Introduction to Astronomy

Lecture 10:

The next big thing(s)

some current and future hot topics in astronomy

University of Sydney
Centre for Continuing Education
Spring 2012

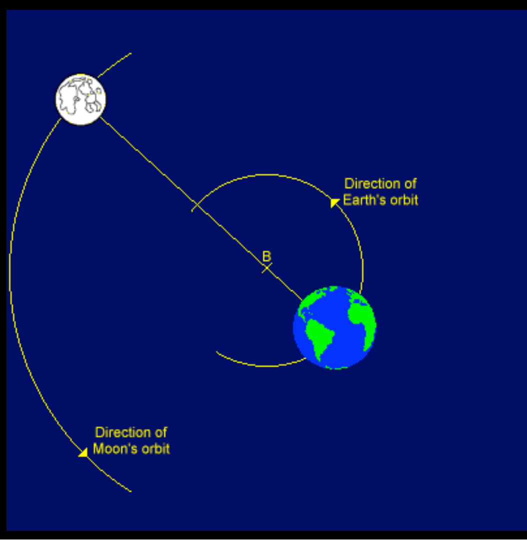
Outline

- The current big thing in Astronomy
  - *expolanets*
- The next big things in Astronomy
  - *astronomy without light: particle astrophysics and gravity waves*
  - *REALLY big telescopes*
  - *space missions*
- To infinity and beyond

Finding planets

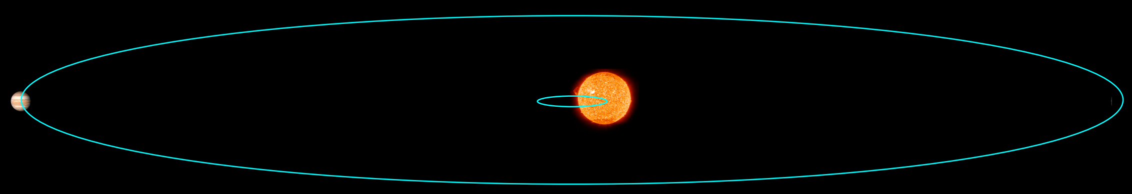
We talk about planets orbiting the Sun, but in fact both planet and Sun move. Two bodies in orbit each move about the *centre of mass* (or *barycentre*).

The centre of mass is closer to the heavier object.



The ratio of the mass of the Sun to the mass of Jupiter is 1000, so the centre of mass is 1000 times closer to the Sun than it is to Jupiter.

The radius of the Jupiter's orbit is just over 1100 times the radius of the Sun, so its barycentre with the Sun lies just above the Sun's surface. Thus as Jupiter executes its 12 year orbit, the Sun executes a much smaller ellipse, wobbling just over one solar diameter.



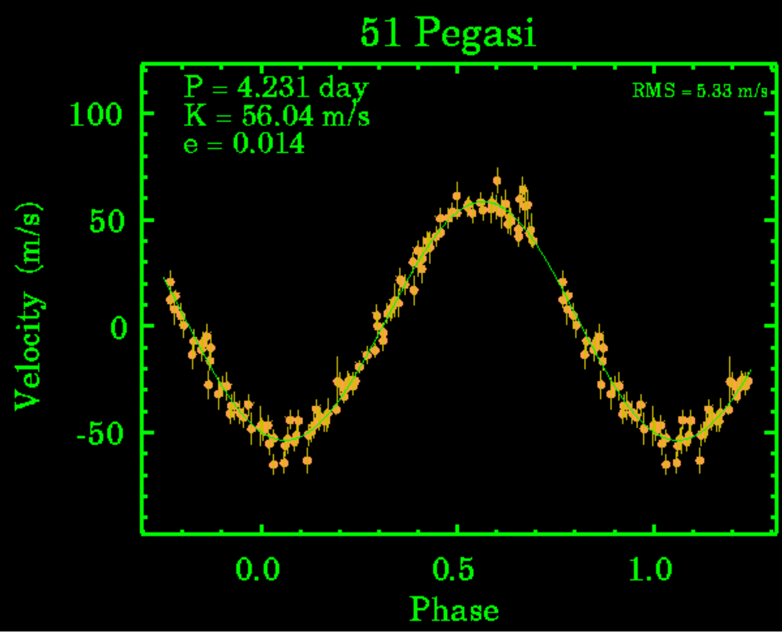
We can't measure the wobble in position, but we can measure the wobble in velocity using the Doppler shift.

The Sun moves about the Sun–Jupiter barycentre at about 12 metres per second, so if we can measure a regular change in a star's velocity of 12 m/s over 12 years, then we can detect a Jupiter-sized planet in a Jupiter-sized orbit.

However, this means we have to be able to measure shifts in velocity to 12/300,000,000, or a precision of 4 in a *billion*.

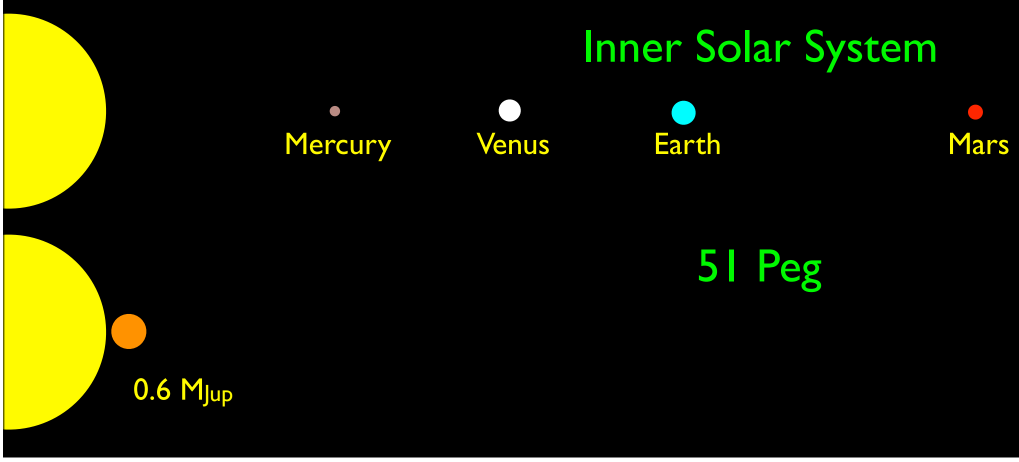
In 1995, Michel Mayor and Didier Queloz, from the Geneva Observatory, announced the discovery of the first extra-solar planet. They had found a regular oscillation of the star 51 Pegasi, a G5 dwarf, very similar to our own Sun, at a distance of 42 lightyears.

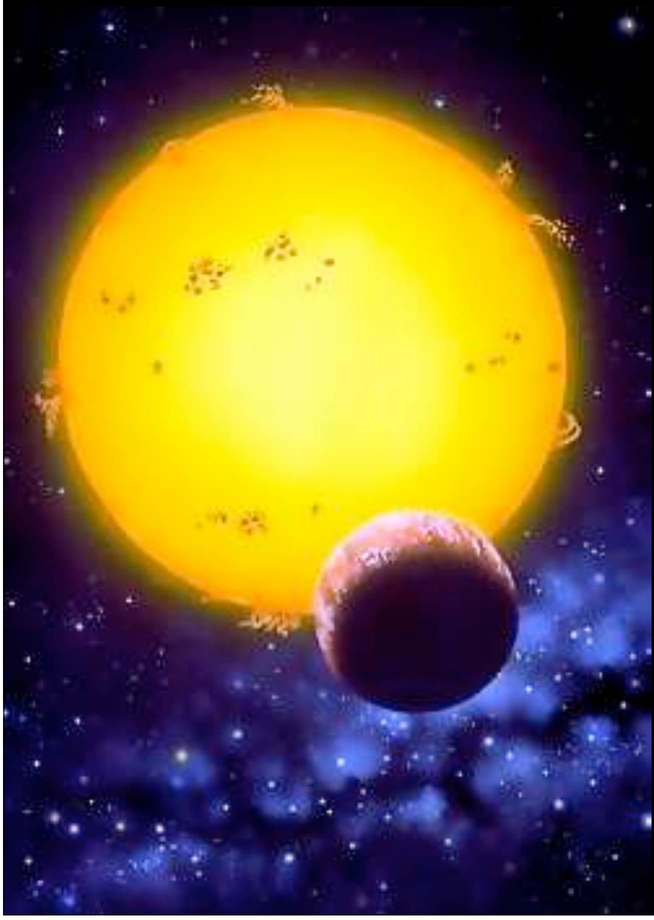
Most astonishingly, the period was only *4.2 days*.



They had found a planet which was 60% as massive as Jupiter, in an orbit much smaller than Mercury's (0.05 AU): a Jovian-mass planet in a sub-Mercurian orbit.

What is such a planet (a gas giant? a giant rocky planet?) doing so close to its star?



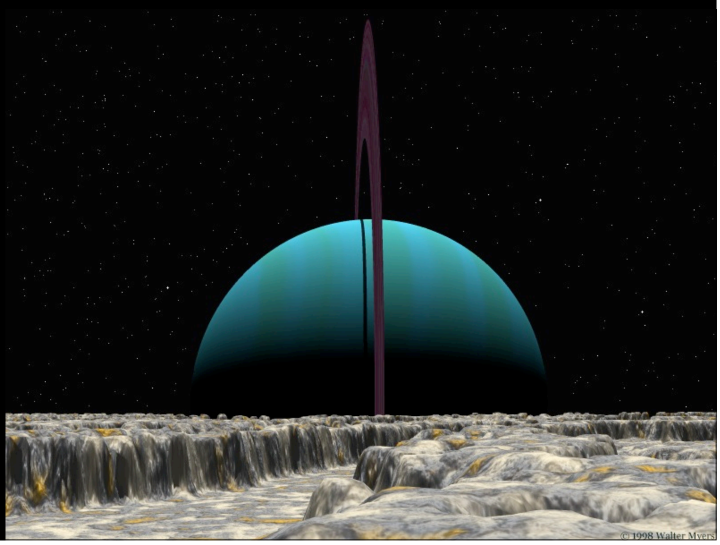


The unlikelihood of forming a massive planet so close to a star could only mean one thing: several people immediately suggested that planets *might not stay put where they were made*.

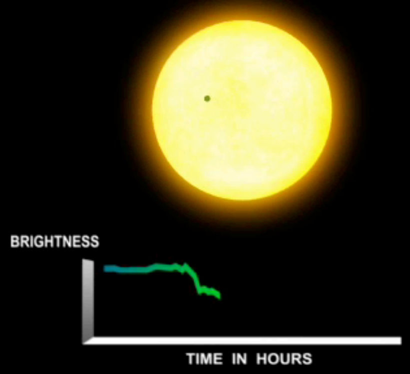
Artist's impression of the planet around 51 Pegasi.

Almost immediately, two new planets were announced, one around 47 Ursa Majoris and one around 70 Virginis, which, at 7.4 M_{Jup}, is still one of the most massive planets found.

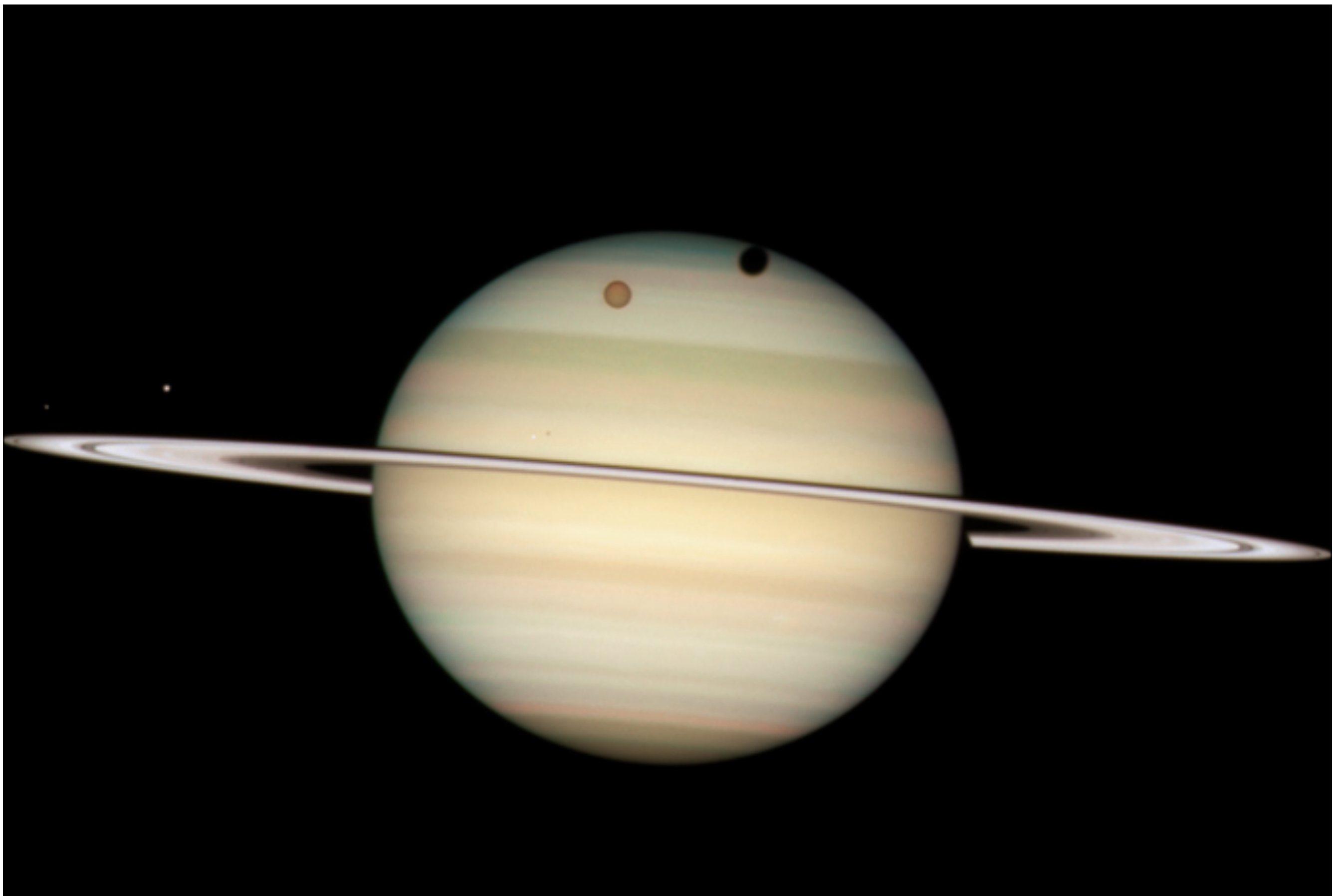
After that, they started arriving at an enormous rate.



The Doppler method is not the only way of finding planets. If the orbit of a planet around a star happens to be edge-on, then once during every revolution, the planet will pass in front of its star in a *transit*. This can be detected by recording the star's brightness very accurately and looking for dips.

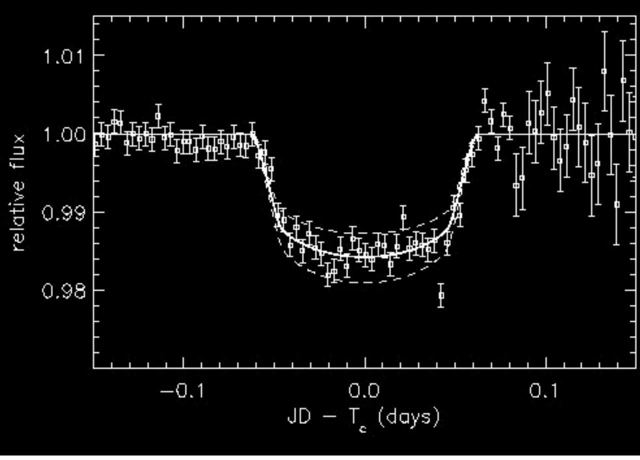


This can only work if the viewing geometry is favourable, and is biased towards finding *large* planets in *small* orbits. As you would have seen with the transit of Venus, terrestrial planets don't cause much of a decrease in the light from the star!



Hubble image of Titan transiting across Saturn, taken in February 2009

185 planets have been found through transits.
Measuring transits of planets which have been detected via velocity variations is particularly valuable because this enable both the mass and the radius to be determined exactly (not just lower limits).



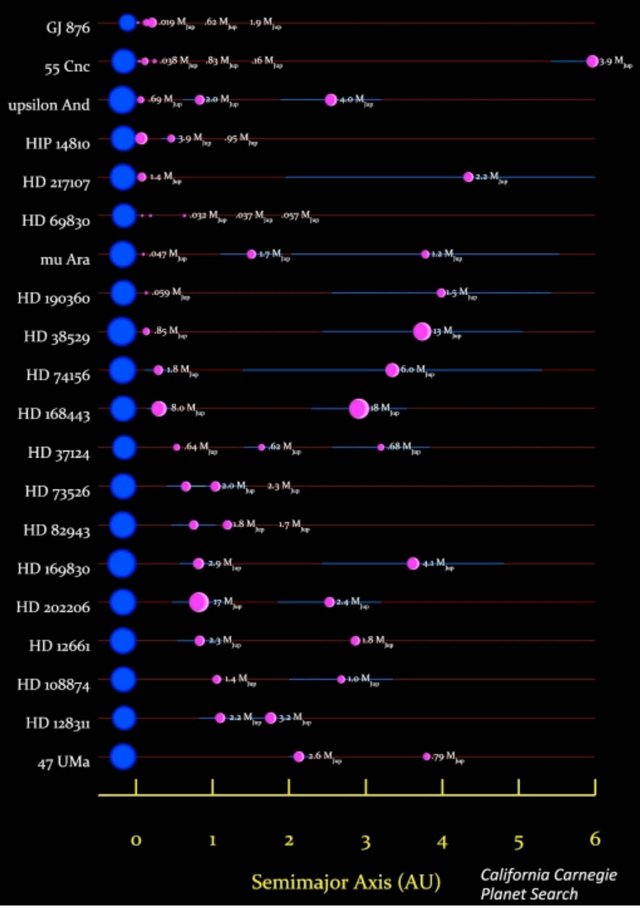
As of November 2012, we know of 850 planets around 669 stars.

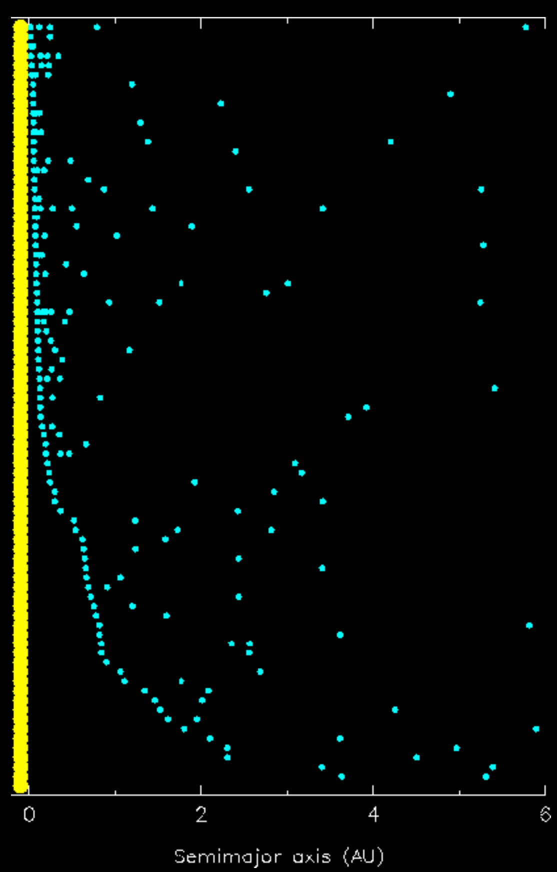
Amongst these 850 planets are:

- 126 multiple planet systems
- ~ 40 planets around red giant stars
- ~ 50 planets in binary star systems, orbiting one member of a wide binary
- 15 circumbinary planets, where the planet orbits both members of a binary

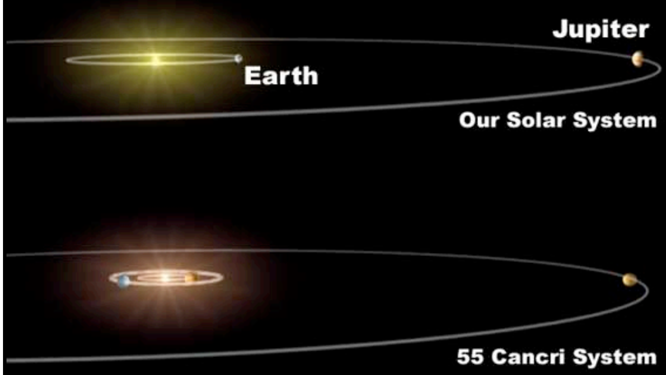
The masses range between ~1 M_{Earth} and about 25 M_{Jup}. Many of them look like 51 Peg-b, the first exoplanet: the so-called *hot Jupiters* – massive planets which orbit very close to their sun.

We now know of 108 systems with more than one planet.





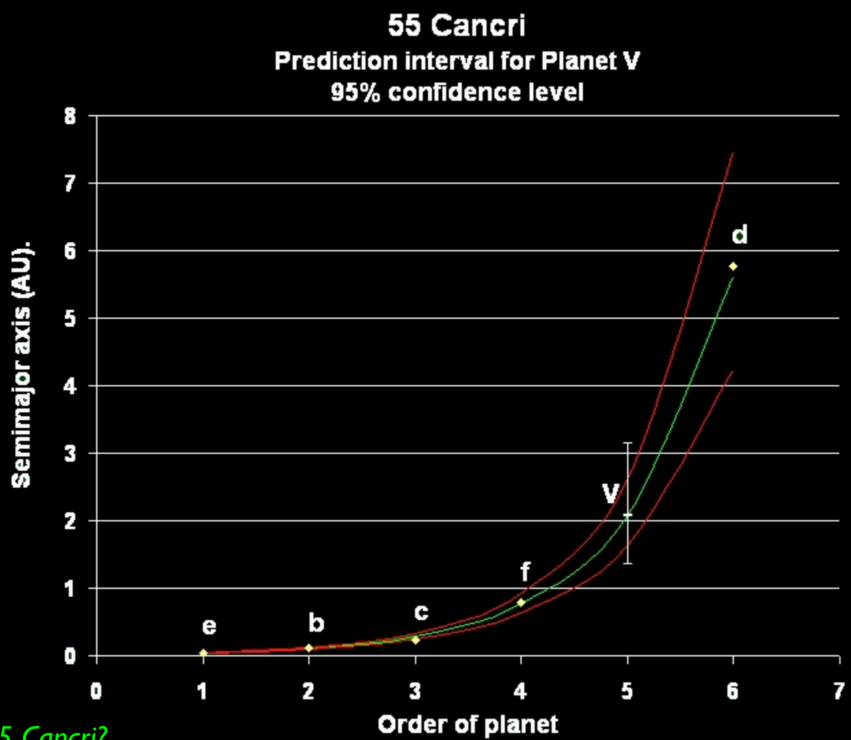
The system around 55 Cancri has five planets. The outermost planet, 55 Cancri d, has an orbit very similar in size to Jupiter's.



It is possible there are smaller (terrestrial?) planets in the gap between f and d.

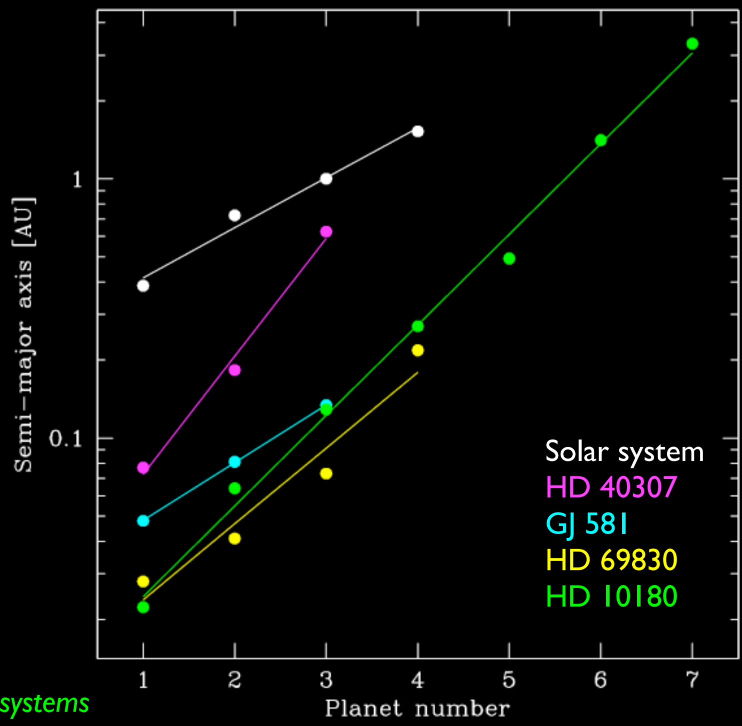
Planet	Mass (M_J)	Distance (AU)	Period (d)
e	0.03	0.04	2.8
b	0.82	0.12	15
c	0.17	0.24	44
f	0.14	0.78	260
d	3.8	5.8	5218

In 2007, an amateur astronomer suggested the 55 Cancri system has a "Bode's Law"-like relationship, which would predict the existence of two more planets.



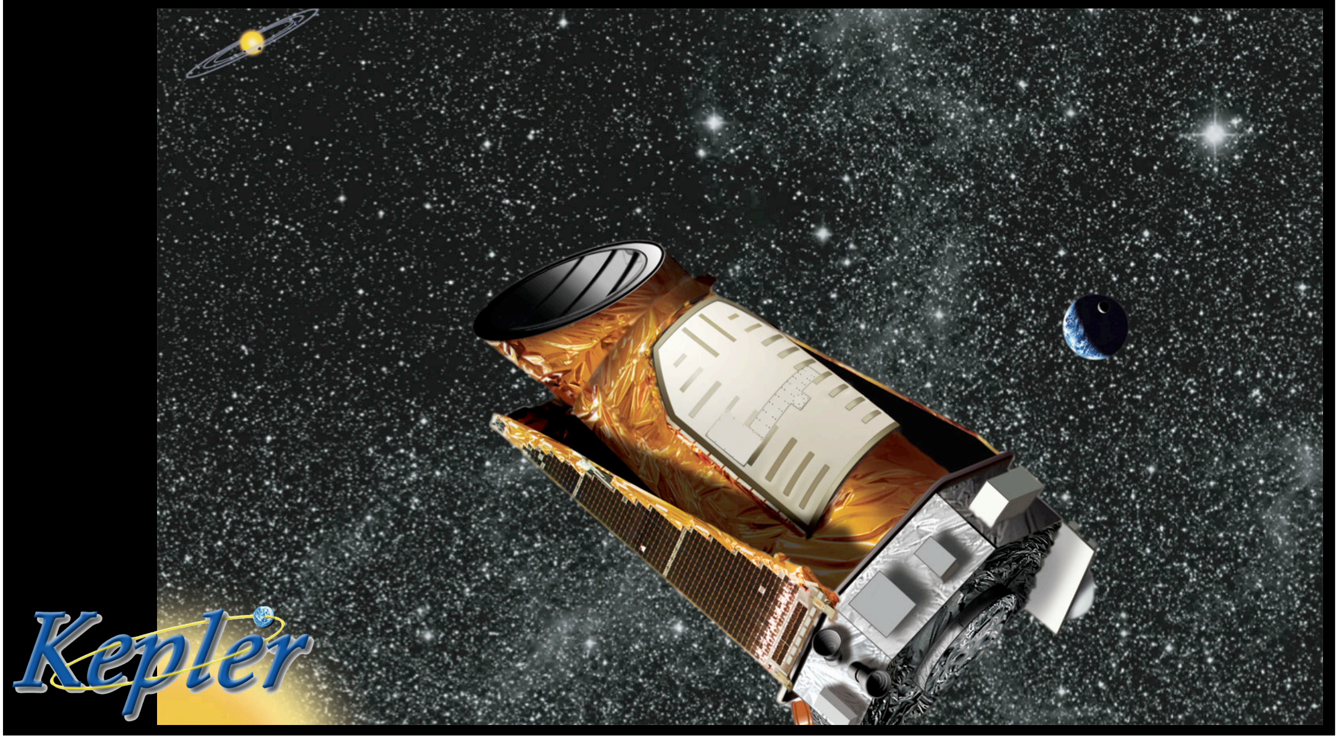
Bode's law with missing planets in 55 Cancri?

However, analysis of more systems suggests that most systems have somewhat regular spacings, but all different.



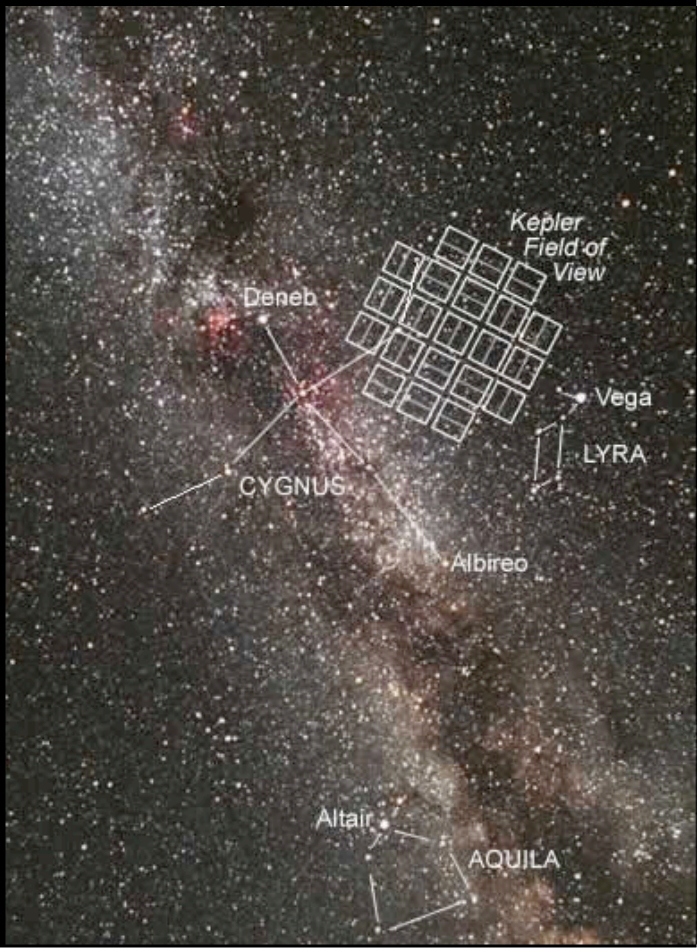
Fits to planet distances for five systems

The *Kepler* mission



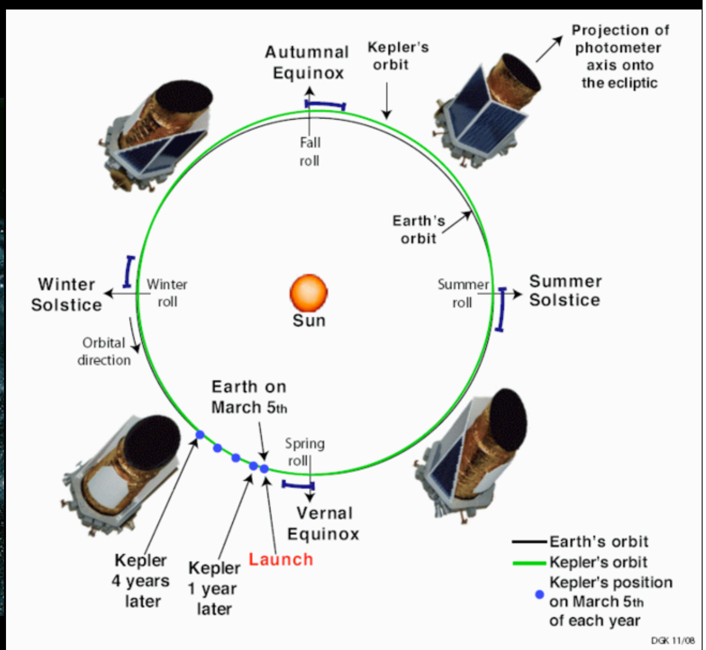
The *Kepler* mission to find transiting planets was launched in March 2009. It is designed to observe 155,000 stars in a single field in Cygnus, observing continuously (every 30 min) for 3.5 years.

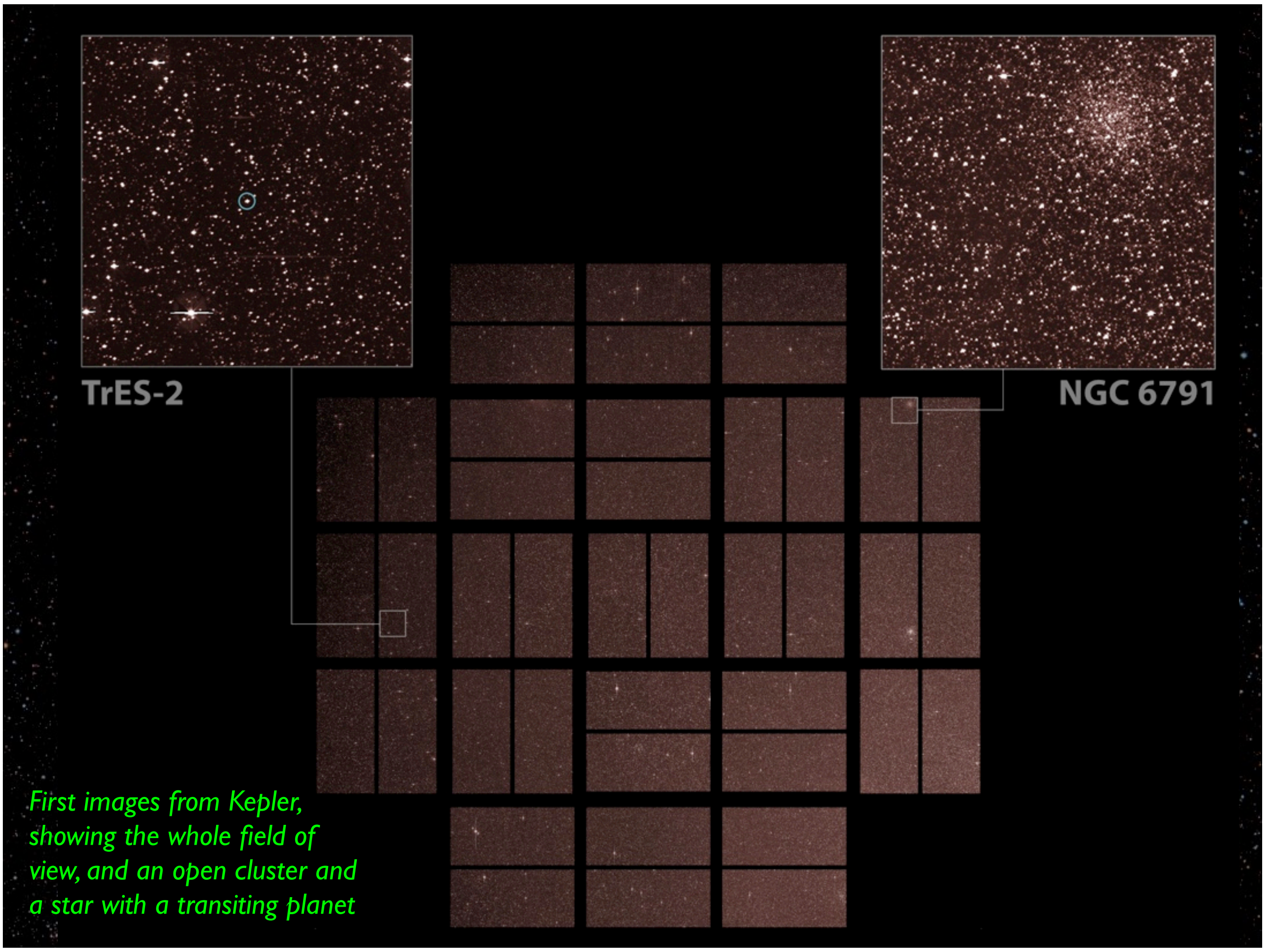
To detect the transit of an Earth-like planet, it needs to detect brightness changes of 1/10,000 when an Earth-sized planet on an Earth-like orbit makes a ~12-hour passage in front of a Sun-sized star.



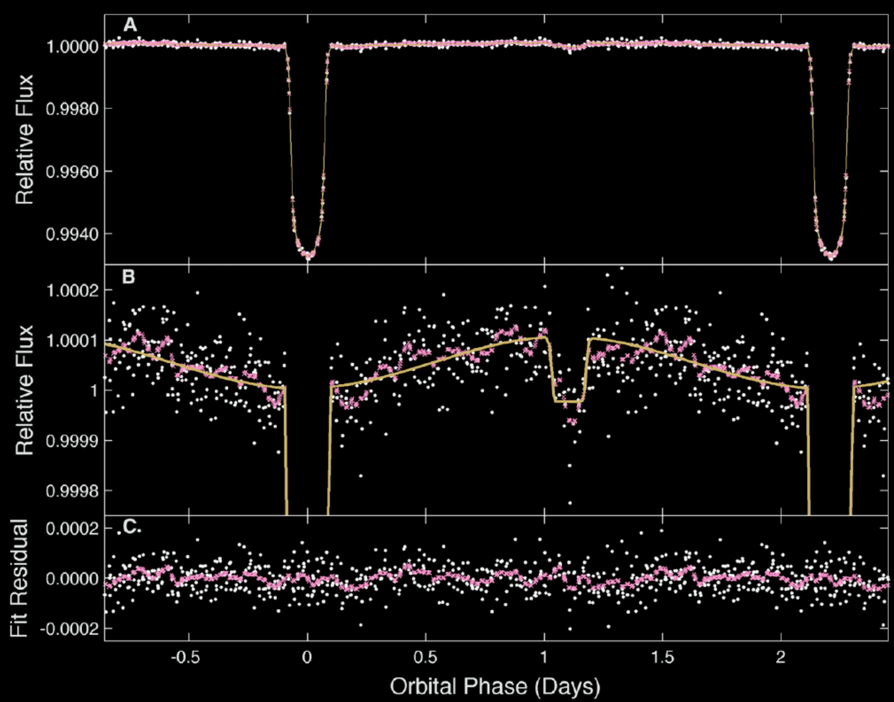
Kepler is in a heliocentric, Earth-trailing orbit, falling gradually further behind the Earth. It is pointing to a region in the Orion arm, in the direction of the Sun's motion around the Galaxy.

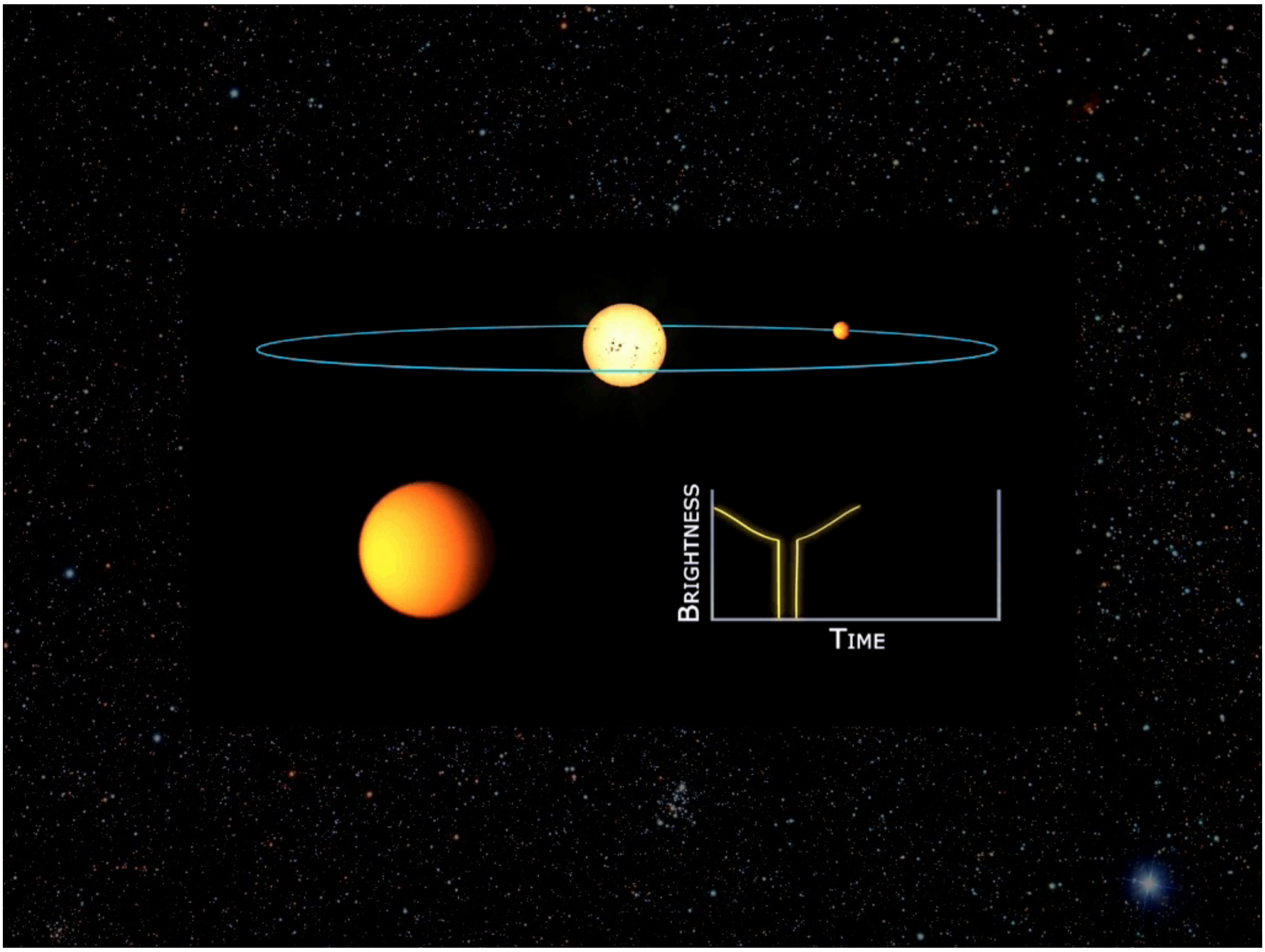
The portion of the Galaxy being observed by Kepler





From its first 10 days of commissioning data, *Kepler* detected a previously known giant transiting exoplanet, HAT-P-7b



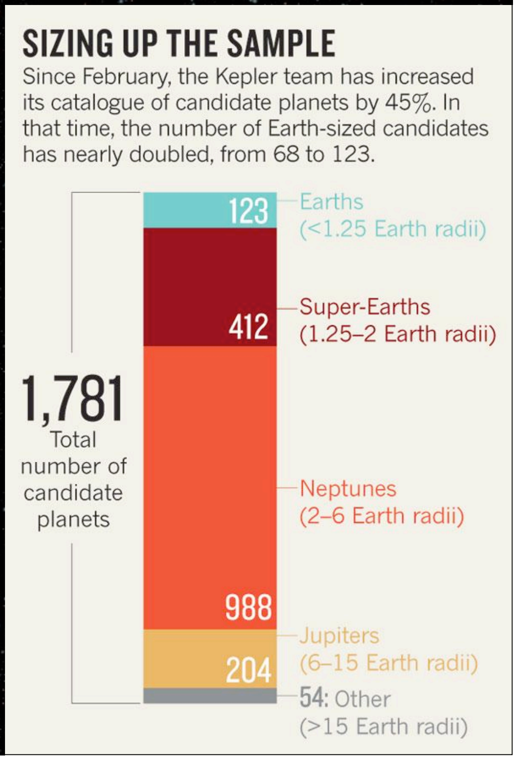


Since then, *Kepler* has been finding planets continuously. Planetary candidates are only confirmed when large ground-based telescopes have detected the radial velocity variations due to the planet. There are so many candidate planets that these confirming observations are now the limiting step.

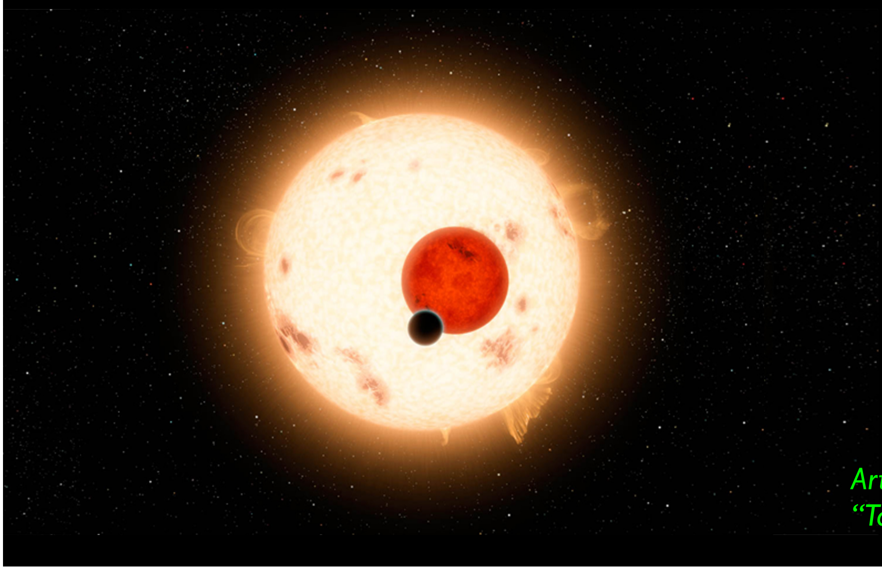
So far, *Kepler* has discovered 95 confirmed planets.

Because the data become public after 1–2 years, the team periodically releases lists of "*Kepler* objects of interest" (KOIs). In February 2011 the *Kepler* team released the latest list of 1235 planetary candidate circling 997 host stars. These candidates are yet to be confirmed, but more than 90% are turning out to be real planets.

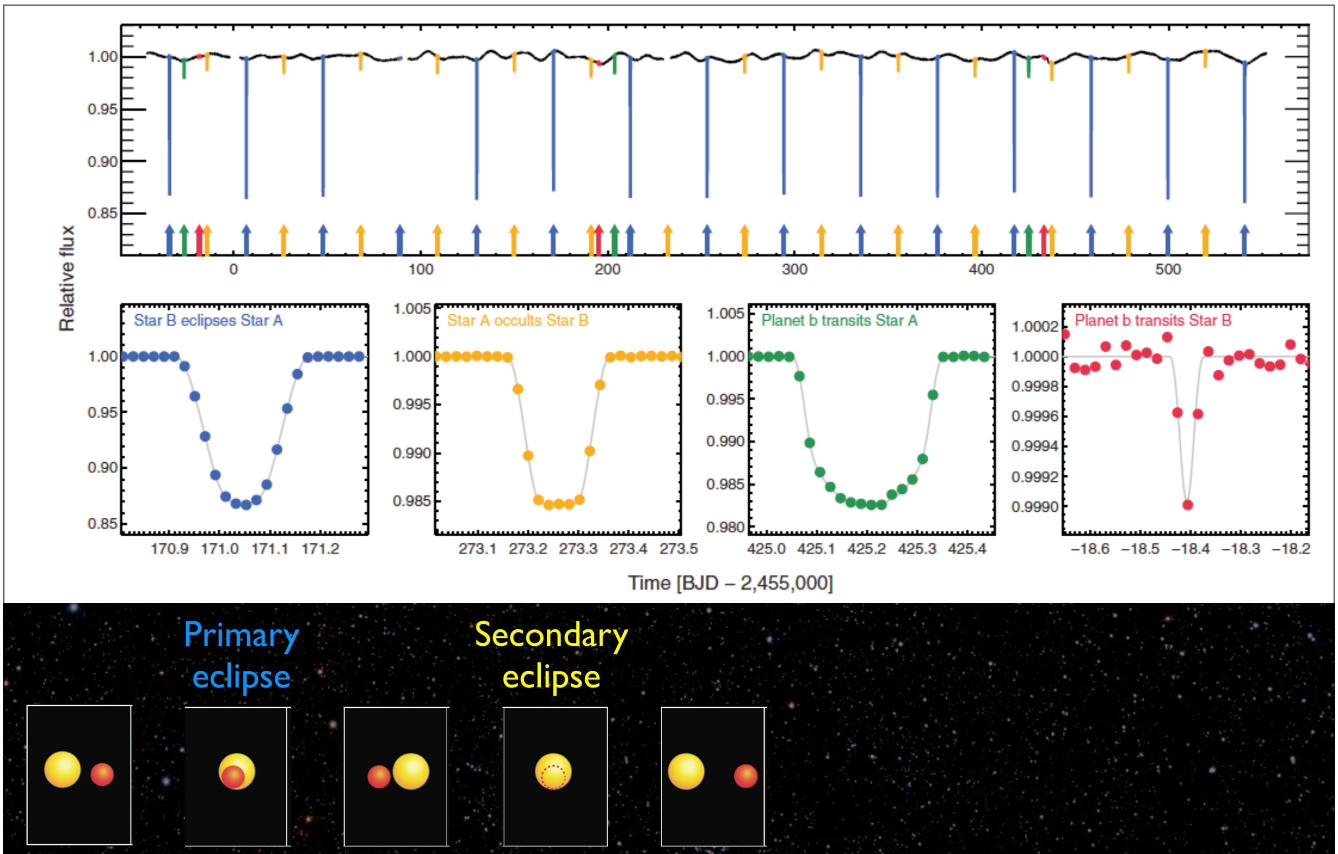
The number of (potential) Earth-sized planets is now 123.



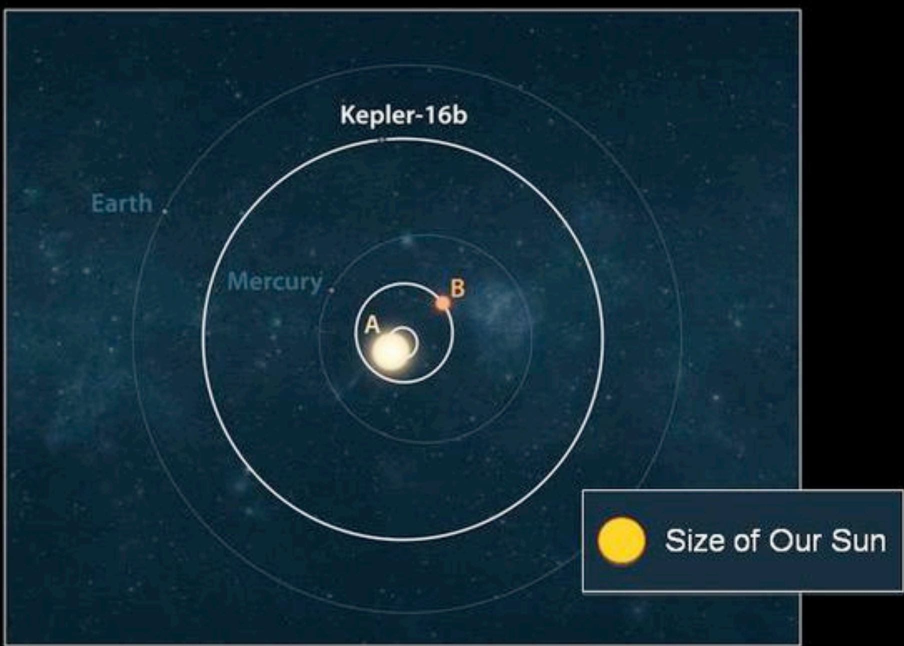
In September 2011, the Kepler team announced the first discovery of a circumbinary planet – a planet orbiting two stars. The two orbiting stars regularly eclipse each other; the planet also transits, each star, and Kepler data from these planetary transits allowed the size, density and mass of the planet to be extremely well determined.



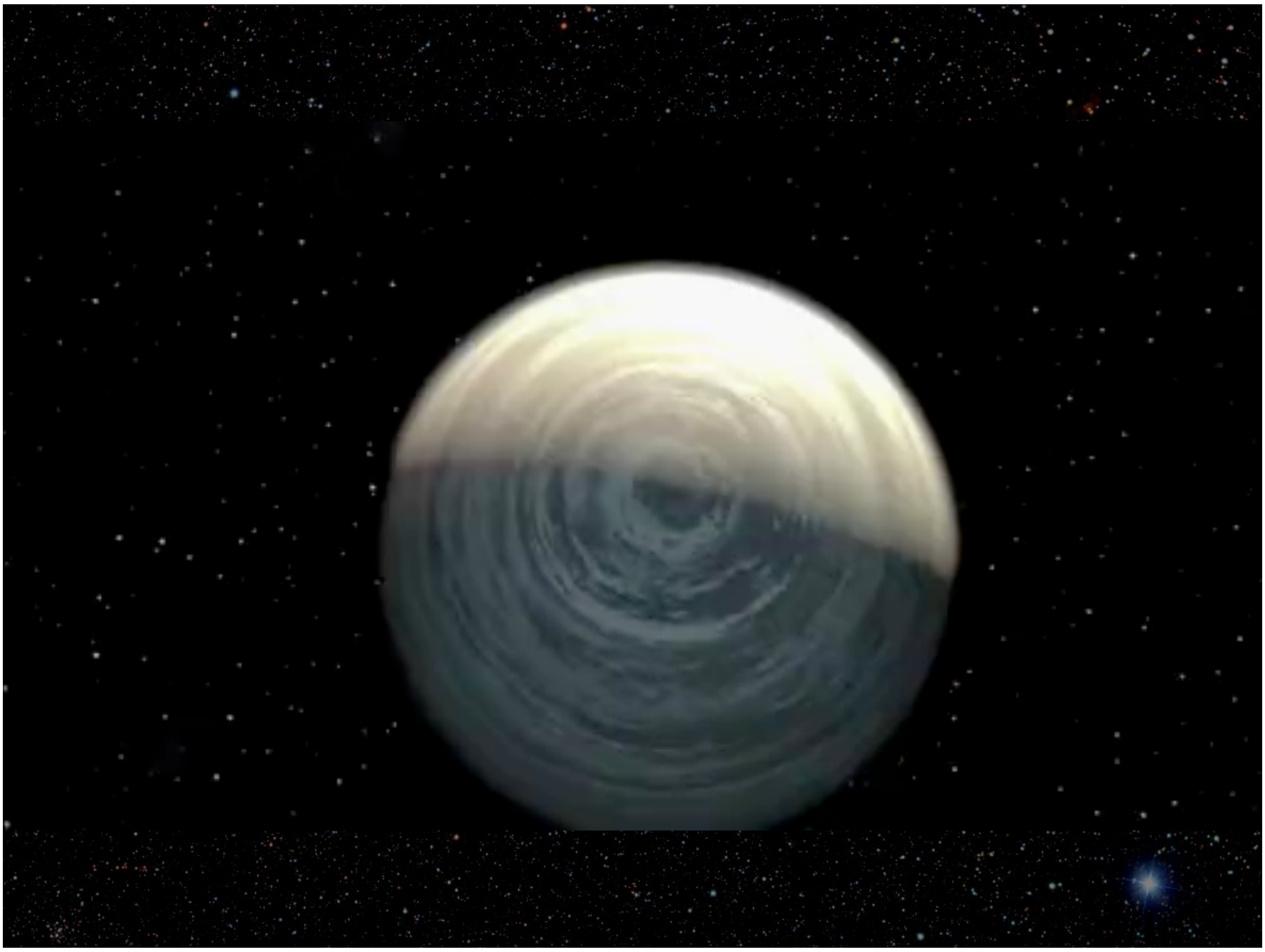
Artist's impression of Kepler-16b , the "Tatooine planet"



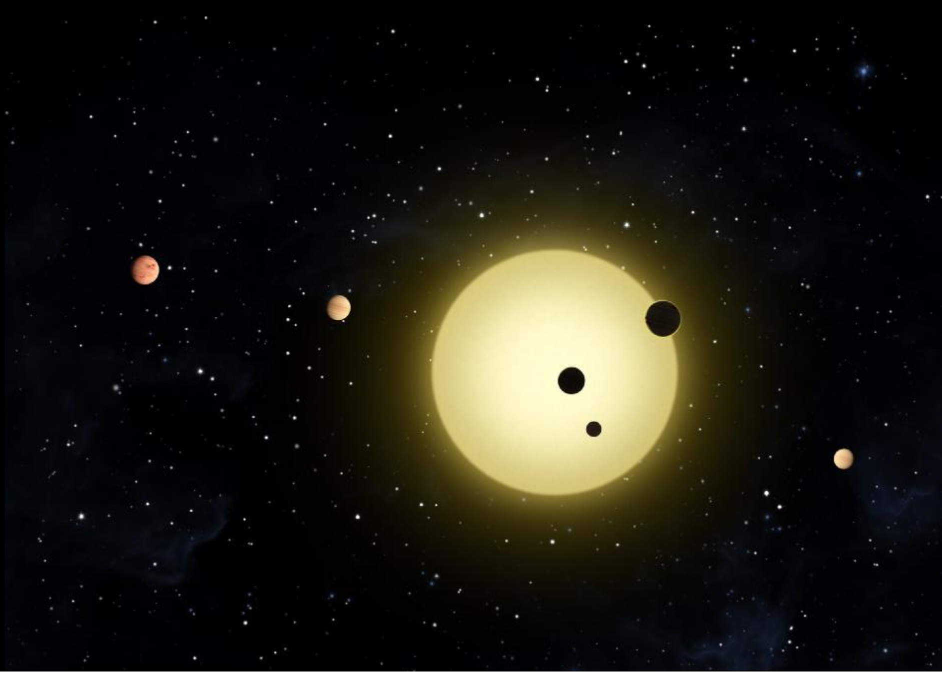
Light-curve of Kepler-16b , showing primary and secondary eclipses, as well as the transits of the planet across each star.

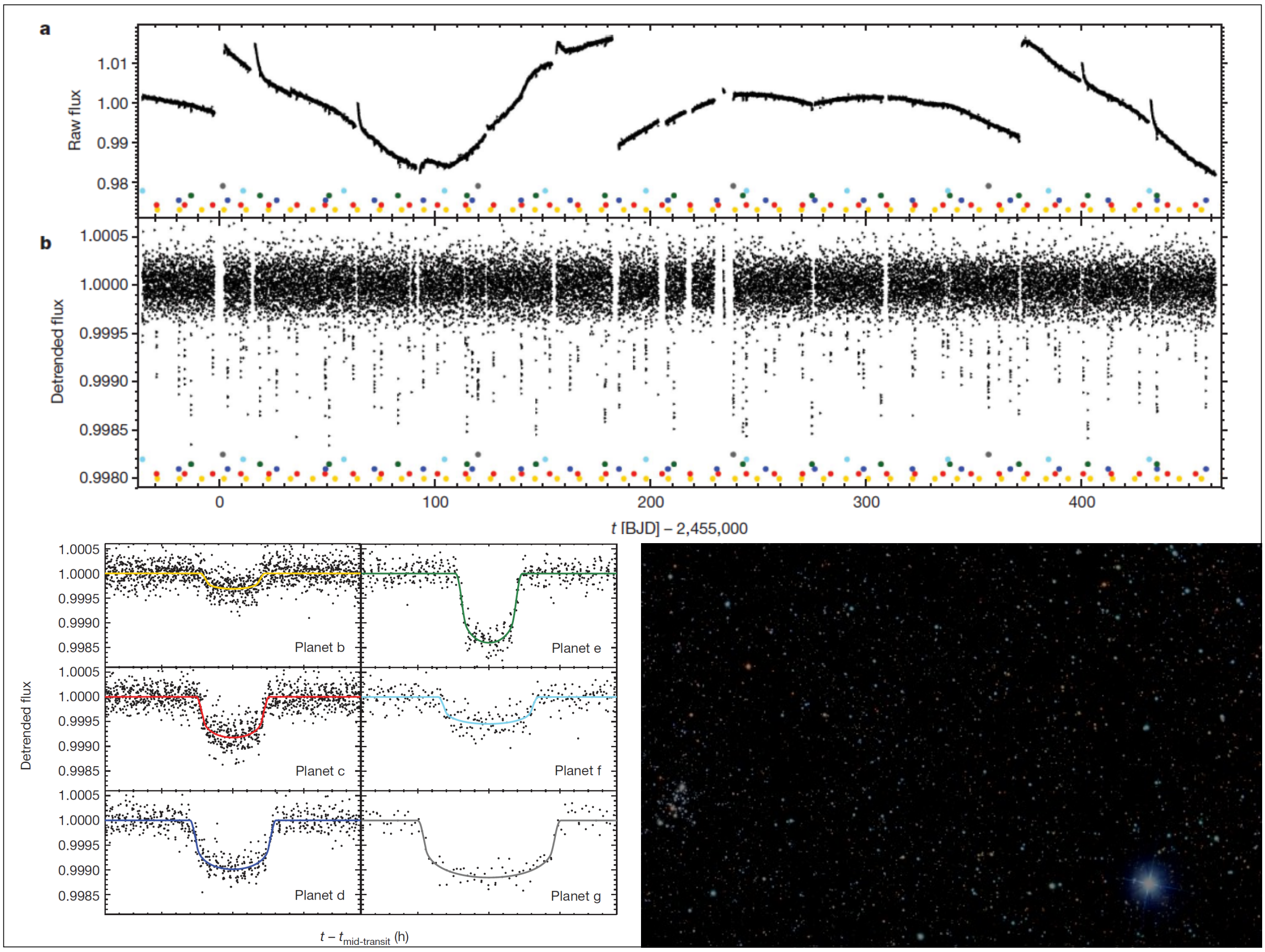


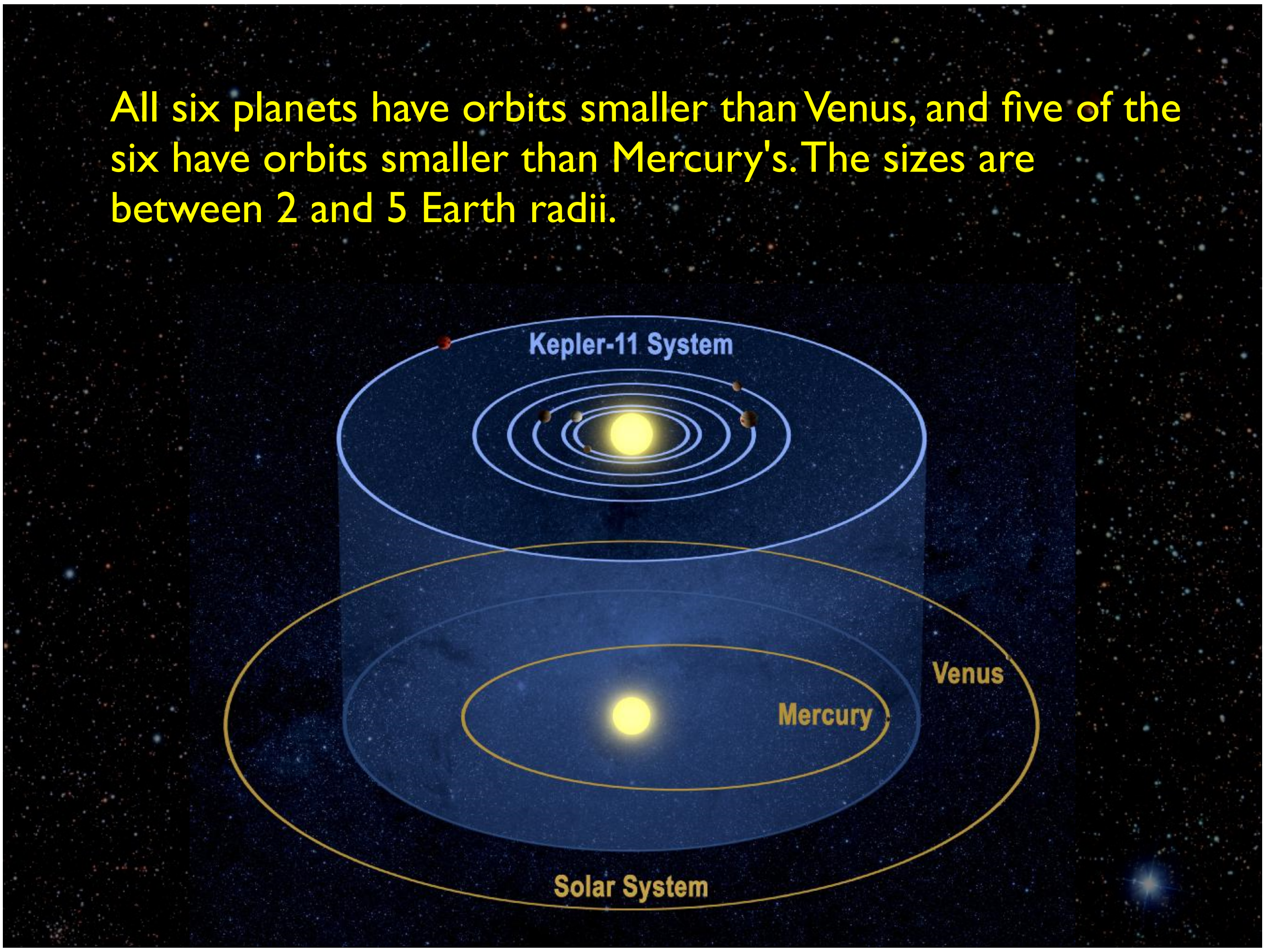
Bird's eye view of the Kepler-16b system. The planet, which is 1/3 the mass of Jupiter, orbits its star at a distance comparable to that of Venus in our own solar system, but is actually cold, as both stars are cooler than our Sun.

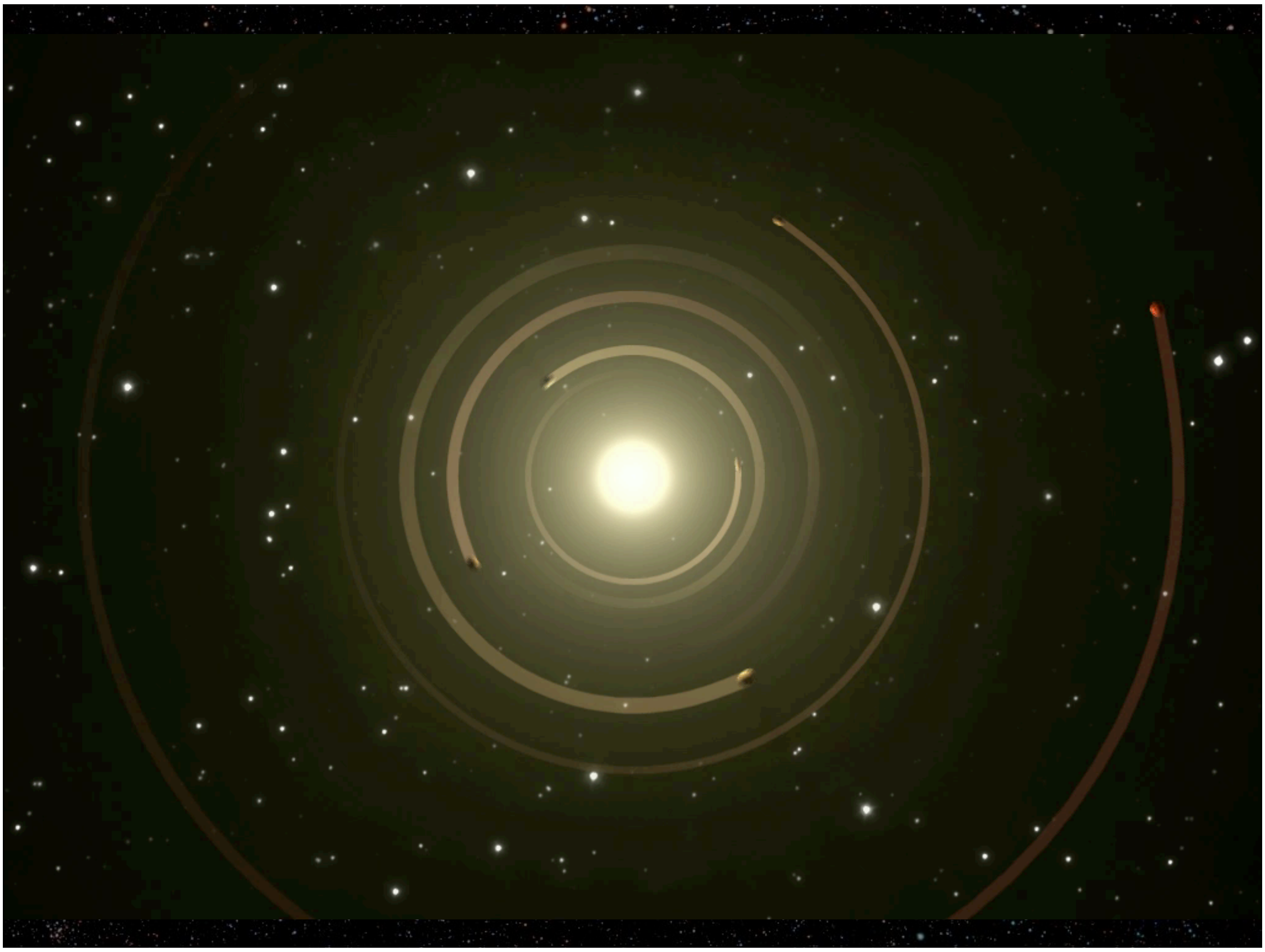


Last year, the Kepler team announced the discovery of a system of *six* low-mass planets transiting Kepler-11.

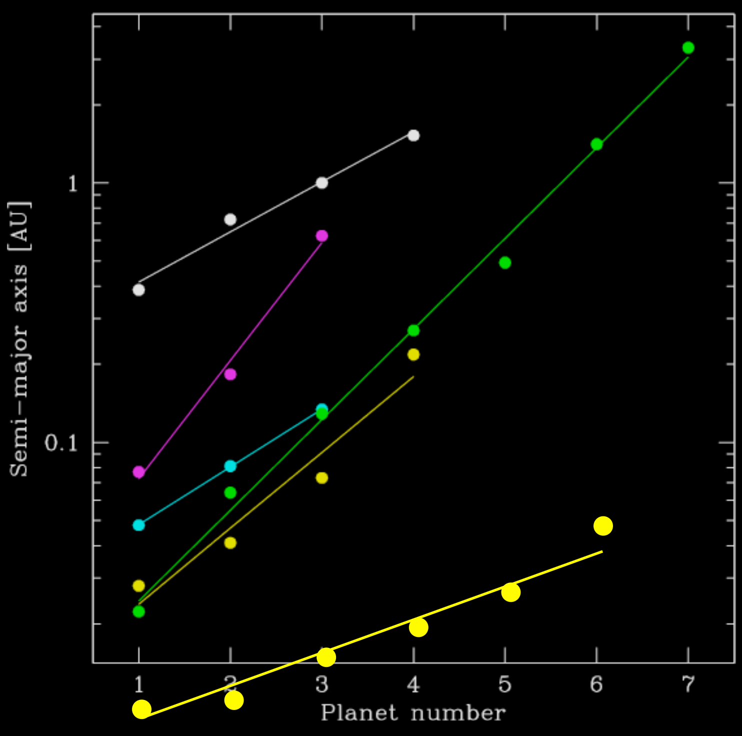



a
Raw flux
1.01
1.00
0.99
0.98
b
Detrended flux
1.0005
1.0000
0.9995
0.9990
0.9985
0.9980
0
100
200
300
400
t [BJD] – 2,455,000
Planet b
Planet e
Planet c
Planet f
Planet d
Planet g
t – t mid-transit (h)


All six planets have orbits smaller than Venus, and five of the six have orbits smaller than Mercury's. The sizes are between 2 and 5 Earth radii.
Kepler-11 System
Venus
Mercury
Solar System



Here's the Bode's law fit for that system:



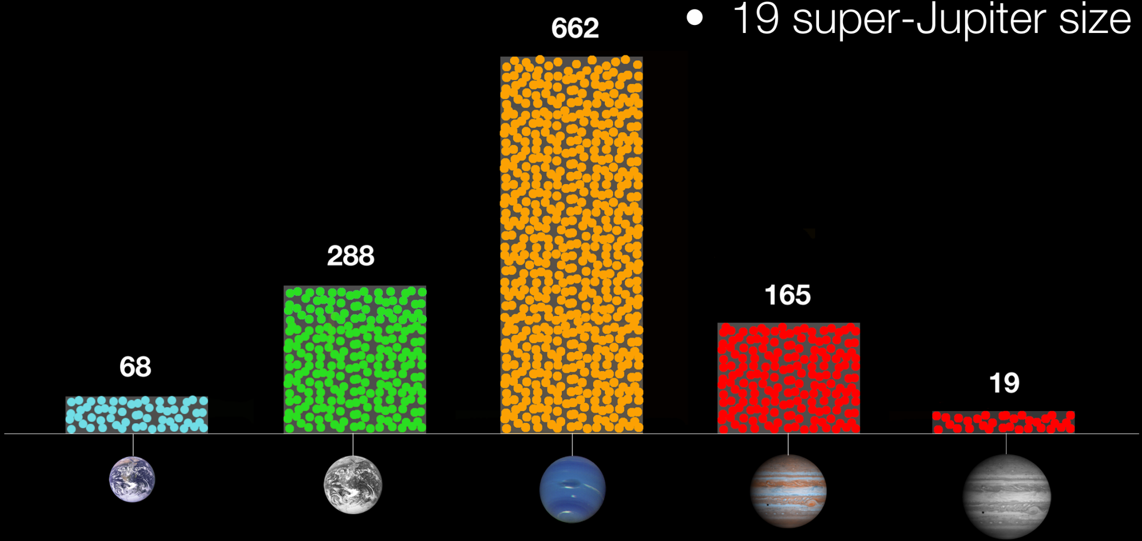
Kepler's findings

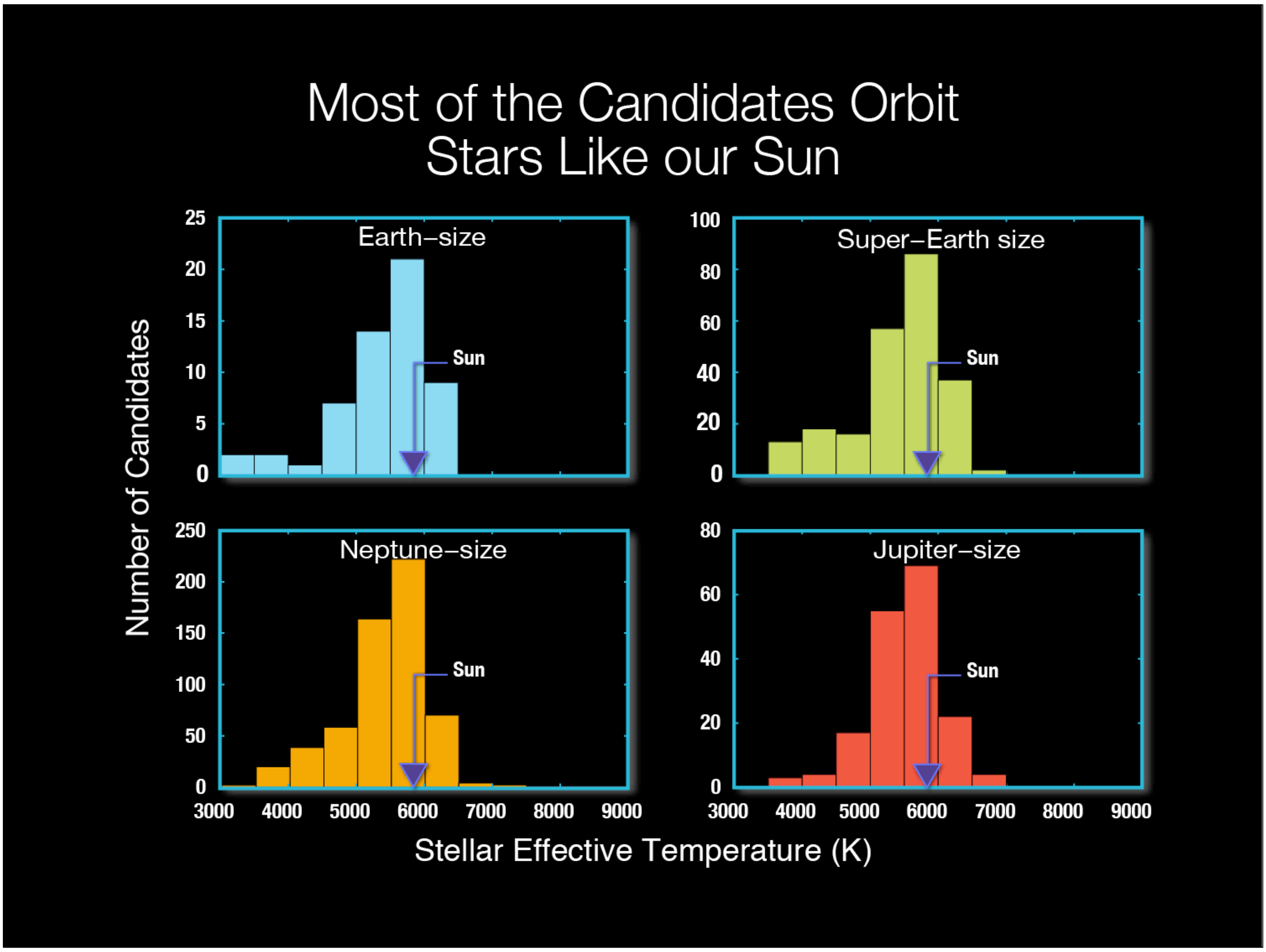
Kepler's planets are pouring in thick and fast. Here are some (preliminary) statistics on what has been found so far.

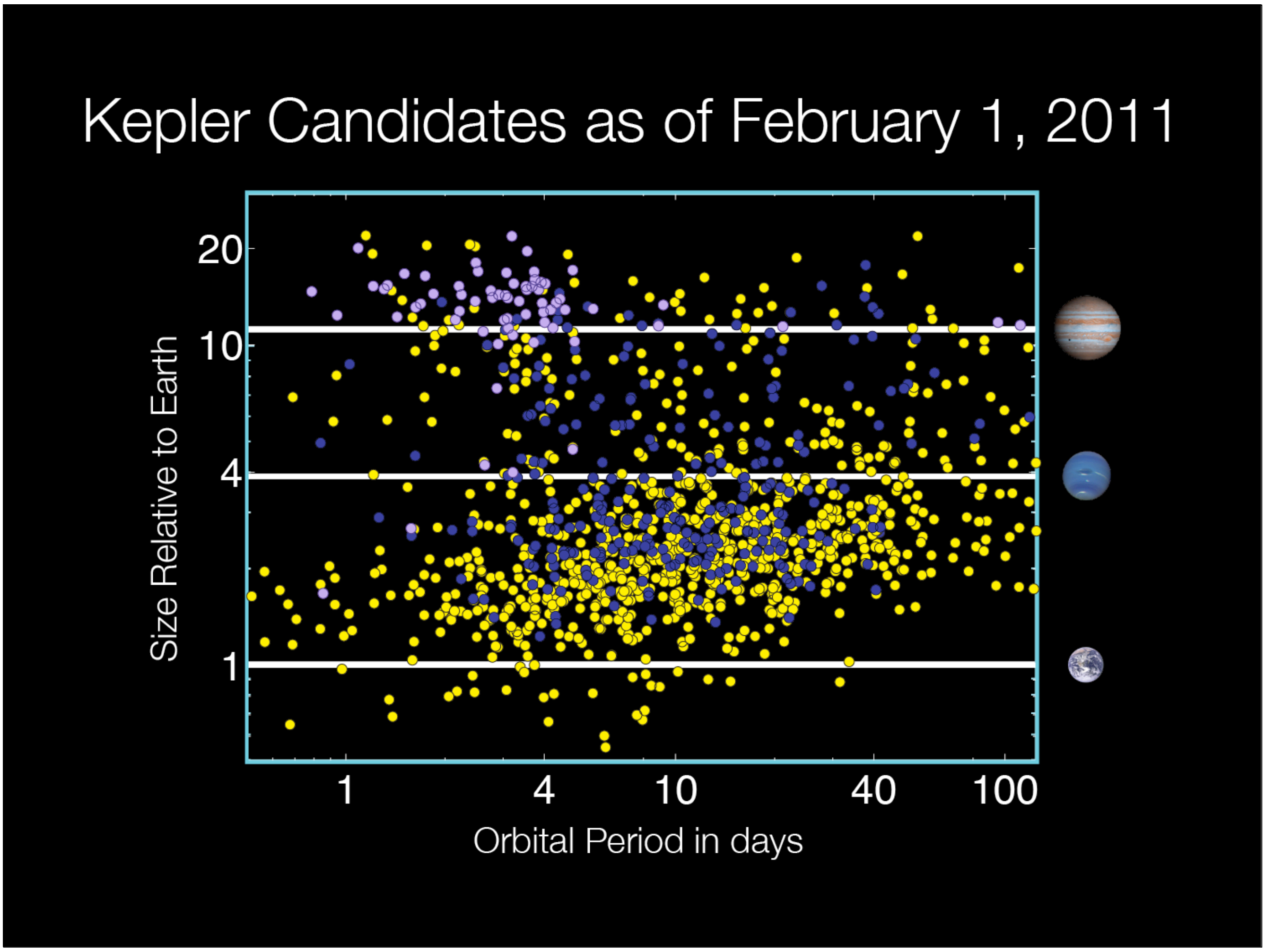
- about half of Sun-like stars have at least one planet with an orbital period of 100 days or fewer
- systems with multiple transiting planets are common (*17% of host stars, 34% of planets*)
- such systems are less likely to include a transiting giant planet
- either systems are likely to be highly co-planar, or typical systems have *many* planets

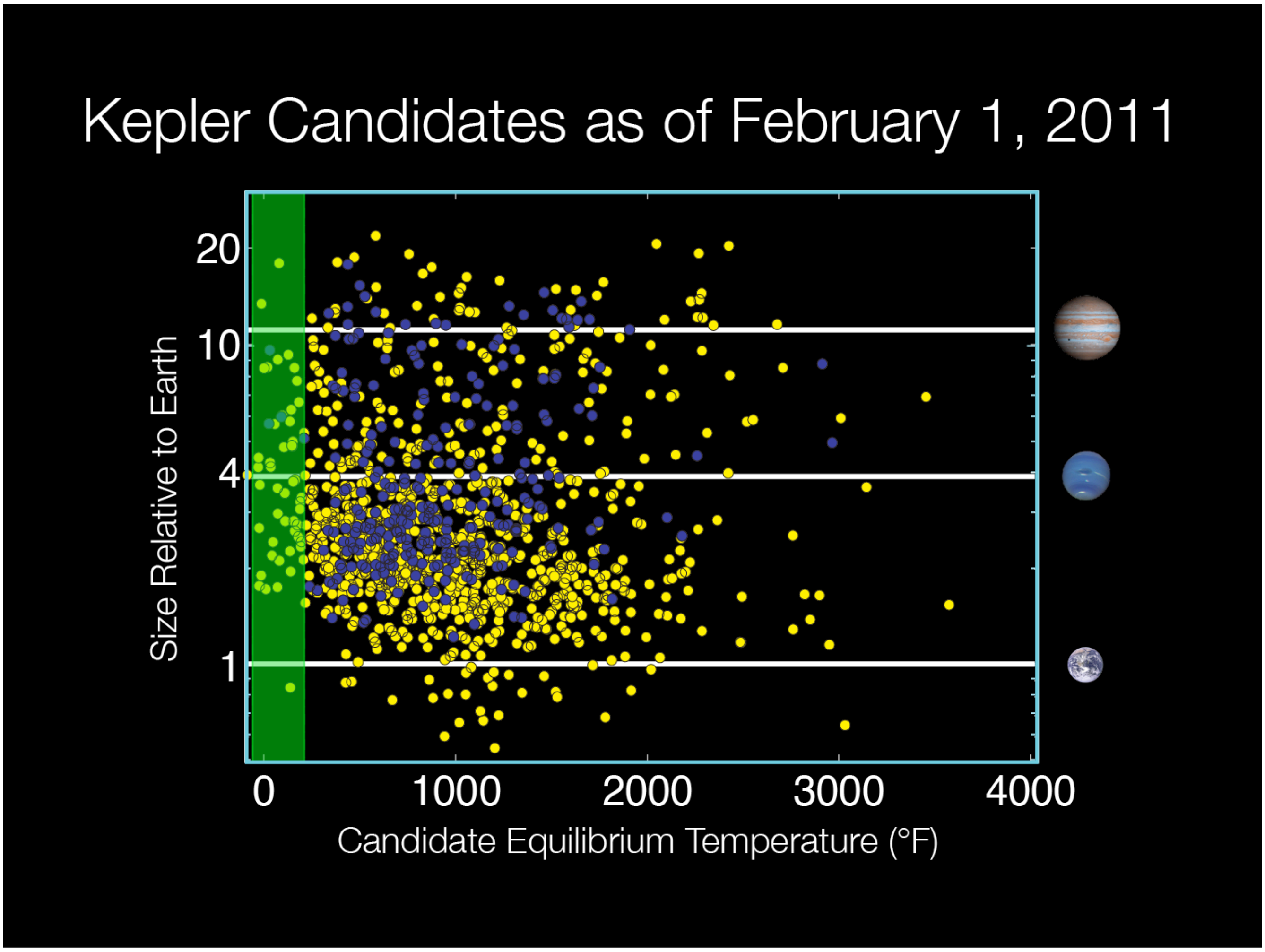
Numbers of Planet Candidates

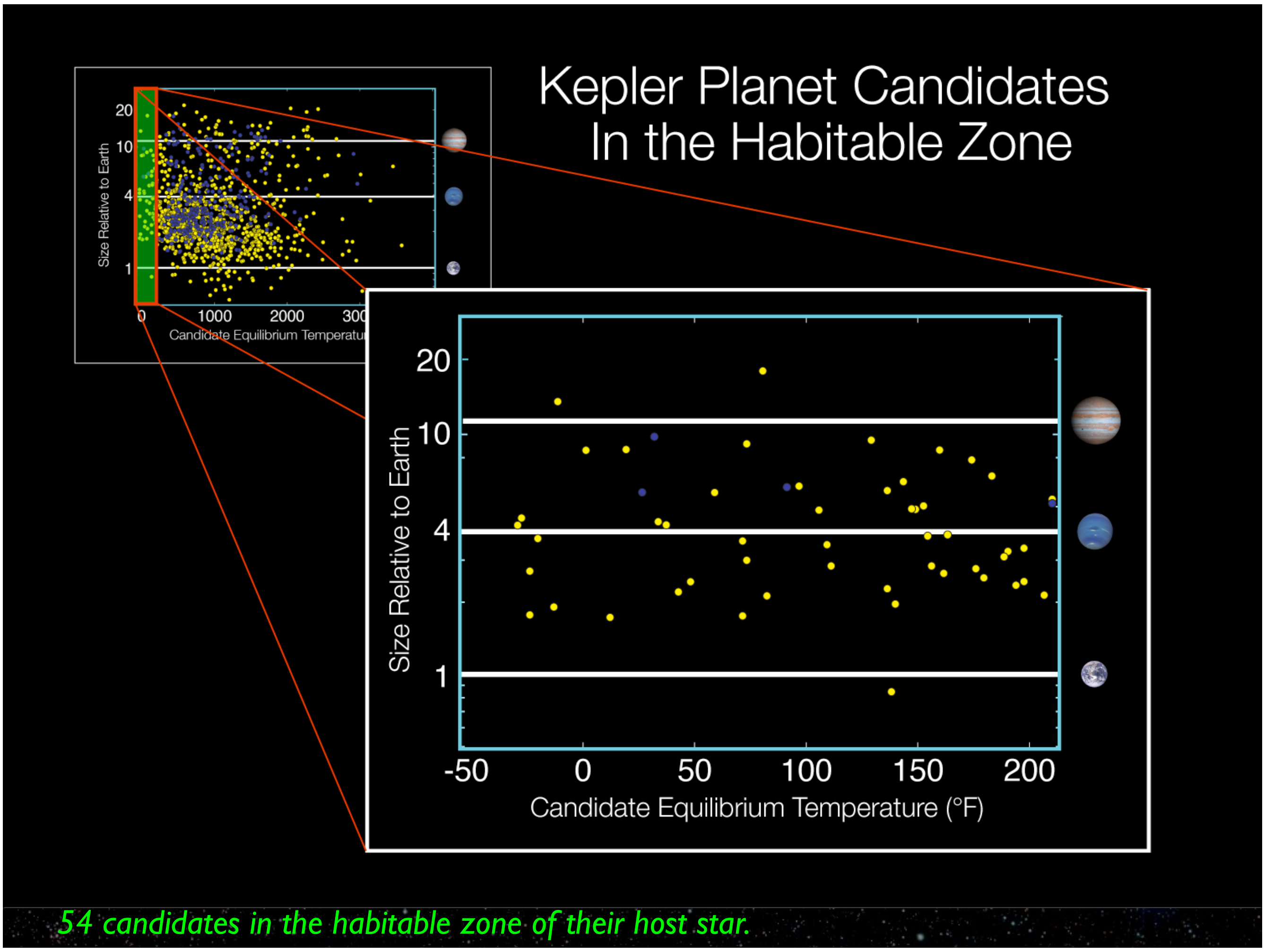
- 68 Earth-size
- 288 super-Earth size
- 662 Neptune size
- 165 Jupiter size
- 19 super-Jupiter size




Most of the Candidates Orbit
Stars Like our Sun
Number of Candidates
Earth–size
Super–Earth size
Neptune–size
Jupiter–size
Sun
Sun
Sun
Sun
25
20
15
10
5
0
100
80
60
40
20
0
250
200
150
100
50
0
80
60
40
20
0
3000 4000 5000 6000 7000 8000 9000
3000 4000 5000 6000 7000 8000 9000
Stellar Effective Temperature (K)


Kepler Candidates as of February 1, 2011
Size Relative to Earth
20
10
4
1
1 4 10 40 100
Orbital Period in days


Kepler Candidates as of February 1, 2011
20
10
4
1
Size Relative to Earth
0
1000
2000
3000
4000
Candidate Equilibrium Temperature (°F)


Kepler Planet Candidates
In the Habitable Zone
20
10
4
1
Size Relative to Earth
-50
0
50
100
150
200
Candidate Equilibrium Temperature (°F)
54 candidates in the habitable zone of their host star.

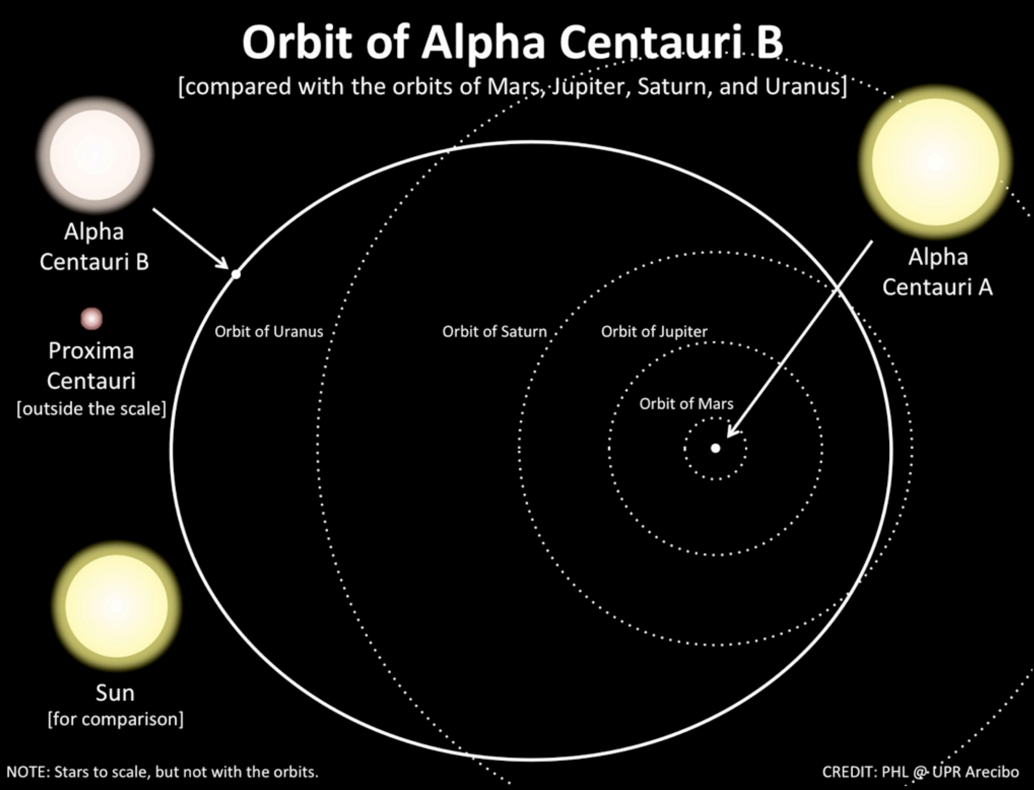
There is a "**Citizen Science**" project associated with *Kepler*, where members of the public identify transit events in the light curves to identify planets that the computer algorithms might miss. Currently, users may have found 69 candidates that were previously unrecognized by the Kepler Mission team.

The first person to flag a potential transit gets credit for the discovery, and is offered authorship on the paper.

* see Fischer et al. 2011, "Planet Hunters: The First Two Planet Candidates Identified by the Public using the Kepler Public Archive Data", http://adsabs.harvard.edu/abs/2012MNRAS.419.2900F

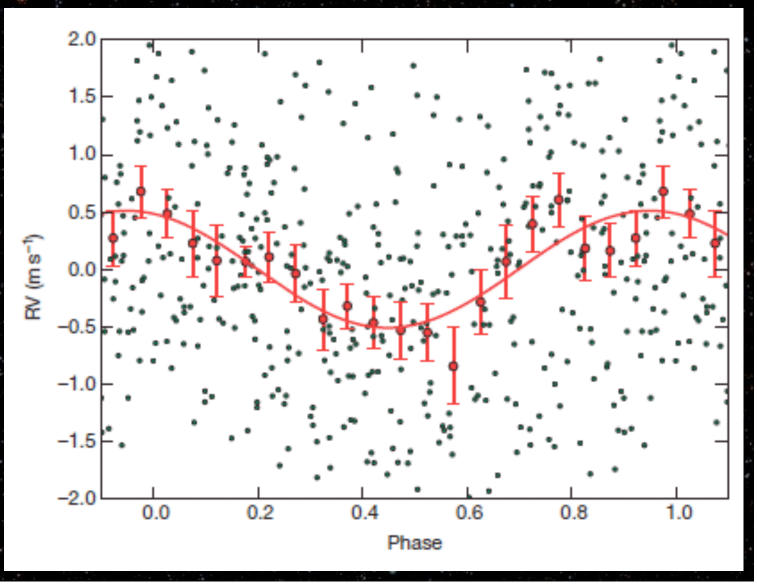
Planet around α Cen B?

In October, ESO scientists announced the discovery of a planet around α Cen B. The planet is in a 3.2 day orbit around the smaller star in the α Cen binary, and has a minimum mass of 1 Earth mass.



Size of the α Cen orbit compared to the Solar System. α Cen Bb orbits α Cen B much closer than Mercury orbits the Sun (distance from α Cen B is 0.04 AU, compared with 17.6 AU for α Cen A).

The signal was *incredibly* small – the Doppler shift in the star's light is only 0.5 m/s – slower than walking speed! This makes it one of the lowest mass planets yet discovered.



The measured wobble in the radial velocities of α Cen B due to the planet

Astronomy without light

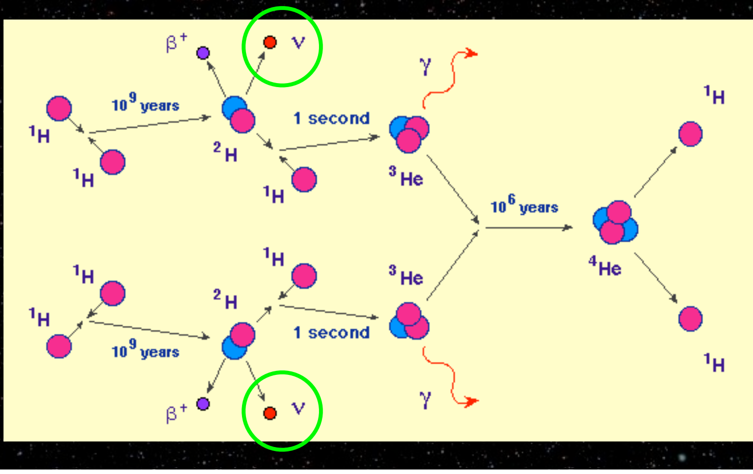
new ways of looking at the Universe

Back in lecture 1, I told you that astronomers could use only electromagnetic radiation to learn about the Universe.

There are actually several experiments going on to observe the Universe in other ways.

Neutrino astronomy

Many astrophysical reactions produce *neutrinos* – sub-atomic particles which have no mass or charge – in particular, the nuclear fusion reactions that power our Sun and other stars. Detecting neutrinos allows us to better understand these reactions.



Unfortunately, neutrinos interact hardly at all with matter, so they are *very* difficult to detect.

Raymond Davis built the first neutrino detector in the 1960s. The detector consisted of 400,000 litres of cleaning fluid (C_2Cl_4) one mile underground in an old mine.

When a chlorine atom captures a neutrino, it is turned into a radioactive isotope of argon. A few dozen events are expected every month.

The results of the experiment were astonishing. Davis detected only about a third of the expected number of neutrinos!

In his Nobel Prize lecture (2002), Raymond Davis says

“The solar neutrino problem lasted from 1967–2001. Over this period neither the measured flux nor the predicted flux changed significantly. I never found anything wrong with my experiment. John Bahcall never found anything wrong with the standard solar model.”

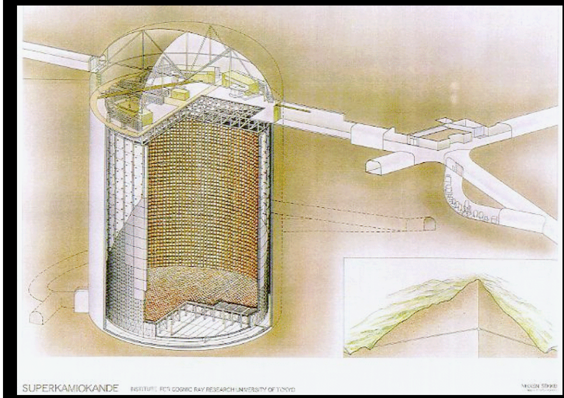
There were several possible explanations for this.

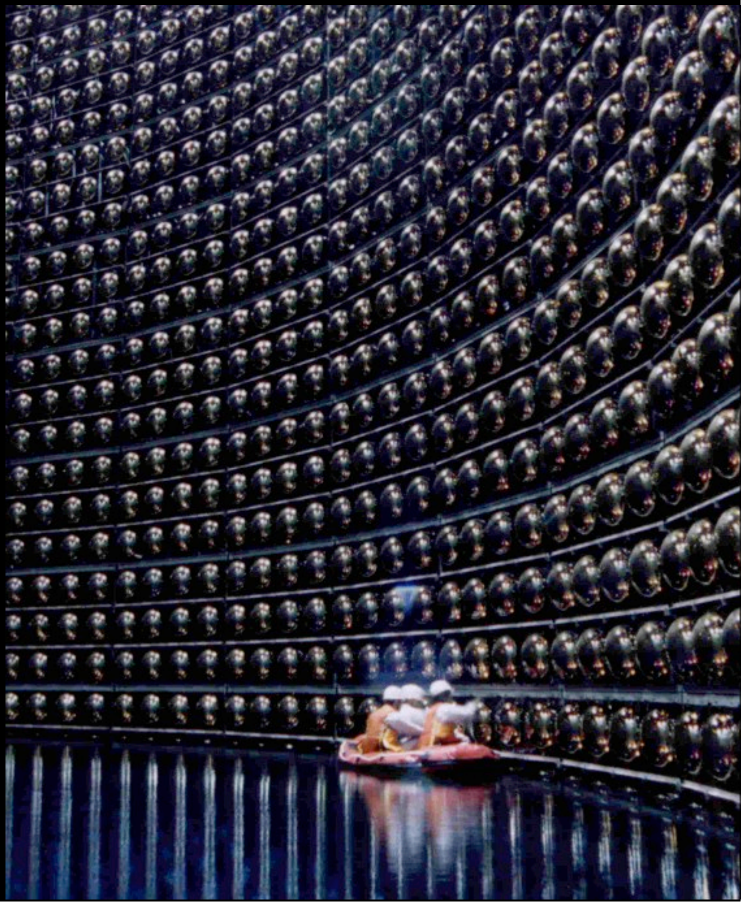
1. Nuclear fusion is not taking place in the Sun *(but other evidence suggests it is)*

2. The experiment was not calibrated properly *(but several other experiments have detected the same result)*

3. The rate of fusion inside the Sun is lower than we thought *(but we know how much energy has to come out!)*

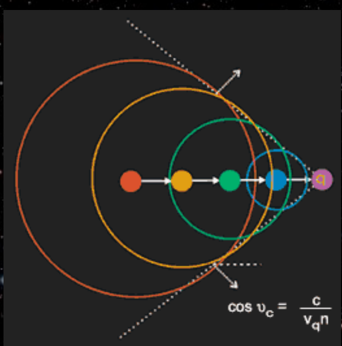
4. Something is happening to some of the neutrinos on the way so we can’t detect them.

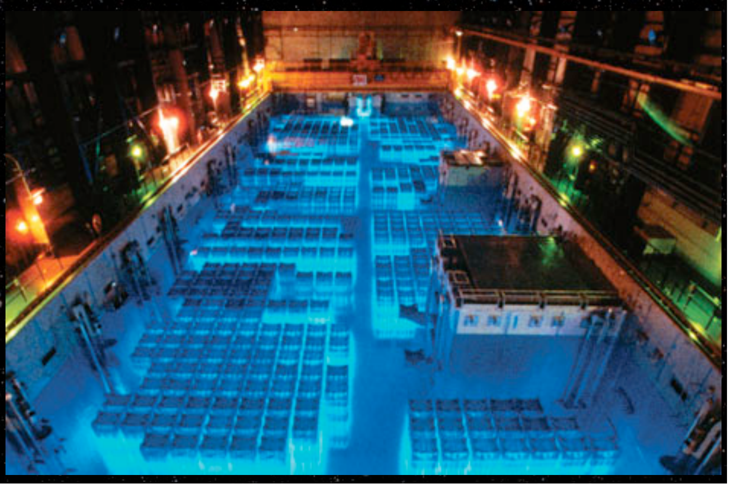




In the late 1990s a new detector called Super-Kamiokande was built in Japan, using 50,000 tonnes of pure water and 11,200 photomultiplier tubes (PMTs) in a 40m high x 40m diameter cylinder.

Super-Kamiokande detects neutrinos using *Cherenkov radiation*. If a charged particle travelling very close to the speed of light travels into a medium where the speed of light is lower (e.g. water), it can find itself travelling faster than (local) light speed (e.g. in water $v_{light} = 0.75c$). This produces a bow shock of light ahead of the particle, called Cherenkov radiation. The advantage is that you can measure the time of arrival and direction of the neutrino.

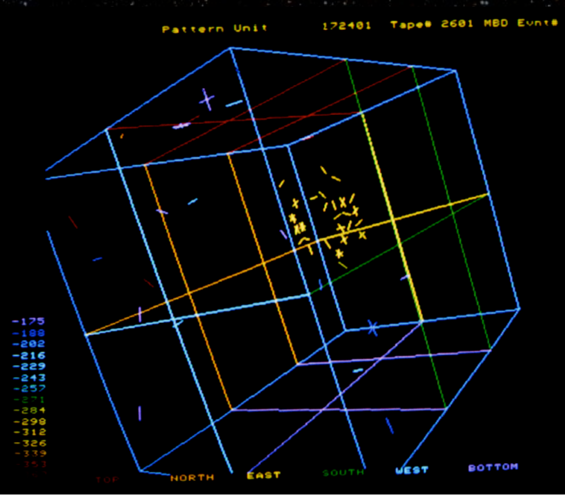




Fuel assemblies cool in a water pond at the French nuclear complex at La Hague. The blue light is generated by Cherenkov radiation, In 1998 a Super-Kamiokande team announced they had detected evidence of neutrinos oscillating between different varieties, only one of which – the electron neutrino – can be detected.

This not only explains the results of the solar neutrino experiment, but also implies that neutrinos have *mass*.

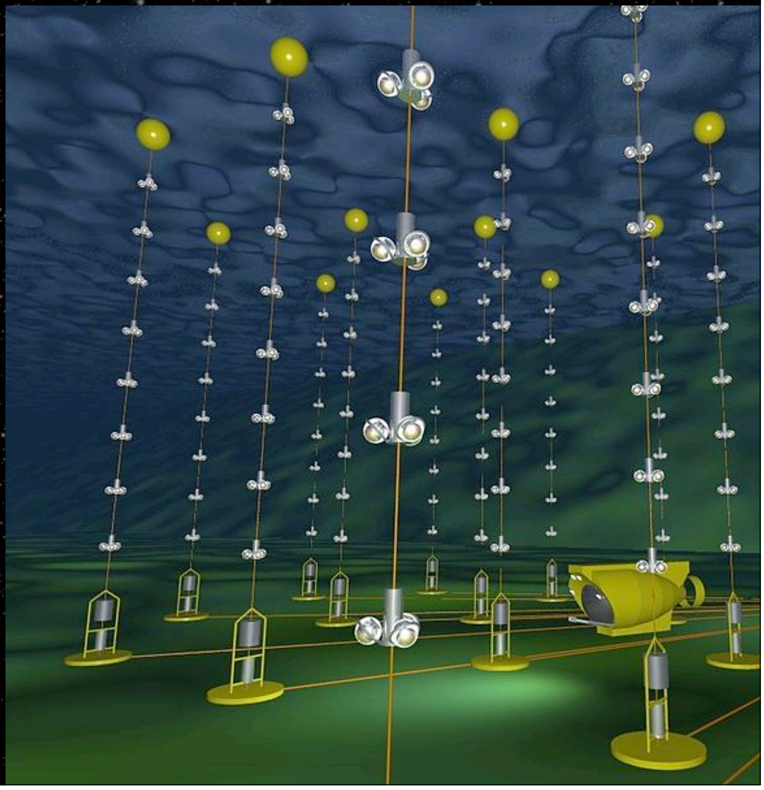
So far, the only extra-solar system object detected by neutrino observatories was SN 1987a. Two neutrino observatories – the Kamiokande experiment in Japan and the IMB experiment in Ohio – both detected a burst of neutrinos associated with the supernova: 12 and 8 events respectively, observed some hours before the optical supernova was spotted. Of course, the connection with the supernova was not realised until after the optical discovery.



One of the neutrino events from the IMB detector. The neutrino produced a flash of light, which was detected by several photo-multiplier tubes: by noting which PMTs responded, the direction and energy of the original neutrino can be deduced.

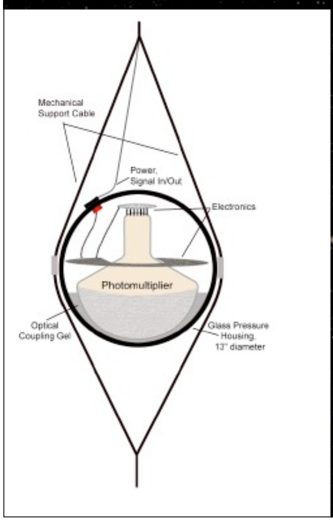
Several of the next generation of neutrino detectors are starting to come online, with much larger detector volumes (~1 km^3), all detecting Cherenkov radiation from neutrino interactions:

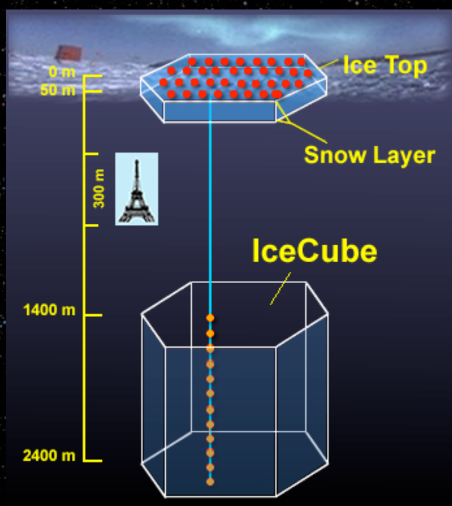
- *NESTOR* and *ANTARES*: towers of PMTs anchored to floor of Mediterranean Sea



- *IceCube*: strings of PMTs lowered into Antarctic ice. Holes are drilled 2 km under the ice to where the ice is clear. The ice acts as a detector a cubic kilometre in size.

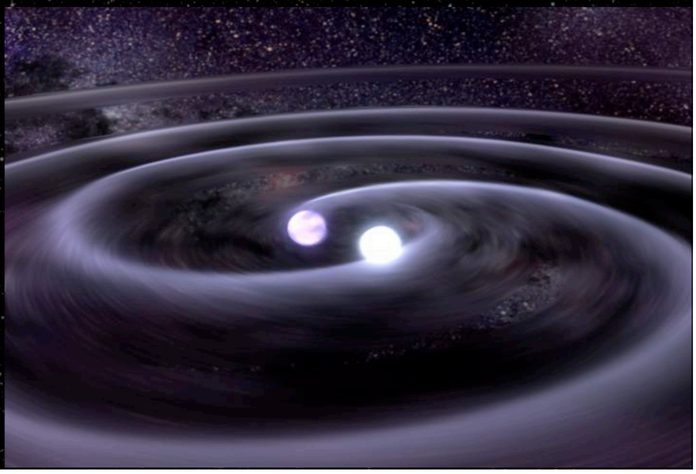
  IceCube is still waiting for a major detection.





Gravitational waves

Remember that in lecture 5, we learned that general relativity predicts the existence of gravitational radiation: fluctuations in space-time which propagate as a wave. The most intense sources of gravity waves will come from e.g. coalescing black holes.



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: 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.

LIGO, the the Laser Interferometer Gravitational Wave Observatory, uses laser interferometry to measure accurate distances between test masses 4 km apart inside vacuum pipe. A passing gravitational wave will slightly stretch one arm as it shortens the other.

LIGO has two installations 3000 km apart to distinguish e.g. seismic events.

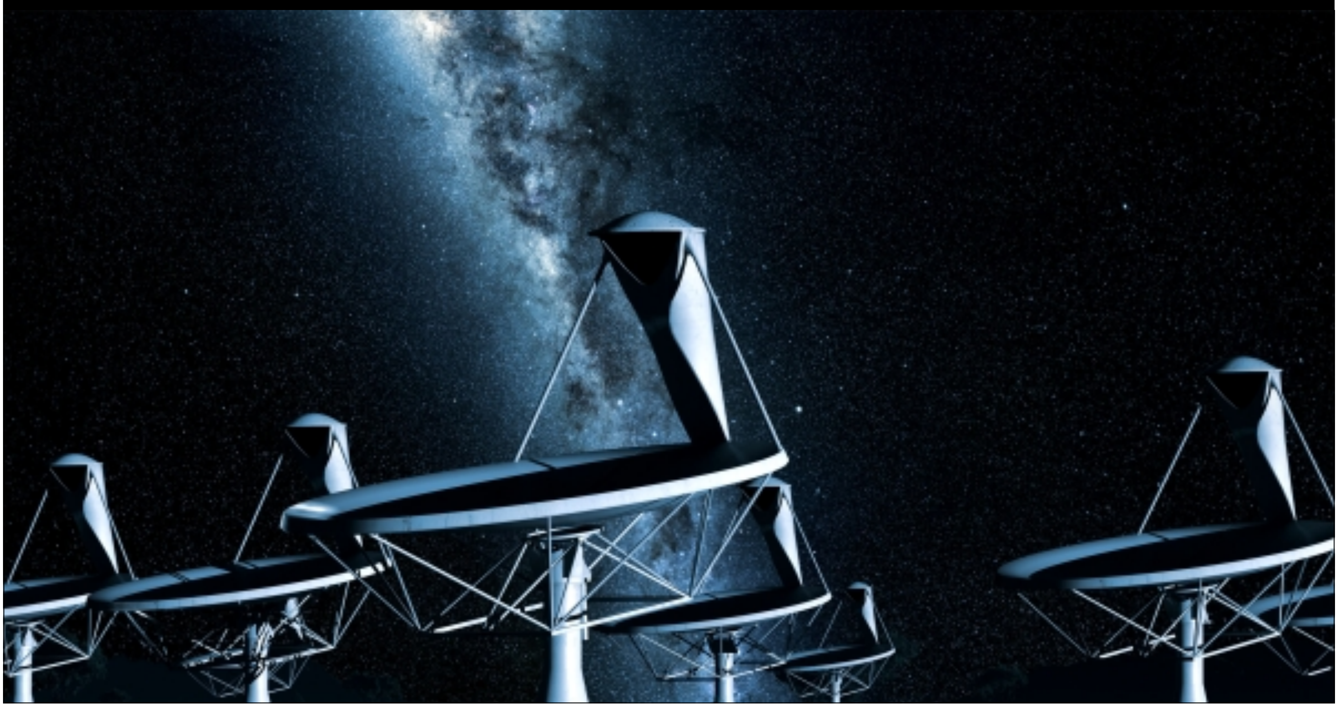
Europe has a similar installation called VIRGO: two 3 km arms using laser interferometry, located near Pisa.

No gravitational waves have yet been detected by any observatory.

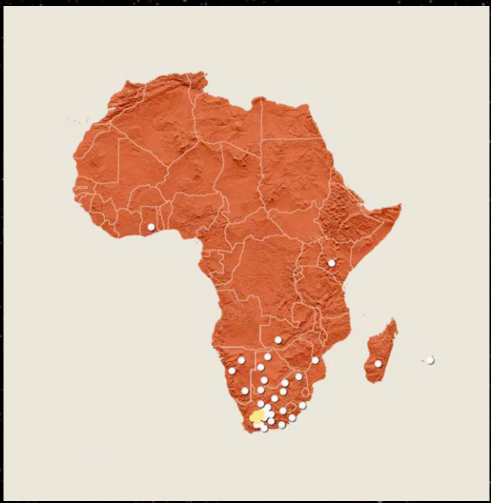
Very Big Telescopes

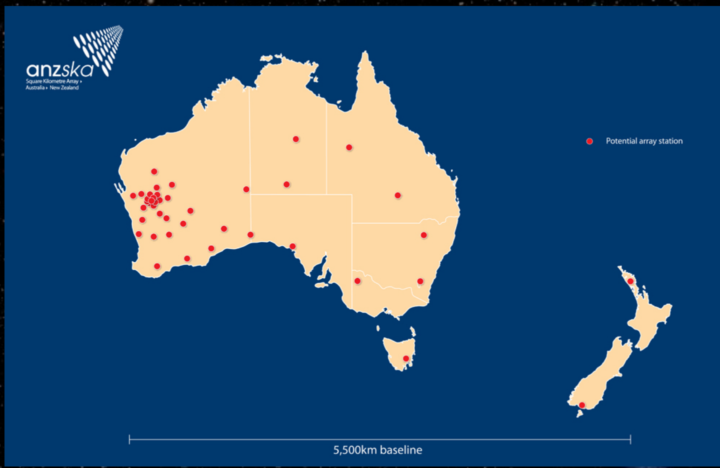
A whole new generation of enormous telescopes, both optical and radio, is currently under construction.

The *Square Kilometre Array* (SKA) is the world's largest radio telescope. The aim is to link multiple dishes with a total collecting area of one square kilometre, making it 50 times more sensitive than any other radio telecope.



The SKA is a global collaboration of 20 countries, including Australia. In May 2012, it was announced that the telescope will be shared between Africa and Australia/New Zealand. The superb sensivity of the SKA will aim to provide answers to fundamental questions about the origin and evolution of the Universe





SKA
SQUARE KILOMETRE ARRAY
www.skatelescope.org

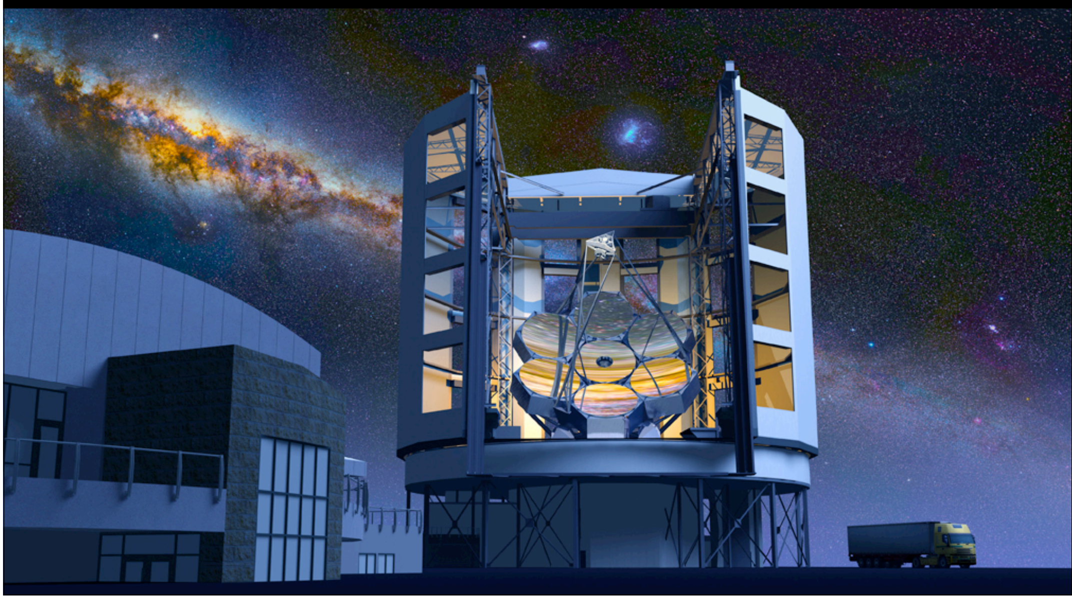
The Square Kilometre Array

Extremely large telescopes

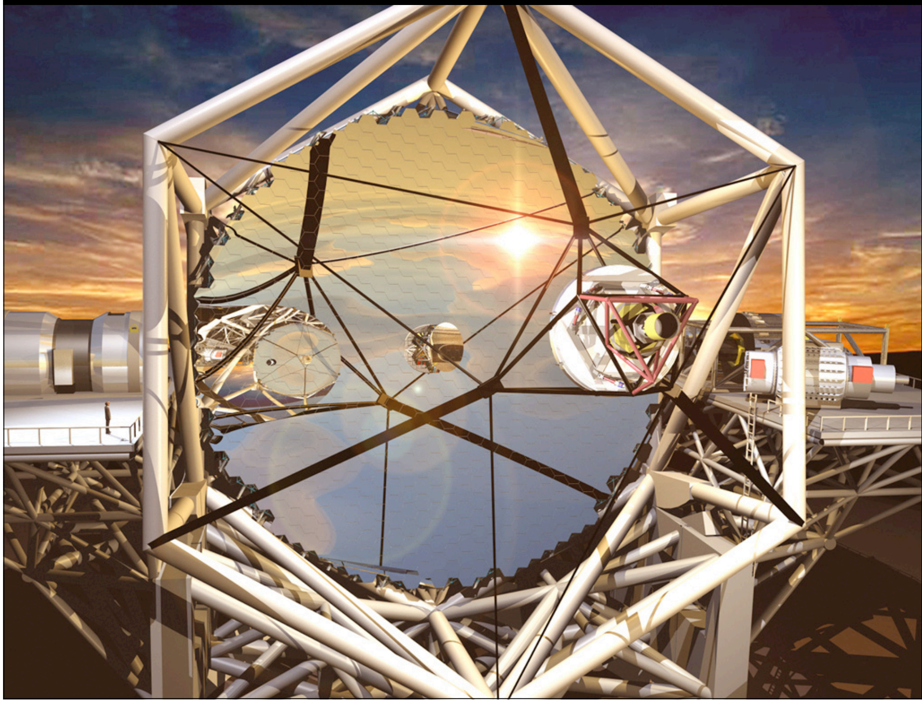
There are currently three projects underway to build optical telescopes with diameters > 20m. ELTs are planned to be able to see back to the very early universe, and to detect Earth-like planets around other stars.

Construction costs are ~ $1 billion for each.

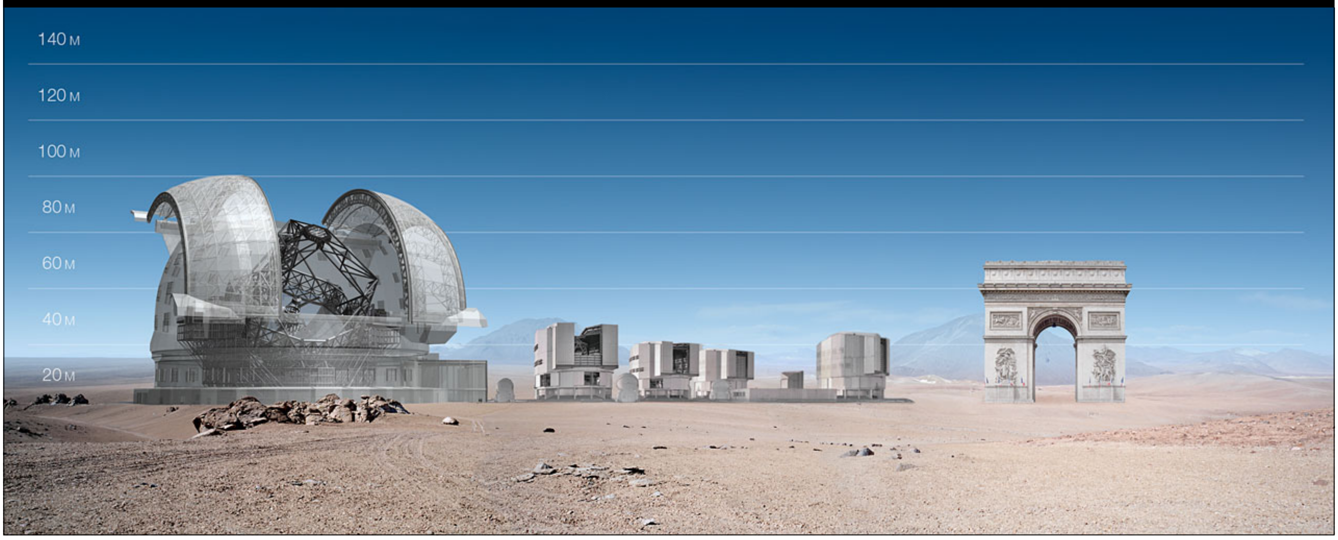
The *Giant Magellan Telescope* (GMT) will consist of seven 8.4-m circular mirrors, and will be located in Chile. Two mirrors have been cast, and will be completed by 2019. Australia is a member of the consortium building the GMT.



The *Thirty Meter Telescope* (TMT) is a 30-m telescope, made up of 492 hexagonal segments, each 1.4 m in diameter. It will be located on Mauna Kea. Construction has not yet begun.



The *European Extremely Large Telescope* (E-ELT) is a 39.3-m telescope consisting of 798 hexagonal segments, each 1.45 meters across but only 50 mm thick. It will be located in Chile. The design has been approved, and the site has been selected; operation will begin early 2020's.



Upcoming space missions

- *Dawn* mission to Vesta and Ceres: arrival at Ceres in February 2015
- *New Horizons* mission to Pluto: arrival 14 July 2015
- *Juno* mission to Jupiter: arriving July 2016
- *Cassini* mission to Saturn: scheduled to fall into Saturn's atmosphere in 2017

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
- Join a local astronomical club: see listing at the Astronomical Society of Australia page http://www.astronomy.org.au/ngn/engine.php?SID=1000022&AID=100136

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

Voyage to the Planets

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

Lives of the Stars

A more detailed look at how stars live and die

Eyes on the Prize

A history of astronomical discoveries which have been awarded the Nobel Prize

That’s all, folks!

Further reading

Quite a few books have been written in recent years about the discovery of planets outside our solar system, but unfortunately most of them seem to have been written immediately after the first few were found in 1996, so are now seriously out of date, barely a decade and a half later! Michel Mayor, co-discoverer of the first planet, has a book called **“New Worlds in the Cosmos: The discovery of exoplanets”** by Michel Mayor and Pierre-Yves Frei, transl. Boud Roukema (Cambridge UP, 2003). It has a good description of what people are now thinking about how to make these planets. Doubtless it will look very dated in a few short years!

- Web-sites can at least stay up-to-date, even if they’re less readable. A couple of good ones:
  - The most complete list is at **“The Extrasolar Planets Encyclopaedia”** http://exoplanet.eu/, but it’s just a giant list of planets, with not much by way of readable information.
  - NASA now has a site called “**PlanetQuest: Exoplanet exploration”** at http://planetquest.jpl.nasa.gov/, which has a host of useful information, including a page to search the catalogue of exoplanets in various ways
  - The California and Carnegie Planet Search, http://exoplanets.org/ has lots of useful things, including nice tools to plot the data
  - space.com has a list of **“The Strangest Alien Planets”** at http://www.space.com/159-strangest-alien-planets.html

- The *Kepler* website is at kepler.nasa.gov: they have loads of good pictures and animations, as well as a live counter telling you how many planets they've found!
- The Citizen Science project **Planet Hunters** is at http://www.planethunters.org; you can help identify transits and find new planet candidates. The site is part of the **zooniverse** project, which has many participatory projects, from identifying galaxies, to exploring features on the Moon, and identifying potential Kuiper Belt targets for New Horizons.
- NASA maintains an "**Upcoming Planetary Launches and Events"** page at http://nssdc.gsfc.nasa.gov/planetary/upcoming.html
- There's a nice book called "**The edge of physics: A journey to earth's extremes to unlock the secrets of the universe**" by Anil Ananthaswamy (Duckworth Overlook, 2010), in which the author travels to all sorts of remote places to find out about some of the new big experiments on cosmology. A fun read, that gives a good feel for some of these exciting new facilities. The author also has a website with photos from his journeys at http://www.edgeofphysics.com.
- 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.

Sources for images used:

- Light house and firefly: from PlanetQuest "Search for another Earth" powerpoint presentation http://planetquest.jpl.nasa.gov/gallery/frequentImages.cfm
- Astrometric displacement due to Jupiter: Planet Quest: Science - Finding planets http://planetquest.jpl.nasa.gov/science/finding_planets.cfm
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- Orbit geometry: from "The Search for and Discovery of Extra-Solar Planets" by Richard Larson, http://www.astro.washington.edu/larson/Astro150b/Lectures/ExtraSolarPlanets/xsp.html
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- HAT-P-7b light curve: from Borucki et al, 2009, "Kepler's Optical Phase Curve of the Exoplanet HAT-P-7b", http://adsabs.harvard.edu/abs/2009Sci...325..709B; animation from http://kepler.nasa.gov/multimedia/animations/
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- Radial velocity curve: from Nature paper http://www.eso.org/public/archives/releases/sciencepapers/eso1241/eso1241a.pdf

- Proton-proton chain: from Astronomy 162: Stars, Galaxies and Cosmology: The Proton-Proton Chain http://csep10.phys.utk.edu/astr162/lect/energy/ppchain.html
- Davis experiment: from "Big World of Small Neutrinos", http://conferences.fnal.gov/lp2003/forthepublic/neutrinos/
- Super-Kamiokande: Diagram: from Super-K at U. of Washington, http://www.phys.washington.edu/~superk/uwgroup.html

  Photo of interior: from Photo Album of the SK detector, http://www-sk.icrr.u-tokyo.ac.jp/doc/sk/photo/index.html
- Cherenkov radiation: from http://spectrum.ieee.org/energy/nuclear/nuclear-wasteland
- Neutrino event from SN1987A: from John Vander Velde http://www-personal.umich.edu/~jcv/imb/imbp4.html#Supernova
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- TMT: http://www.tmt.org/gallery/photo-illustrations
- E-ELT: http://www.eso.org/public/images/archive/search/?adv=&subject_name=Extremely%20Large%20Telescope
- Juno at Jupiter: from wikipedia http://en.wikipedia.org/wiki/Juno_%28spacecraft%29
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