AY2 Announcements

- Quiz 4: Thursday Dec 5 (last day of class)

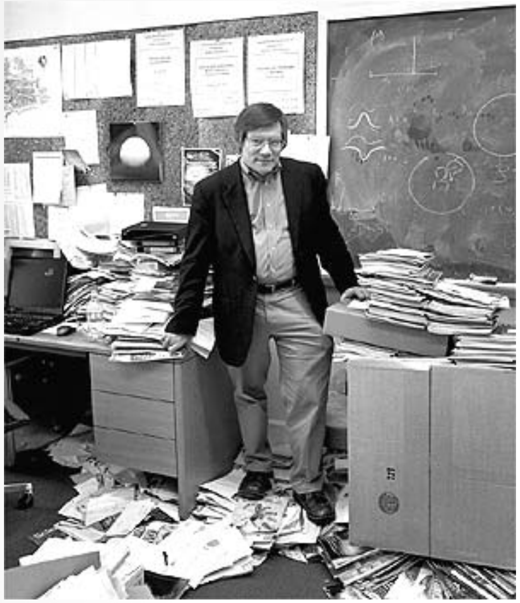
- Final: Dec 12, noon – 3pm
  - Final is cumulative and largely drawn from the quizzes
- Special Study Section TODAY 3:30-5:30 ISB 365

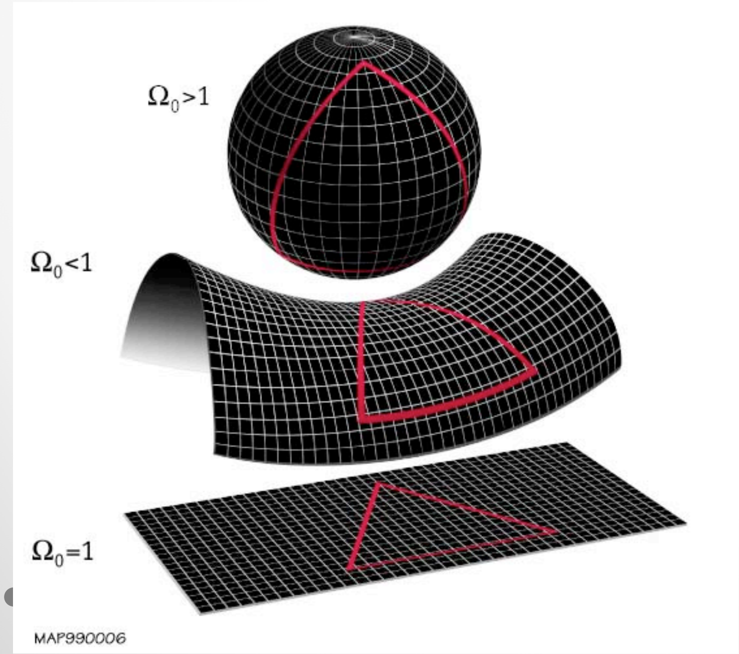
- Final study session with Miranda: Dec 10, 9am – noon CHECK HERE FOR LOCATION Will be Zoom broadcast and recorded.

- Don’t forget sections! https://astro2.sites.ucsc.edu

Last Lecture

Are Astronomers Inflating the Truth?

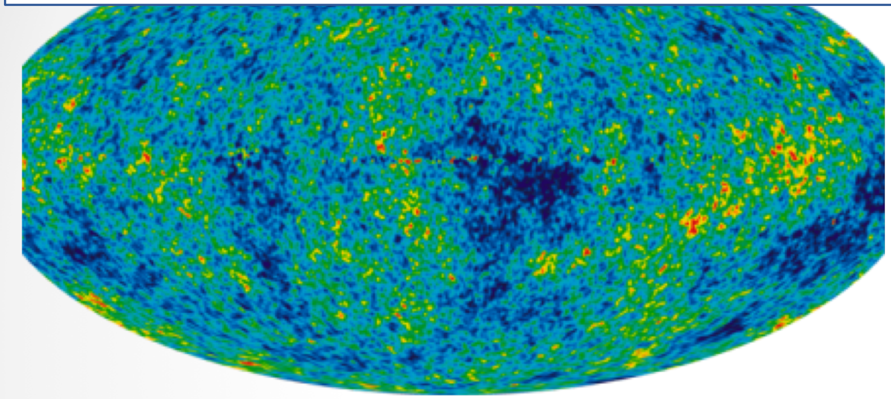


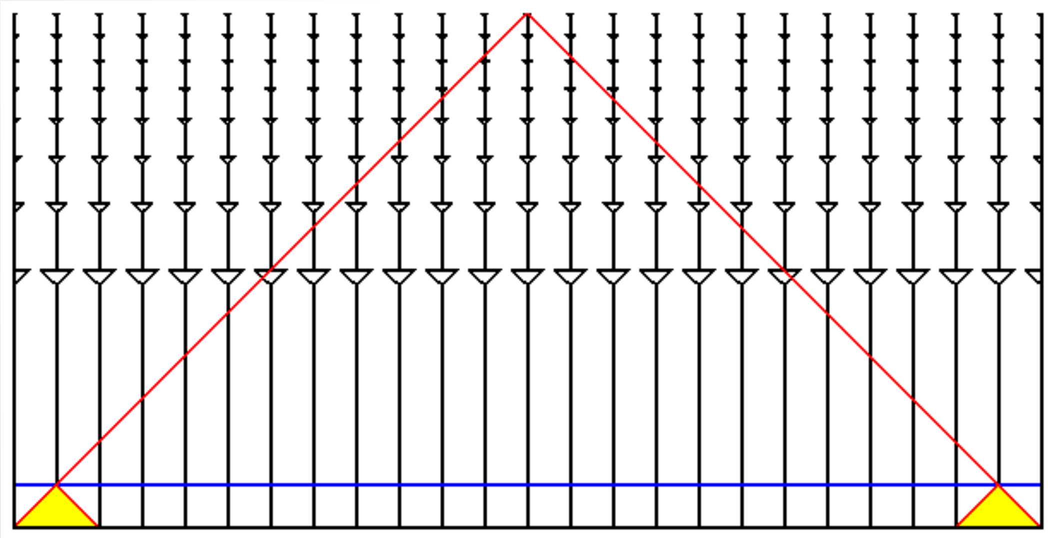


- In the 1970s three problems with the Big Bang were widely discussed:
  - Horizon problem
  - Flatness problem
  - Relic monopole problem
  - Origin of cosmic structures
- Universe expands by 10^{26} between 10^{-36} and 10^{-32} seconds after the Big Bang

Horizon Problem

Pre-Inflation the entire observable Universe was in causal contact

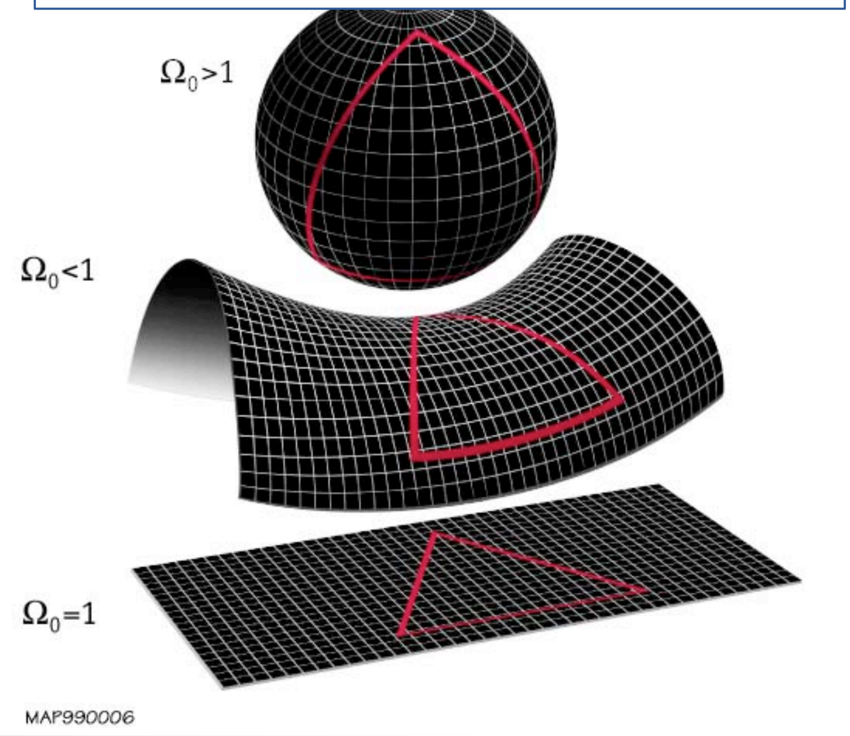




- Cosmic Microwave Background looks the same (statistically) in every direction
- But, the opposite sides of the sky should not have been in "contact" at 380,000 years after the HBB
- How could they be the same temperature to 1 part in 100,000?

Flatness Problem

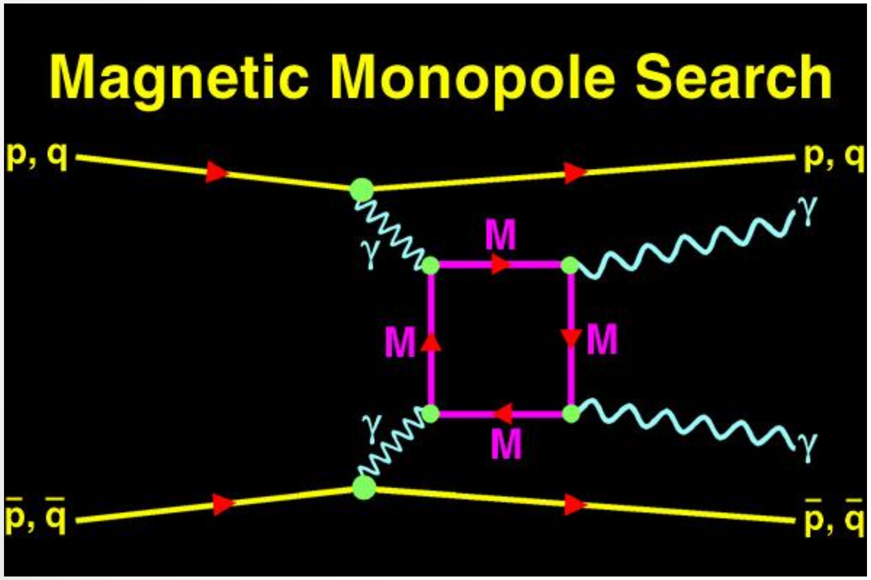
Huge increase in size naturally drives Universe to be spatially flat



- The mass/energy in the Universe causes an overall "warp" in space time
- There is a critical density of mass/energy that makes the Universe spatially "flat"
- "Ω"= ratio of mass/energy density to the critical mass for a flat universe
  - Ω_M is the contribution of matter (and photons) to the density

Magnetic Monopoles

Monopole freezeout occurred pre-Inflation and monopole density diluted by $(10^{26})^3$

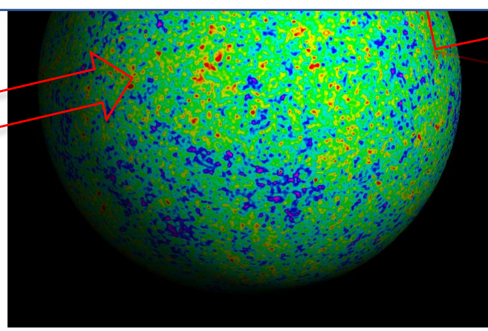


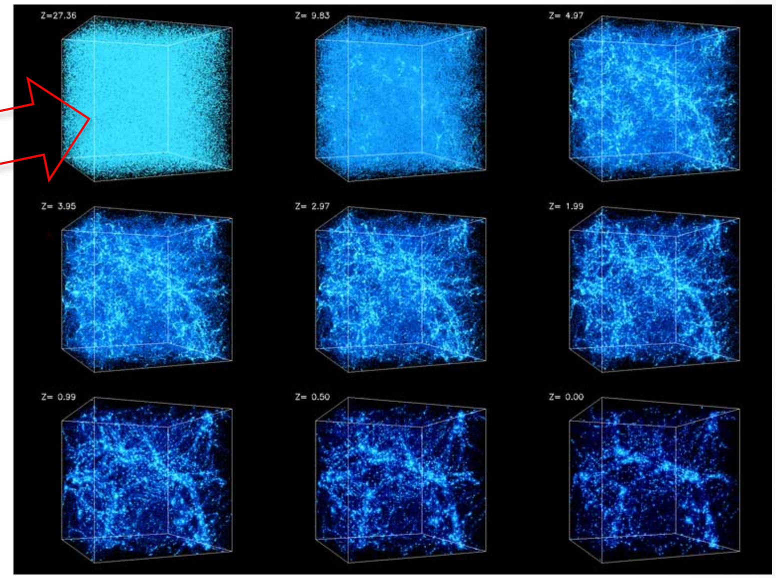
- Predicted by Dirac to explain discrete electric charges in 1930s
- A part of modern String Theory and other GUTS theories predict the presence of massive monopoles that should exist at early times and be stable
- None found: density 10^{-29} that of protons

Seeds of Galaxies

Quantum fluctuations pre-Inflation grew with Inflation to provide the inhomogeneities seen in the CMB

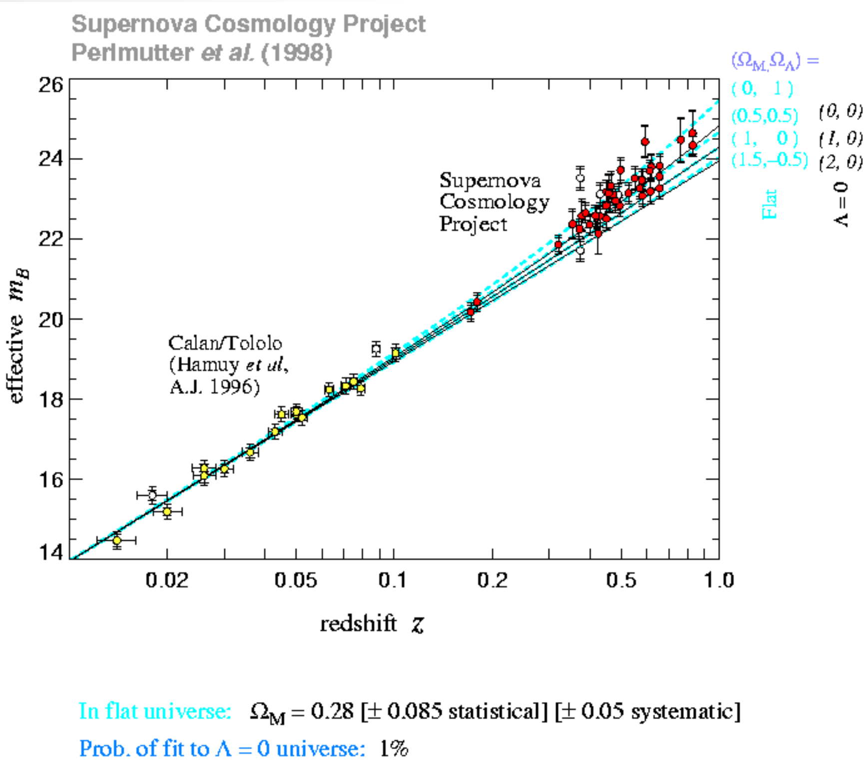
?





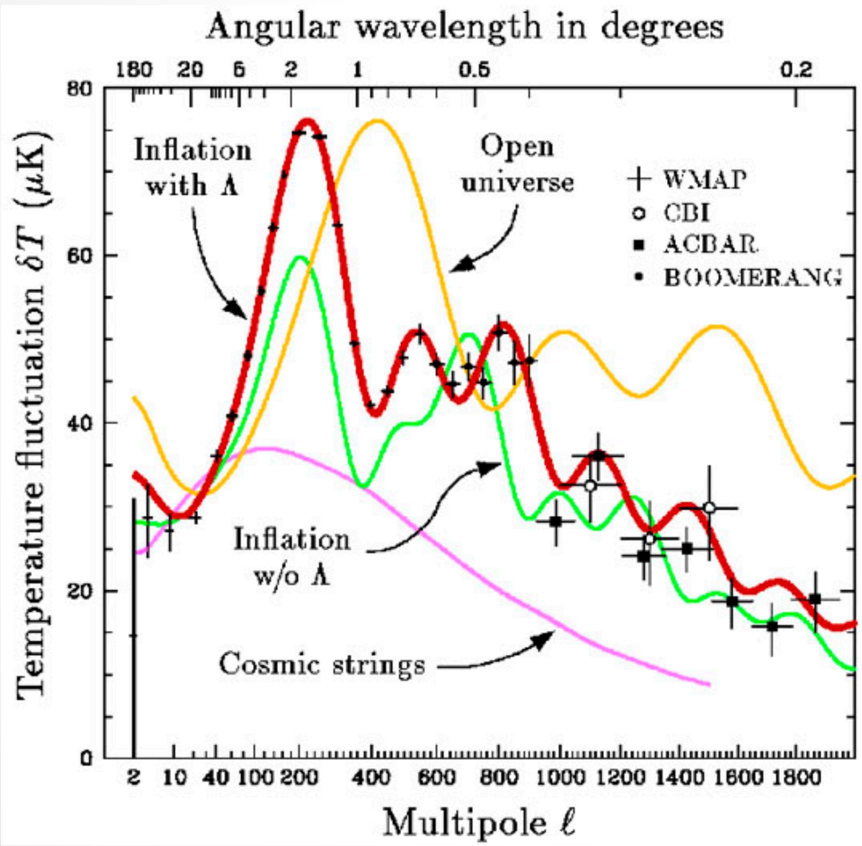
- We can grow the ripples seen in the CMB into the galaxies and large scale structure we see today (with Dark Matter) but what is the origin of the initial inhomogeneities?

Dark energy



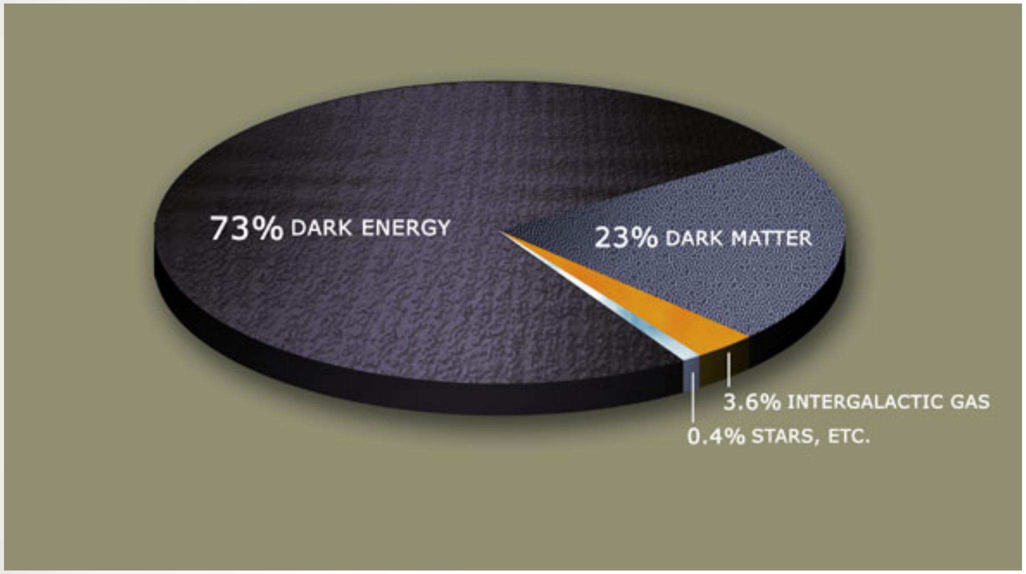
- Obervations of SN 1 at large distances and lookback times show the expansion was slower in the past
- Λ, the cosmological constant was not zero, but rather had a value of ~0.72: consistent with that needed to reconcile the Universe expansion age and stellar ages

ΛCDM Universe



- Combining all these concepts and comparing with the distributions of the CMD flucutuations makes the outcome pretty clear

The Universe



- The mass/energy budget of the Universe is now well established
- Dark Energy dominates, Dark Matter a distance second
- Everything else is just a smattering

The long view

- Cold and Dark

iClicker

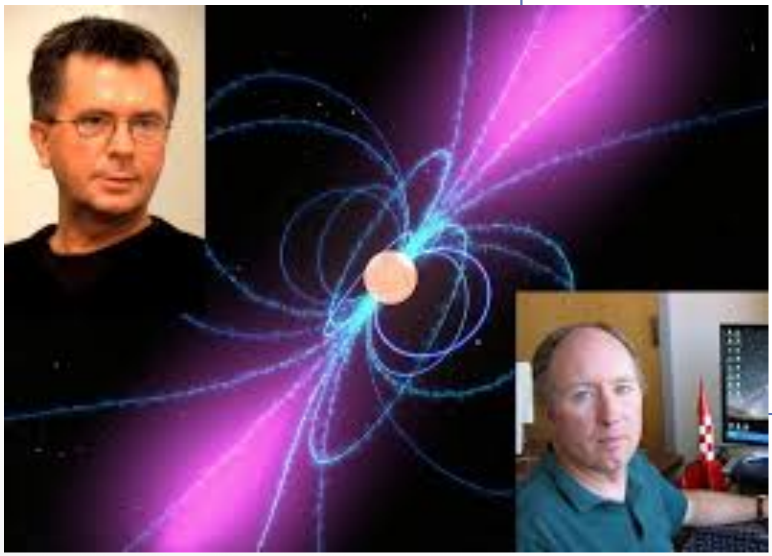
Which of the statements below best describes the "Horizon Problem" in cosmology?

A. Because of the finite speed of light we can only see out to a certain distance: the "cosmic horizon"
B. The cosmic background radiation is extremely uniform in mean temperature even at large angles there was no causal contact when the Universe was 380,000 years old
C. The curvature of space time is exactly "flat": $\Omega=1$
D. Our view of the distant universe is distorted beyond the light-speed horizon

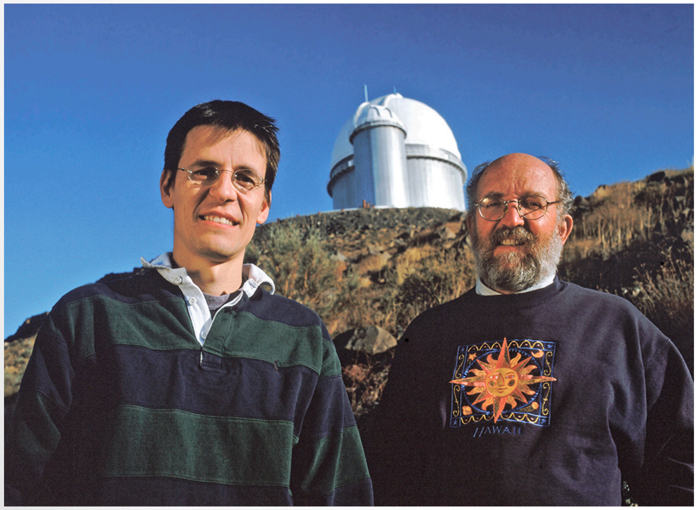
Last Topic: Exoplanets

- There is a long history of looking for planets orbiting stars other than the Sun
- All claims before 1992 were proven false

1992 Aleksander Wolszczan and Dale Frail unexpectedly discovered two planets orbiting a pulsar



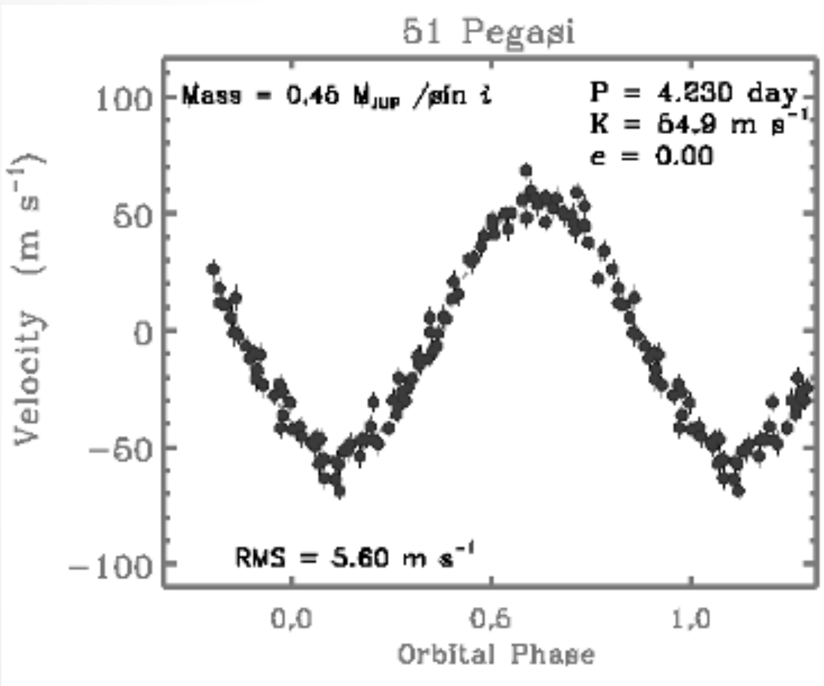
The 1st discovery of a planet orbiting a main-sequence star other than the Sun kicked off a new field of science in 1995



Didier Queloz and Michel Mayor (Swiss astronomers) announced 51 Pegasi b on October 6, 1995

Nobel Prize in 2019

51 Pegasi b



- 51 Peg b was about the mass of Jupiter, *but its orbit was only 4 days* (Mercury's orbit is 88 days)
- "Hot jupiter" took everyone by surprise
- No Solar System analogue, theory problems

Radial Velocity Method

- The original method for inferring planets is based on:
  - Reflex motions
  - Precision radial velocity measurements to astonishing accuracy (1 meter/sec)
- Much of the development and discovery has UC/Lick/Keck roots

Radial velocity detection

- The Sun and Earth orbit their "barycenter"
- Over an earth year the Sun's reflex motion is 0.1m/sec
- For Jupiter it is 12.8 m/sec over 12 years
- Very hard to measure!! Human's walk about 1 m/sec, Usain Bolt does 12 m/sec

RV planet detection

- The early observations were subject to enormous scrutiny
- However, once they knew to look for that signal, exoplanets started being discovered at a fast rate

THE NEW YORK TIMES, TUESDAY, APRIL 5, 2005

It Orbits a Star, but Does It Qualify for Planethood?

By DENNIS OVERBYE

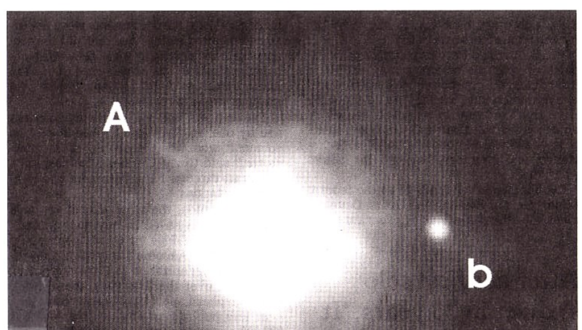
Astronomers have produced what they say could be the first direct image of a planet around another Sun-like star. But the work has touched off intense debate about whether the orbiting object's mass has been determined accurately enough to count as a planet.

At issue is a reddish object that appears to be orbiting GQ Lup, a very young star about 450 light-years from here in the constellation Lupus. In marked contrast to other extrasolar planets that have been detected in recent years racing around in scorching proximity to their home stars, the new planet is 20 times as far from its star as Jupiter is from the Sun, about nine billion very cold miles, and probably takes 1,200 Earth years to complete a single orbit.

Being able to see and dissect the light from a distant object is the key to understanding what it is made of, how hot it is and how it relates to the worlds we know and love. But is the new object really a planet?

In a paper for the journal Astronomy and Astrophysics, posted on the Web last week, the discovery team, led by Dr. Ralph Neuhaeuser of Jena University in Germany, calculated that the object was about twice as massive as Jupiter but refrained from using the loaded word "planet," calling it a "companion." According to some theoretical models, it could be massive enough to be a brown dwarf, which is a kind of failed star.

If the preliminary estimate is anywhere near correct, the new planet will take its place as another landmark in an accelerating cavalcade of discoveries that have left astronomers fumbling for synonyms for



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Centripetal Force

Question: Use Kepler's(1571-1620)third law to find mass of GQ Lup star? Use the data in the second paragraph. The gravitational constant is 6.67 X 10*-27 Nm*2/kg*2 . Hint: Do entire solution in metric mks system.

European Southern Observatory

A Sun-like star (A), called GQ Lup, is orbited by an object (b) that may be a planet.

near a brown dwarf in Hydra, but it has not yet been confirmed to be orbiting the dim star. The team says it will report new results soon.

Last month a team using the Spitzer Space Telescope discerned the heat radiation from a Jupiter-mass planet in the

ever planetary progeny they may have created are still forming, giving off excess heat and making them easier to see. That proved to be the case; GQ Lup is only 156 times as bright as the planet.

Dr. Neuhaeuser's group spotted it last year using the European Southern Observa-

"This is a beautiful piece of science," said Dr. Ben Oppenheimer of the American Museum of Natural History and a fellow planet hunter.

Many astronomers, however, urged caution. Besides questions over the mass of the planet, its orbit, so far from its star, presents a challenge to theorists.

A renowned discoverer of planets, Dr. Geoffrey W. Marcy of the University of California, Berkeley, said the uncertain mass and the enormous orbit of the planet were "both cause for puzzlement."

But Dr. Alan Boss, of the Carnegie Institution of Washington, said that even if the models were off by a factor of two or three,

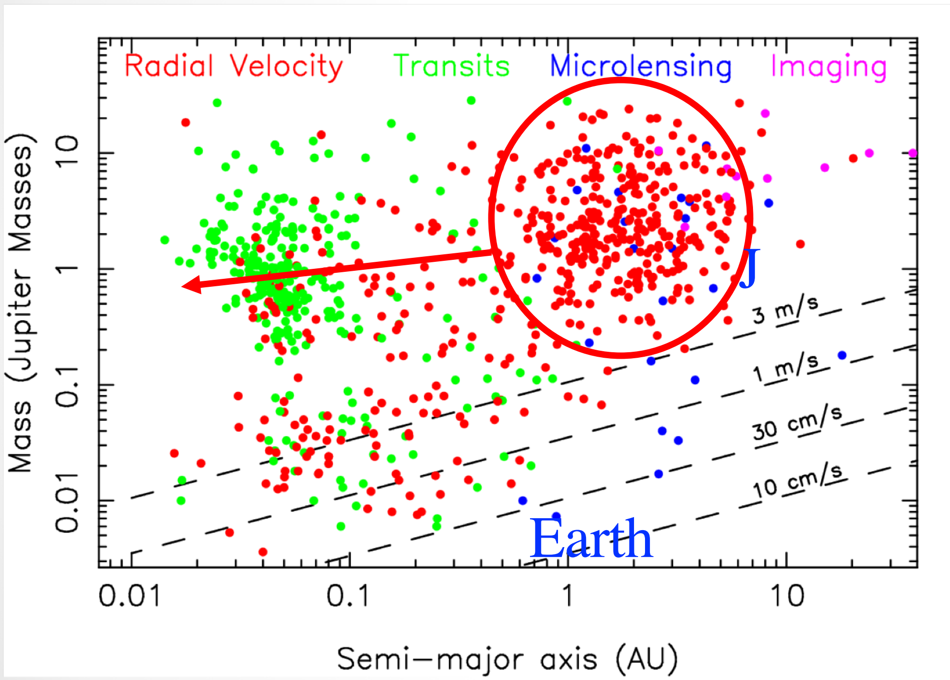
A reddish mass in another solar system may be a landmark.

the mass of the GQ Lup object would still be comfortably below the cutoff — 13 Jupiters — between planets and brown dwarfs.

He said he thought that the group had done its homework and that it was possible that in the end all the caveats would be met and, as he put it, "Bingo, they've finally gotten what we've all been looking for."

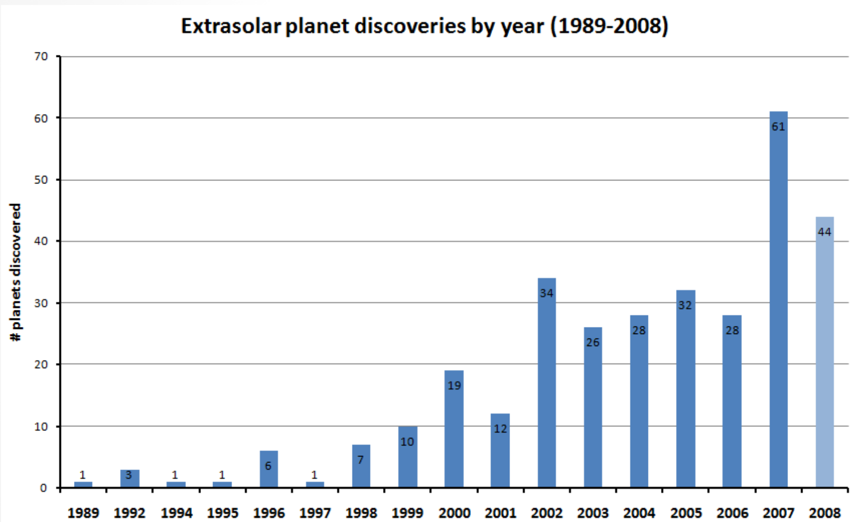
In an e-mail message, Dr. Wuchterl pointed out that the calculations of mass had been buttressed by spectroscopic measurements of the planet's gravitational field, which were consistent with a mass of one or two Jupiters, confirming its likely plan-

RV Planet Selection Effects



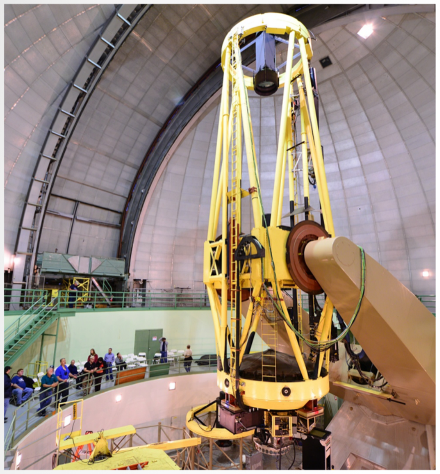
- Larger mass planets produce a larger reflex motion at fixed distance and host star mass
- Closer planets produce larger reflex motion at fixed planet and host star mass
- Smaller mass host planets have a larger reflex motion at fixed planet mass and distance

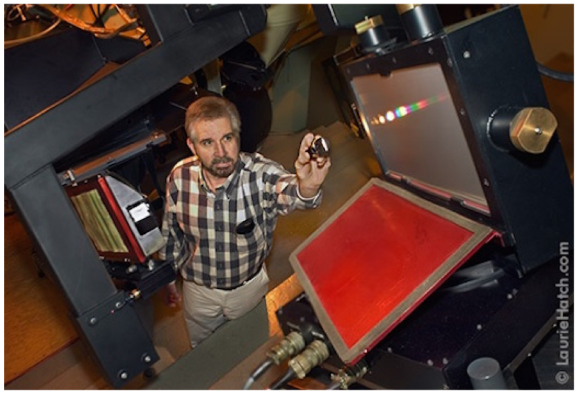
RV exoplanets

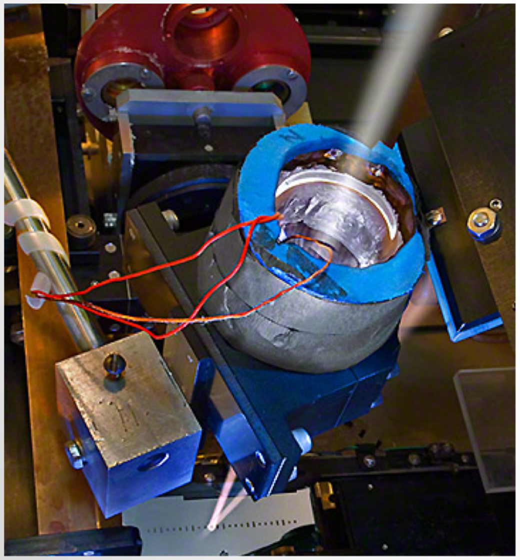


- After the initial announcement some planets were discovered in older data
- 12 years after 51 Peg b there were more than 300 known exoplanets

Lick, Keck, ESO



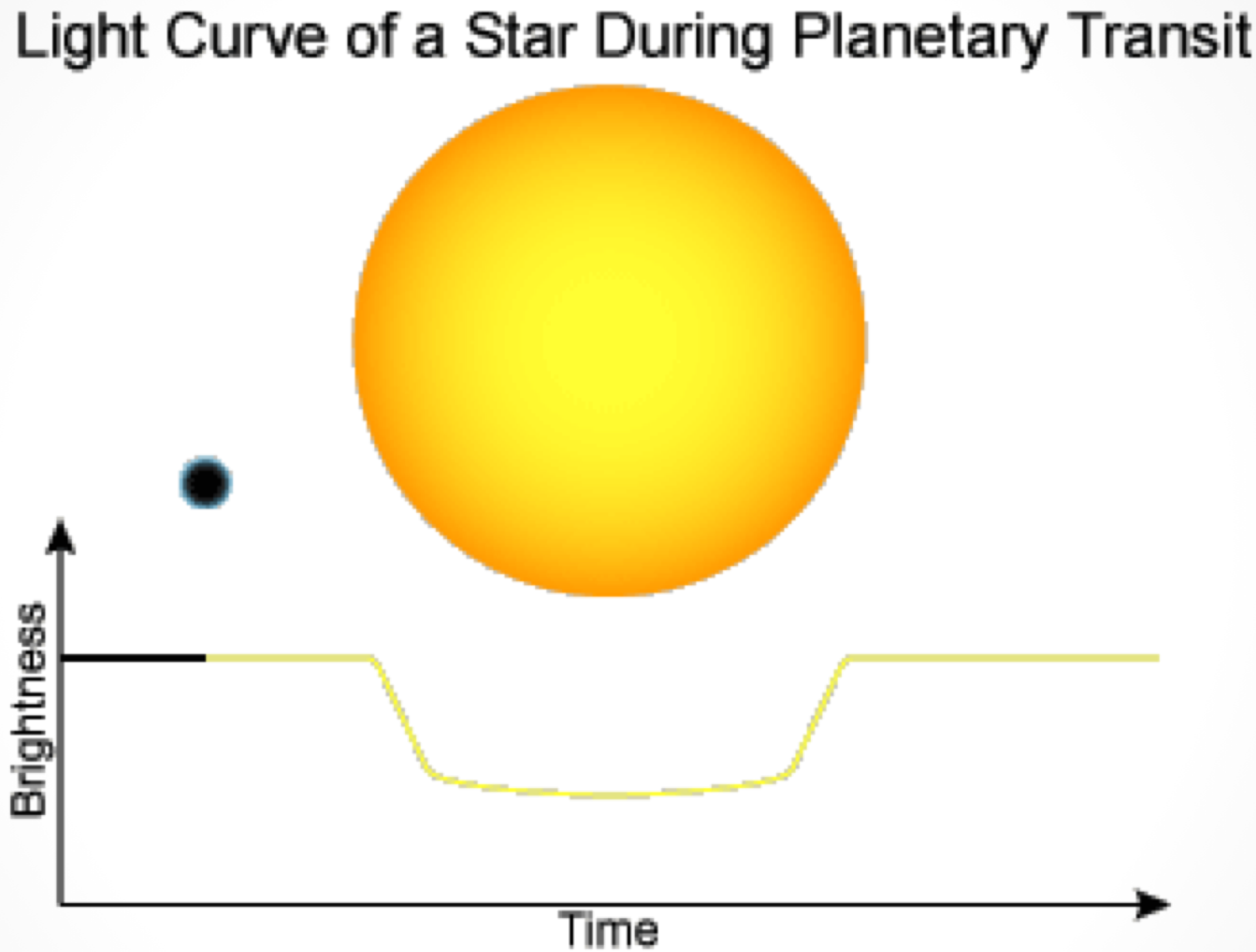




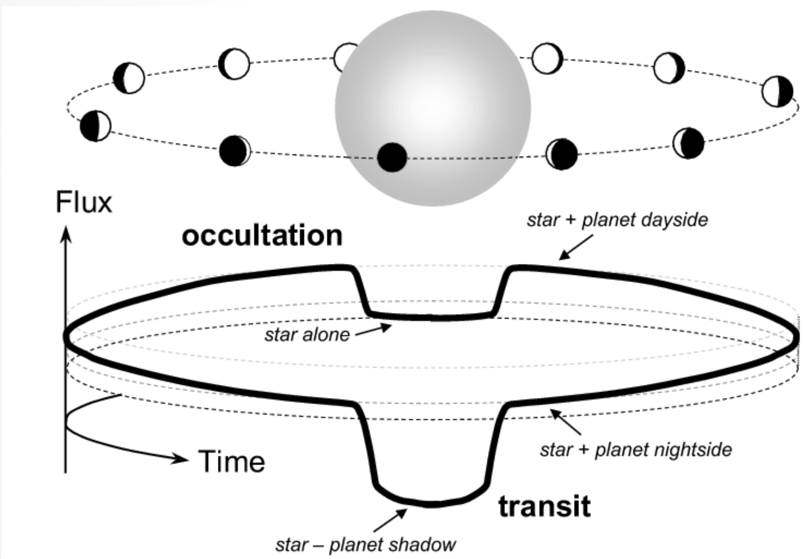
- University of California astronomers and UCSC astronomers have played a world-leading role
- Built and used the most important instruments at UCSC and deployed them at Lick Obs and Keck Obs
- Developing techniques for stability and software for analysis has been key

Transiting Planets

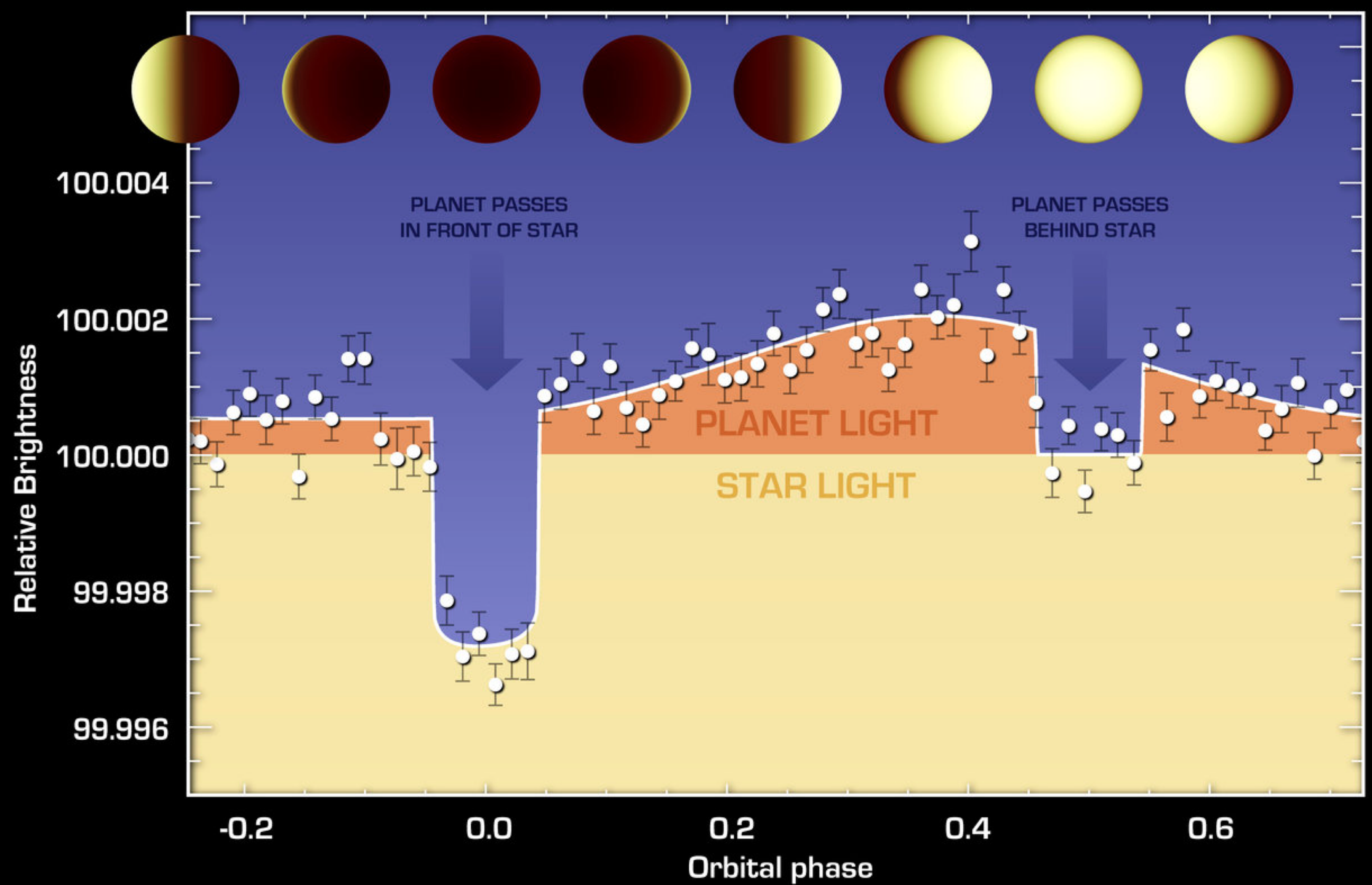
- Radial velocity searches were hard and “expensive” in observing time
- Strong bias toward more massive planets in close orbits
- Around 2006 people started looking for planets “transiting” their host star


Light Curve of a Star During Planetary Transit
Brightness
Time

Transiting basics

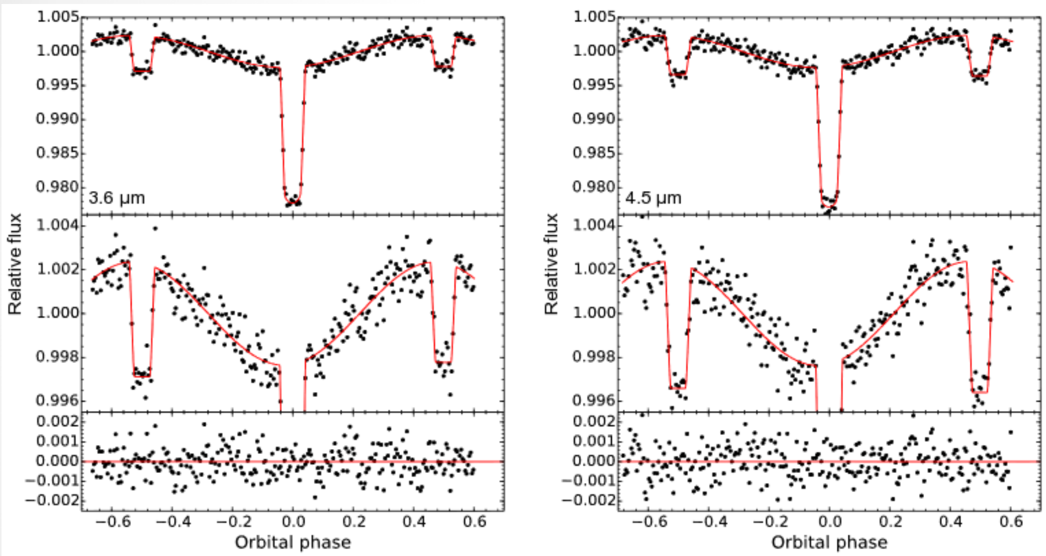


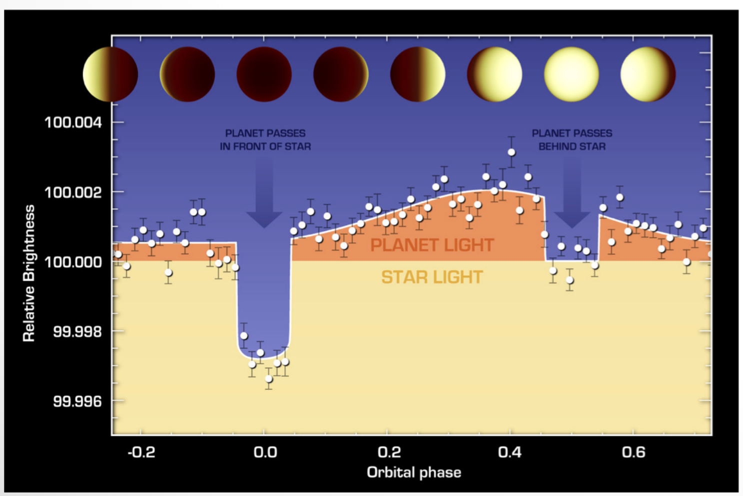
- For systems with orbits that are very closely in the line of sight, when the cooler planet crosses the hotter disk of the star, the total flux goes down: transit
- There is a more complex increase and decrease in total flux during "occultation" (secondary eclipse)



PLANET PASSES
IN FRONT OF STAR
PLANET PASSES
BEHIND STAR
PLANET LIGHT
STAR LIGHT
100.004
100.002
100.000
99.998
99.996
Relative Brightness
-0.2
0.0
0.2
0.4
0.6
Orbital phase

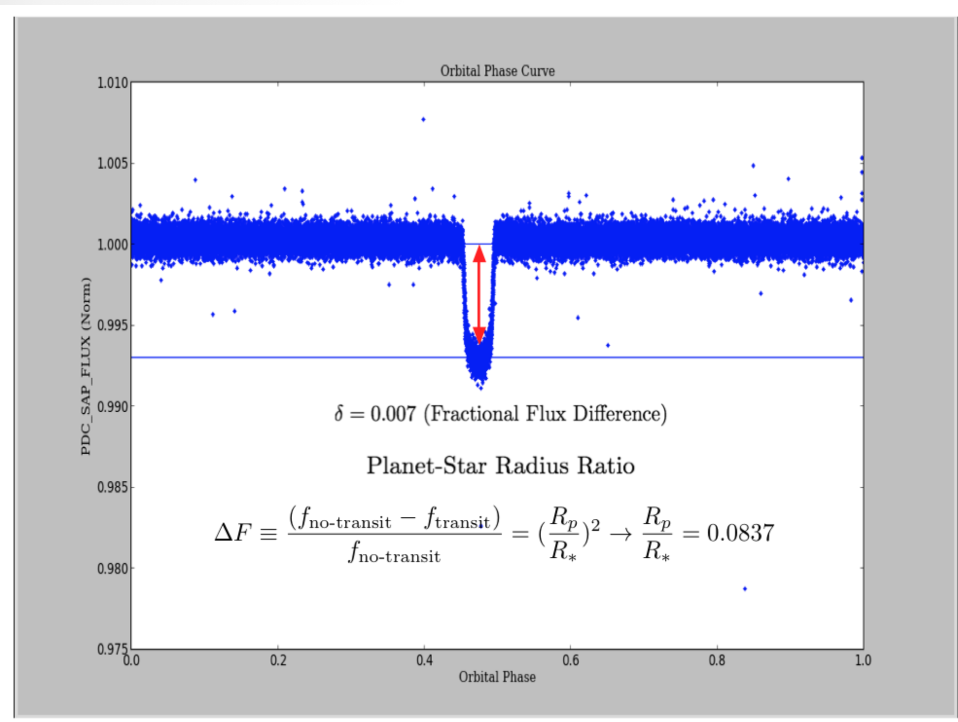
The predicted light curves are seen!





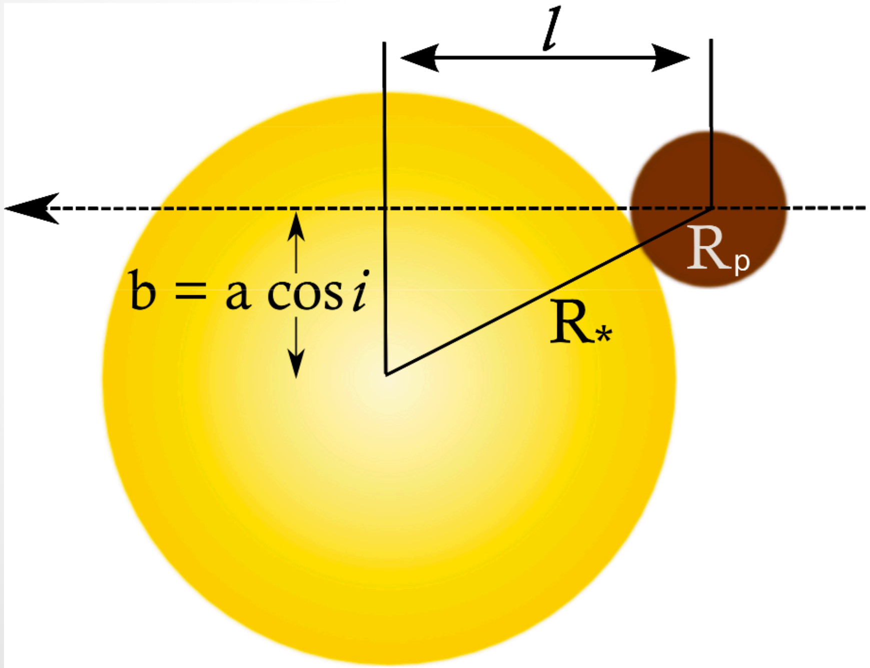
- The orbit period is easily determined
- The relative size of the planet and star are measured with some understanding of temperature
- The tilt of the orbit with respect to the Earth is known

Transit Details



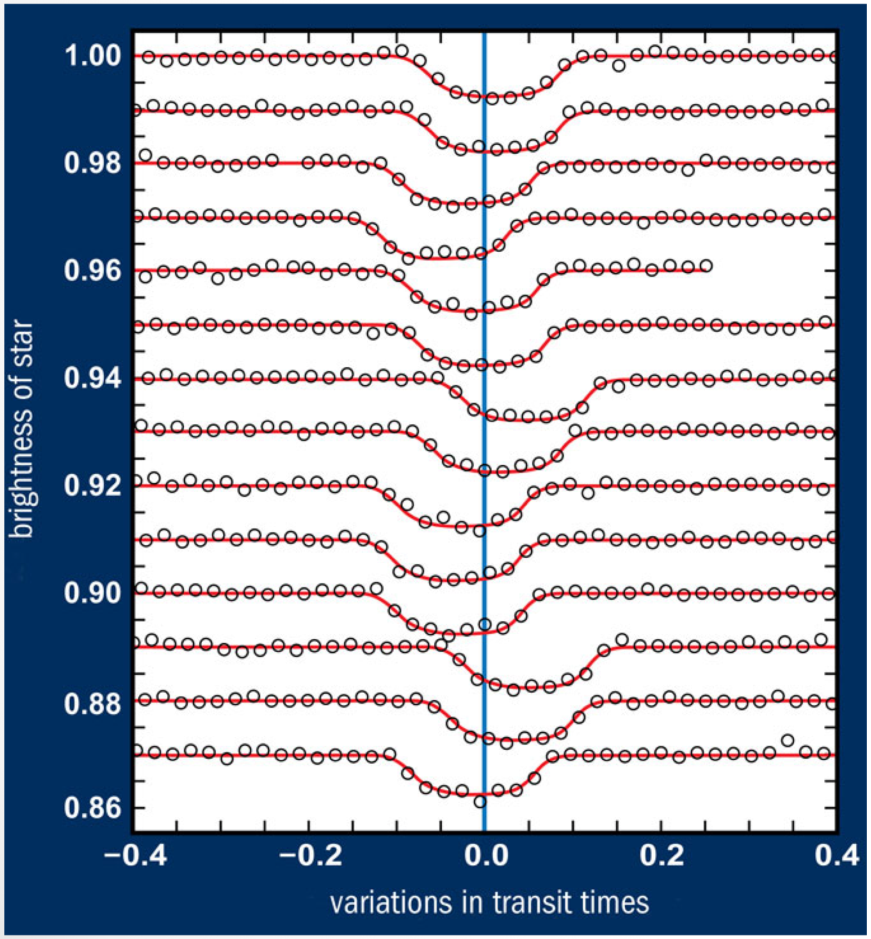
- Planets tend to be small compared to stars and the signal is very small (2-30 parts per 1000)
- Hard to measure from the ground with changing atmospheric conditions

Transit Details continued



- The details of the geometry are important
- "grazing" transits by binary stars can masquerade as exoplanets
- Long-lived star spots can cause confusion

Science: Are we sure?



- Have demonstrated the transits are caused by planets in two ways:
  - Followup radial velocity measurements
  - "transit timing variations" for multiplanet systems

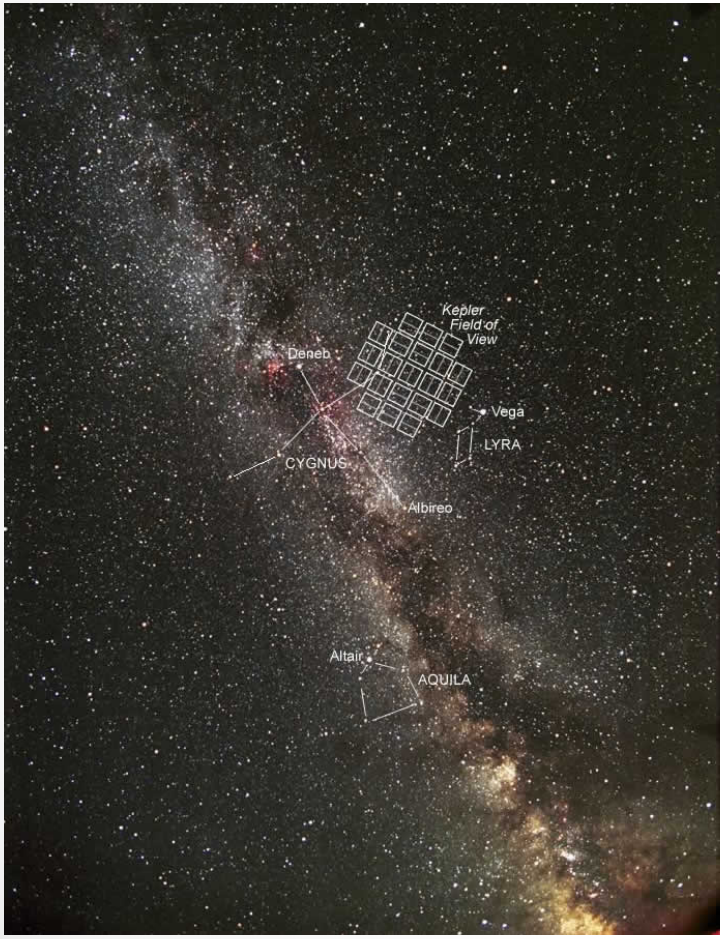
Transit observations

- From the ground this is hard as the brightness variations are typically smaller than 1%
- Nevertheless some heroic monitoring efforts were put together in the middle 2000s

The Kepler Satellite

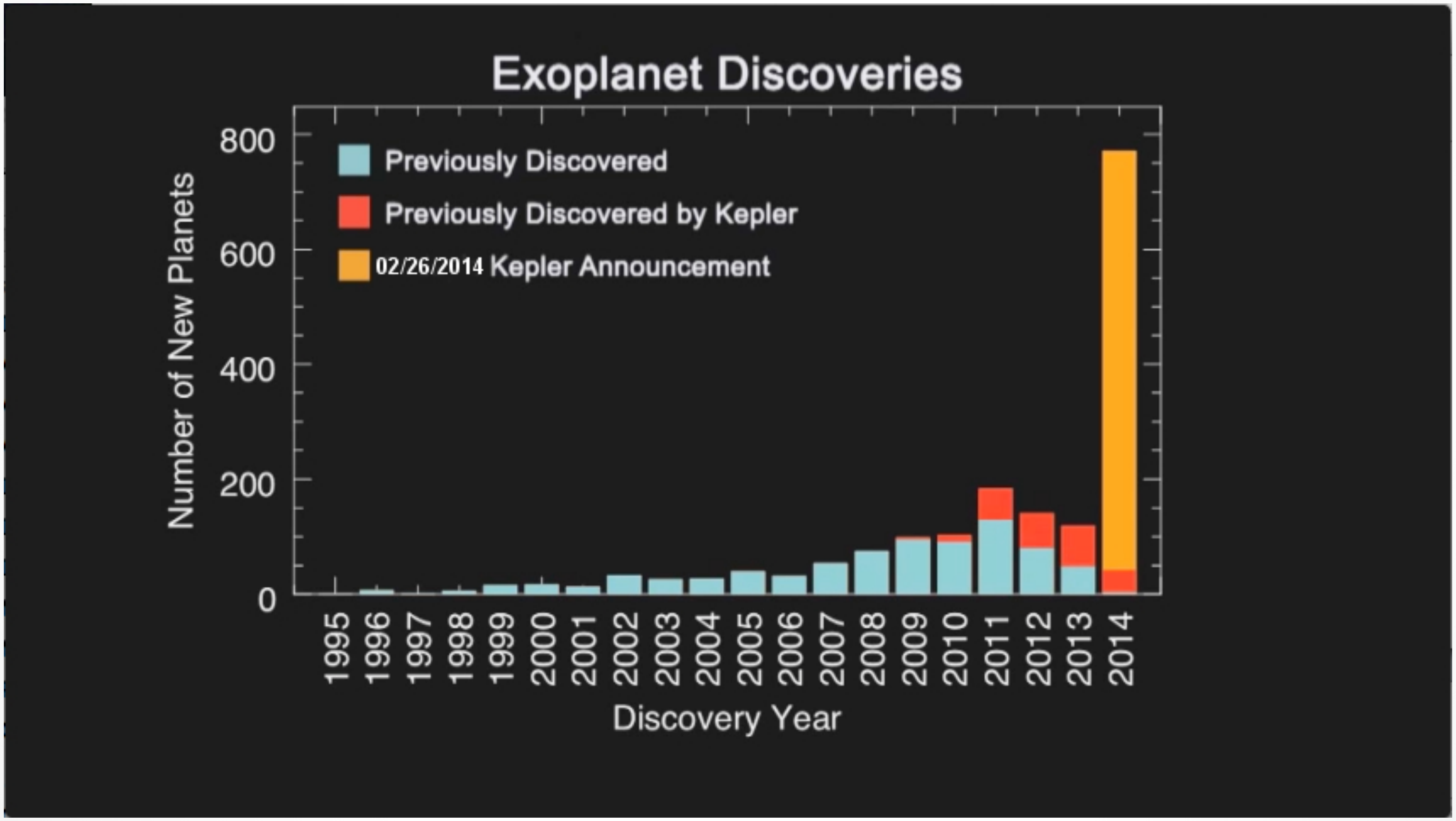
- Launched March 2009
- 1.4m primary mirror
- Focal plane of 42 large CCDs
- Earth-trailing orbit around the Sun
- Pointed at one location for four years

The Kepler Mission

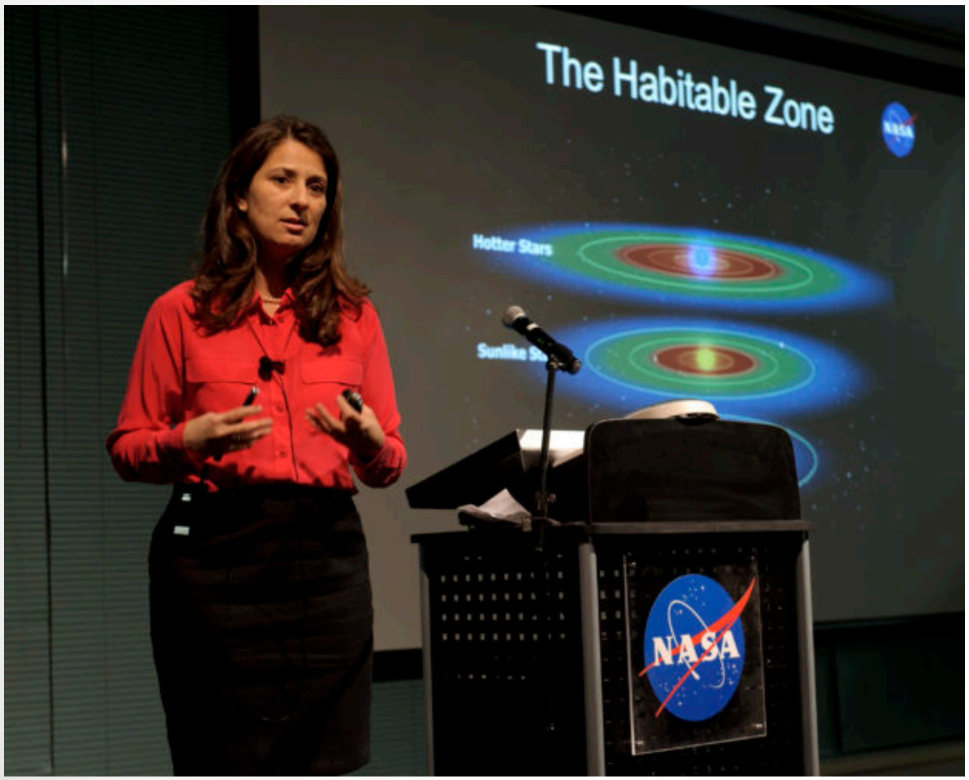


- Observed primary field reading out ever six seconds to produce high-cadence "light curve" for ~145,000 stars
- The stability of observing above the atmosphere allowed very high precision: 0.01% in brightness

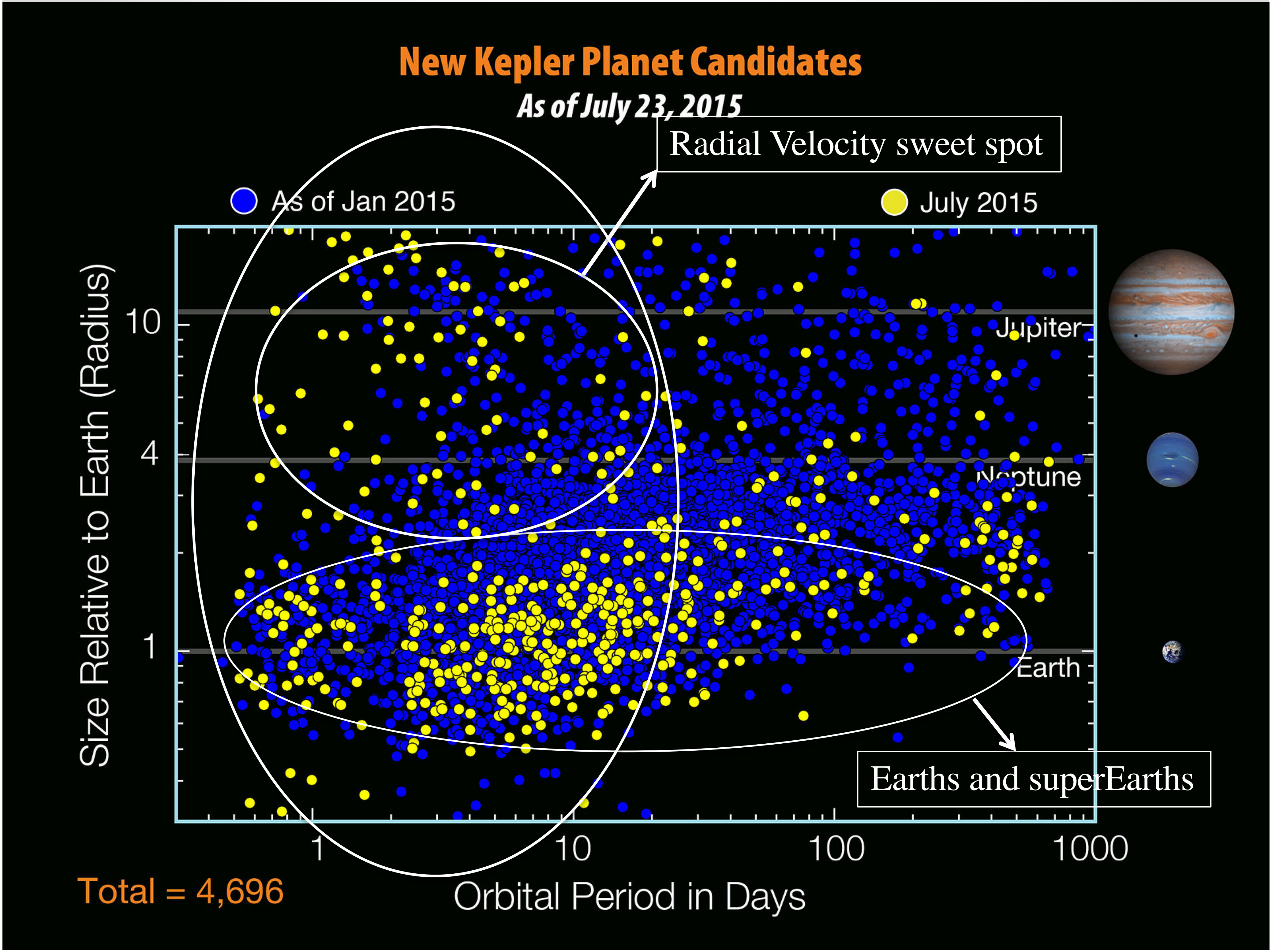
Kepler as a game changer



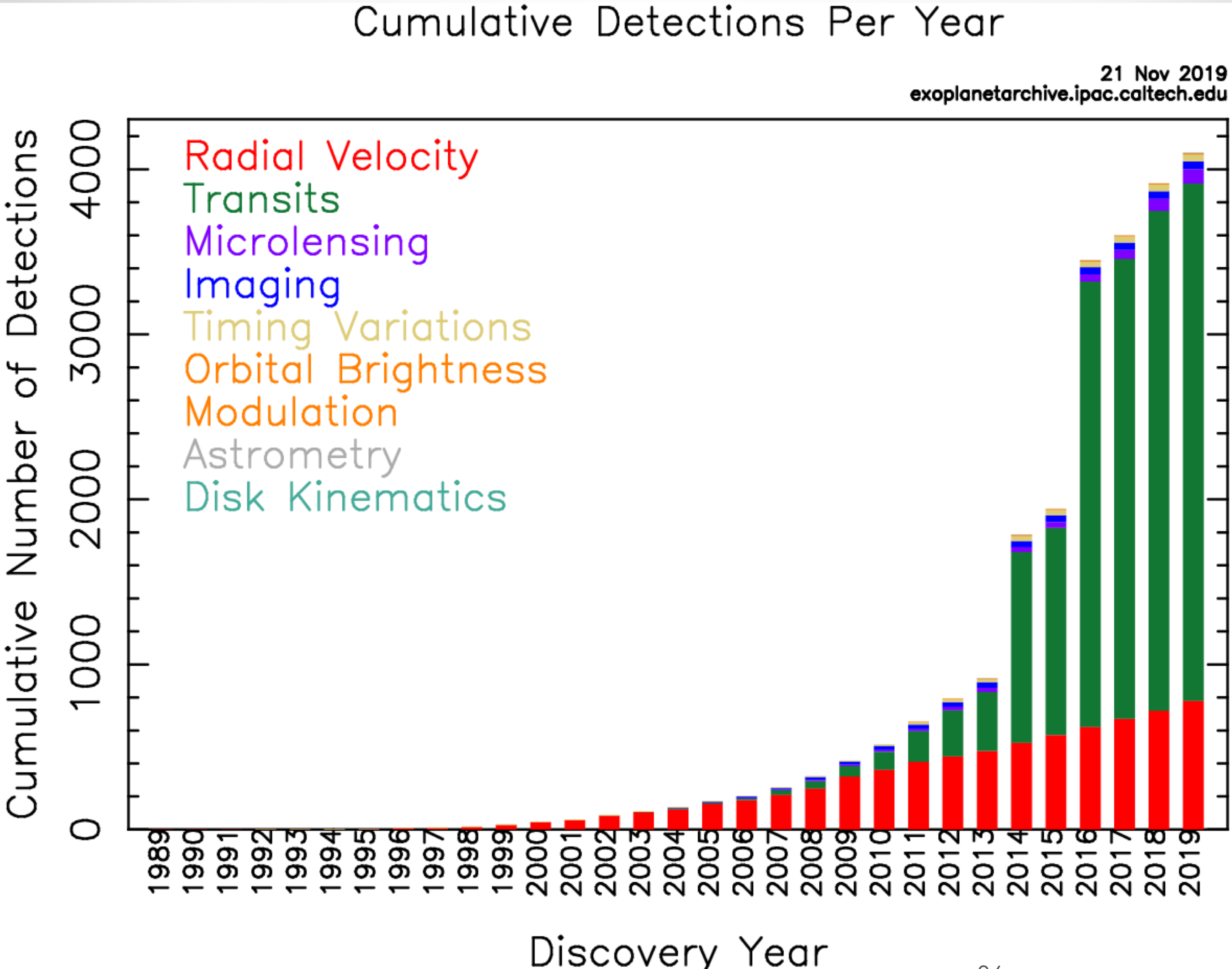
UCSC-Kepler



- Former UCSC student Natalie Batalha was Kepler Mission Scientist now a member of the UCSC Astronomy Department



New Kepler Planet Candidates
As of July 23, 2015
Radial Velocity sweet spot
As of Jan 2015
July 2015
Size Relative to Earth (Radius)
10
4
1
Jupiter
Neptune
Earth
Earths and superEarths
1
10
100
1000
Total = 4,696
Orbital Period in Days


Cumulative Detections Per Year
21 Nov 2019
exoplanetarchive.ipac.caltech.edu
Radial Velocity
Transits
Microlensing
Imaging
Timing Variations
Orbital Brightness
Modulation
Astrometry
Disk Kinematics
Cumulative Number of Detections
0
1000
2000
3000
4000
1989
1990
1991
1992
1993
1994
1995
1996
1997
1998
1999
2000
2001
2002
2003
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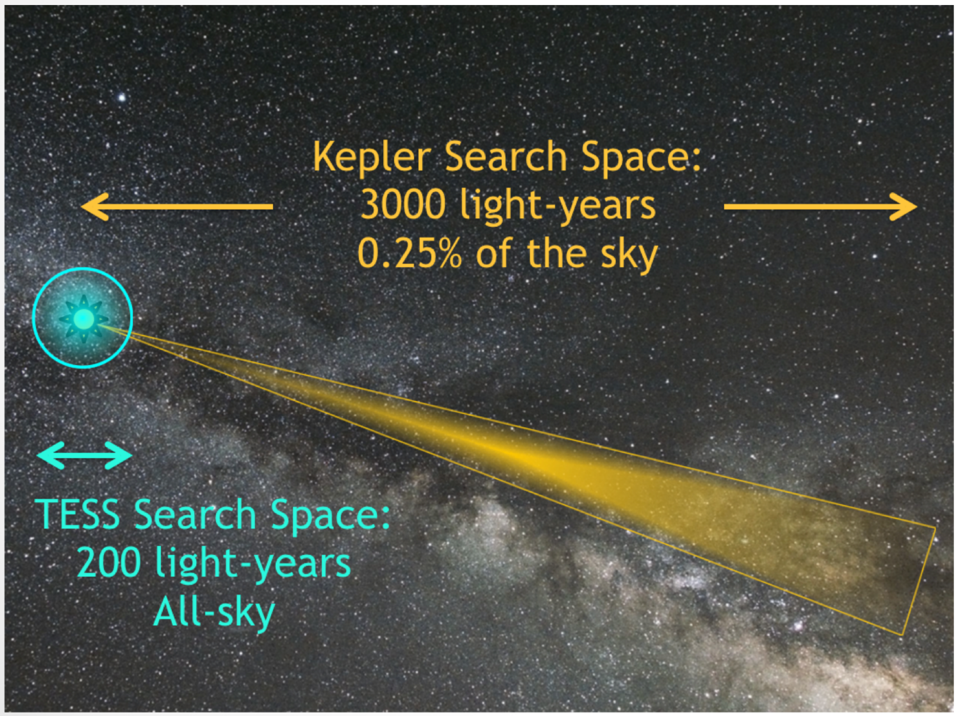
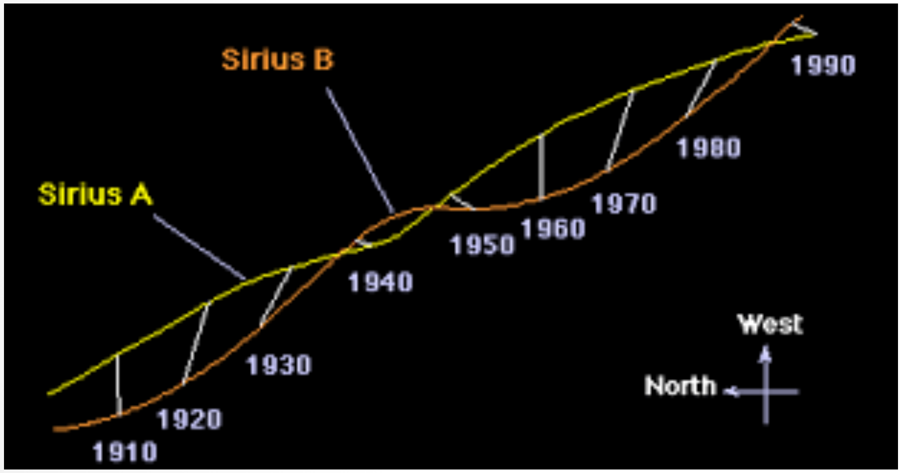
2017
2018
2019
Discovery Year

TESS



- The Kepler Mission ended in 2018 when they ran out of fuel for reaction wheels
- In April 2018, a new space mission was launched to continue searching for exoplanets using the transit technique
- TESS concentrates on all-sky and nearby stars

Other techniques



- "astrometric" detection follows motion of orbit on the sky of host star
- Very few discoveries, but wait for large-scale space-based measurements: estimates are GAIA will find 70,000 high-mass planets in its 10-year mission(!)

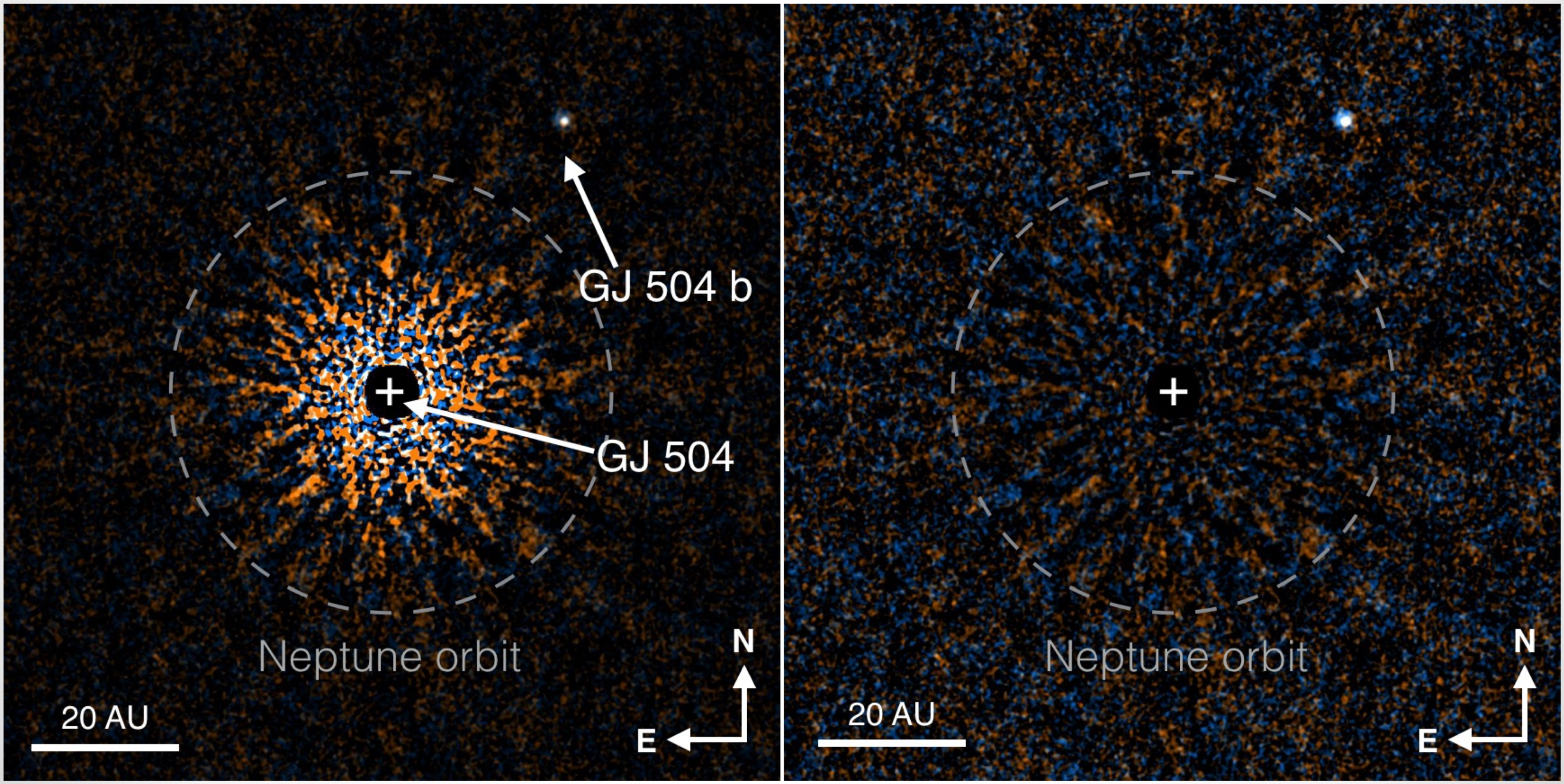
Gravitational Lenses

- Very sensitive technique, but also rare, one-time event
- Because for well-aligned events there is a large magnification, this can reveal low-mass planets

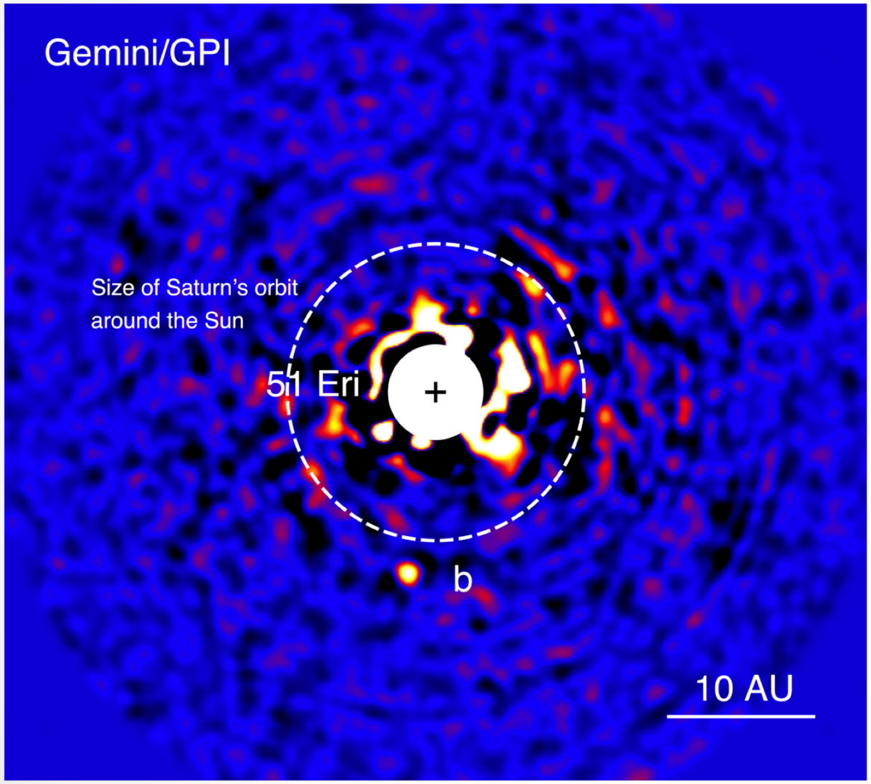
Direct Imaging: firefly by a lighthouse

- This is hard because:
  - planets tend to be fainter than parent stars by factors of more than 10^7 (10 million)
  - Need to find a way to block the light from the host star using a "coronagraph"

Direct imaging

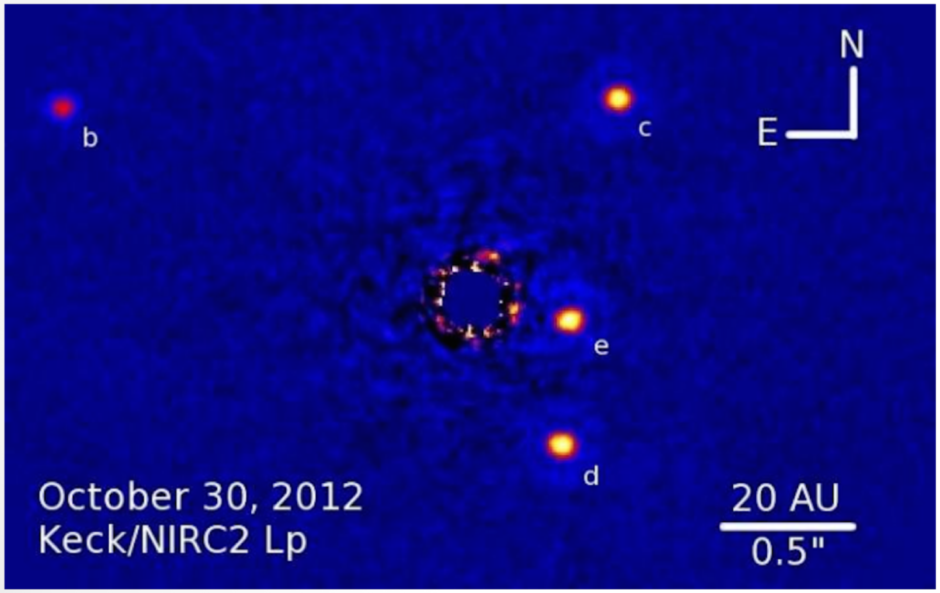


Direct Imaging



- It is also hard because at the distances of even the nearest stars the separation on the sky is very small and gets smaller with distance
- Typically a few tenths of an arcsecond
- Need largest telescopes and adaptive optics or space

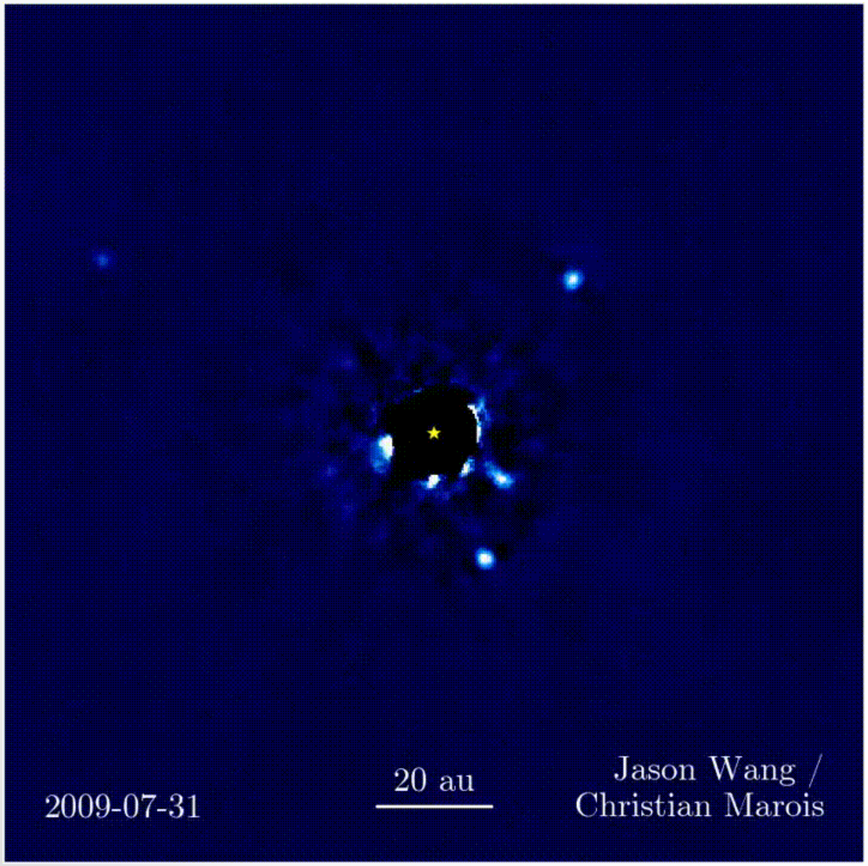
Direct Imaging

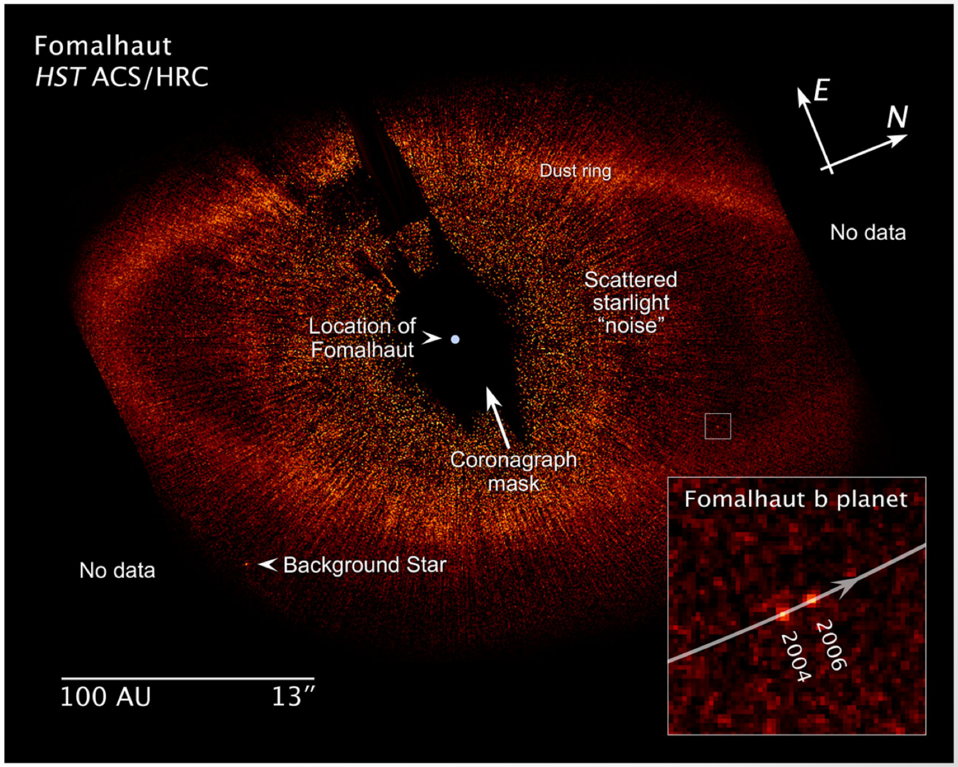


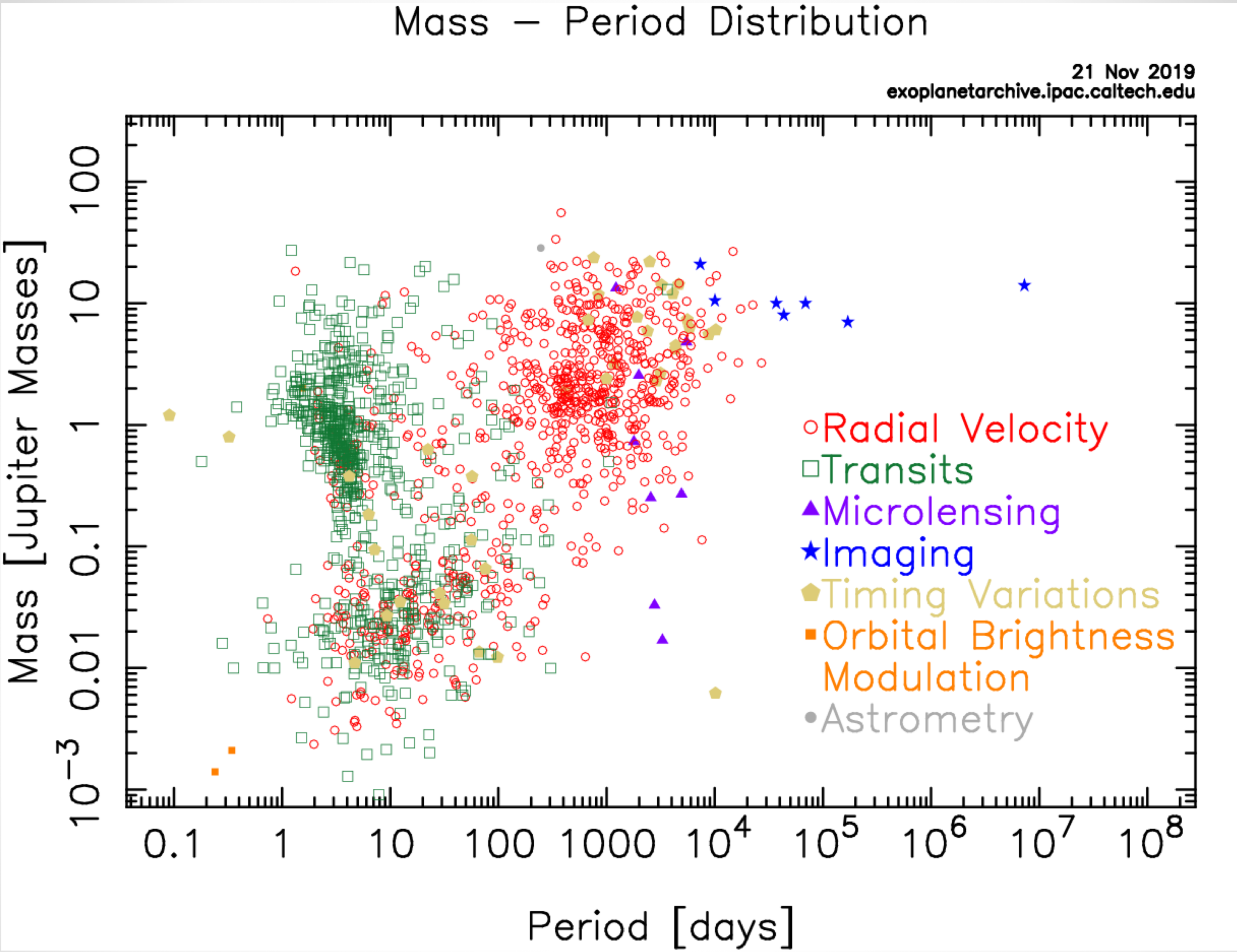
- But, it works!
- As of 2019 there are 24 directly imaged exoplanets
- They tend to be the equivalent of outer Solar System planets because of the angular separation problem
- One big advantage of directly imaging the planets is it is possible to take spectra of their atmospheres

Direct Imaging

- How do know they are not just background sources?
- Orbits





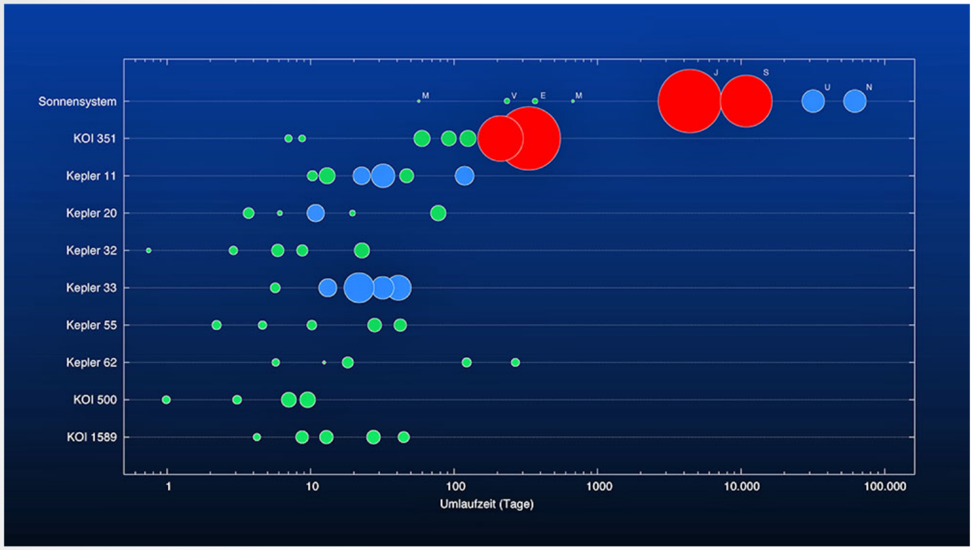

Mass – Period Distribution
21 Nov 2019
exoplanetarchive.ipac.caltech.edu
Mass [Jupiter Masses]
100
10
1
0.1
0.01
10^{-3}
0.1
1
10
100
1000
10^4
10^5
10^6
10^7
10^8
Period [days]
Radial Velocity
Transits
Microlensing
Imaging
Timing Variations
Orbital Brightness Modulation
Astrometry

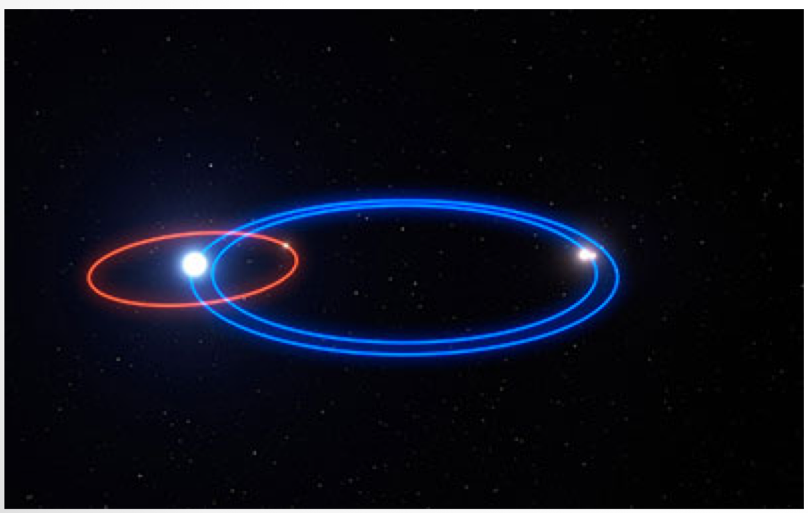
Planet demographics

- https://apod.nasa.gov/apod/ap151205.html
- Database on exoplanets

- On average in the Galaxy there are 1.6 planets per star
- ~300 billion planets in the Galaxy
- ~11 billion Earth-like planets
- Based on 4099 planets including 671 systems with more than one planet

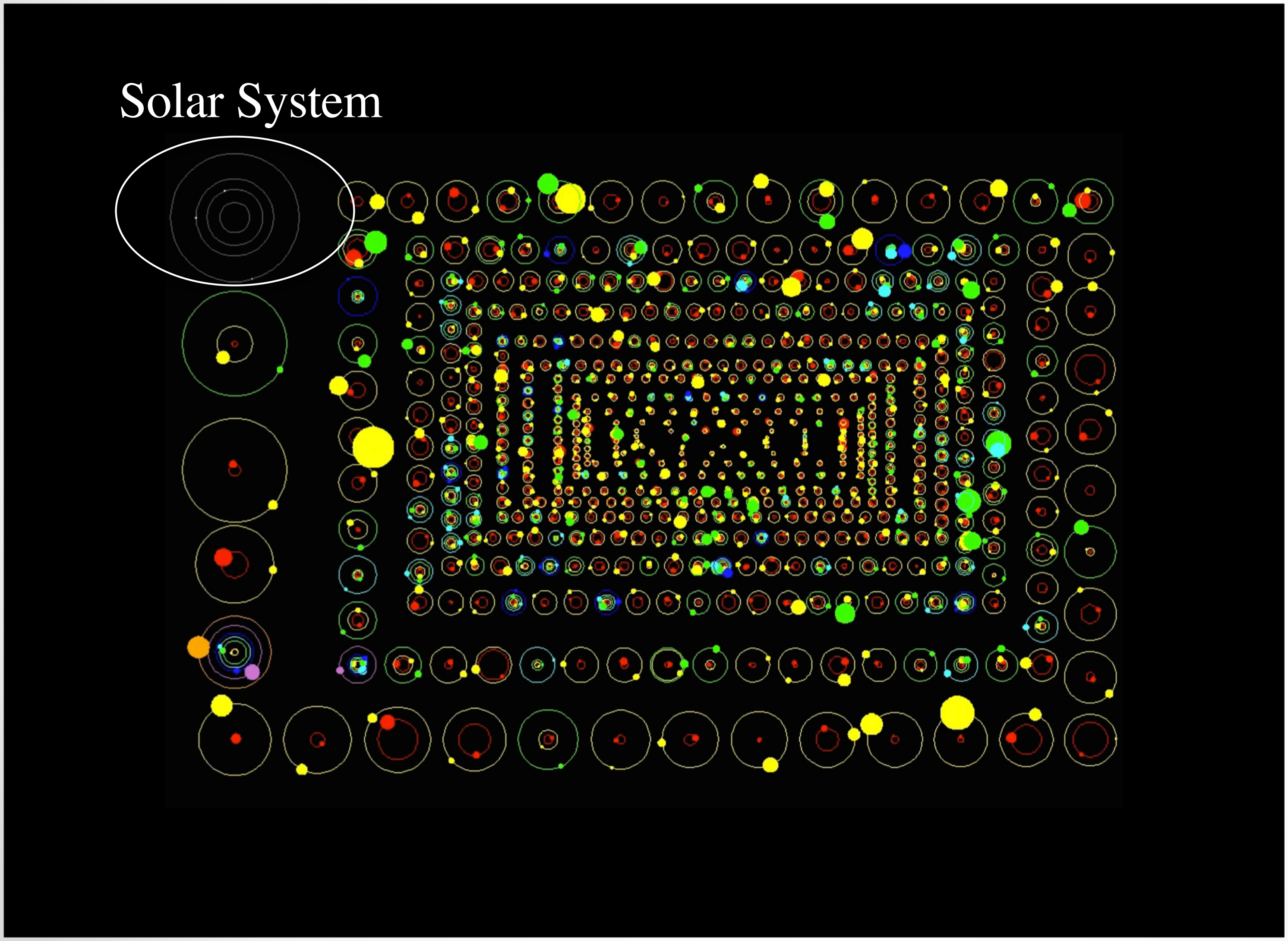
Demographics



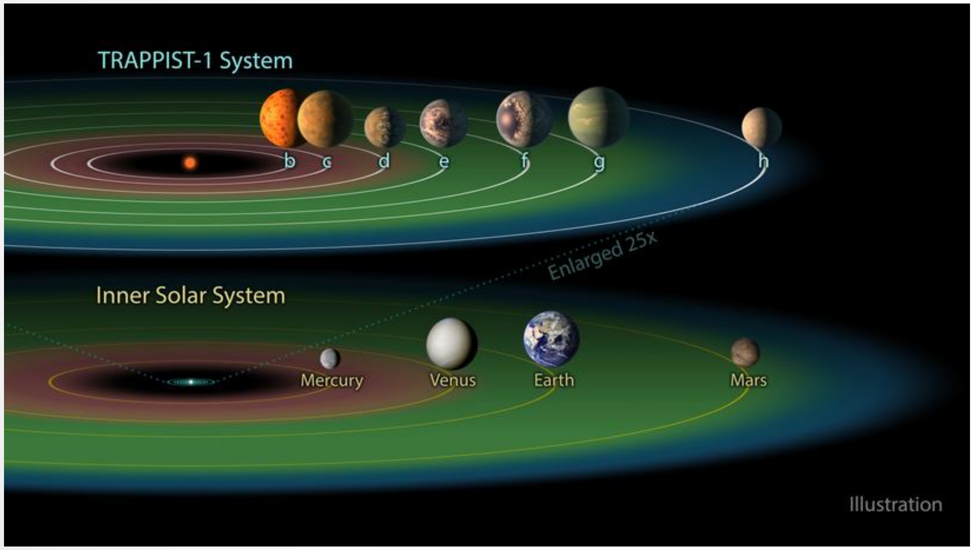


- 21 systems known with five planets
- 5 systems known with 6 planets
- 3 systems known with 7 planets
- 2 systems with 8 planets
- Planets unexpectedly found in binary and triple star systems

What have we learned?



The Solar System is not typical

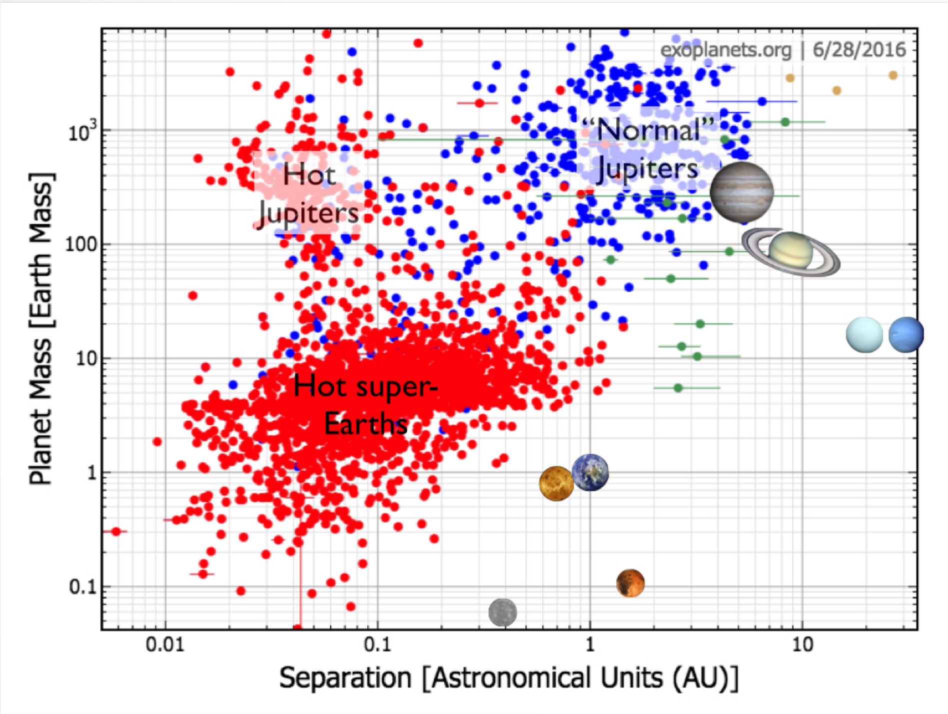


- Most multiple systems discovered to date are far more compact
- Don’t forget the strong biases in the detection processes, but even modeling this, the Solar System stands out.

http://exoplanets.tommykrueger.com/app/

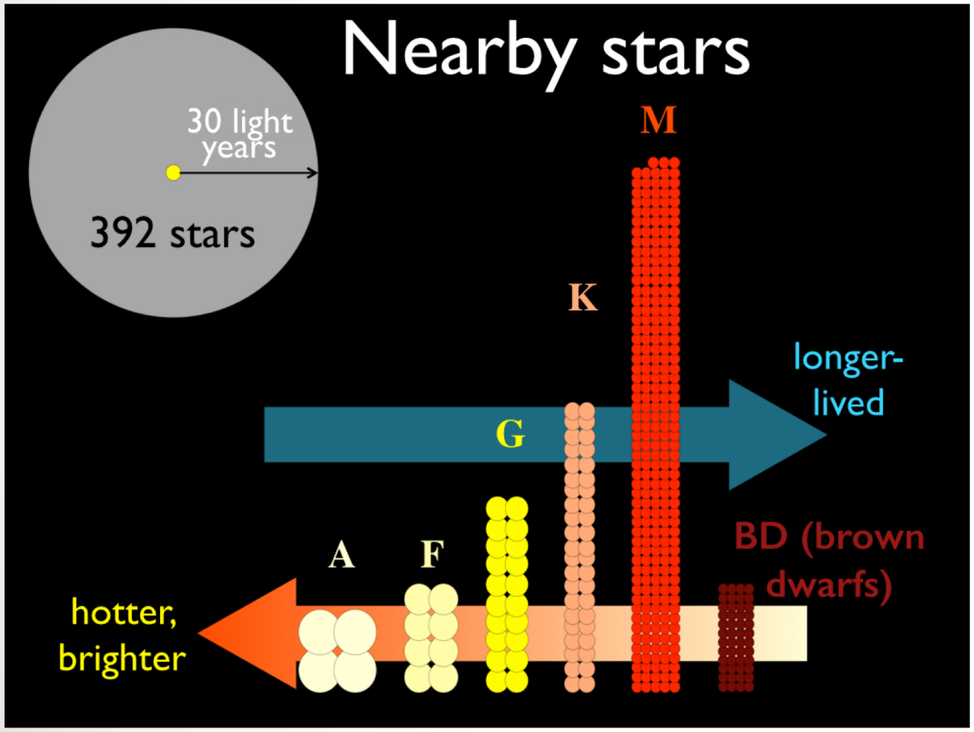
http://exoplanets.org

What have we learned?



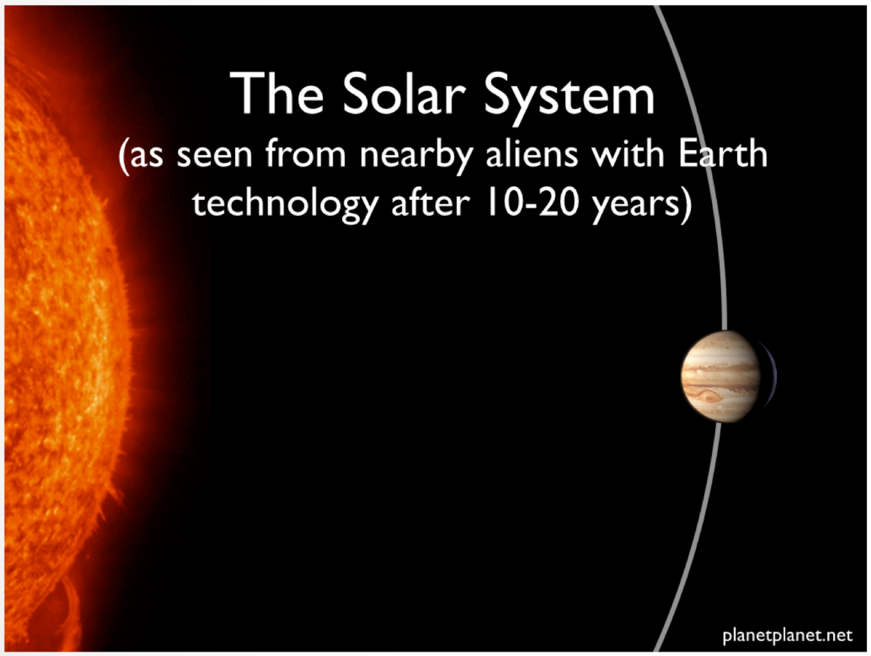
We also are missing the most common planet seen in the galaxy: "super-Earths" or "mini-Neptunes"

Why the differences?



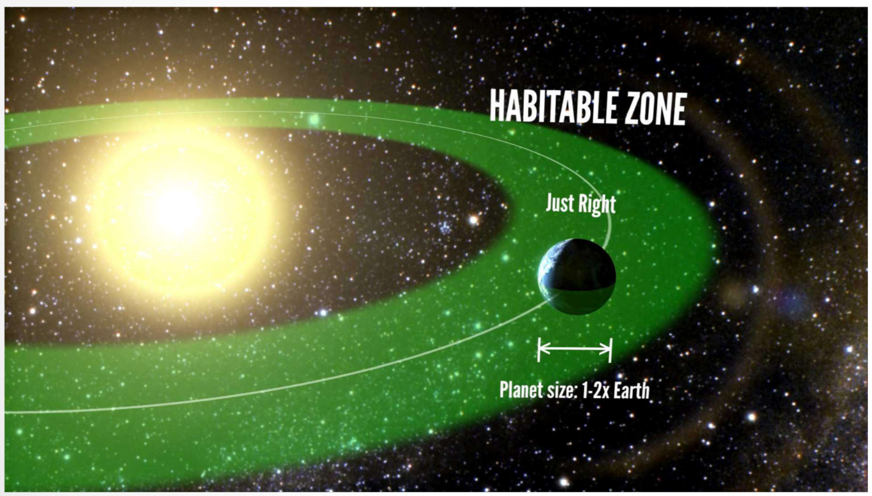
- We may need to account for differences in host stars better
- Evolution of planet systems may be stronger than we think
  - Early evolution may be strong and chaotic
  - Longer-term evolution may also be chaotic

Why the differences?



- We may still be in the phase when detection bias is dominating our views
- As the samples grow from using different methods, this will be sorted out and "correction factors" will be replaced with data

Life, the Universe and Everything



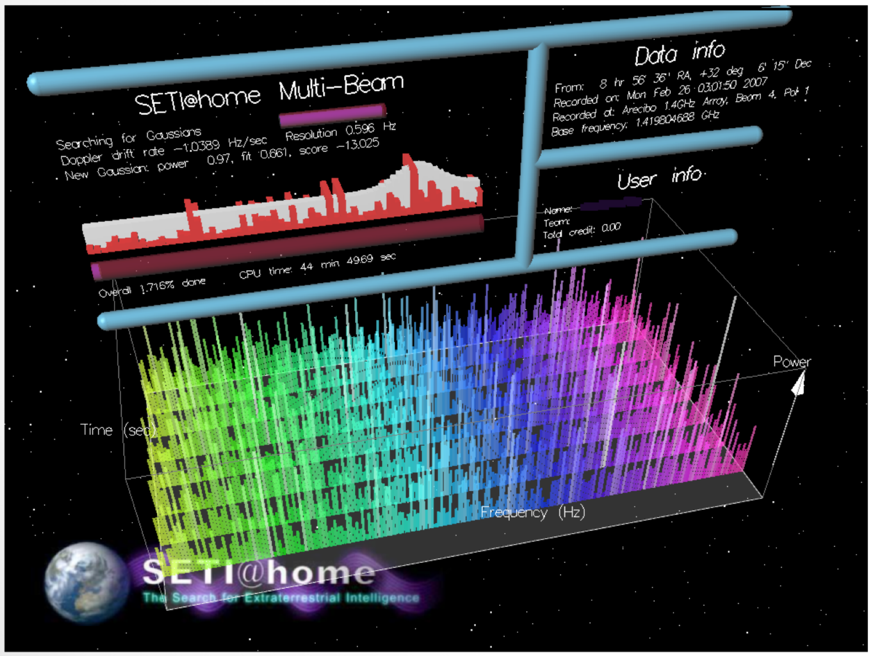
- The search for life off the Earth got serious in the 1960s
- This was 35 years before the first exoplanet was announced
- Concentration was on detecting leaked radio waves from an intelligent civilization

SETI

1994 Ithaca Carl Sagan, Frank Drake

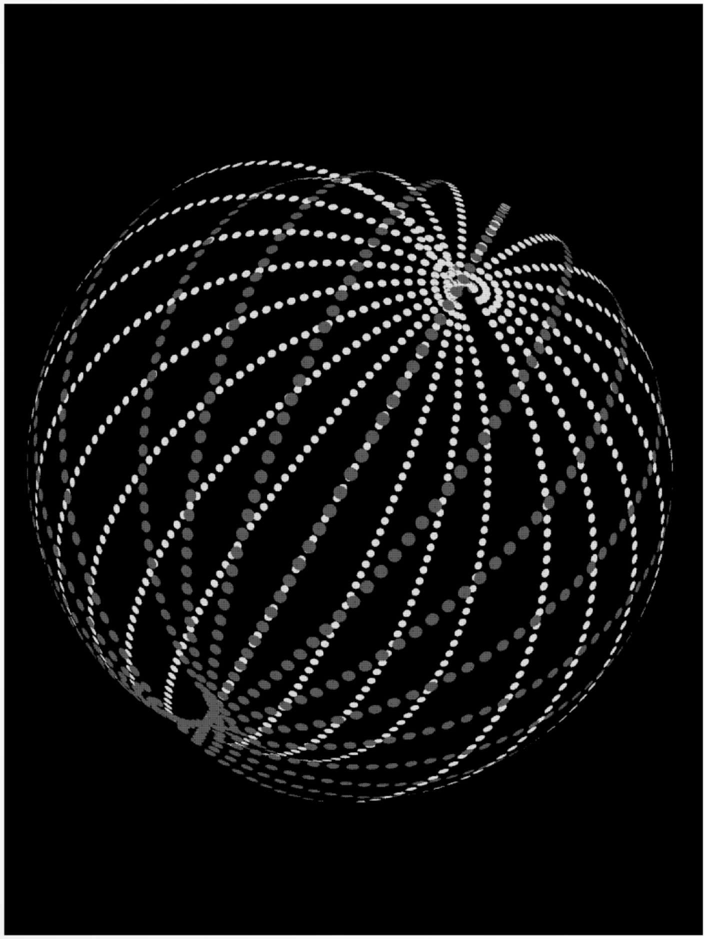
- Carl Sagan and Frank Drake were the leaders of the efforts
- The idea was to observe nearby stars over many radio bands and look for signals that could not be explained by natural sources

SETI 2019



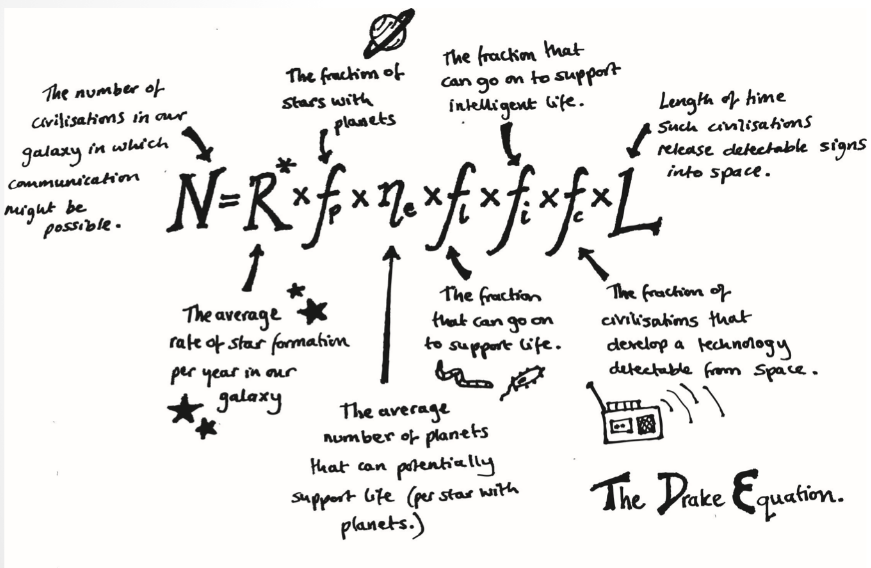
- With the discovery that the Galaxy is filled with planetary systems the interest in SETI was reignited
- Paul Allen, Franklin Antonio, Yuri Milner ($100M "Breakthrough Listen") donated millions of $ to support a burst of activity

SETI: other approaches



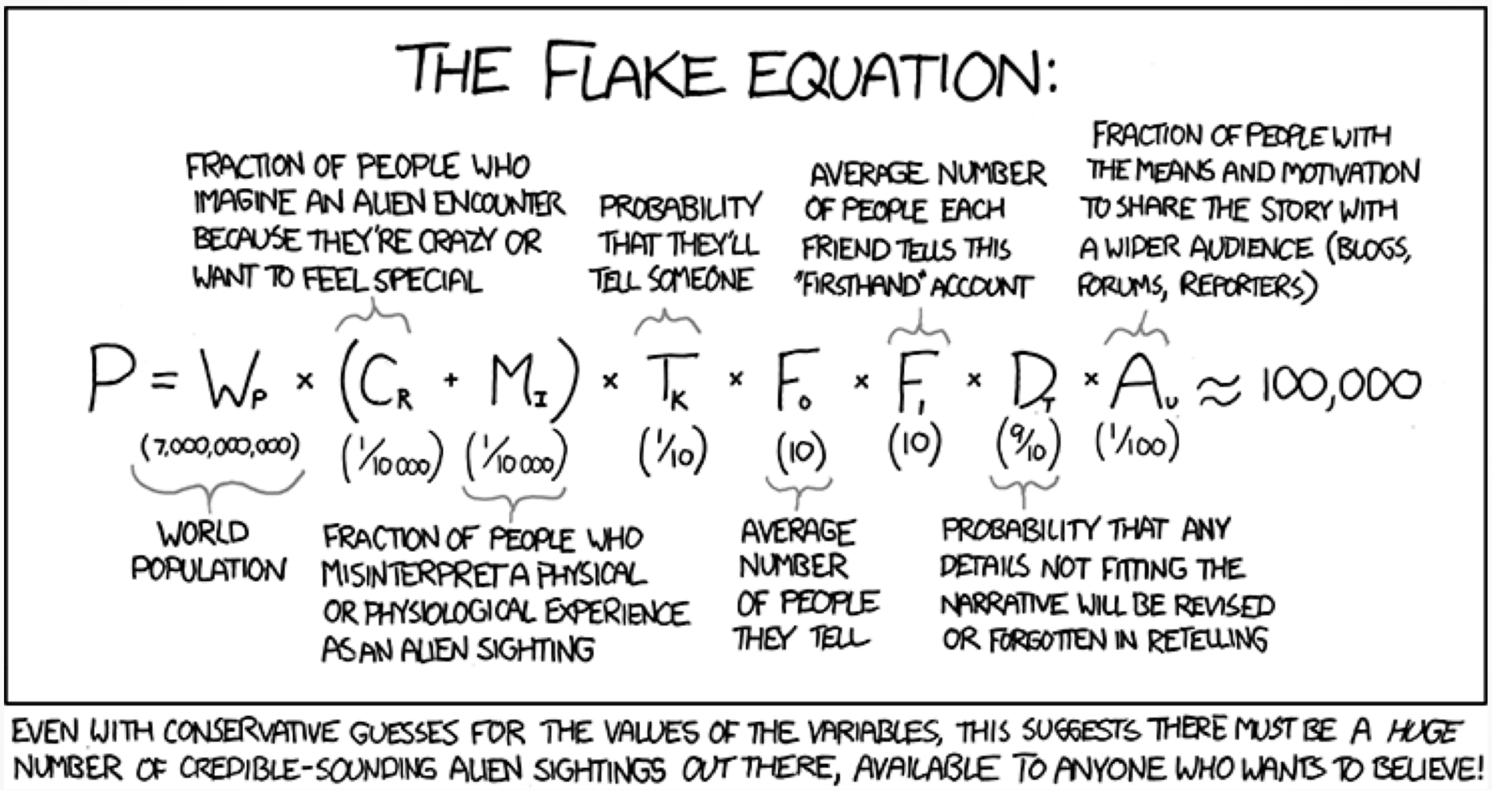
- There are a number of SETI offshoots searching for "technosignatures"
- Lasers (Optical SETI at Lick Observatory)
- City lights on the dark sides of known exoplanets
- Dyson Spheres

The Drake Equation

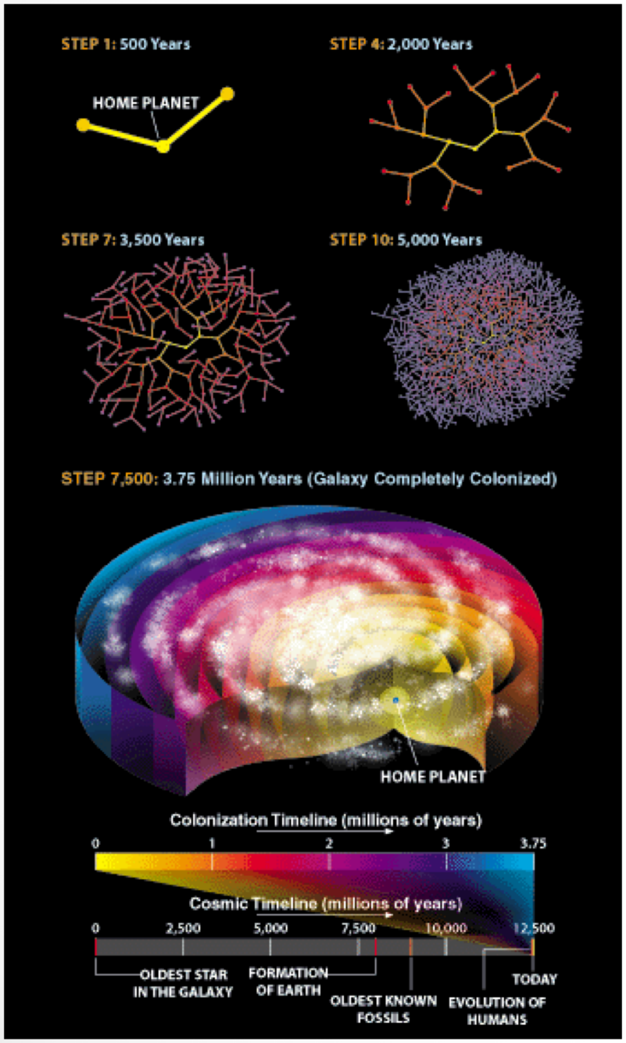


- Frank Drake first wrote down an equation that was intended to quantify the possibility of life based on several (poorly-known) factors
- As time has gone on the factors are becoming much better constrained


N=R*×fp×ne×fl×fi×fc×L

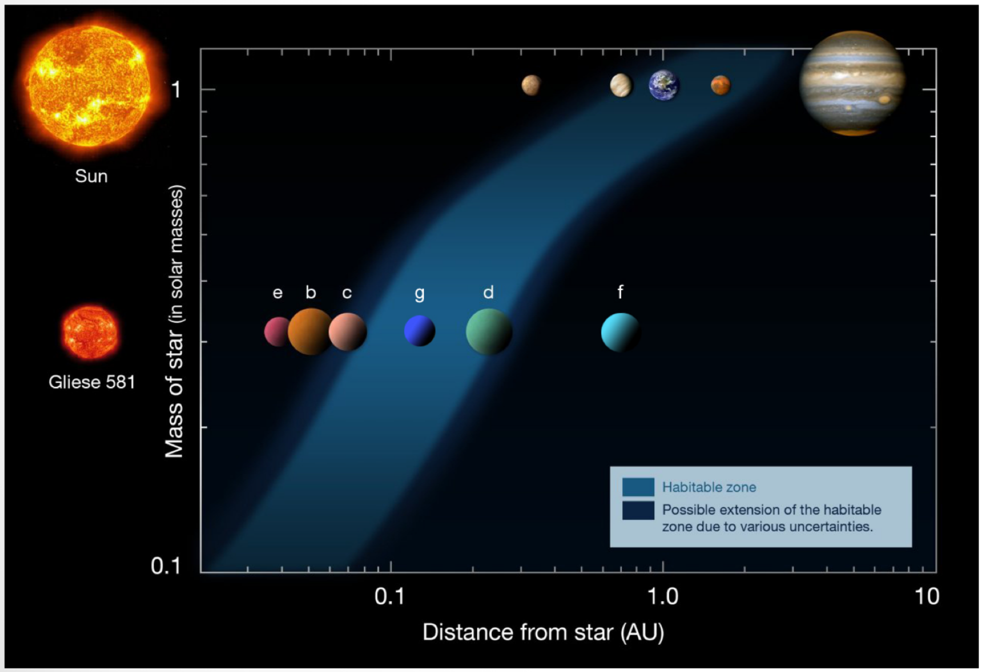

THE FLAKE EQUATION:
FRACTION OF PEOPLE WHO IMAGINE AN ALIEN ENCOUNTER BECAUSE THEY'RE CRAZY OR WANT TO FEEL SPECIAL
PROBABILITY THAT THEY'LL TELL SOMEONE
AVERAGE NUMBER OF PEOPLE EACH FRIEND TELLS THIS "FIRSTHAND" ACCOUNT
FRACTION OF PEOPLE WITH THE MEANS AND MOTIVATION TO SHARE THE STORY WITH A WIDER AUDIENCE (BLOGS, FORUMS, REPORTERS)
$P = W_P \times (C_R + M_I) \times T_K \times F_0 \times F_1 \times D_T \times A_U \approx 100{,}000$
(7,000,000,000) (1/10 000) (1/10 000) (1/10) (10) (10) (9/10) (1/100)
WORLD POPULATION
FRACTION OF PEOPLE WHO MISINTERPRET A PHYSICAL OR PHYSIOLOGICAL EXPERIENCE AS AN ALIEN SIGHTING
AVERAGE NUMBER OF PEOPLE THEY TELL
PROBABILITY THAT ANY DETAILS NOT FITTING THE NARRATIVE WILL BE REVISED OR FORGOTTEN IN RETELLING
EVEN WITH CONSERVATIVE GUESSES FOR THE VALUES OF THE VARIABLES, THIS SUGGESTS THERE MUST BE A HUGE NUMBER OF CREDIBLE-SOUNDING ALIEN SIGHTINGS OUT THERE, AVAILABLE TO ANYONE WHO WANTS TO BELIEVE!

Fermi's Paradox



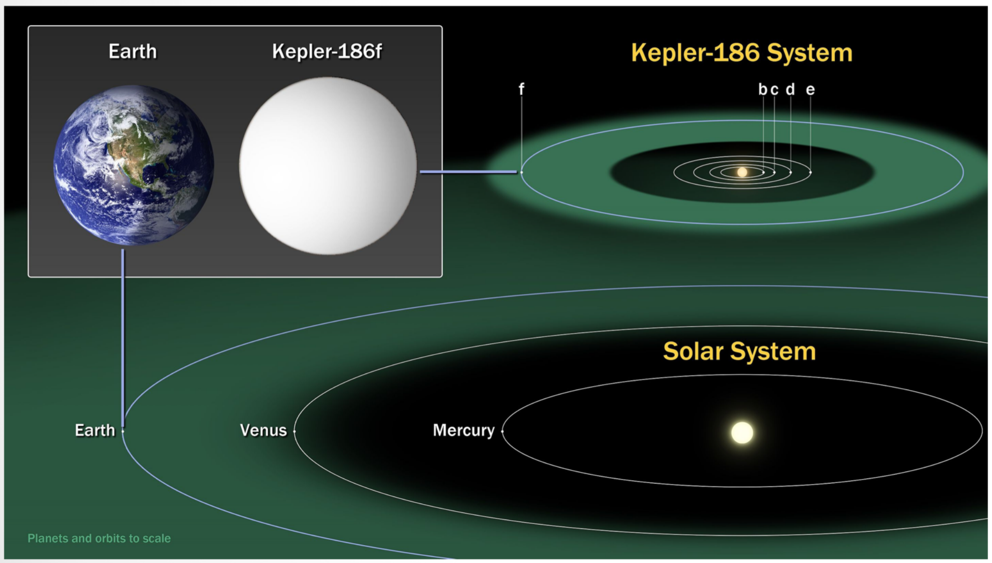
Fermi was a prominent physicist from the first half of the 1900s who considered the rapid advance of human technologies over only a few hundred years, the vastness of the Galaxy and asked "why have we not been visited by an advanced civilization?"

Biosignatures, Habitability and Exoplanets

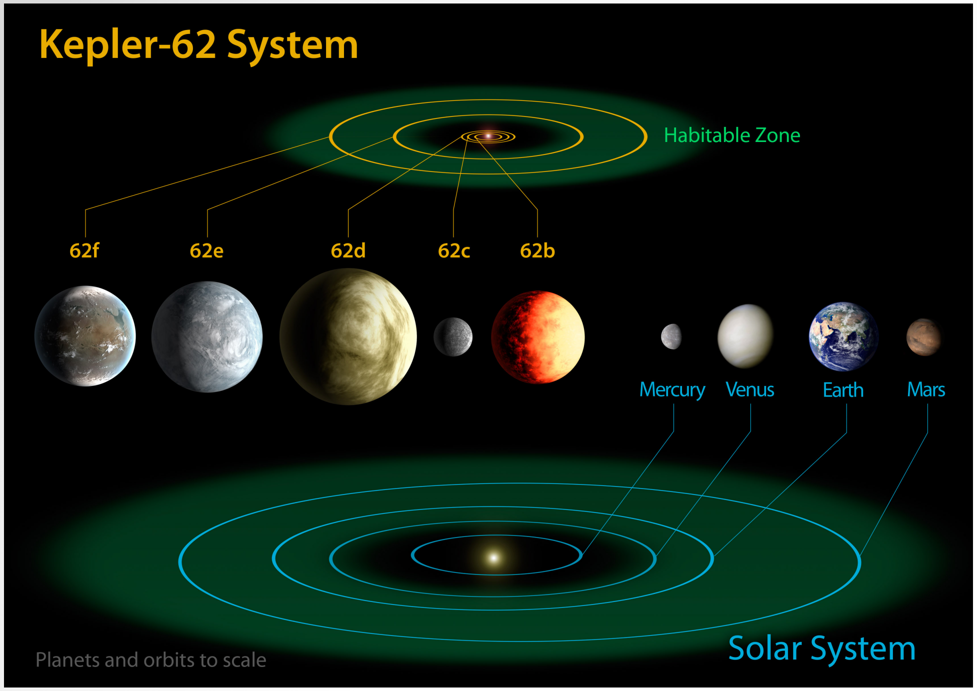


- Originally the "habitable zone" was the orbits around a star where water could exist in liquid form
- Further from hotter stars, closer to cooler stars
- Concept extended to other solvents and to include properties of specific stars like element abundances

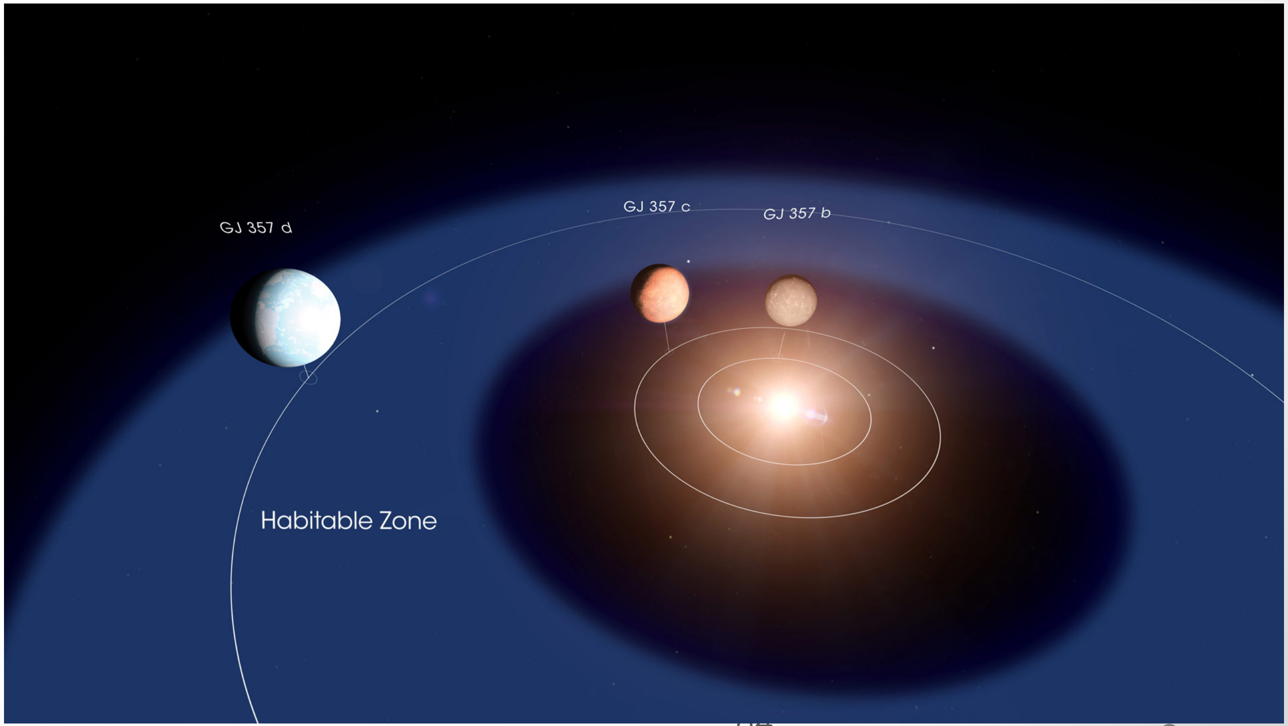
Habitable Zone



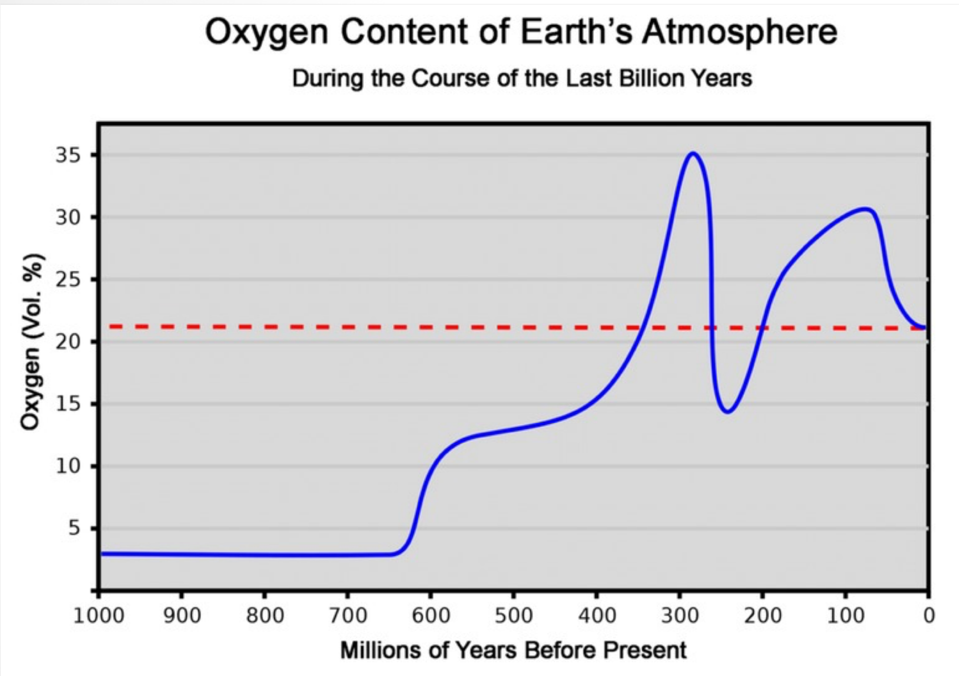
- First exoplanets in the habitable zone were discovered in 1996 and were gas giants
- With Kepler, we now have many super-Earths in the HZ and the first Earth-like planets in the HZ of other stars



Early TESS discovery

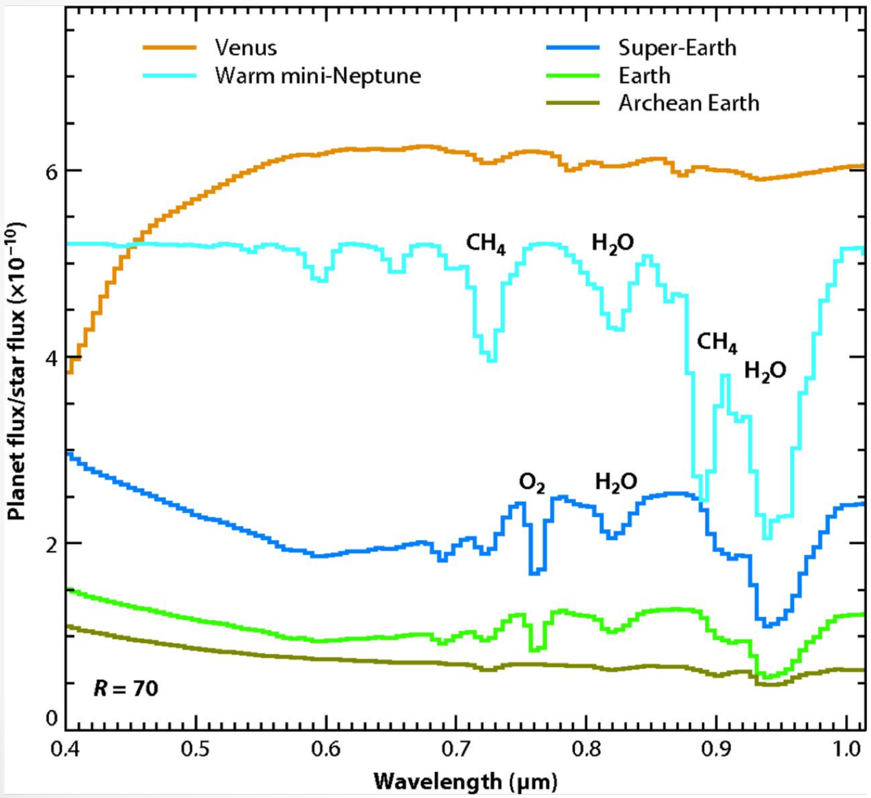


Biosignatures



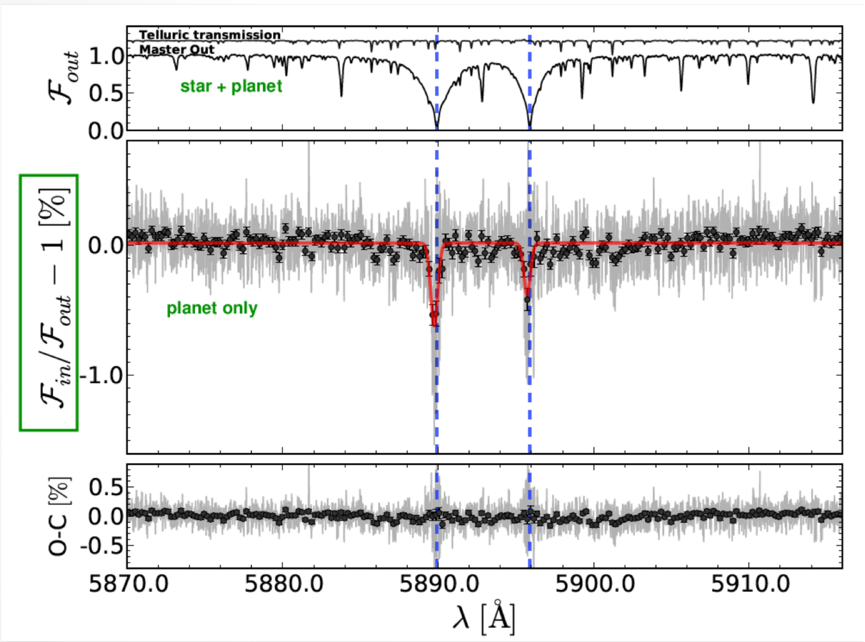
- With the HZ planets we now have targets to look for any kinds of life signs (not only intelligent life: think about Earth history)
- Looking for signatures in the spectra of exoplanets of chemistry that indicates life

Biomarkers



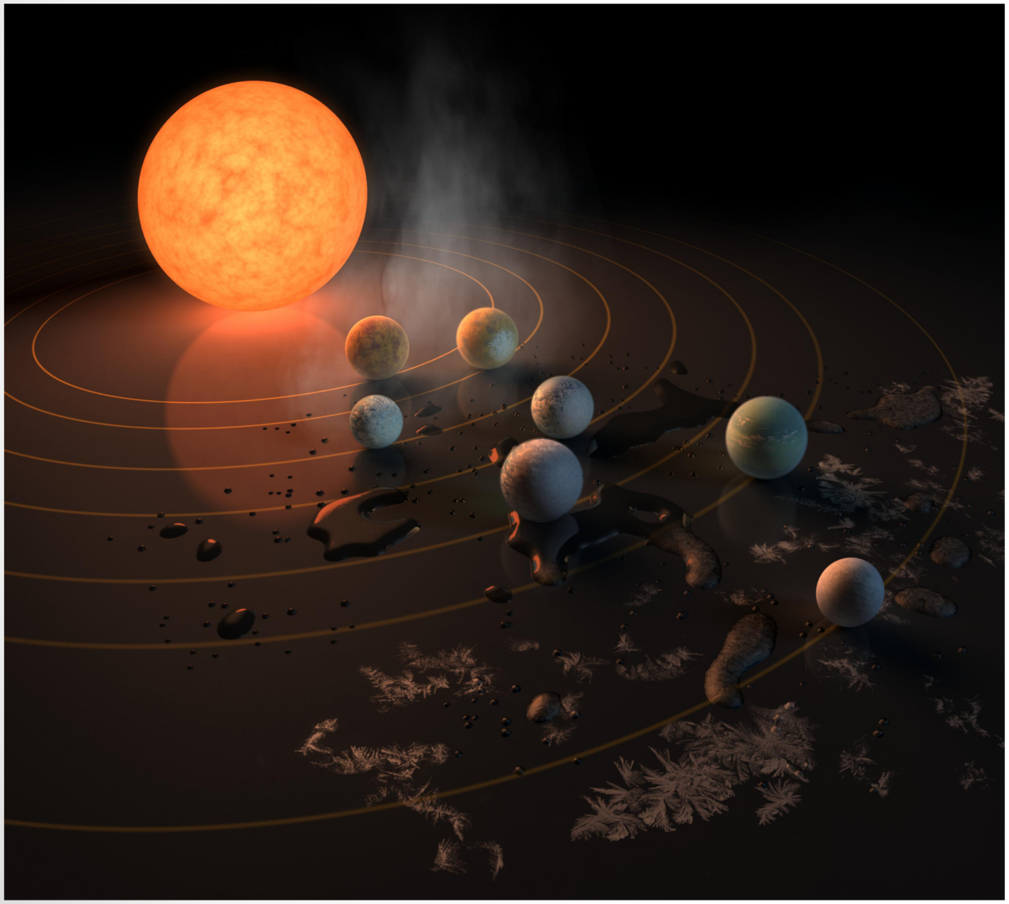
- Oxygen and oxygen-based molecules is a key biomarker
- The "red edge" of absorption due to chlorophyll would be for exoplanets with significant areas of plants
- Methane in the presence of oxygen probably requires bacteria (methanogens)

Biomarkers



- This is hard! So far we have had to rely on differential spectroscopy in and out of eclipse to try and tease out an exoplanet atmosphere spectrum
- Good for the era of really big telescopes

SETI, Biomarkers, what do we know?



- Nothing!
- But we are right at the very beginning of a new field of science
- Stand by for super-SETI, JWST, Tess, TMT…
- If life off Earth is discovered, it will be the most important discovery of all time


THE END
IS NEAR
HERE