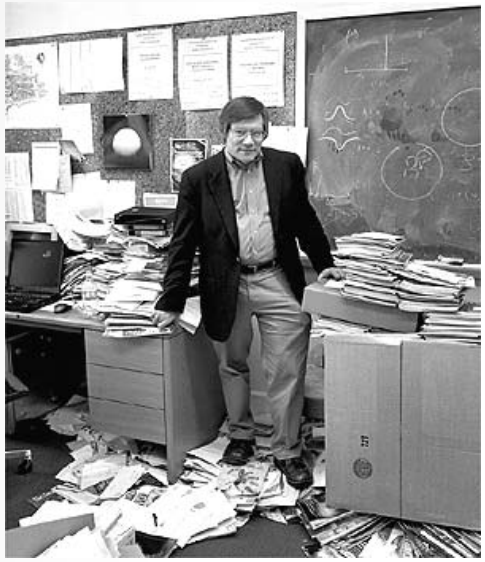
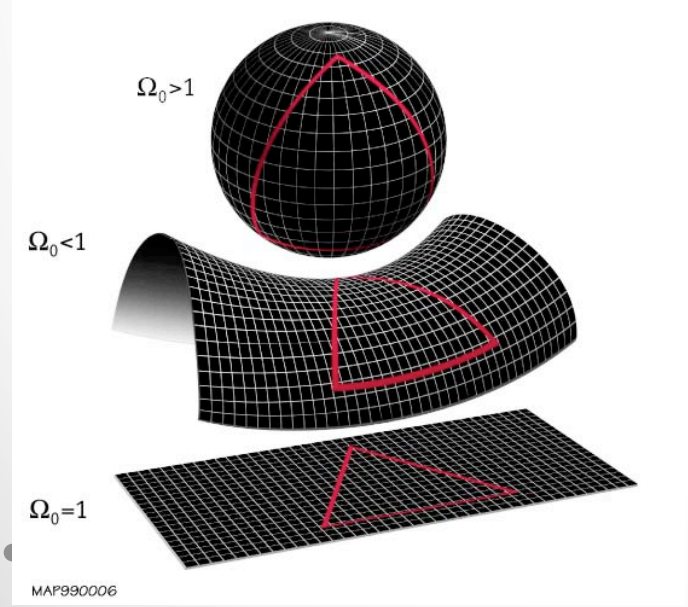
AY1 Announcements

- Quiz 4: Thursday June 8 (last day of class)
- Final: Wednesday June 14, 4pm -7pm

Last Lecture

Are Astronomers Inflating the Truth?

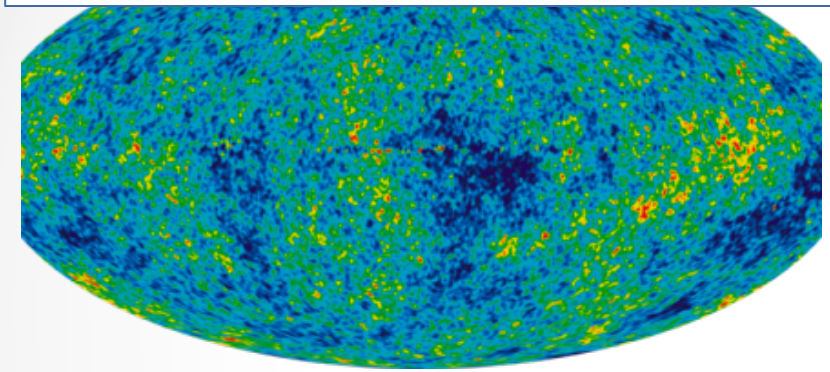


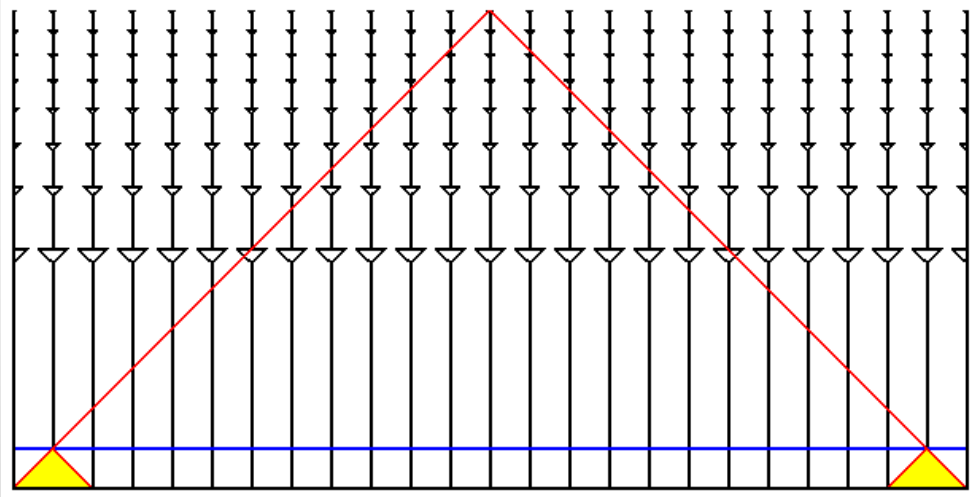


- In the 1970s three problems with the Big Bang were widely discussed:
  - Horizon problem
  - Flatness problem
  - Relic monopole problem
  - Origin of cosmic structures
- Universe expands by 10^{26} between 10^{-36} and 10^{-32} seconds after the Big Bang

Horizon Problem

Pre-Inflation the entire observable Universe was in causal contact

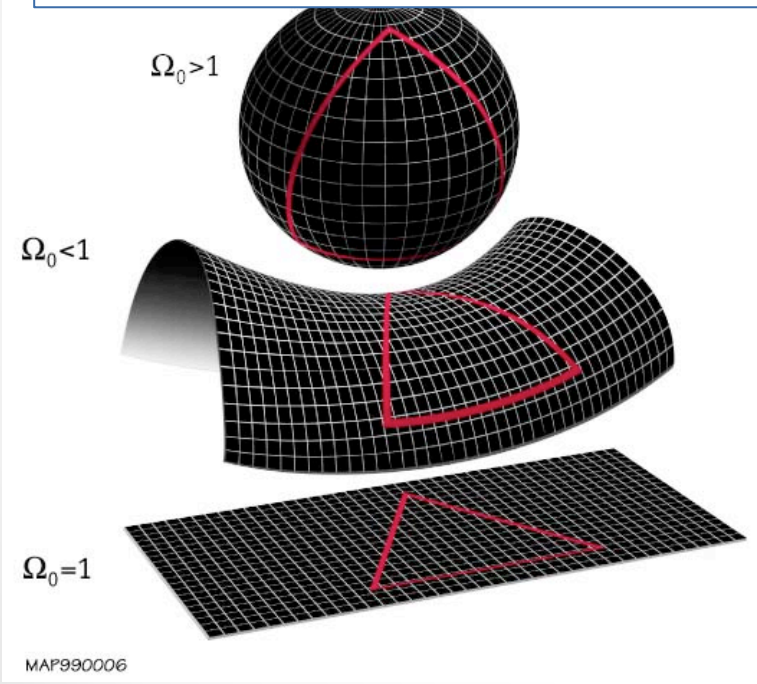




- Cosmic Microwave Background looks the same (statistically) in every direction
- But, the opposite sides of the sky should not have been in "contact" at 380,000 years after the HBB
- How could they be the same temperature to 1 part in 100,000?

Flatness Problem

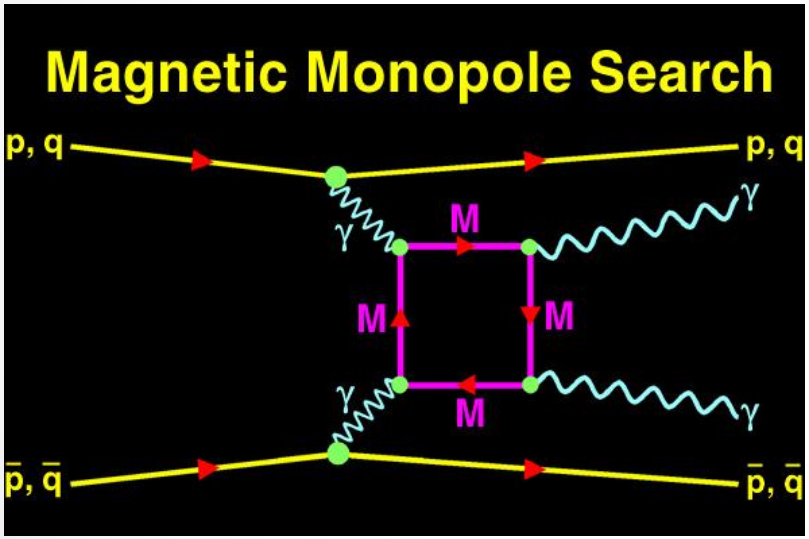
Huge increase in size naturally drives Universe to be spatially flat



- 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 preInflation and monopole density diluted by $(10^{26})^3$

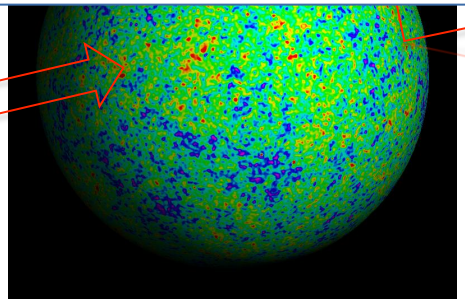


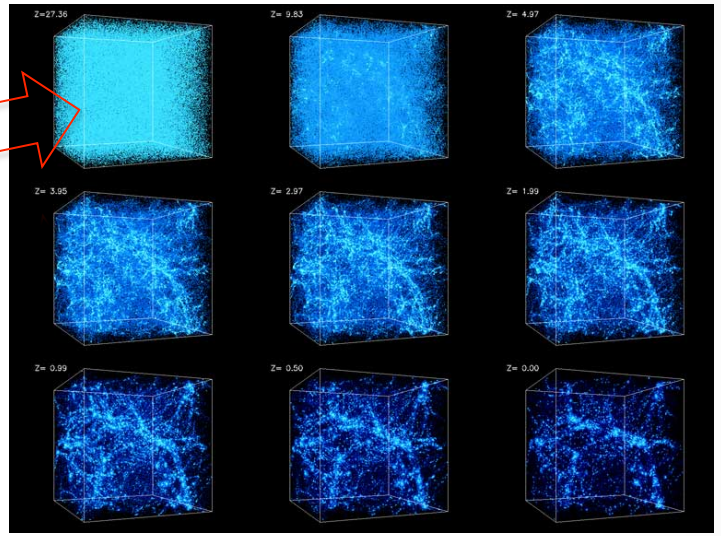
- Predicted by Dirac to explain discrete electric charges in 1930s
- A part of modern String Theory and other GUTS theories predict the presence of massive monopoles that should exist at early times and be stable
- None found: density 10^{-29} that of protons

Seeds of Galaxies

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

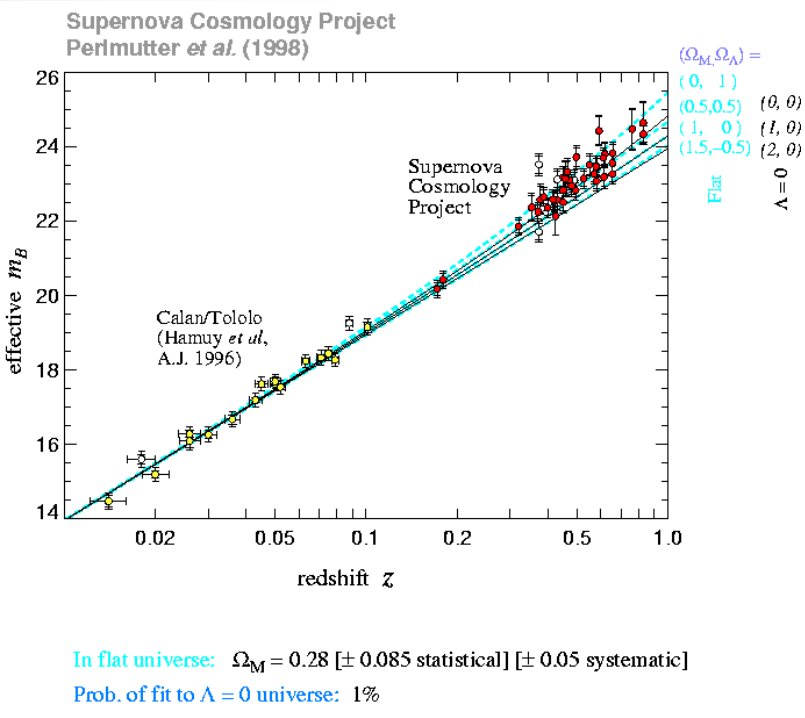
?





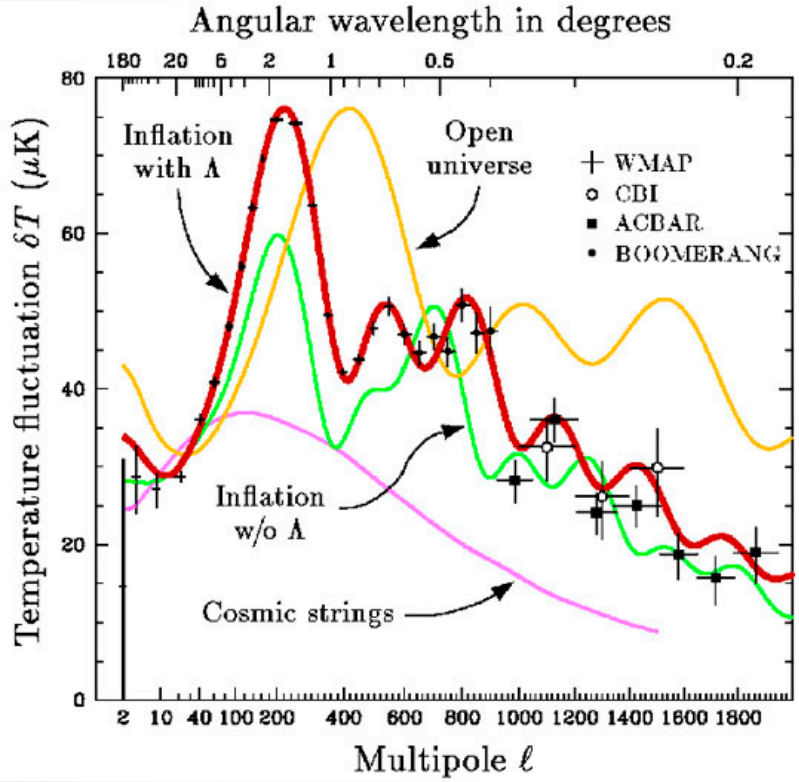
- We can grow the ripples seen in the CMB into the galaxies and large scale structure we see today (with Dark Matter) but what is the origin of the initial inhomogeneities?

Dark energy



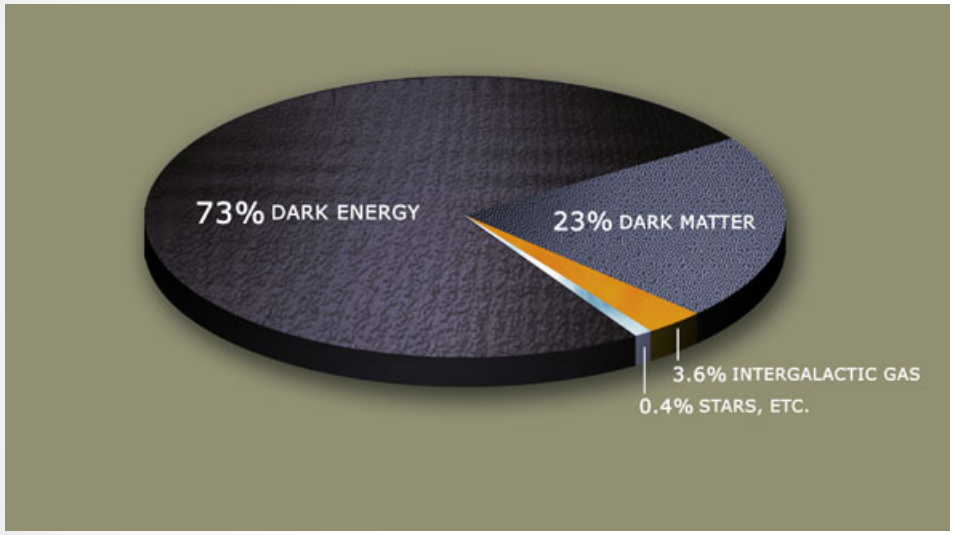
- Obervations of SN 1 at large distances and lookback times show the expansion was slower in the past
- Λ, the cosmological constant was not zero, but rather had a value of ~0.72: consistent with that needed to reconcile the Universe expansion age and stellar ages

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

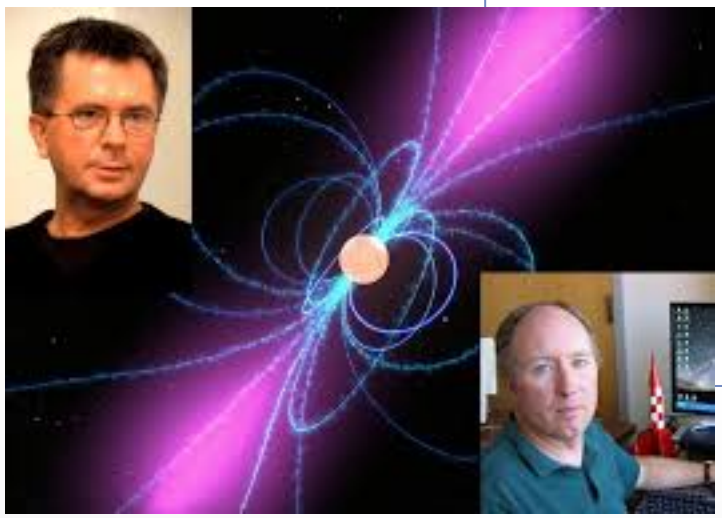
Which of the statements below best describes the "Horizon Problem" in cosmology?

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

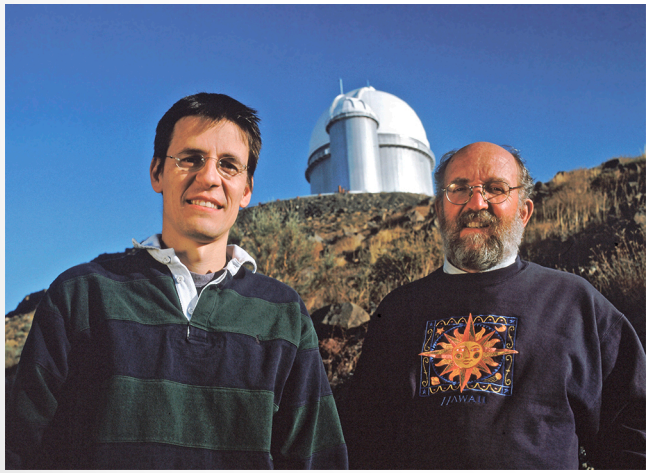
Last Topic: Exoplanets

- 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

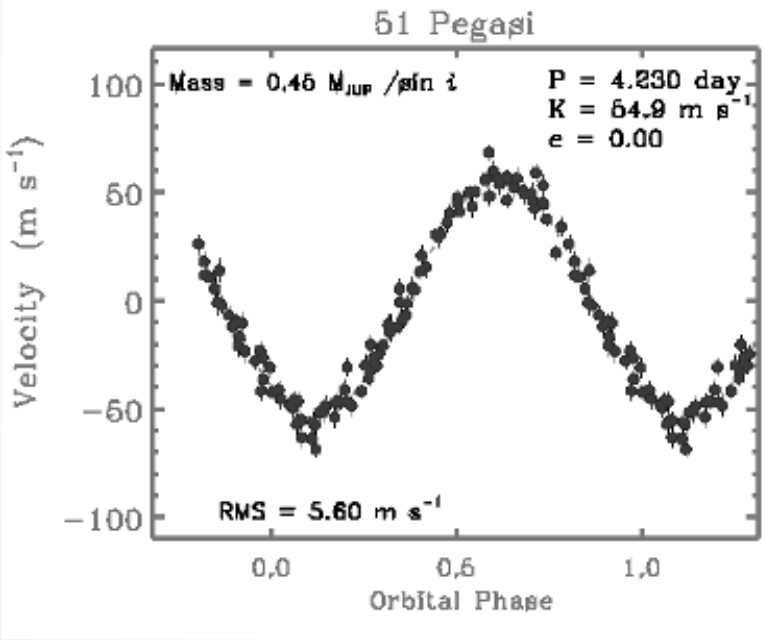


The 1st discovery of a planet orbiting a main-sequence star other than the Sun kicked off a new field of science in 1995



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

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
- 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

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

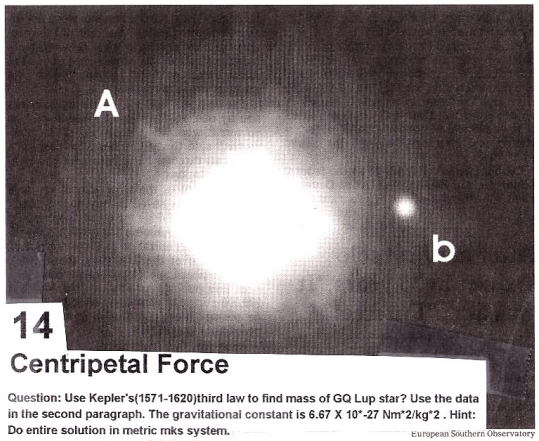
Astronomers have produced what they say could be the first direct image of a planet around another Sun-like star. But the work has touched off intense debate about whether the orbiting object's mass has been determined accurately enough to count as a planet.

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



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.

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

"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,

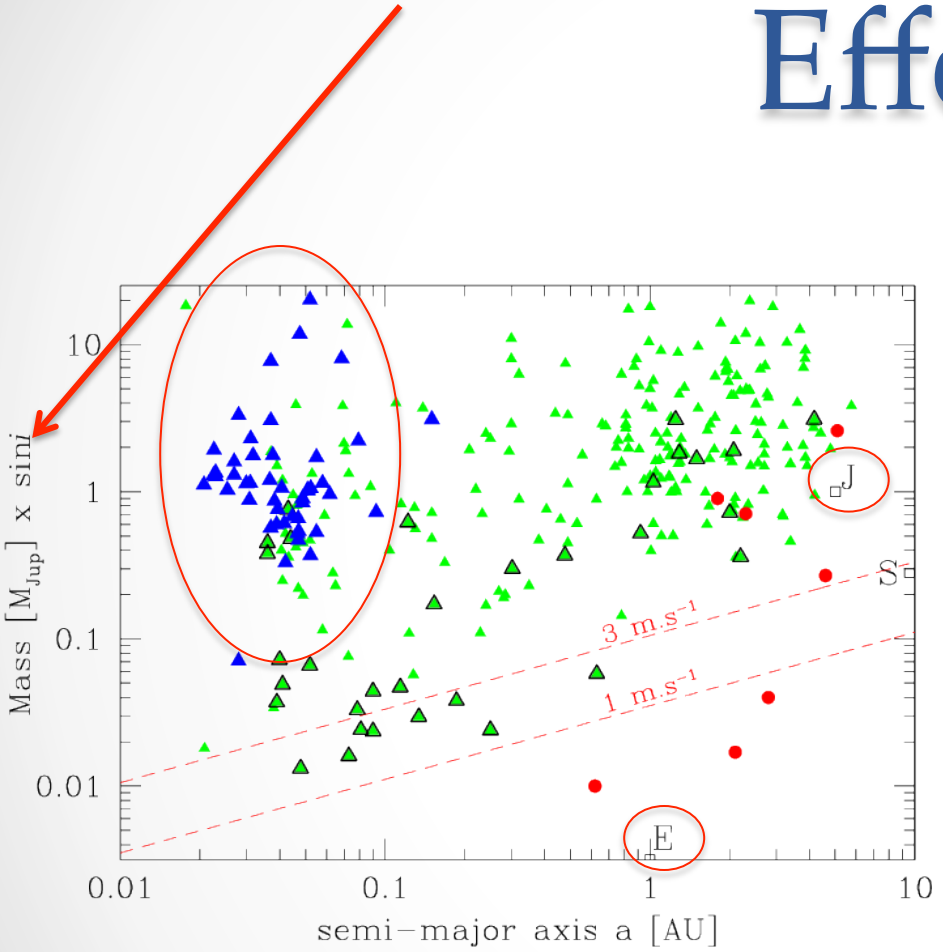
A reddish mass in another solar system may be a landmark.

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."

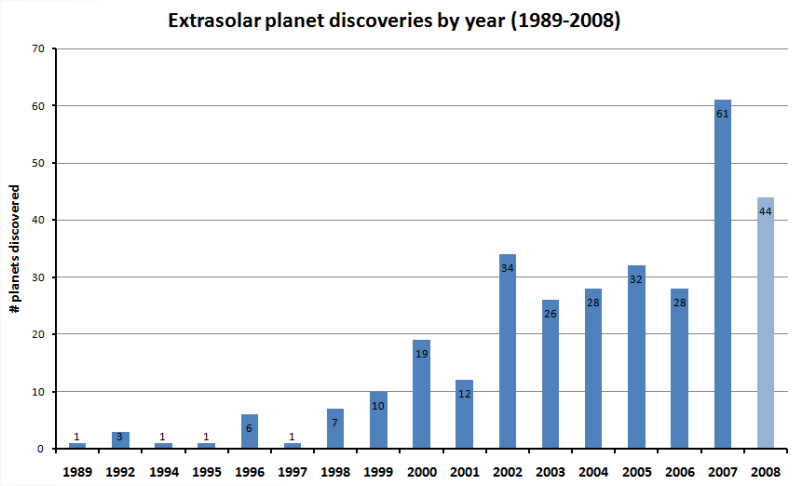
In an e-mail message, Dr. Wuchterl pointed out that the calculations of mass had been buttressed by spectroscopic measure-

RV Planet Selection Effects



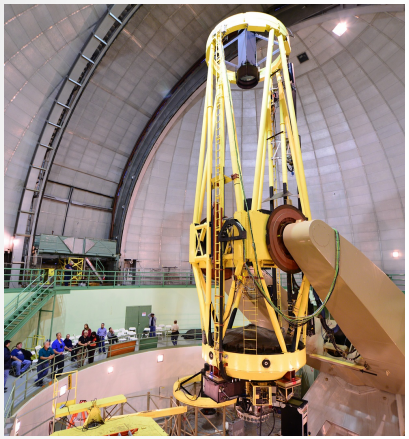
- Larger mass planets produce a larger reflex motion at fixed distance and host star mass
- Closer planets produce larger reflex motion at fixed planet and host star mass
- Smaller mass host planets have a larger reflex motion at fixed planet mass and distance

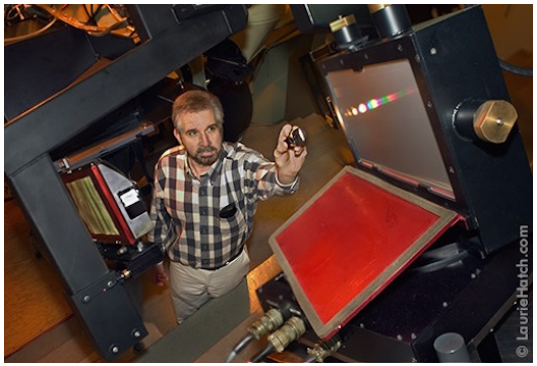
RV exoplanets

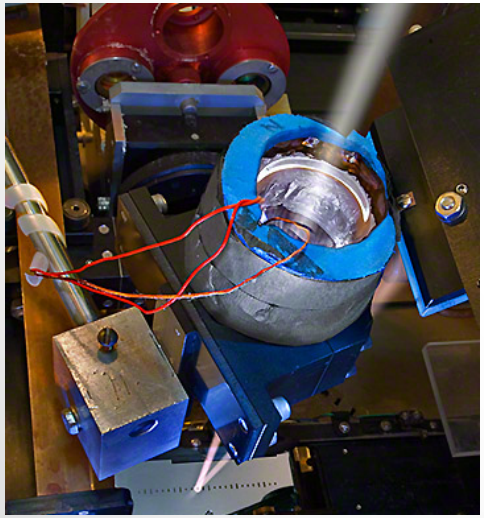


- After the initial announcement some planets were discovered in older data
- 12 years after 51 Peg b there were more than 300 known exoplanets

Lick, Keck ESO





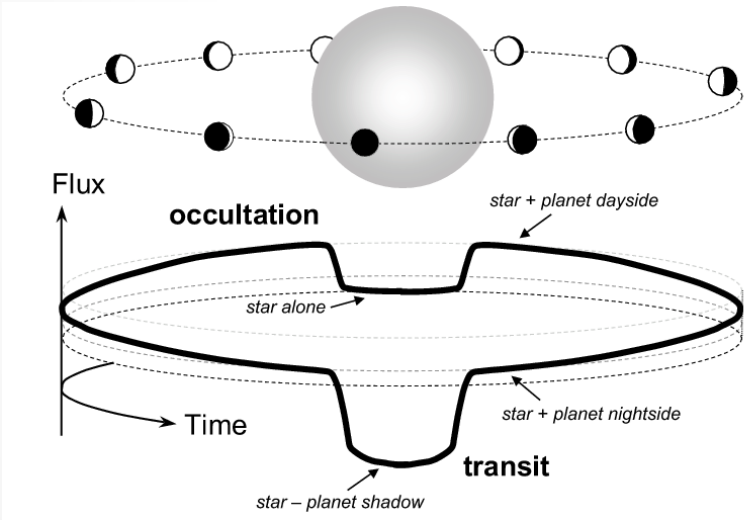


- University of California astronomers and UCSC astronomers have played a world-leading role
- Built and used the most important instruments at UCSC and deployed them at Lick Obs and Keck Obs
- Developing techniques for stability and software for analysis has been key

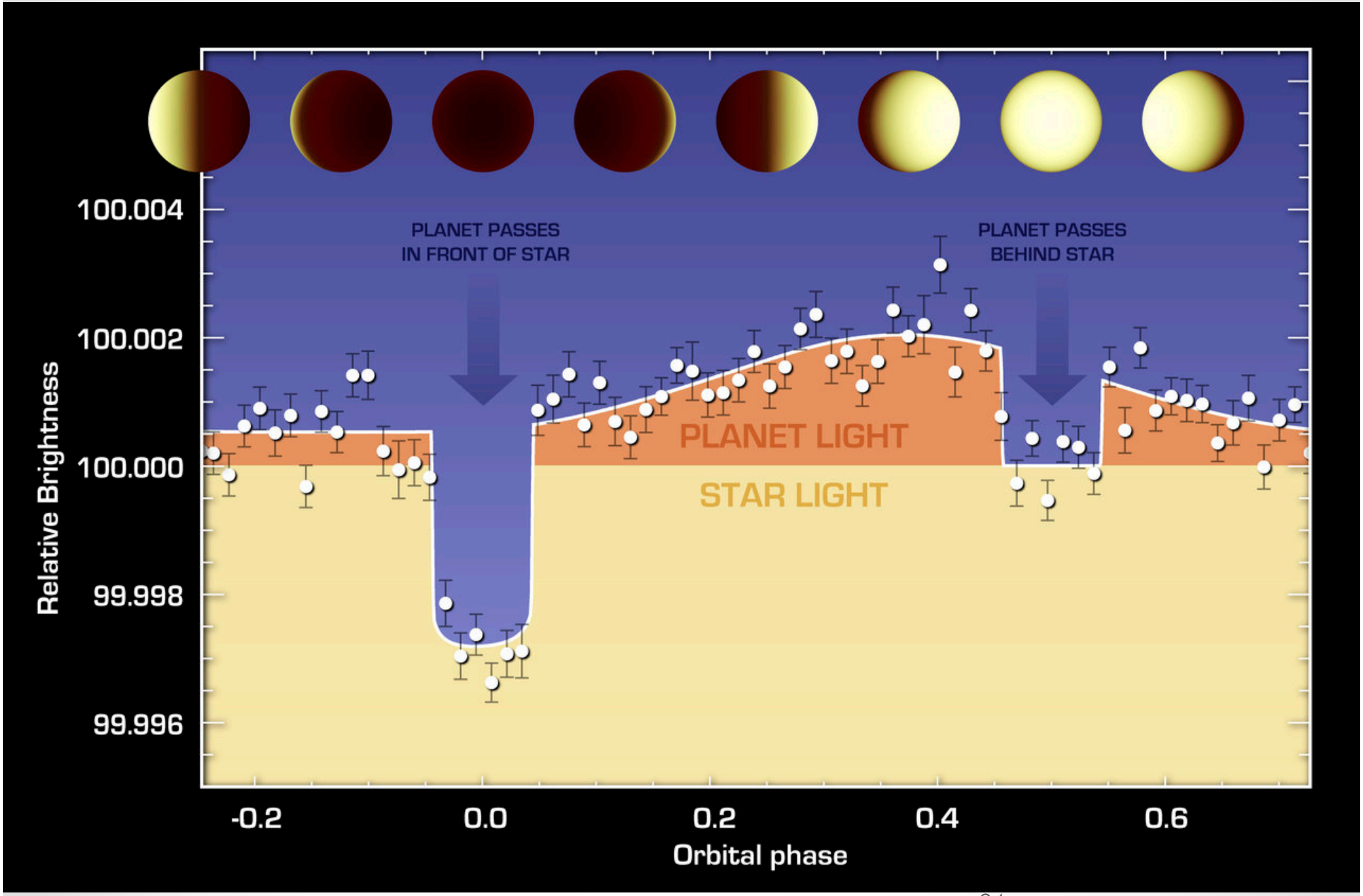
Transiting Planets

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

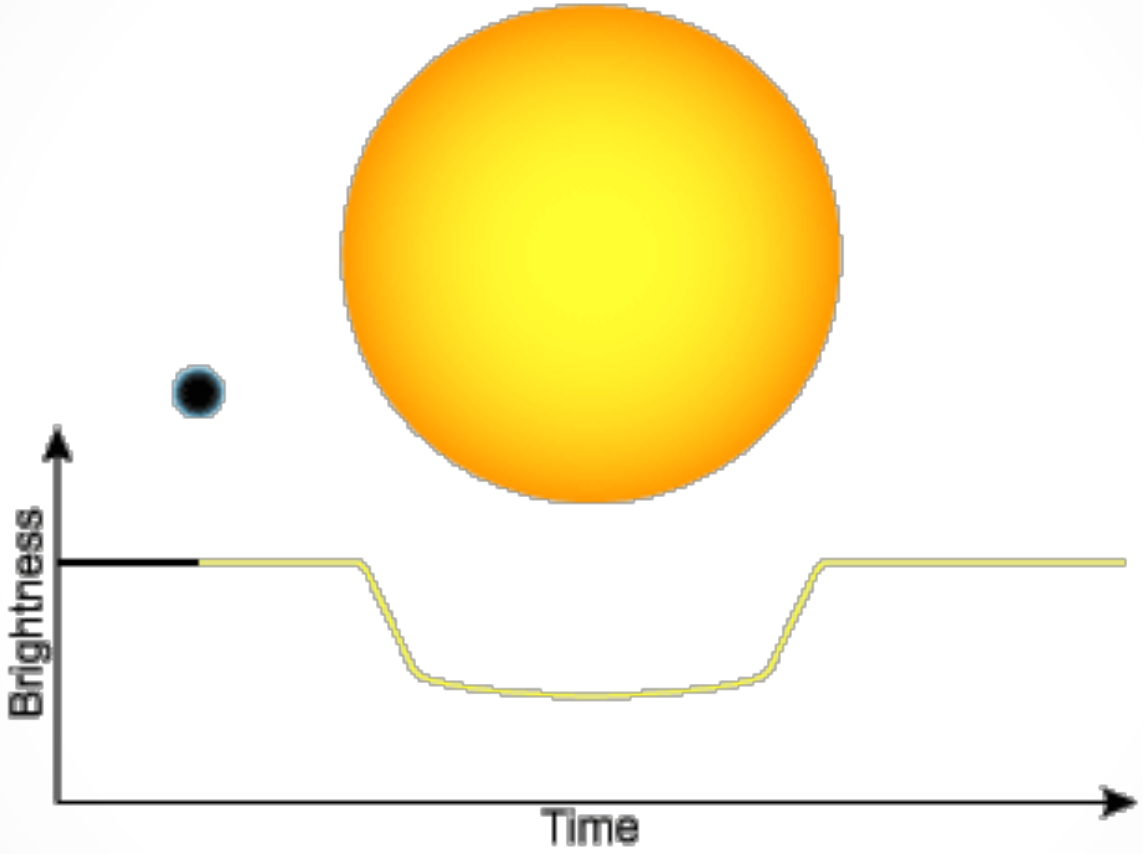
Transiting basics



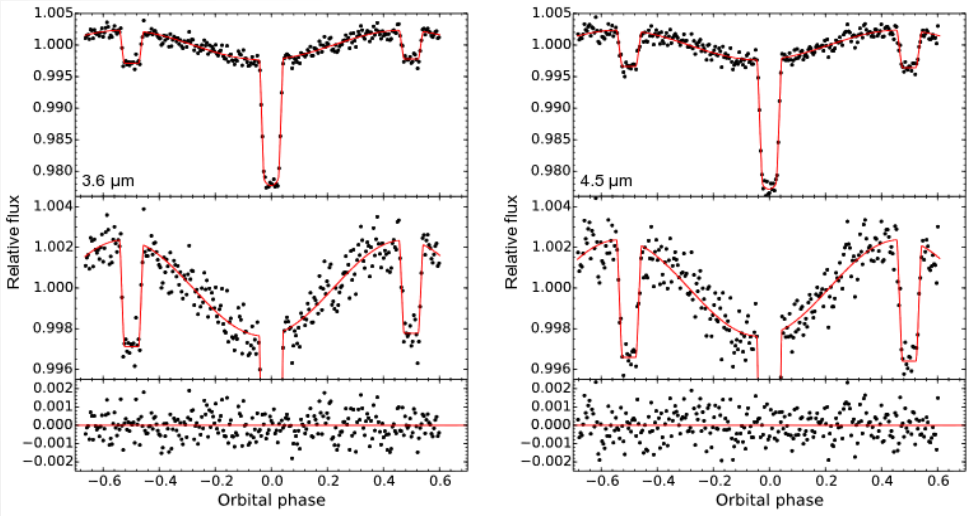
- For systems with orbits that are very closely in the line of sight, when the cooler planet crosses the hotter disk of the star, the total flux goes down: transit
- There is a more complex increase and decrease in total flux during "occultation" (seconda ry eclipse)


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

Light Curve of a Star During Planetary Transit

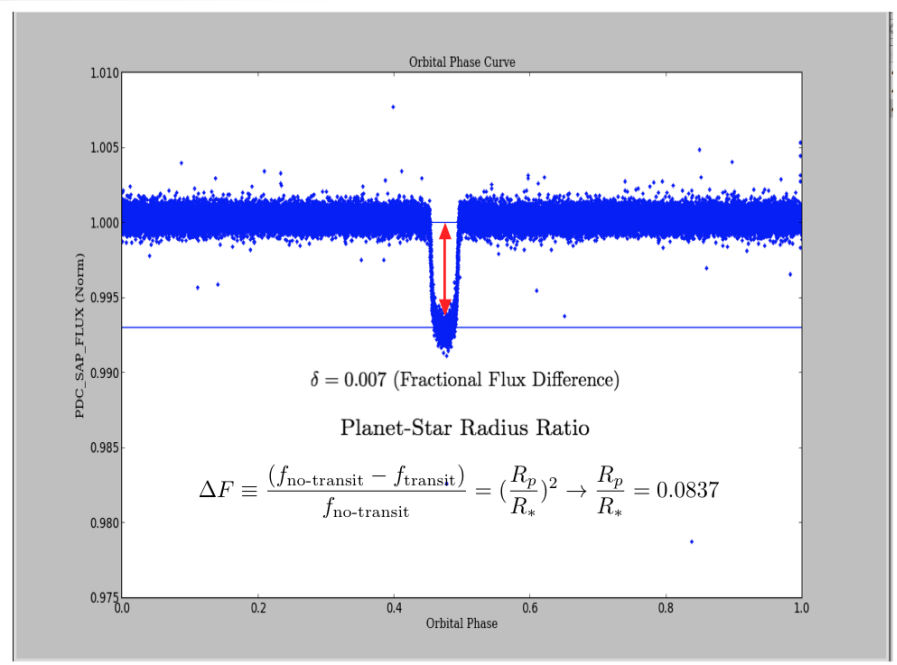


The predicted light curves are seen!



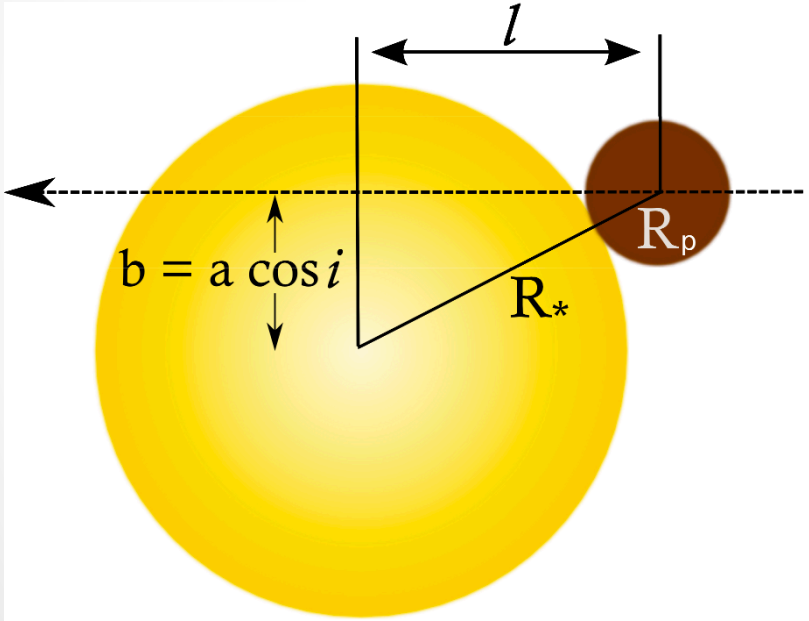
- The orbit period is easily determined
- The relative size of the planet and star are measured with some understanding of temperature
- The tilt of the orbit with respect to the Earth is known

Transit Details



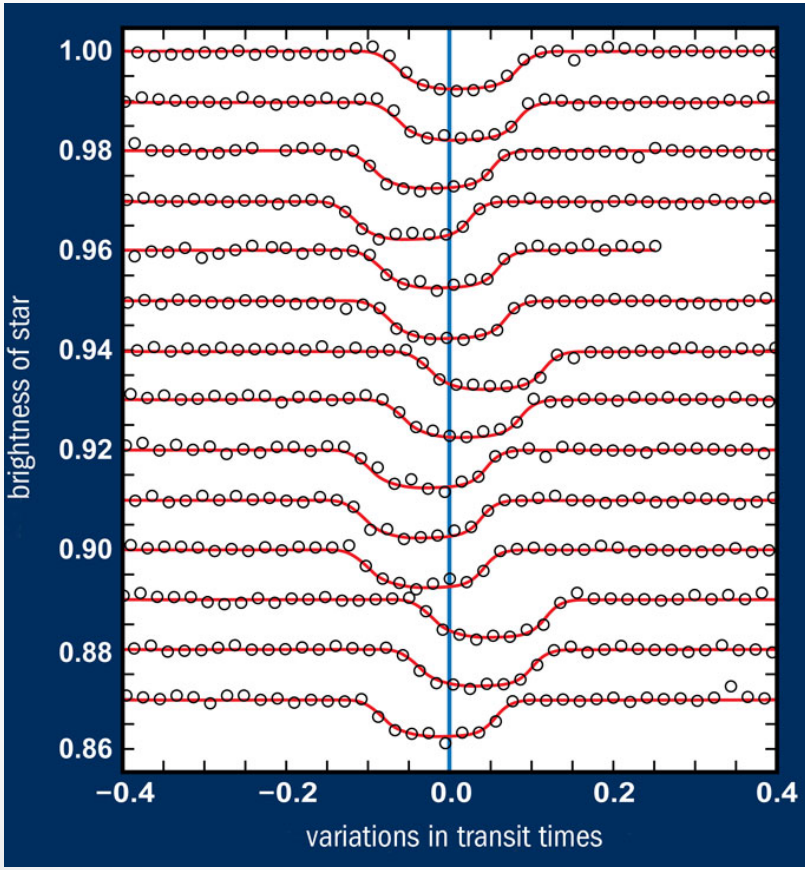
- Planets tend to be small compared to stars and the signal is very small (2-30 parts per 1000)
- Hard to measure from the ground with changing atmospheric conditions

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:
  - "transit timing variations" for multiplanet systems
  - Followup radial velocity measurements

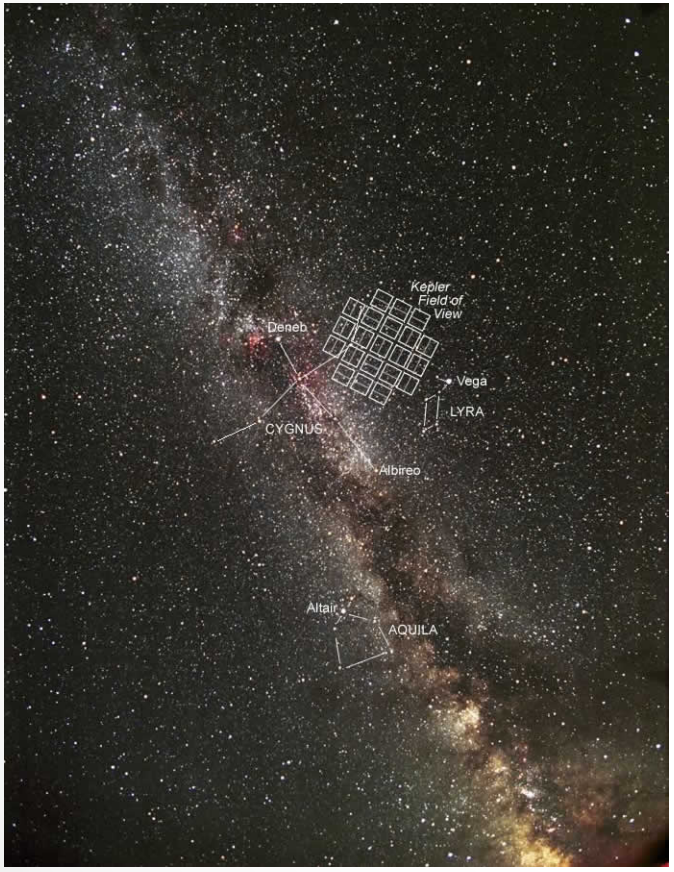
Transit observations

- 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

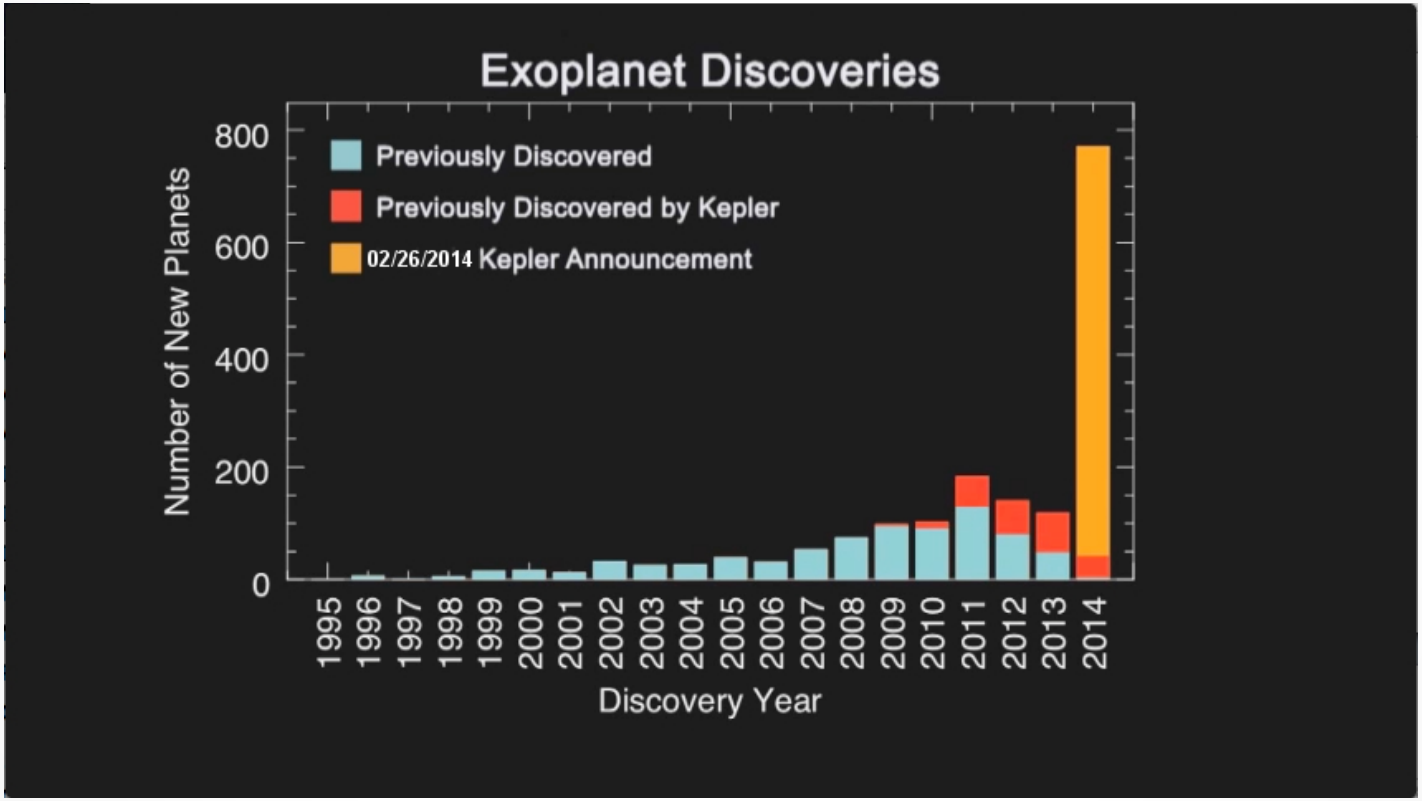
- Launched March 2009
- 1.4m primary mirror
- Focal plane of 42 large CCDs
- Earth-trailing orbit around the Sun
- Pointed at one location for four years

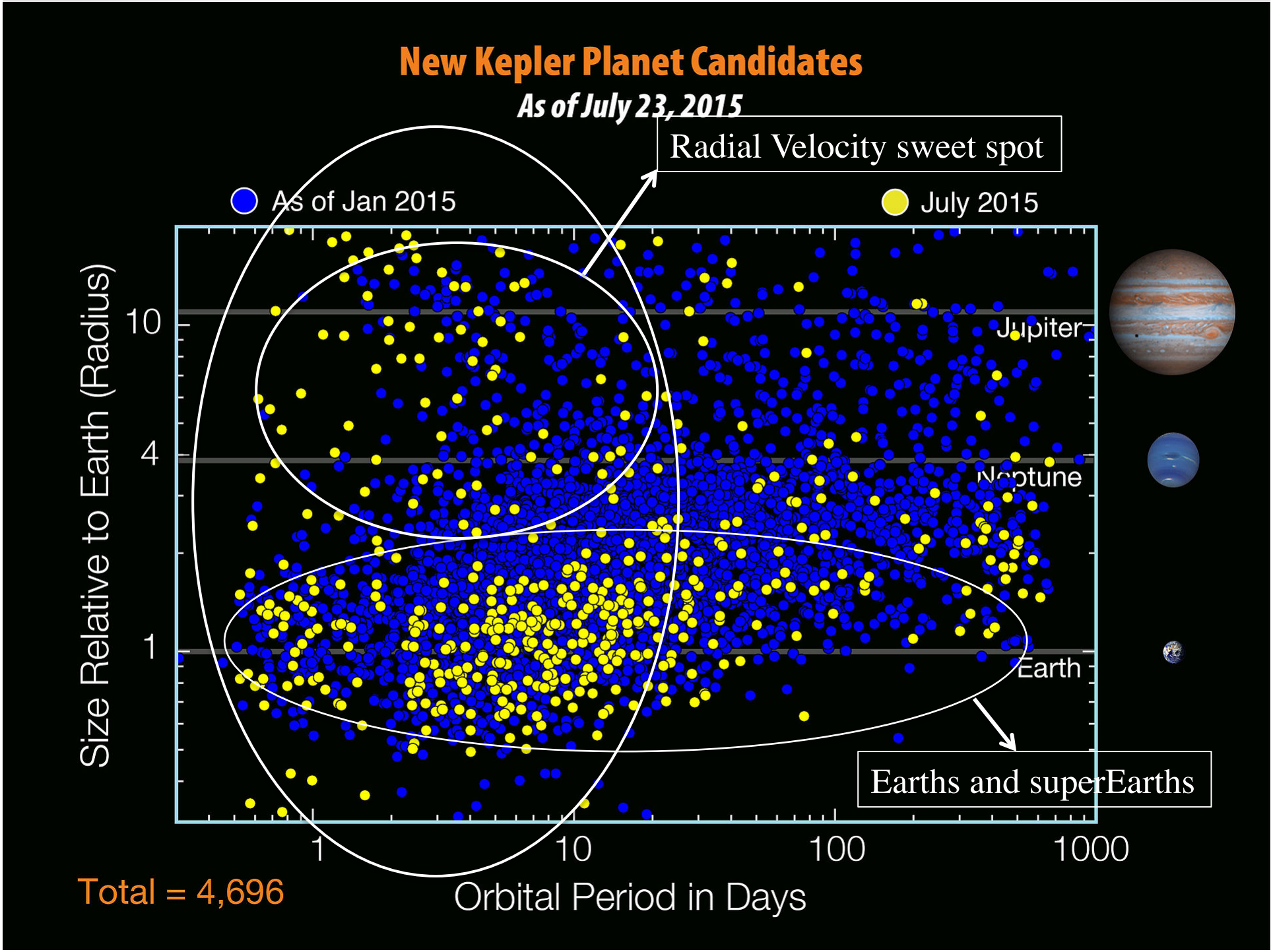
The Kepler Mission

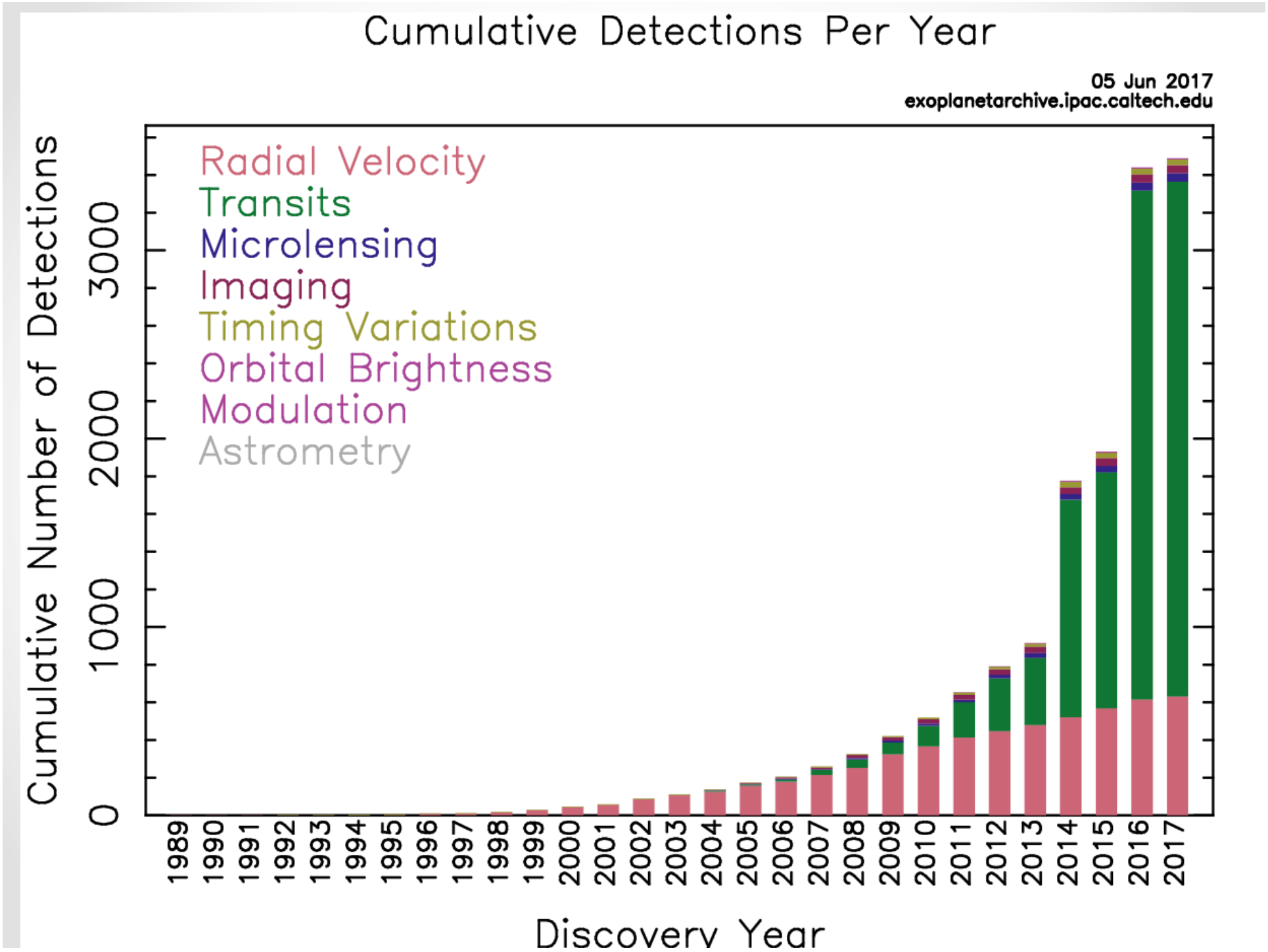


- Observed primary field reading out ever six seconds to produce high-cadence "light curve" for ~145,000 stars
- The stability of observing above the atmosphere allowed very high precision: 0.01% in brightness

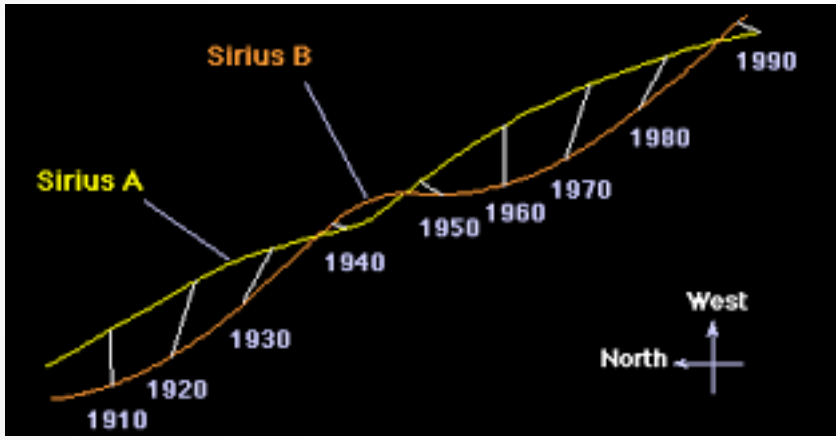
Kepler as a game changer




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
Orbital Period in Days
Total = 4,696


Cumulative Detections Per Year
05 Jun 2017
exoplanetarchive.ipac.caltech.edu
Radial Velocity
Transits
Microlensing
Imaging
Timing Variations
Orbital Brightness
Modulation
Astrometry
Cumulative Number of Detections
0
1000
2000
3000
1989
1990
1991
1992
1993
1994
1995
1996
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
Discovery Year

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(!)

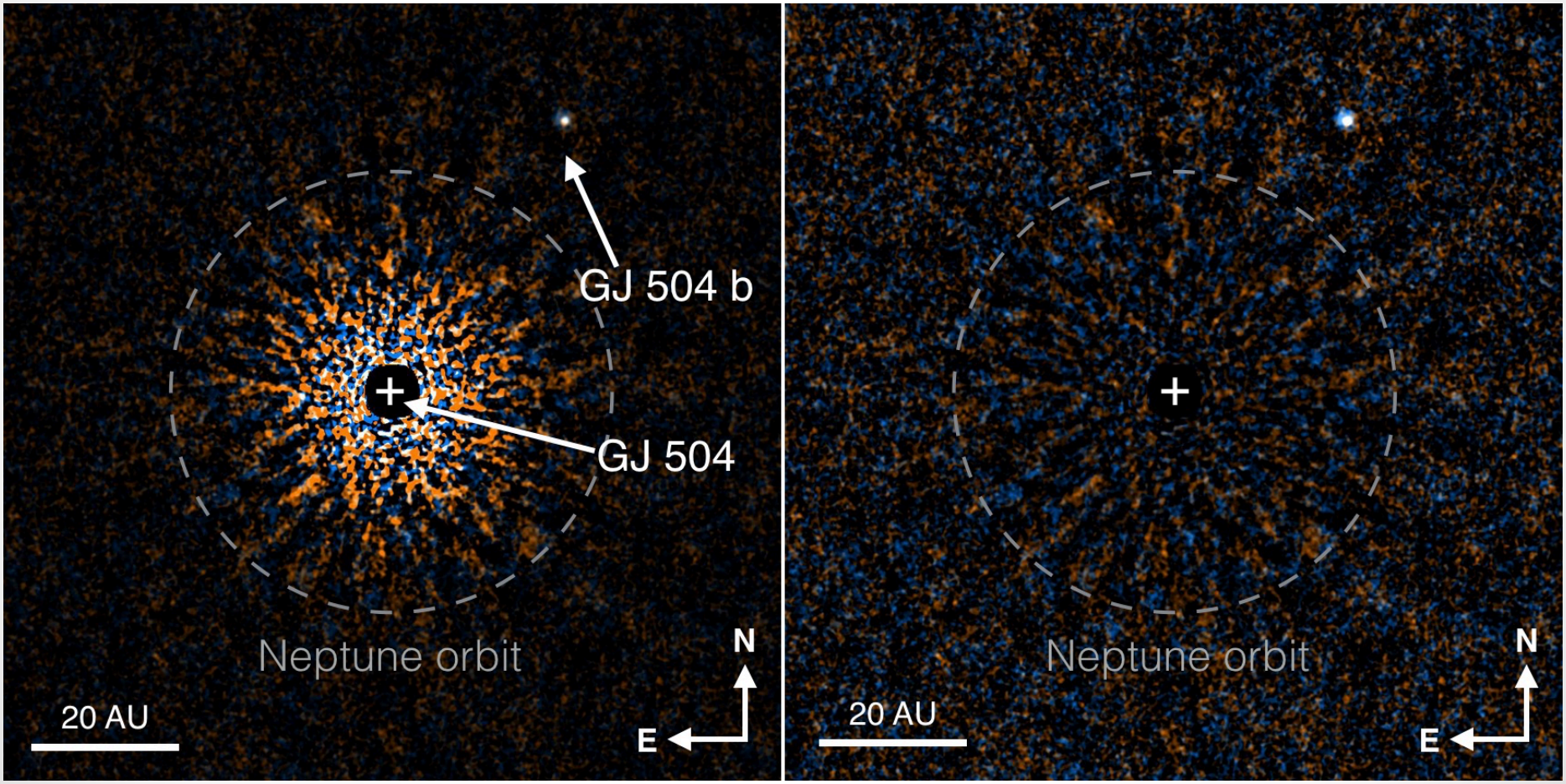
Gravitational Lenses

- 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

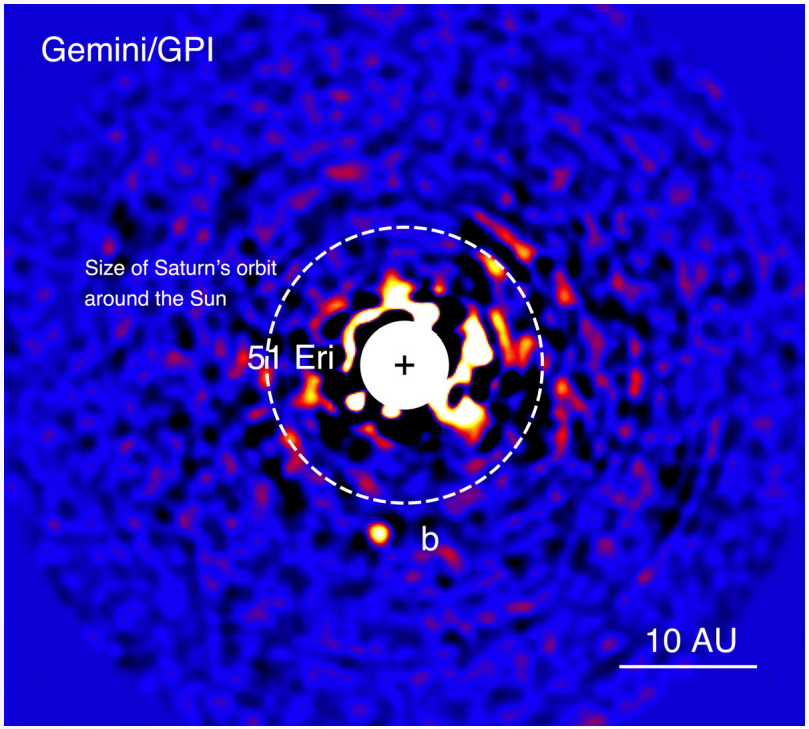
Direct Imaging: firefly by a lighthouse

- 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

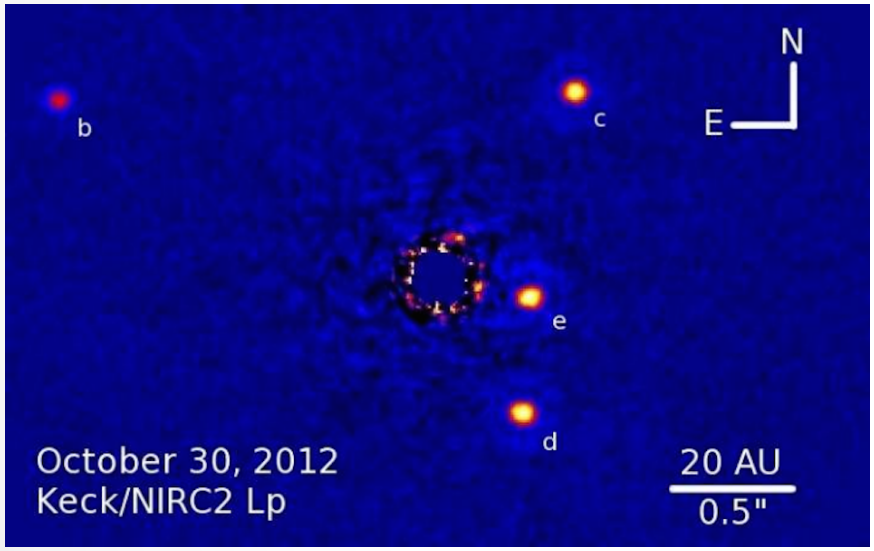


Direct Imaging



- 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

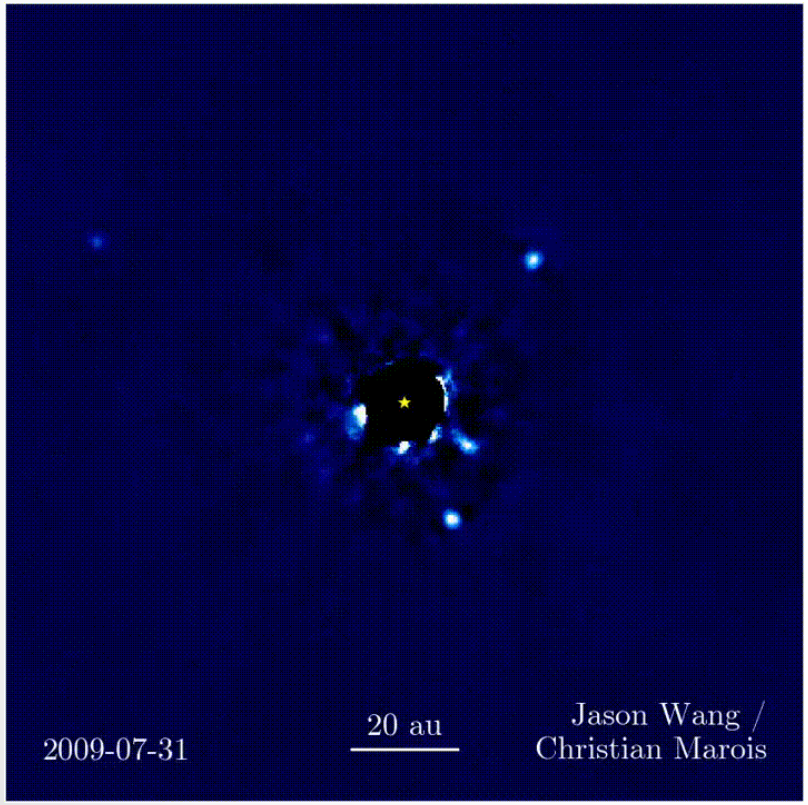
Direct Imaging

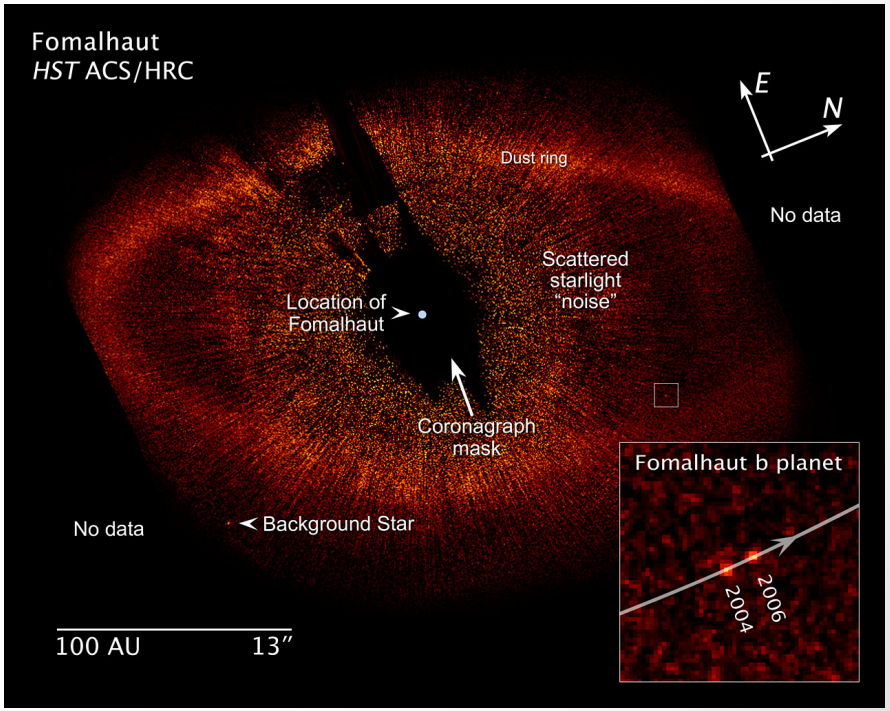


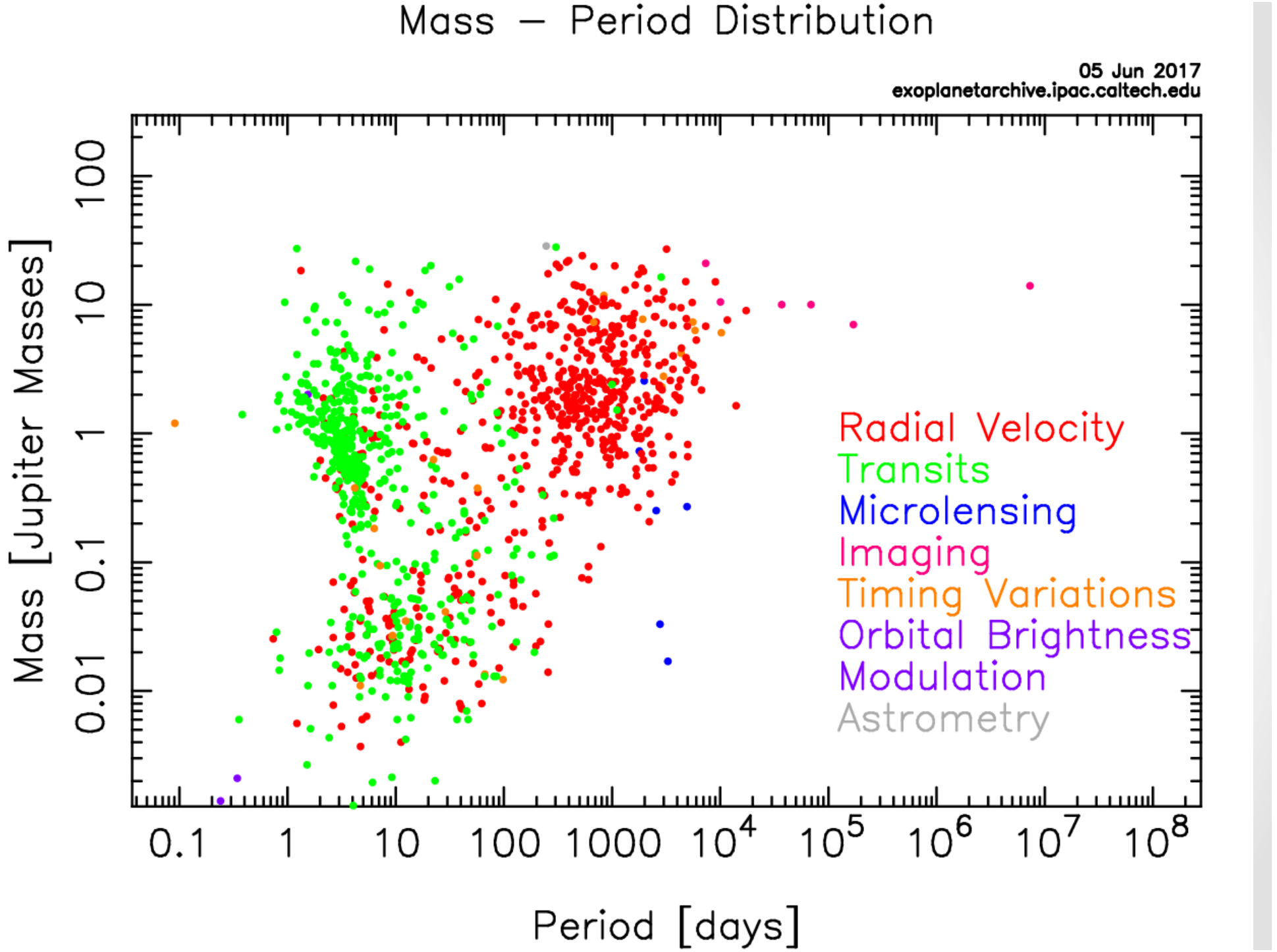
- But, it works!
- As of 2017 there are around 20 directly imaged plants
- They tend to be the equivalent of outer Solar System planets because of the angular separation problem
- One big advantage of directly imaging the planets is it is possible to take spectra of their atmospheres

Direct Imaging

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





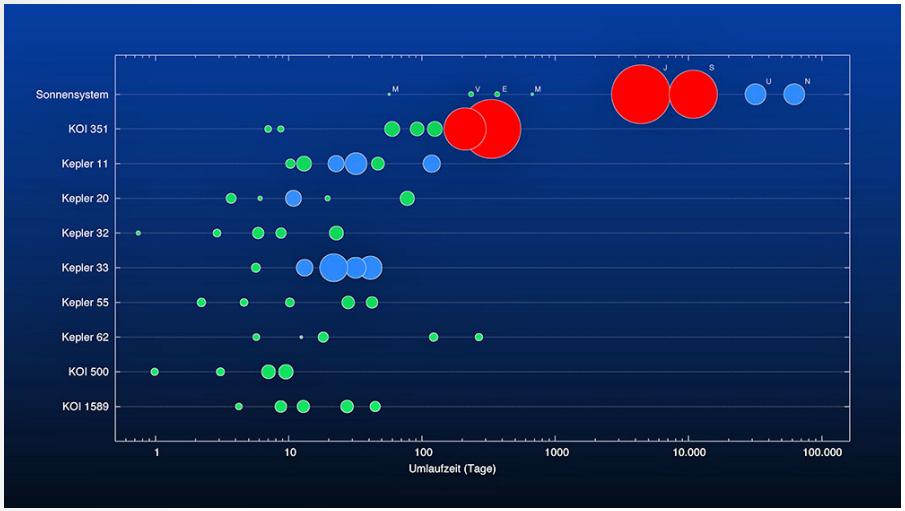

Mass – Period Distribution
05 Jun 2017
exoplanetarchive.ipac.caltech.edu
Mass [Jupiter Masses]
0.01
0.1
1
10
100
Period [days]
0.1
1
10
100
1000
10^4
10^5
10^6
10^7
10^8
Radial Velocity
Transits
Microlensing
Imaging
Timing Variations
Orbital Brightness Modulation
Astrometry

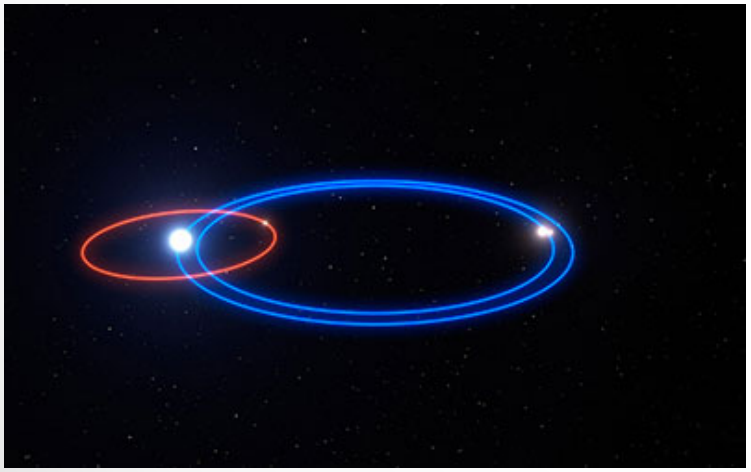
Planet demographics

- https://apod.nasa.gov/apod/ap151205.html

- On average in the Galaxy there is at least 1 planets per star
- ~300 billion planets in the Galaxy
- ~11 billion Earth-like planets
- Based on 3610 planets including 610 systems with more than one planet

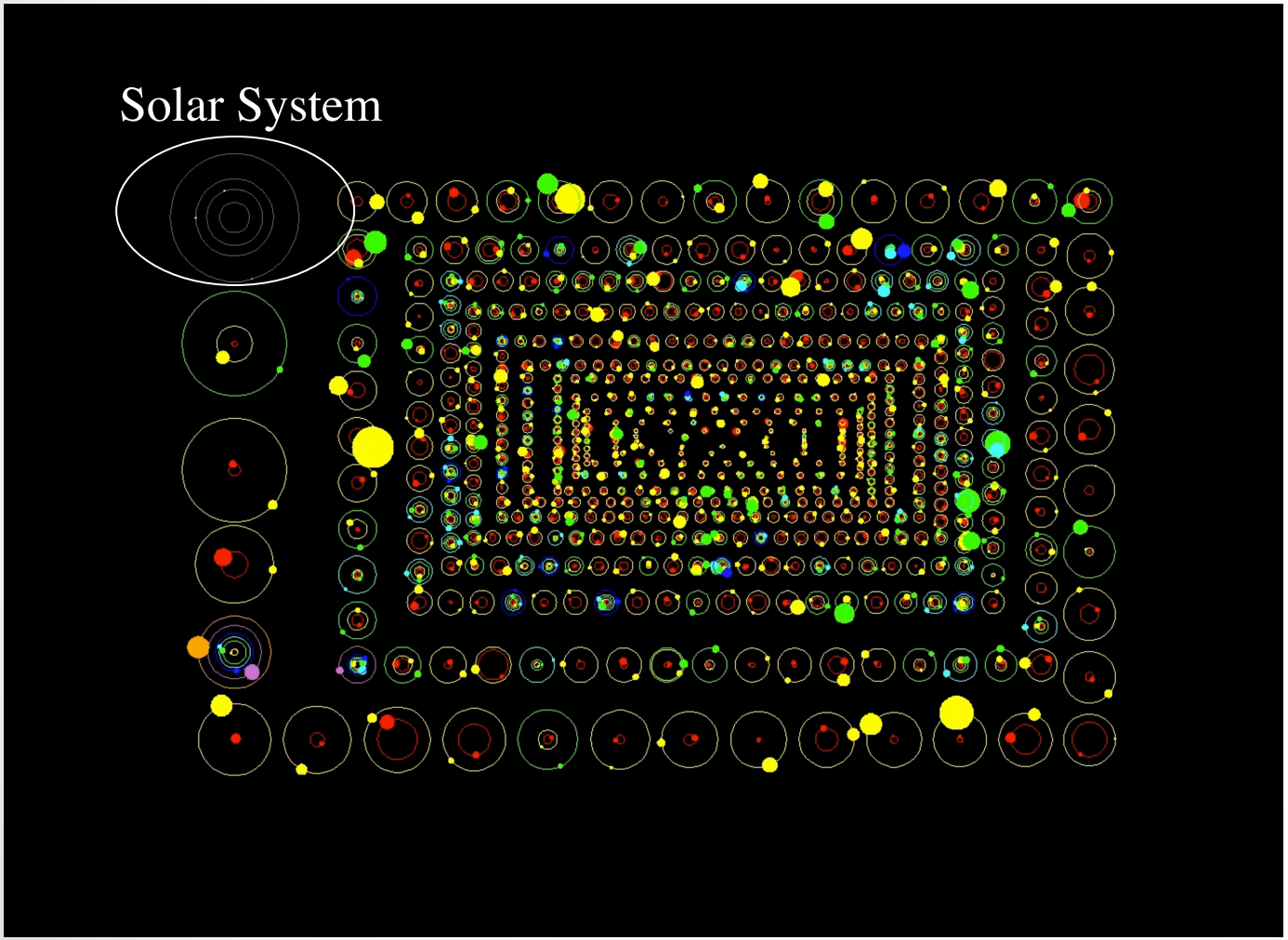
Demographics



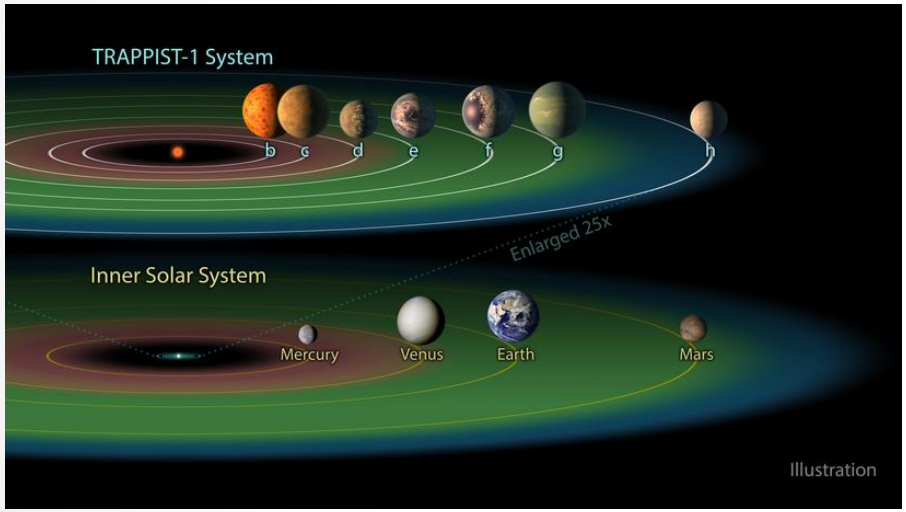


- 28 systems known with four planets
- 21 systems known with five planets
- 4 systems known with 6 planets
- Planets unexpectedly found in binary and triple star systems

What have we learned?



The Solar System is not typical

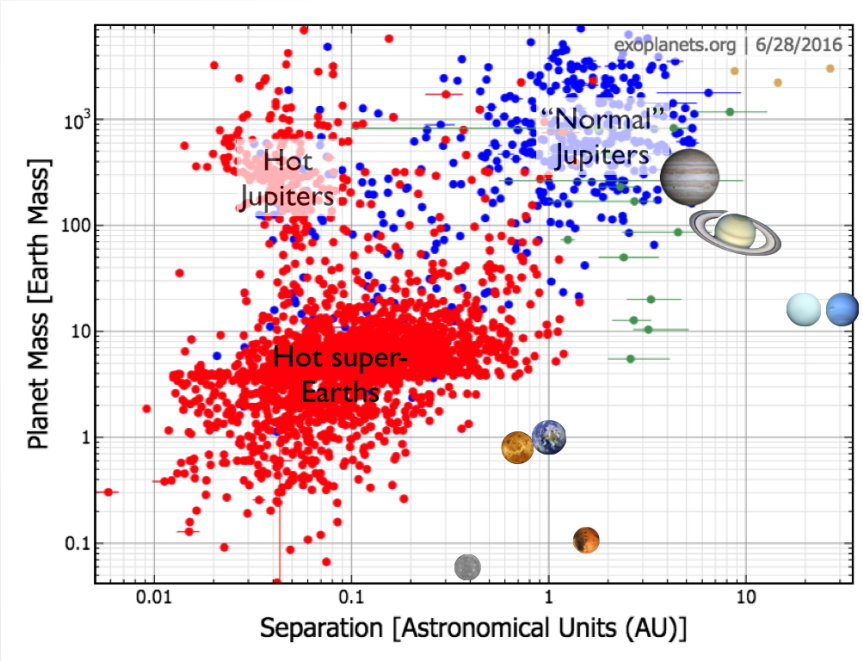


- Most multiple systems discovered to date are far more compact
- Don't forget the strong biases in the detection processes, but even modeling this, the Solar System stands out.

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

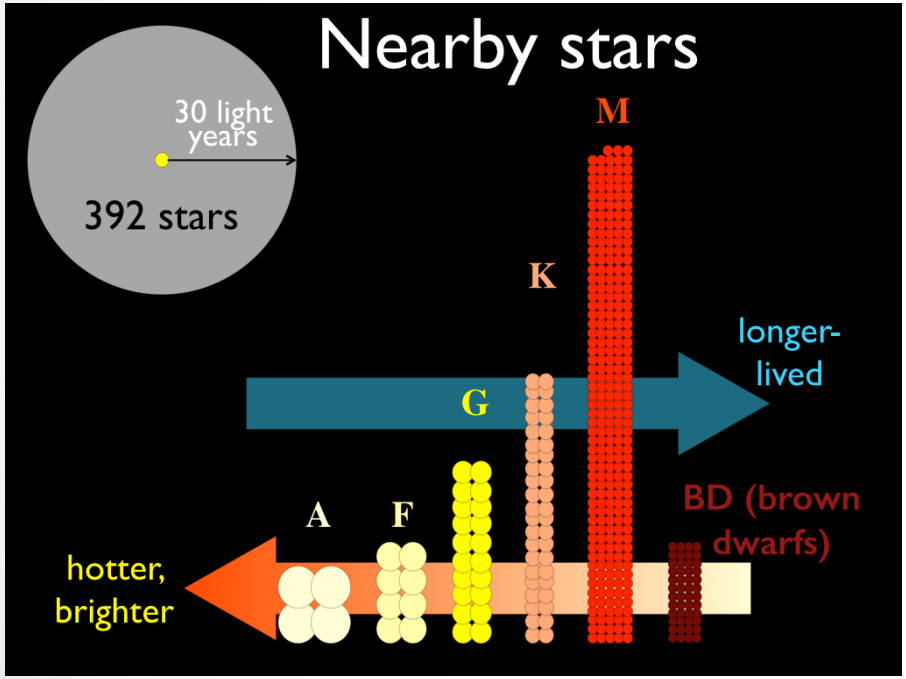
http://exoplanets.org

What have we learned?



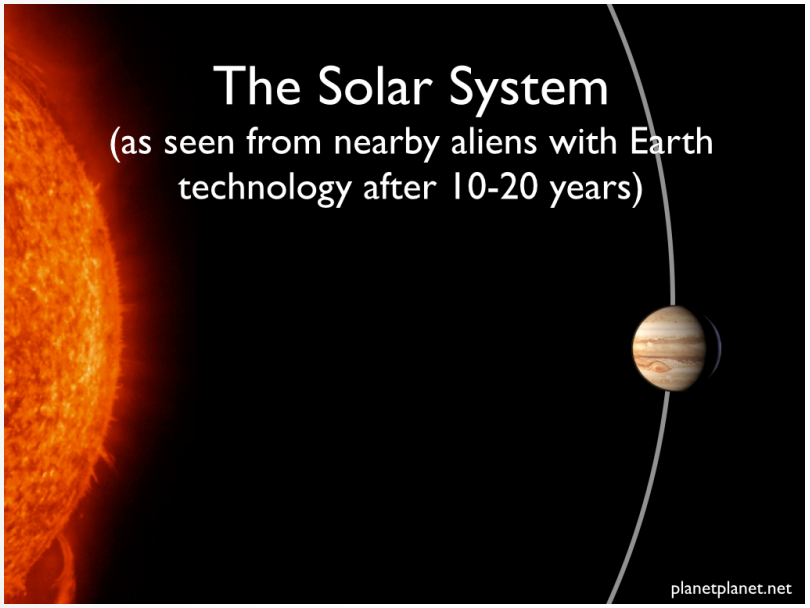
We also are missing the most common planet seen in the galaxy: "super-Earths" or "mini-Neptunes"

Why the differences?



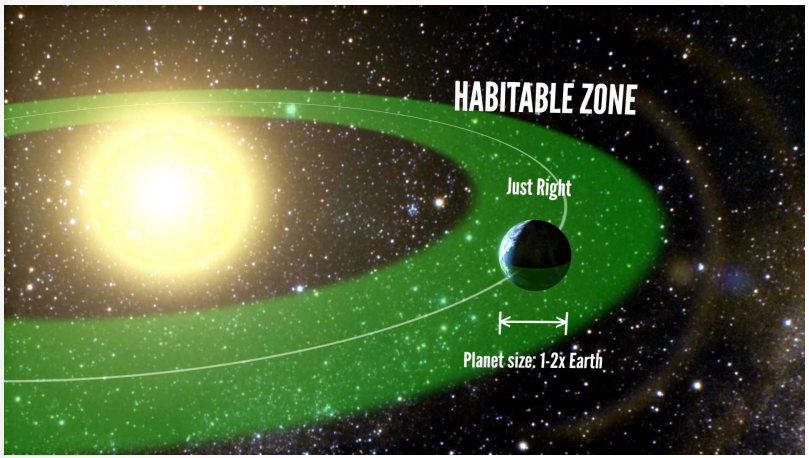
- We may need to account for differences in host stars better
- Evolution of planet systems may be stronger than we think
  - Early evolution may be strong and chaotic
  - Longer-term evolution may also be chaotic

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

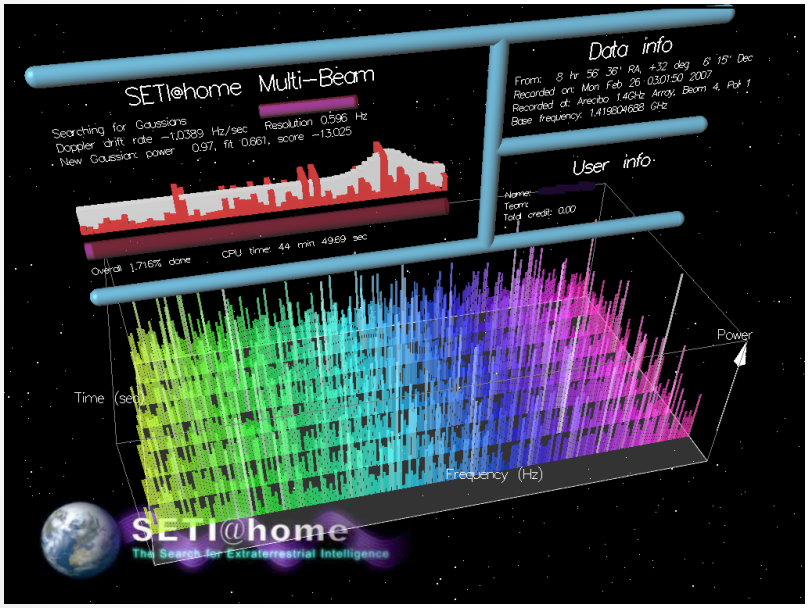


- The search for life off the Earth got serious in the 1960s
- This was 35 years before the first exoplanet was announced
- Concentration was on detecting leaked radio waves from an intelligent civilization

SETI

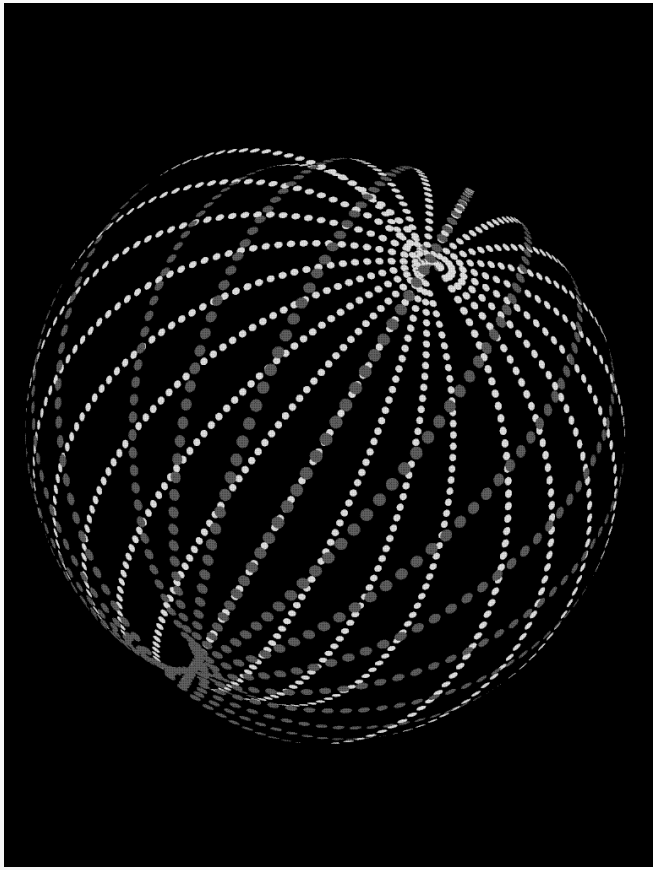
- Carl Sagan and Frank Drake were the leaders of the efforts
- The idea was to observe nearby stars over many radio bands and look for signals that could not be explained by natural sources
- Got NASA funding in the 1970s, canceled by Proxmire in 1995

SETI 2017



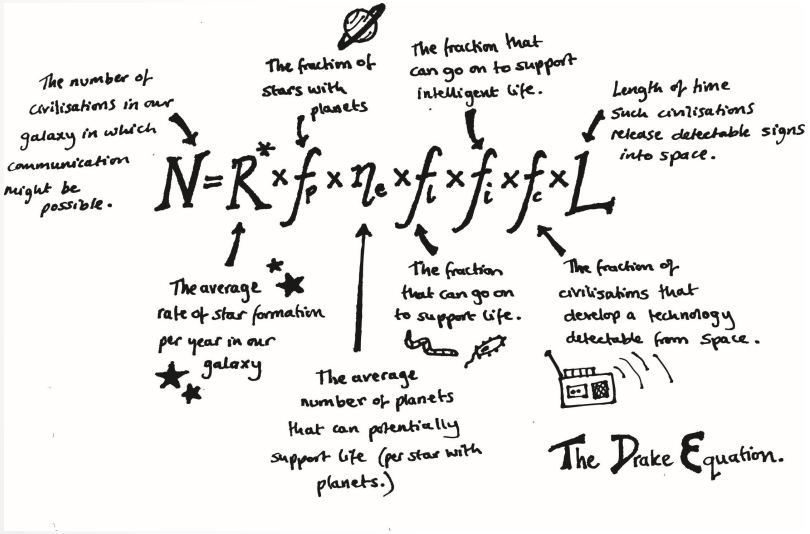
- With the discovery that the Galaxy is filled with planetary systems the interest in SETI was reignited
- Paul Allen, Franklin Antonio, Yuri Milner ($100M "Breakthrough Listen") donated millions of $ to support a burst of activity

SETI: other approaches



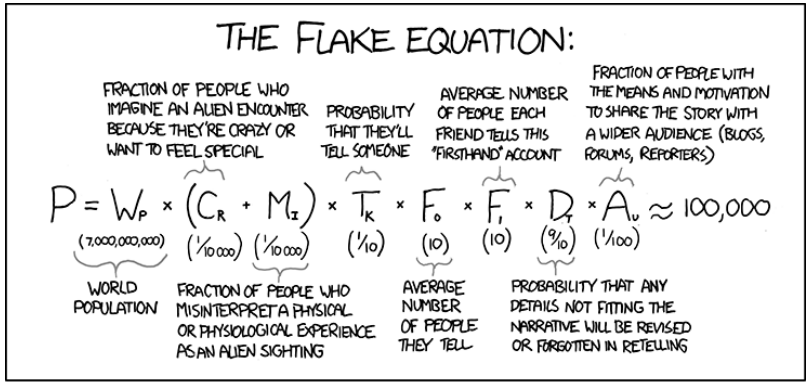
- There are a number of SETI offshoots searching for "technosignatures"
- Lasers (Optical SETI at Lick Observatory)
- City lights on the dark sides of known exoplanets
- Dyson Spheres

The Drake Equation



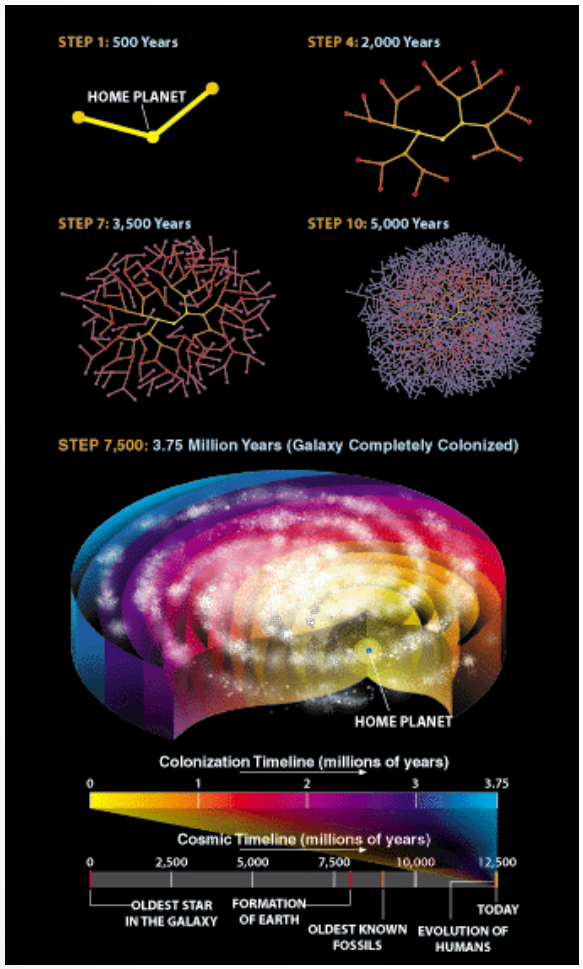
- Frank Drake first wrote down an equation that was intended to quantify the possibility of life based on several (poorly-known) factors
- As time has gone on the factors are becoming much better constrained

N = R* × fp × ne × fl × fi × fc × L



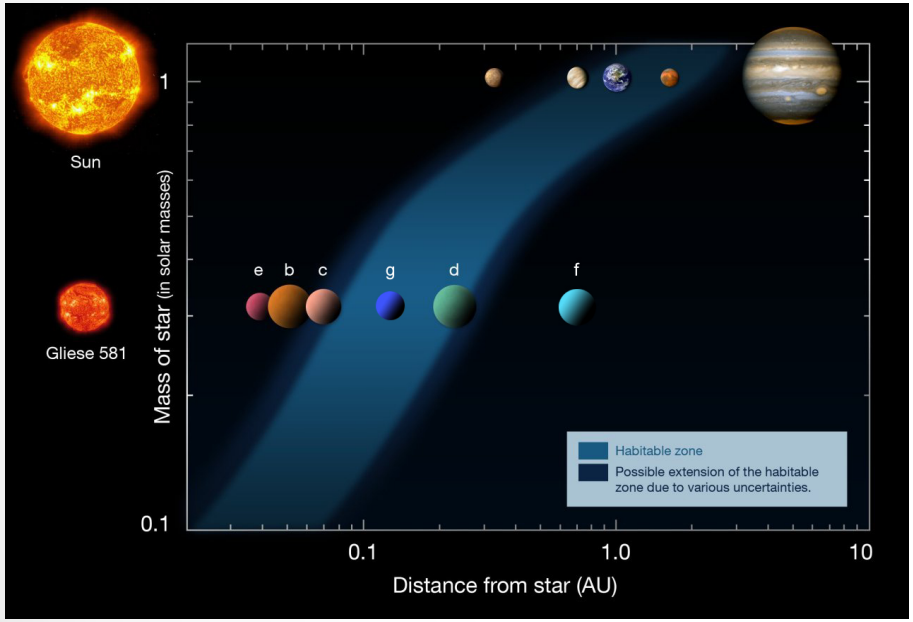
EVEN WITH CONSERVATIVE GUESSES FOR THE VALUES OF THE VARIABLES, THIS SUGGESTS THERE MUST BE A *HUGE* NUMBER OF CREDIBLE-SOUNDING ALIEN SIGHTINGS OUT THERE, AVAILABLE TO ANYONE WHO WANTS TO BELIEVE!

Fermi's Paradox



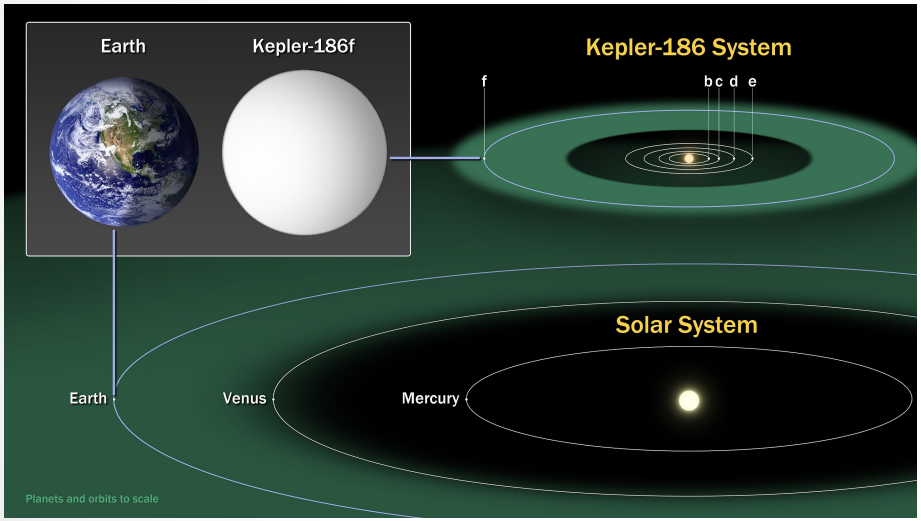
Fermi was a prominent physicist from the first half of the 1900s who considered the rapid advance of human technologies over only a few hundred years, the vastness of the Galaxy and asked "why have we not been visited by an advanced civilization?"

Biosignatures, Habitability and Exoplanets



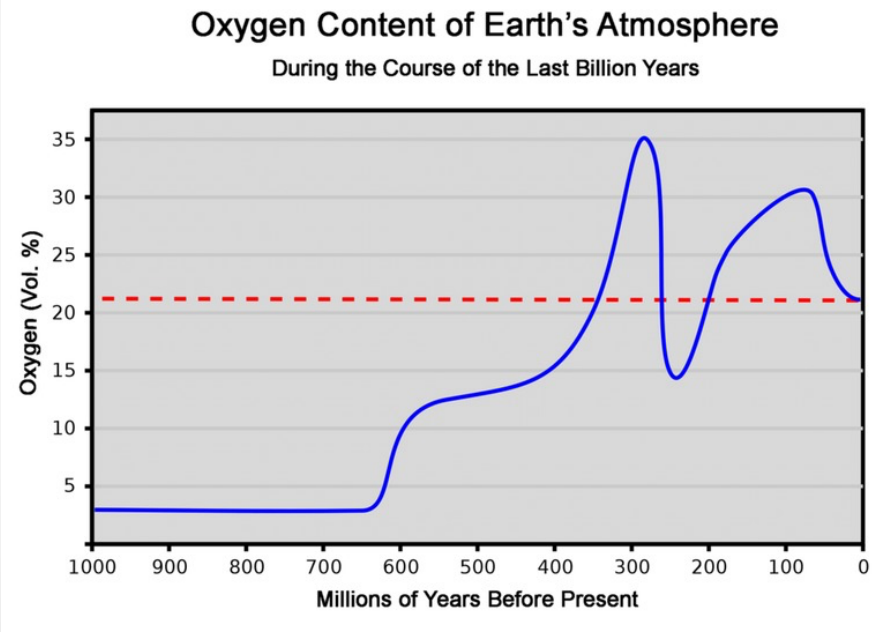
- Originally the "habitable zone" was the orbits around a star where water could exist in liquid form
- Further from hotter stars, closer to cooler stars
- Concept extended to other solvents and to include properties of specific stars like element abundances

Habitable Zone



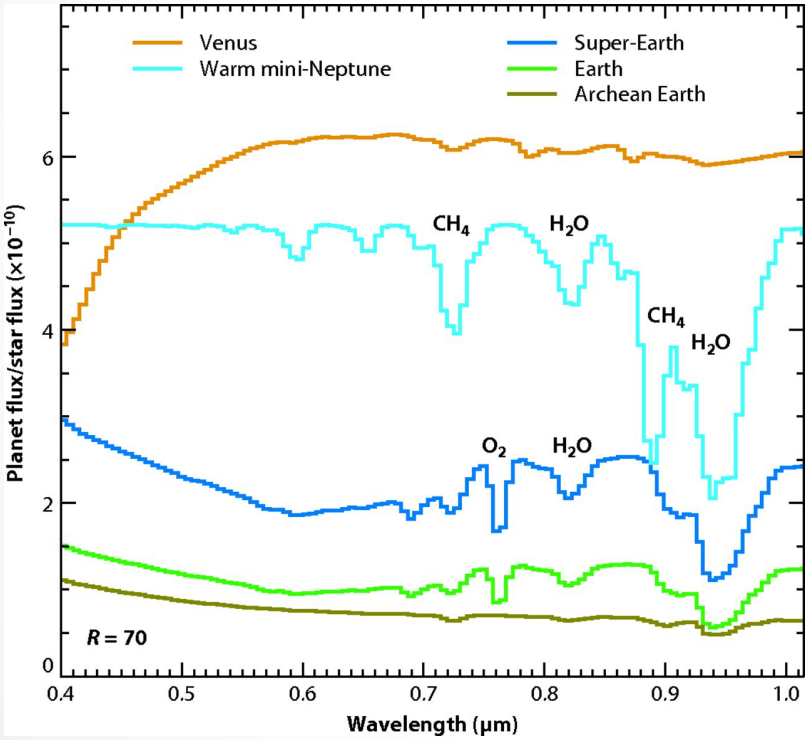
- First exoplanets in the habitable zone were discovered in 1996 and were gas giants
- With Kepler, we now have many super-Earths in the HZ and the first Earth-like planets iin the HZ of other stars

Biosignatures



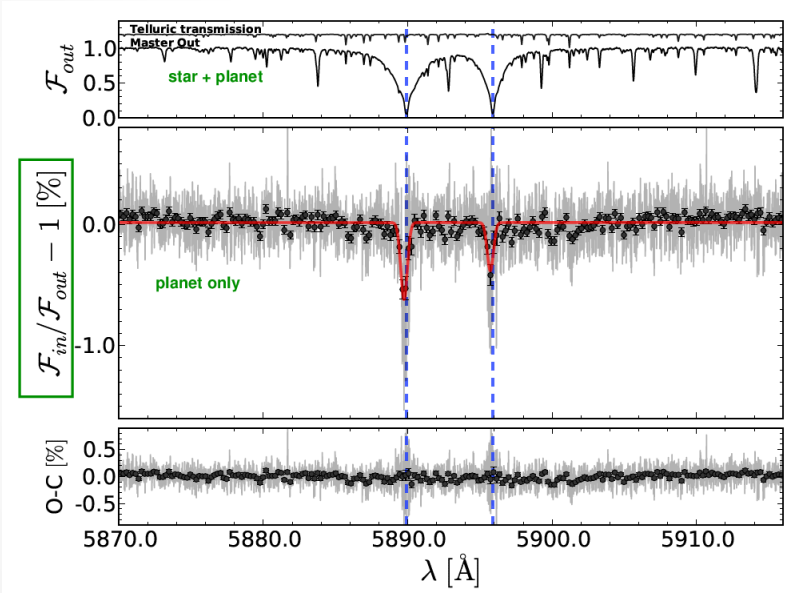
- With the HZ planets we now have targets to look for any kinds of life signs (not only intelligent life: think about Earth history)
- Looking for signatures in the spectra of exoplanets of chemistry that indicates life

Biomarkers



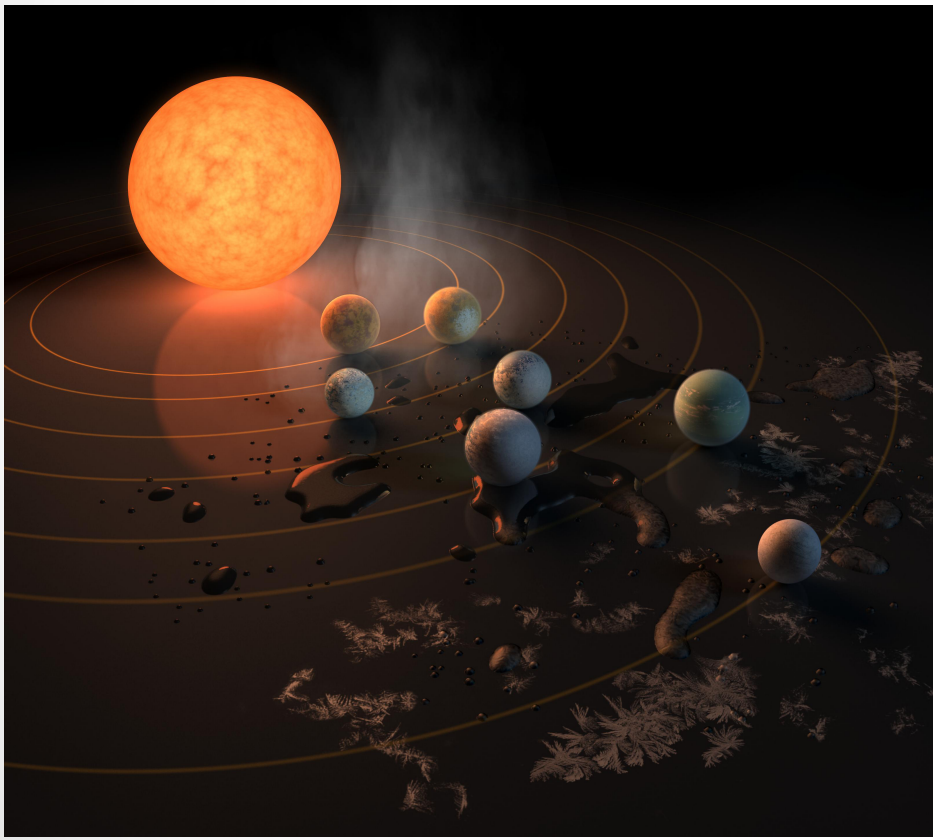
- Oxygen and oxygen-based molecules is a key biomarker
- The "red edge" of absorption due to chlorophyll would be for exoplanets with significant areas of plants
- Methane in the presence of oxygen probably requires bacteria (methanogens)

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