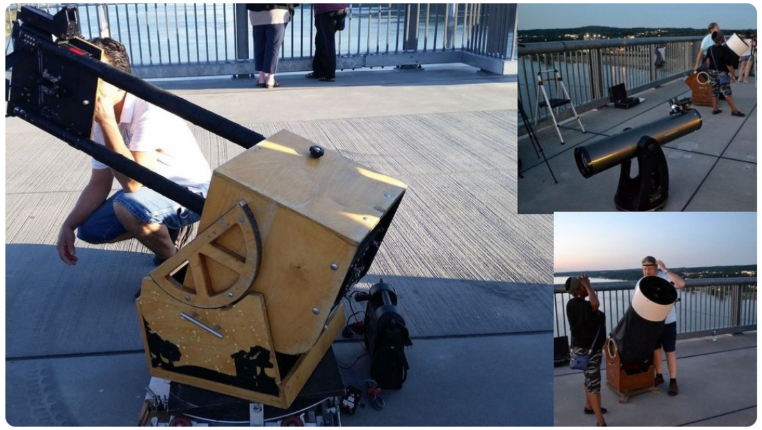
Multi-Messenger Astronomy

Eric Myers
Department of Physics & Astronomy, SUNY New Paltz
and
Mid-Hudson Astronomical Association

23 September 2021

Mid-Hudson Astronomical Association



Mid-Hudson Astronomical Association

New Paltz, NY
1,925 members · Public group
Organized by **MHAA O.** and **11 others**

Share:

About | Events | Members | Photos | Discussions | More | Join this group

What we're about

We are a group of people in the Mid-Hudson Valley who are interested in Astronomy and Science. We hold monthly star parties at Lake Taghkanic State Park, and monthly presentations at SUNY New Paltz -- both open to the public. We also participate in local education and outreach event; our members are available to make presentations or arrange for public observations of the night sky or the sun, and to help beginners learn how to get started in astronomy. When the weather allows, we often set up telescopes on the Walkway Over the Hudson when they hold their Walkway At Night events....

Organizers

MHAA O. and **11 others**
Message

Members (1,925)

See all

Meetings every month (3rd Tuesday)

- Via Zoom (due to CoViD)
- Presentation at 8:00 PM
- (Business meeting 7:30 PM)
- Soon to be back as SUNY New Paltz

Star Parties every month (Friday close to a new moon) at Lake Taghkanic State Park

- no telescope required
- bring a telescope if you want
- (must register with car info)

Various outreach and education activities at public libraries, schools, Walkway Over the Hudson, and other local venues.

Visit http://midhudsonastro.org for calendar of events (on Meetup.com)

The Three Messengers

Mercury
Messenger of the Romans

Light
(Electromagnetic Waves)

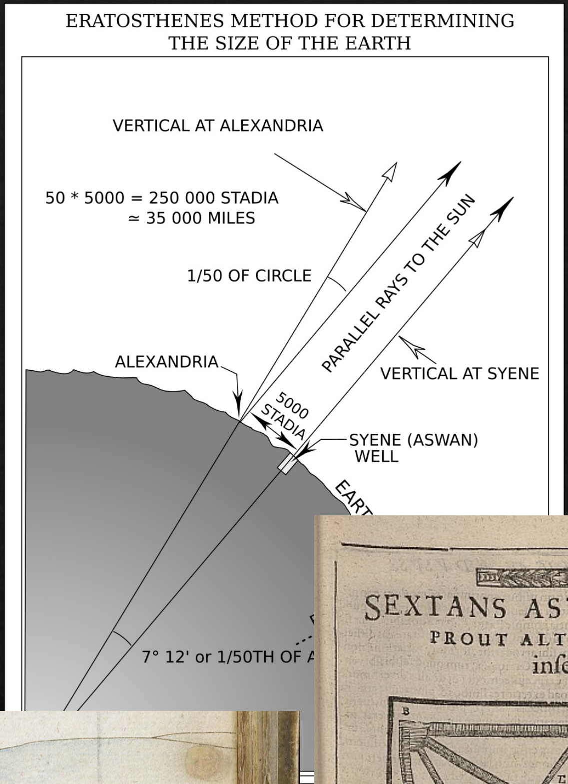
Hermes
Messenger of the Greeks

Gravitational Waves

Hermod (Hermóðr)
Messenger of the Norse

Cosmic Rays
(principally Neutrinos)

Naked-Eye Astronomy

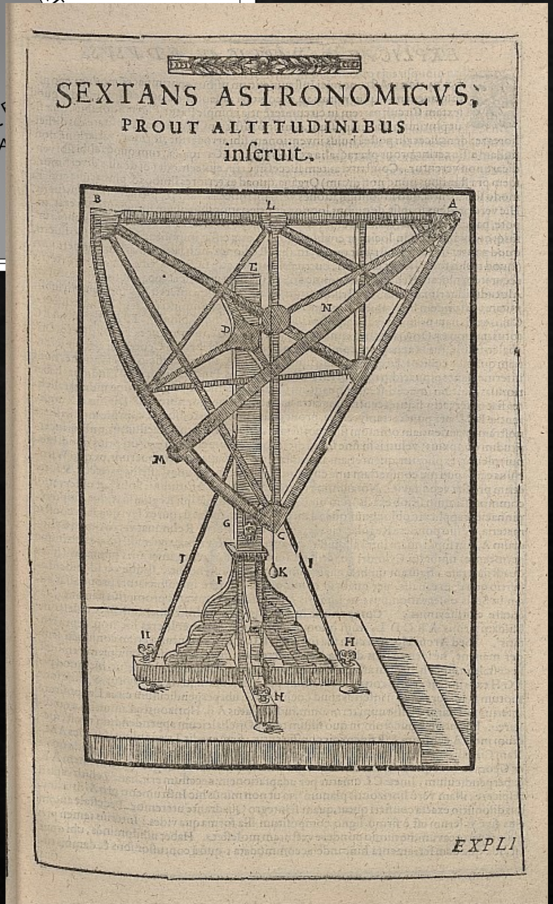


Eratosthenes
240 BC

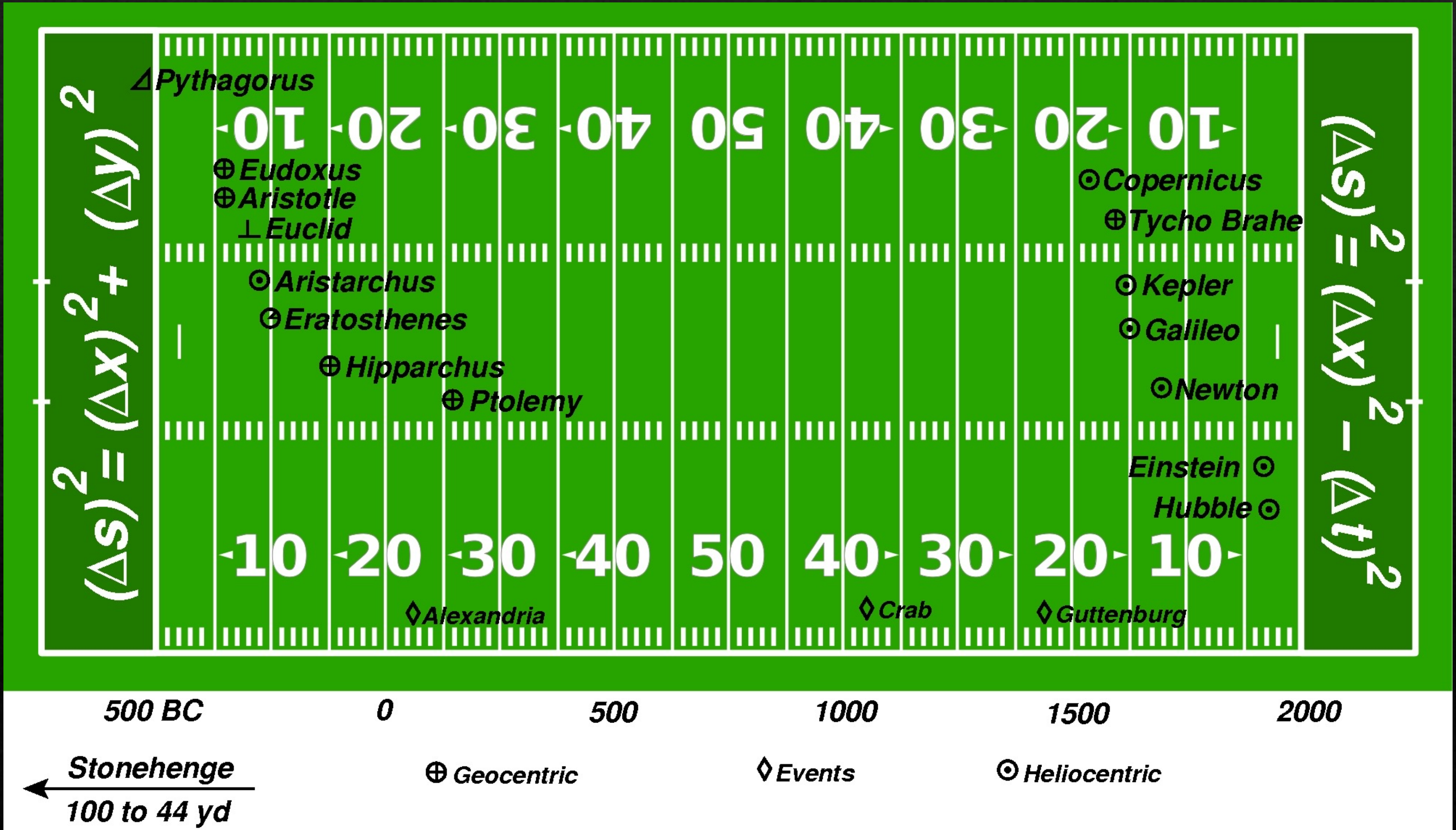
Tycho Brahe
~1600 AD

Galileo Galilei
1609 AD

Stonehenge
3000 to 2000 BC



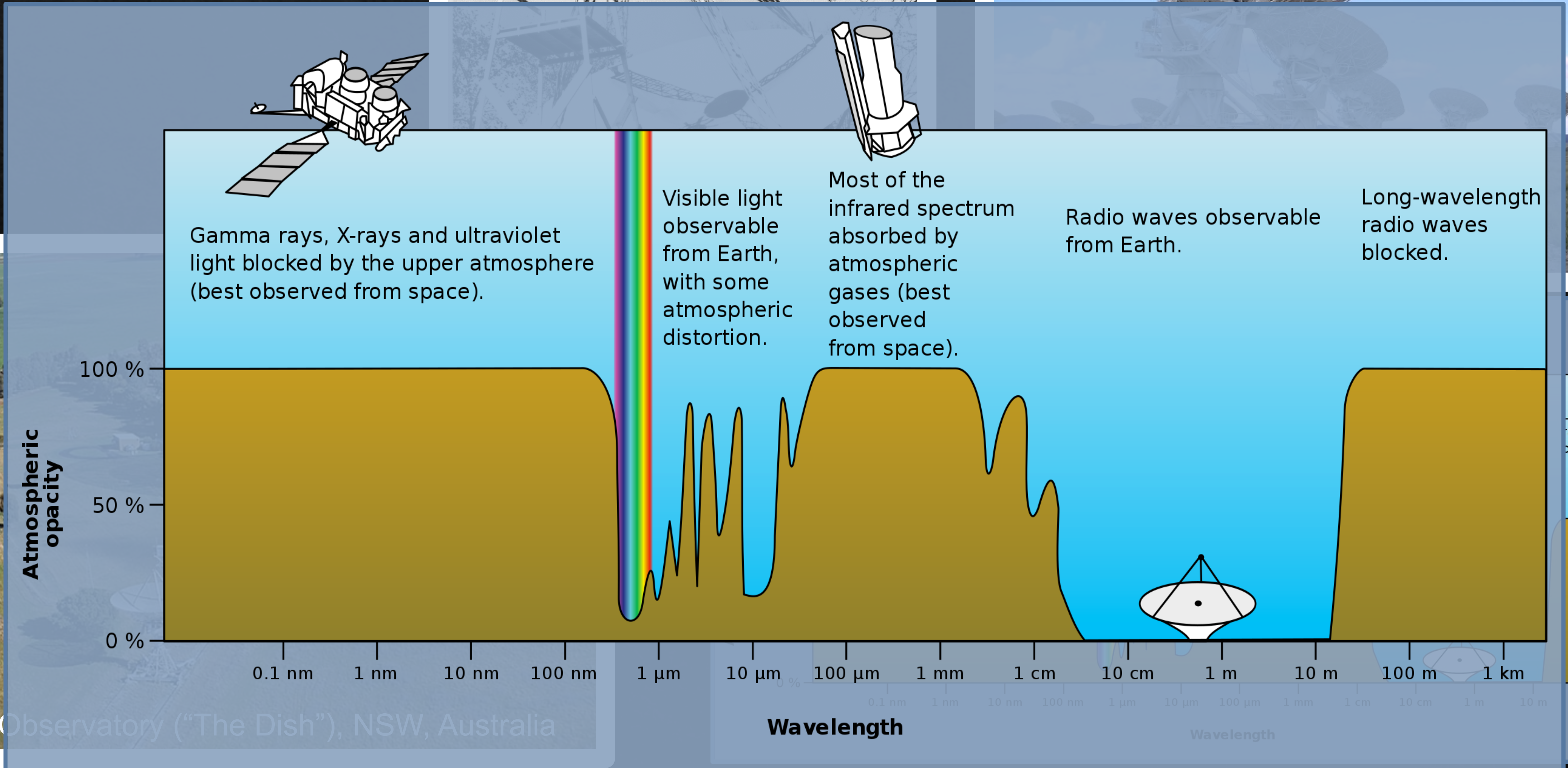
History of (Western) Astronomy as a Football Field

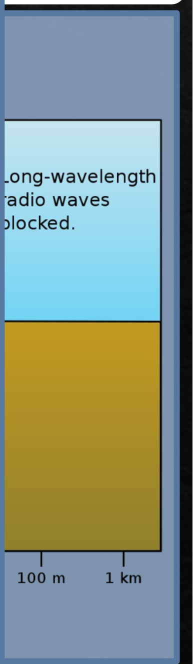


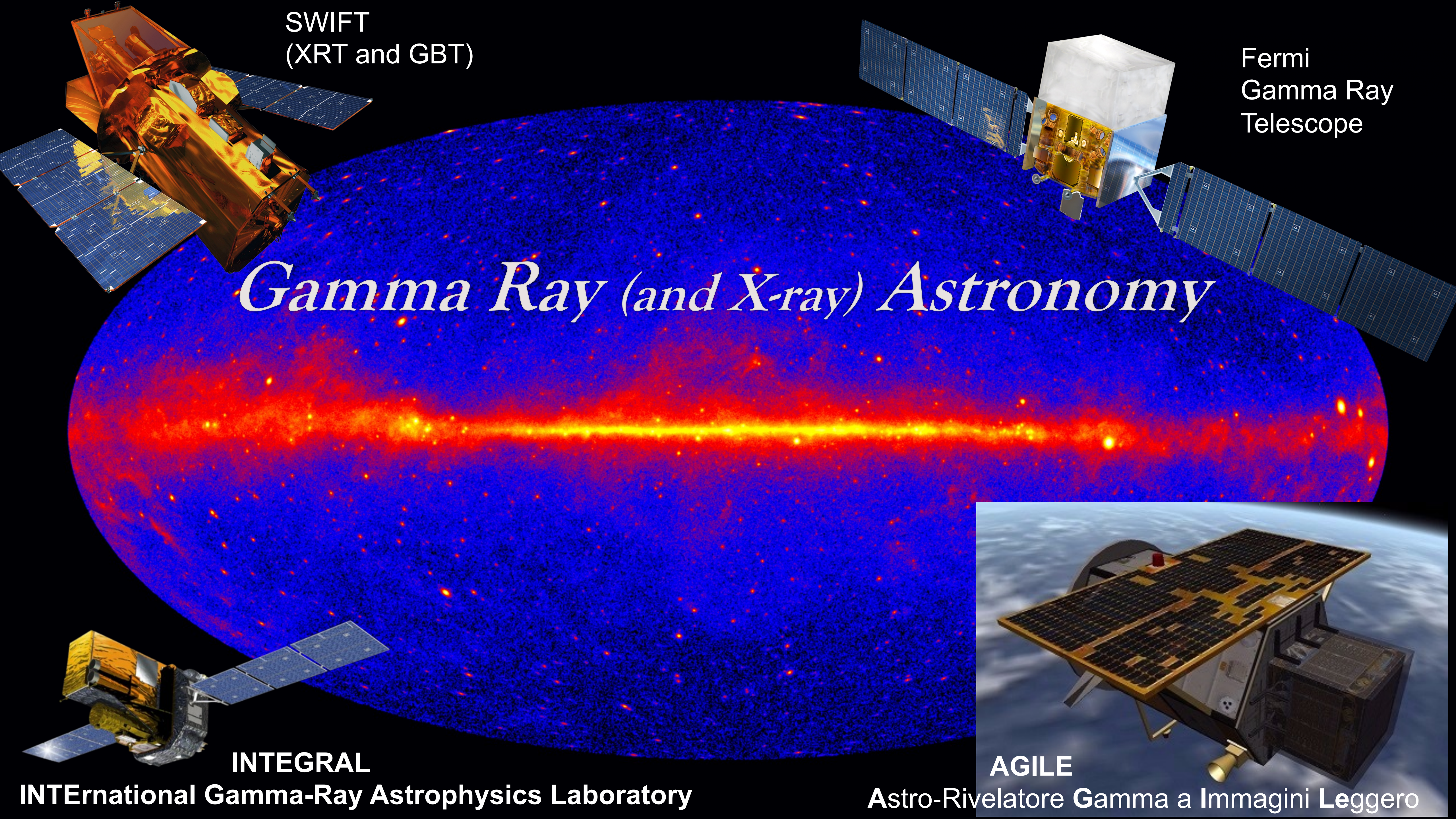
Modern Observatories

The world's largest optical reflecting telescopes having aperture diameters over 8 meters.
(Wikipedia)

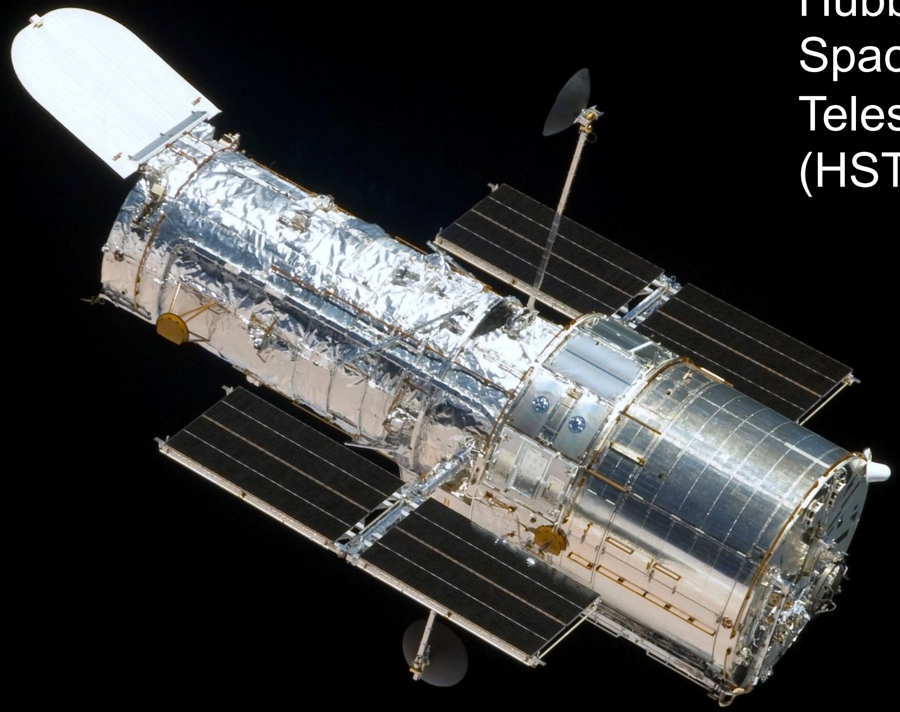
Radio Astronomy






SWIFT
(XRT and GBT)
Fermi
Gamma Ray
Telescope
Gamma Ray (and X-ray) Astronomy
INTEGRAL
INTErnational Gamma-Ray Astrophysics Laboratory
AGILE
Astro-Rivelatore Gamma a Immagini Leggero

Optical Satellites



Hubble Space Telescope (HST)

James Web Telescope (2021-2026)

JWT launch scheduled for 18 DEC 2021!

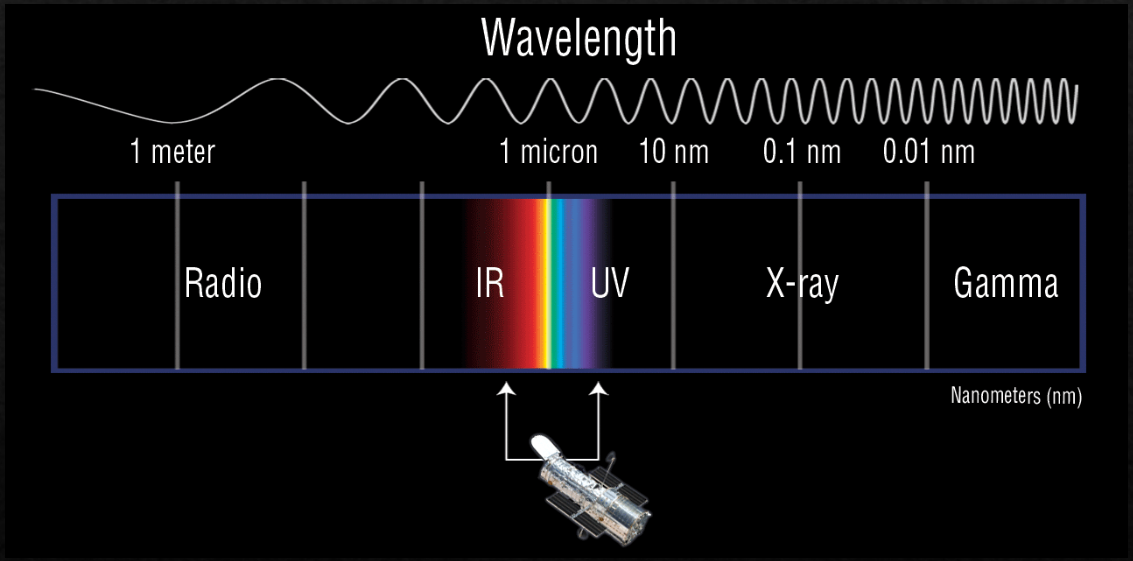
Transiting Exoplanet Survey Satellite (TESS)

(Not a real satellite - parked at L2)

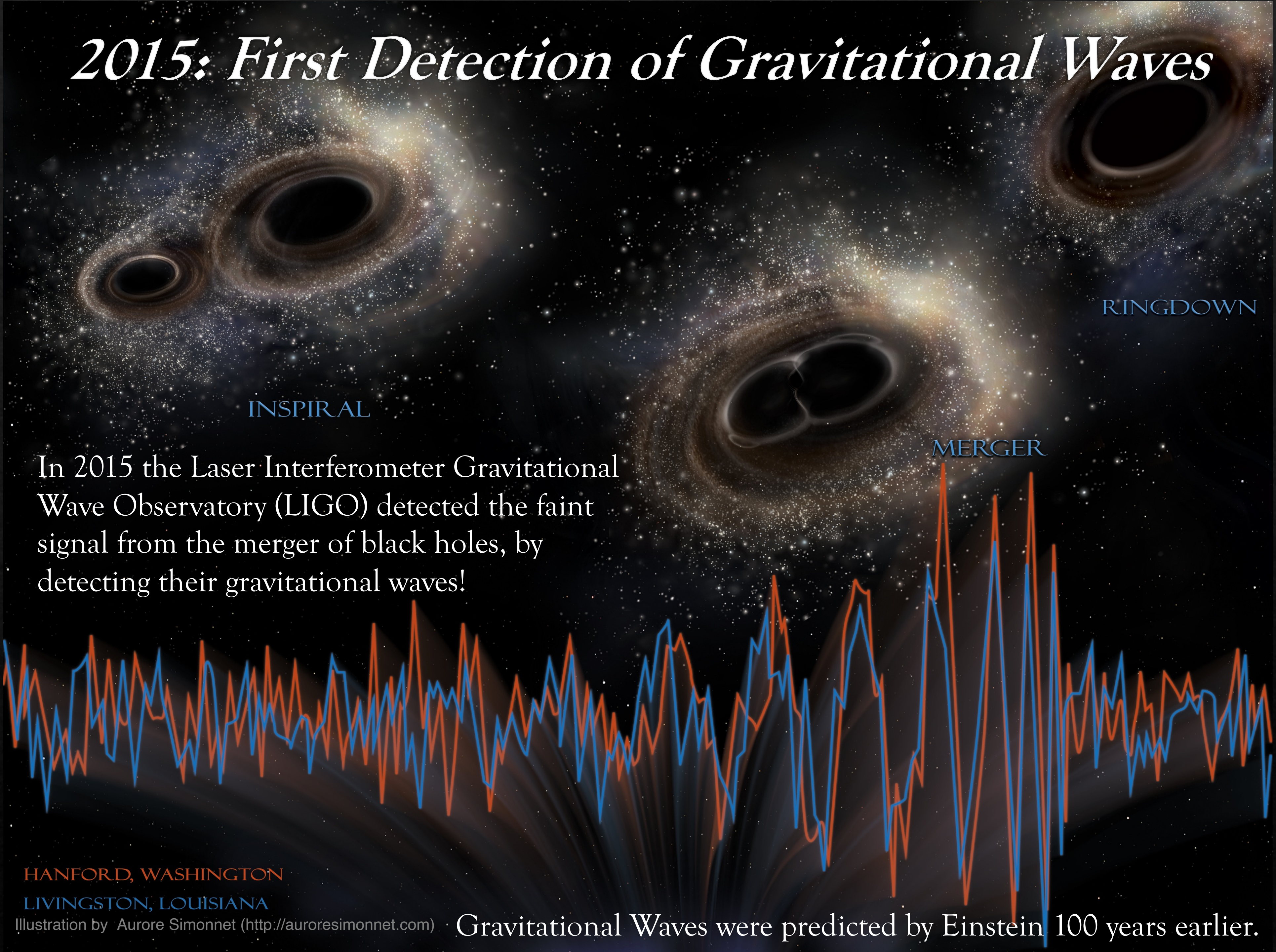
GAIA Space Observatory

The First Messenger:

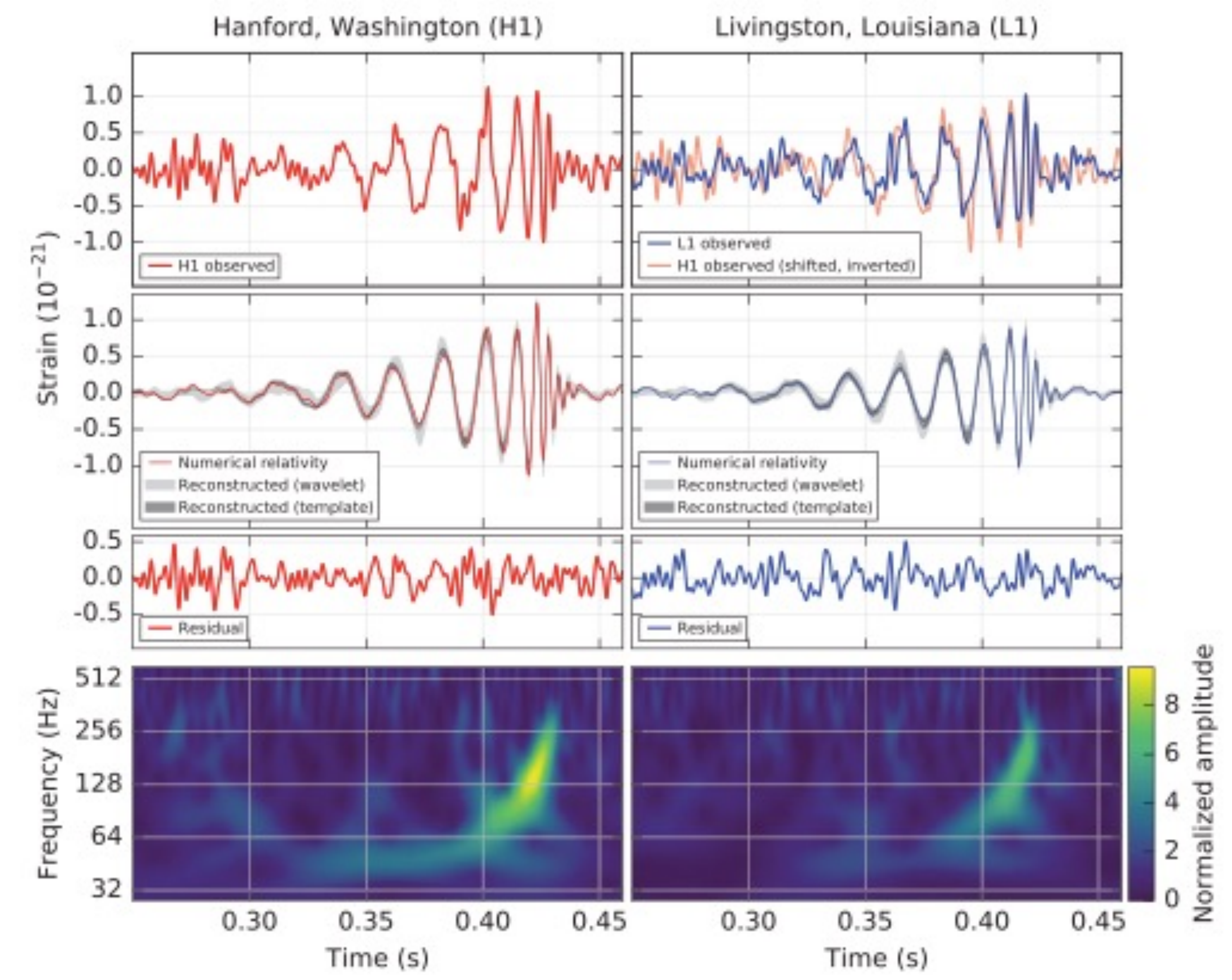
Electromagnetic Waves



Until very recently, everything we have learned about the Universe has come to us via photons, which are electromagnetic waves.


2015: First Detection of Gravitational Waves
INSPIRAL
MERGER
RINGDOWN
In 2015 the Laser Interferometer Gravitational Wave Observatory (LIGO) detected the faint signal from the merger of black holes, by detecting their gravitational waves!
HANFORD, WASHINGTON
LIVINGSTON, LOUISIANA
Illustration by Aurore Simonnet (http://auroresimonnet.com)
Gravitational Waves were predicted by Einstein 100 years earlier.

Event GW150914

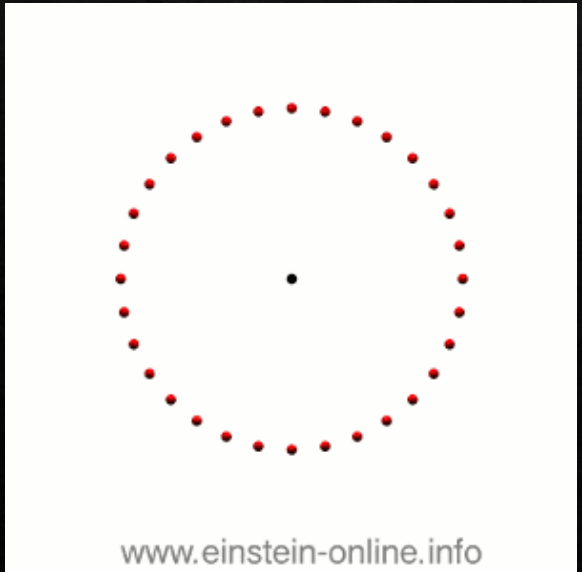


Abbott, et. al., Physical Review Letters 116, 061102 (2016) - Figure 1

What are Gravitational Waves?

Gravitational Waves (GW's) are *quadrupole* distortions of space-time which travel at the speed of light.

GW's are transverse – the distortion is perpendicular to the direction of travel.



Unlike even light, GW's are unimpeded by anything in their way.

Predicted by Einstein in 1916

Detected by LIGO in 2015

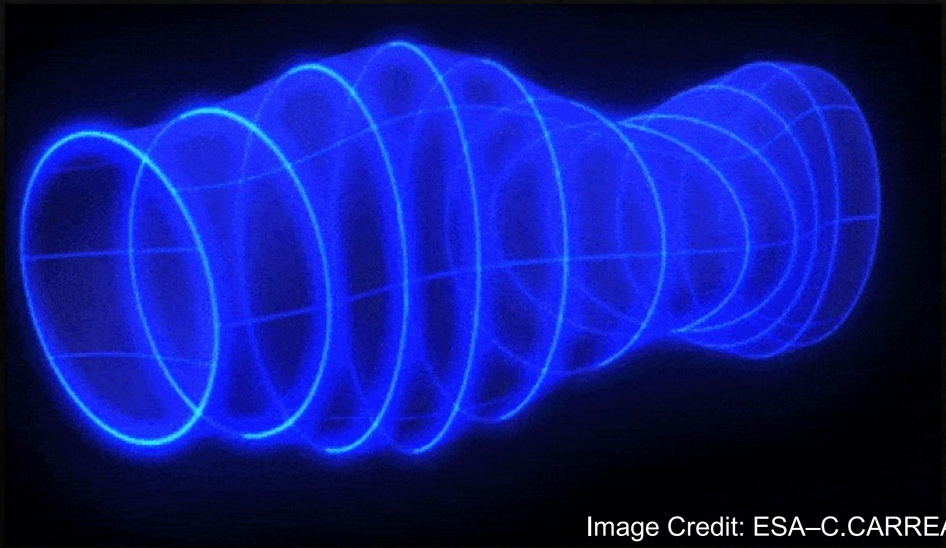
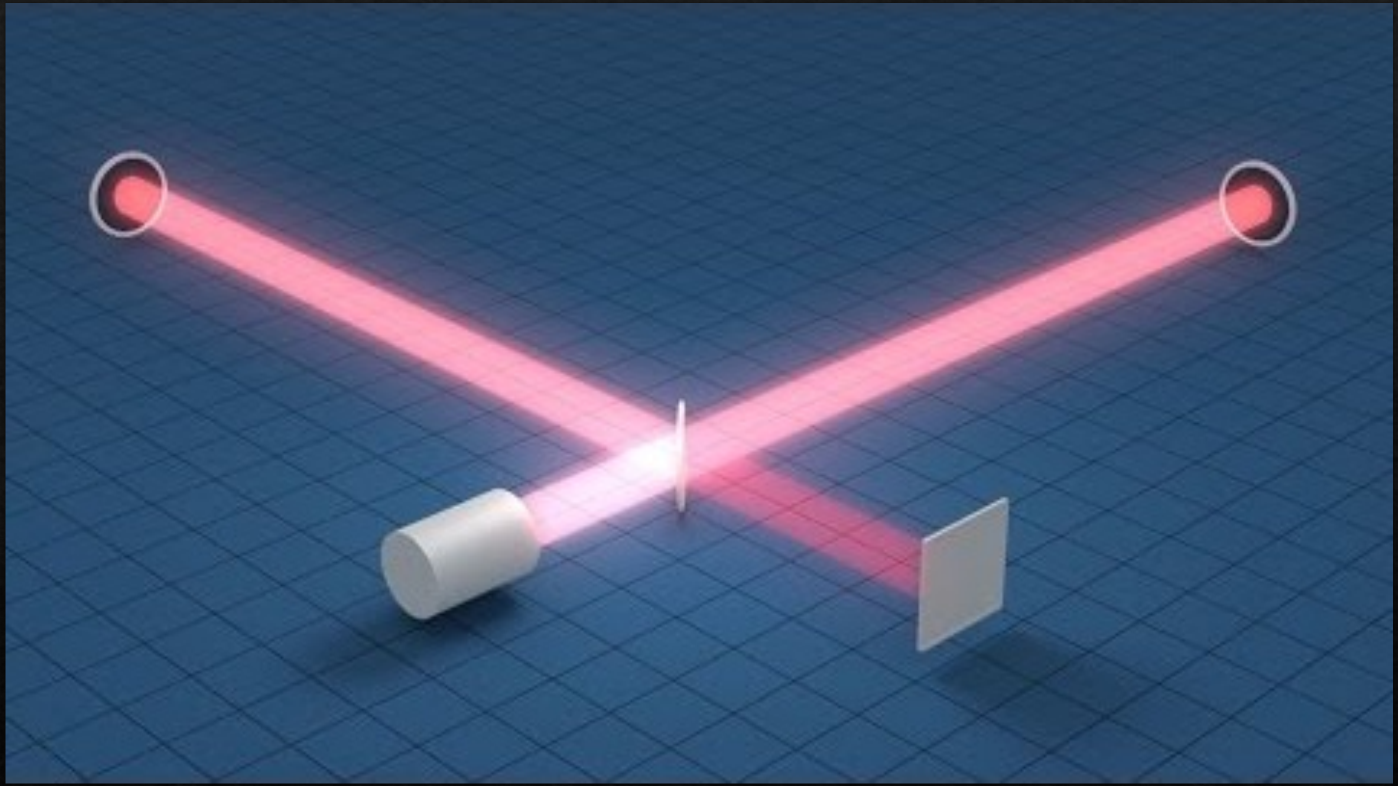


Image Credit: ESA–C.CARREAU

How does LIGO work?



Michelson Interferometer

Sources

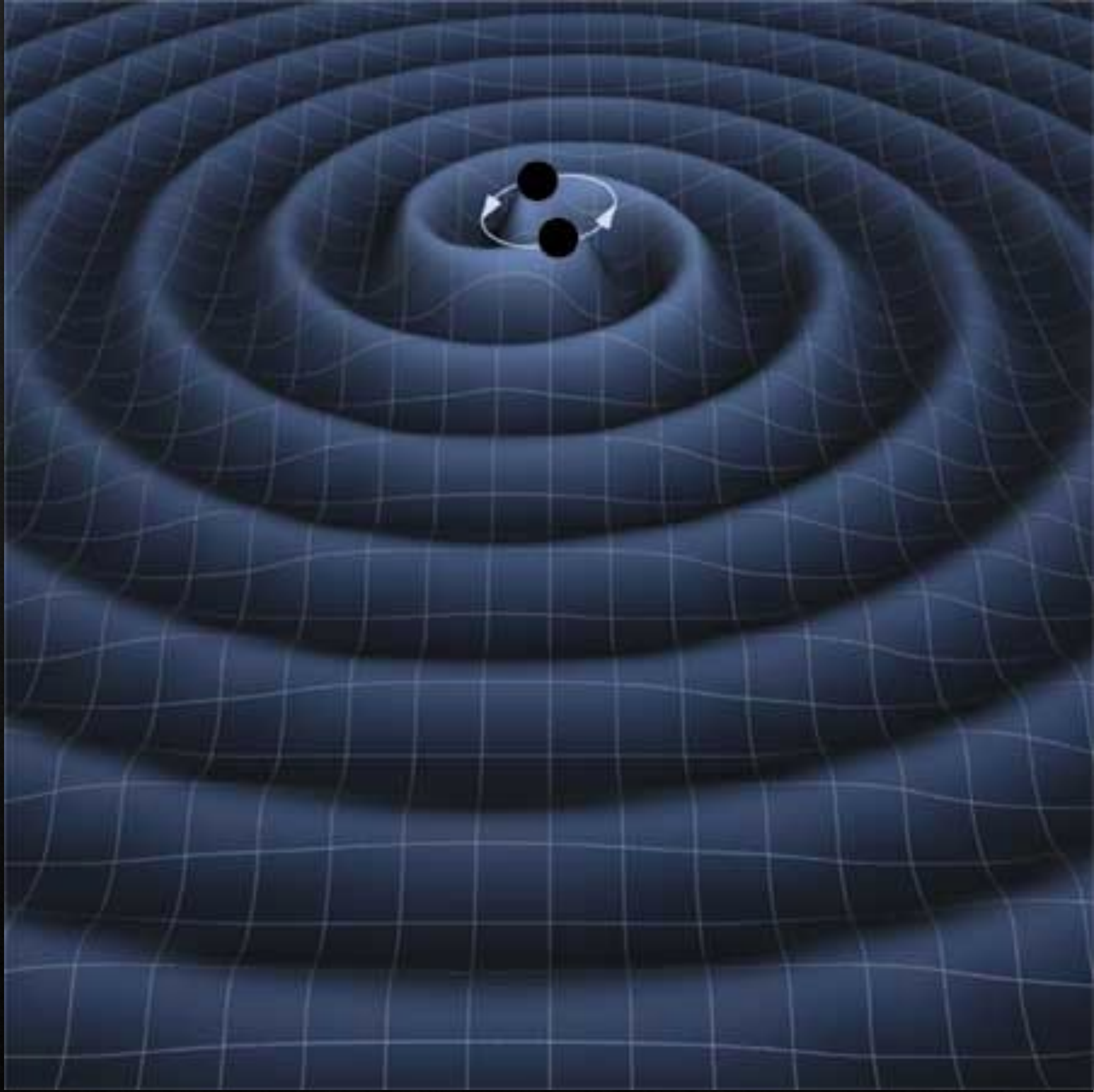
1. Compact Binary Coalescence (CBC):
   - Black Hole – Black Hole (detected!)
   - Black Hole – Neutron Star (detected)
   - Binary Neutron Star (detected!)
   - White Dwarf binary (not yet)

2. Continuous Wave (CW) Sources, such as spinning (asymmetric) Neutron Stars - *Gravitational Pulsars* (not yet)

3. Primordial Gravitational Waves from the early universe (false alarm in 2014, but not yet)

4. Unmodeled Bursts, such as supernovae, cosmic string cusps, or other transient events   (not yet)

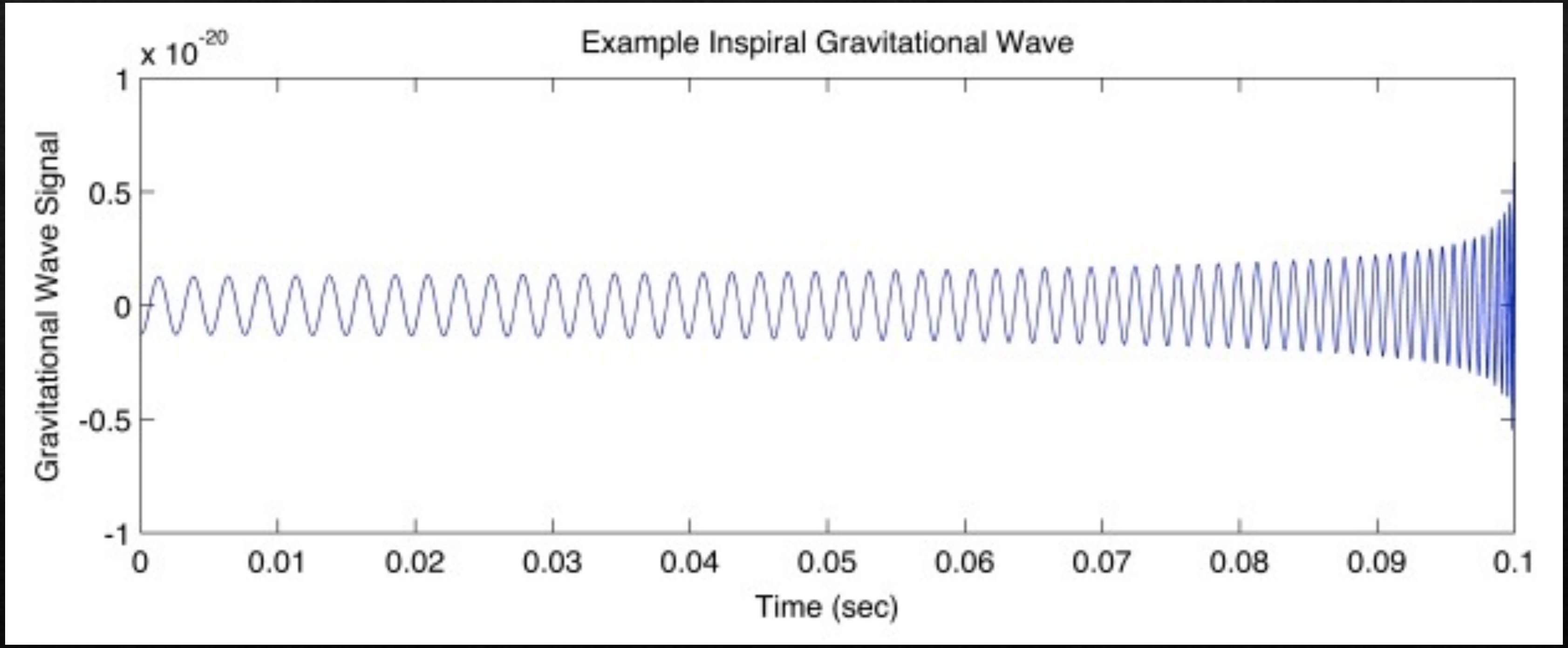
5. Something else?   (Requires a changing quadrupole moment, so a spherically symmetric explosion won't do.)



[Image: T. Carnahan (NASA GSFC)]

What is the sound of two black holes colliding?

Gravitational waves are not sound waves, but the frequencies can be comparable to the audio range, so we can listen to them.



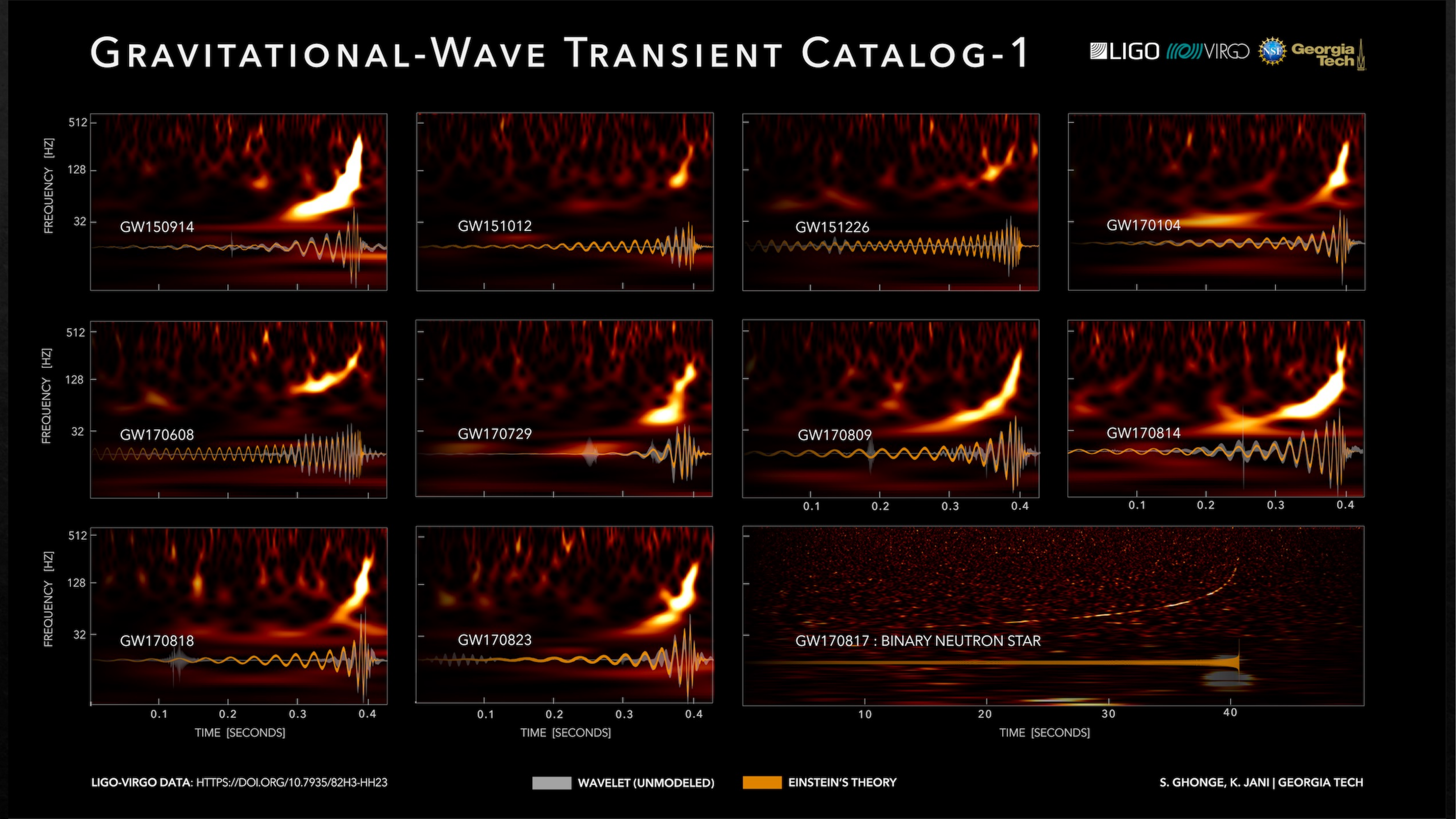
http://www.ligo.org/science/GW-Inspiral.php

LISTEN TO IT!

Chirp!

http://gmunu.mit.edu/sounds/comparable_sounds/comparable_sounds.html

Image Source: New Scientist


GRAVITATIONAL-WAVE TRANSIENT CATALOG-1
LIGO
VIRGO
NSF
Georgia Tech
FREQUENCY [HZ]
512
128
32
GW150914
GW151012
GW151226
GW170104
GW170608
GW170729
GW170809
GW170814
GW170818
GW170823
GW170817 : BINARY NEUTRON STAR
0.1
0.2
0.3
0.4
10
20
30
40
TIME [SECONDS]
LIGO-VIRGO DATA: HTTPS://DOI.ORG/10.7935/82H3-HH23
WAVELET (UNMODELED)
EINSTEIN'S THEORY
S. GHONGE, K. JANI | GEORGIA TECH

Event GW170817

Gravitational wave signals of the merger of two neutron stars were detected by Virgo, LHO and LLO at 12:41:04 UTC on 17 August 2017

A 2 second gamma ray burst, GRB 170817A, was detected by both Fermi and INTEGRAL satellites 1.7 seconds after the merger time.

Within hours, and for many days, telescopes around the world detected the event in optical and infrared.

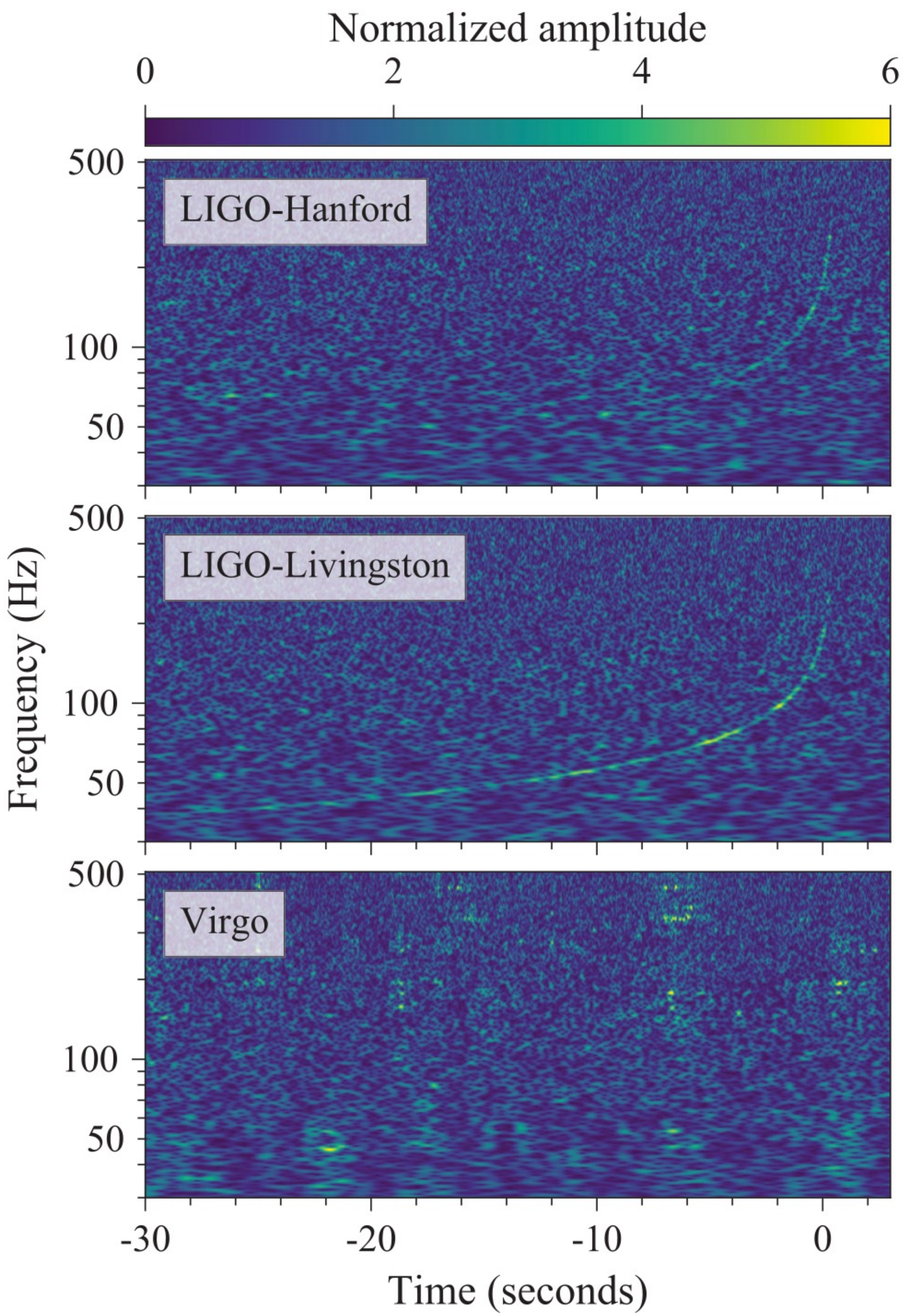
The host galaxy was identified, giving a better measure of distance.

Detected in ultraviolet by Swift-GRB satellite.

X-rays detected 9 days later by Chandra X-ray Observatory.

Radio signal detected 16 days later by VLA.

A paper summarizing all Multi-Messenger observations
[The Astrophysical Journal Letters, 848:L12 (59pp), 2017 October 20]
has almost 4,000 authors!



Keeping Up on the latest GW's

GraceDB — Gravitational-Wave Candidate Event Database

HOME | PUBLIC ALERTS | SEARCH | LATEST | DOCUMENTATION | LOGIN

Latest — as of 15 November 2019 16:55:16 UTC

Test and MDC events and superevents are not included in the search results by default; see the query help for information on how to search for events and superevents in those categories.

Query:

Search for: Superevent

Search

UID	Labels	t_start	t_0	t_end	FAR (Hz)	UTC Created
S191110af	ADVNO EM_Selected SKYMAP_READY DQOK GCN_PRELIM_SENT	1257462422.079116	1257462422.183200	1257462422.287284	2.499e-09	2019-11-10 23:10:59 UTC
S191110x	PE_READY ADVNO EM_Selected SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1257444539.210120	1257444540.210120	1257444541.210120	2.930e-11	2019-11-10 18:09:05 UTC
S191109d	PE_READY ADVOK EM_Selected SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1257296854.204590	1257296855.220703	1257296856.278186	1.537e-13	2019-11-09 01:07:46 UTC
S191105e	PE_READY ADVOK EM_Selected SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1256999738.931152	1256999739.933105	1256999740.933105	2.283e-08	2019-11-05 14:35:45 UTC
S190930t	ADVOK EM_Selected SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1253889264.685342	1253889265.685342	1253889266.685342	1.543e-08	2019-09-30 14:34:30 UTC
S190930s	PE_READY ADVOK EM_Selected SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1253885758.235347	1253885759.246810	1253885760.253734	3.008e-09	2019-09-30 13:36:04 UTC
S190928c	ADVNO EM_Selected SKYMAP_READY DQOK GCN_PRELIM_SENT	1253671923.328316	1253671923.364500	1253671923.400684	6.729e-09	2019-09-28 02:14:18 UTC
S190924h	PE_READY ADVOK EM_Selected SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1253326743.785645	1253326744.846654	1253326745.876674	8.928e-19	2019-09-24 02:19:25 UTC
S190923y	ADVOK EM_Selected SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1253278576.645077	1253278577.645508	1253278578.654868	4.783e-08	2019-09-23 12:56:22 UTC
S190915ak	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1252627039.685111	1252627040.690891	1252627041.730049	9.735e-10	2019-09-15 23:57:25 UTC

https://gracedb.ligo.org/latest/
https://gracedb.ligo.org/superevents/public/O3/

https://apps.apple.com/us/app/gravitational-wave-events/id1441897107

The Second Messenger:

Gravitational Waves

Starting in 2015, the detection of gravitational waves has opened up a whole new branch of astronomy.

Event GW170817 was the first co-observation of the collision of two neutron stars using both electromagnetic and gravitational detectors.

SN1987a

Light from a supernova in the Large Magellanic Cloud arrived on Earth on 24 February 1987

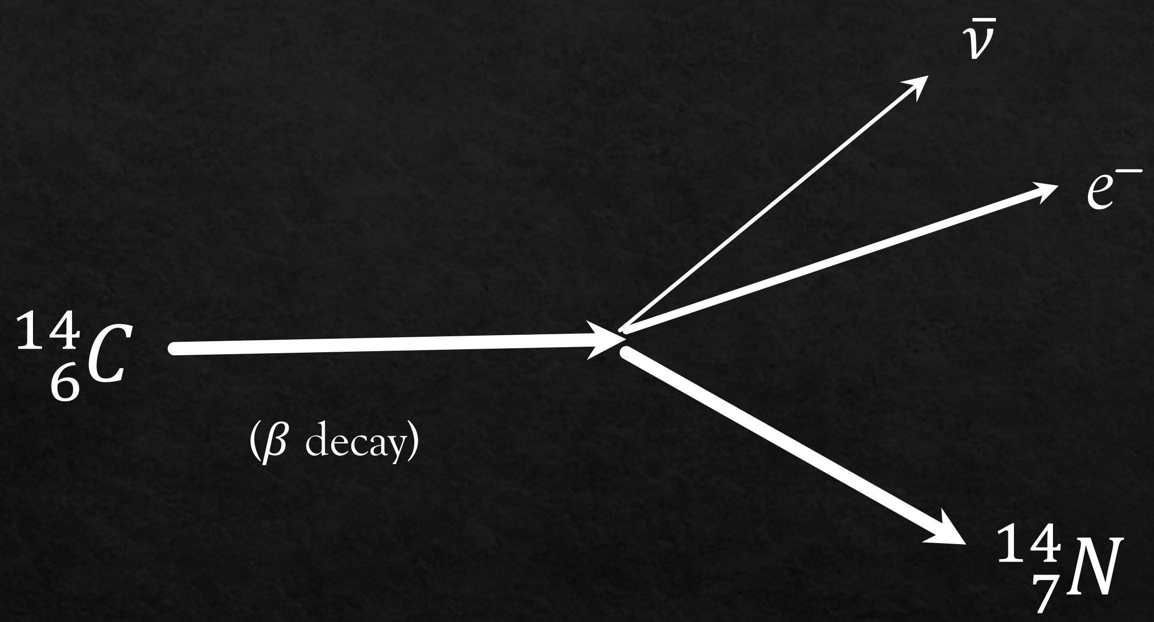
Three physics experiments running at the time were attempting (unsuccesfuly) to observe the decay of protons. Each detected a burst of antineutrinos two or three hours before visible light reached Earth.

IMB (Irvine-Michigan-Brookhaven) in a salt mine under Lake Erie
Detected 8 antineutrinos.

KamiokaNDE II in Japan
Detected 12 antineutrinos

BURST experiment in Baksan River valley in Russia
Detected 5 antineutrinos

What are neutrinos?



To save the principle of Conservation of Energy, Wolfgang Pauli proposed (1930) an electrically neutral particle he called the “neutron”.

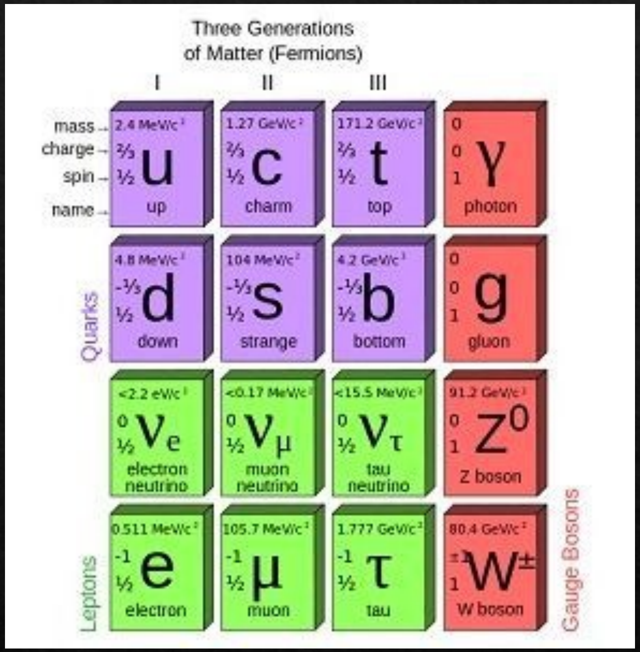
James Chadwick discovered what we now call the neutron in 1932.
So Enrico Fermi proposed naming Pauli’s particle the “neutrino.”

Neutrinos were first detected <u>directly</u> by Clyde Cowan and Frederick Reines in 1956 (Nobel Prize for Reines in 1995.)

Cosmic Gall
by John Updike (1960)

Neutrinos, they are very small.
They have no charge and have no mass
And do not interact at all.
The earth is just a silly ball
To them, through which they simply pass,
Like dustmaids down a drafty hall
Or photons through a sheet of glass.
They snub the most exquisite gas,
Ignore the most substantial wall,
Cold-shoulder steel and sounding brass,
Insult the stallion in his stall,
And, scorning barriers of class,
Infiltrate you and me! Like tall
And painless guillotines, they fall
Down through our heads into the grass.
At night, they enter at Nepal
And pierce the lover and his lass
From underneath the bed—you call
It wonderful; I call it crass.

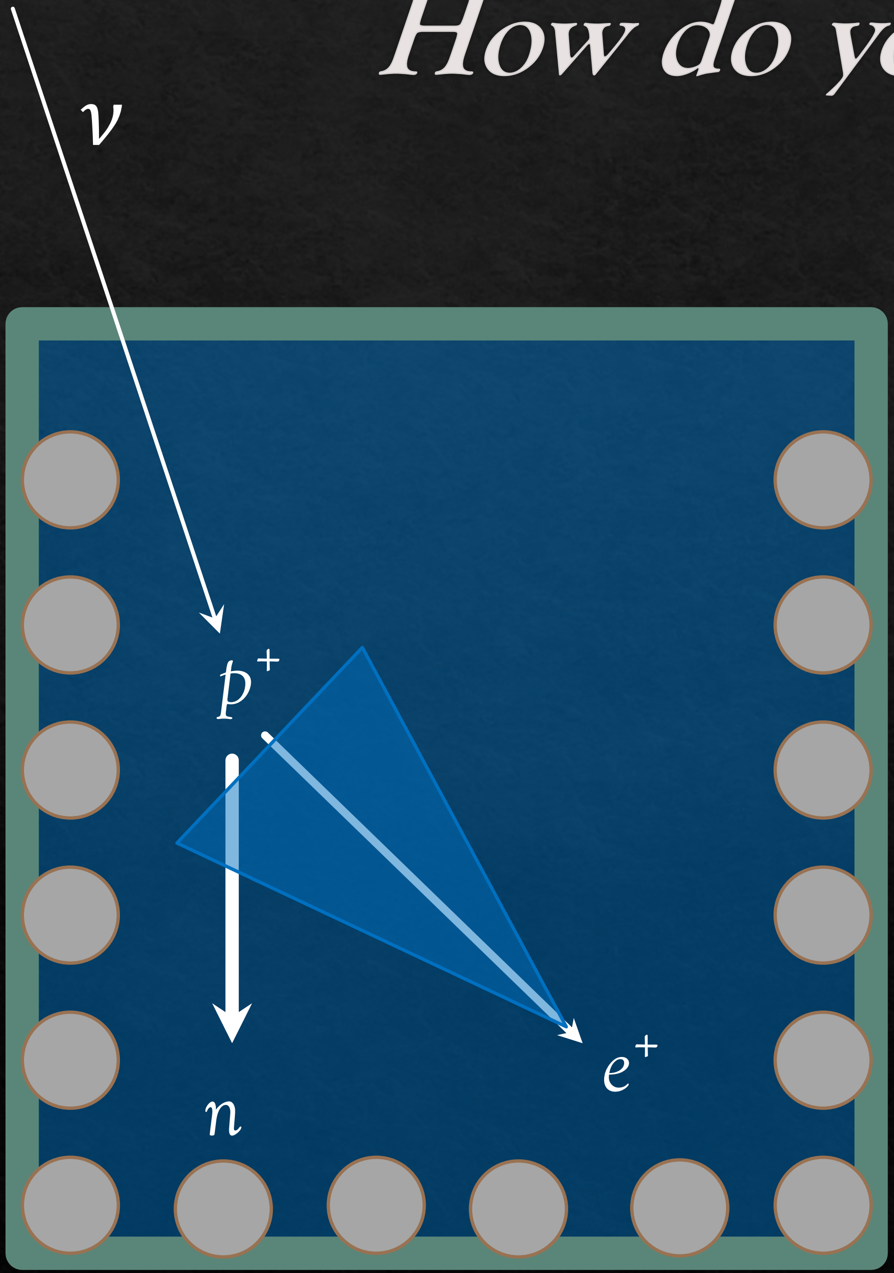
Properties of Neutrinos



- Neutrinos have no electric charge
- Neutrinos interact via the Weak nuclear force
- Neutrinos are unaffected by the Strong nuclear force
- Neutrinos come in 3 "flavors" – electron, muon, and tau
- Neutrinos were thought to have zero rest mass, but…
- Neutrinos experience "flavor mixing," and thus are thought to have a small mass

The Standard Model of Particle Physics has massless neutrinos – so we know the Standard Model is Wrong!

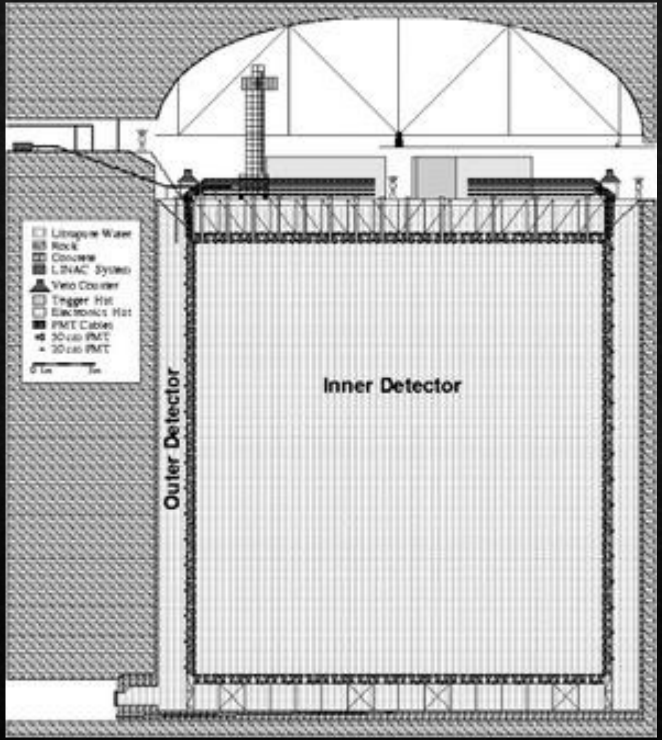
How do you detect neutrinos?



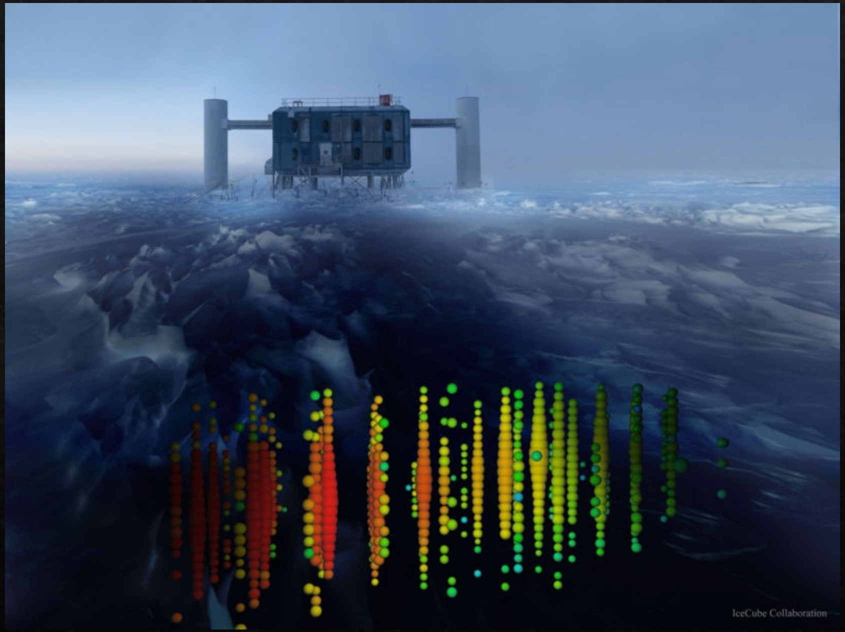
- Get a BIG tank of water
- Neutrino strikes a proton in a water molecule, turning it into a neutron, and expelling a positron (e^+).
- Energy and Momentum are conserved
- If the positron travels faster than the speed of light *in the water* then this produces Cherenkov radiation (it's like the bow wave of a boat on water).
- Detect Cherenkov radiation with PhotoMultiplier Tubes (PMT's)

  \- lots of PMT's!

Current Neutrino Observatories



Super KamiokaNDE (Neutrino Detection Experiment), Japan



IceCube
South Pole Neutrino Observatory

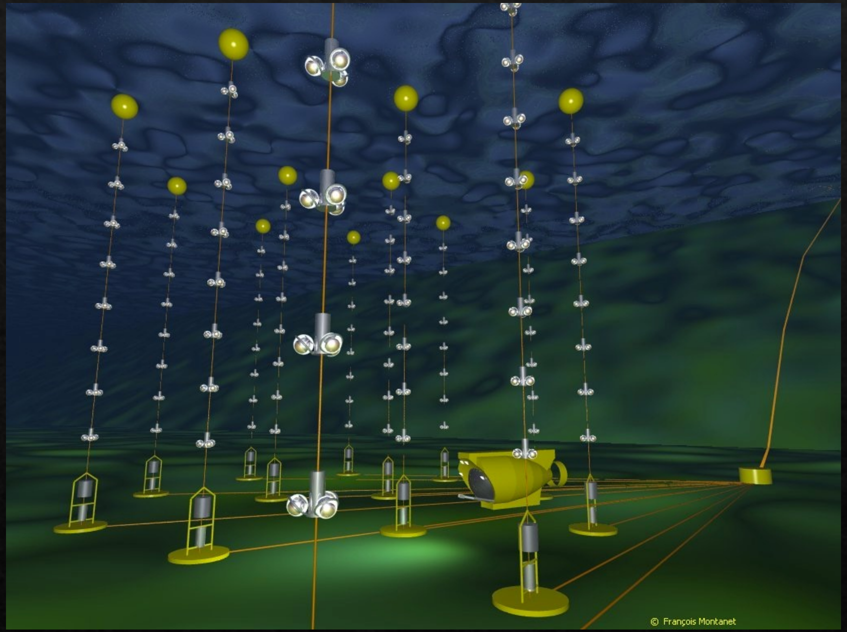


Image by François Montanet

ANTARES
2.5 km under the Mediterranean Sea, off the south coast of France.

New all-sky search reveals potential neutrino sources

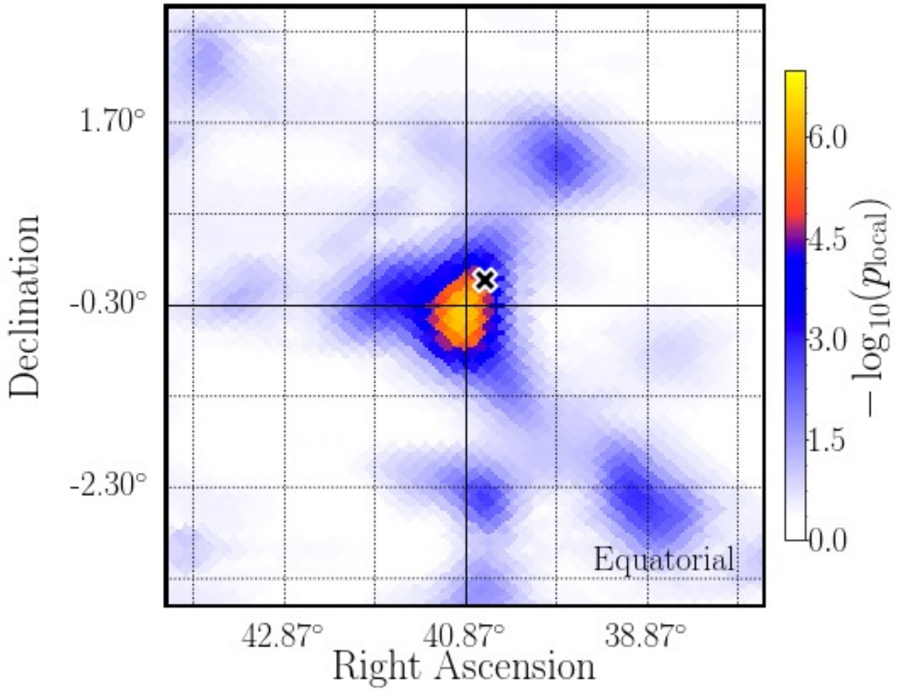
By Madeleine O'Keefe, 21 Oct 2019 10:00 AM

For over a century, scientists have been observing very high energy charged particles called cosmic rays arriving from outside Earth's atmosphere. The origins of these particles are very difficult to pinpoint because the particles themselves do not travel on a straight path to Earth. Even gamma rays, a type of high-energy photon that offers a little more insight, are absorbed when traversing long distances.

The IceCub
ice at the S
to galaxies
neutrinos. T
radiation ne

Unlike cosm
them a prac
a source of
ray source.

After 10 years of searching for origins of astrophysical neutrinos, a new all-sky search provides the most sensitive probe of time-integrated neutrino emission of point-like sources.
The IceCube Collaboration presents the results of this scan in a paper submitted recently to



The pre-trial probability of the observed signal being due to background in a 5x5 degree window around the most significant point in the Northern Hemisphere (the hottest spot); the black cross marks the Fermi-3FGL coordinates of the galaxy NGC 1068. Credit: IceCube Collaboration

"After 10 years of searching for origins of astrophysical neutrinos, a new all-sky search provides the most sensitive probe of time-integrated neutrino emission of point-like sources. The IceCube Collaboration presents the results of this scan in a paper submitted recently to *Physical Review Letters*."

The Third Messenger:

Neutrinos

The detection of neutrinos from SN1987a opened up another new branch of astronomy, and led to the creation of multiple neutrino observatories.

They are now starting to get enough data to pinpoint individual sources.

The Challenges of Multi-Messenger Astronomy

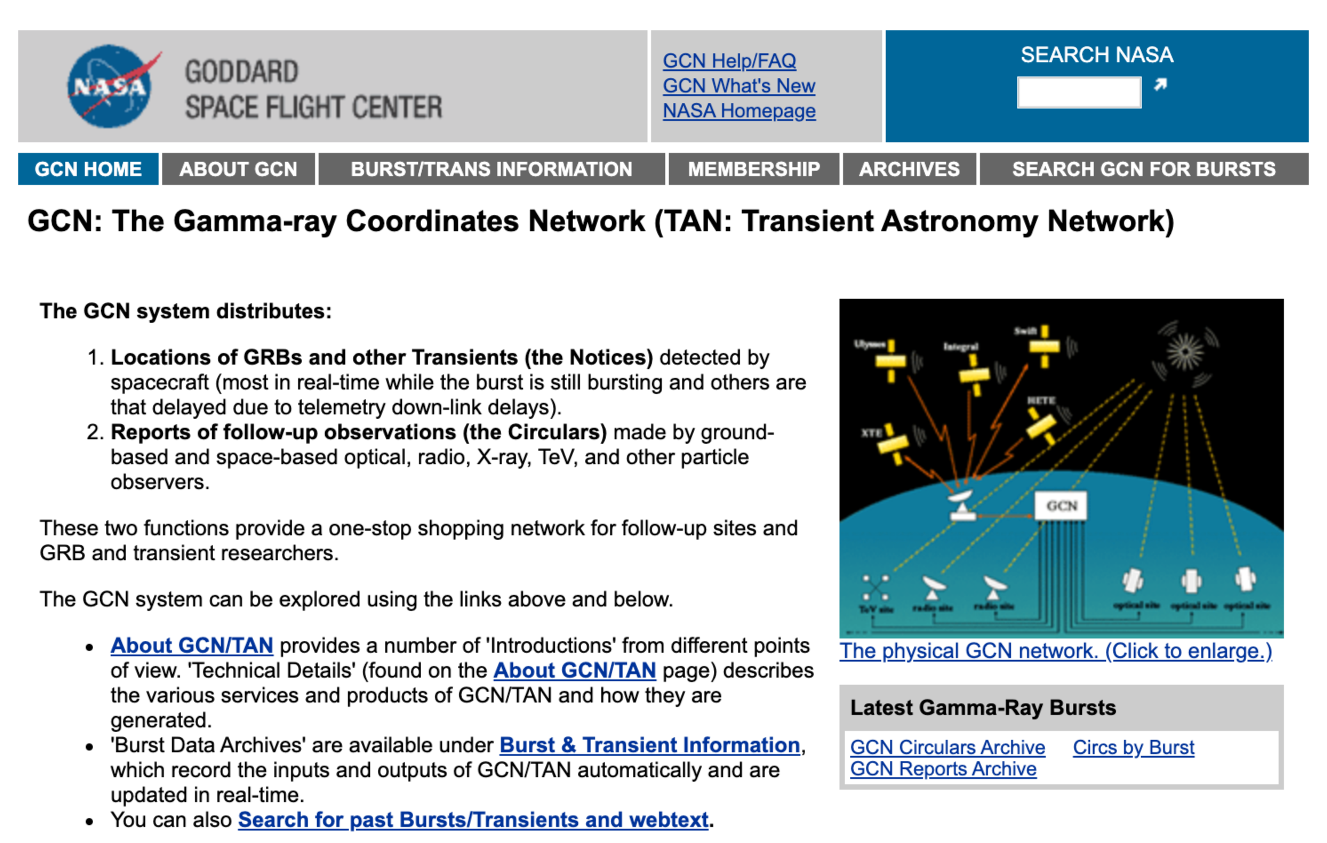
How do you get everybody working together?

- Gravitational Wave detectors are *omnidirectional* -- they collect signals from any direction (but are better in some directions than others).
- Neutrino detectors are sort-of omnidirectional, but more sensitive in the downward direction (they use the Earth to shield out background).
- Some Gamma ray and X-ray satellite instruments have a wide field of view, but are generally not steerable. Others are omnidirectional (so called "4π" coverage)
- Telescopes have a narrow (sometimes very narrow) field of view, and won't see something unless pointed in the right direction.

GCN Notices and Circulars

When a gamma-ray burst or a gravitational wave event is detected, the originating observatory issues a “Notice” to the network (and possibly revisions).

Follow up observations from other observatories (or upper limits, or lack of detection) are sent out as “Circulars”



GODDARD SPACE FLIGHT CENTER

GCN Help/FAQ
GCN What's New
NASA Homepage

SEARCH NASA

GCN HOME | ABOUT GCN | BURST/TRANS INFORMATION | MEMBERSHIP | ARCHIVES | SEARCH GCN FOR BURSTS

GCN: The Gamma-ray Coordinates Network (TAN: Transient Astronomy Network)

The GCN system distributes:

1. **Locations of GRBs and other Transients (the Notices)** detected by spacecraft (most in real-time while the burst is still bursting and others are that delayed due to telemetry down-link delays).
2. **Reports of follow-up observations (the Circulars)** made by ground-based and space-based optical, radio, X-ray, TeV, and other particle observers.

These two functions provide a one-stop shopping network for follow-up sites and GRB and transient researchers.

The GCN system can be explored using the links above and below.

- **About GCN/TAN** provides a number of 'Introductions' from different points of view. 'Technical Details' (found on the **About GCN/TAN** page) describes the various services and products of GCN/TAN and how they are generated.
- 'Burst Data Archives' are available under **Burst & Transient Information**, which record the inputs and outputs of GCN/TAN automatically and are updated in real-time.
- You can also **Search for past Bursts/Transients and webtext**.

The physical GCN network. (Click to enlarge.)

Latest Gamma-Ray Bursts

GCN Circulars Archive
Circs by Burst
GCN Reports Archive

https://gcn.gsfc.nasa.gov/

Forbes

Billionaires Innovation Leadership Money Business Small Business Lifestyle Lists Advisor Featured More

117,264 views | Jul 30, 2019, 02:00am

Has LIGO Just Detected The 'Trifecta' Signal That All Astronomers Have Been Hoping For?

NO

[redacted]

Ethan Siegel Senior Contributor
Starts With A Bang Contributor Group
Science

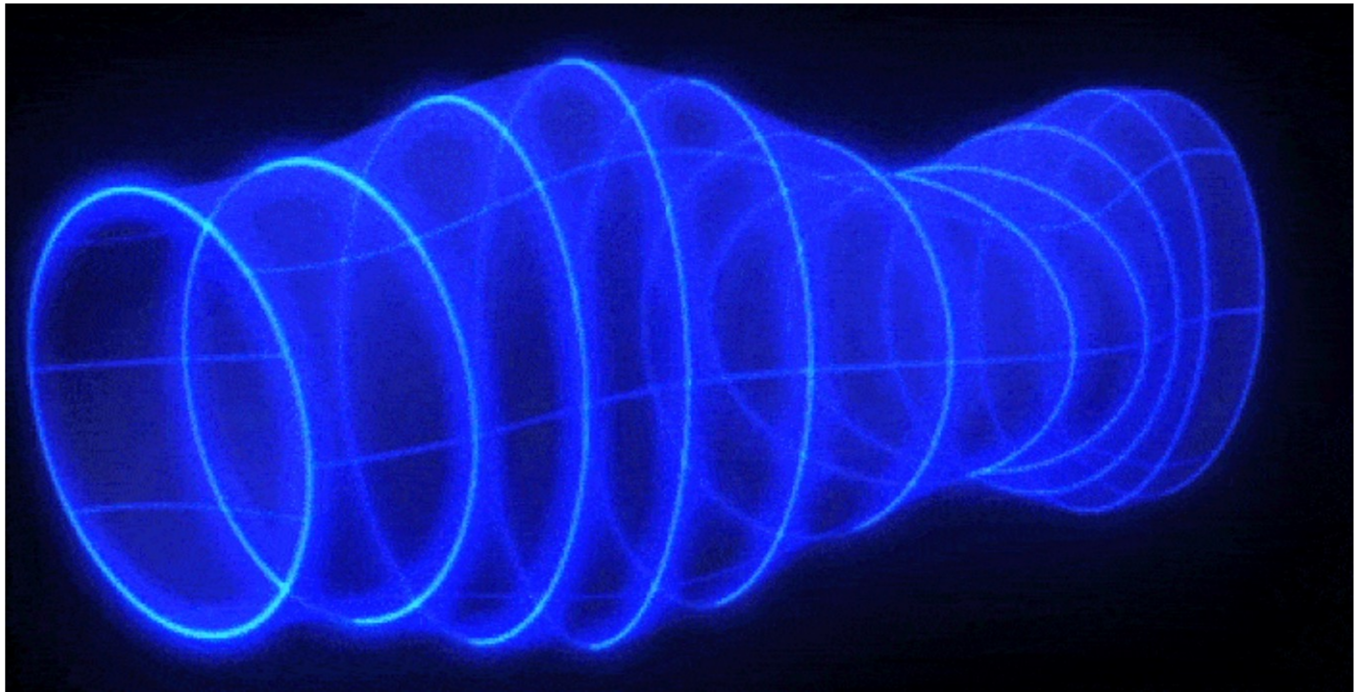
The Universe is out there, waiting for you to discover it.

LIGO announced S190728q on 28 July 2019 at 06:59 UTC

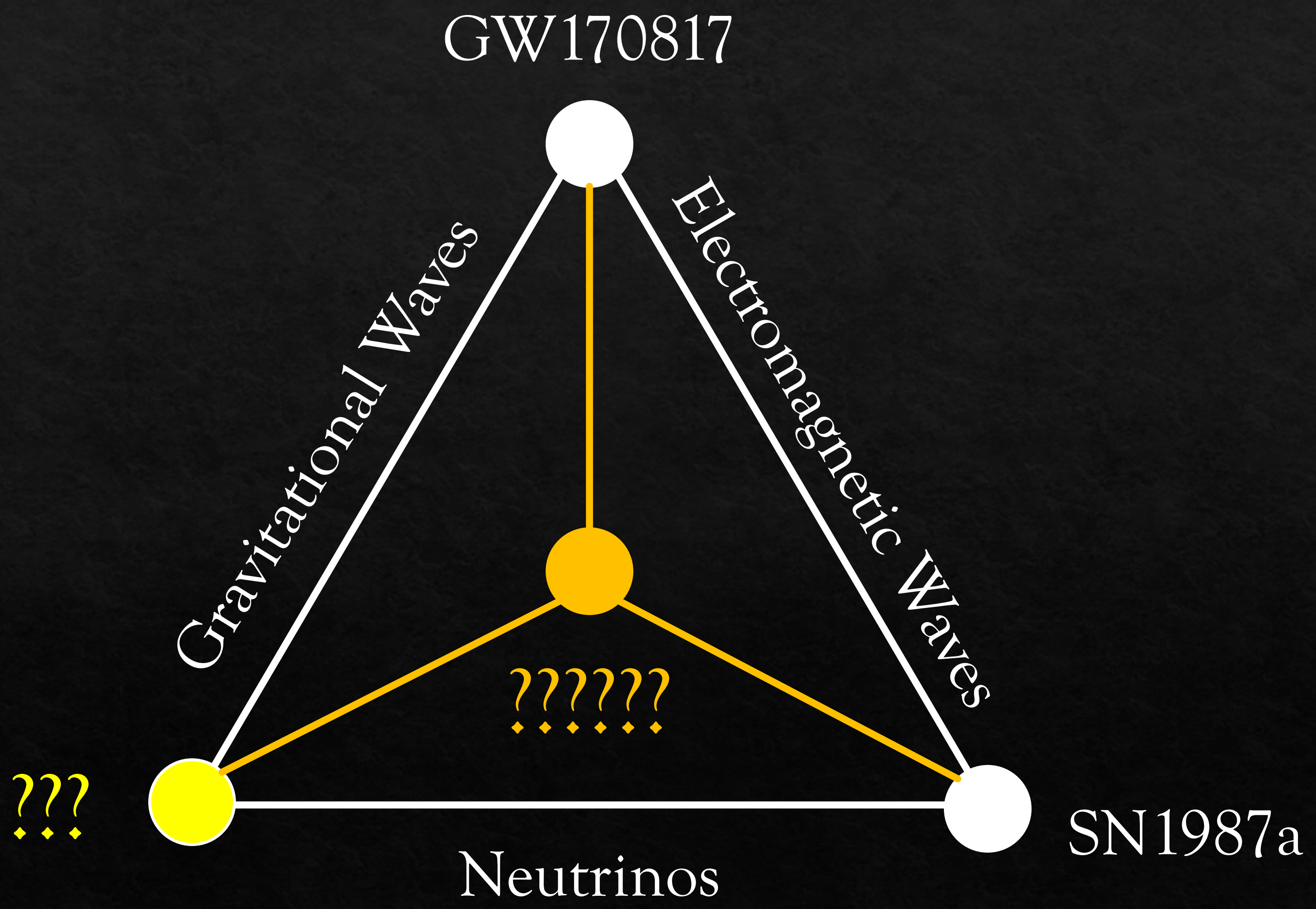
IceCube reported detecting a single neutrino from the same direction
…but 360 seconds EARLIER.

There was an optical transient nearby
…but 18 hrs earlier, and not quite the right direction.

Read GCN Circulars…



Progress so far...



The Three Messengers

Light
(Electromagnetic Waves)

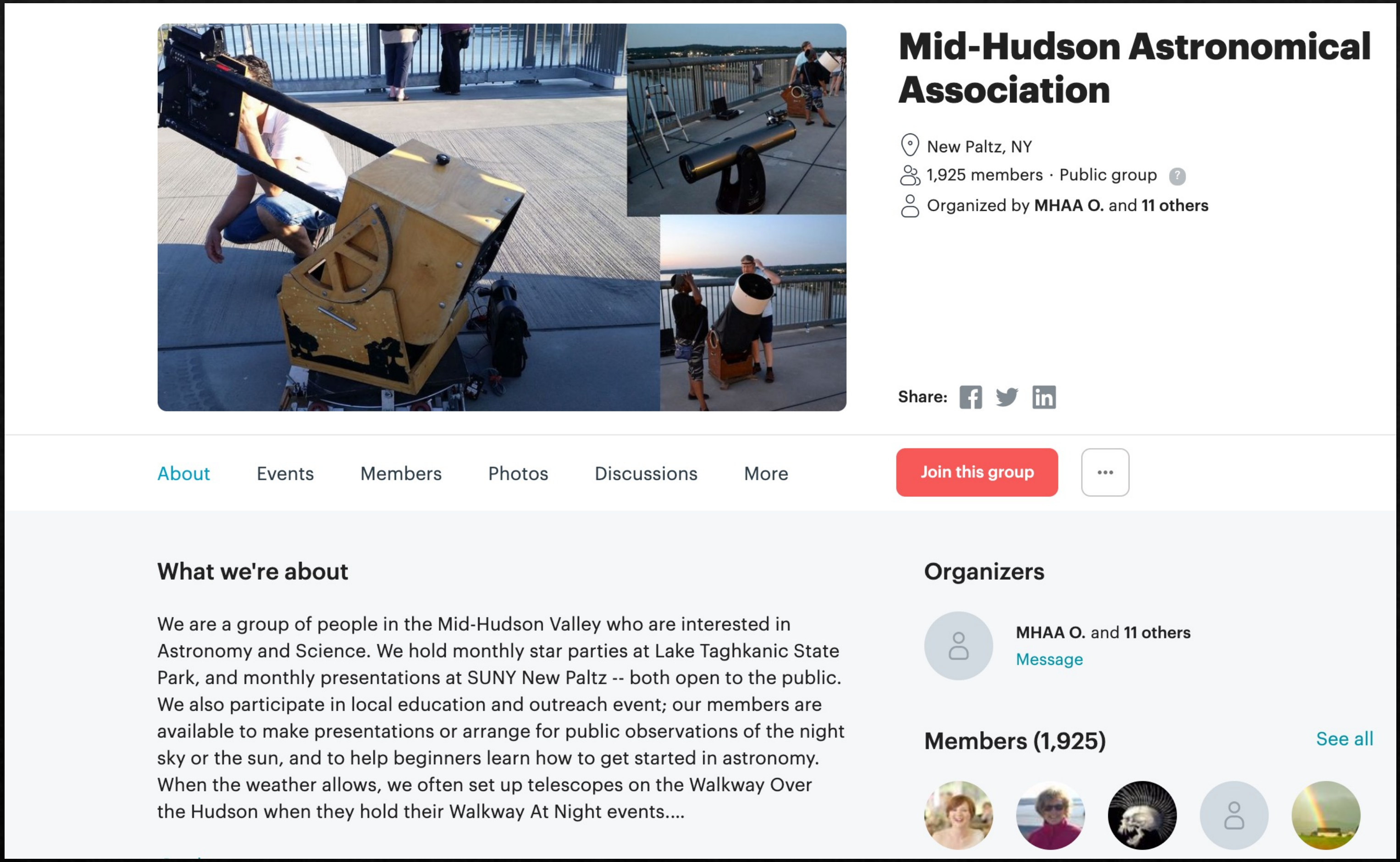
Gravitational Waves

Cosmic Rays
(principally Neutrinos)

When will they appear all at the same time?

Hopefully soon!

Mid-Hudson Astronomical Association



Meetings every month (3rd Tuesday)

- Via Zoom
- Presentation at 8:00 PM
- (Business meeting 7:30 PM)
- Soon to be back as SUNY New Paltz

Star Parties every month (Friday close to a new moon) at Lake Taghkanic State Park

- no telescope required
- bring a telescope if you want
- (must register with car info)

Various outreach and education activities at public libraries, schools, Walkway Over the Hudson, and other local venues.

Visit http://midhudsonastro.org for calendar of events (on Meetup.com)

Additional Slides for Questions

KAGRA and LIGO—India

"We have built an exact copy of that instrument that can be used in the LIGO-India Observatory," says David Shoemaker, leader of the Advanced LIGO Project and director of the MIT LIGO Lab, "ensuring that the new detector can both quickly come up to speed and match the U.S. detector performance."

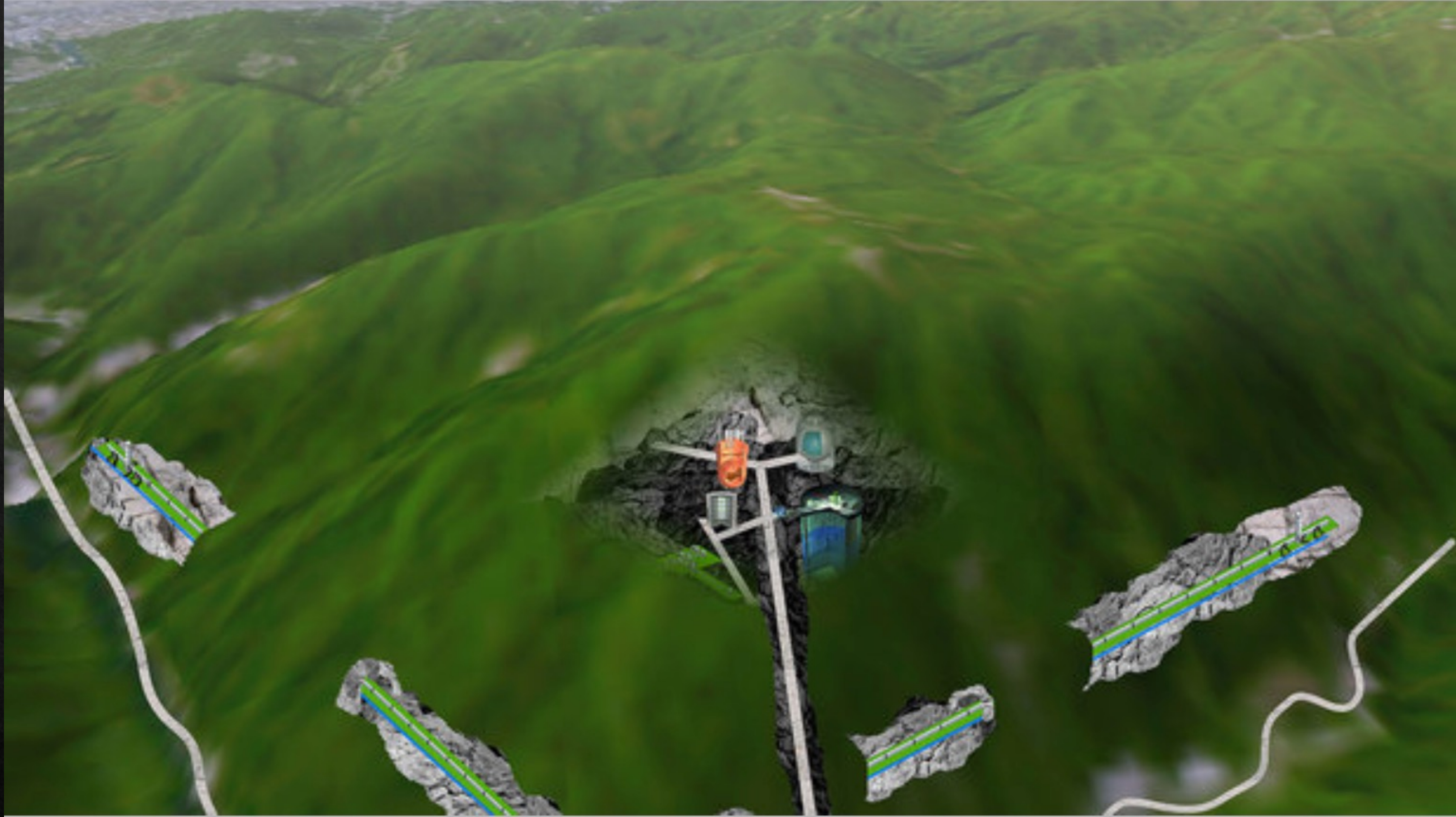
Image © Tarun Souradeep, from http://www.natureasia.com/en/nindia/article/10.1038/nindia.2016.20

KAGRA

The KAmioka GRAvitational wave detector

Located in a zinc and lead mine under a mountain in western Japan.

(The same mountain used for a famous experiment which attempted to observe the decay of the proton years ago.)



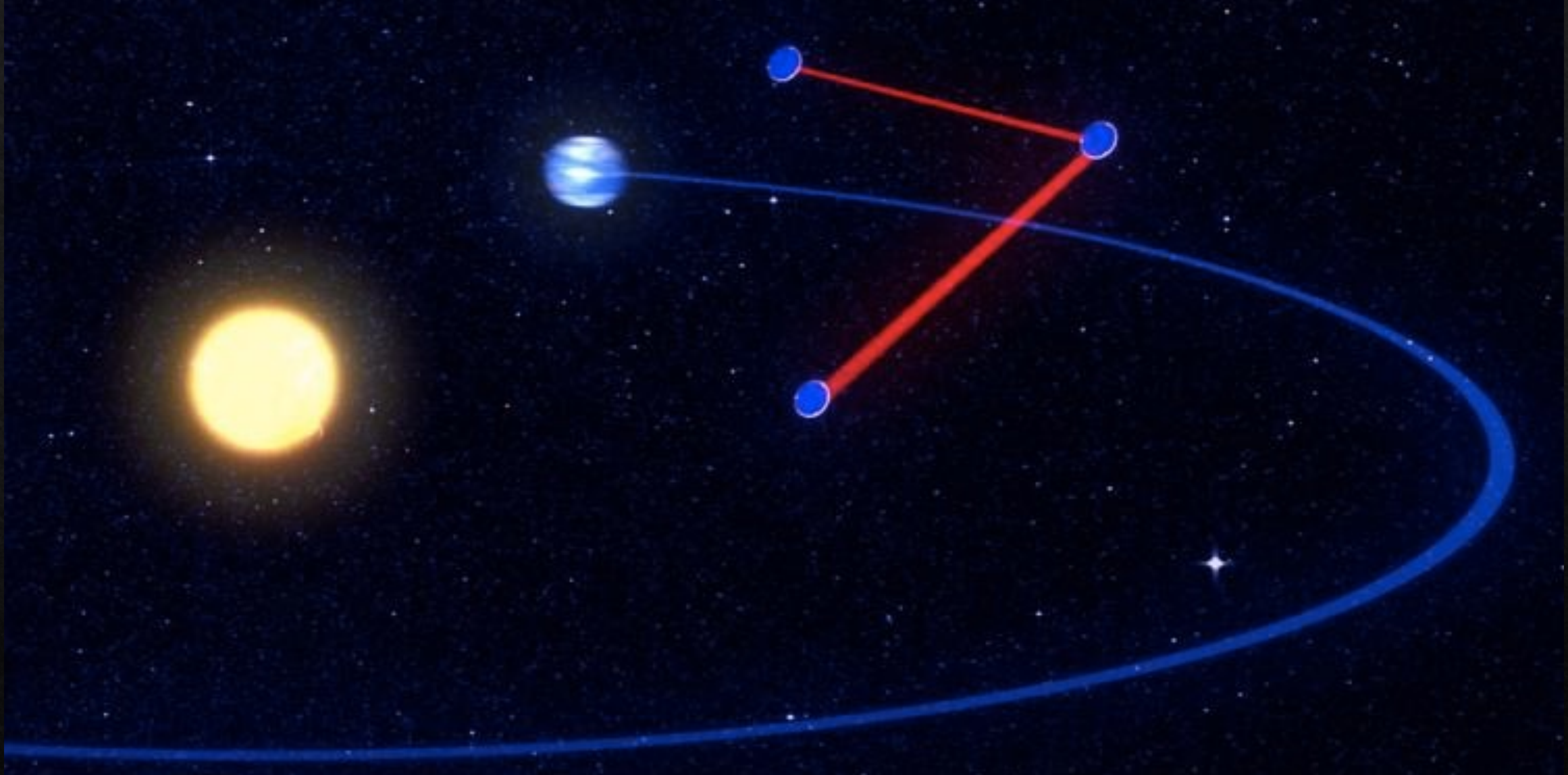
An illustration of the underground KAGRA gravitational-wave detector in Japan. Image credit: ICRR, Univ. of Tokyo.

KAGRA to Join LIGO and Virgo in Hunt for Gravitational Waves

News Release • October 4, 2019

LISA

Laser Interferometer Space Antenna



The LISA mission originally consisted of one “Mother” and two “Daughter” spacecraft orbiting the Sun in a triangular configuration, connected by the two arms of a laser interferometer.

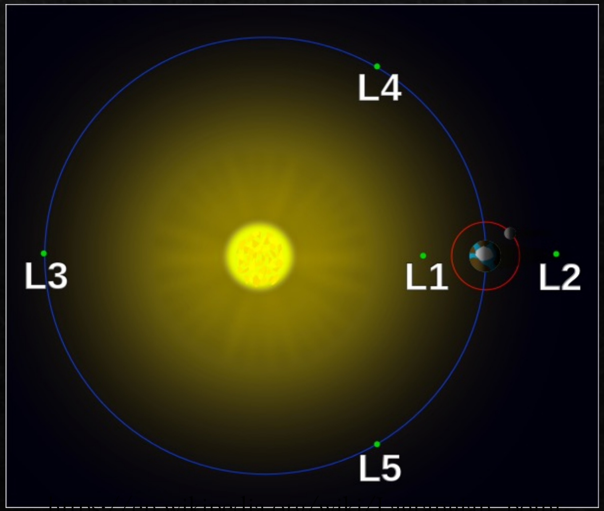
The formation trails Earth in its orbit by 20° and the plane of the triangle is 60° from the plane of the ecliptic.

Latest LISA Mission

https://lisa.nasa.gov/

Each of three spacecraft carry two test masses, two lasers, and two telescopes, forming 3 interferometers with 2.5 Gm arms.

Lagrange Points:



Learn more at

https://www.lisamission.org/

and

https://lisa.nasa.gov/