Introduction to Astronomy Lecture10: The next big things

– *LIGO and Gaia*

Presented by
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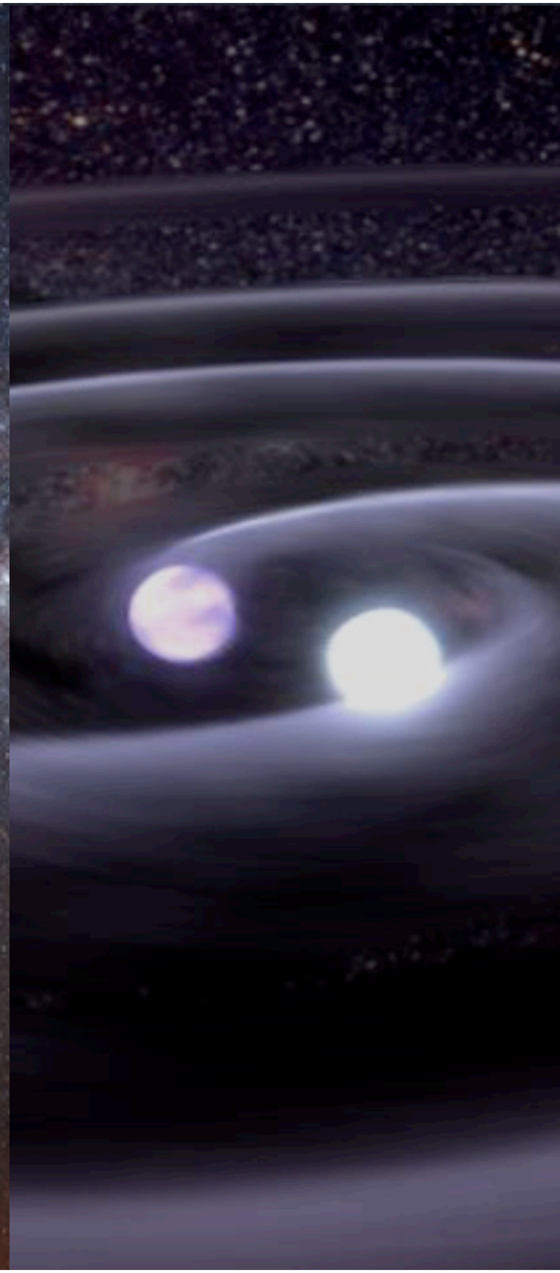
School of Physics

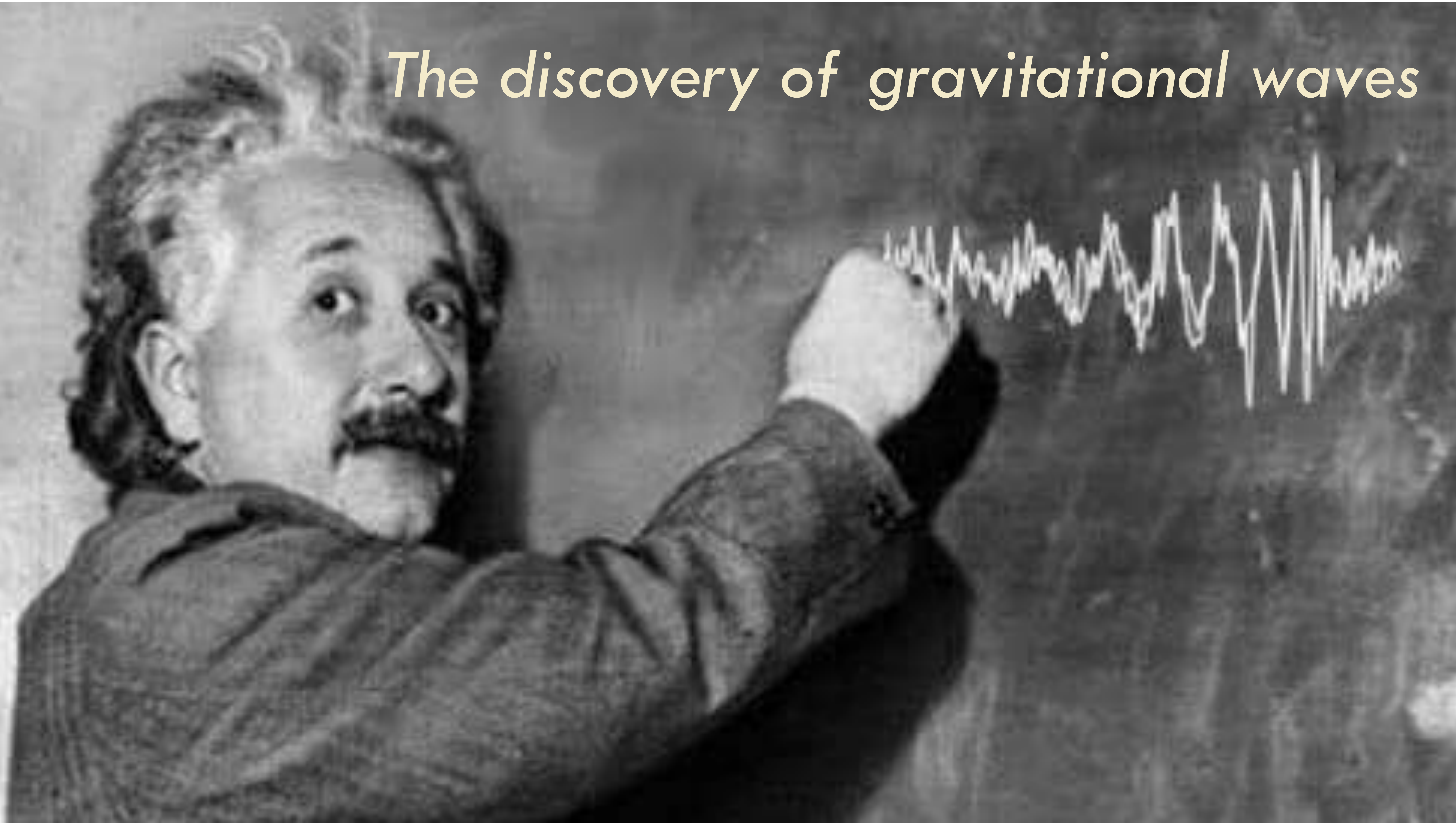
Spring 2018



THE UNIVERSITY OF SYDNEY

In tonight's lecture

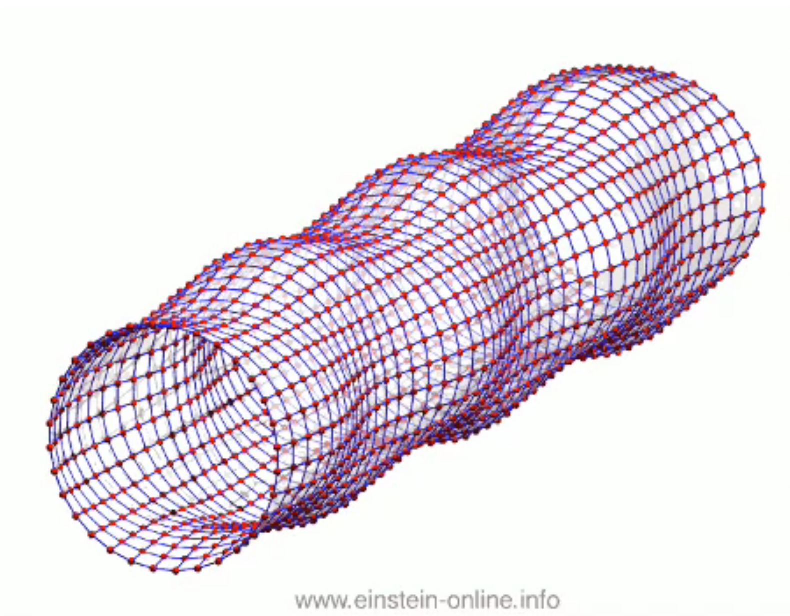
- The birth of gravitational wave astronomy
  – *LIGO and the birth of a new science*
- The *Gaia* mission
  – *mission to measure the Galaxy*
- To infinity and beyond!


The discovery of gravitational waves

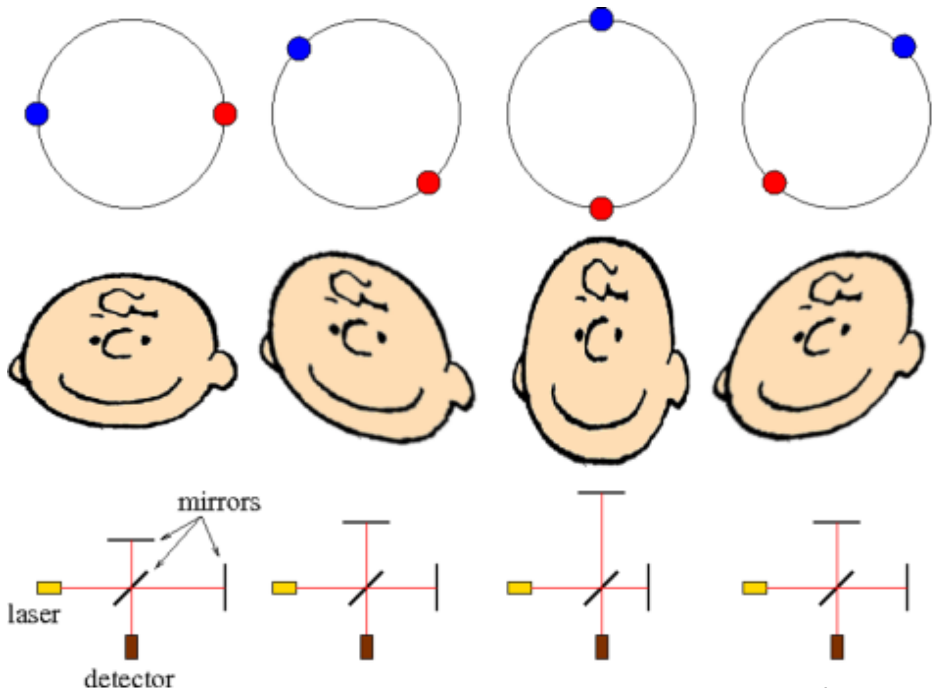
Gravitational waves

In lecture 5, I mentioned that general relativity predicts the existence of *gravitational radiation*: fluctuations in space-time which propagate as a wave.

Gravitational waves are detected by detecting a change in lengths, e.g. the change in the distance between two objects.

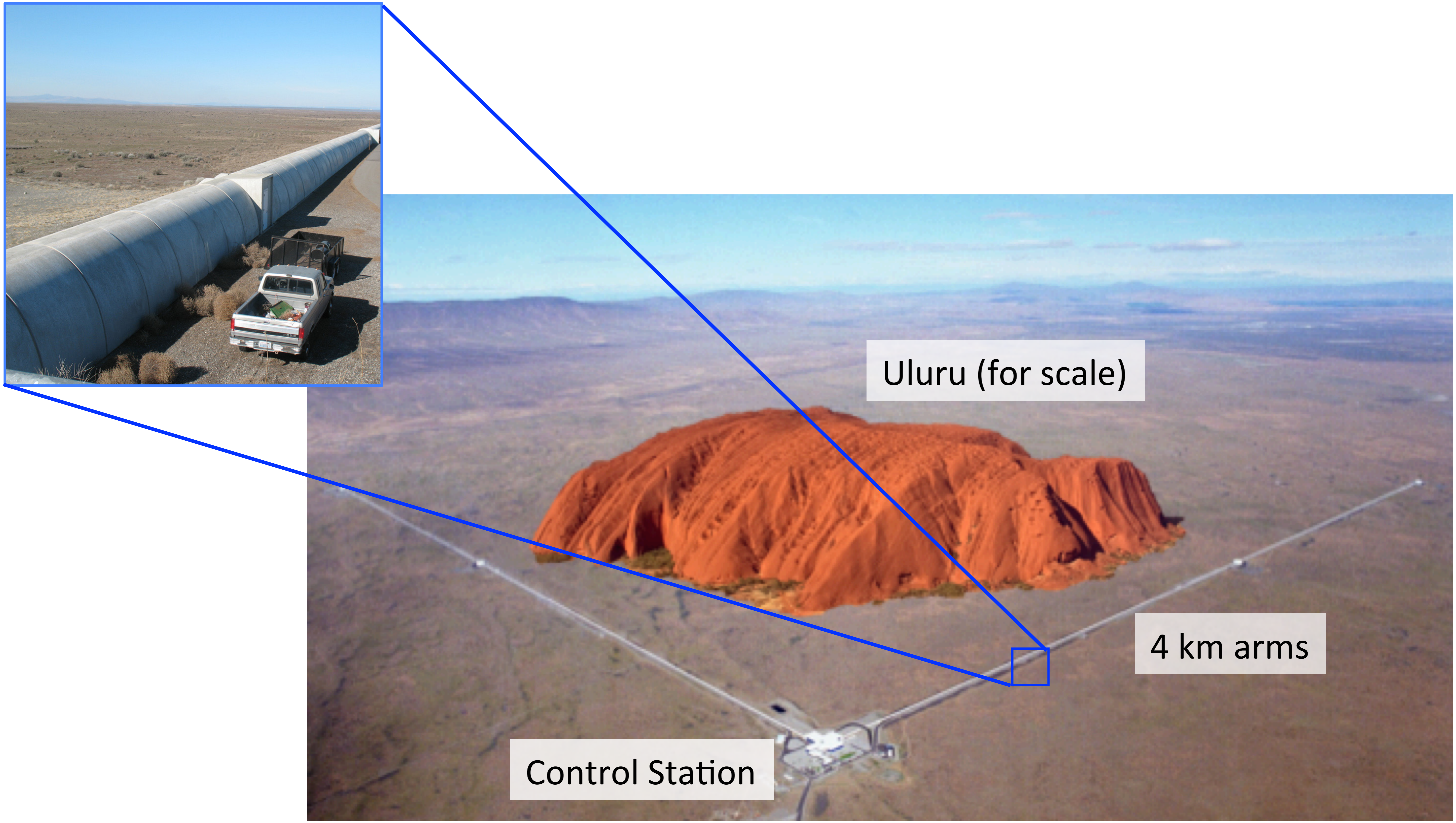


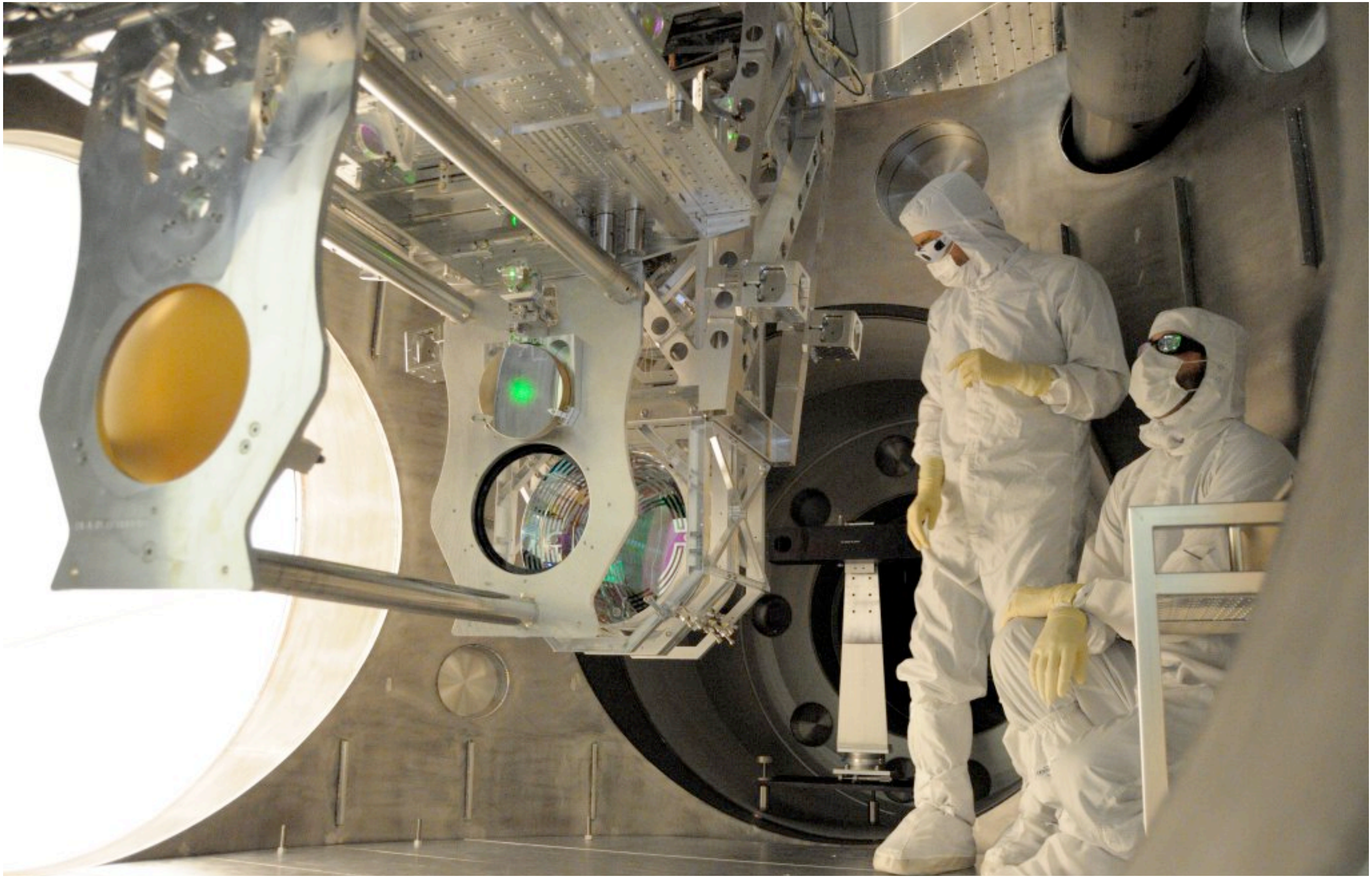
The effect is *extremely* weak: the most violent event produces changes of about 1 part in 10^{21}. To measure this, you need to be able to measure the change in length equal to 0.1% x diameter of a proton over 4 km.

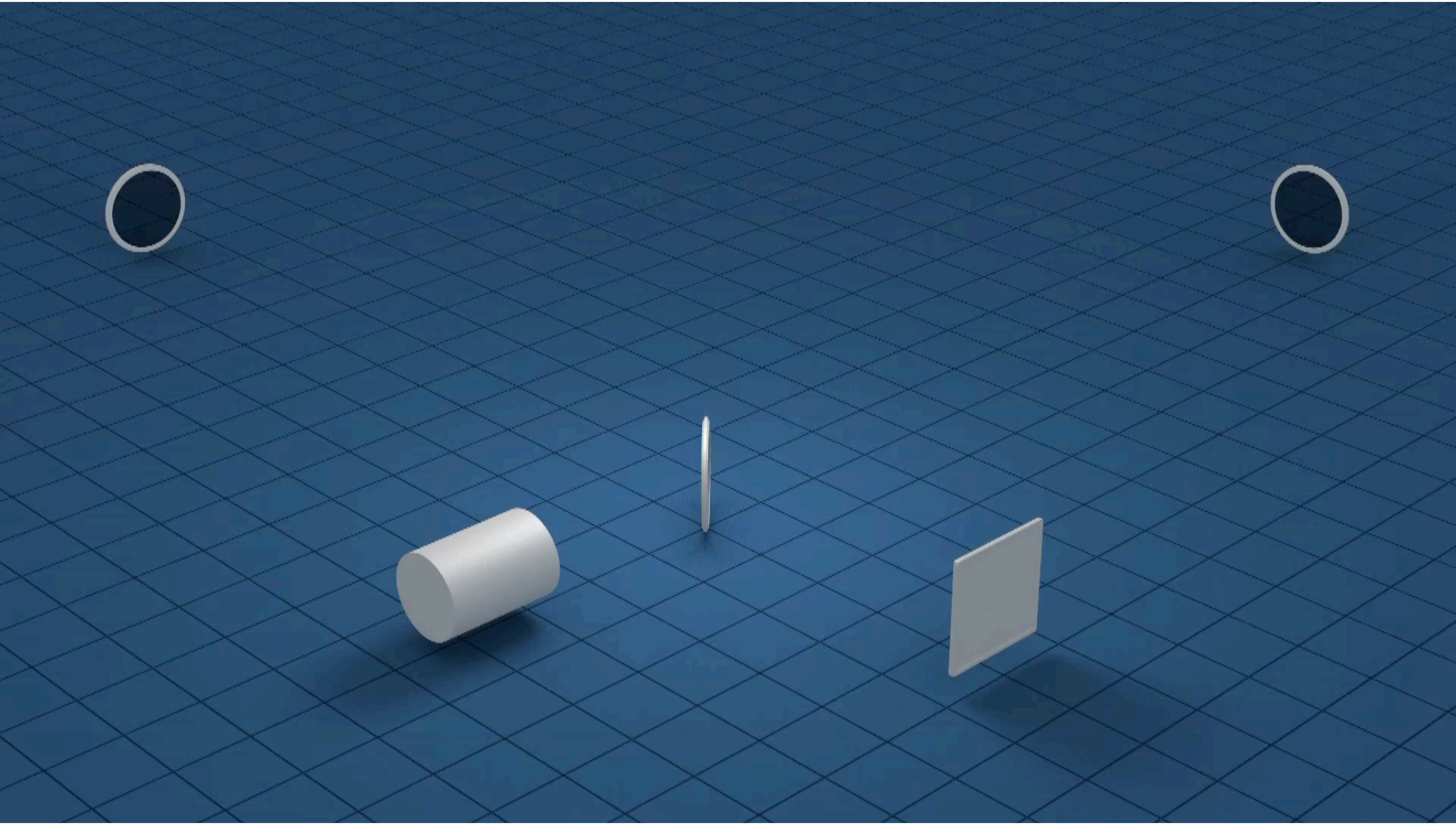


Detecting gravitational waves by measuring a distortion (image by Matthew Francis)

The LIGO "observatory" is made up of two identical and widely separated interferometers situated in sparsely populated, out-of-the-way places: LIGO Hanford in southeastern Washington State, and LIGO Livingston, 3002 km away near Baton Rouge, Louisiana. Each arm is 4 km long.

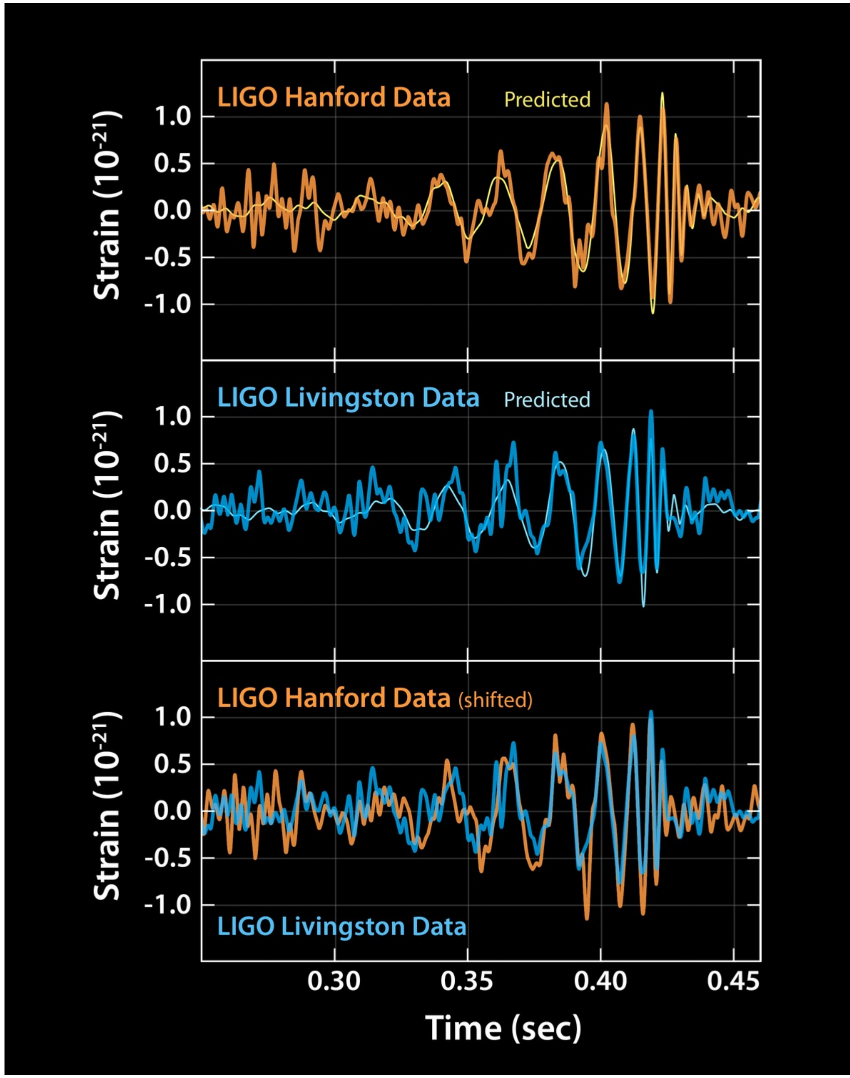

Uluru (for scale)
4 km arms
Control Station





The LIGO binary black hole merger GW150914

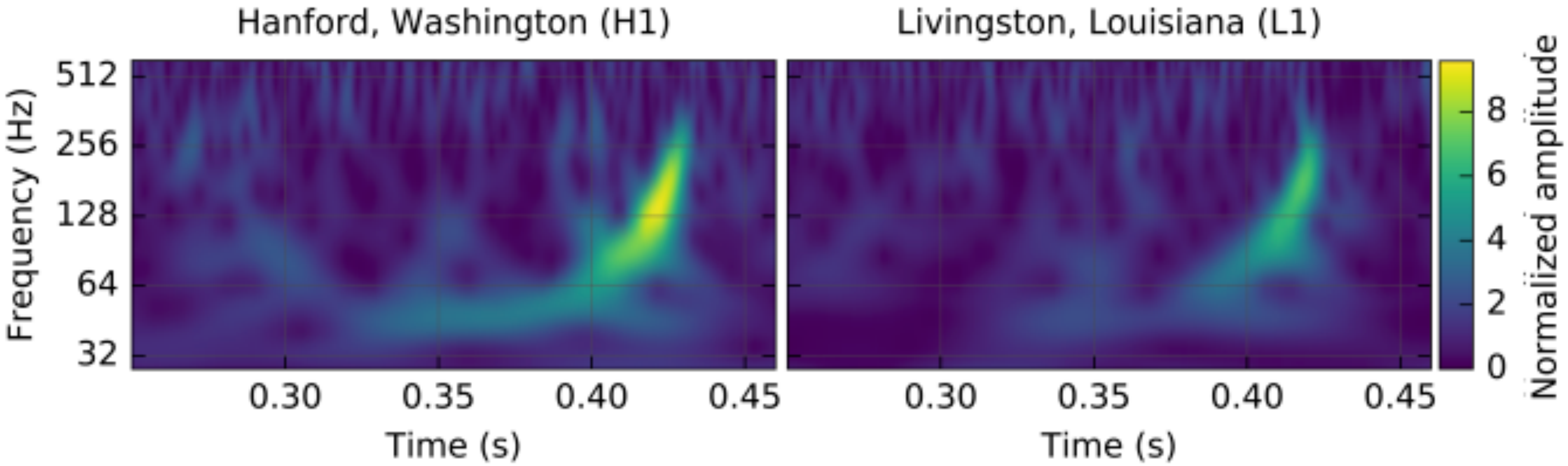
On 14 September 2015 a signal was detected by the two arms of LIGO.

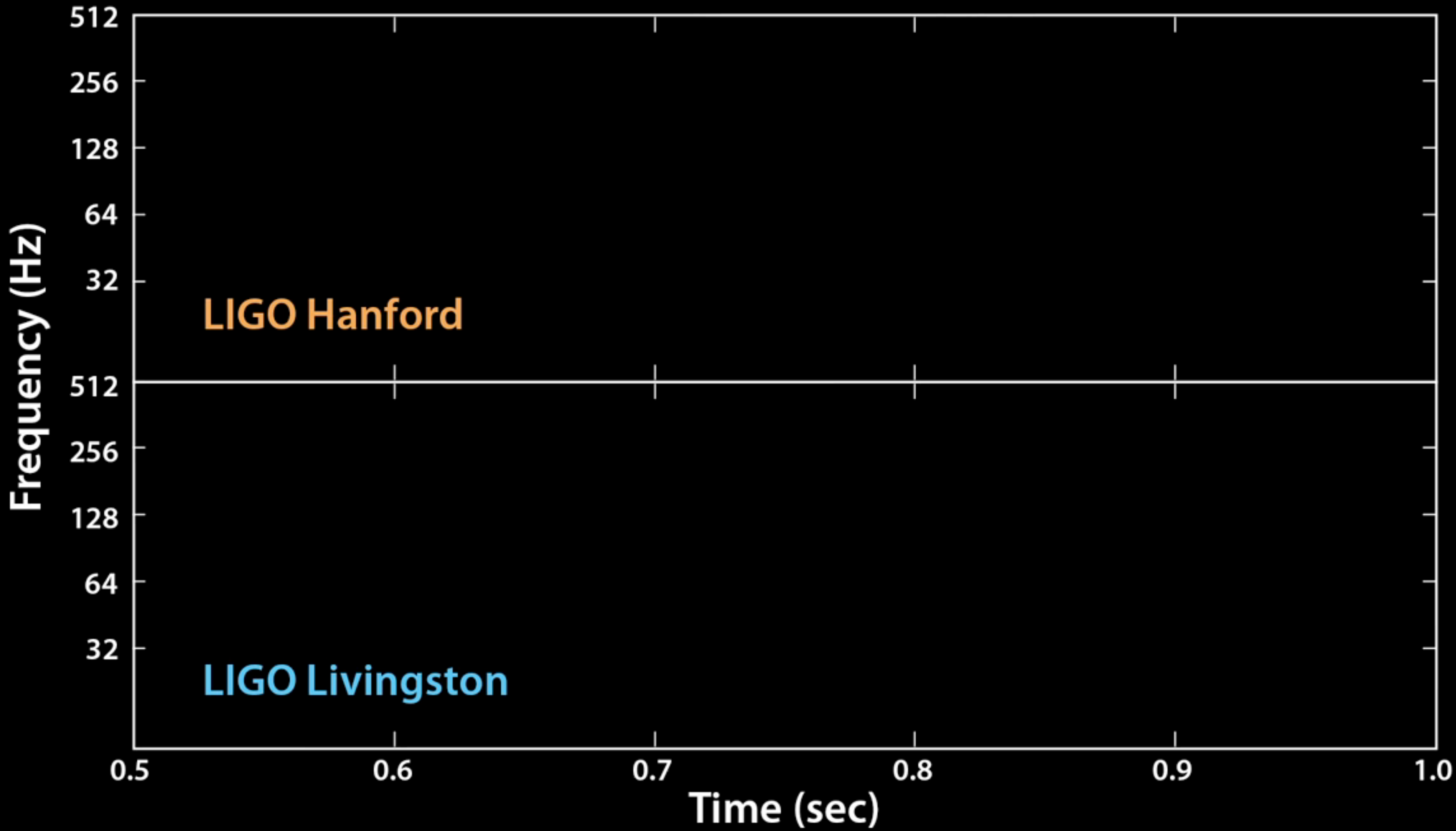


The gravitational wave event seen by the two LIGO detectors. Top two plots show the measured strain, compared to a numerical relativity waveform for two merging black holes.

The third plot shows the data from both detectors, with the data from H1 shifted by 6.9 ms and inverted.

Over 0.2 s, the signal increases in frequency and amplitude in about 8 cycles, from 35 to 150 Hz (the “chirp”). The most plausible explanation for this signal is the inspiral of two orbiting masses due to gravitational wave emission.





512
256
128
64
32
LIGO Hanford
512
256
128
64
32
LIGO Livingston
Frequency (Hz)
0.5
0.6
0.7
0.8
0.9
1.0
Time (sec)

The masses of the black holes can't be measured directly, but we can get a particular combination of them, called the "chirp mass":

$$\mathcal{M} = \frac{(m_1 m_2)^{3/5}}{(m_1 + m_2)^{1/5}} = \frac{c^3}{G}\left[\frac{5}{96}\pi^{-8/3} f^{-11/3}\dot{f}\right]^{3/5},$$

The observed frequency and frequency derivative give $\mathcal{M} \sim 30\ M_\odot$.

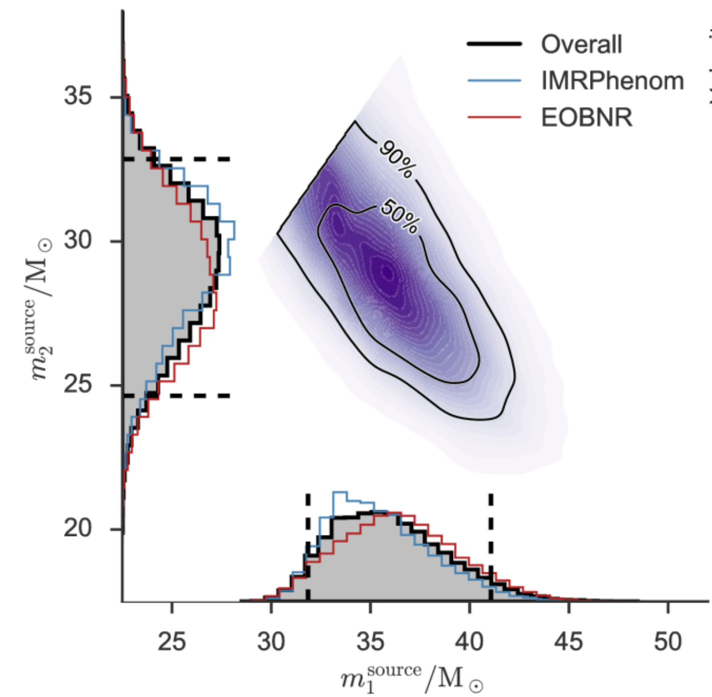
We can rule out one object being a neutron star, so both objects must be black holes.

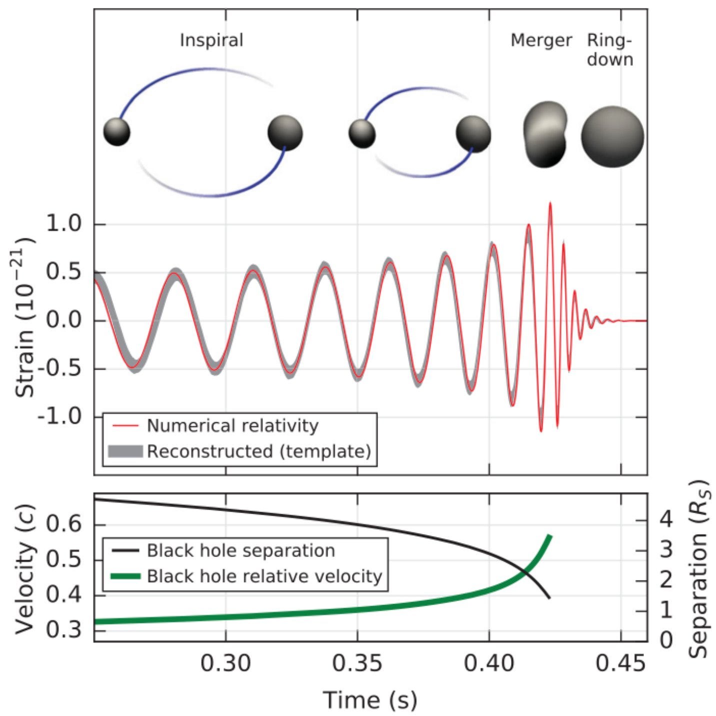
Best estimate for masses:

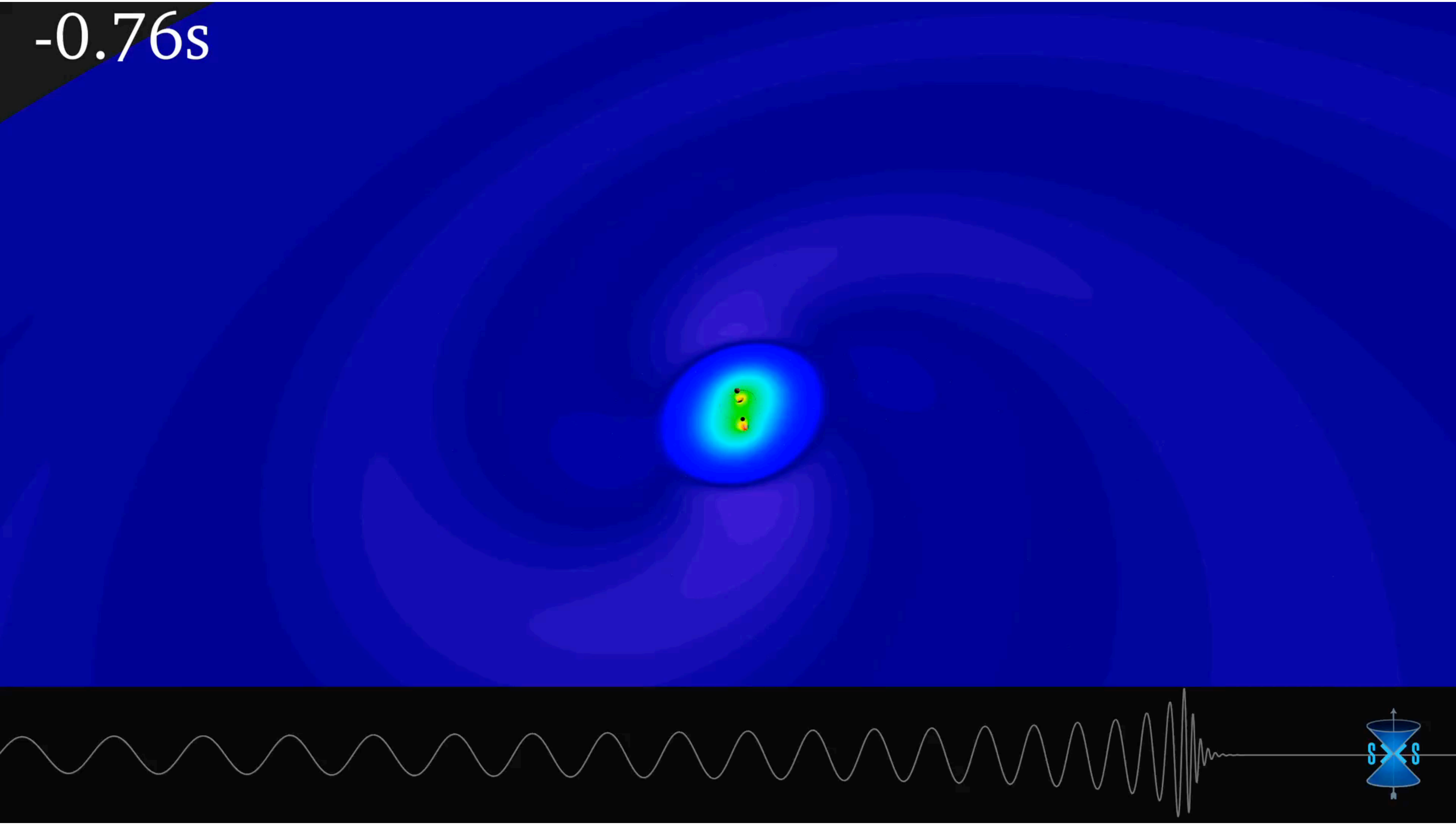
$$36^{+5}_{-4} M_\odot \text{ and } 29^{+4}_{-4} M_\odot$$

Final BH mass: $62^{+4}_{-4} M_\odot$

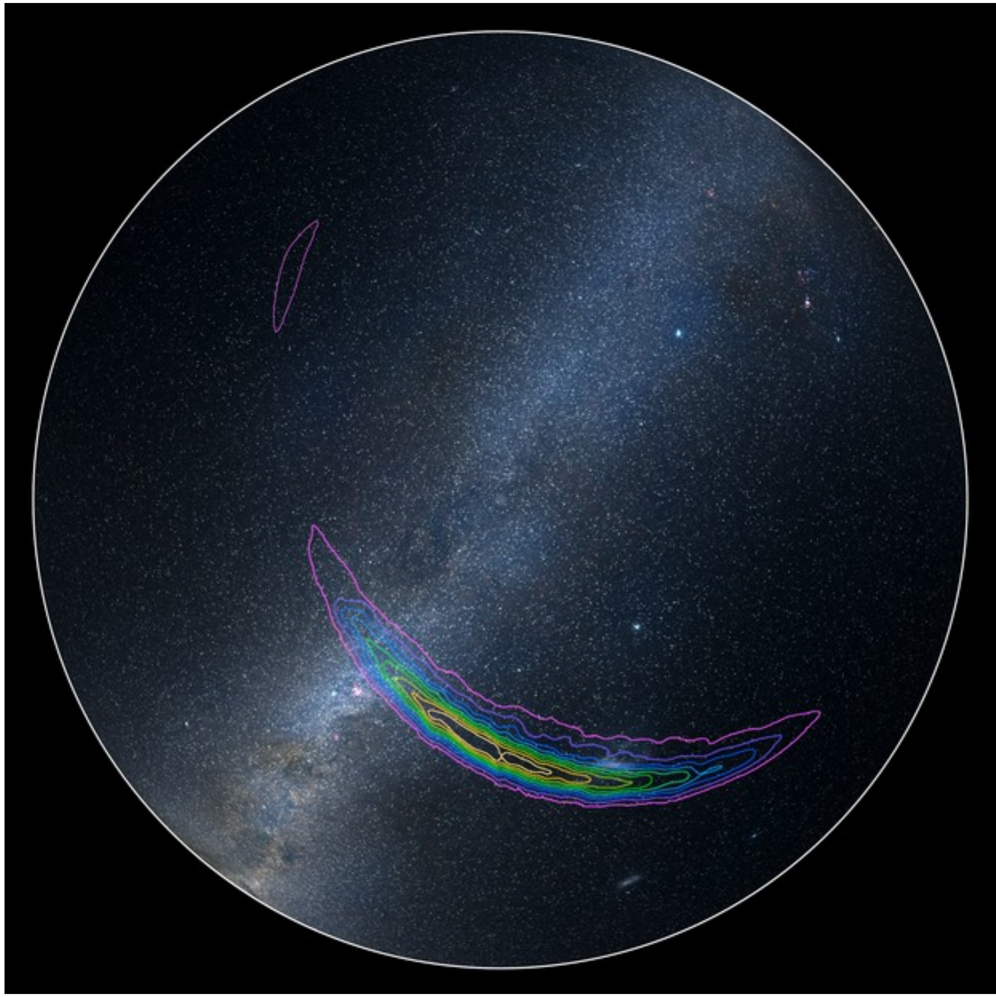
so $3.0^{+0.5}_{-0.5} M_\odot c^2$ radiated away as gravitational waves.





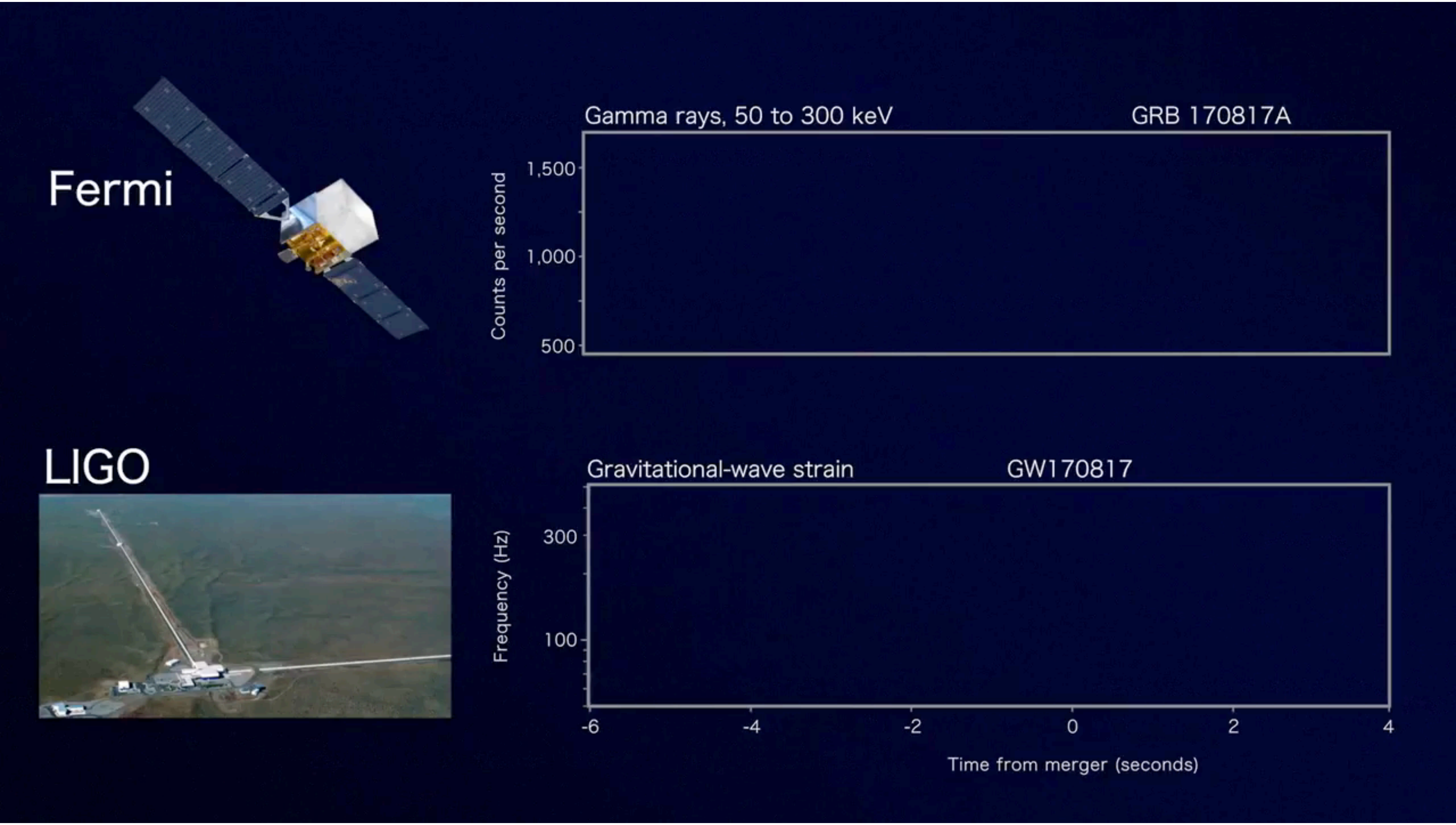

-0.76s

From strength of signal, we get weak limits on position and distance of source: the source is localised to a 600 deg^2 area in the Southern hemisphere, and the distance to the source is about 400 Mpc.

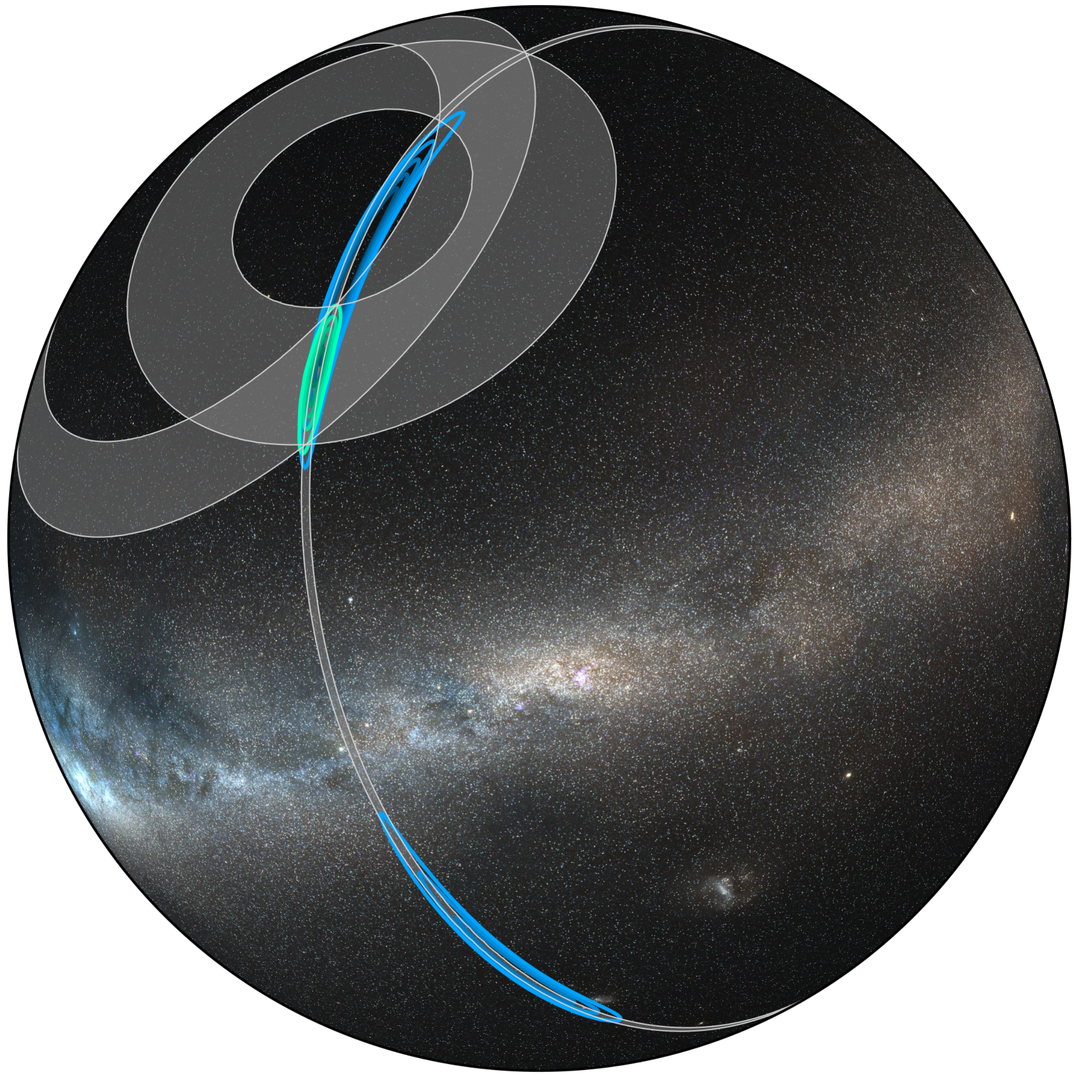


Then, on 27 August 2017, something else happened.

At 10:41pm Sydney time, the *Fermi* Gamma-ray Burst Monitor detected a short gamma ray burst. 6 minutes later a gravitational wave candidate was announced that was consistent with a binary neutron star merger. This event, now known as GW170817 was the first detection of a neutron star merger.

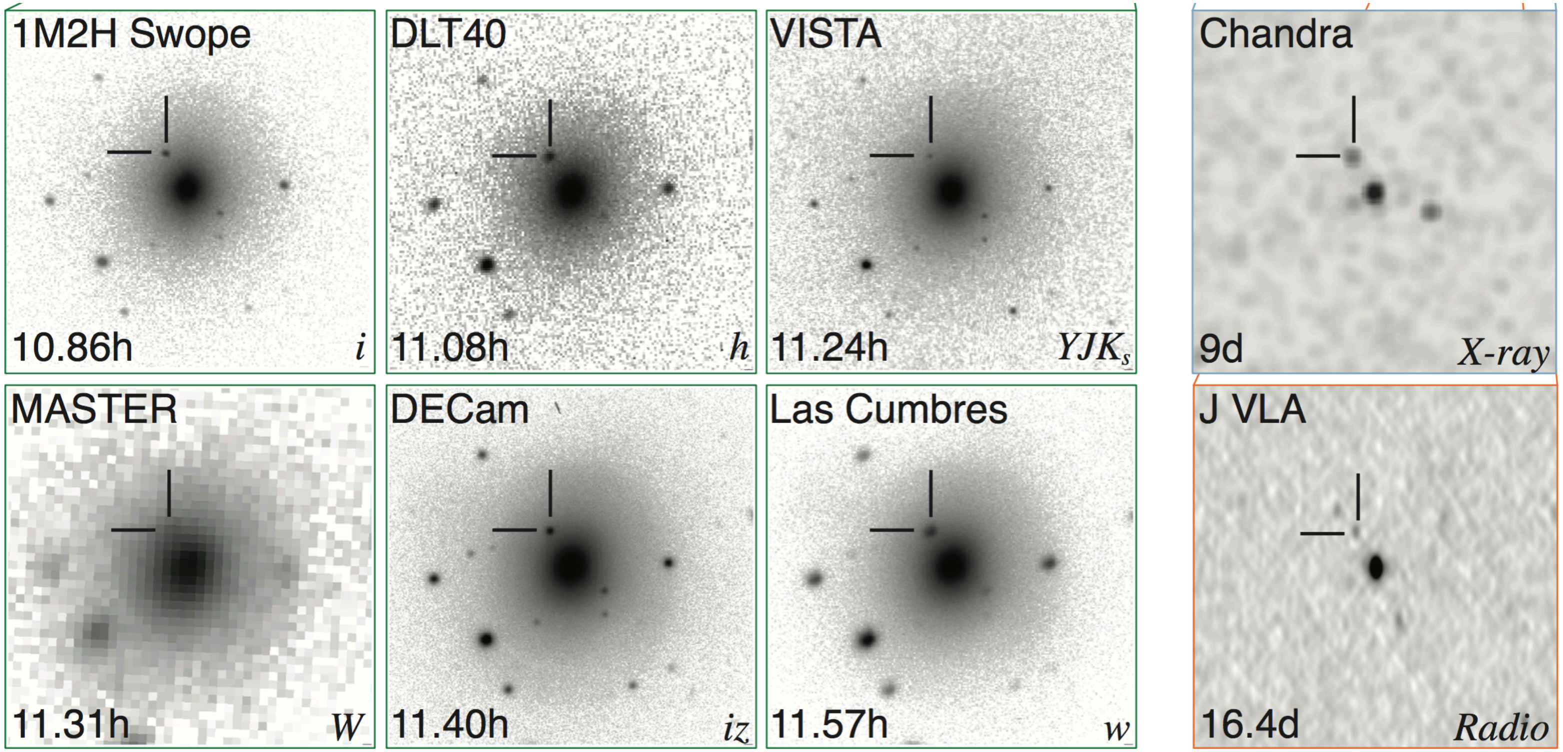

Fermi
LIGO
Gamma rays, 50 to 300 keV
GRB 170817A
Counts per second
1,500
1,000
500
Gravitational-wave strain
GW170817
Frequency (Hz)
300
100
-6
-4
-2
0
2
4
Time from merger (seconds)

By combining data from the *Fermi* and *Integral* space missions with data from LIGO and the European interferometer Virgo, scientists were able to confine the source of the waves to a 30-square-degree sky patch.

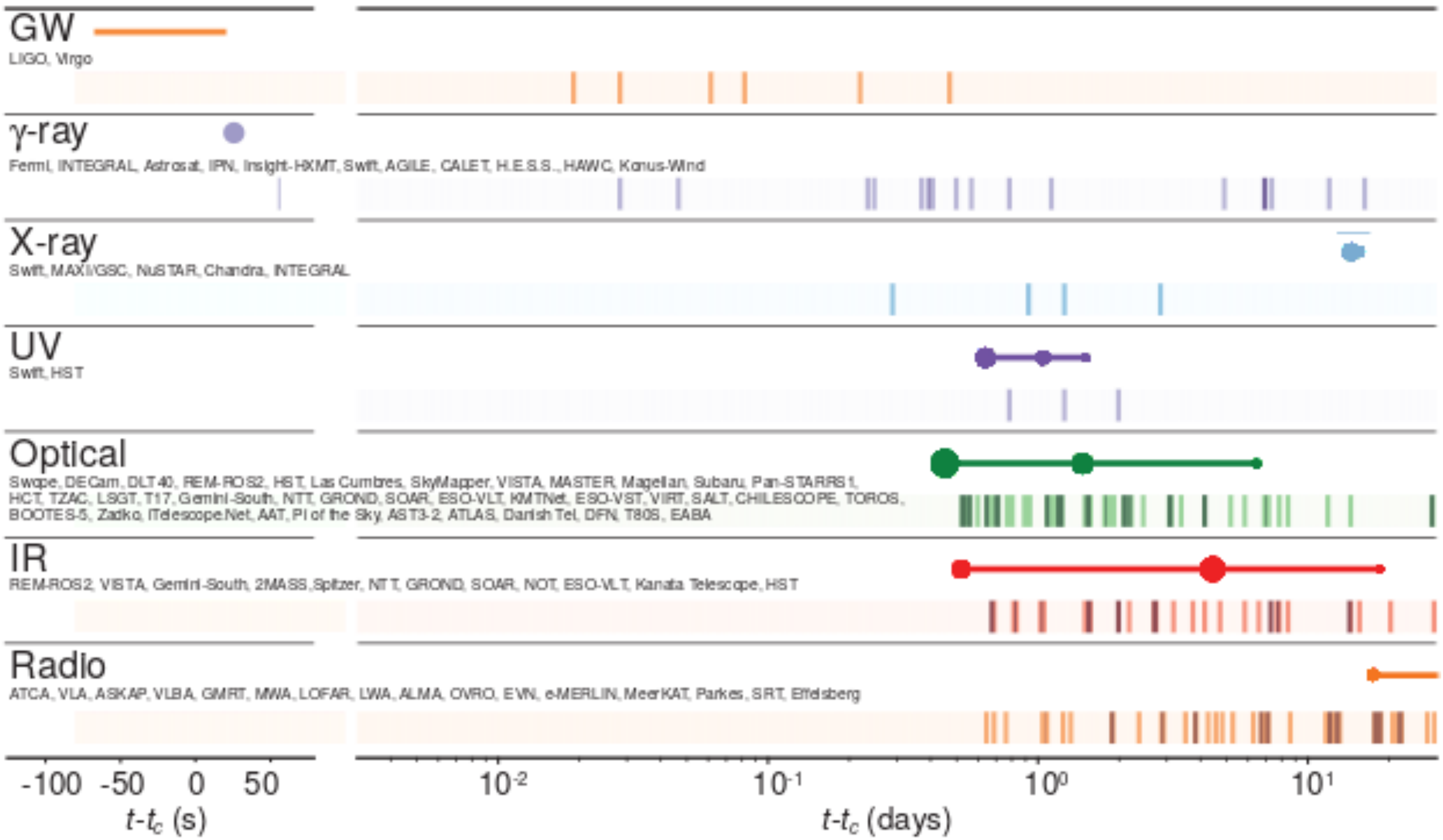


Credit: LIGO/Virgo/NASA/Leo Singer (Milky Way image: Axel Mellinger)

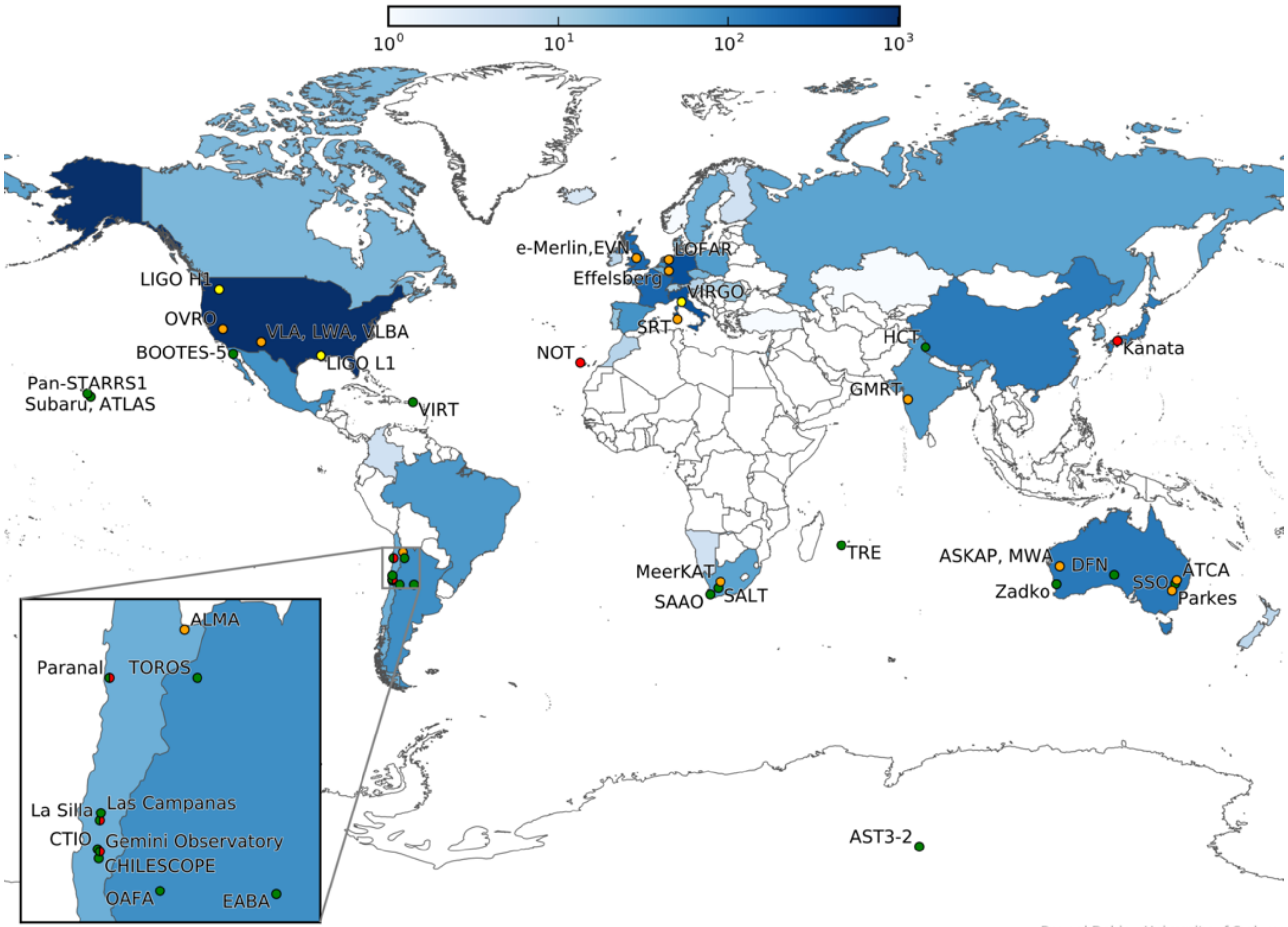
Immediately, telescopes all over the world started observing galaxies in this patch of sky, looking for the source of the event. Within 10 hours of the event, a telescope in Chile had detected an optical transient in an unremarkable galaxy, NGC 4993.



Nearly two weeks later, an X-ray and a radio object were detected at the same position.



Over 3,500 individuals from 953 institutions were involved in the follow-up of this event, using 90 telescopes spread out across every continent on Earth and in space.



All together, the observations produced a picture of what happened during the merger:

- there was an initial gamma-ray burst at the time of the merger
- then a longer afterglow seen in optical, ultraviolet and infrared light, resulting from the radioactive decay of heavy elements produced in the explosion
- much later: delayed X-ray and radio emission

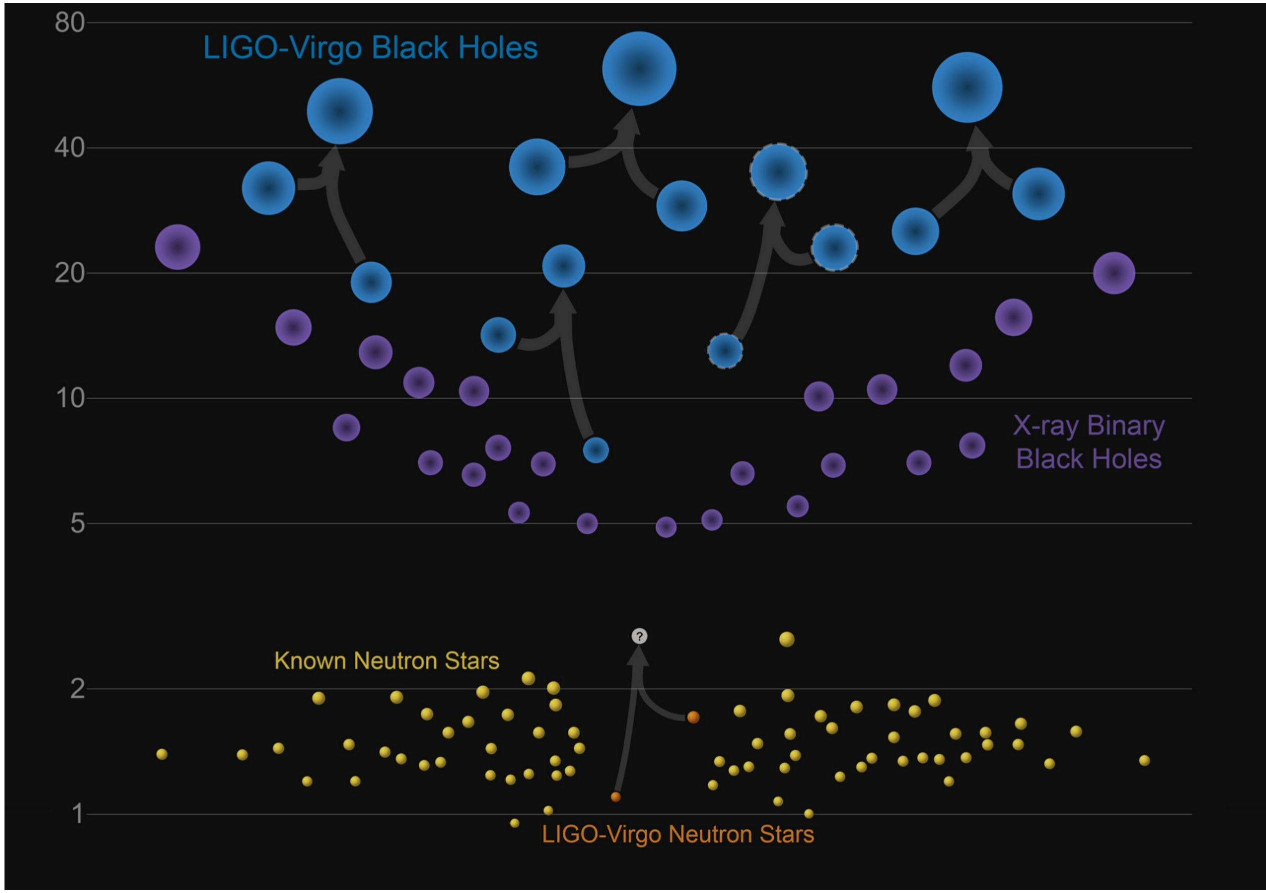

RIPPLES OF GRAVITY,
FLASHES OF LIGHT:
WORLD'S OBSERVATORIES
WITNESS A COSMIC CATACLYSM

What did we learn from GW170817?

- What is the remnant of a neutron star merger?
- Does gravity behave as Einstein predicted?
- Where do the heaviest elements in the Universe come from?
- How fast is the Universe expanding?

…and more!

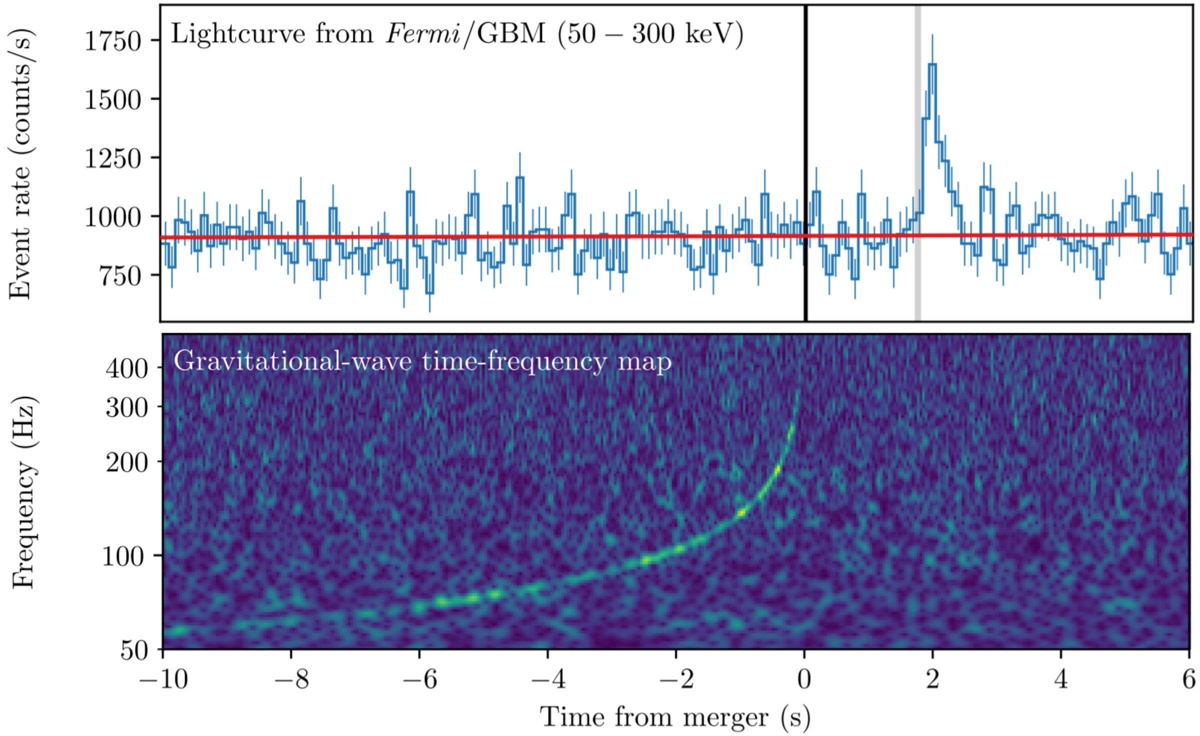
The mass of the object that formed from the merger has a mass somewhere between all the known neutron stars and all the known black holes. While we suspect the merger formed a black hole, it might instead have left behind a hyper massive neutron star, which might later collapse to a black hole.



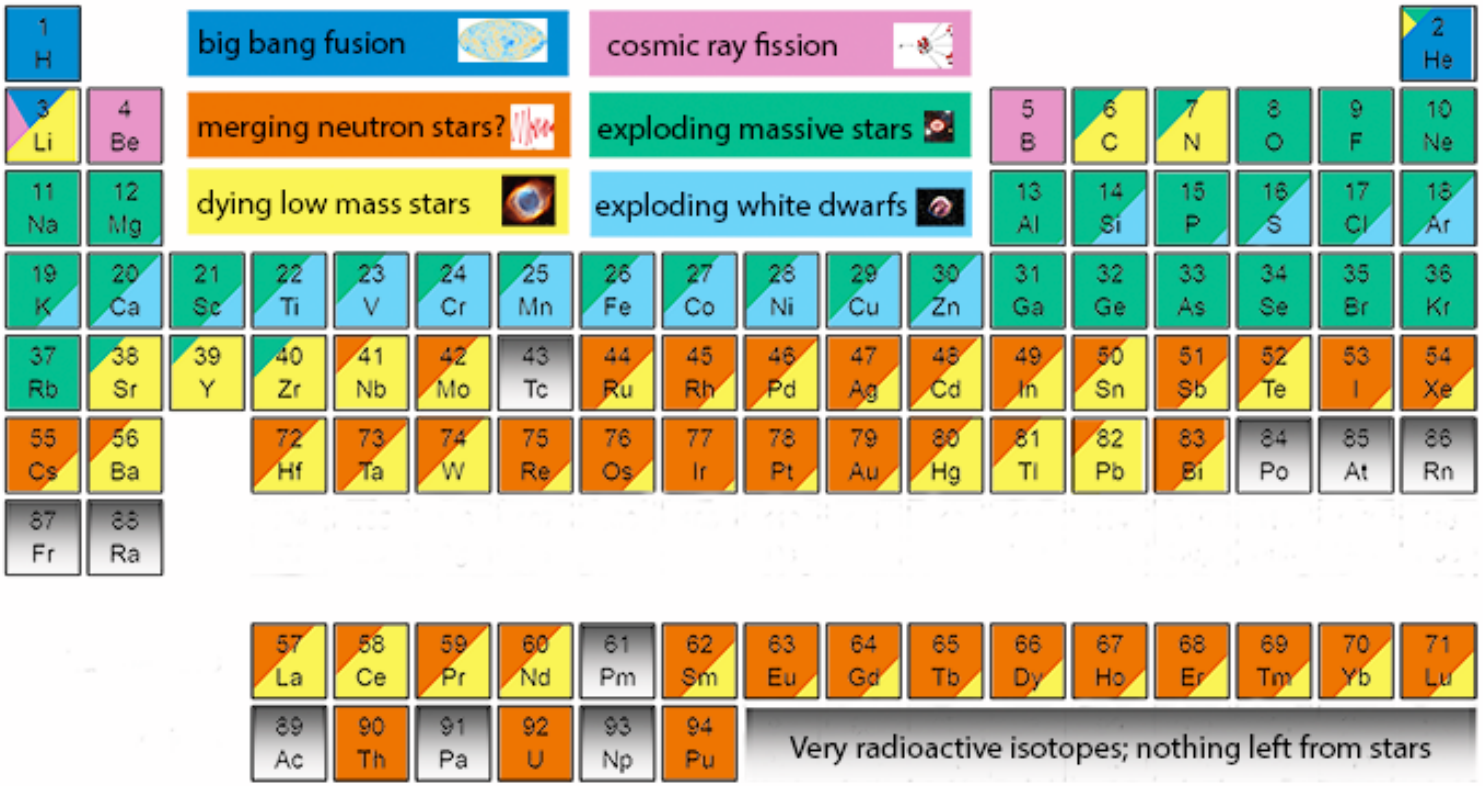
The difference in arrival time between the gravitational waves and gamma-rays can be used to estimate the speed of gravity.

The gravitational waves arrived 1.7 seconds later than the gamma-rays, over a distance of 120 million light years, meaning they are travelling at the same speed to one part in 10^{15}.

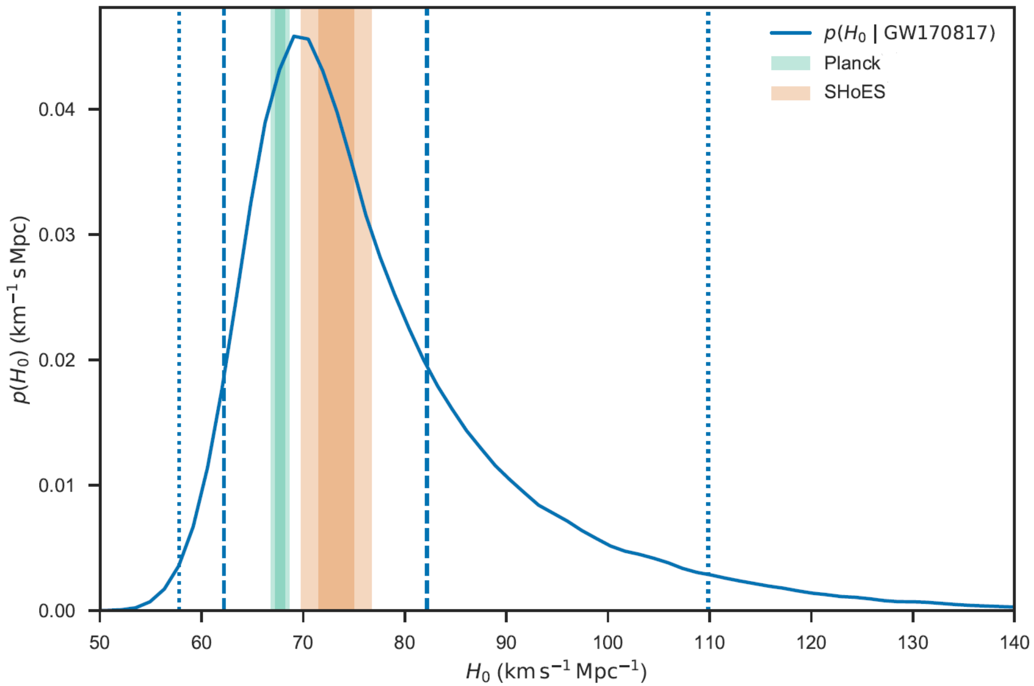
If the gamma-rays were emitted slightly later than the gravitational waves (late collapse of a hyper massive neutron star?) then the speeds can be identical.



The optical spectrum contained evidence of the formation of heavy elements in the explosion itself, including approximately ten Earth masses of gold and platinum.



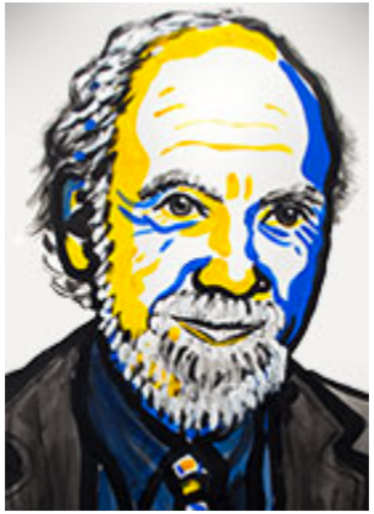
And what's more, we've now got the possibility of measuring the distances to galaxies in a completely new way, using gravitational wave events as "standard sirens". With only one event, gravitational waves don't yet resolve which of the two (slightly different) values for the Hubble Constant is right — but as more events are discovered, it might be possible.



The Nobel Prize in Physics 2017

Rainer Weiss

Prize share: 1/2



Barry C. Barish

Prize share: 1/4

Kip S. Thorne

Prize share: 1/4

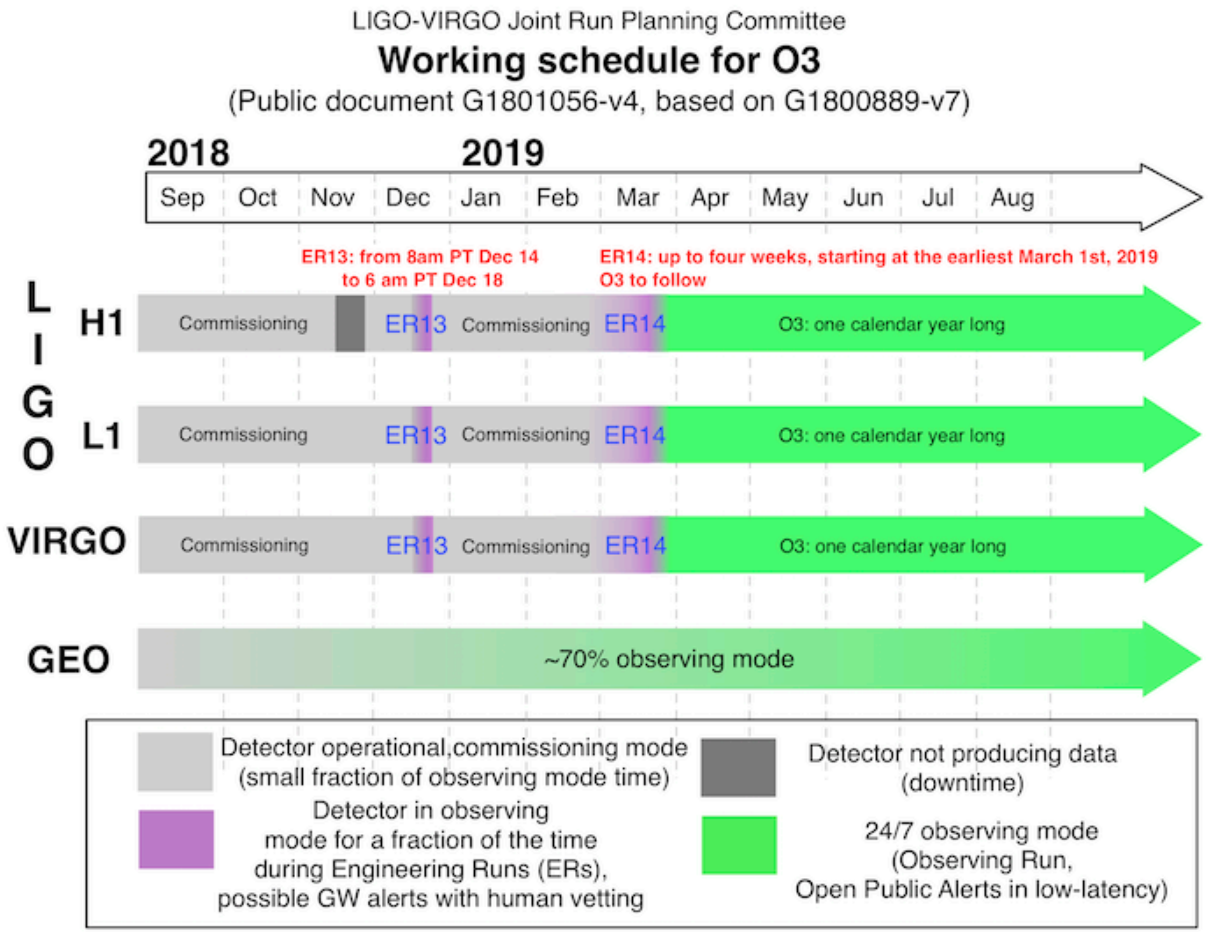
The Nobel Prize in Physics 2017 was divided, one half awarded to Rainer Weiss, the other half jointly to Barry C. Barish and Kip S. Thorne *"for decisive contributions to the LIGO detector and the observation of gravitational waves"*.

LIGO's third observing run starts in February next year.

Predictions are they could see several black hole mergers per week.

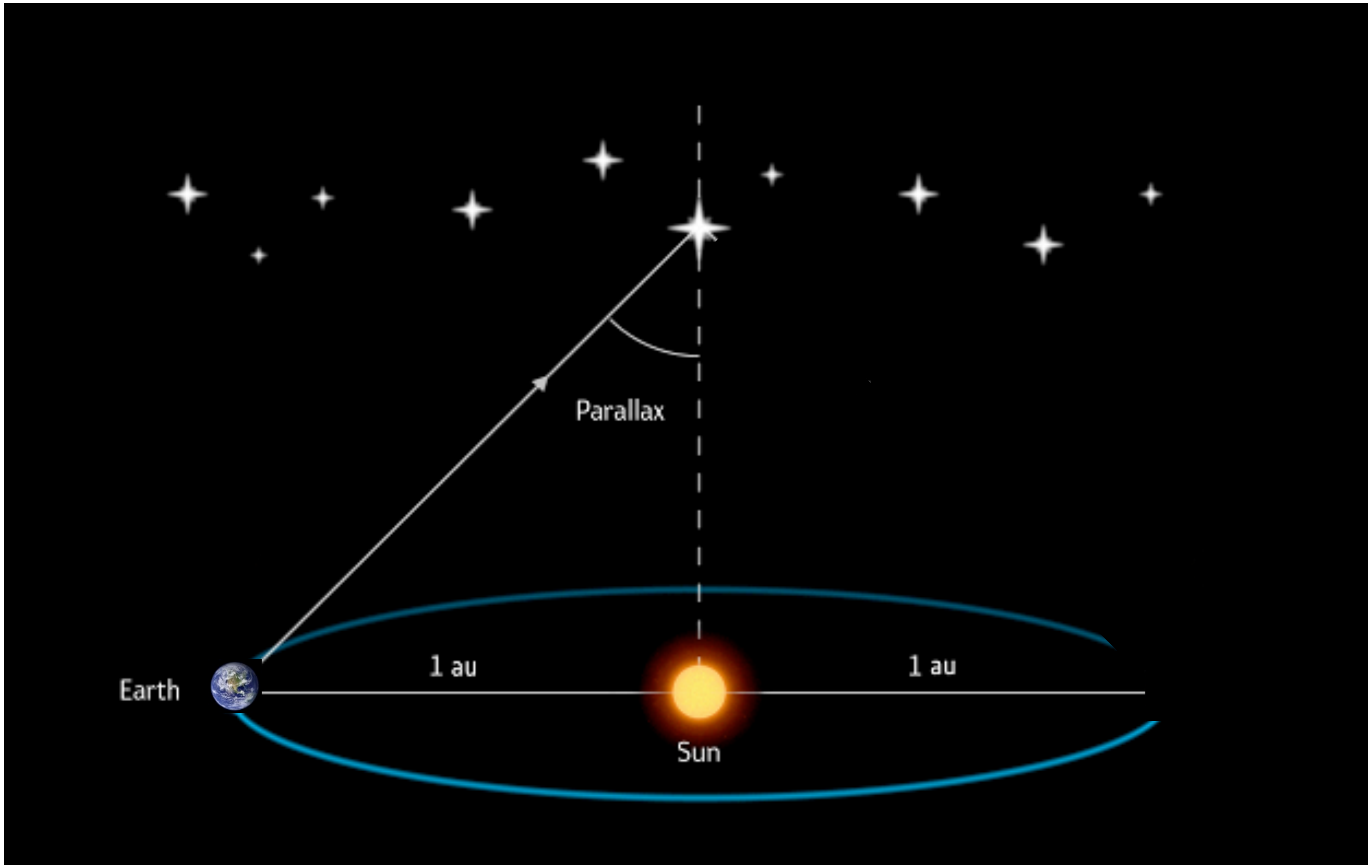
Other targets of interest include black hole-neutron star binaries (rate unknown).

For the first time, all LIGO alerts will be public.



Hipparcos and Gaia

Remember back in lecture 3, we worked out that we can use triangulation to measure the distances to the stars, but the only baseline long enough is the size of the Earth's orbit.



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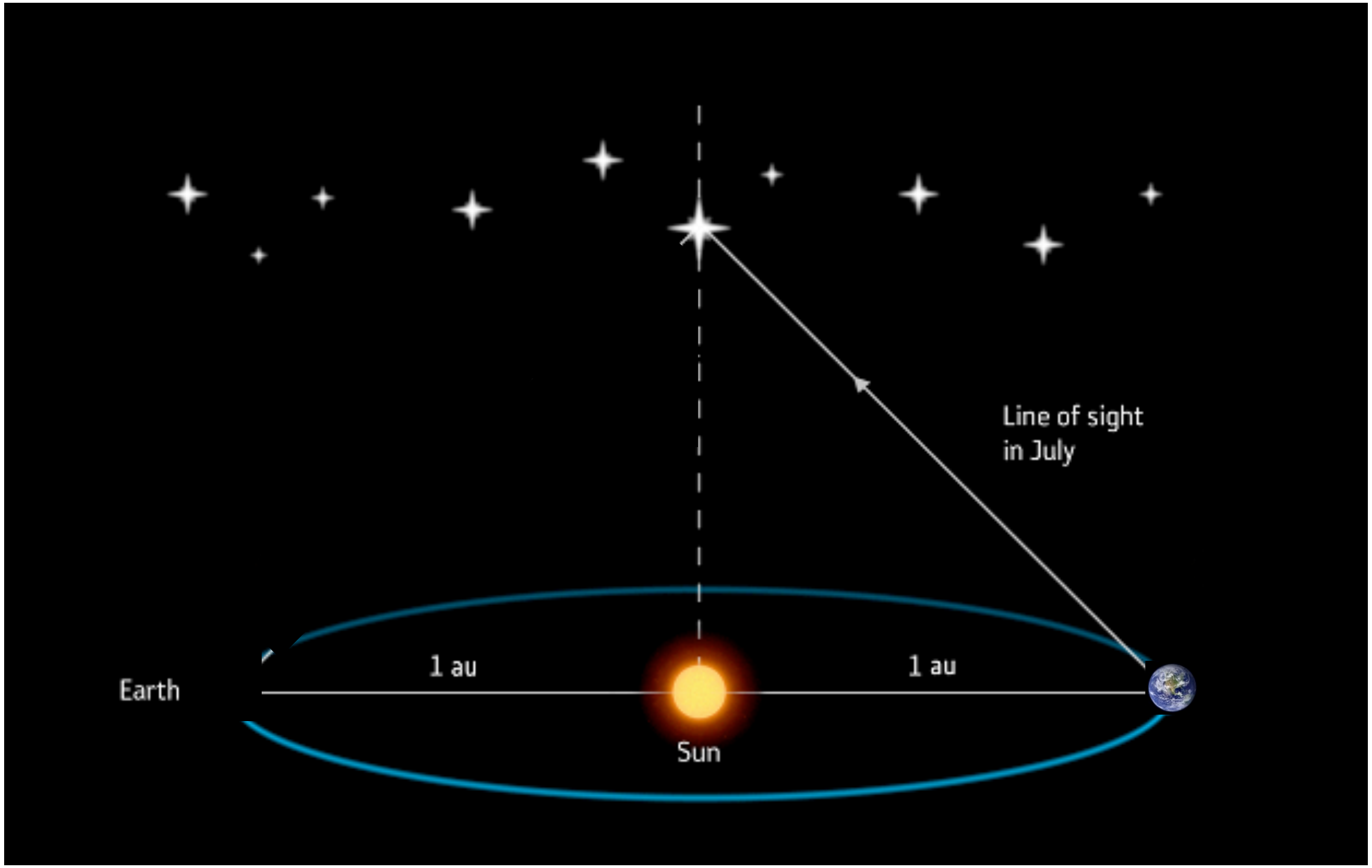
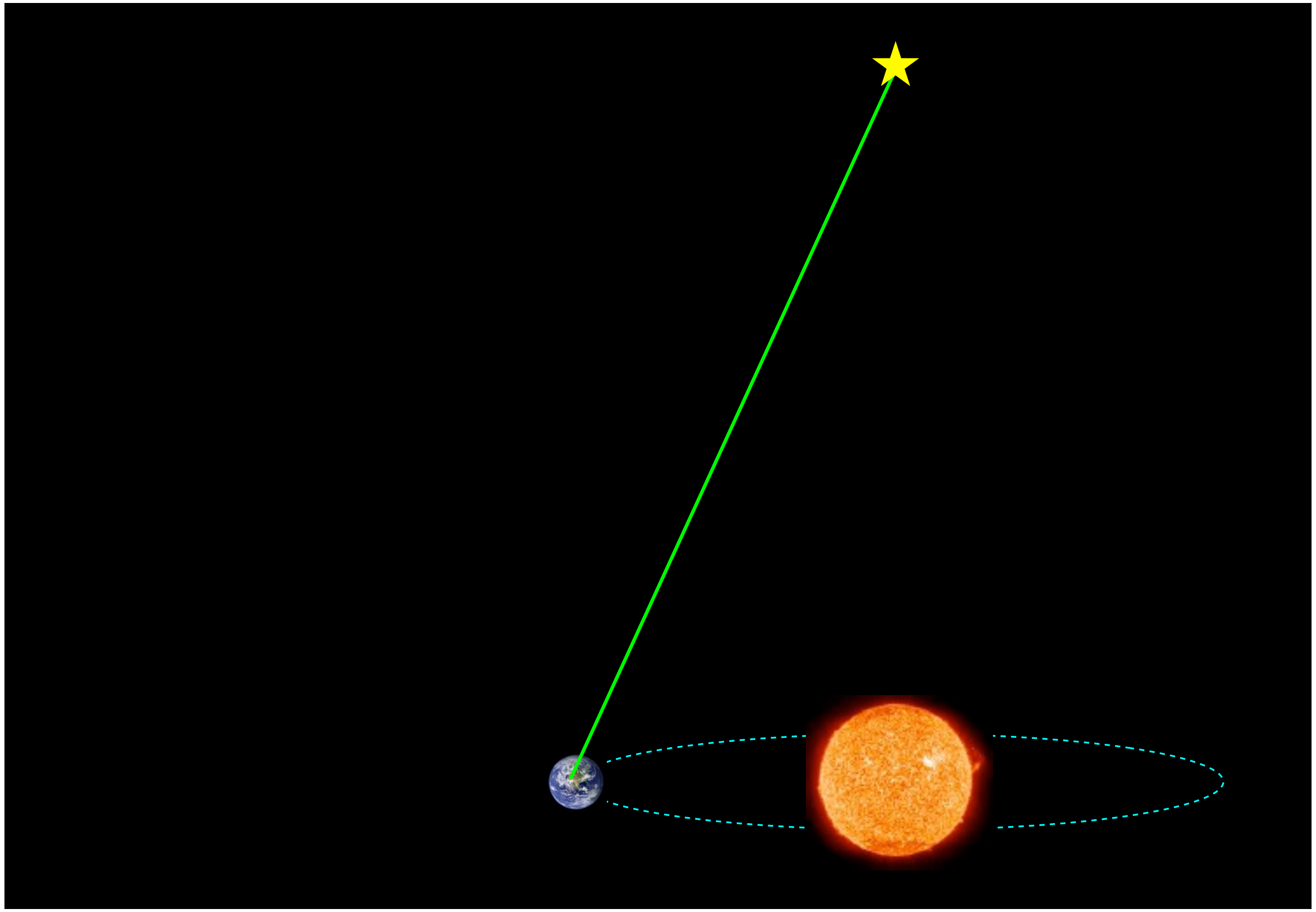


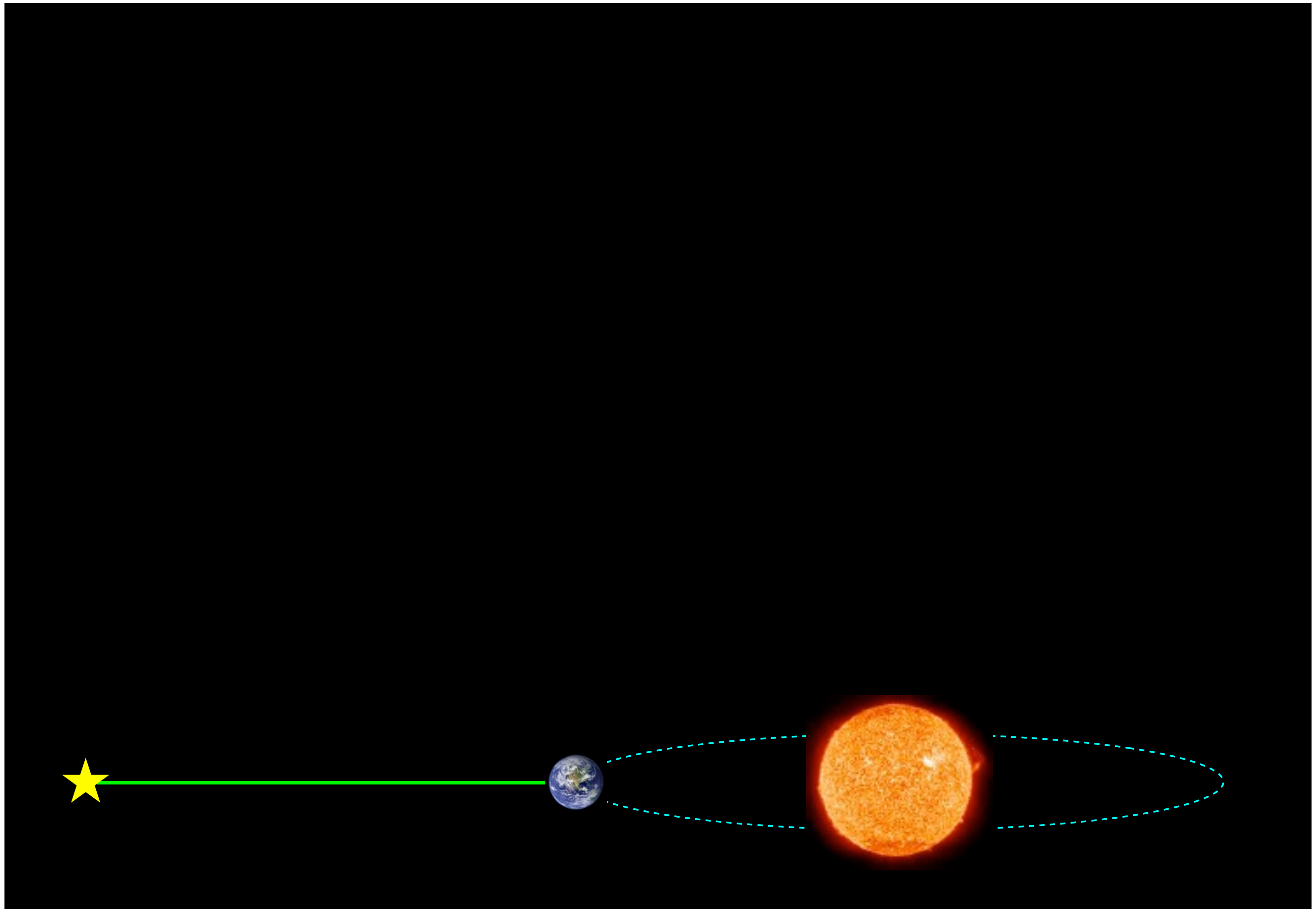
The closer the star, the bigger the wobble.

A star directly above the ecliptic will move in a circle.



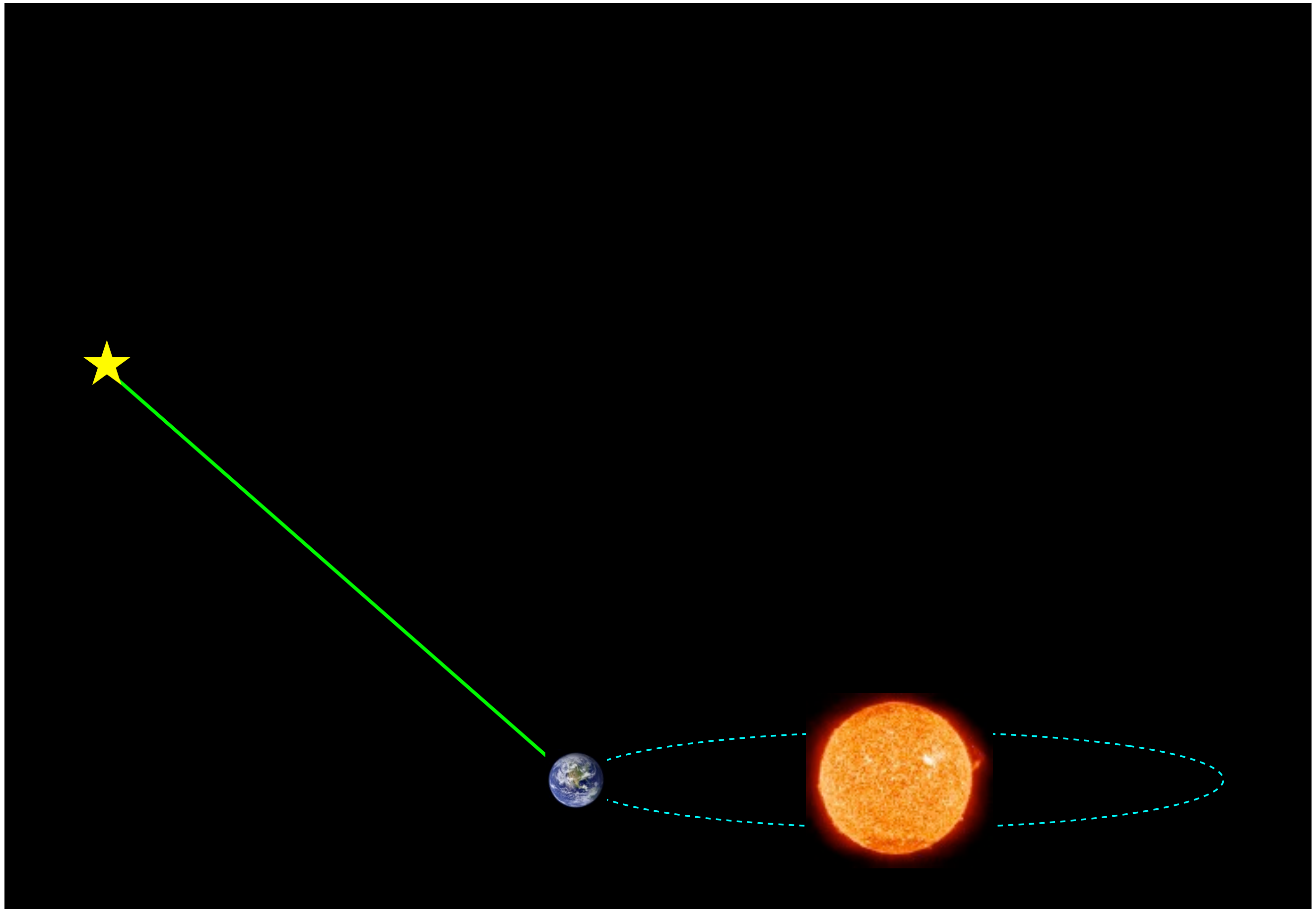
The closer the star, the bigger the wobble.

A star in the ecliptic plane will move in a straight line.

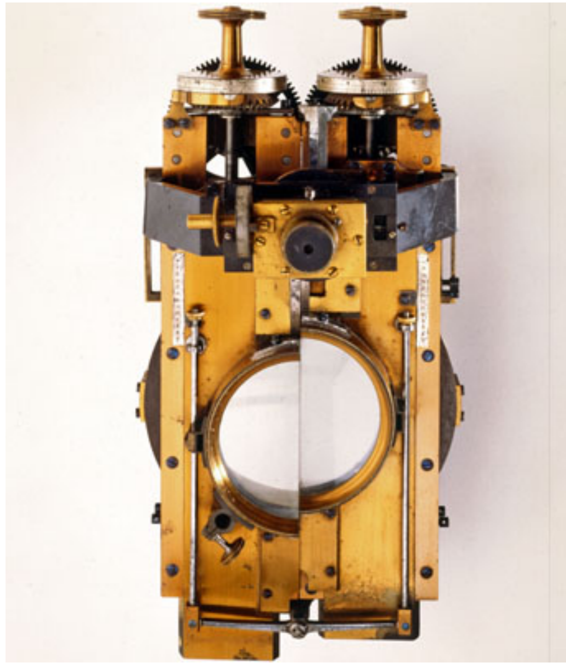


The closer the star, the bigger the wobble.

A star in between will move in an ellipse: the closer the star's position to the ecliptic, the flatter the ellipse.

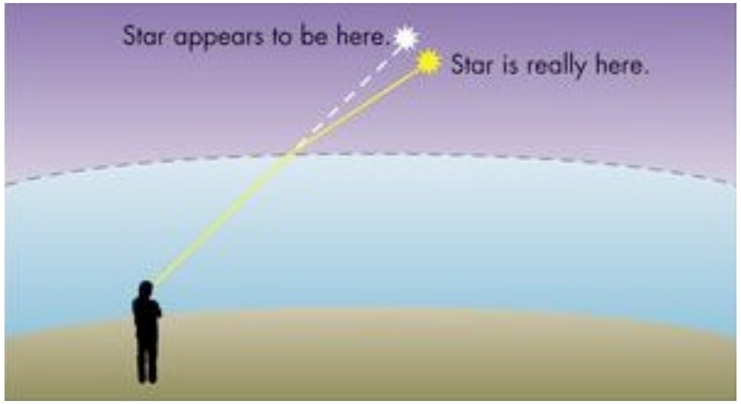


The first parallax was measured in 1838 by Friedrich Bessel. He found that the star 61 Cygni wobbled by 0.314 arc seconds over the course of the year, so is at a distance of about 10 light years. Even the nearest star, Alpha Centauri, has a parallax of only 0.74 arcseconds, which is tiny.



Bessel used a special telescope called a heliometer, which has a split lens, allowing small angles to be measured very accurately

There are all sorts of problems which make the measurement of parallax hard:

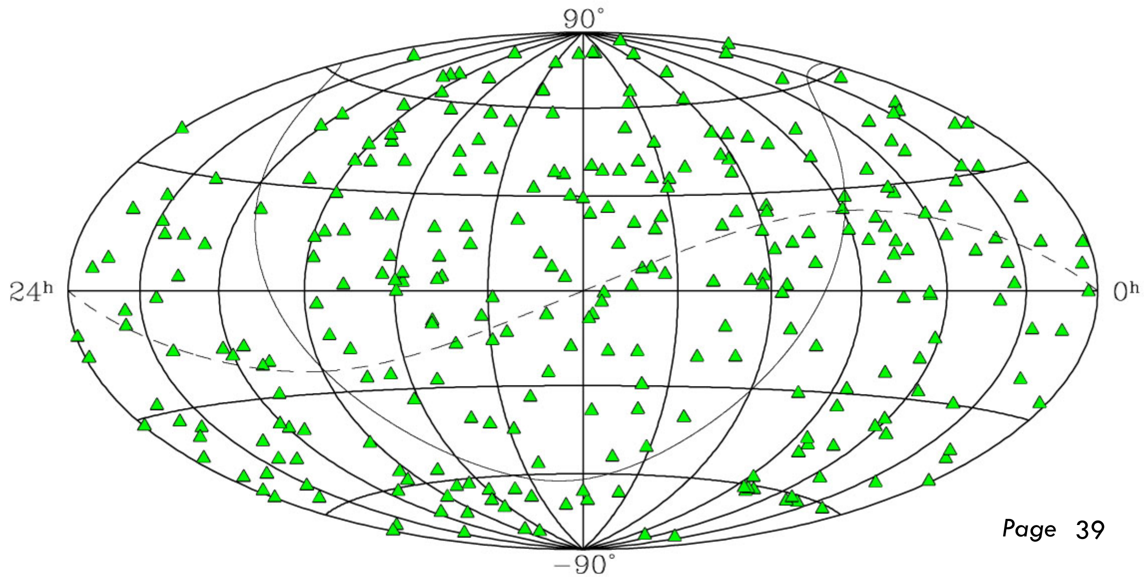


– seeing

– atmospheric refraction

– *precession* and *nutation* (the Earth's axis wobbles)

– reference points

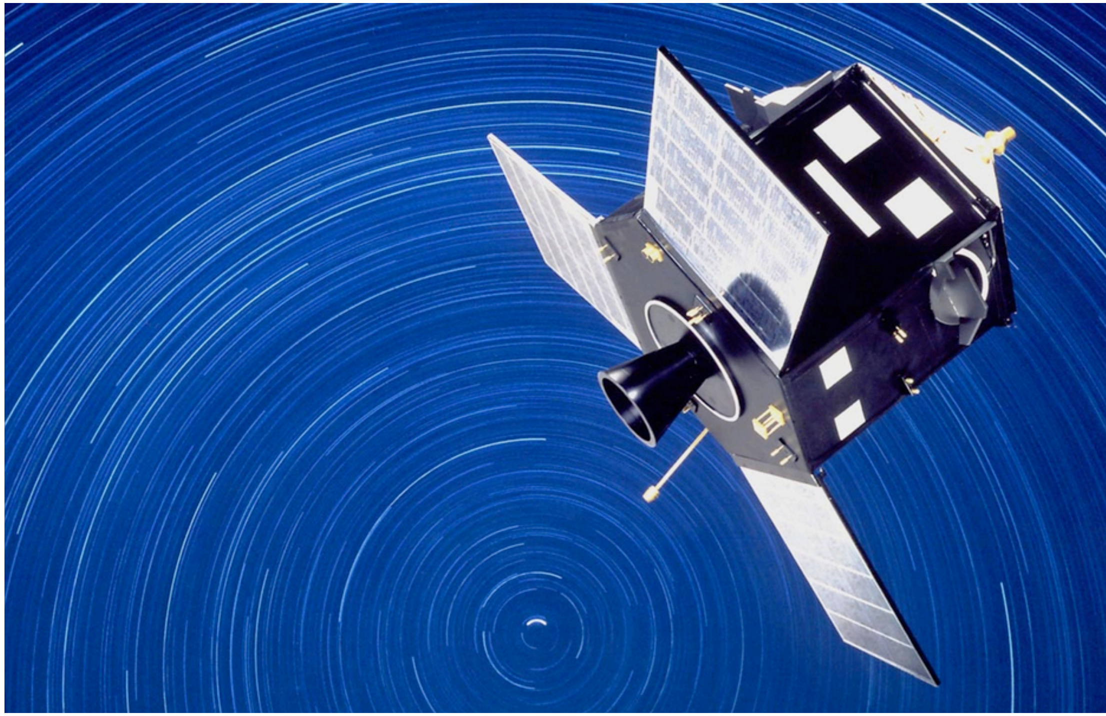


The defining and candidate sources which make up the International Celestial Reference Frame.

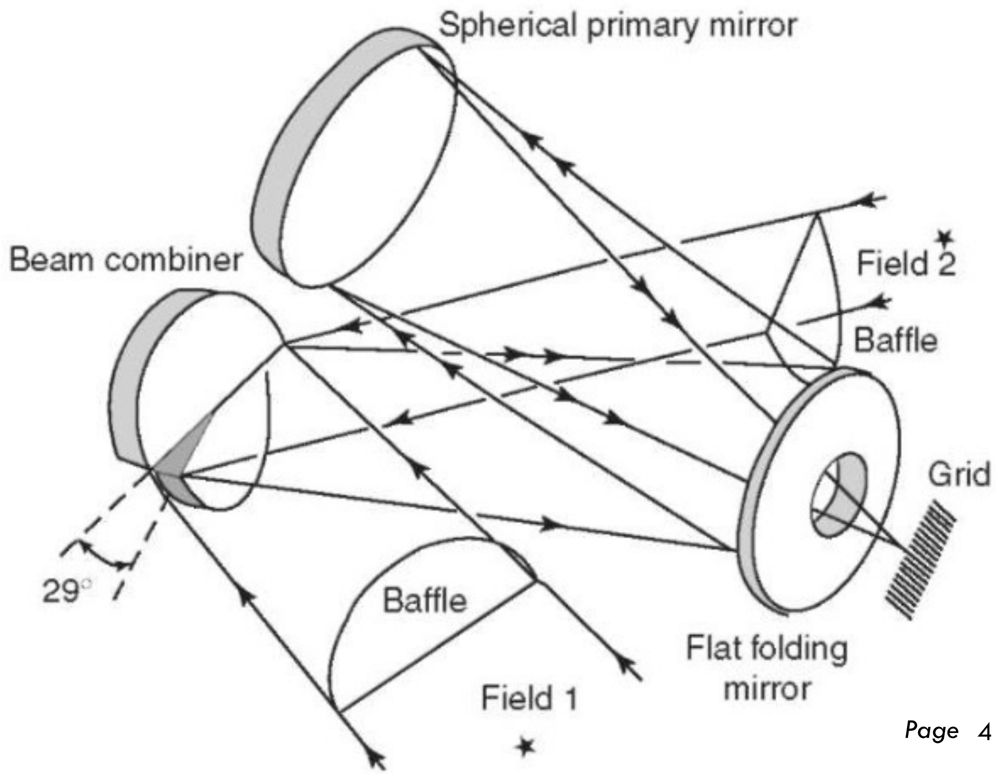
In 1989 the European Space Agency launched the *Hipparcos* mission.

By observing from space, *Hipparcos* avoided many of the problems associated with ground-based measurements.

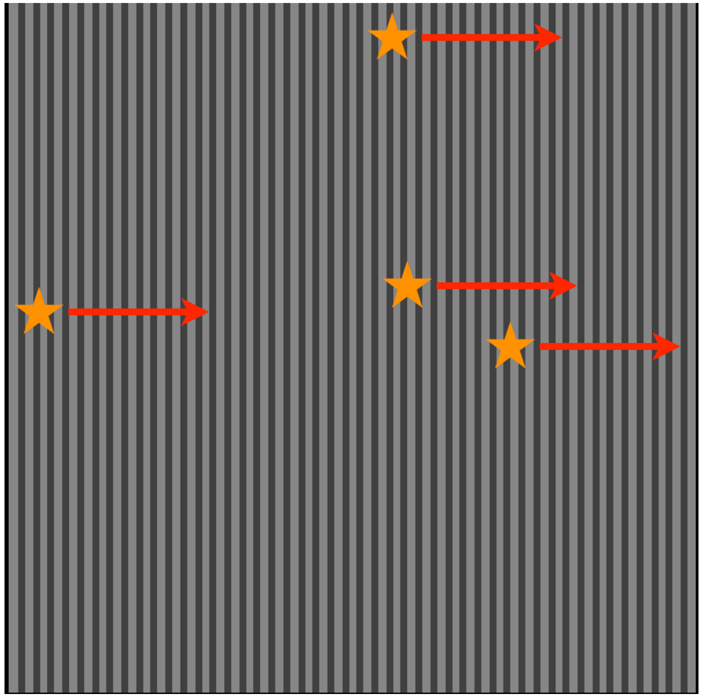
Its revolutionary aim: to determine positions, parallaxes and proper motions for over 100,000 stars – all at the *same time*.



The heart of *Hipparcos*: a split mirror, which looked at two parts of the sky at the same time, so as the satellite spun around it simultaneously observed two fields 58° apart. This connects the measurements of stars in different parts of the sky, making the whole map much more accurate.

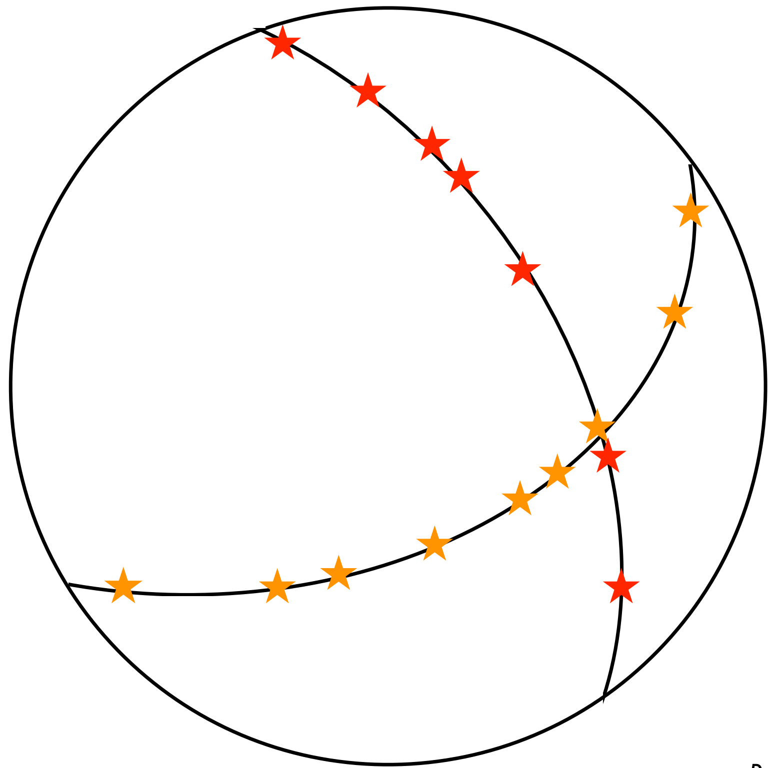


The satellite spun around in slowly changing directions, so almost the entire sky was covered. Stars, whose positions were known in advance, drifted across a finely-spaced grid of slits, thus determining their positions in the direction of spin very accurately.

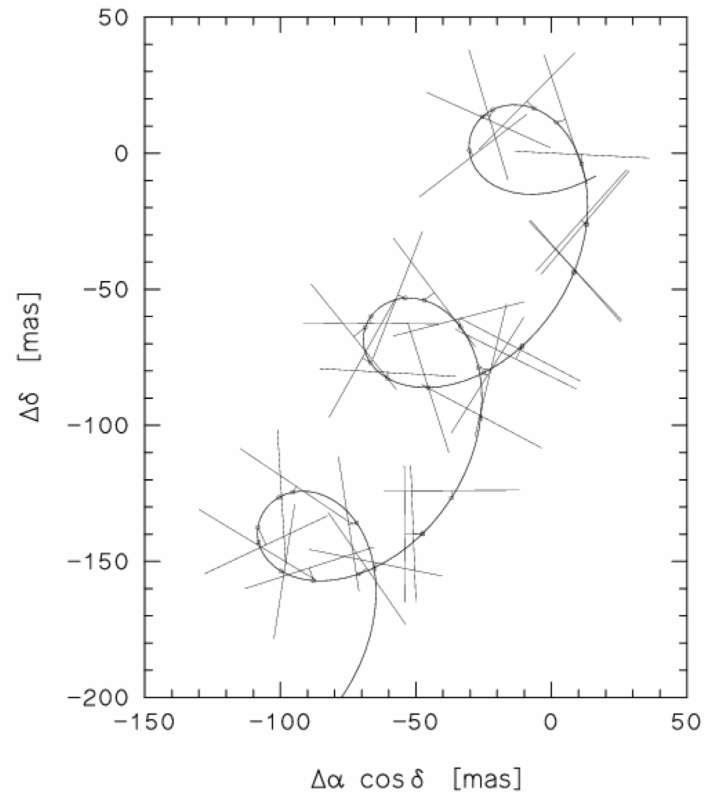


Effectively, the angular distance between stars was measured along great circles in the sky, with about 2000 stars per orbit, and 2768 orbits in total.

When many such orbits were combined together, the locations and motions of all the stars could be determined with high precision.



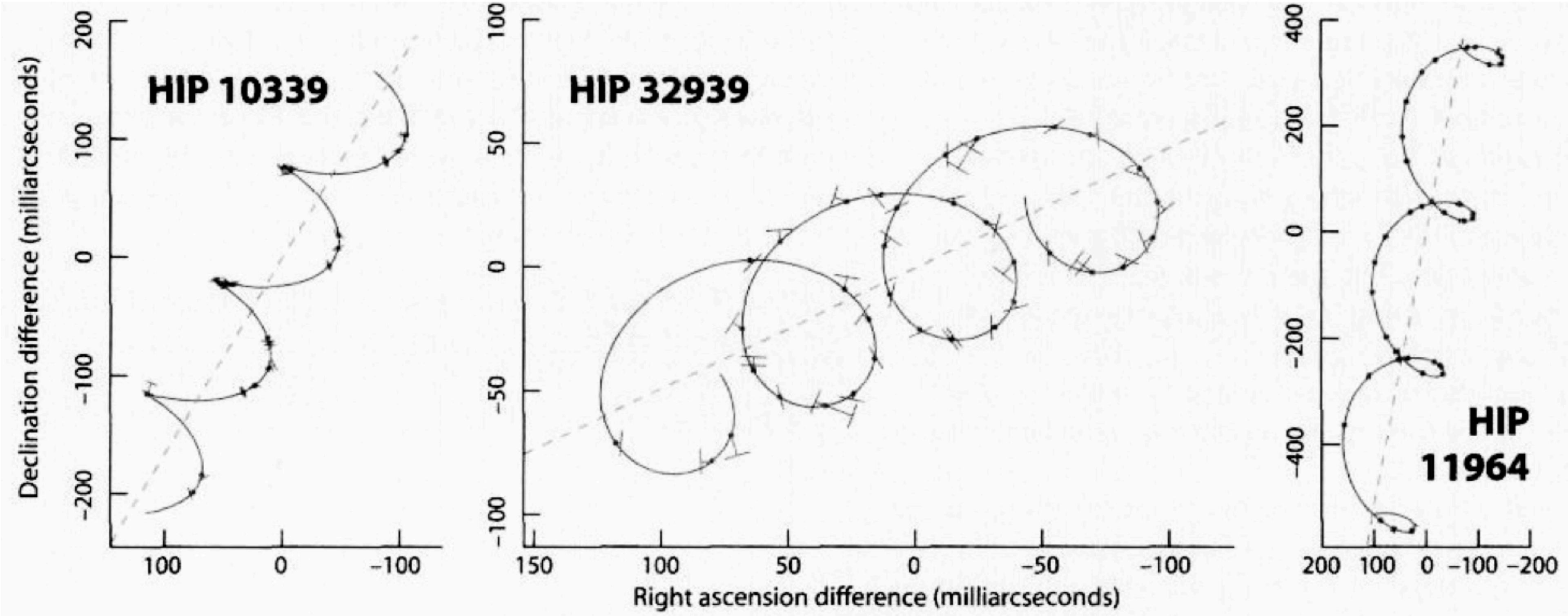
Because the location of each star was very well determined in the direction of rotation, but not so well determined in the other direction, each observation of a star constrained its position to be on one of the straight lines in the following picture. A star was observed between 30 and 150 times, depending on where in the sky it was.



The positions are fit with a five parameter curve:

– x, y position
– x, y velocity
– parallax

More examples of the apparent paths of stars across the sky, and the astrometric fits to them.



The positions, velocities and parallaxes of all the stars were solved in one giant calculation.

In the first solution, for instance, using only the 40,000 best observed stars, there were

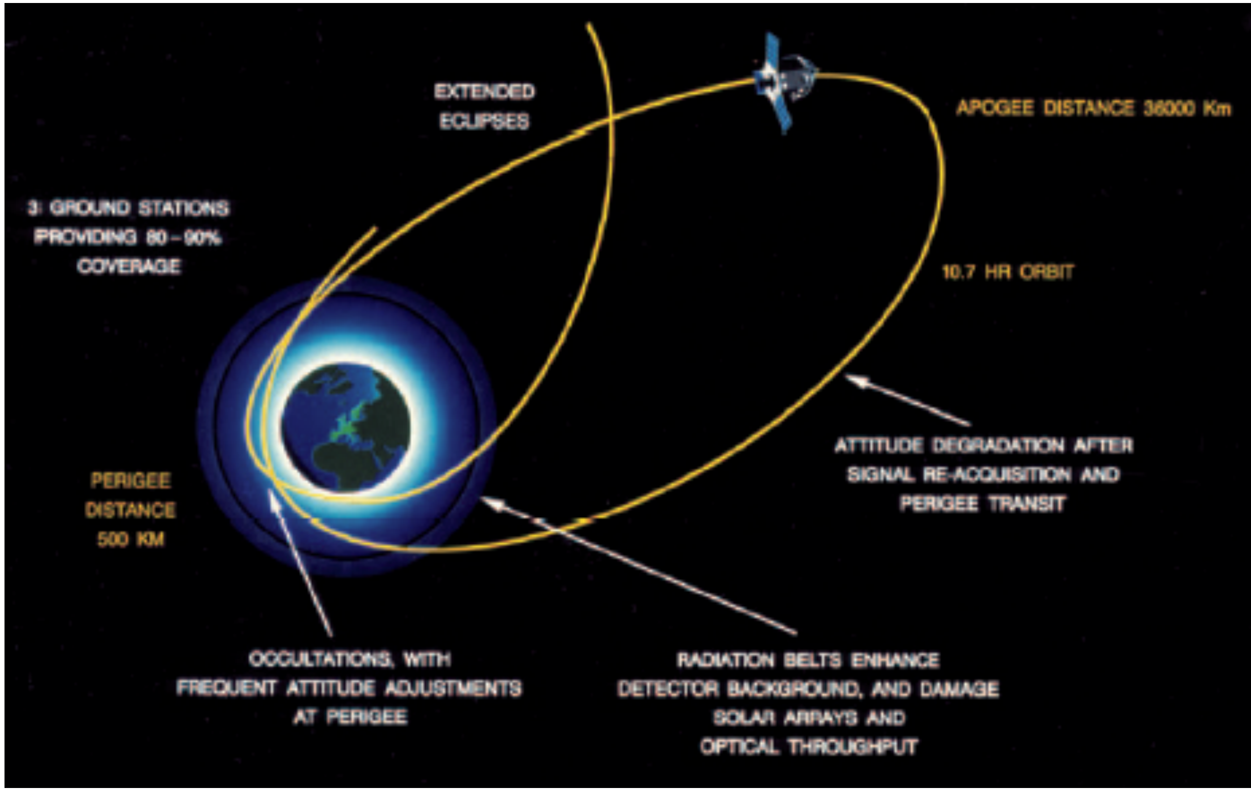
- 10^6 simultaneous equations with
- 200,000 astrometric parameters (5 per star)
- 2000 parameters describing the orientation of satellite
- <10 instrumental parameters

Because there were many more observations per star than needed to measure these five parameters, *Hipparcos* was also extremely good at finding binaries and multiple stars.

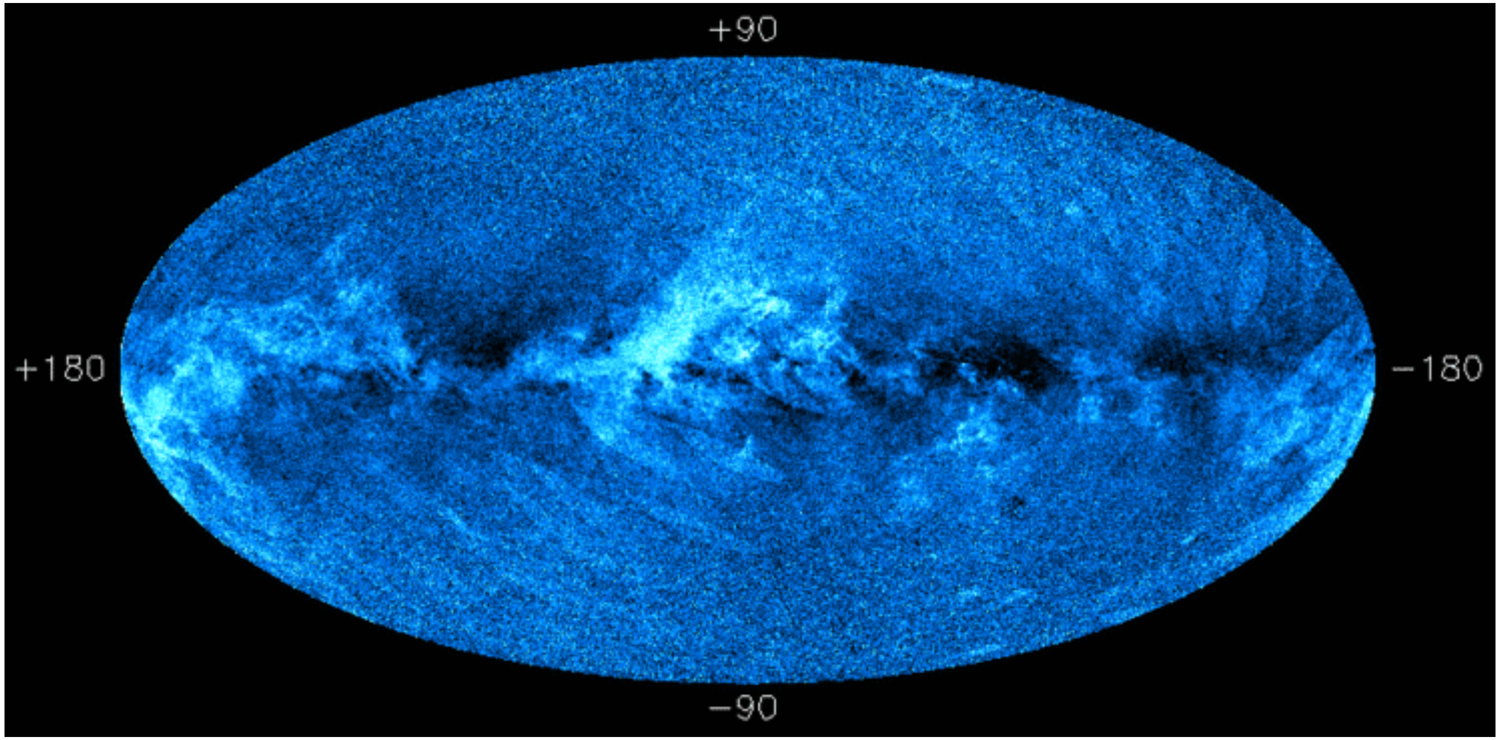
Hipparcos was launched on an Ariane 4 rocket on 8 August 1989, destined for a geostationary orbit.

However, the apogee boost motor failed, leaving *Hipparcos* in a highly elliptical orbit (perigee 500 km, apogee 36,500 km)

Despite this potentially catastrophic failure, *Hipparcos* successfully observed for 3.5 year, completing 2768 orbits, and produced results even better than the original aims.

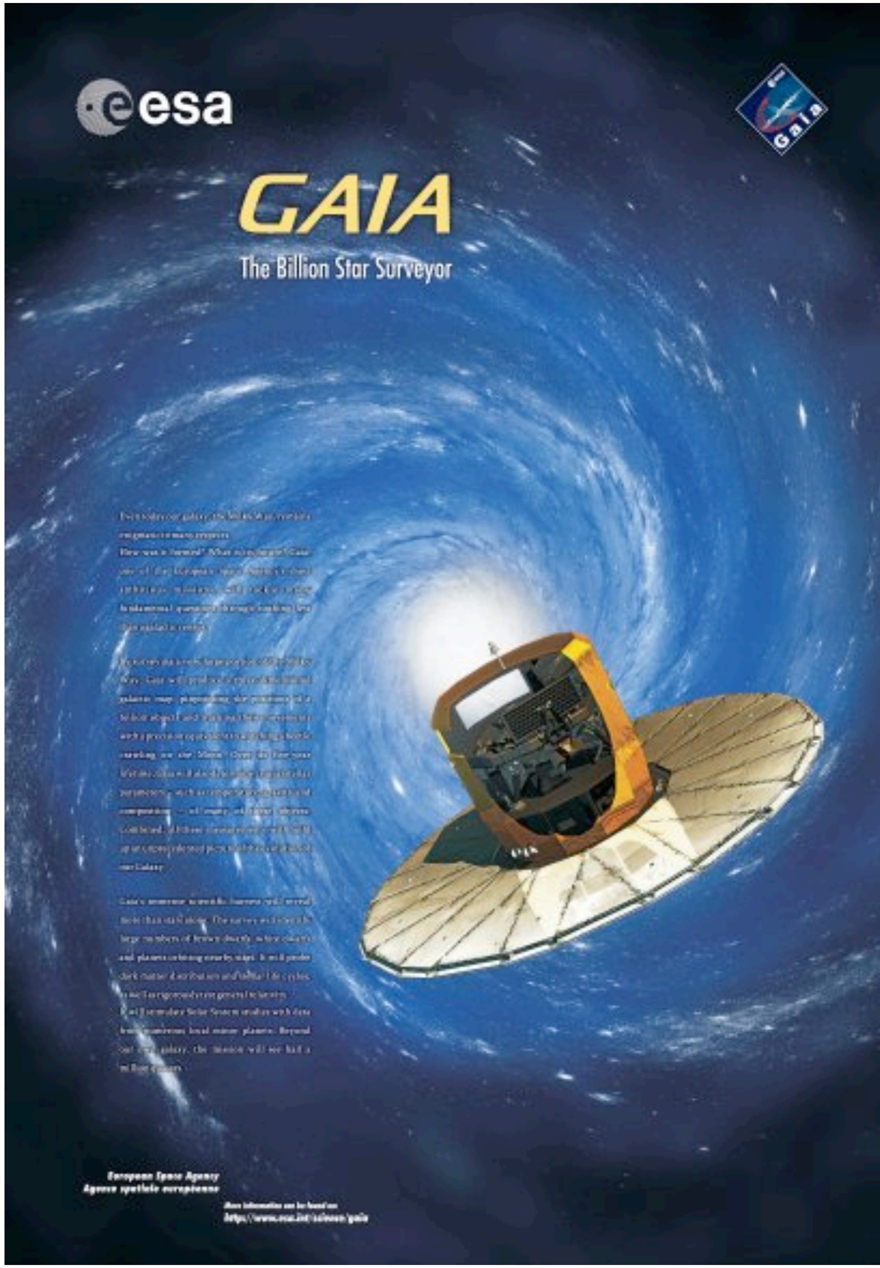


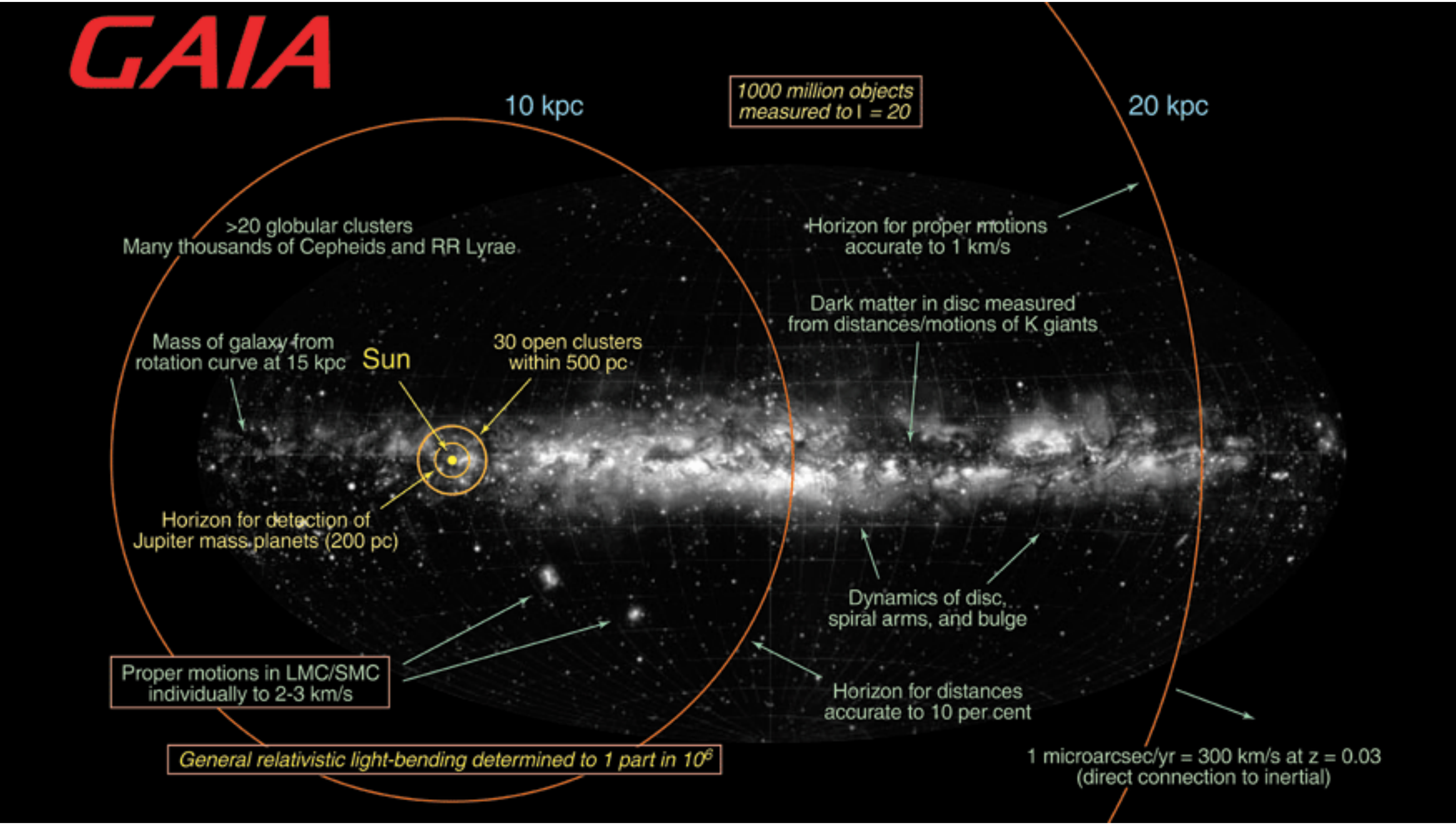
The final results, after reductions by two independent teams, were released in 1997: positions and distances for 118,000 stars, 8200 new variable stars including 273 Cepheid variables, and 24,000 binary/multiple star systems, including *doubling* the number of eclipsing binaries known.



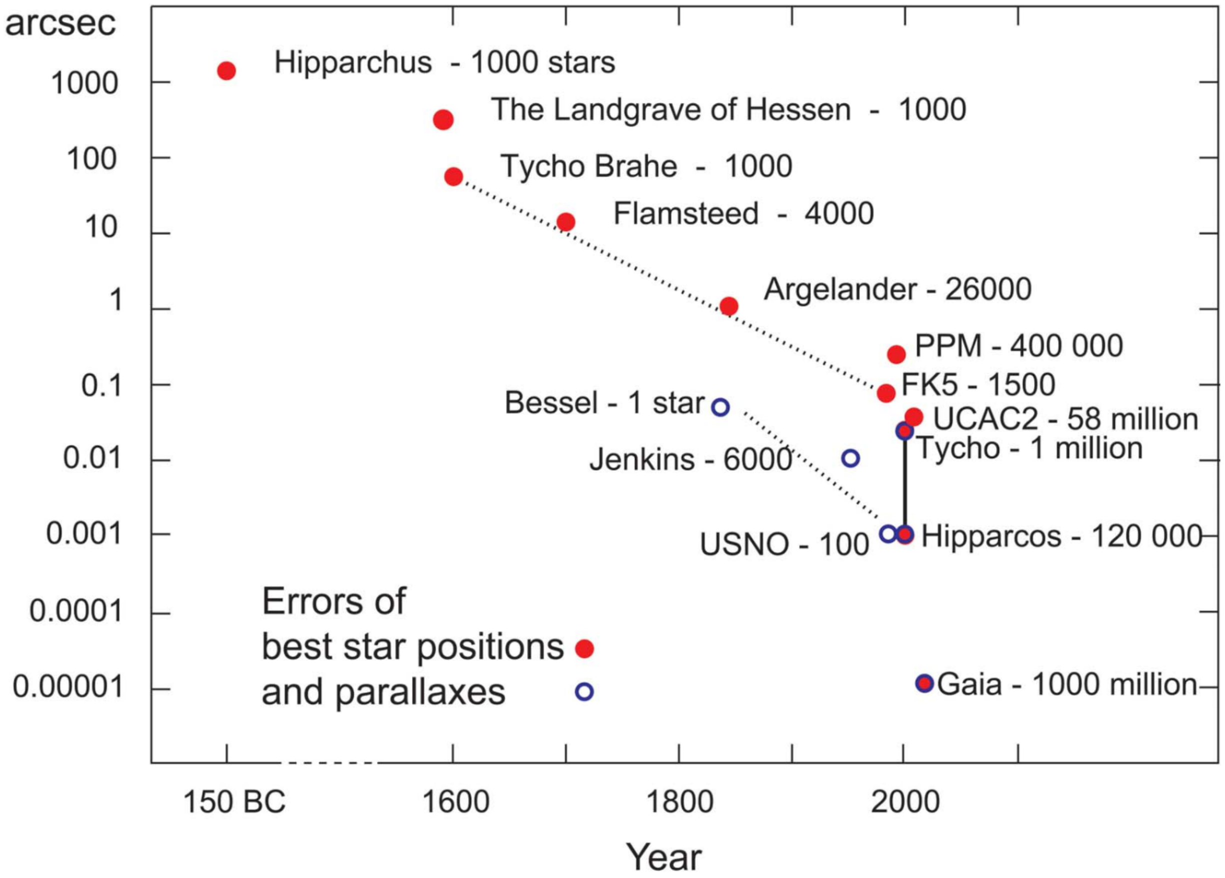
Gaia is the successor to *Hipparcos*. It is designed to make the largest and most precise 3D chart of our Galaxy by measuring

- positions and velocities for at least one billion stars (1% of the stars in the Milky Way)
- spectroscopy for about 150 million stars
- one billion objects observed on the average 70 times over 5 years mission is 40 million stars a day (400 million measurements a day)

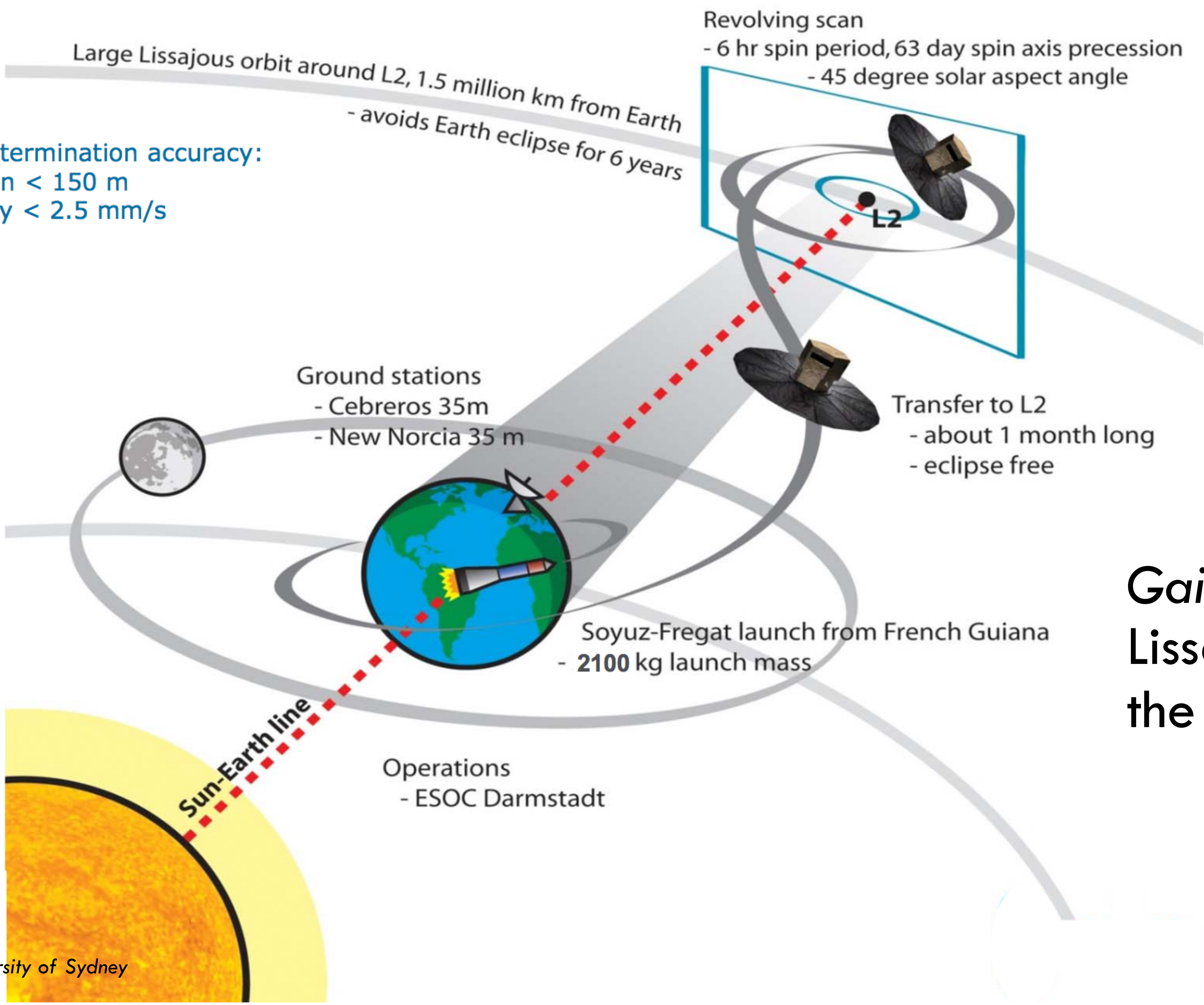



GAIA
10 kpc
1000 million objects measured to I = 20
20 kpc
>20 globular clusters
Many thousands of Cepheids and RR Lyrae
Horizon for proper motions accurate to 1 km/s
Dark matter in disc measured from distances/motions of K giants
Mass of galaxy from rotation curve at 15 kpc
Sun
30 open clusters within 500 pc
Horizon for detection of Jupiter mass planets (200 pc)
Dynamics of disc, spiral arms, and bulge
Proper motions in LMC/SMC individually to 2-3 km/s
Horizon for distances accurate to 10 per cent
General relativistic light-bending determined to 1 part in 10^6
1 microarcsec/yr = 300 km/s at z = 0.03
(direct connection to inertial)

Gaia represents a dramatic improvement in our ability to measure the positions and parallaxes of stars.



Orbit determination accuracy:
- position < 150 m
- velocity < 2.5 mm/s

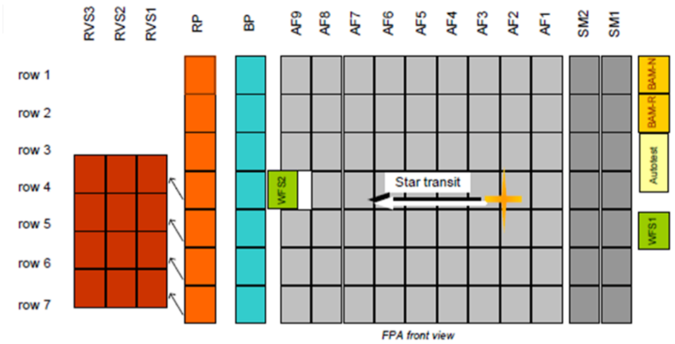


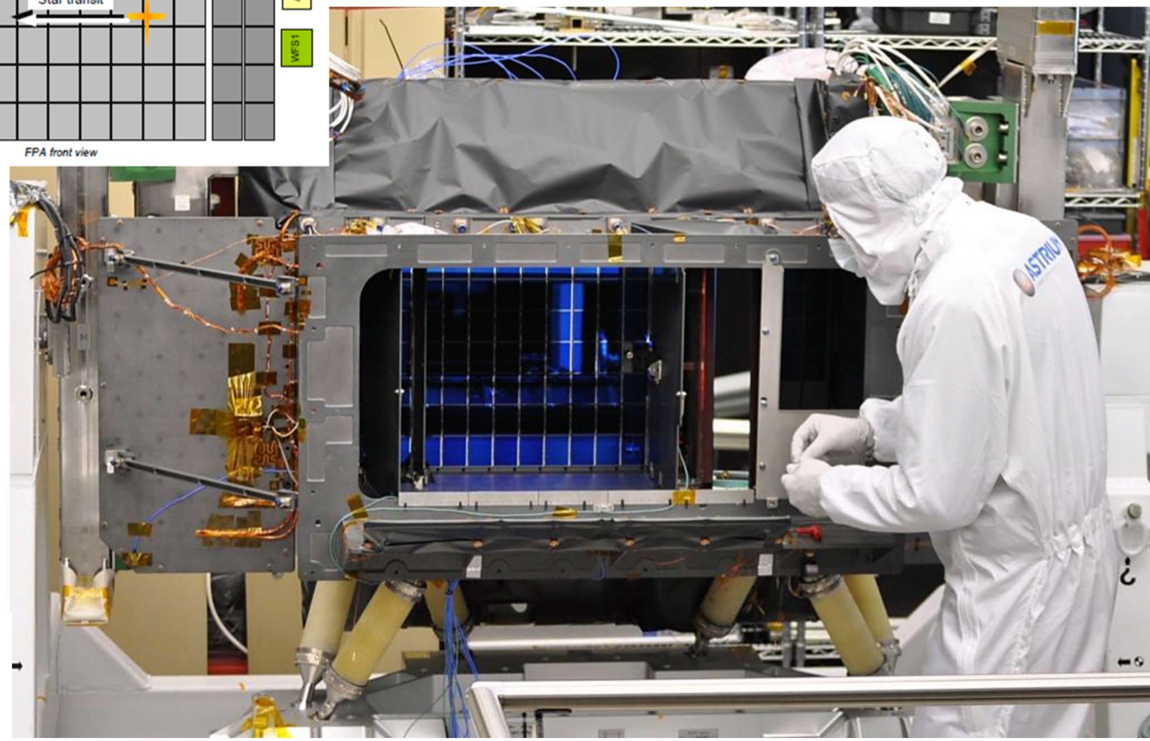
Gaia operates in a Lissajous orbit around the Sun-Earth L_2 point.

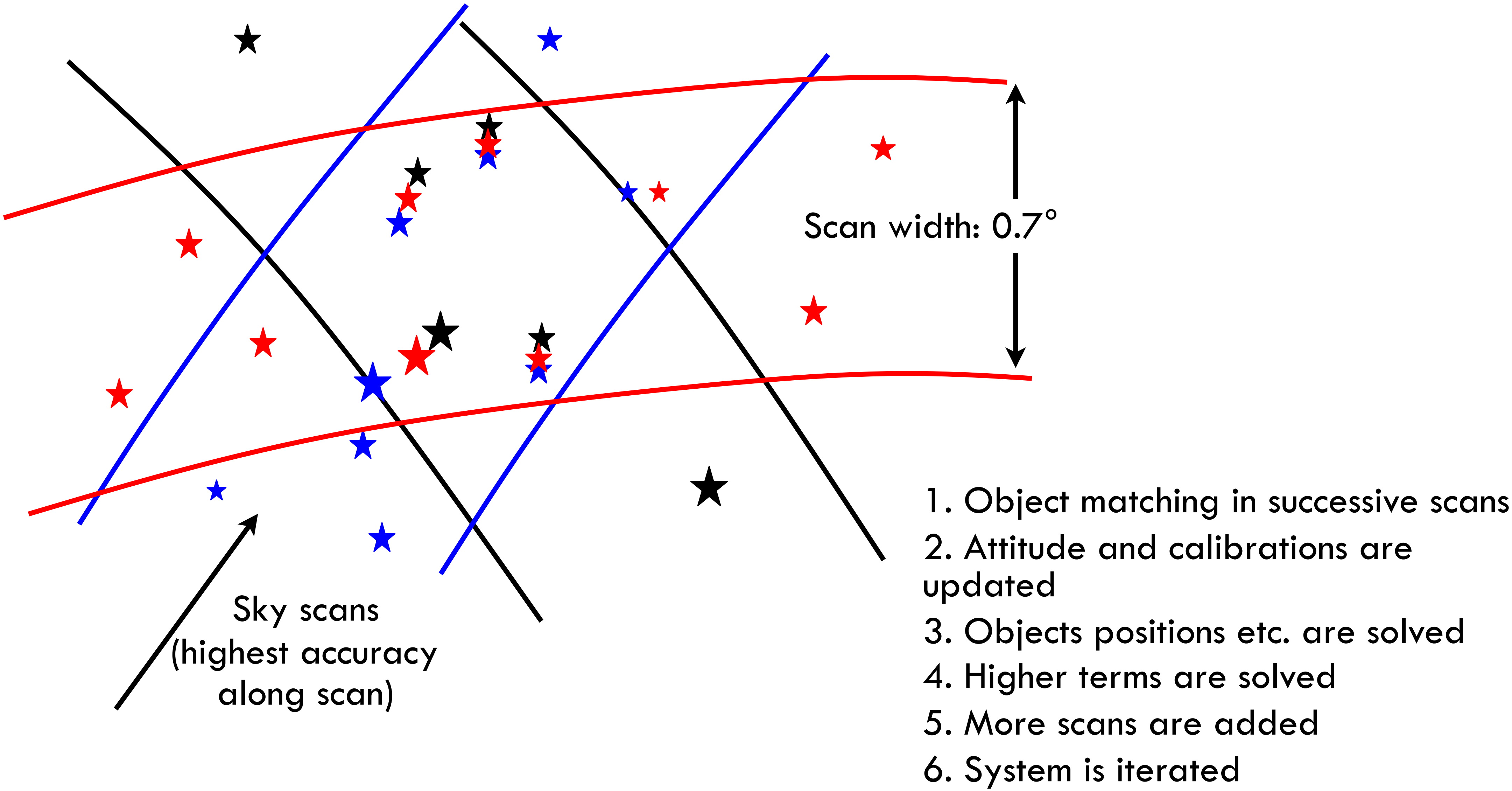
European Space Agency


esa
From launch to orbit
gaia

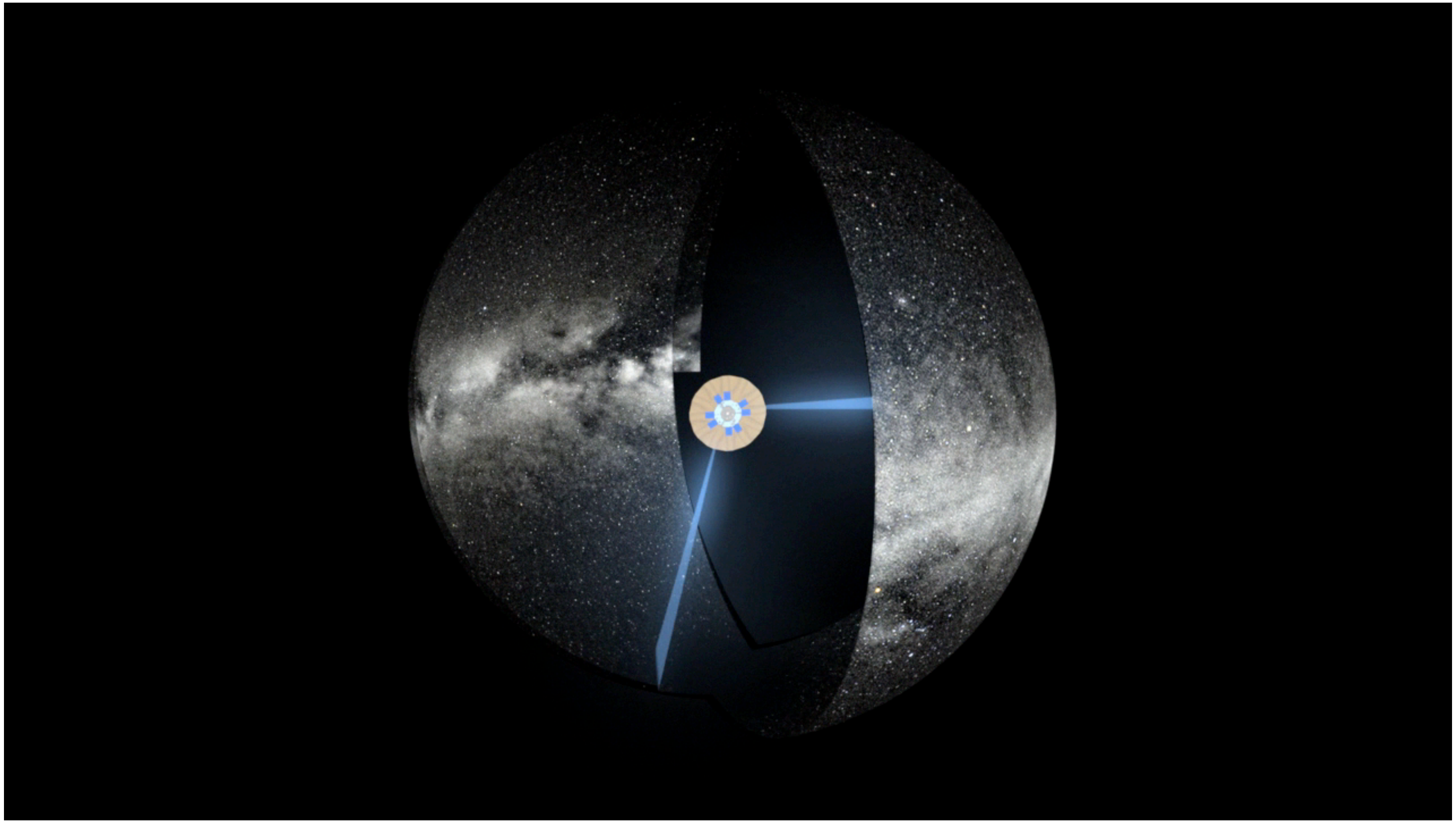
Instead of a single detector, *Gaia* has an array of 102 CCDs, totalling about 1 Gpixels. As stars drift across this array, *Gaia* takes the equivalent of a giant panorama image along each strip.







Scan width: 0.7°
Sky scans
(highest accuracy
along scan)
1. Object matching in successive scans
2. Attitude and calibrations are updated
3. Objects positions etc. are solved
4. Higher terms are solved
5. More scans are added
6. System is iterated



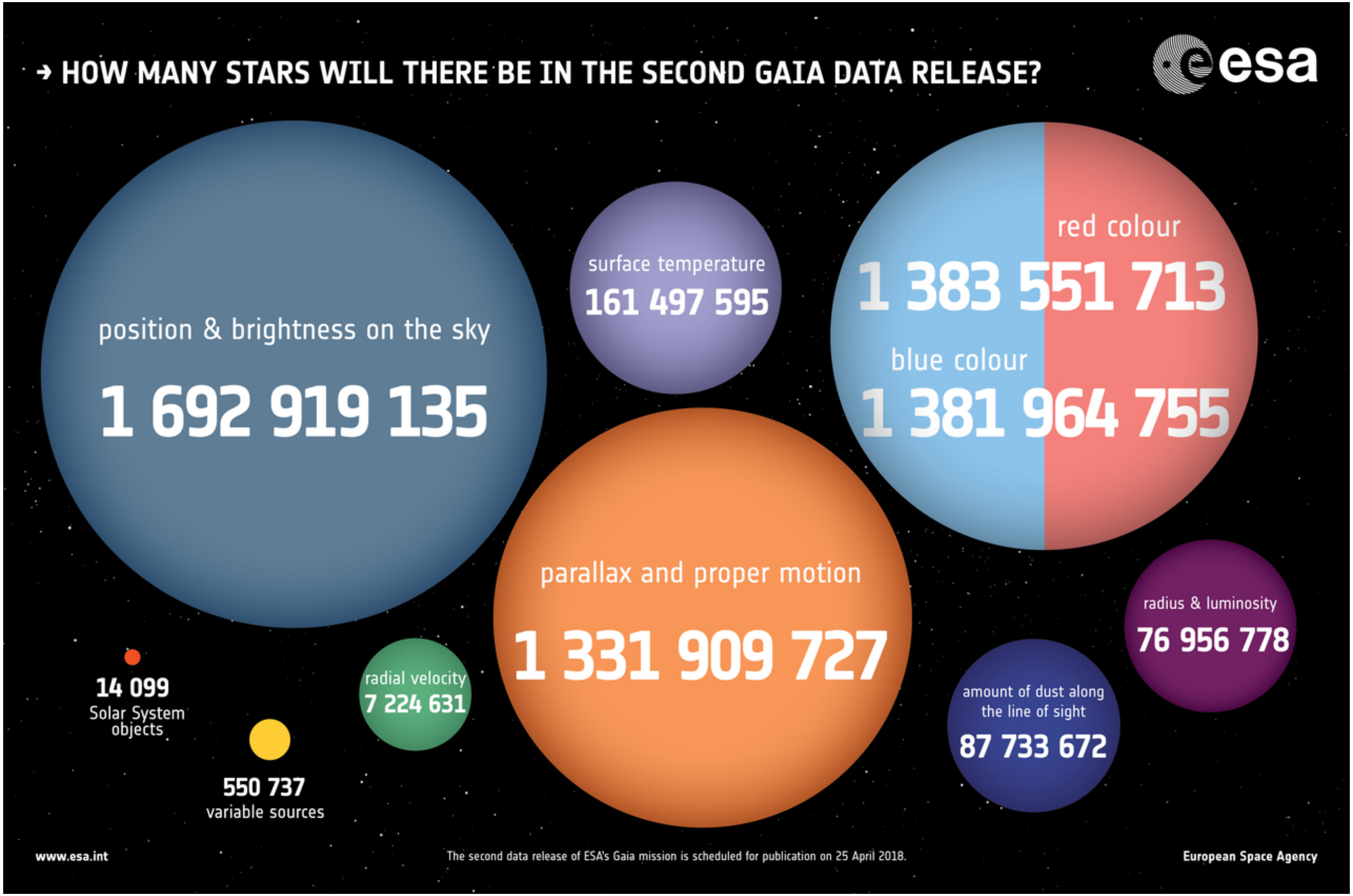
Animation illustrating how Gaia scans the sky during its all-sky survey.

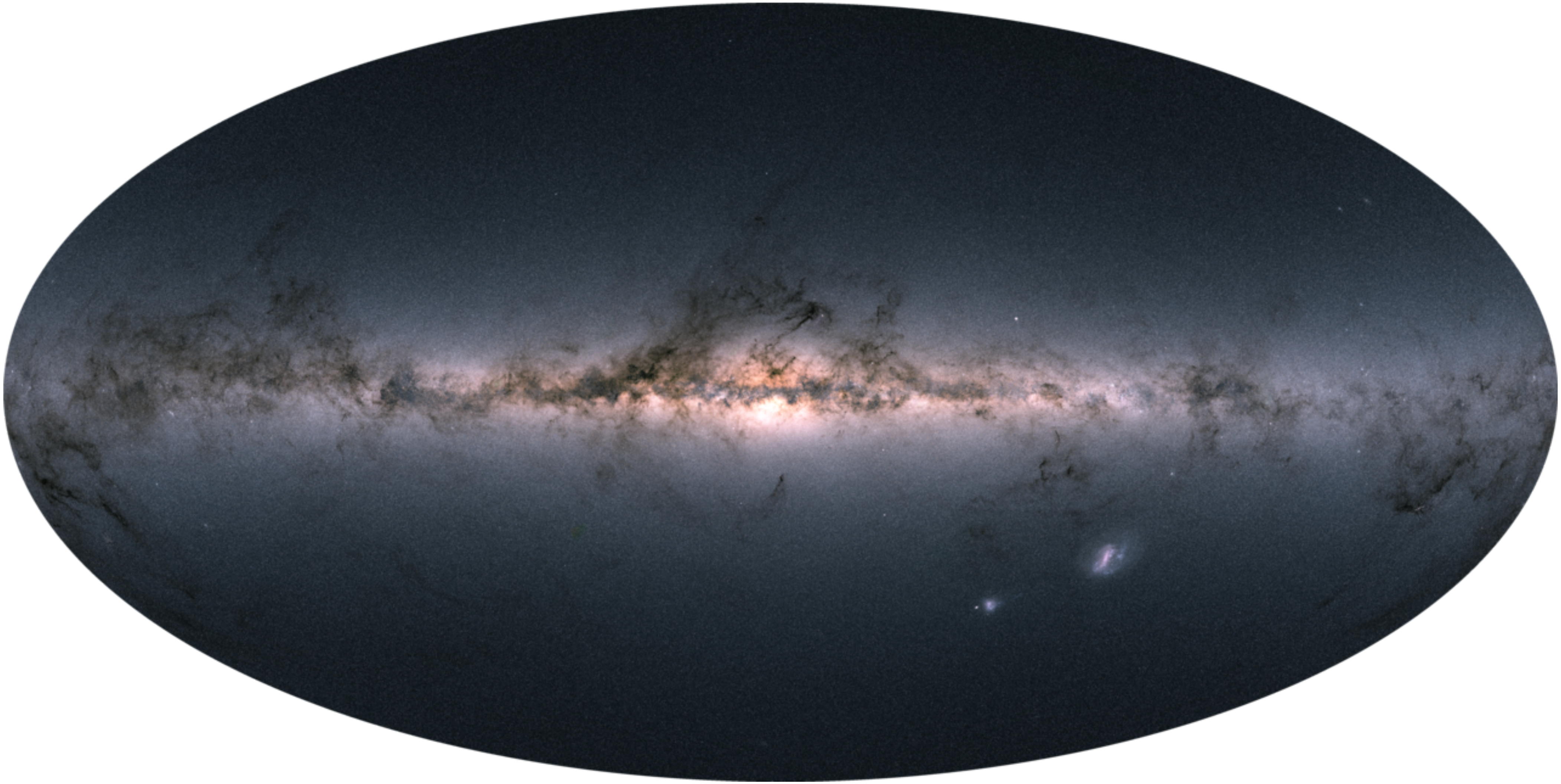
Animation illustrating parallax and proper motion (exaggerated by 10,000 times)

Gaia was launched in December 2013, and reached its final destination at the L_2 point in January 2014. It began science observations in August of that year.

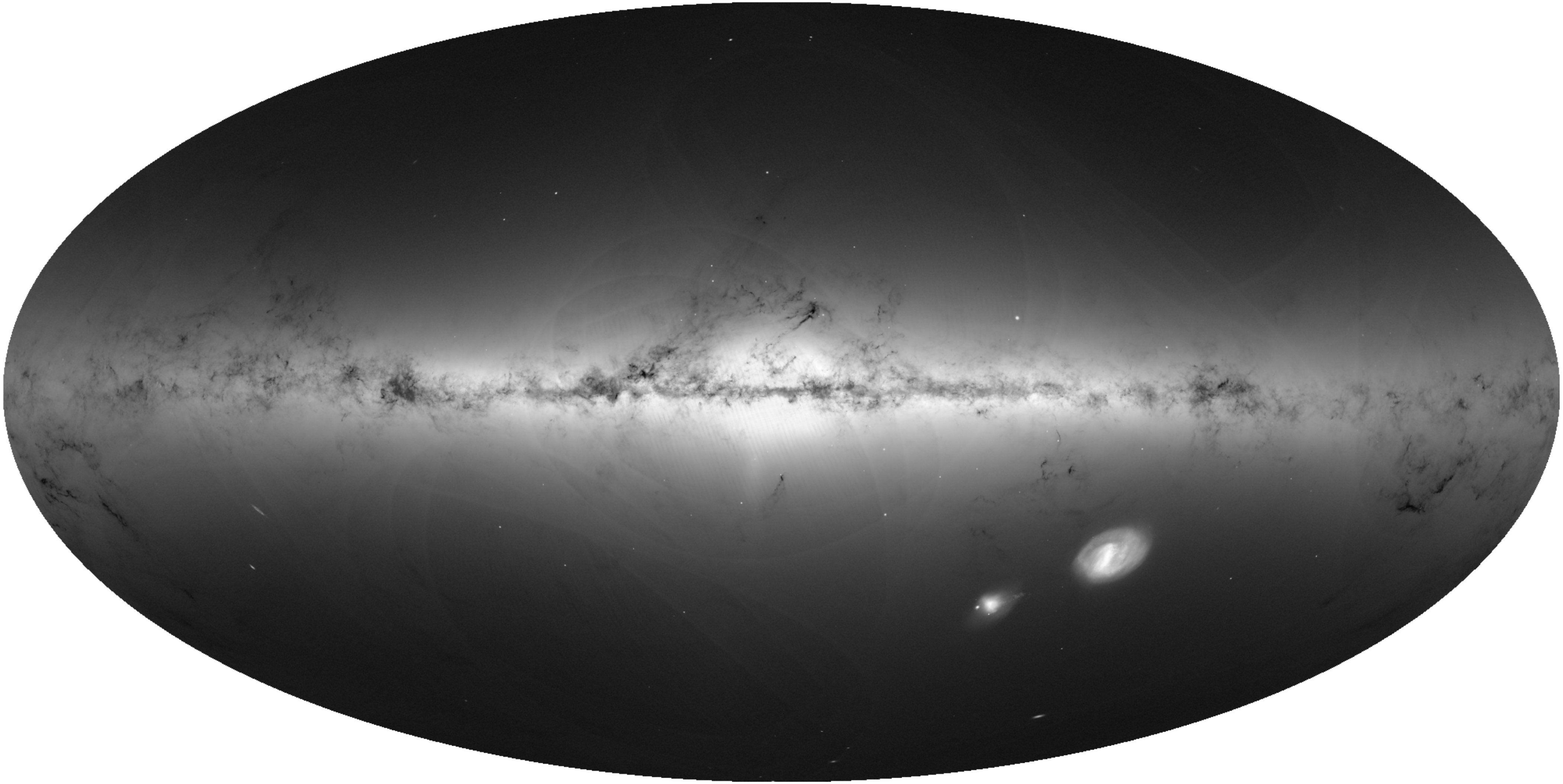
Two data releases have now been made; the first containing positions and magnitudes for a billion stars, the second (DR2, released in April 2018) also containing proper motions, and radial velocities for about 7 million stars.

Here are some of the highlights so far.

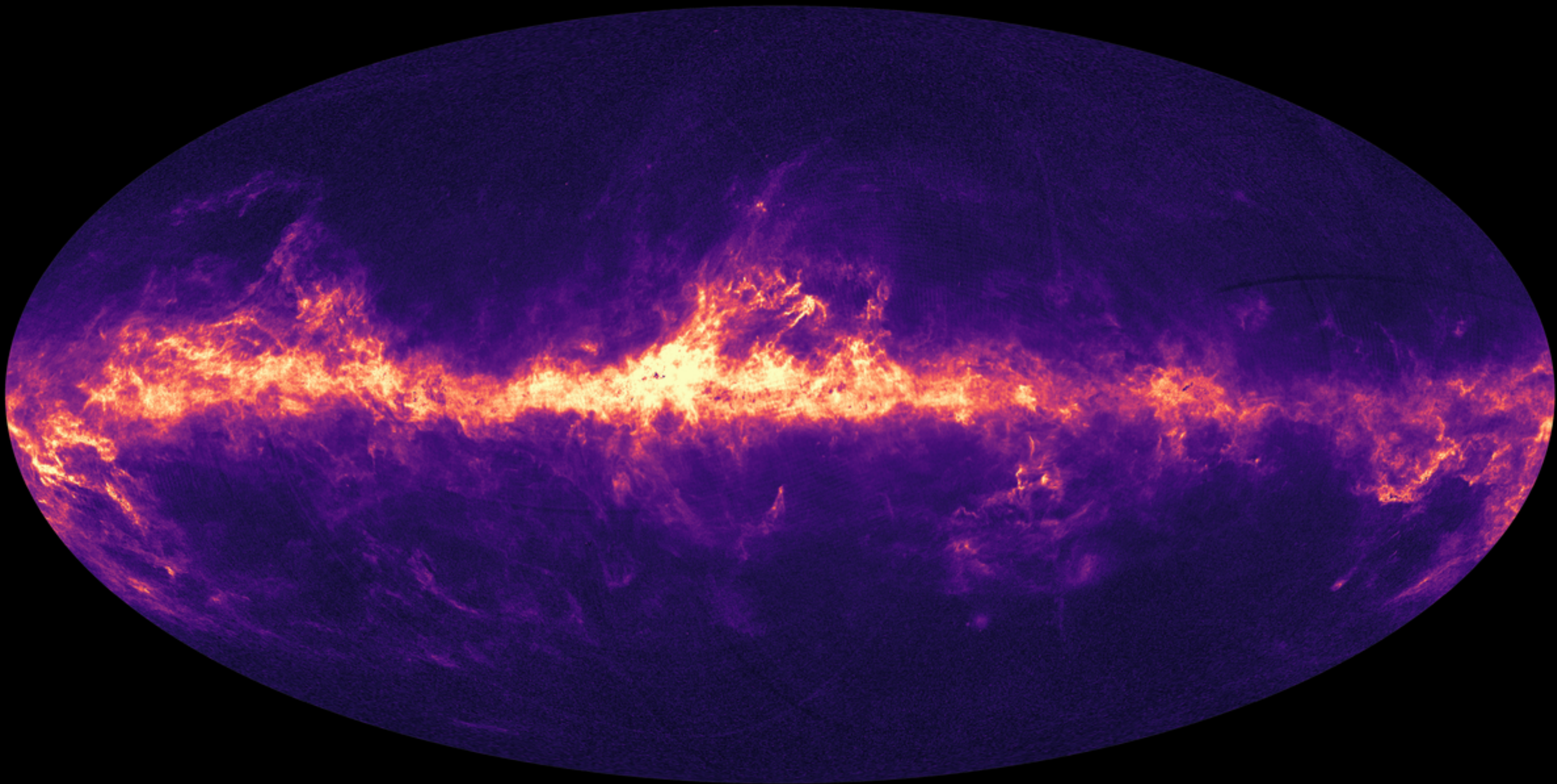

→ HOW MANY STARS WILL THERE BE IN THE SECOND GAIA DATA RELEASE?
esa
position & brightness on the sky
1 692 919 135
surface temperature
161 497 595
red colour
1 383 551 713
blue colour
1 381 964 755
parallax and proper motion
1 331 909 727
radius & luminosity
76 956 778
amount of dust along the line of sight
87 733 672
radial velocity
7 224 631
14 099
Solar System objects
550 737
variable sources
www.esa.int
The second data release of ESA's Gaia mission is scheduled for publication on 25 April 2018.
European Space Agency



Gaia's map showing the total brightness and colour of stars



Gaia's map of star density, based on measurements of nearly 1.7 billion stars from DR2

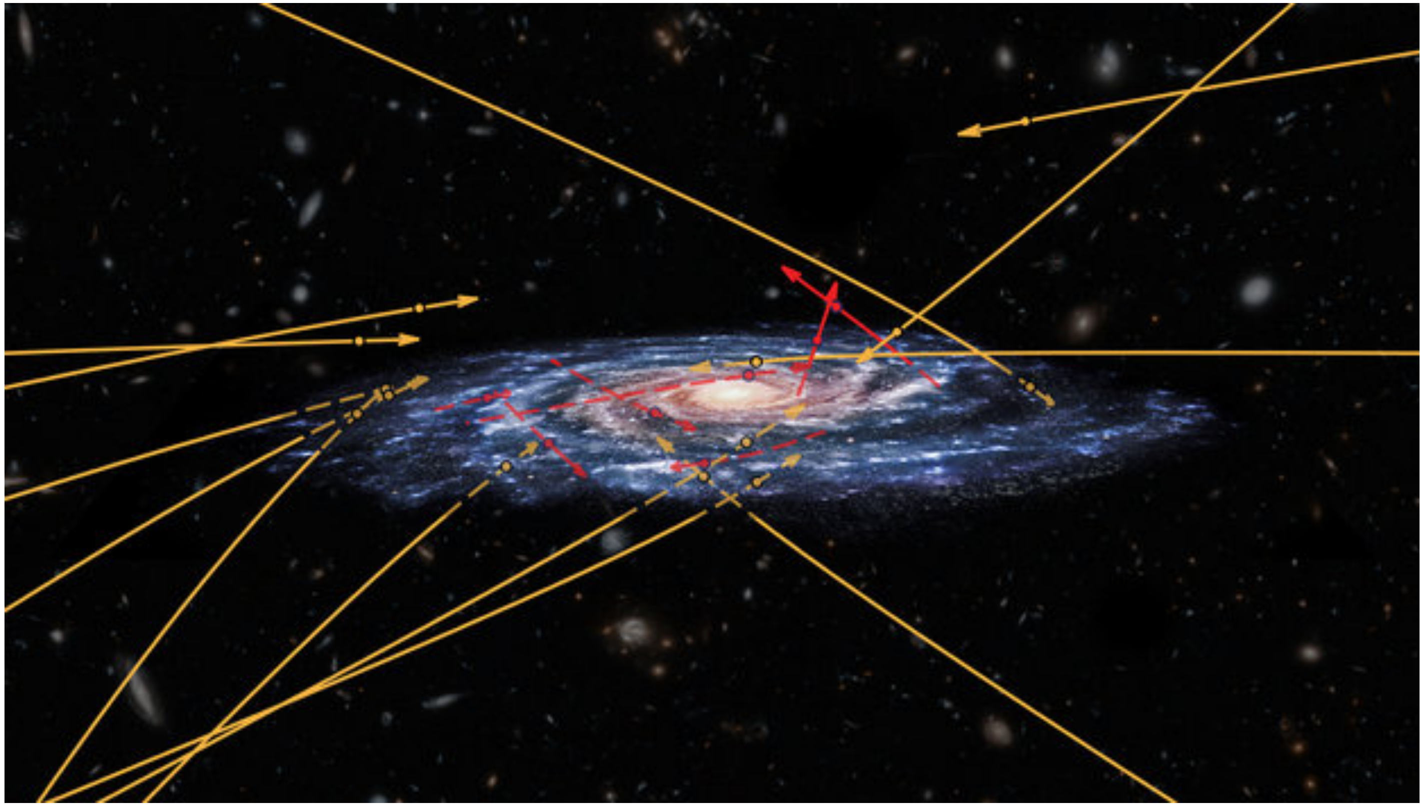


Gaia's view of the dust

Gaia has measured the motions of stars in the Sculptor dwarf galaxy, a satellite galaxy of the Milky Way. This enabled astronomers to determine the orbit of Sculptor around the Milky Way, and to show that stars in the Sculptor dwarf galaxy move preferentially on elongated radial orbits. This confirms that the dwarf galaxy contains a large amount of dark matter.

Gaia has identified twenty “hypervelocity” stars — but instead of being kicked out of the Milky Way, they are headed inwards.

They might come from a neighbouring galaxy on a collision course, or have been accelerated by an encounter with a supermassive black hole.

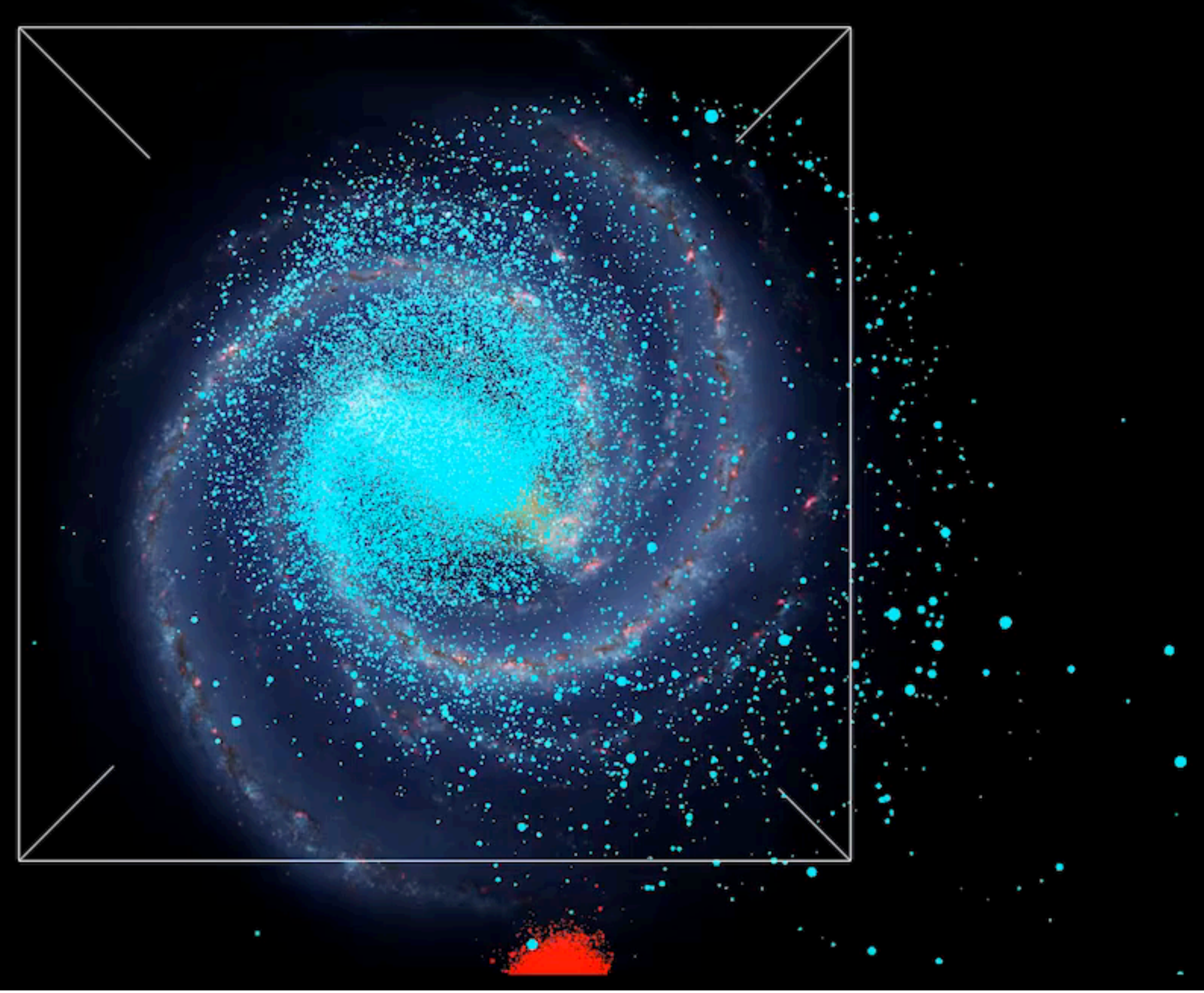


The University of Sydney

Recently, astronomers have identified a group of stars moving along elongated trajectories in the opposite direction to the majority of the Galaxy's stars, including the Sun.

These stars are probably the remnants of a merger with another galaxy early in its life, around 10 billion years ago.

The authors have named this galaxy this galaxy *Gaia-Enceladus* after one of the Giants in ancient Greek mythology, who was the offspring of Gaia, the Earth, and Uranus, the Sky.



Computer simulation of the merger between a galaxy like the young Milky Way and a smaller galaxy.

Gaia Data Release 3 is expected around early 2021. The final data release will take place some time after that, and will include

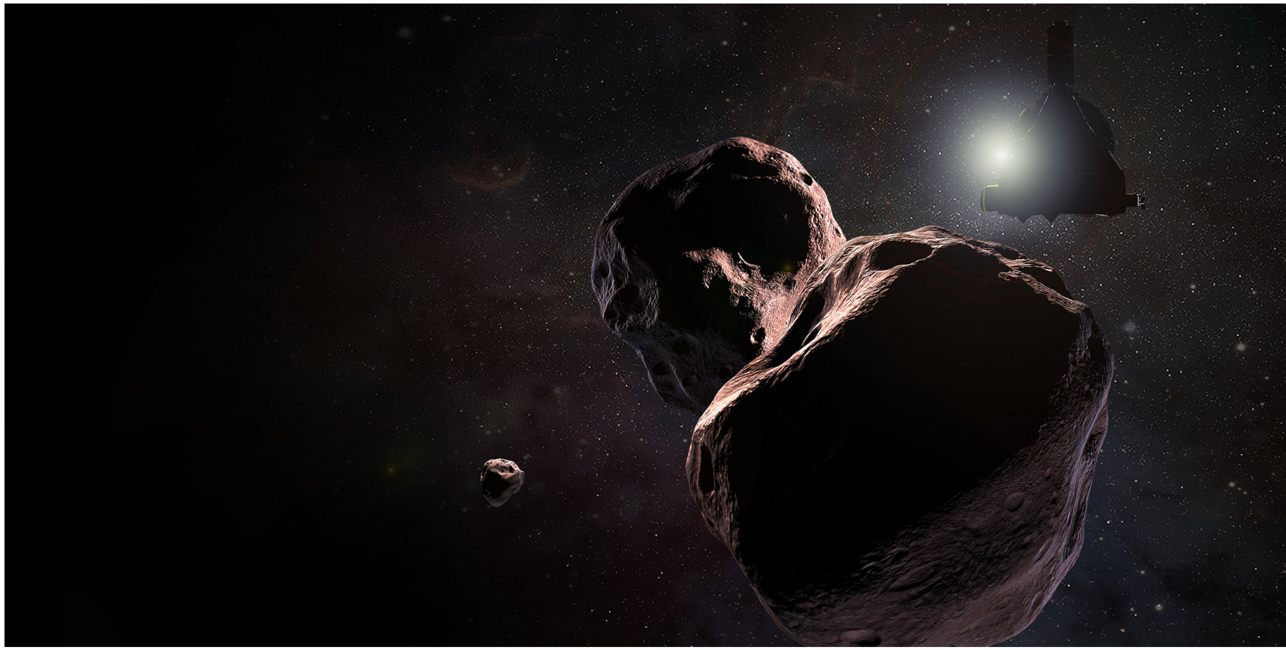
- full astrometric, photometric, and radial-velocity catalogues
- catalogues of variables stars and binaries
- a list of exo-planets
- a list of solar system objects.

Upcoming space missions

New Horizons will perform a flyby of Ultima Thule on 1 January, 2019

Mars 2020 rover will launch in 2020

James Webb Space Telescope: the much-delayed successor to Hubble in infrared light, will launch in in March 2021



There are known knowns. These are things we know that we know. There are known unknowns. That is to say, there are things that we know we don't know. But there are also unknown unknowns. There are things we don't know we don't know.

– Donald Rumsfeld, 2002

To infinity and beyond!

- Read "Astronomy Picture of the Day" for all the best astronomy images and news http://http://apod.nasa.gov/apod/
- Read an astronomy blog, like "Bad Astronomy" http://www.slate.com/blogs/bad_astronomy.html or "Snapshots from Space" http://www.planetary.org/blogs/emily-lakdawalla/
- Join a local astronomical club: see listing at the Astronomical Society of Australia page https://astronomy.org.au/amateur/amateur-societies/australia/

And, of course, attend more Continuing Education courses! Future courses include

Quarks to the Cosmos

Ten great discoveries in modern astronomy and physics

begins March 2019

Lives of the Stars

A more detailed look at how stars live and die

begins August 2019

Voyage to the Planets

A look at the solar system in the era of space exploration

running in 2020

That's all, folks!

Further reading

- The LIGO website is at https://www.ligo.org/ and https://www.ligo.caltech.edu/; they have loads of good pictures and animations
- The Gaia website is at http://sci.esa.int/gaia/
- Several books have already been written about LIGO and the search for gravitational waves. I enjoyed "**Ripples in spacetime**: Einstein, gravitational waves, and the future of astronomy" by Govert Schilling (Harvard University Press, 2017).
- Fred Watson's book "**Stargazer**: The life and times of the telescope" doesn't really get as far as ELTs, except in passing, but he does give you an excellent feel for why astronomers always want a bigger telescope.
- Michael Perryman, who led the *Hipparcos* project, has written a book about it called "**The Making of History's Greatest Star Map**" (Springer, 2010). A bit of a dry read, but interesting none the less.