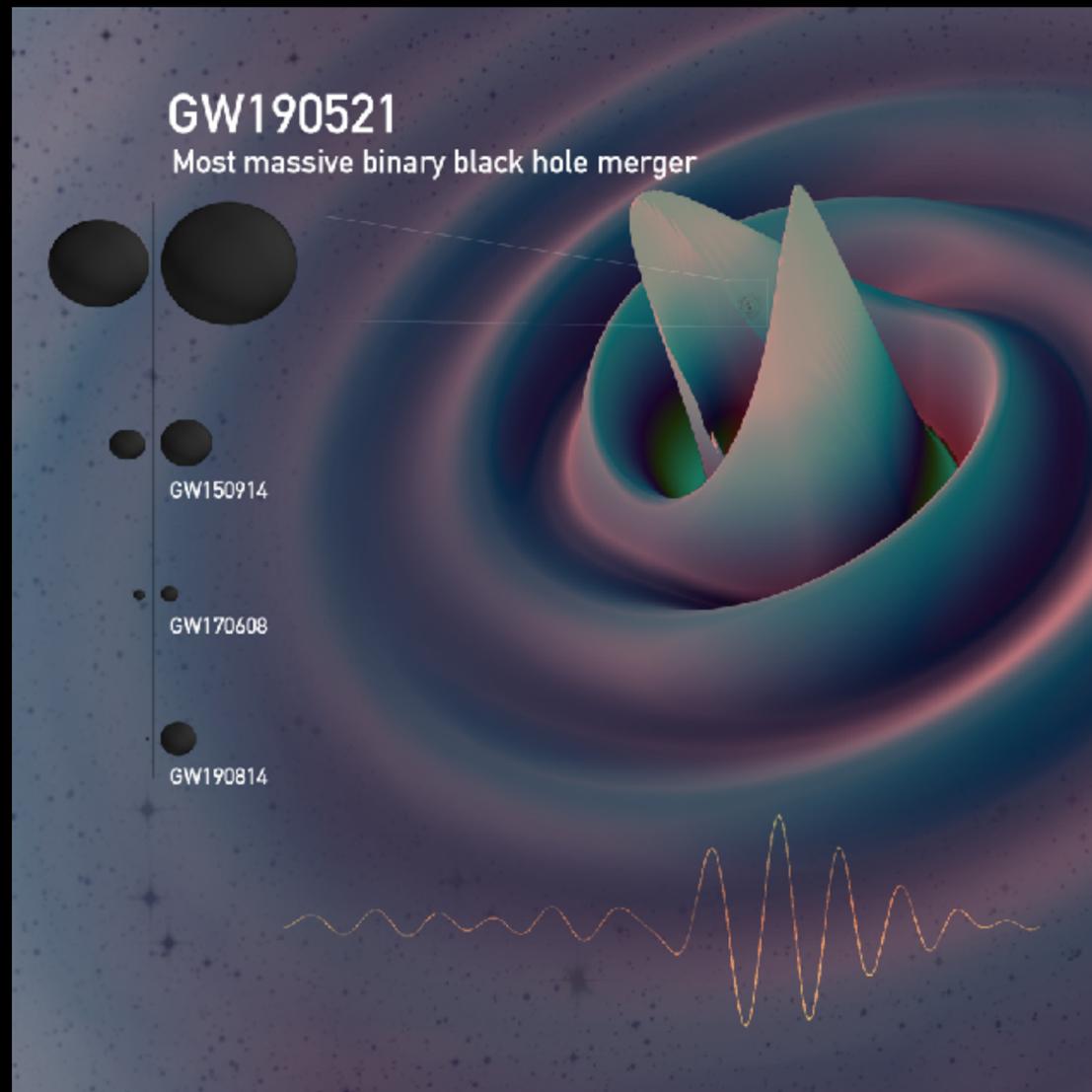
- probe star formation rate at different points in the Universe evolution
- Probe of relative element abundance (a star's composition affects its evolution)



GW190521

PRL 125, 101102 (2020)

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



[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.

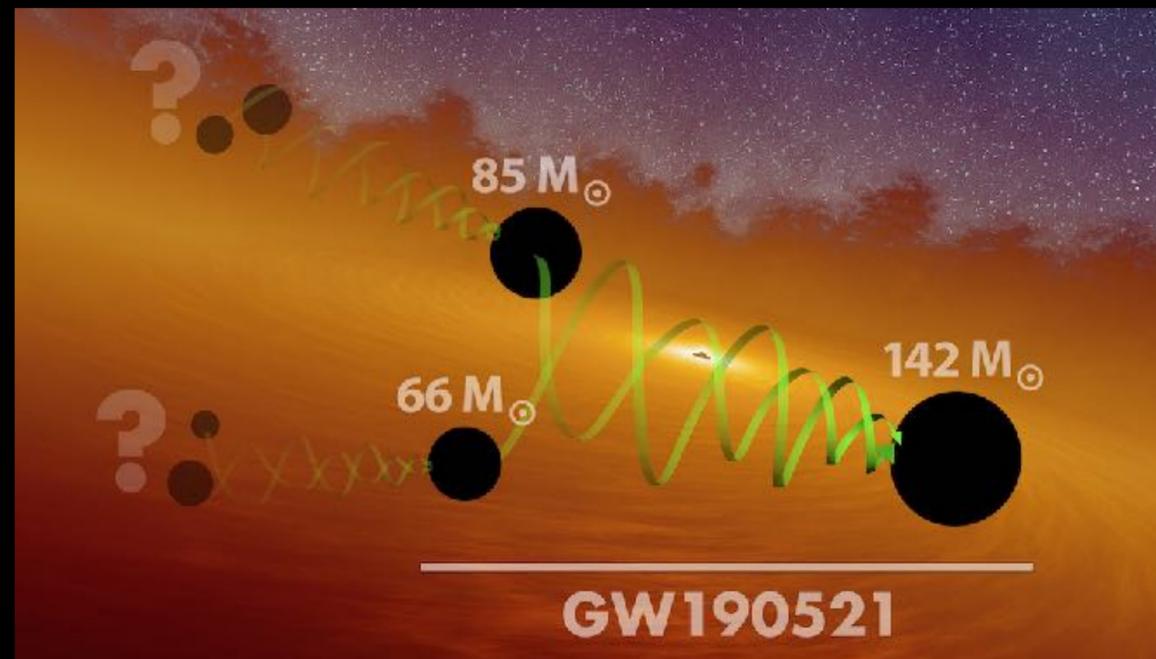


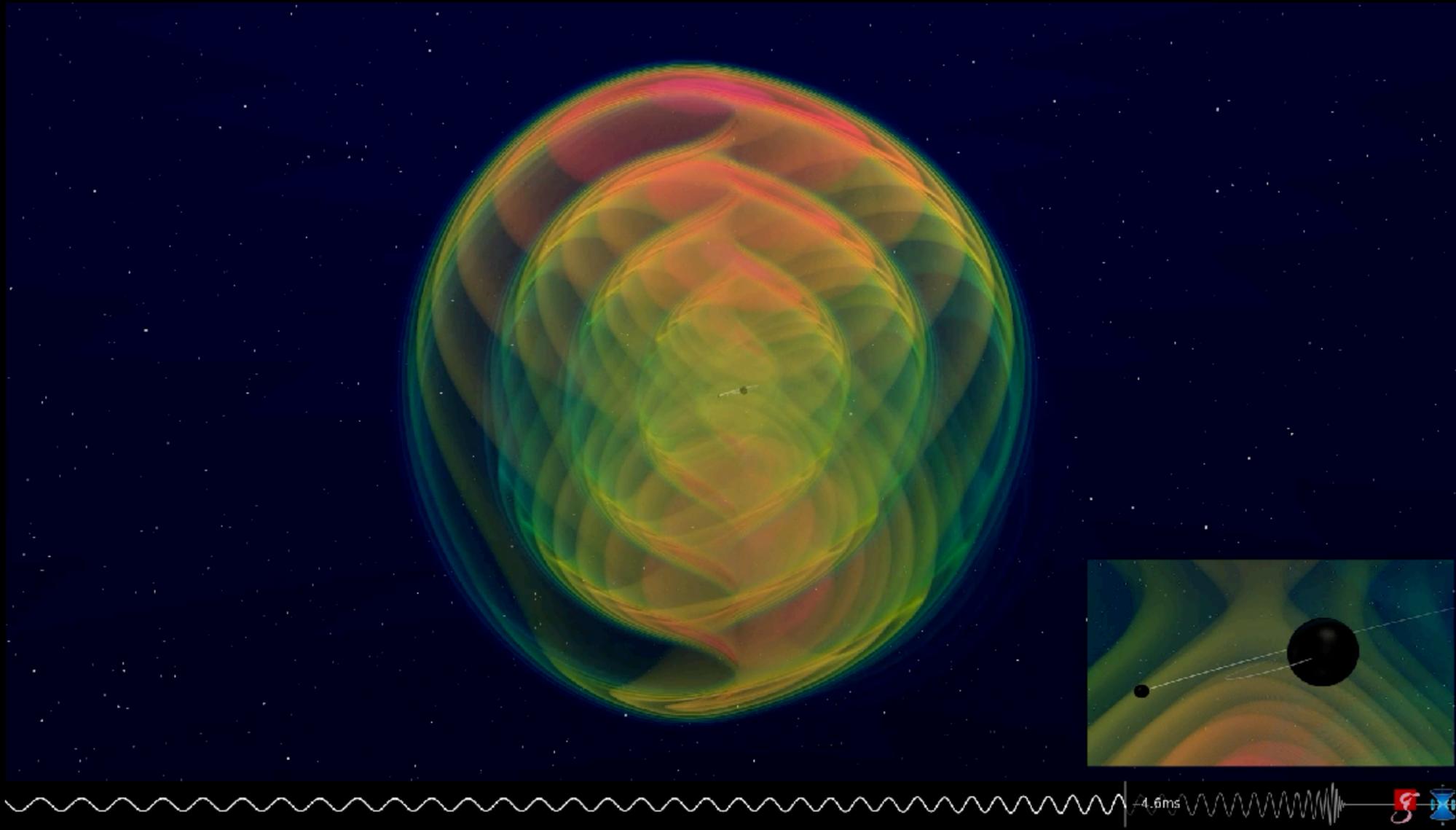
Image credit: LIGO/Caltech/MIT/R. Hurt (IPAC).



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?



Discovery
12 April 2019

Distance
2.4 billion light years away
(740 Mpc)

3 Detectors
Three detectors made the observation: the two LIGO detectors in the USA and Virgo in Italy.

Binary Black Hole

Unequal Masses
This is the first BBH detection where the two black holes had very different masses

Higher Harmonics
This event allowed the hum of higher harmonics to be measured in the signal. These allow new tests of General Relativity. Everything continues to be consistent with Einstein's theory following these tests.

BBH

Premerger
30 suns, 8 suns

Merger
1 suns GW energy

Remnant
37 suns

GW190412

H L V

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



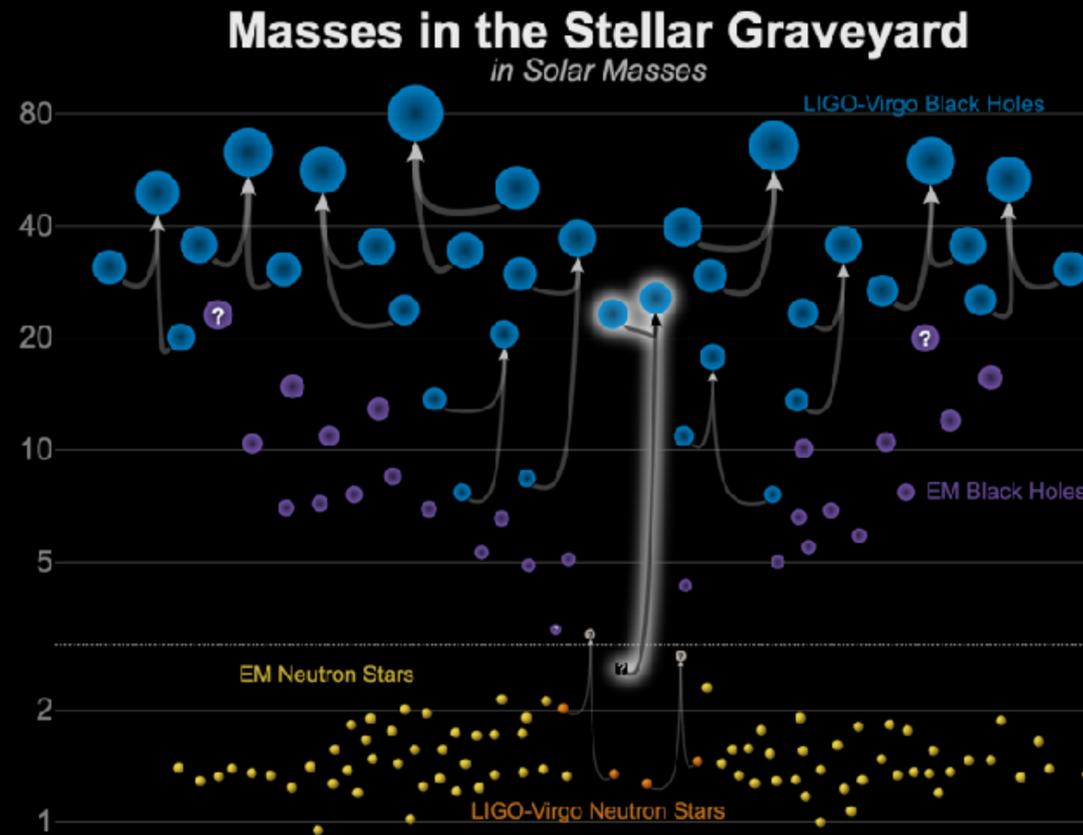
GW190814

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)



Updated 2020-05-16
LIGO-Virgo | Frank Elefsky, Aaron Geller | Northwestern

Insufficient SNR for tidal deformability analysis

No EM counterpart

Challenges understanding of formation mechanisms

18.5 deg²

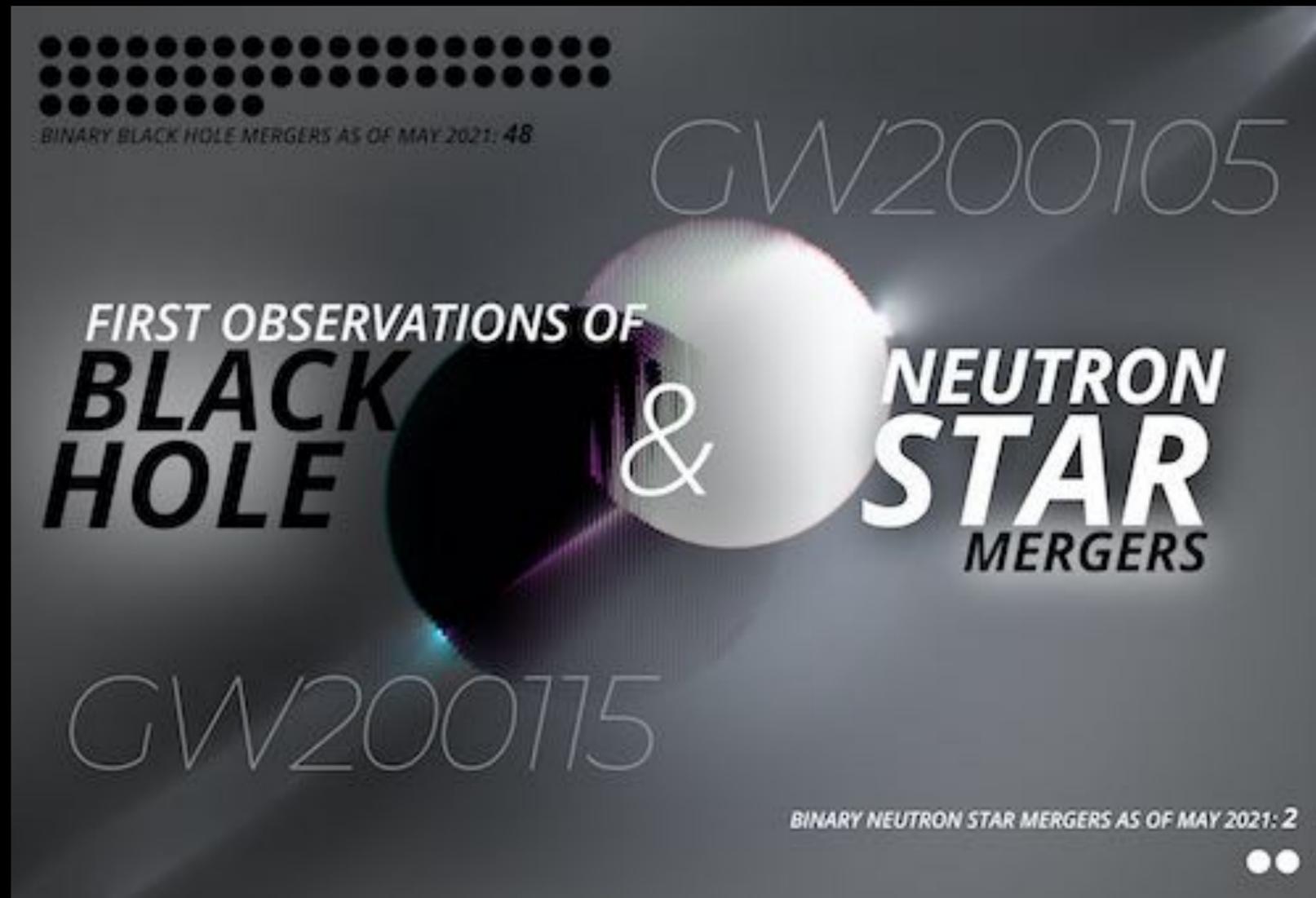
240 Mpc

q=0.1

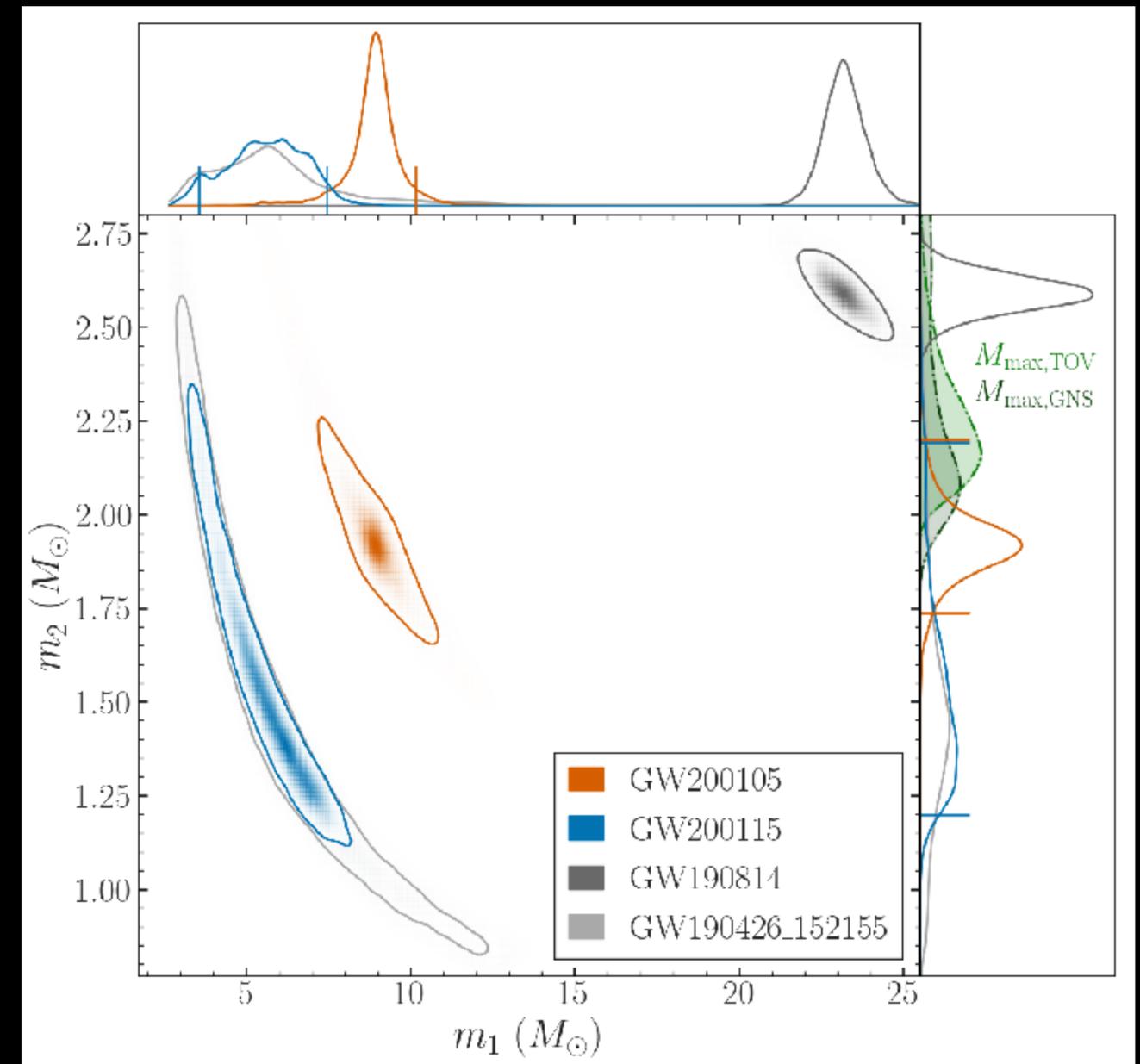
1-23/Gpc³/y

NSBH: GW200105 and GW200115

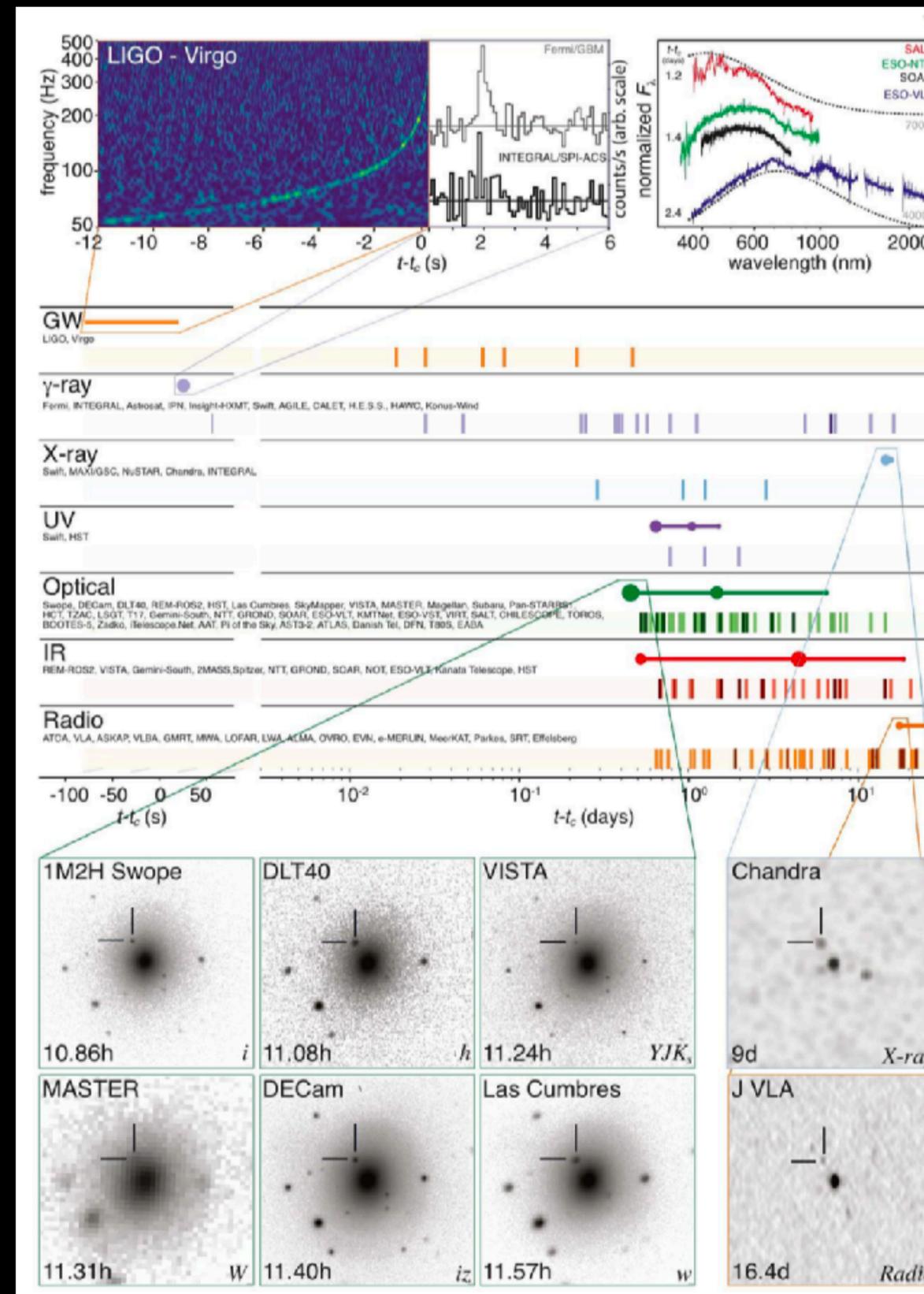
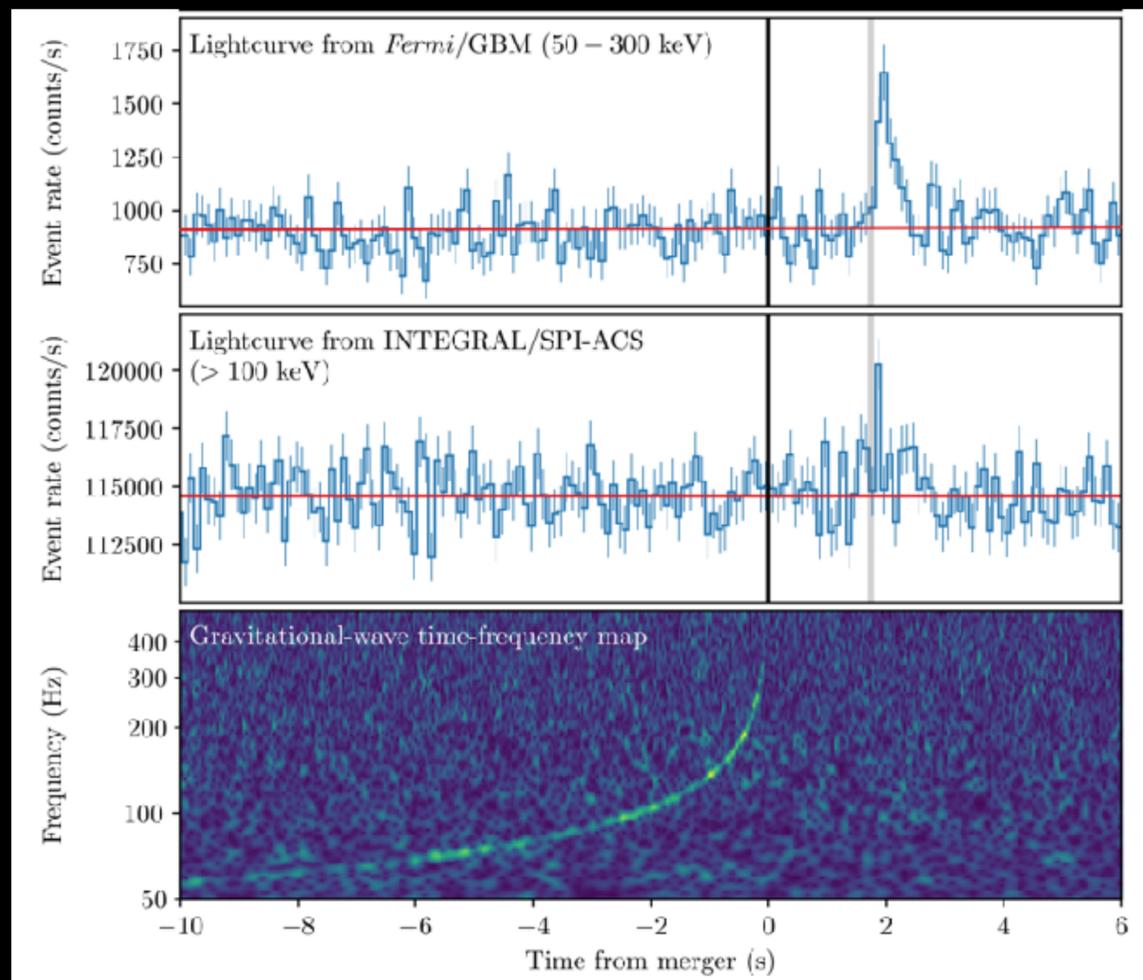
GW200105: $8.9+1.9 M_{\odot}$ GW200115: $5.7+1.5 M_{\odot}$ No EM counterpart found



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



GW170817 Binary Neutron Star Merger



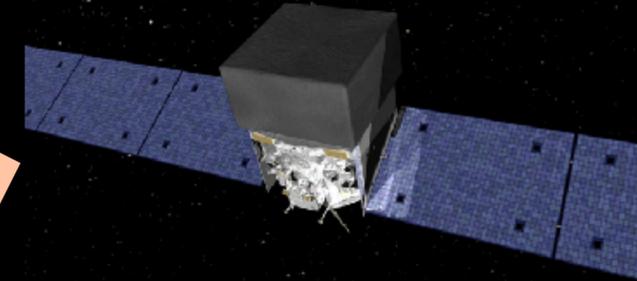
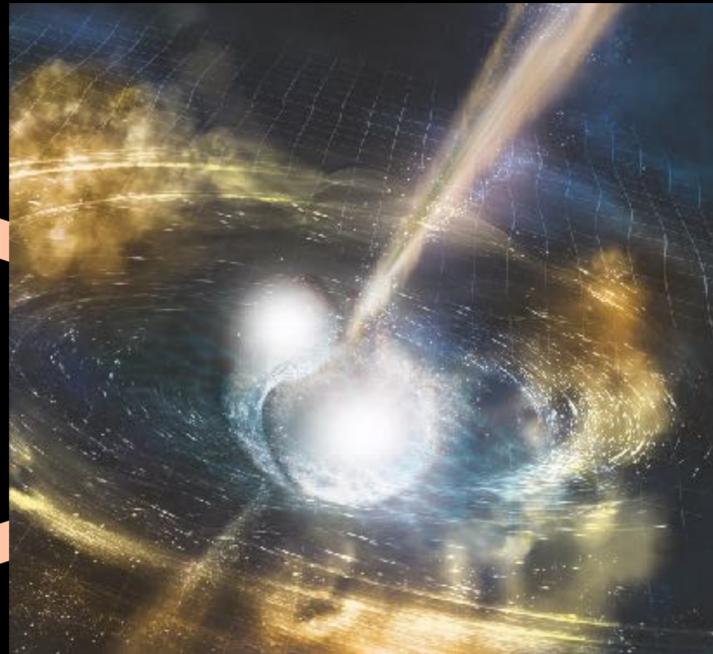
*Multi-messenger
Observations of a
Binary Neutron Star
Merger*
The Astrophysical
Journal Letters,
848:L12, 2017

Multi-messenger Astronomy with Gravitational Waves



Gravitational Waves

Binary Neutron Star Merger



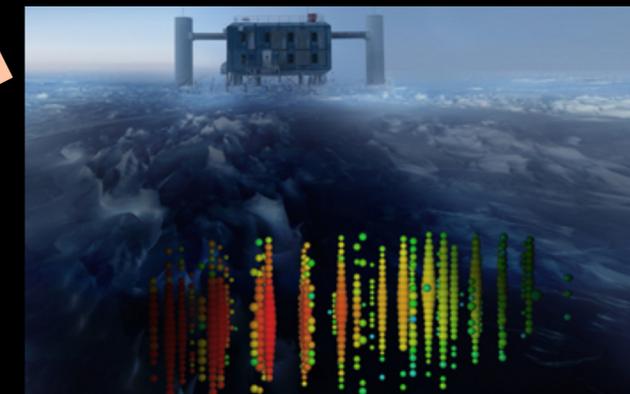
X-rays/Gamma-rays



Visible/Infrared Light

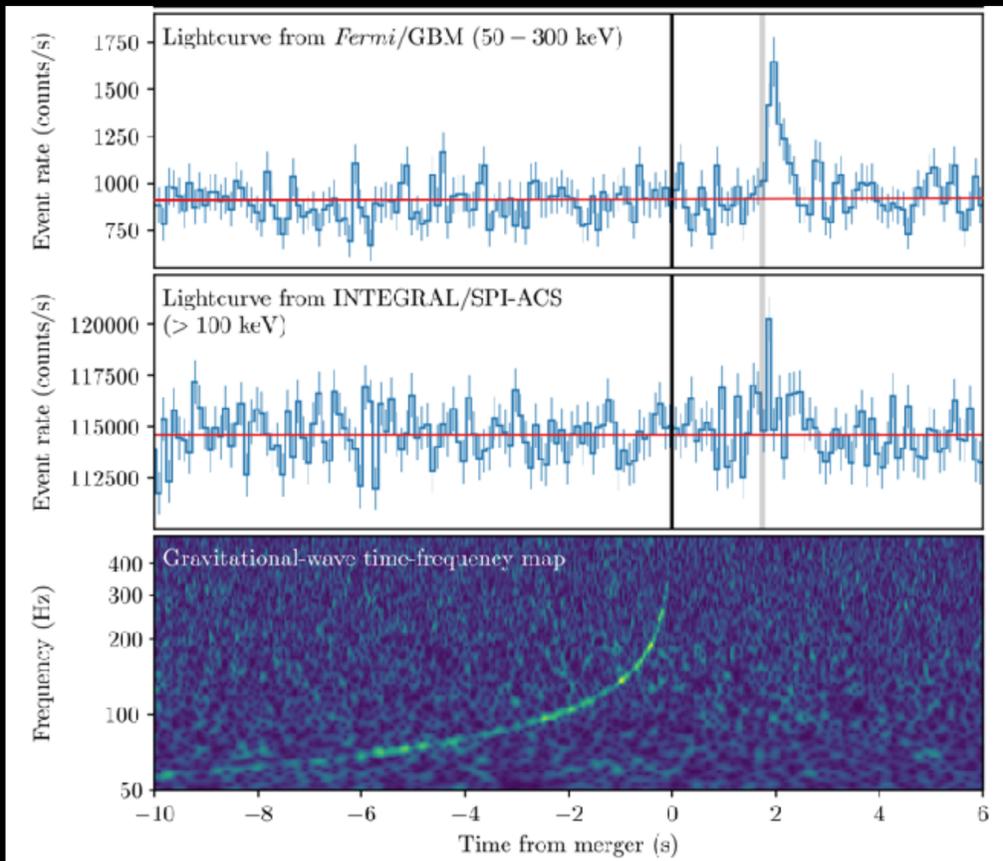


Radio Waves

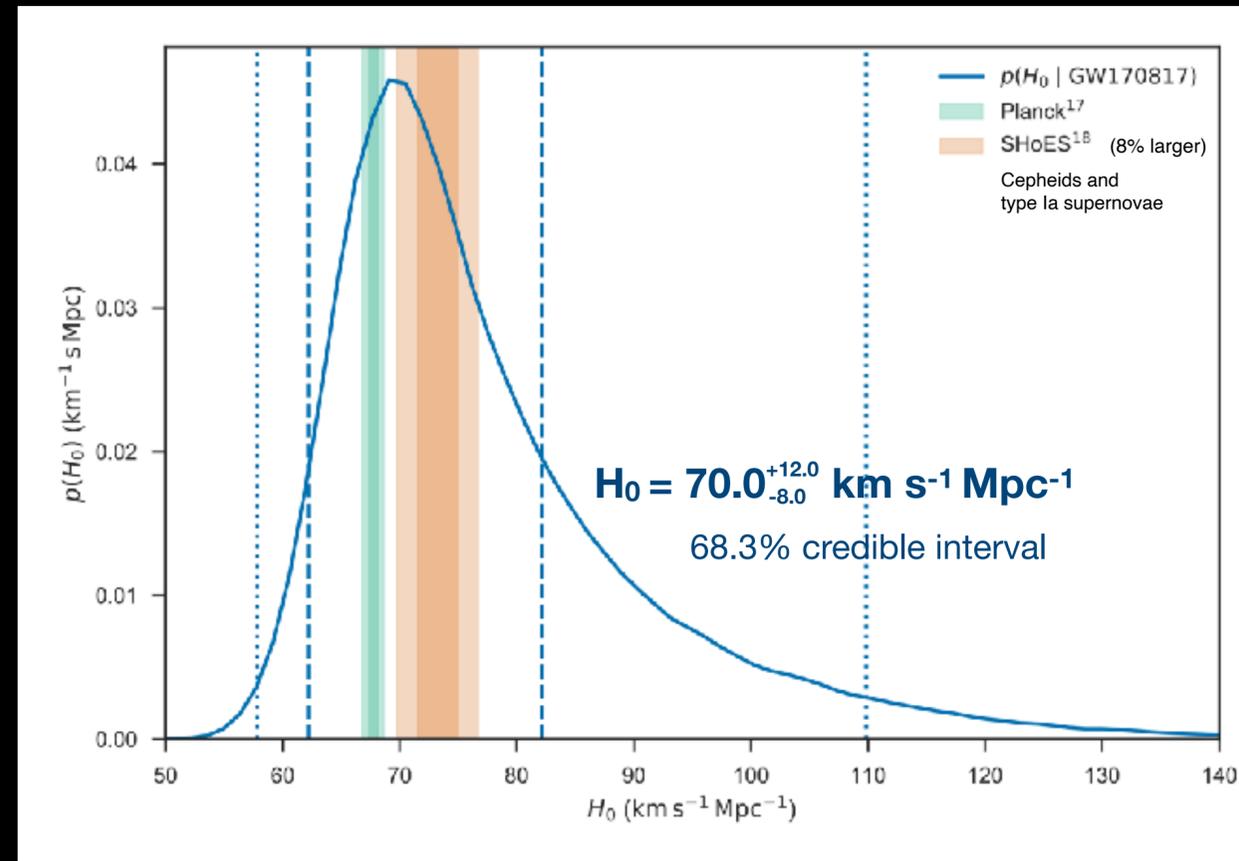


Neutrinos

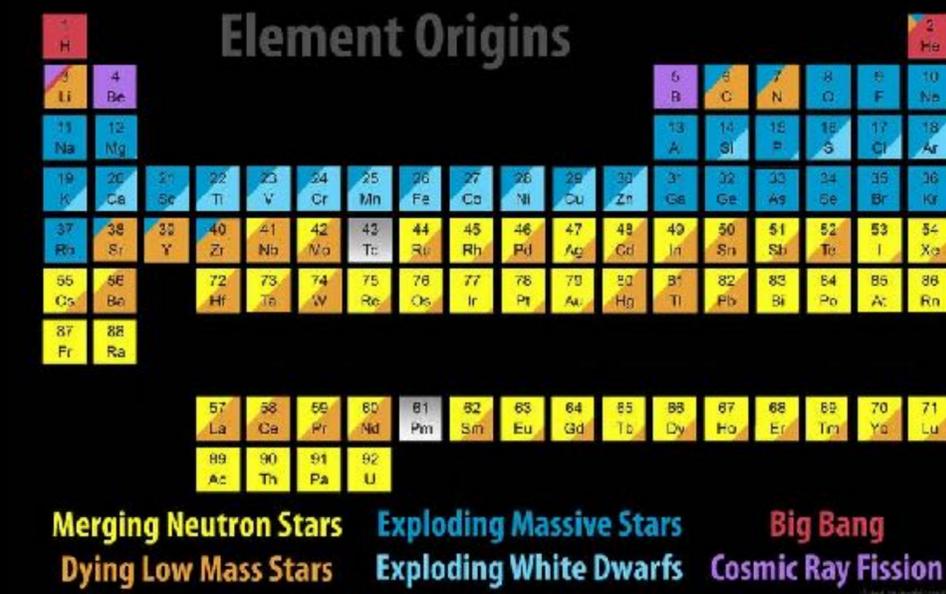
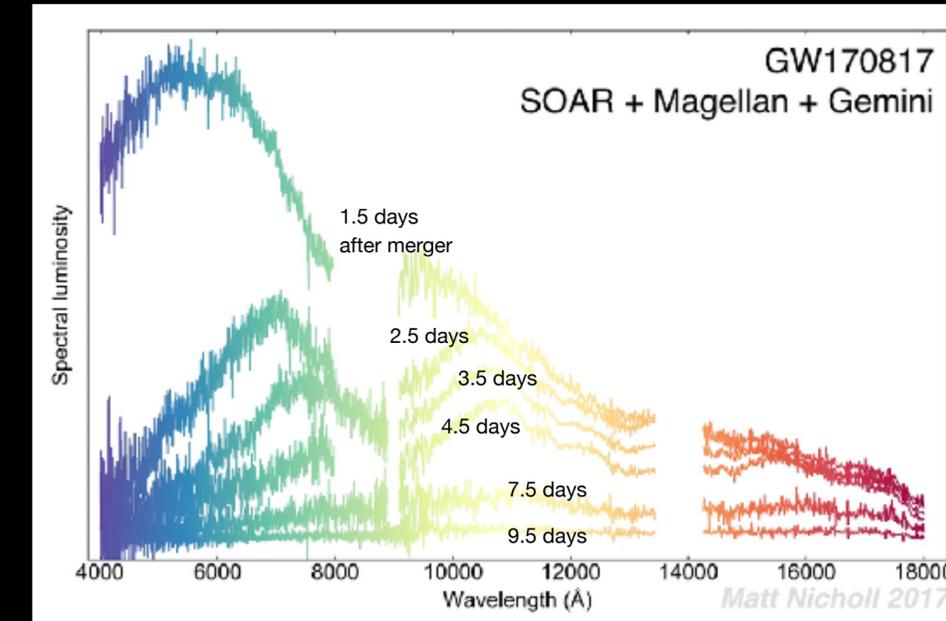
Multi-Messenger Science from GW170817



Neutron star mergers and Gamma Ray Bursts



Measuring the Hubble Constant



Neutron star mergers and Kilonovae

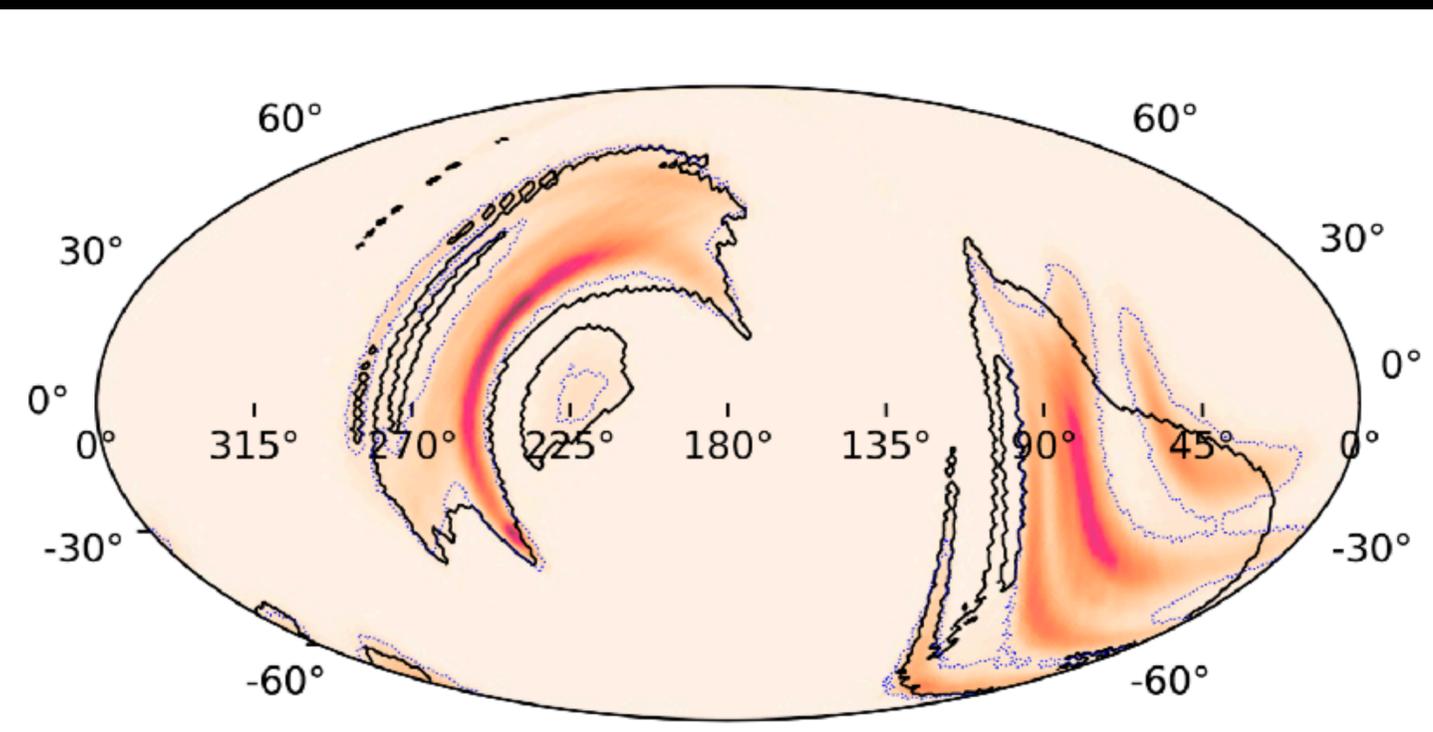


GW190425

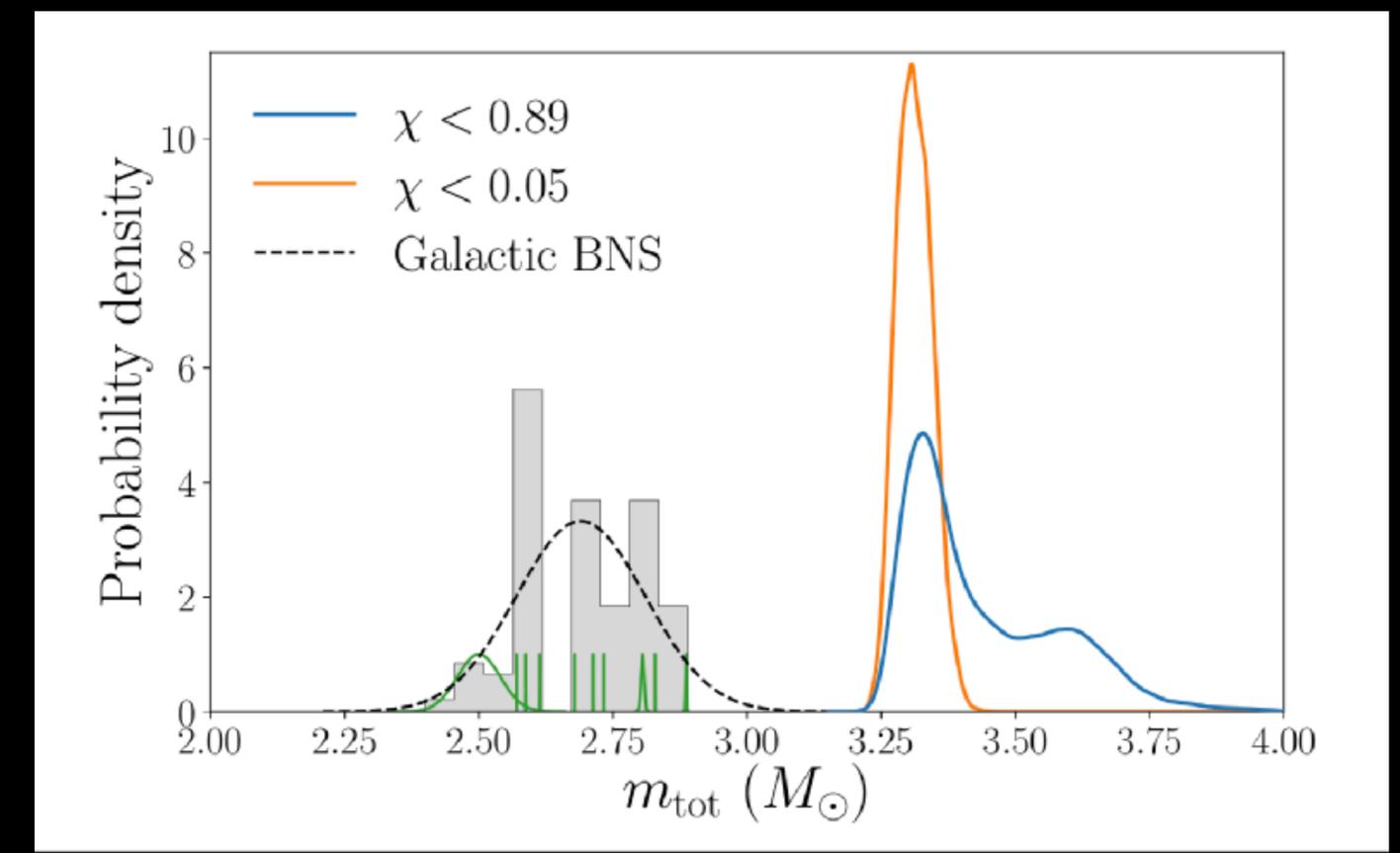
ApJL 892 (2020) L3

Observation of a compact binary coalescence with total mass $\sim 3.4 M_{\odot}$

BNS = Binary Neutron Stars



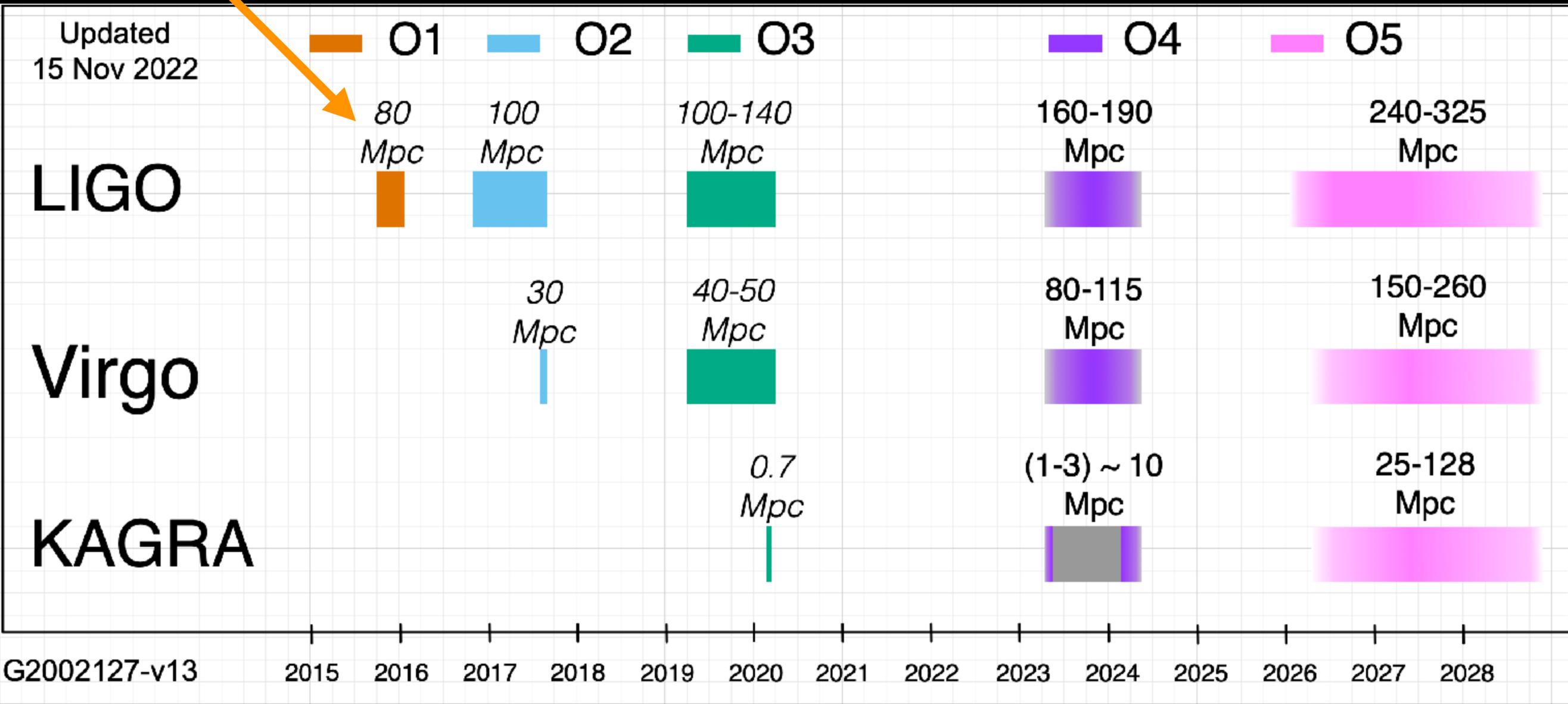
Map uses data from LIGO Livingston and Virgo



- 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

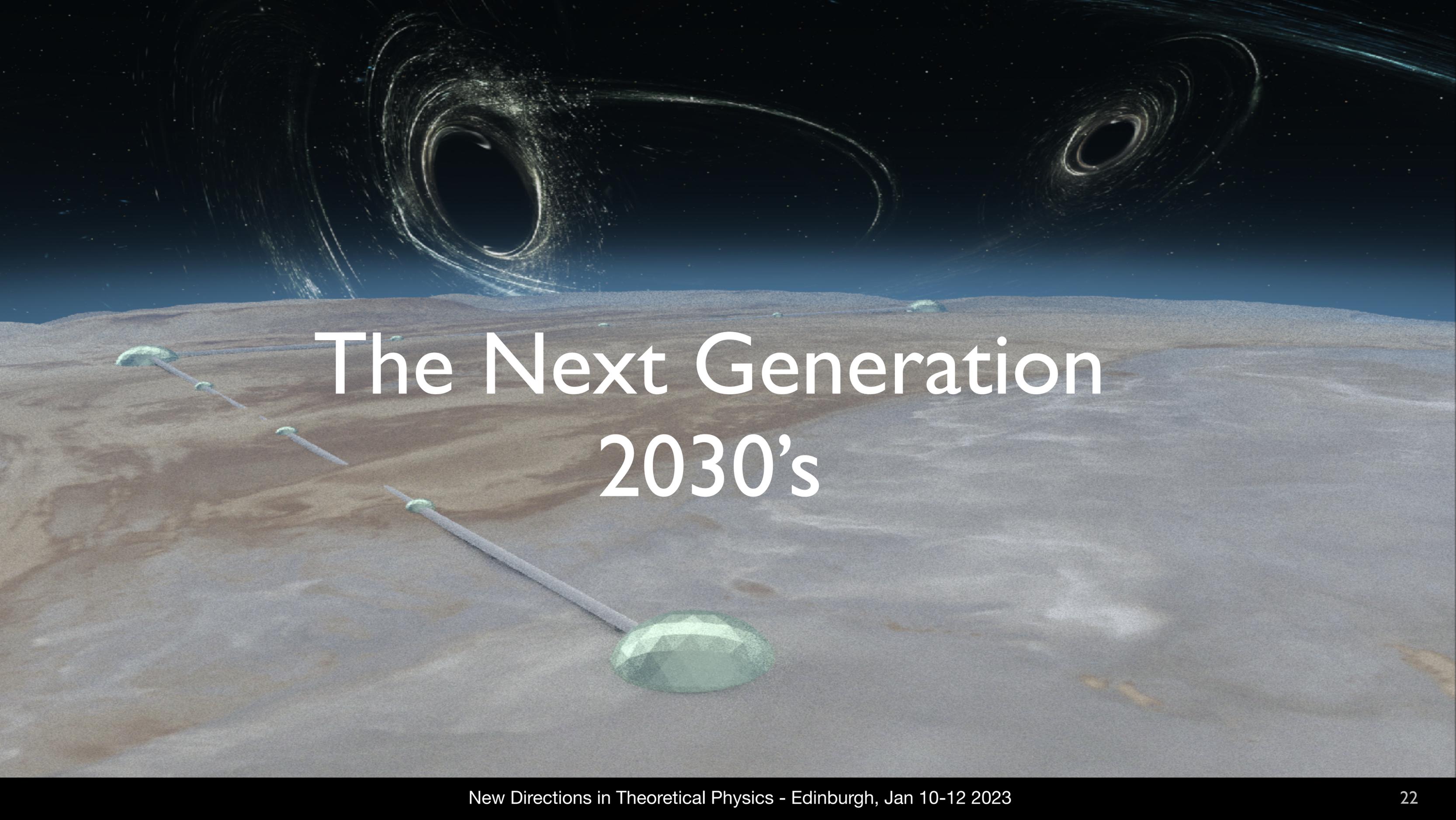
~100 BBH/year ($z \leq 2$)

~1-2 NS-BH/year

~ 10-30 BNS/year ($z \leq 0.1$)

38-44% (12-16%) events with 90% credible region smaller than 20 deg² (5 deg²).

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

The background of the slide is a digital illustration of a desolate, greyish-brown landscape. In the foreground, a series of glowing green, dome-shaped structures are connected by thin, grey lines, resembling a futuristic infrastructure or a path. The sky is dark and filled with stars, with two prominent, swirling black holes or gravitational wells in the upper half of the frame. The overall aesthetic is sci-fi and futuristic.

The Next Generation 2030's

Third Generation

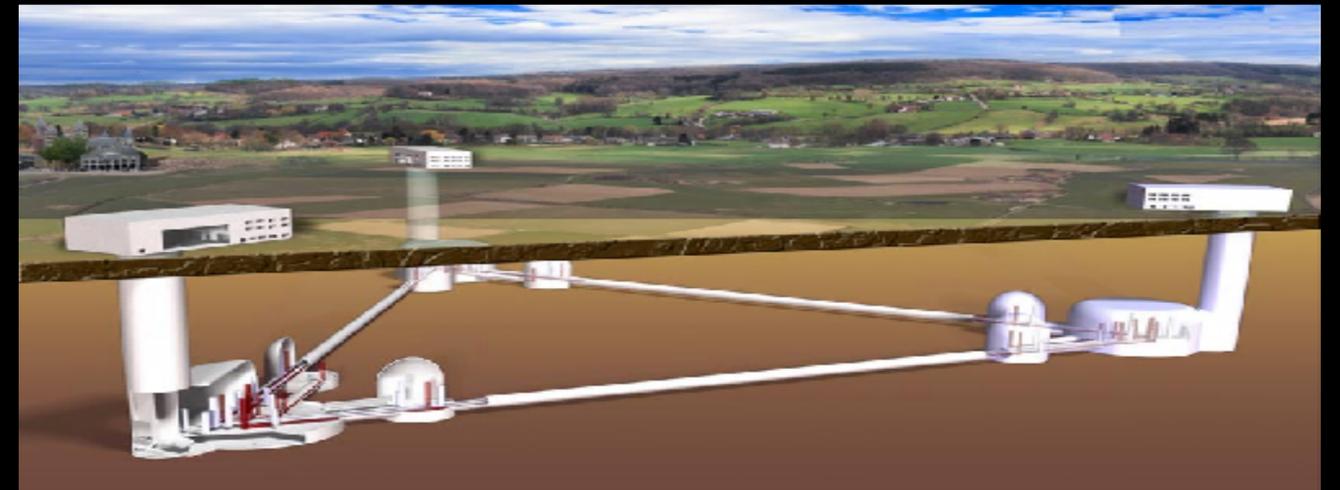
$\sim 10^5$ binary coalescences per year (circa 2035)

Cosmic Explorer

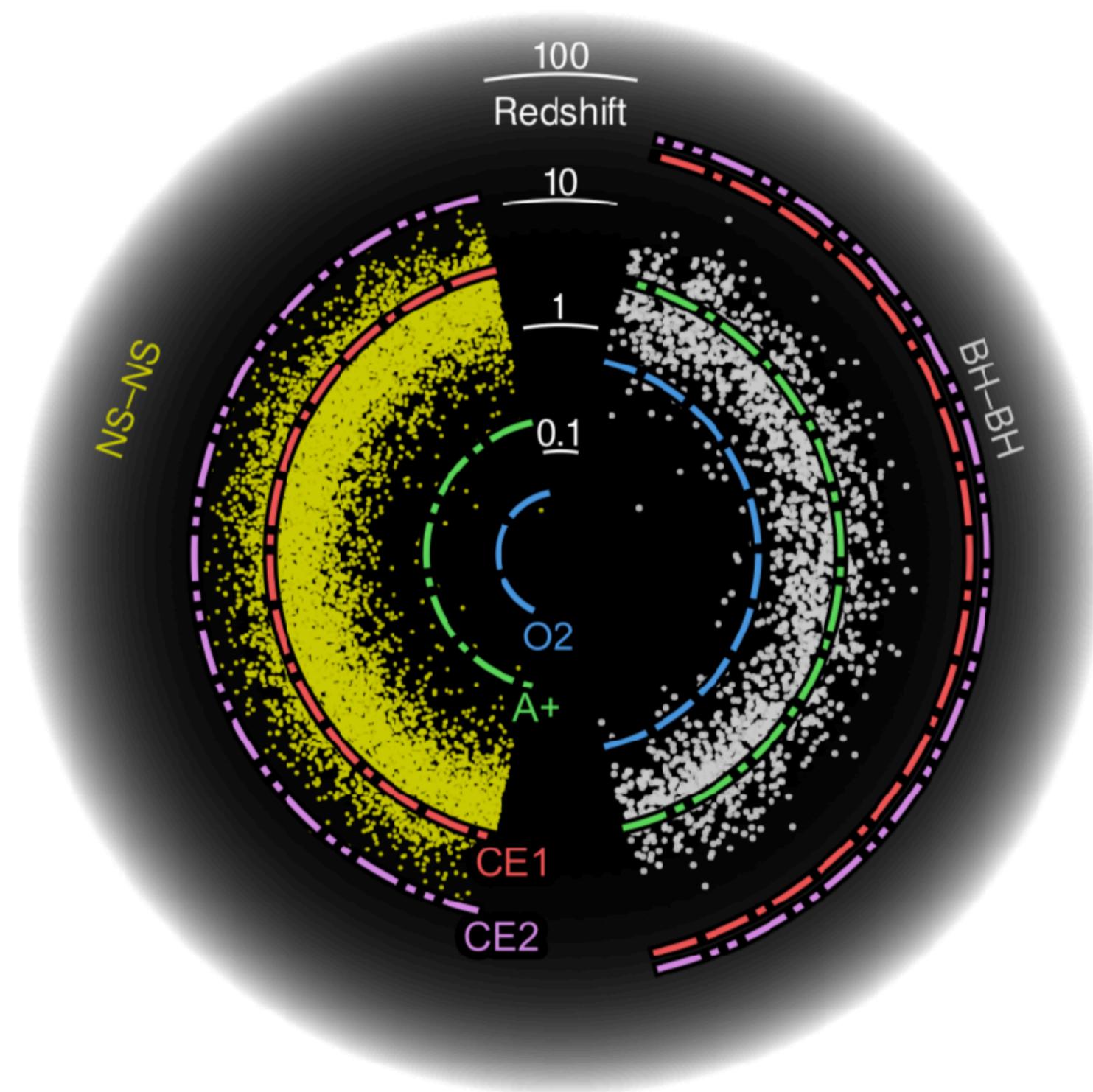
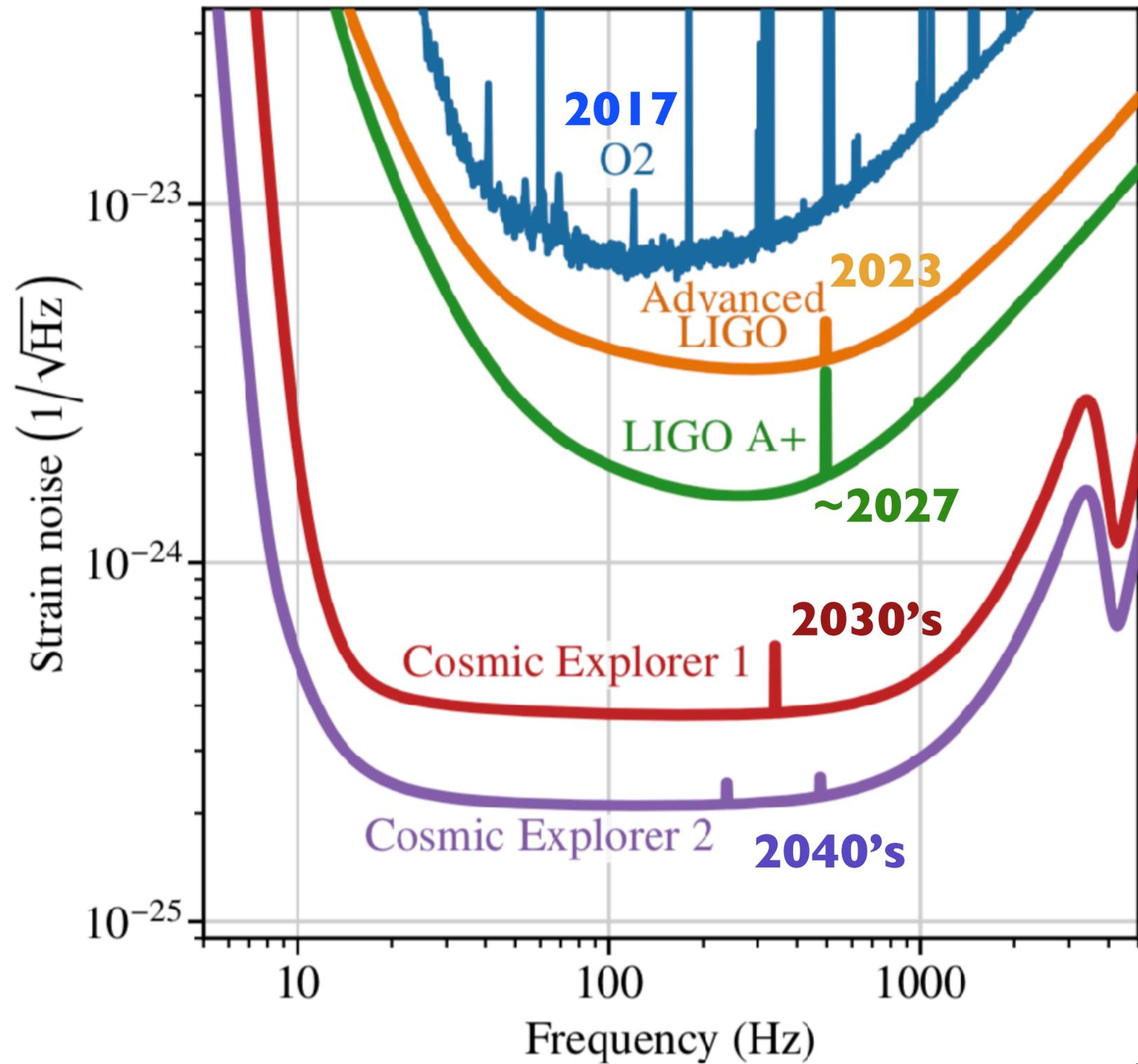


- NSF-funded US conceptual design study well under way
- 40km surface Observatory baseline
- Signal grows with length – not most noise sources
- Stage 1 (~2035) Extension of A+ technologies
- Stage 2 (~2045) Cryogenics, new material for test masses and coatings

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

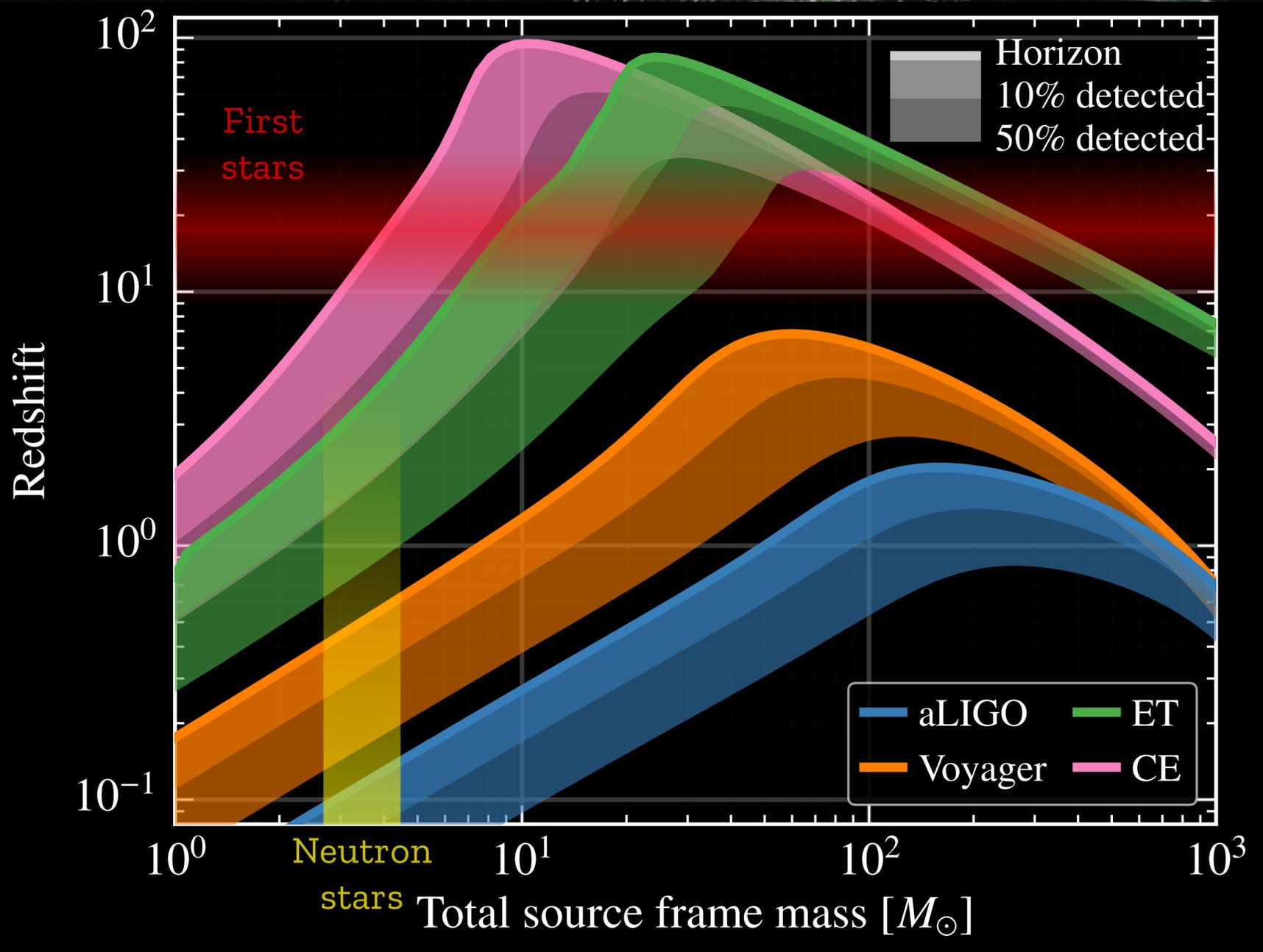


Table 1: Expected detections per year (N), number detected with a resolution of < 1 , < 10 and < 100 sq. deg. (N_1 , N_{10} and N_{100} , respectively) and median localization error (M in sq. deg.), in a network consisting of LIGO-Hanford, LIGO-Livingston and Virgo (HLV), HLV plus KAGRA and LIGO-India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

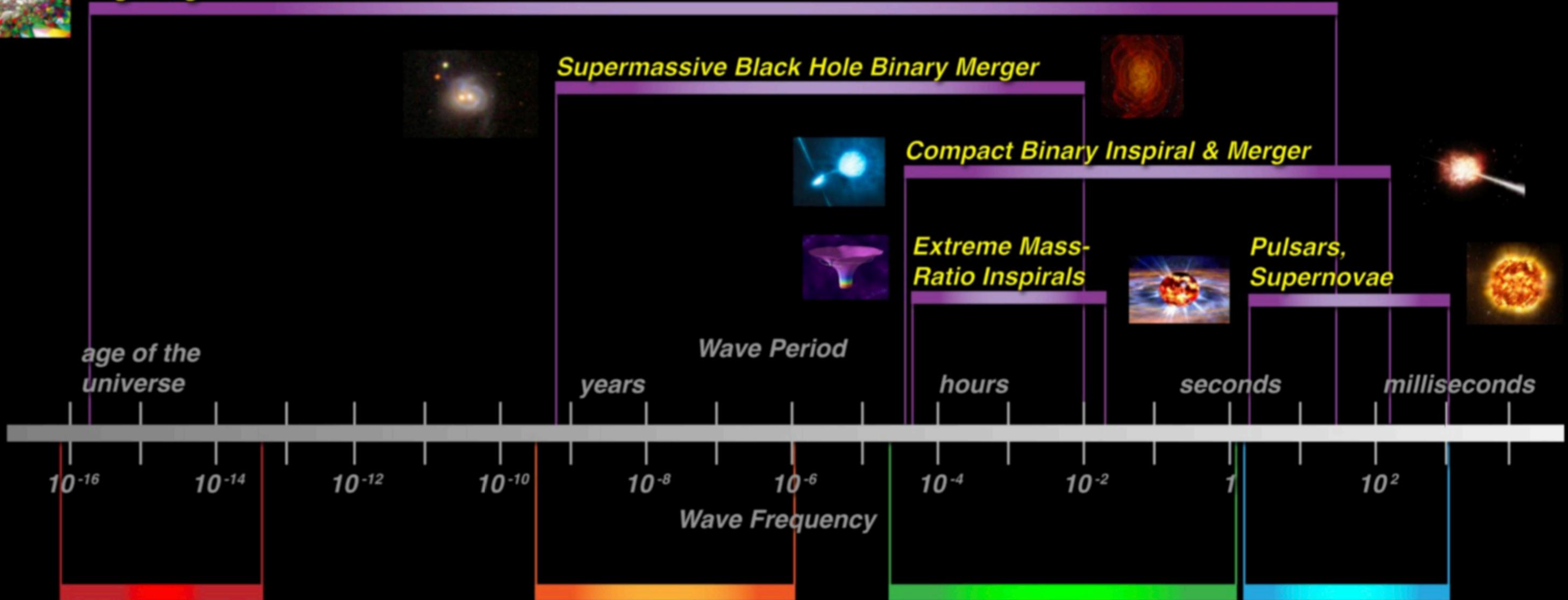
The Gravitational Wave Spectrum

Sources

Detectors



Big Bang

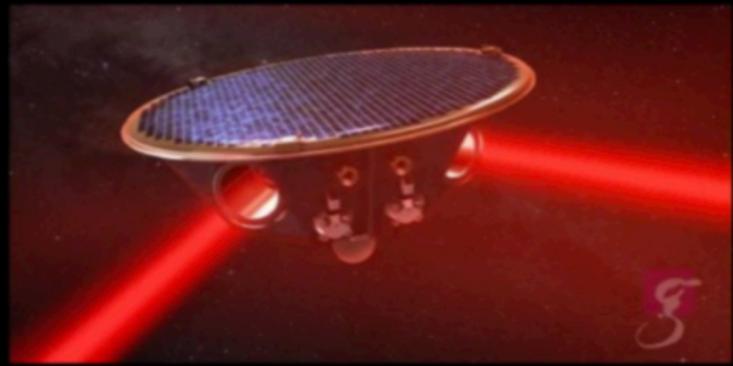
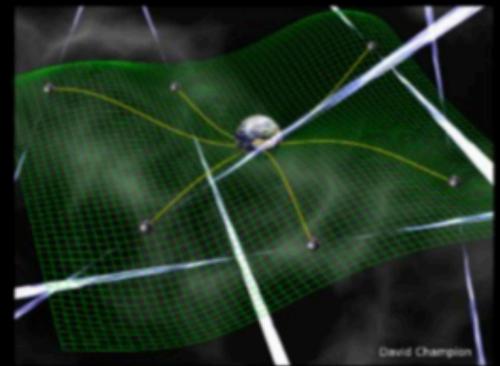
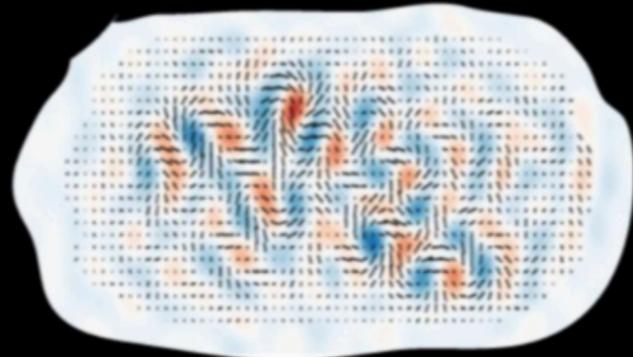


CMB Polarization

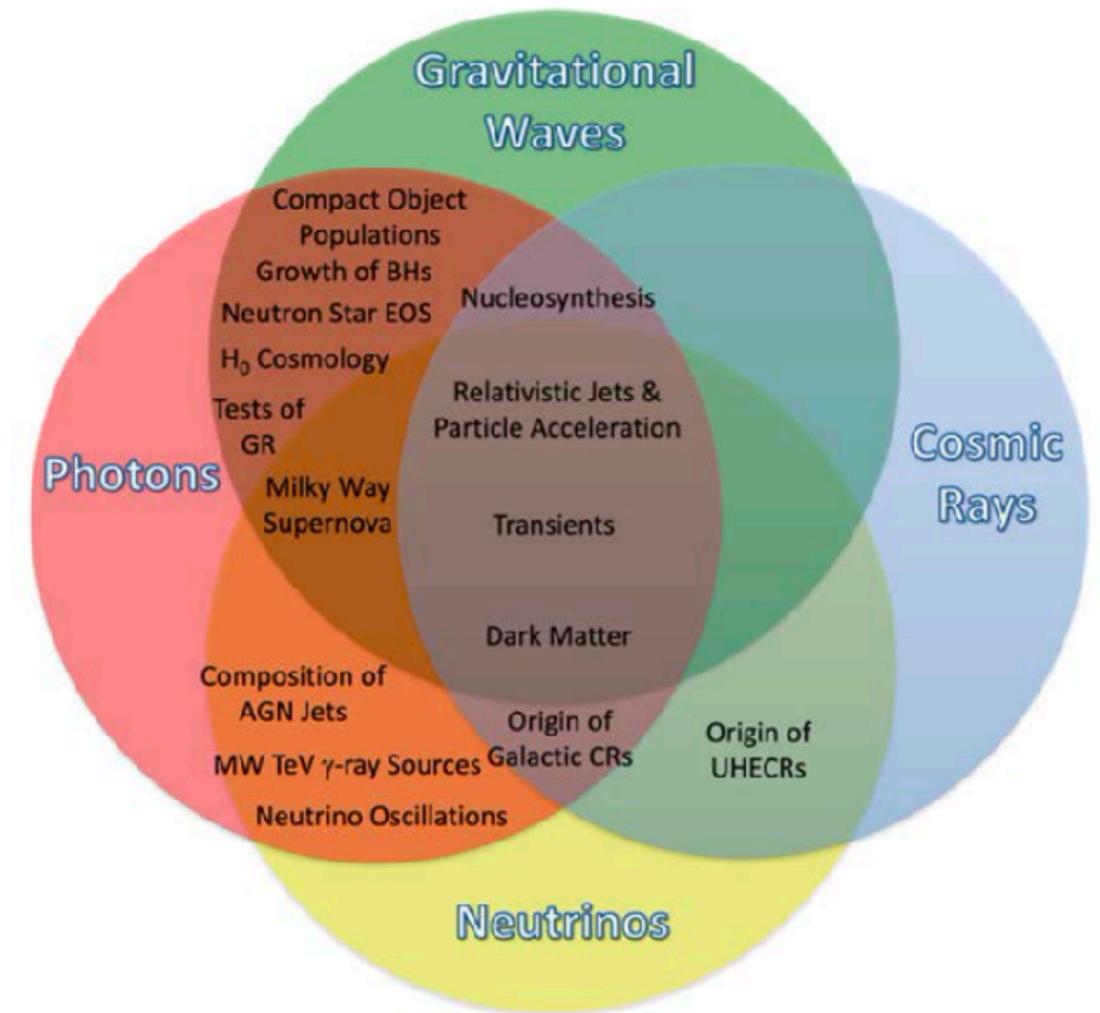
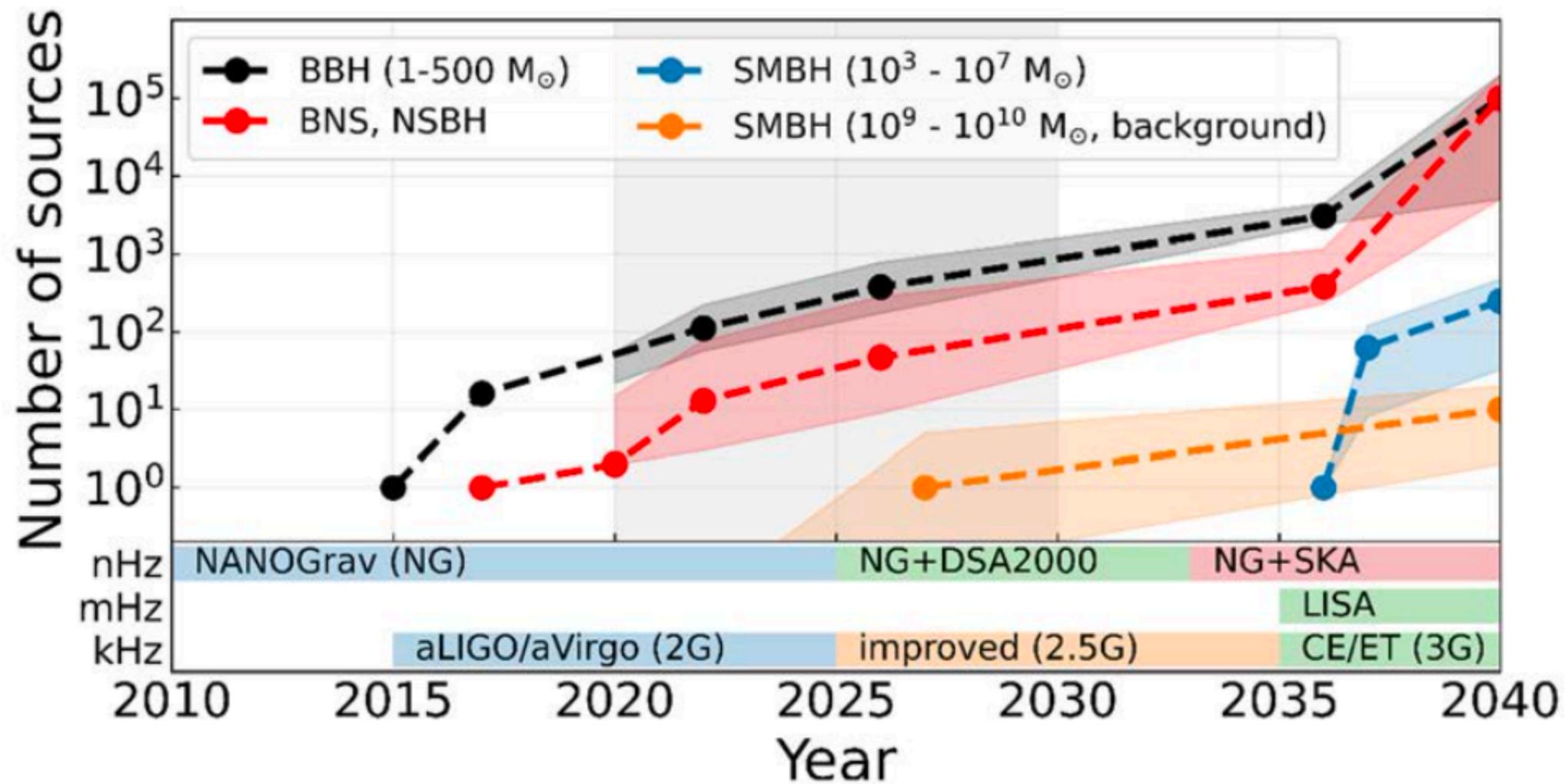
Radio Pulsar Timing Arrays

Space-based interferometers

Terrestrial interferometers



Pathways To Discovery



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