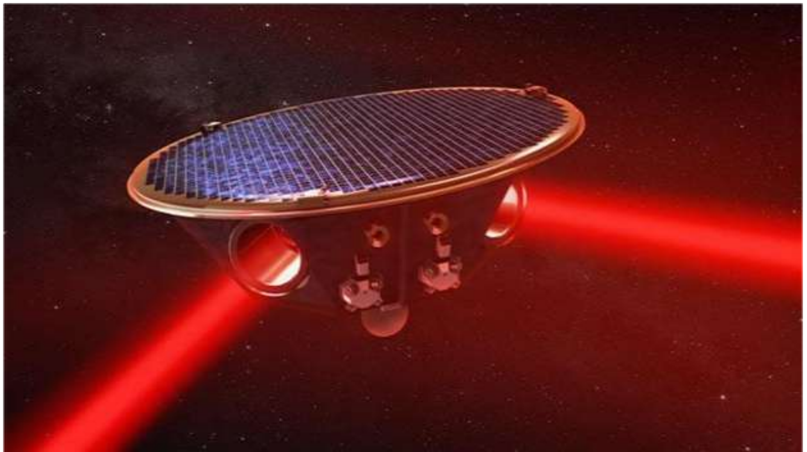
Lecture 13: Gravitational Wave Astronomy (and other topics)

Vera Rubin Observatory construction video



Rutgers Physics 346: Observational Astrophysics
April 20, 2021

Homework for Thursday, April 22

Due: Quiz #12 will appear on Canvas Assignments at 4:20pm, due at noon tomorrow (April 21).

Do: Be ready to work with your 2nd project group during Thursday's Project Meeting.

Due: Presentations will take place during class on April 27 & 29.

Due: Project reports will be due on Thursday, May 6.

Quiz #11: For natural guide star observations, why does an adaptive optics image show higher Strehl ratios for objects closer in the sky to the guide star?

Answer: Light from objects closer to the guide star passes through turbulence more similar to what the light from the guide star passes through, and therefore wavefront correction based on measurements of the guide star works better for them than for objects farther away on the sky. Strehl ratio is higher when less of the original light is scattered outwards from the object's true location by turbulence.

Where should we build telescopes?

Astronomers seek to build telescopes where the best conditions will prevail for observations over the largest fractions of each year.

At radio (centimeter) wavelengths: build your telescope as far away from sources of RFI as you can!

Examples: Green Bank Telescope in the National Radio Quiet Zone in West Virginia; MeerKAT in a legally protected radio quiet zone in South Africa.

Caveat: it is not possible to get away from satellite RFI anywhere on the surface of the Earth. (New satellite "constellations" like Starlink will make this worse.)

Where should we build telescopes?

Astronomers seek to build telescopes where the best conditions will prevail for observations over the largest fractions of each year.

At millimeter wavelengths: build your telescope above as much of the atmosphere's water vapor as you can!

Examples: Atacama Large Millimeter/submillimeter Array (ALMA) in the Chilean Andes; Northern Extended Millimeter Array (NOEMA) in the French Alps.

Caveat: at the highest altitudes, it is often difficult to find a large enough flat area for an array of millimeter wavelength telescopes.

Where should we build telescopes?

Astronomers seek to build telescopes where the best conditions will prevail for observations over the largest fractions of each year.

At optical/near-IR wavelengths: build your telescope at a high, dry, isolated site with smooth airflow over the top! (High and dry means fewer clouds; isolated means less light pollution, at least until new satellite “constellatons” are launched; smooth airflow due to a ridge or isolated peak will reduce turbulence and improve seeing.)

Examples: Gemini telescopes, which are located in the Chilean Andes and on the extinct (?) Hawaiian volcano Maunakea.

Where should we build telescopes?

Astronomers seek to build telescopes where the best conditions will prevail for observations over the largest fractions of each year.

At gamma ray, X-ray, UV, and far-IR wavelengths: build your telescope in space! This is also a good strategy if you want to avoid atmospheric turbulence at other wavelengths (e.g., as the *Hubble Space Telescope* does).

Caveat: space missions are a lot more expensive than ground-based telescopes, and if they require cryogens to cool detectors, they will have short lifetimes.

Where should we build telescopes?

Astronomers seek to build telescopes where the best conditions will prevail for observations over the largest fractions of each year.

Question for discussion: what if the site with the best conditions for observations at a given wavelength also has deep cultural significance for a particular group?

- does it matter if the cultural group owns the site?
- does it matter if astronomers provide a lot of money to support educational initiatives for the cultural group?
- does it matter if the cultural group has a history of being exploited by a colonial power?

This is a salient question for Maunakea at present with protests over the construction of the Thirty Meter Telescope (TMT).

Gravitational waves: prediction

Gravitational waves (GWs) = ripples in (i.e., changes in the curvature of) spacetime predicted to exist by Albert Einstein in 1916:

+ generated by the rapid acceleration of massive objects (e.g., neutron stars or black holes orbiting each other)
+ travel at the speed of light
+ cause distances between objects to increase and decrease as they pass

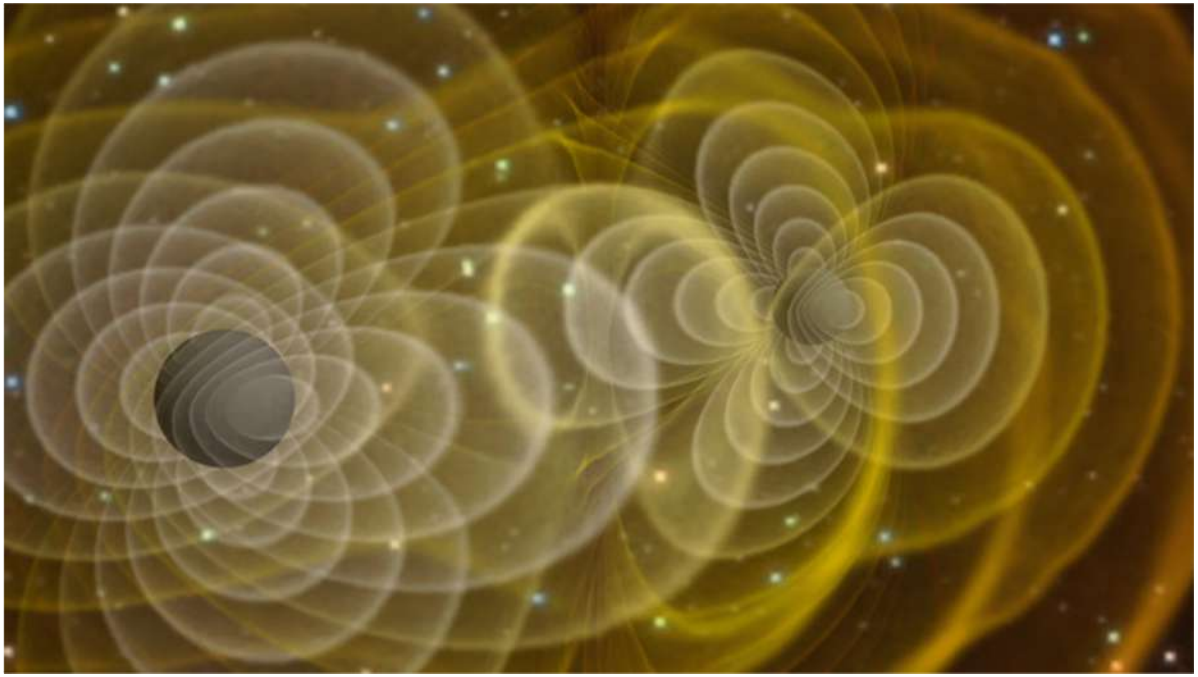
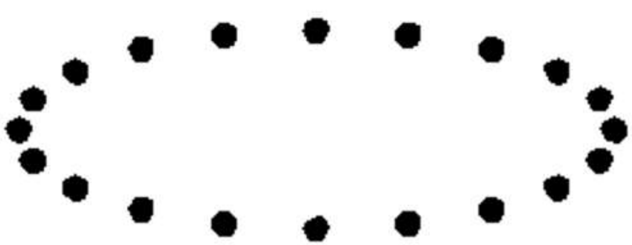


Image credit: Henze/NASA/LIGO

Gravitational waves: details

GWs are produced when a system has a time-varying quadrupole moment of its mass distribution (vs. time-varying dipole moment of its charge distribution for electromagnetic waves)

+ GWs are transverse waves
+ GW polarizations are “+” (plus) and “x” (cross); names inspired by effects on a ring of test particles



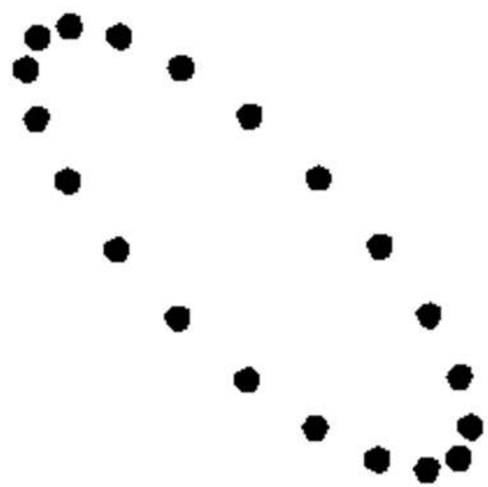
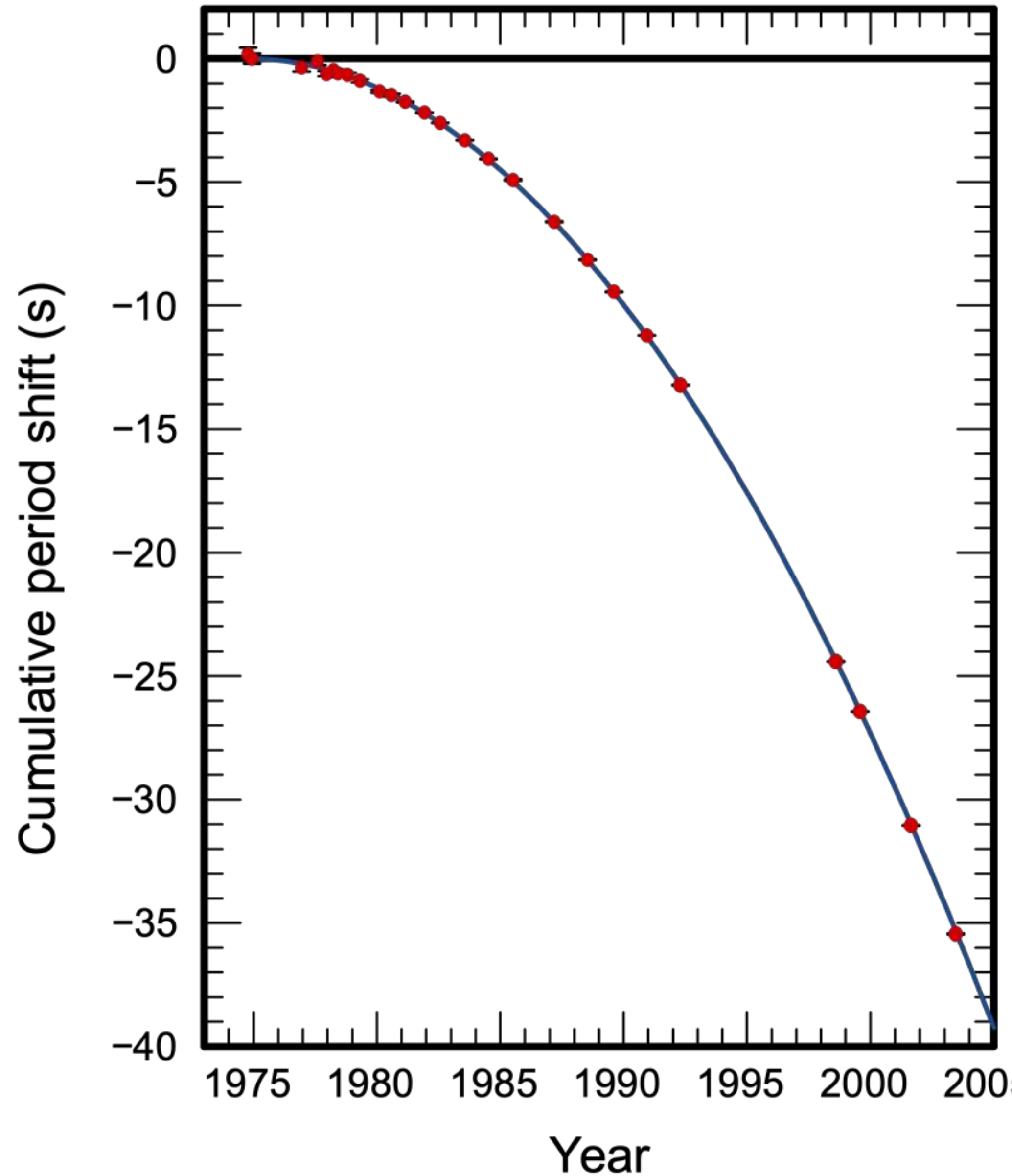


Image credit: brilliant.org

Gravitational waves: indirect detection

First proof of existence of GWs = spindown of binary neutron star PSR1913+16, discovered in 1974 by New Jersey radio astronomers Russell Hulse and Joe Taylor (1993 winners of Nobel Prize in Physics)

Clear indication that energy is being lost from system at rate expected from predictions of general relativity.



Weisberg & Taylor (2005)

Gravitational waves: direct detection

Goal = measure very slight changes in distances caused by passage of gravitational waves

- **+ pulsar timing teams compare the distances between consecutively arriving pulsar pulses**
- **+ LIGO and similar instruments compare the distances between two arms of an interferometer**

How do we know we've detected a real signal?

- **+ use multiple independent detectors to confirm signal detection and obtain directional information, which is key for electromagnetic followup**

"First rule in government spending: why build one when you can have two at twice the price?" – Contact

LIGO

Laser Interferometer Gravitational-wave Observatory (LIGO)
= pair of detectors located in Hanford, WA (left) and Livingston, LA (right) – arms are 4km long
+ funded by US National Science Foundation

LIGO: what's in those tubes?

Michelson interferometer with some bells and whistles…

+ Fabry-Perot cavities allow reflection of light ~280 times (for effective arm length of 1120 km)
+ laser beam power boosted by recycling mirrors (not shown here)

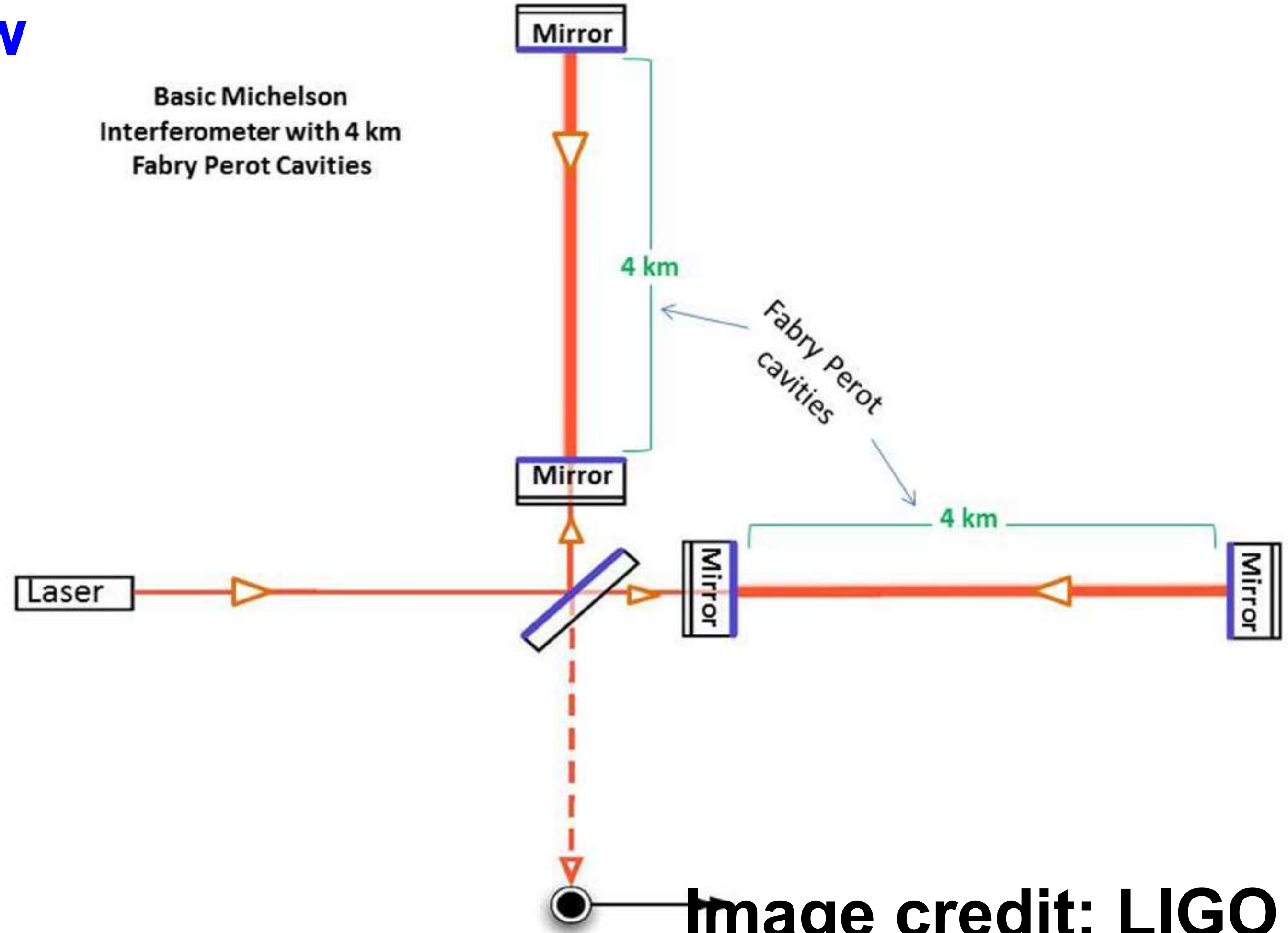
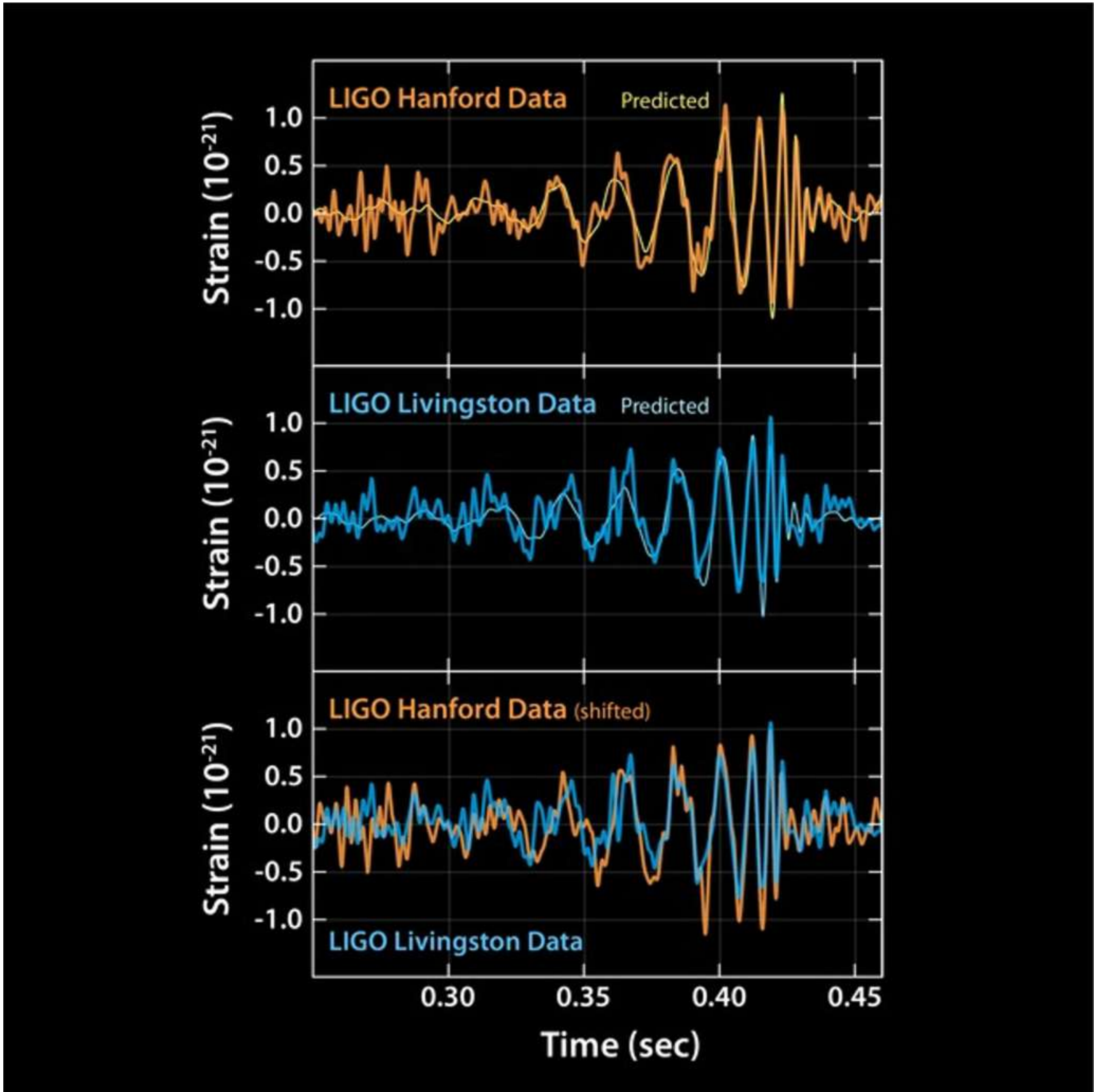


Image credit: LIGO

LIGO's first detection

LIGO event GW150914

+ localized to within a 150 deg^2 area
+ distance ~ 440 Mpc
+ produced by merger of two black holes with masses ~30 and ~35 times the mass of the Sun
+ no secure electromagnetic counterpart



[Listen to the "chirp"]

Image credit: LIGO

A growing global network

LIGO will continue to improve in sensitivity, and work with a growing number of international partner facilities.

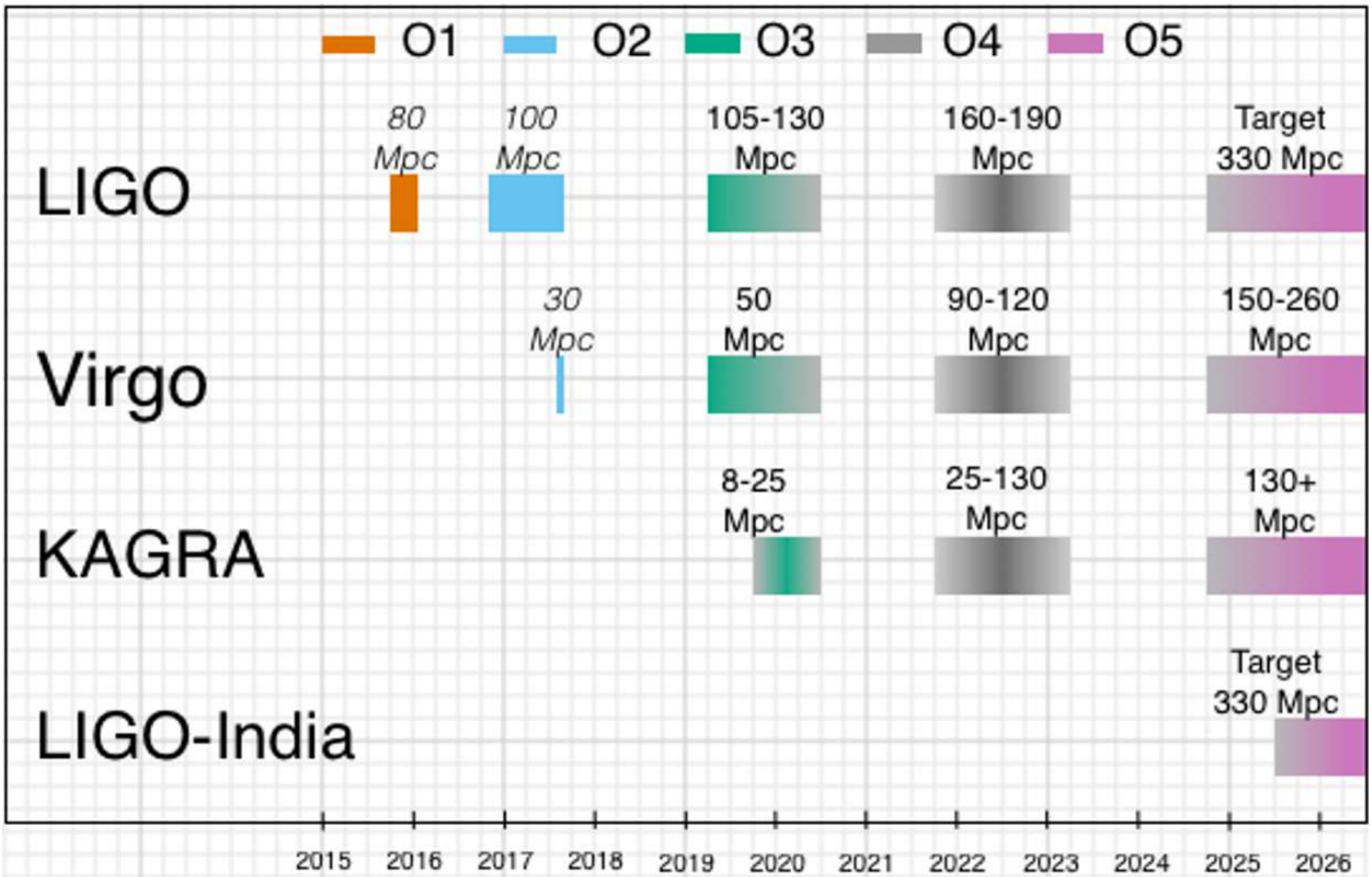


Image credit: LIGO

LIGO's sixth detection

Event GW170817:

+ detected by LIGO and (at low S/N) VIRGO, so quickly localized to 31 deg^2
+ clear electromagnetic counterpart: gamma ray burst GRB170817A detected 1.74s after GW event
+ optical counterpart seen in NGC4993 (D ~ 40 Mpc)
+ produced by merger of two neutron stars with total mass ~2.8 times the mass of the Sun

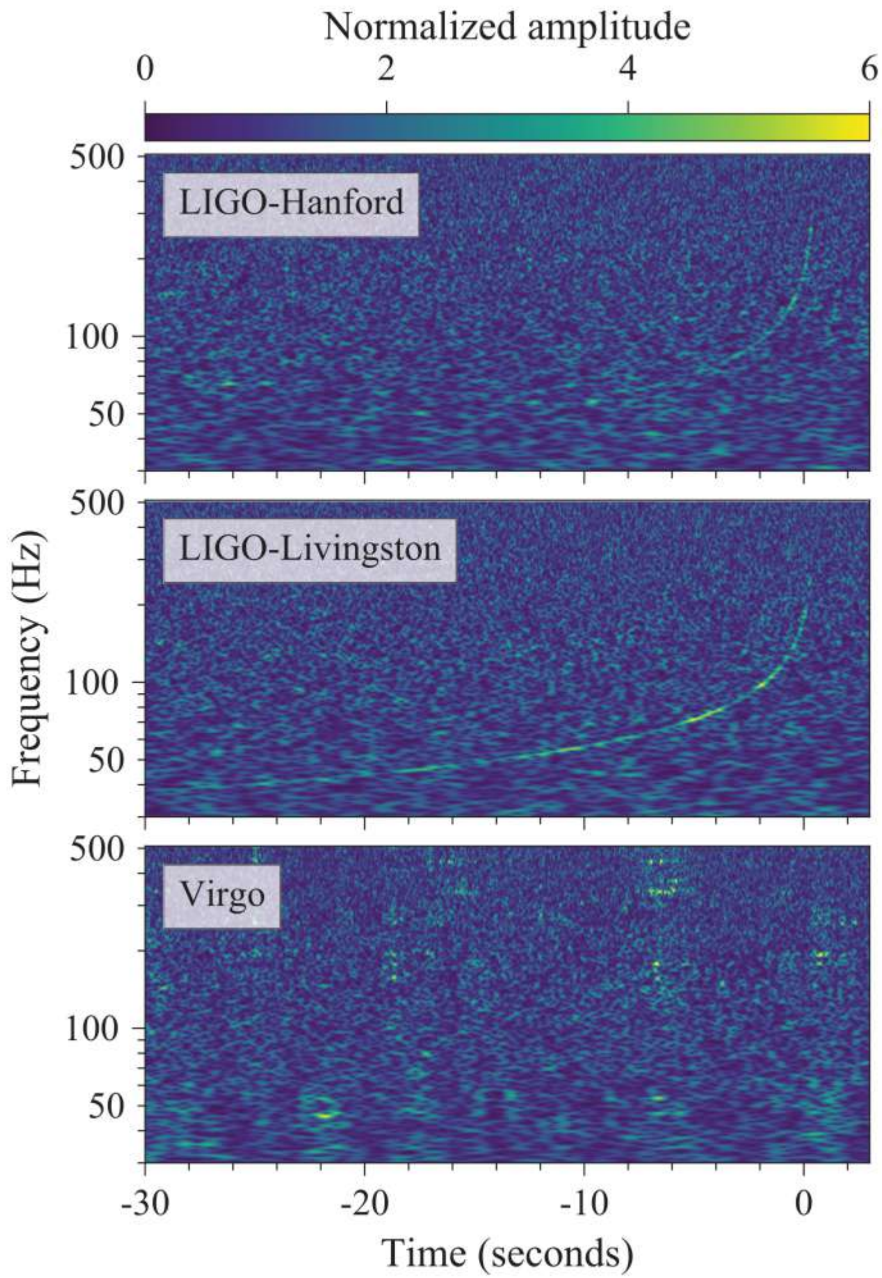
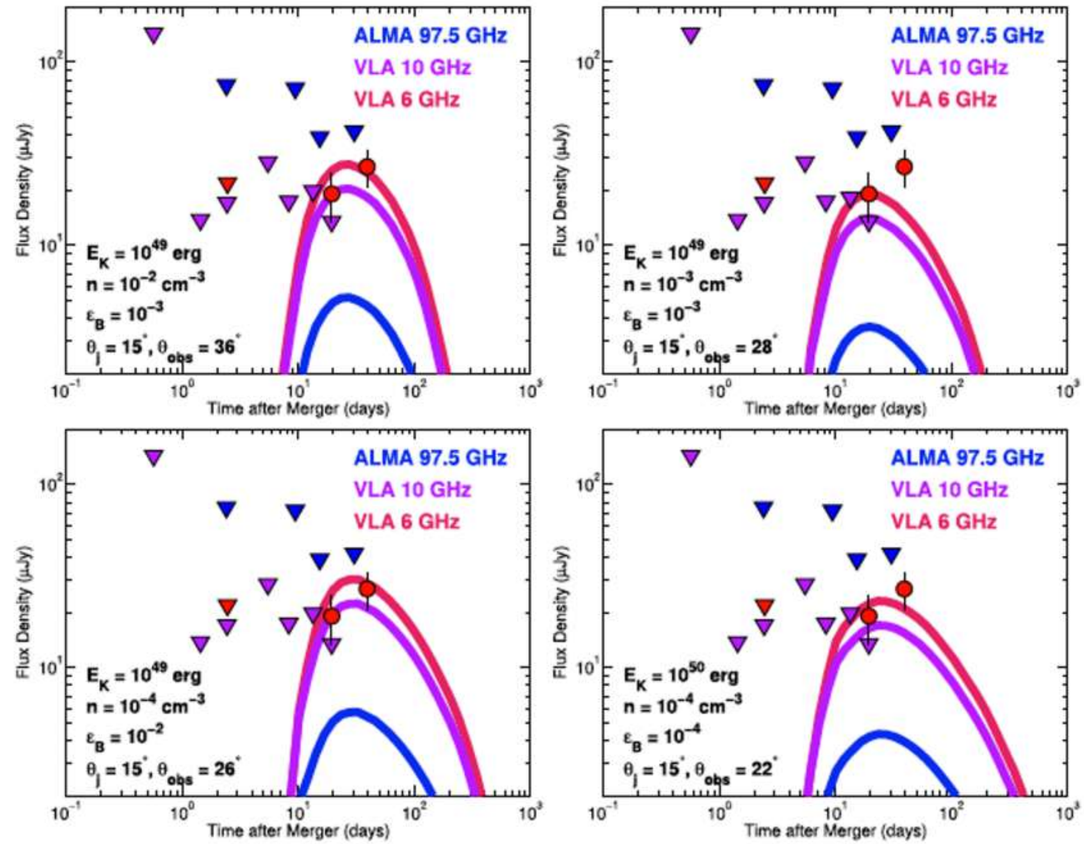


Image credit: LIGO/VIRGO

GW170817: electromagnetic followup

GW170817 apparently resulted in a kilonova event:
short gamma ray burst + long afterglow due to decay of radioactive elements
+ optical spectra + color evolution different from those of any known supernova
+ radio observations can test models for jet production, afterglow physics – but current data do not distinguish between quasi-spherical ejecta at high speed vs. collimated ejecta at extremely high speed



Alexander et al. (2017)

GW170817: a key followup paper

Time-domain astronomy is a fast-moving field!

The Electromagnetic Counterpart of the Binary Neutron Star Merger LIGO/Virgo GW170817. VI. Radio Constraints on a Relativistic Jet and Predictions for Late-time Emission from the Kilonova Ejecta

K. D. Alexander[1], E. Berger[1], W. Fong[2,14], P. K. G. Williams[1], C. Guidorzi[3], R. Margutti[2], B. D. Metzger[4], J. Annis[5], P. K. Blanchard[1], D. Brout[6], D. A. Brown[7], H.-Y. Chen[8], R. Chornock[9], P. S. Cowperthwaite[1], M. Drout[10,14], T. Eftekhari[1], J. Frieman[5,8], D. E. Holz[8,11], M. Nicholl[1], A. Rest[12,13], M. Sako[6], M. Soares-Santos[5], and V. A. Villar[1]

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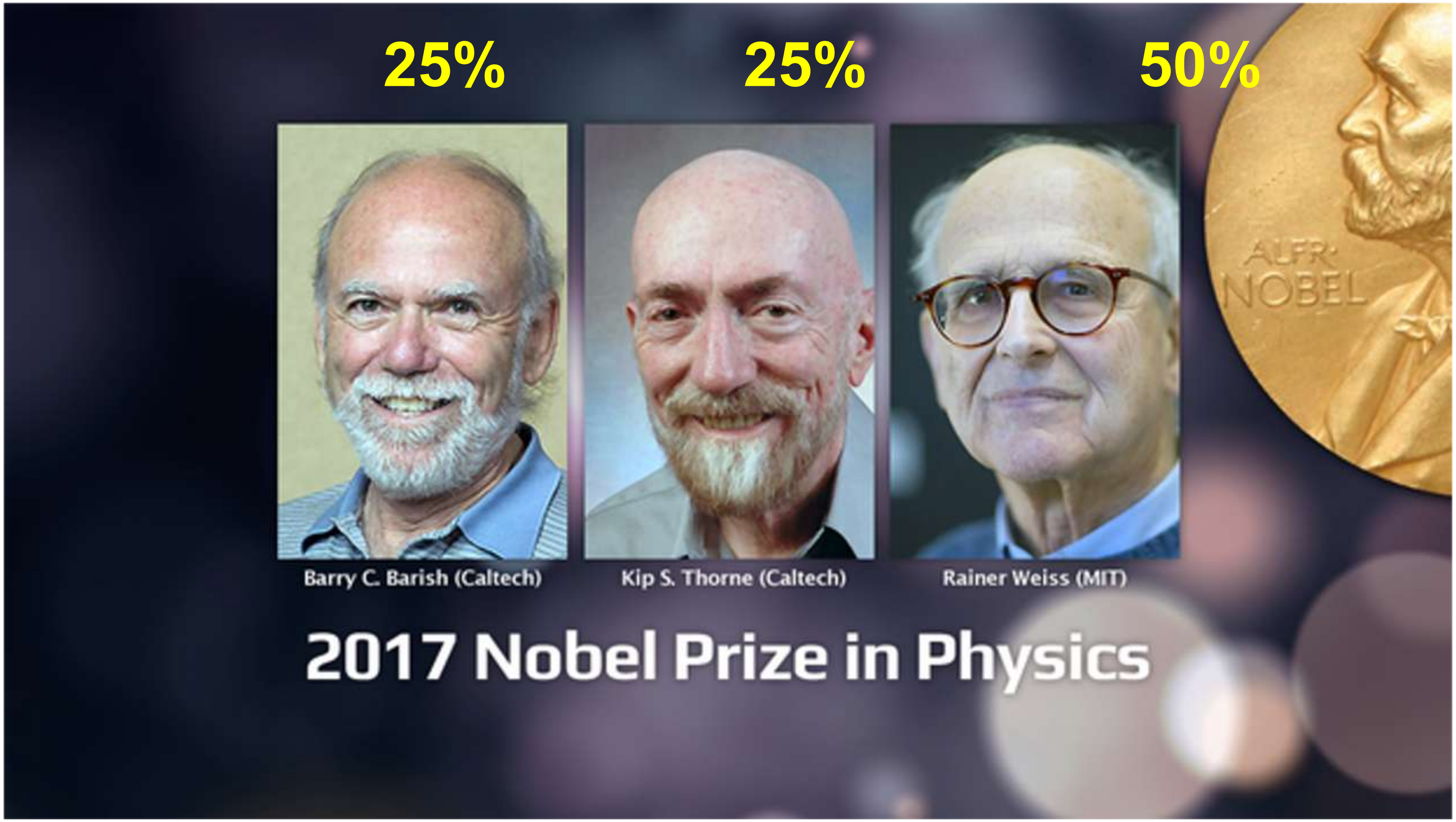
LIGO recognized by 2017 Nobel Prize



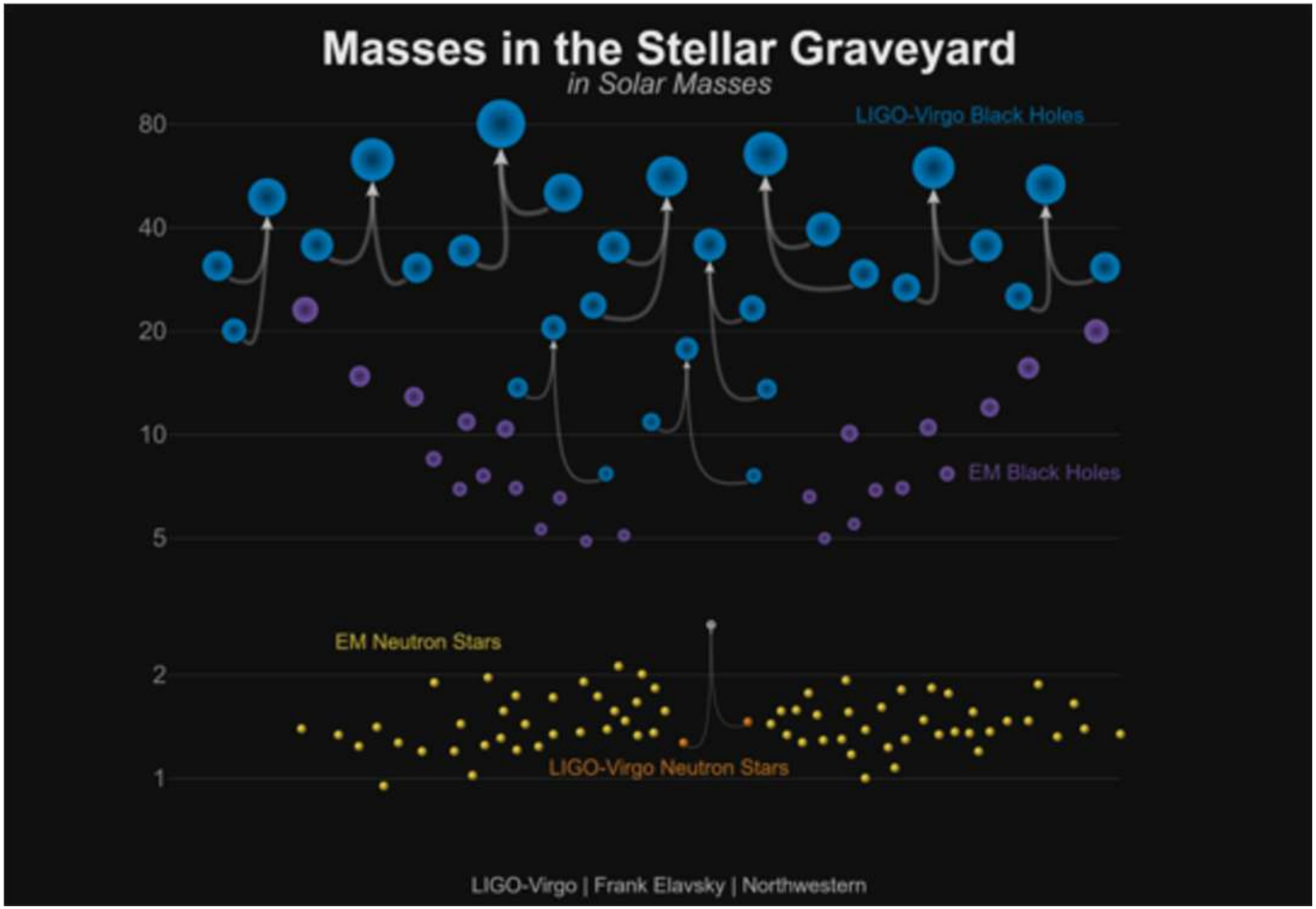
"...for decisive contributions to the LIGO detector and the observation of gravitational waves."

From Rainer Weiss's Nobel lecture...

"All three of us – Barry Barish, Kip Thorne and I – want to recognize the critical role played by the scientists, engineers, students, technicians, and administrators of the LIGO laboratory and LIGO Scientific Collaboration who are responsible for opening a new field of scientific research: Gravitational Wave Astronomy and Astrophysics. We are also deeply indebted to the United States National Science Foundation, which was willing to take a risk in supporting a new field that required significant technical development and with an uncertain knowledge of sources but certain that, should it succeed, it would have a profound influence on our understanding of physics and the universe."

LIGO detections

2015-17: LIGO had 11 secure detections (10 BH-BH, 1 NS-NS).

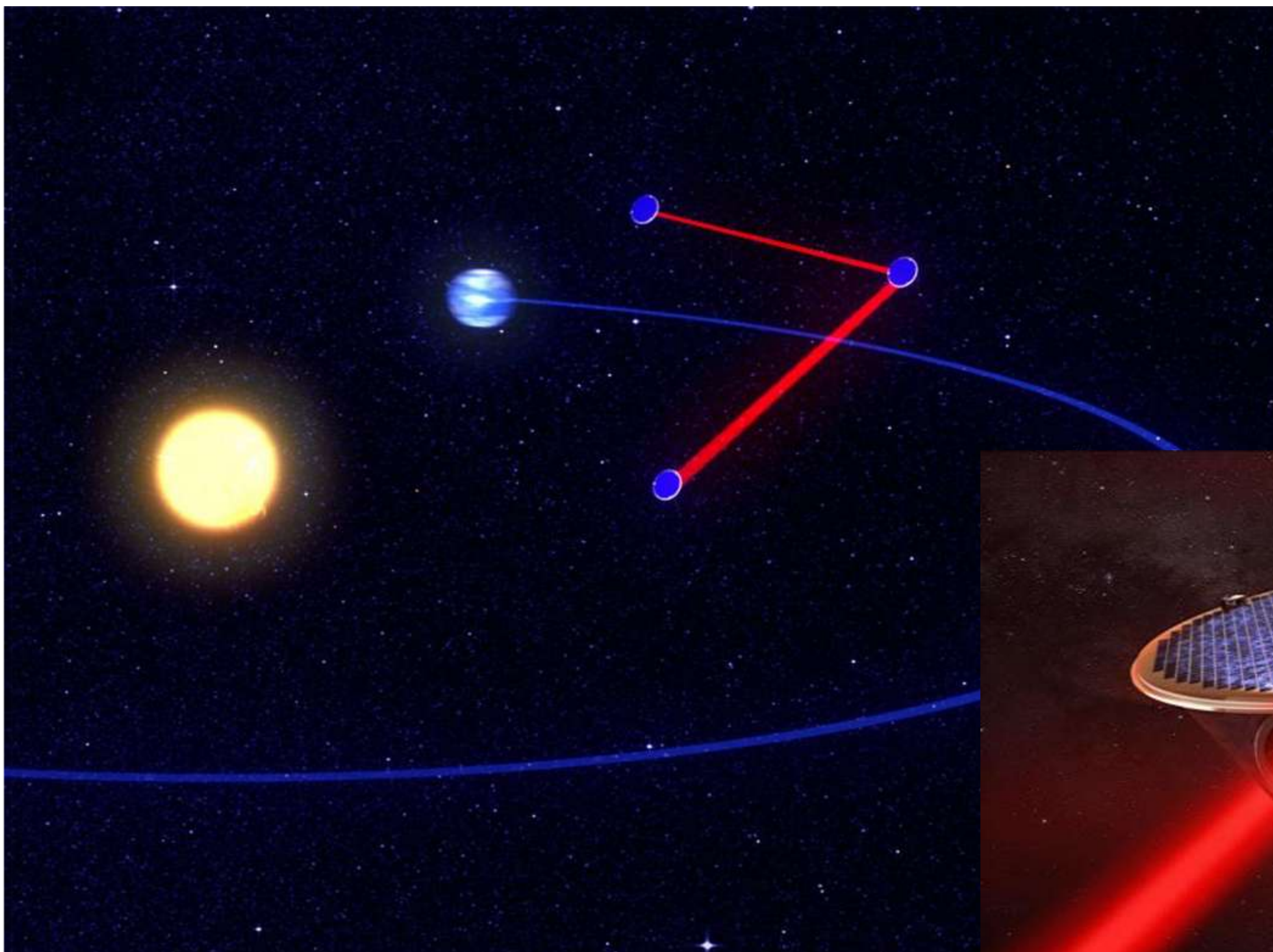


Third observing run "O3" yielded 56 event alerts between April 8, 2019 and March 16, 2020 (before March 27 shutdown due to COVID-19 and detector upgrades).

A planned ESA/NASA mission: LISA

Laser Interferometer Space Antenna (LISA):

three spacecraft separated by 2.5 million km will fly in formation, creating a Michelson interferometer



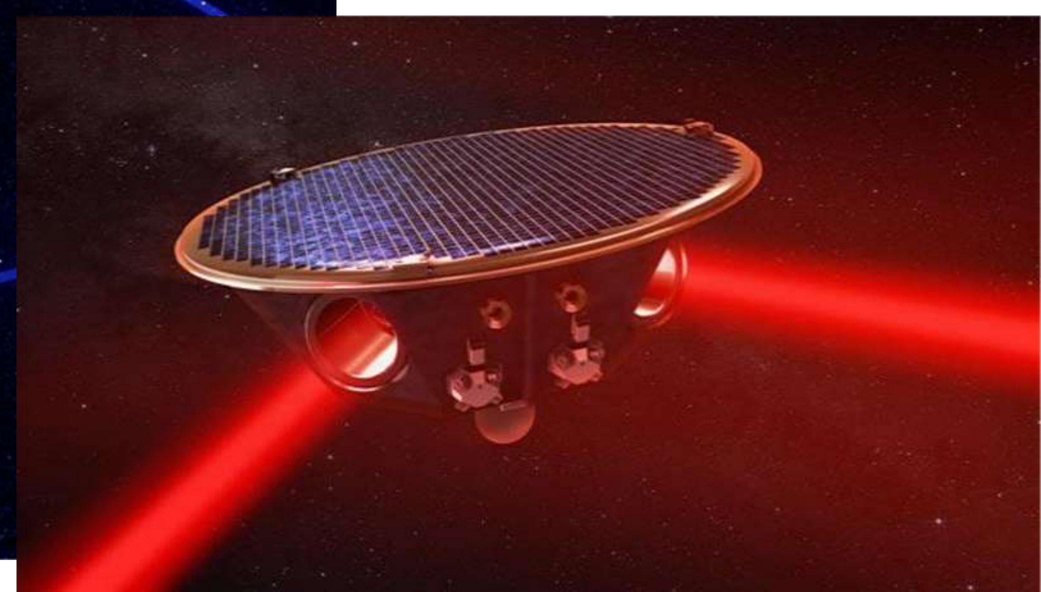


Image credit: ESA

Longer wavelengths, larger detectors