Jet Propulsion Laboratory
California Institute of Technology

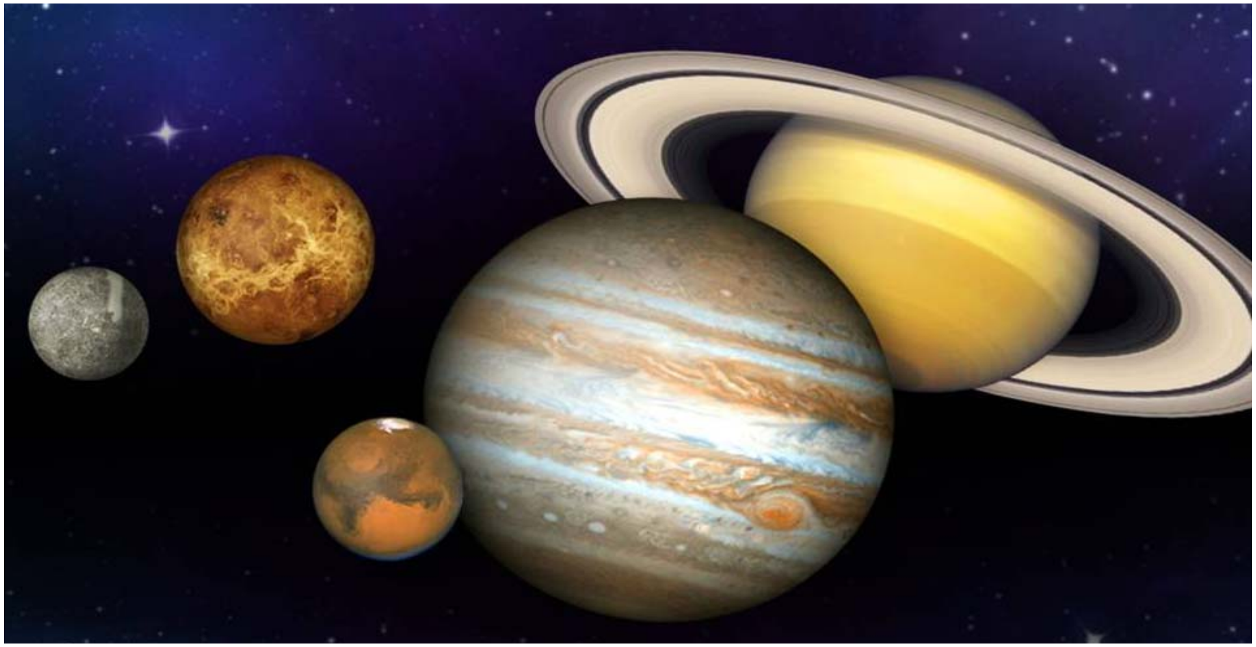
Exoplanets

Wes Traub

KISS Workshop on Planetary Magnetic Fields

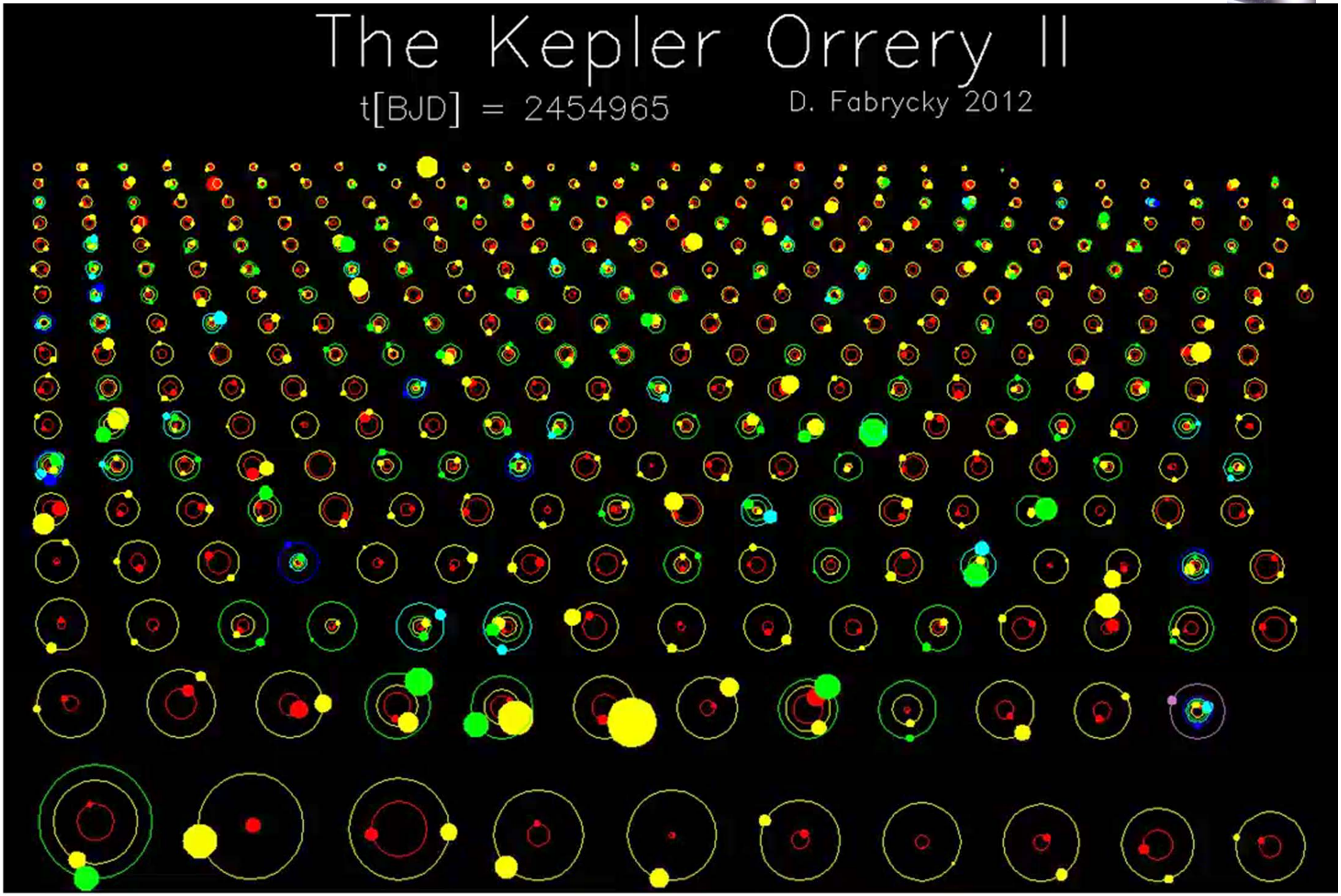
12-16 August 2013, Caltech

Before the 1990s: 9 Planets (-1!)



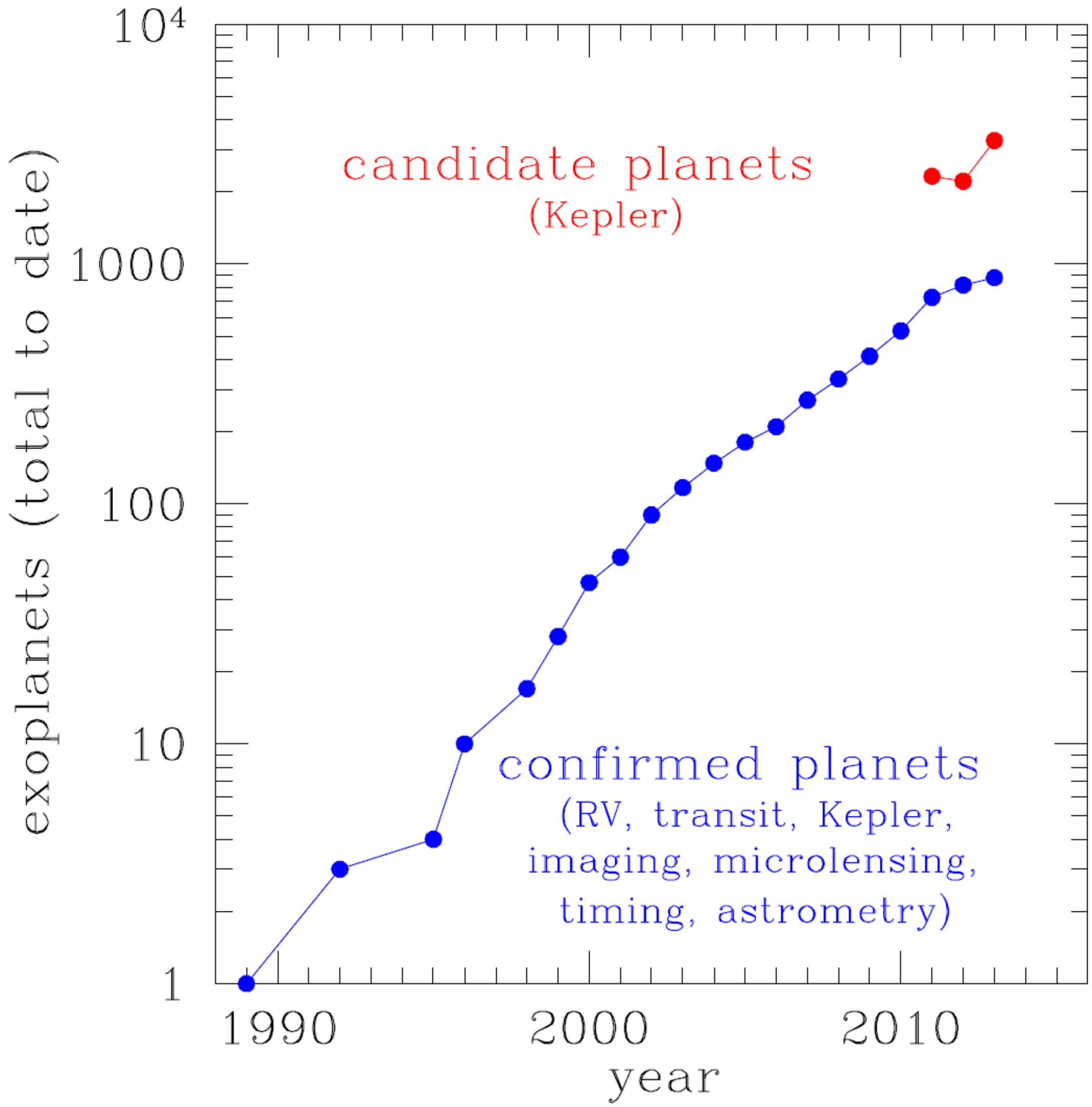
Mercury, Venus, Earth, Mars
Jupiter, Saturn
Uranus, Neptune
(Pluto)

After the 1990s: 882 + 3548 exoplanets



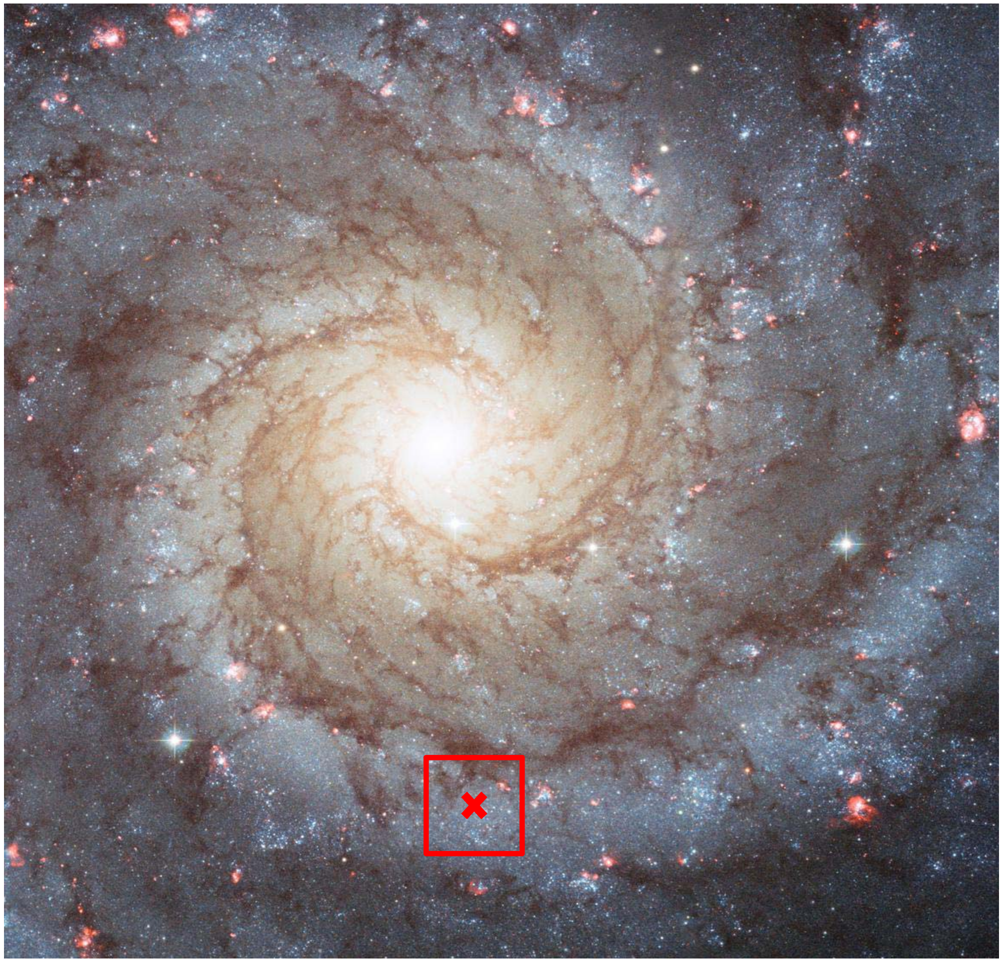
Total # exoplanets, confirmed & candidates

ExoPlanet Exploration Program



Ref.: data from http://exoplanetarchive.ipac.caltech.edu/docs/counts_detail.html and http://exoplanet.eu/

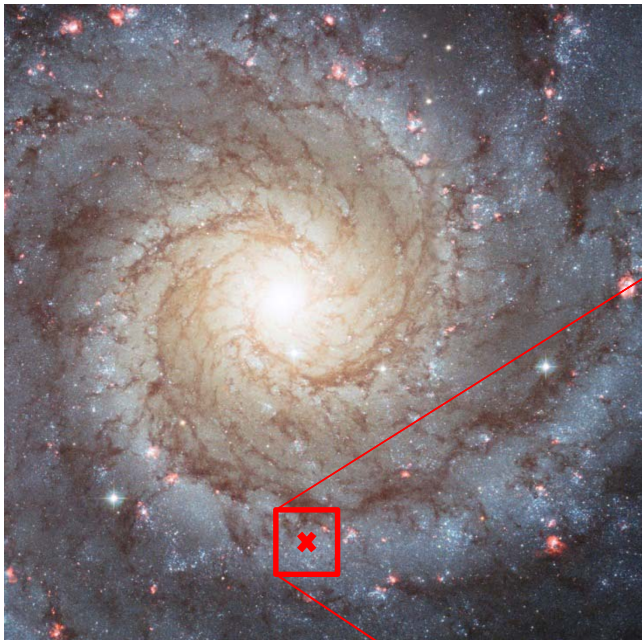
Where are these exoplanets?

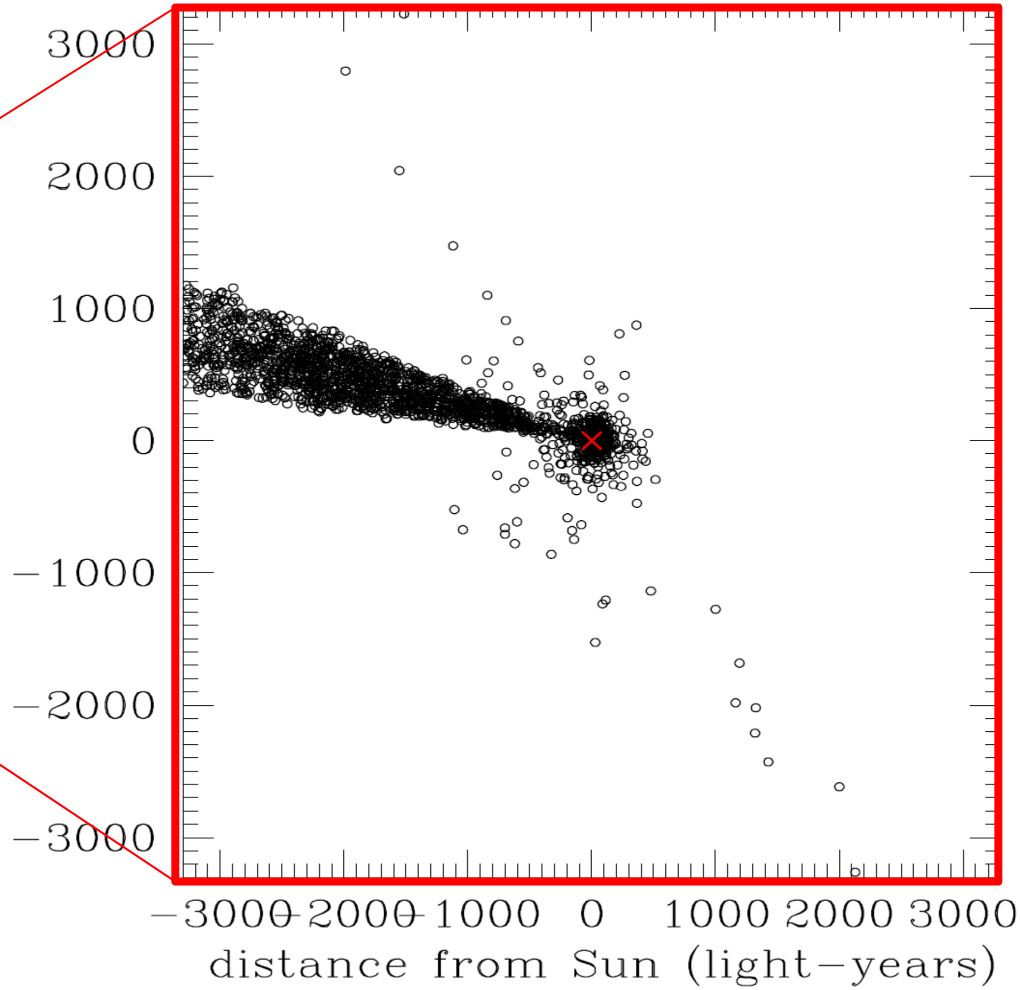


We are at the X in our Milky Way galaxy.

Photo: Hubble Space Telescope image of M74, a grand-design spiral galaxy like our own.

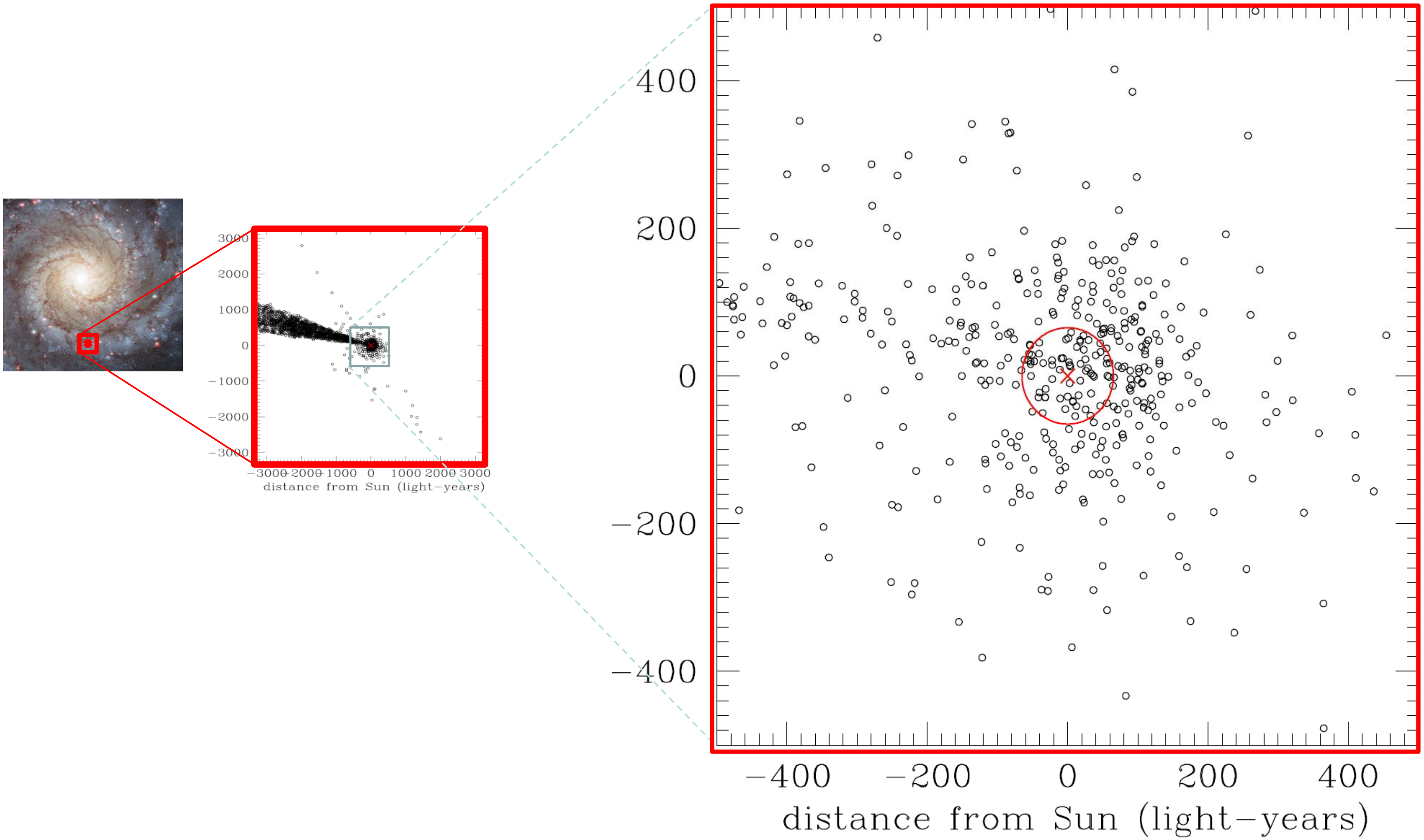
Most known exoplanets are from Kepler





Other “spokes” are from ESA’s Corot.
Local “cloud” of points from ground-based telescopes.

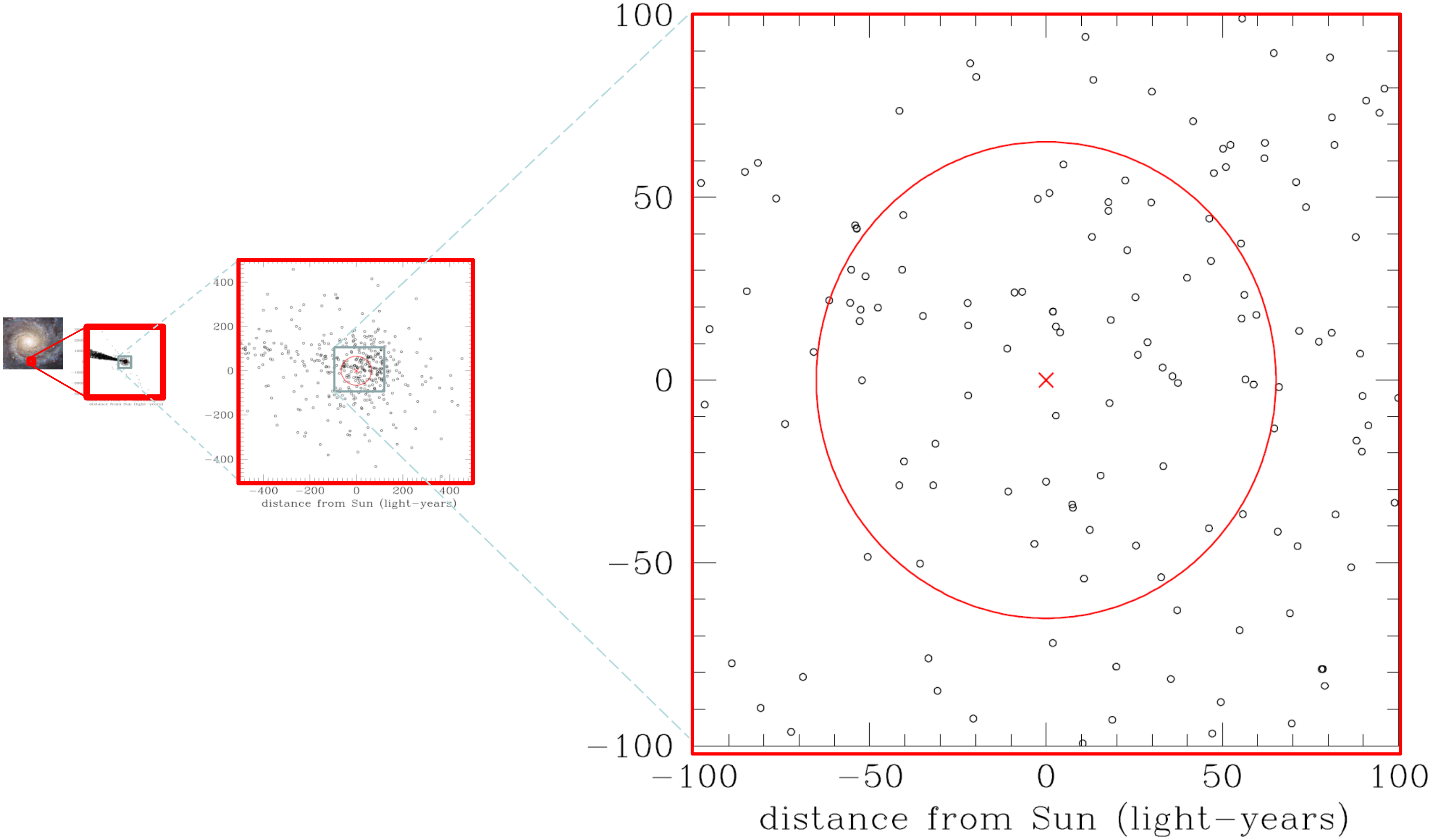
A closer look …



Red circle is the nearest 65 light years, about the limit of direct imaging of

And even closer …

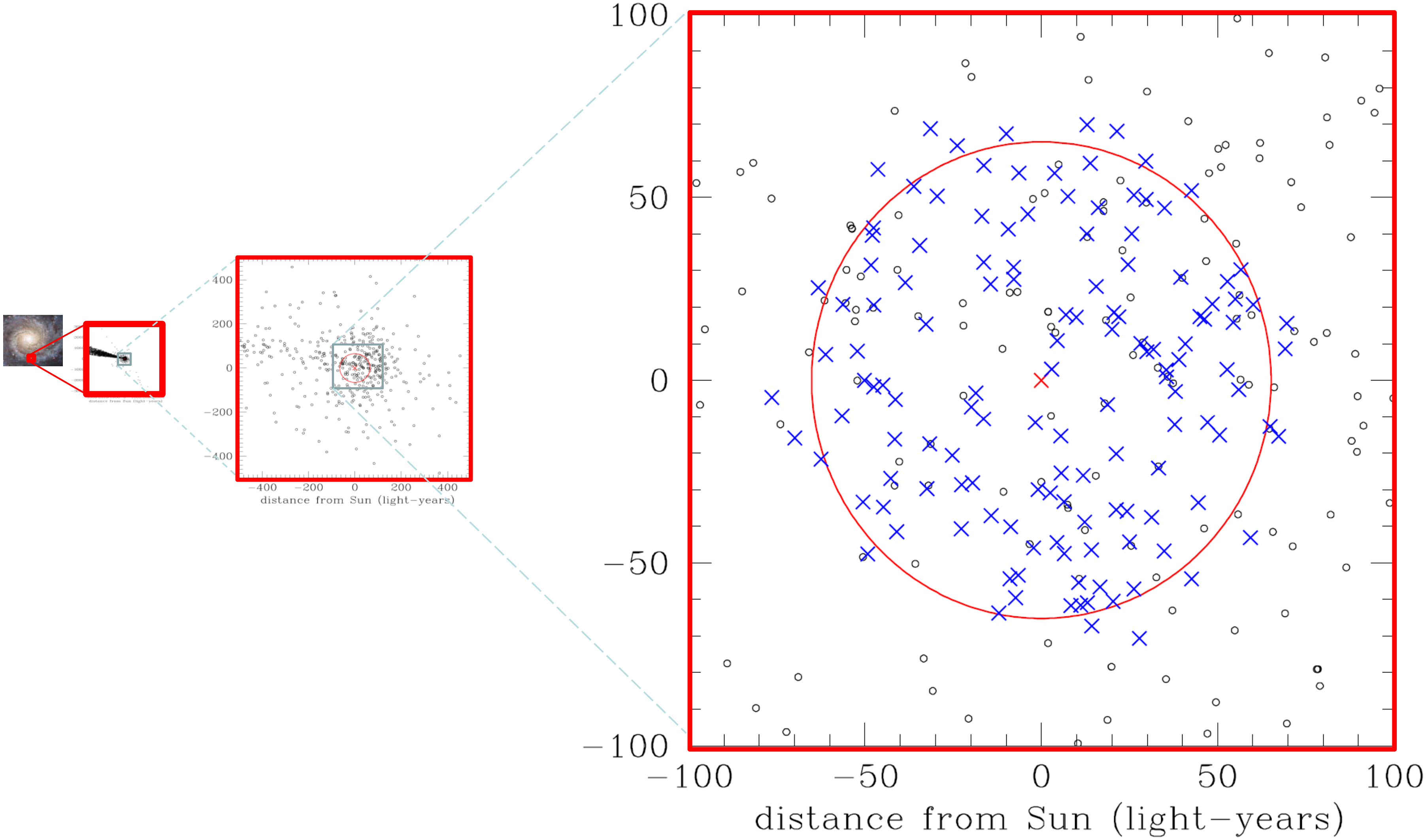
ExoPlanet Exploration Program



Each dot is a star with 1-4 known exoplanets around it.

And now add the AFTA target stars …

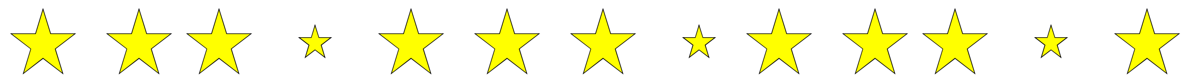
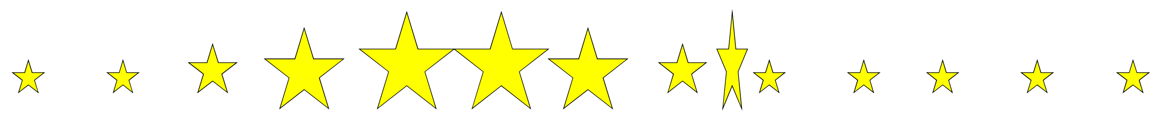
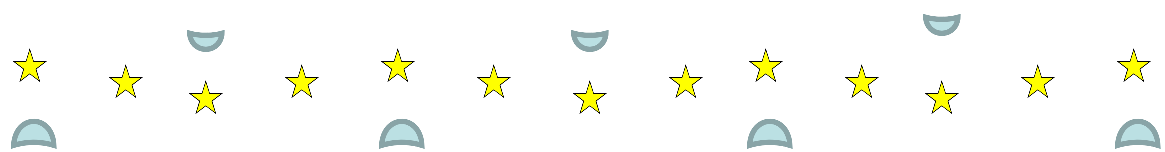
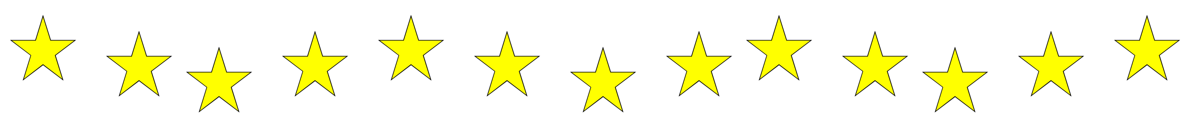
ExoPlanet Exploration Program



Each X is a prime target star for searching for "Earth-like" planets, out to 65 light years.

So there are many nearby stars where we can search for "Earth-like" exoplanets!

5 Ways to Find & Characterize Exoplanets

- Radial velocity 
- Transits 
- Microlensing 
- Imaging 
- Astrometry 

Exoplanet Science News

ExEP

ExoPlanet Exploration Program

Exoplanet Scorecard, as of July 21, 2013

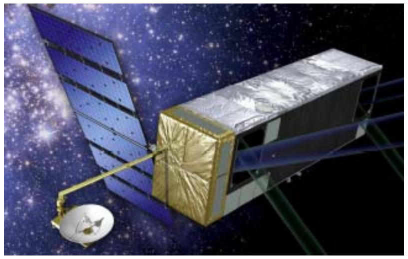
Detection Method	No. of exoplanets
Astrometry	2
Imaging	27
Radial velocity	535
Transit	286
Transit or eclipse timing	8
Gravitational microlensing	18
Pulsar timing	5
Total Confirmed	881
Kepler candidates	3278
Total Confirmed plus Candidates	**4159**

Ref.: http://exoplanetarchive.ipac.caltech.edu/docs/counts_detail.html

Direct images of exoplanets

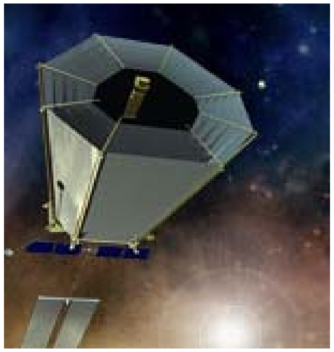
A "direct image" would show an Earth-like exoplanet as a faint blob close to its ten-billion times brighter parent star.

Using a spectroscope on the faint blob, we could analyze its colors, to discover water vapor, oxygen, carbon dioxide, methane, clouds, continents, length of day, average temperature, and search for signs of life. *And magnetic fields??*



Planned but not built:

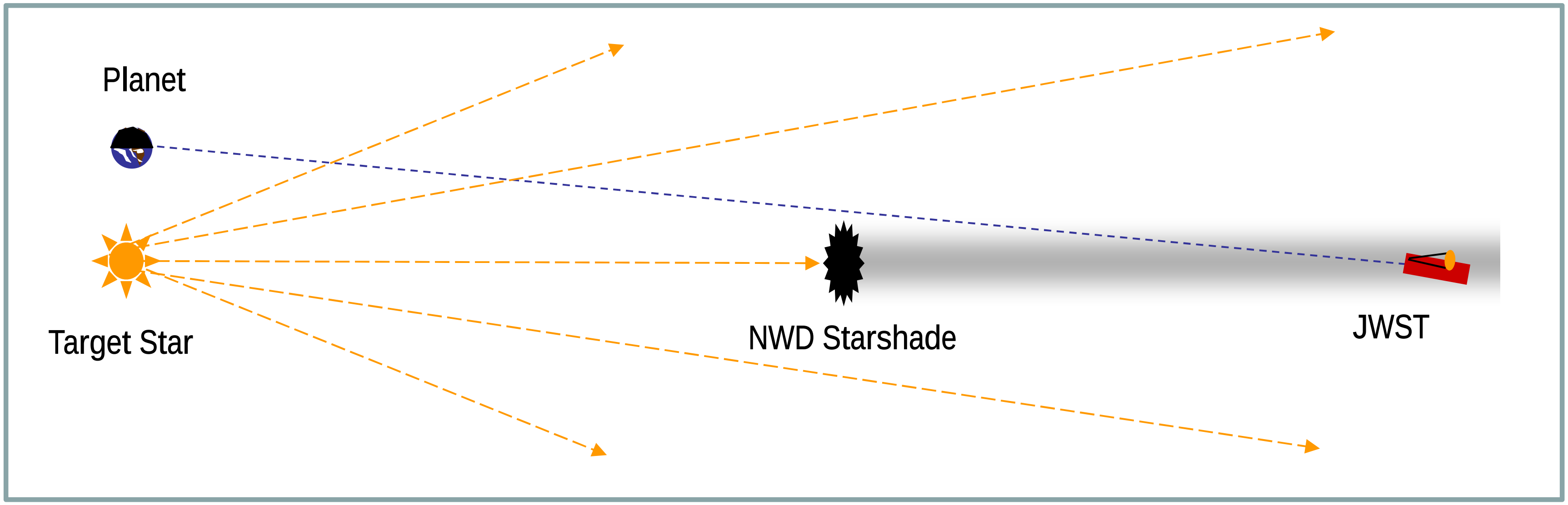
The Space Interferometer Mission (SIM) was recommended by 2 Decadal Surveys to find planets around nearby stars (1990 & 2000), but dropped by the most recent Decadal Survey (2010).

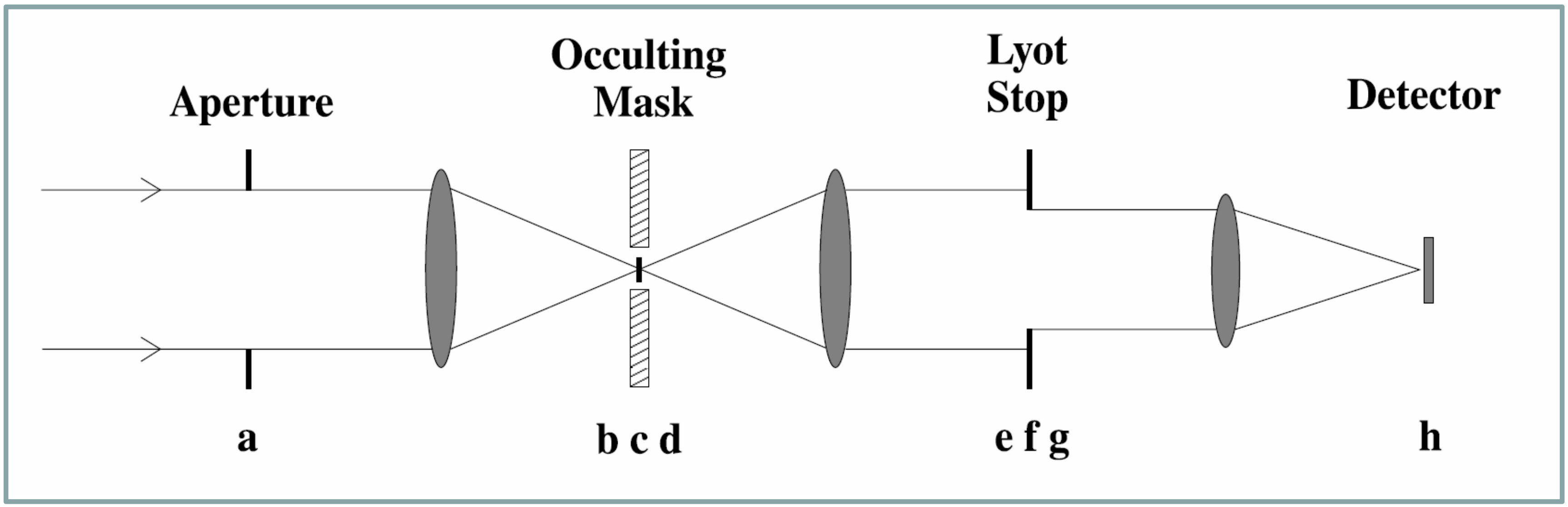


The Terrestrial Planet Finder Coronagraph (TPF-C) was chosen by NASA to directly image exoplanets, using visible light (2002), but postponed by Congress (2007).

The Terrestrial Planet Finder Interferometer (TPF-I) was also chosen by NASA to directly image exoplanets, using infrared light (2000), also postponed by Congress (2007).

External and Internal Coronagraphs



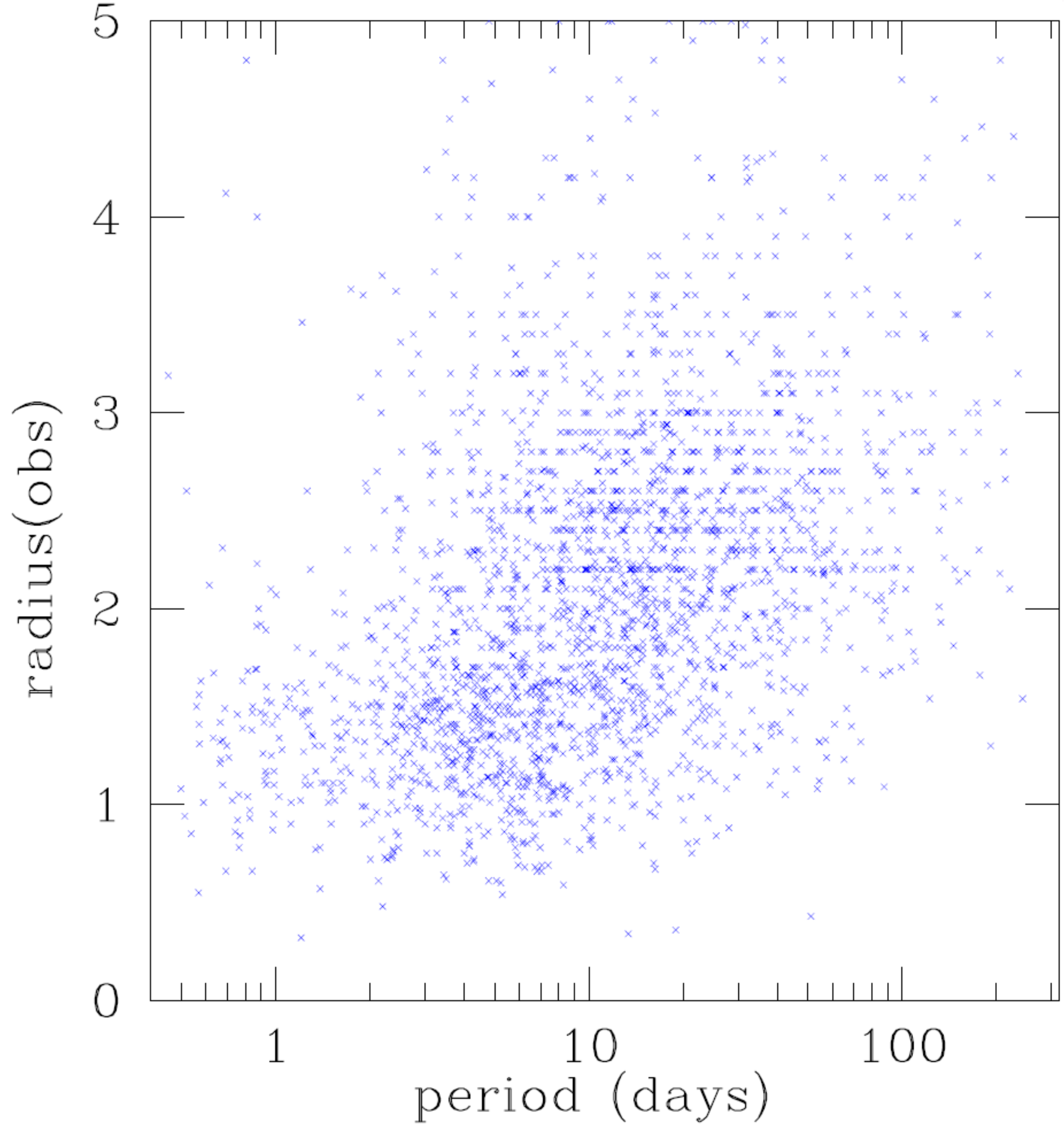


Current plans for exoplanets

- Kepler completed its mission, found 138 planets, & 3548 candidates
- Ground-based and space-based telescopes will find more planets, and give hints about what some of them are like (temperature, composition, etc)
- TESS will search for transits
- WFIRST/AFTA has gravitational microlensing for exoplanets, plus a coronagraph for direct imaging of exoplanets & disks, with a new start in late 2016, launch in 2024

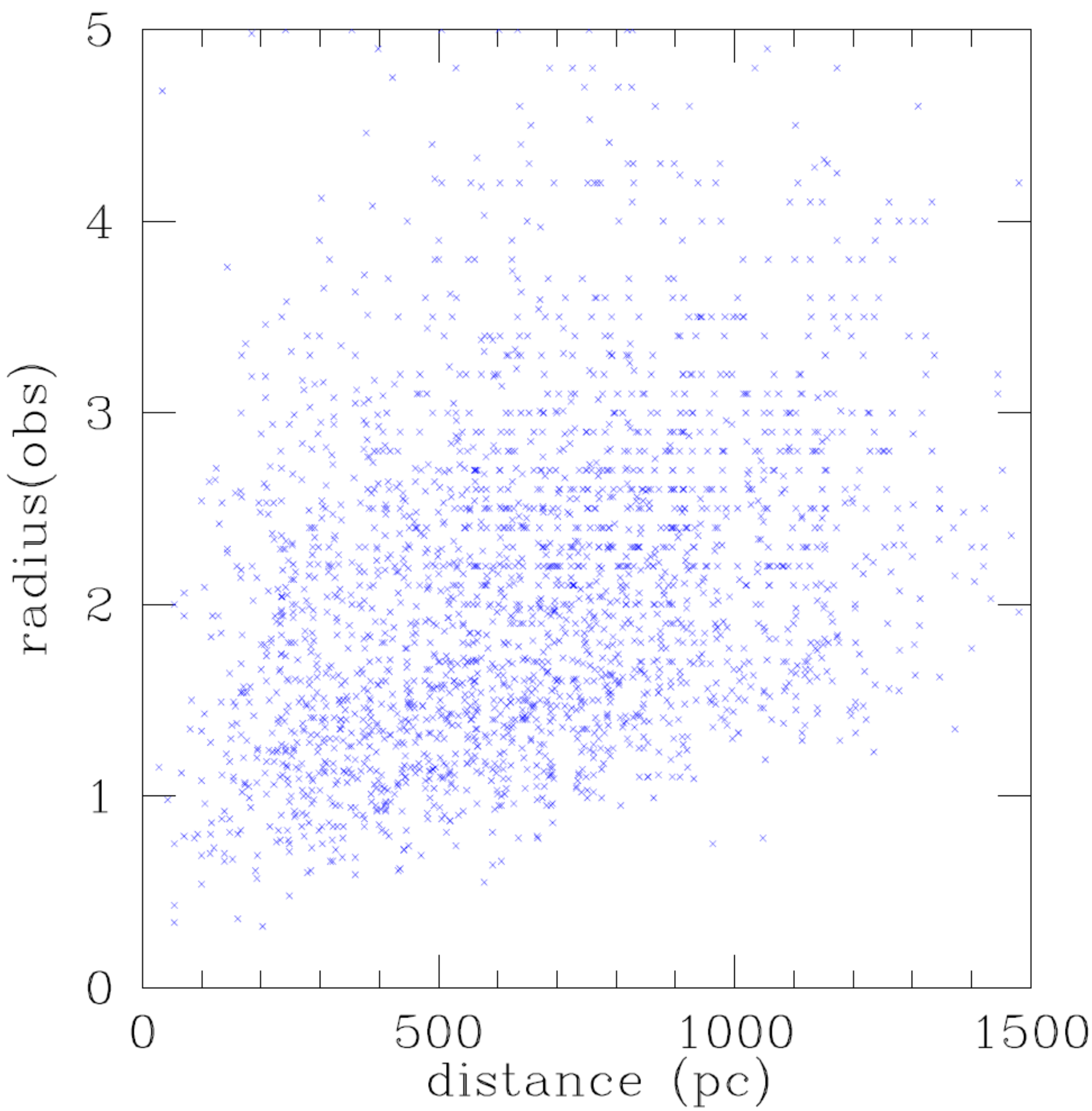
Radius vs Period (Kepler)

ExoPlanet Exploration Program



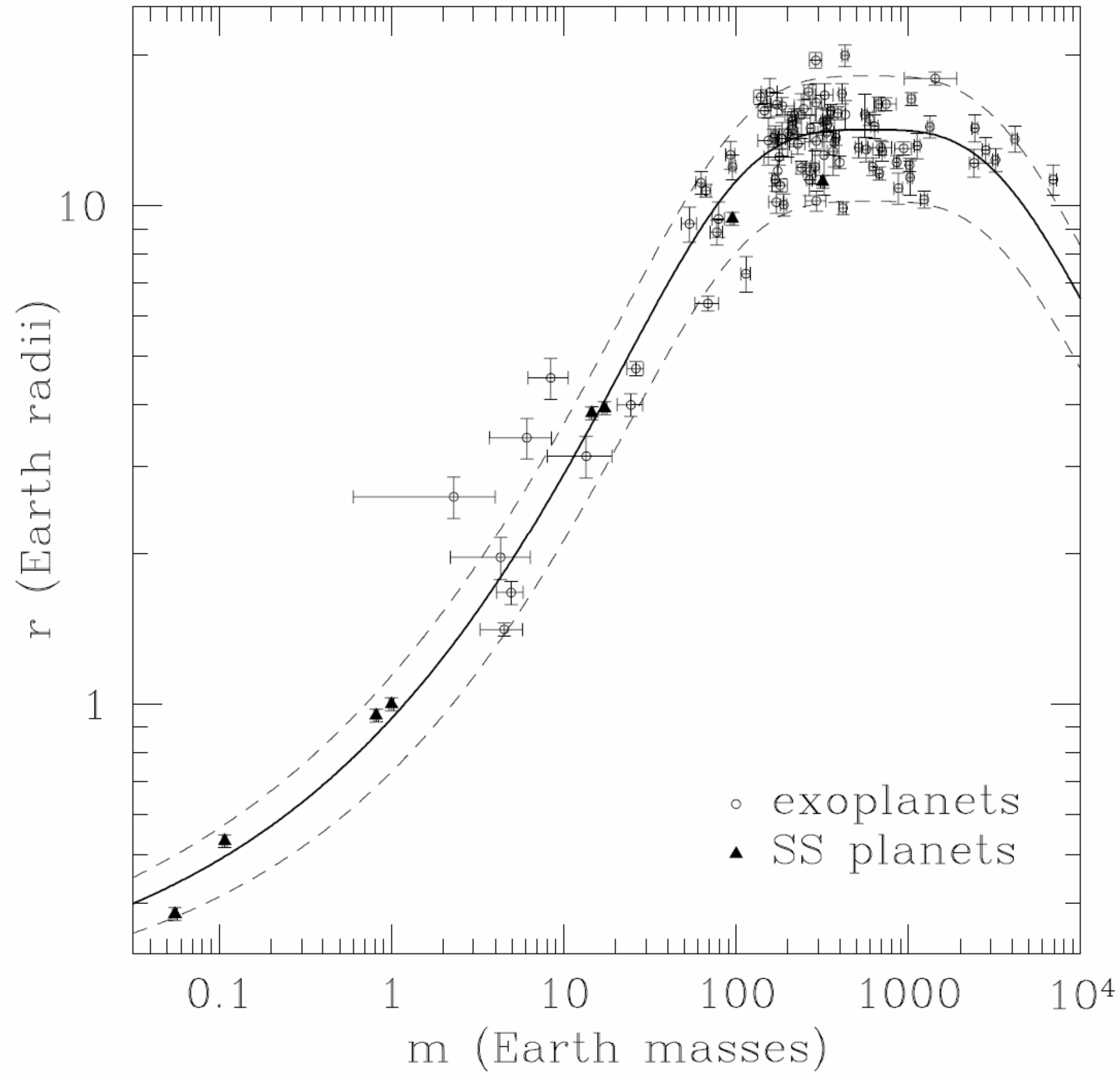
Radius vs Distance (Kepler)

ExoPlanet Exploration Program



All measured planet masses & radii

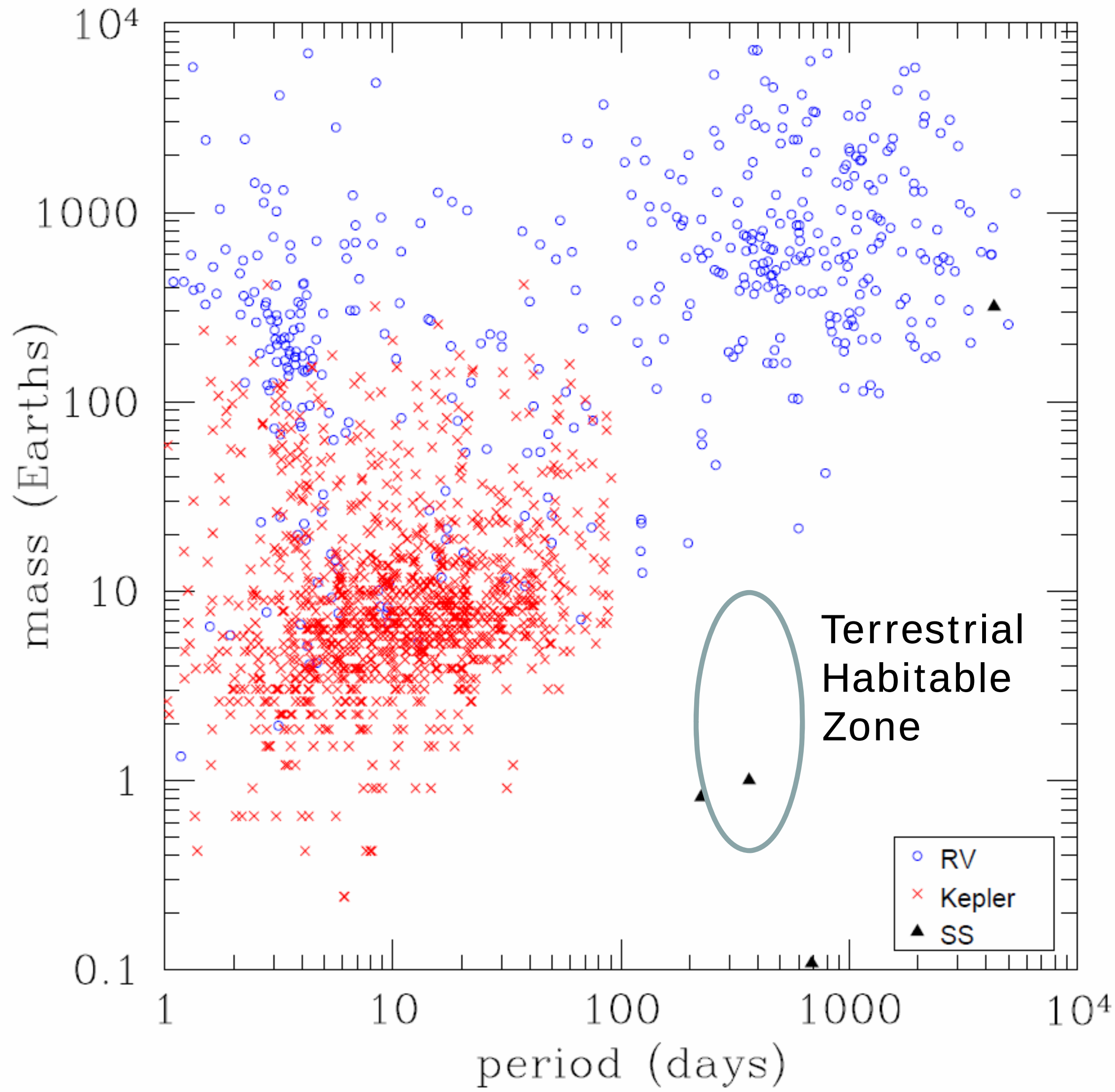
ExoPlanet Exploration Program



Smooth curve is a best fit to all data.
Curve can be used to convert Kepler's radii to Kepler masses.

All exoplanet Msin(i) and M(Kepler, est.) masses vs orbital period

ExoPlanet Exploration Program



AFTA modified to show Earths & strong zodi/EKB

ExoPlanet Exploration Program

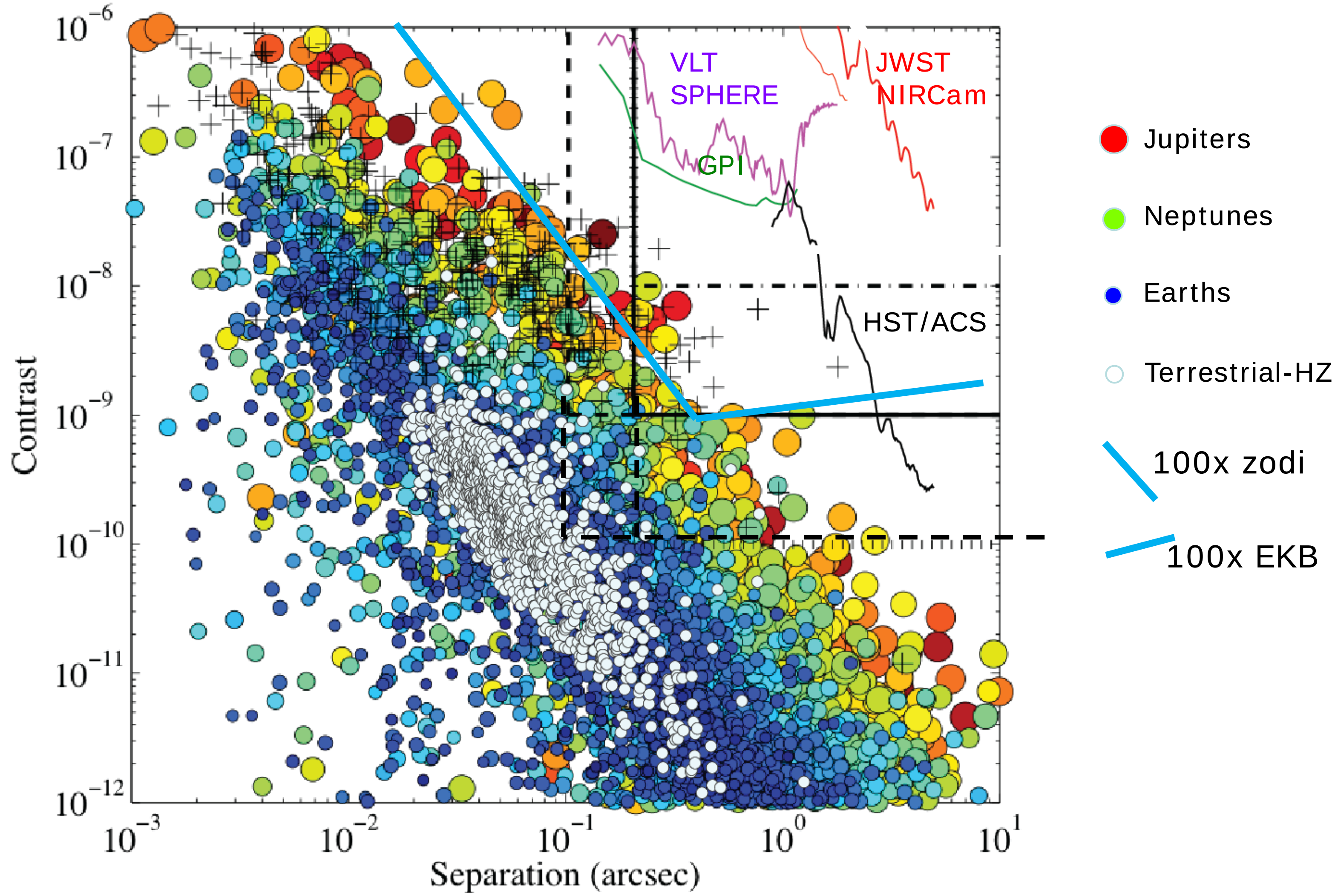


Fig. from AFTA Final Report 2013, for 2.4-m, modified by Traub & Lawson

New Ground-based Exoplanet Instruments 2013-2020

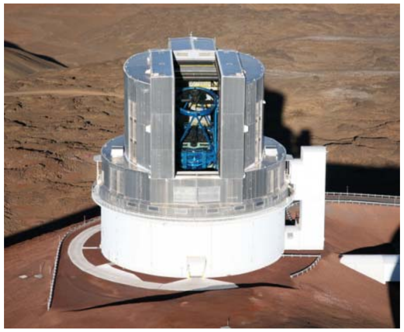
Extreme AO on 8–10-m class telescopes

Palomar P1640

Gemini Planet Imager

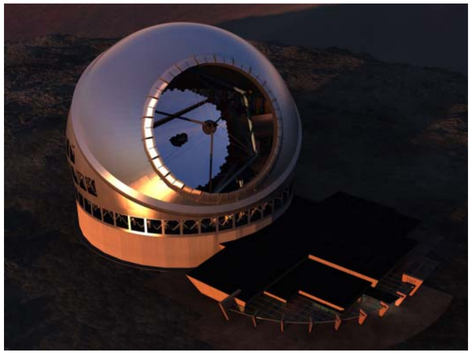
ESO VLT-SPHERE

Subaru SCExAO

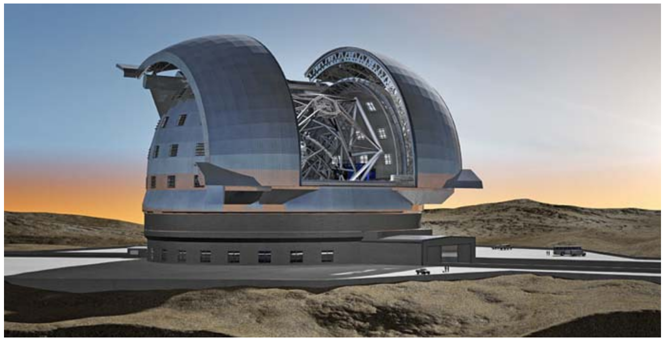


Extreme AO on Extremely Large Telescopes (30–42m diameter)

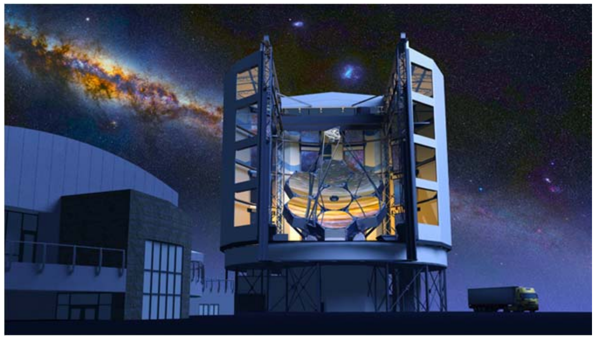
Thirty Meter Telescope



European Extremely Large Telescope

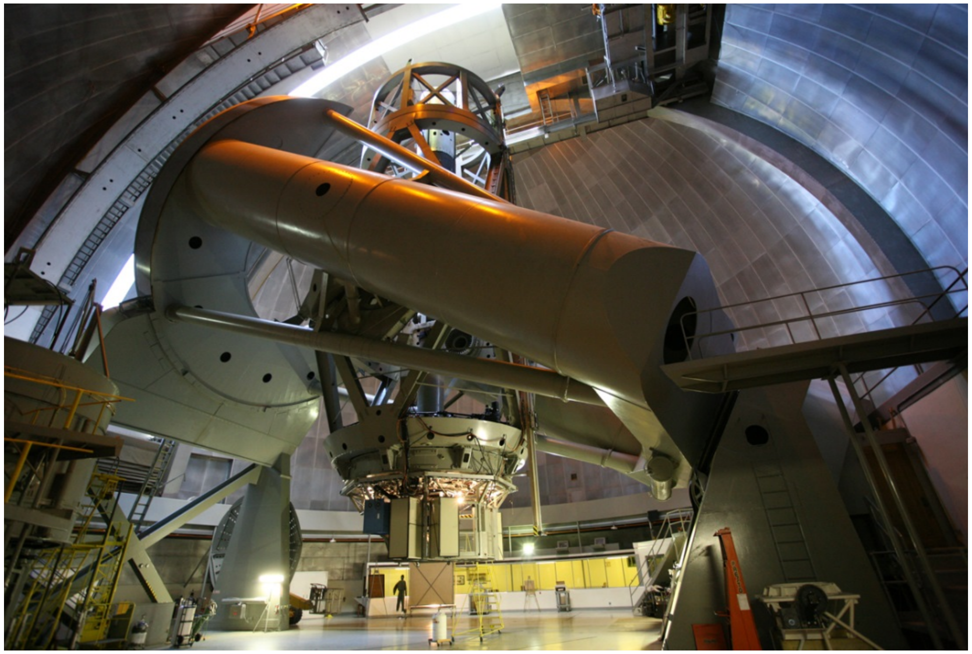


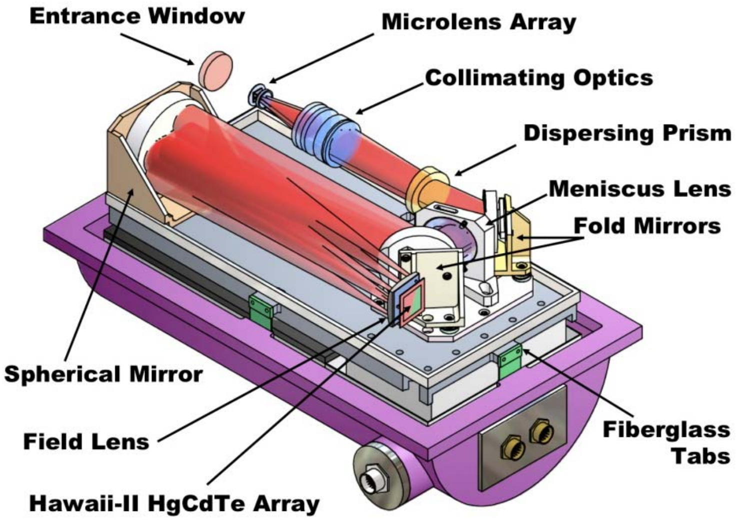
Giant Magellan Telescope

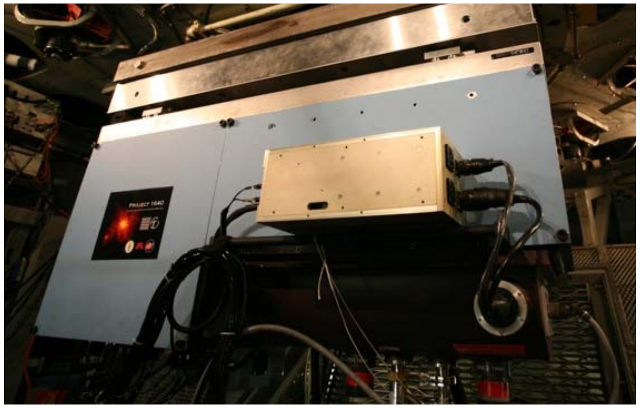


Palomar P1640

ExoPlanet Exploration Program



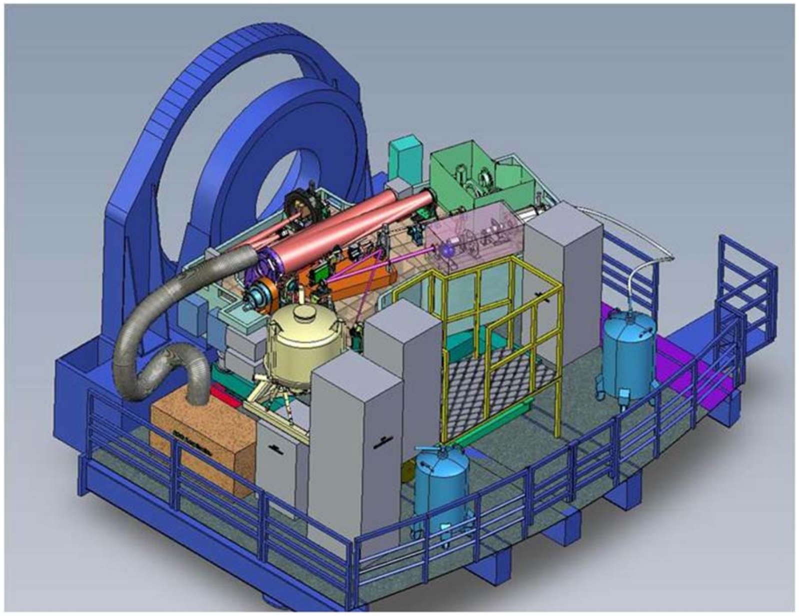


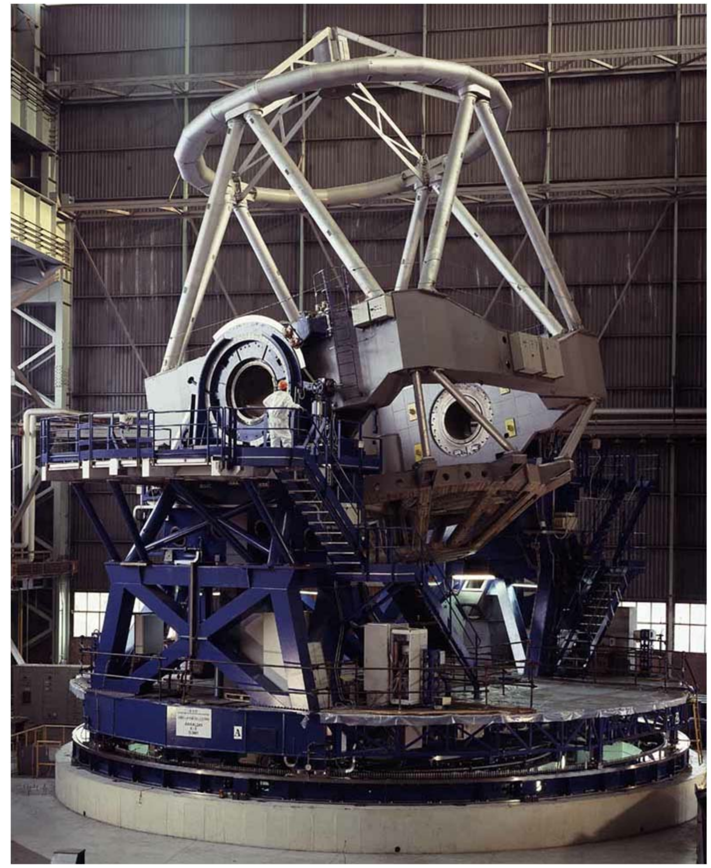


- Northern Hemisphere; Now operational.
- 5-m telescope; 3388 actuator-DM
- Calibration interferometer
- Mounted at Cassegrain focus
- IFS (1.05–1.75 microns), APLC.

Images courtesy of Ben Oppenheimer (AMNH)

Very large Telescope: SPHERE





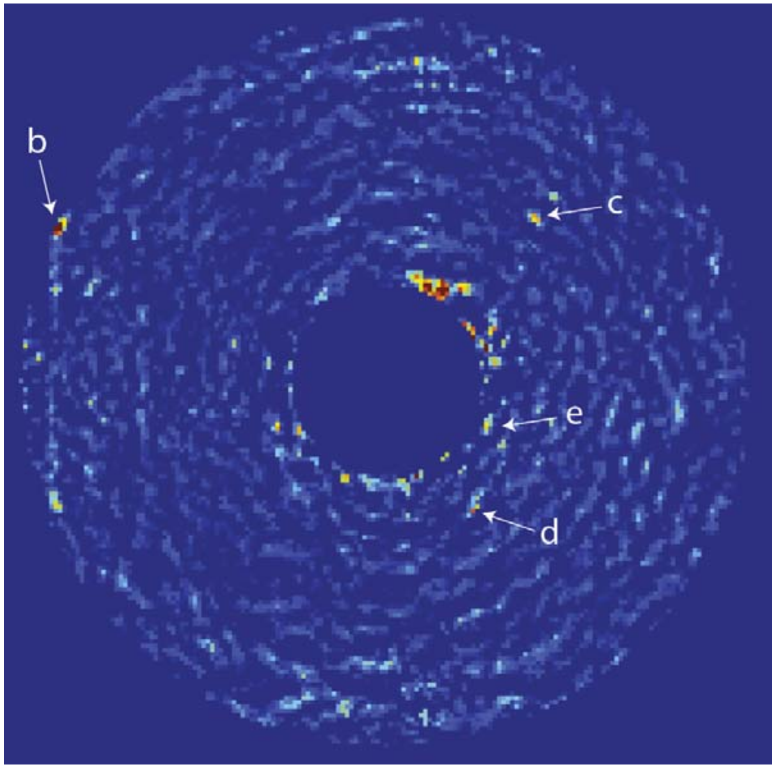
- Southern Hemisphere, 8-m telescope
- Large optics minimize Talbot effects
- No calibration interferometer
- Mounted on Nasmyth platform; 41 x 41 actuator extreme AO
- Three instruments: ZIMPOL (500–900 nm), simultaneous: IRDIS, IFS (0.95–1.6 µm).

Images courtesy of European Southern Observatory

4 Exoplanet Spectra in One Shot

ExoPlanet Exploration Program

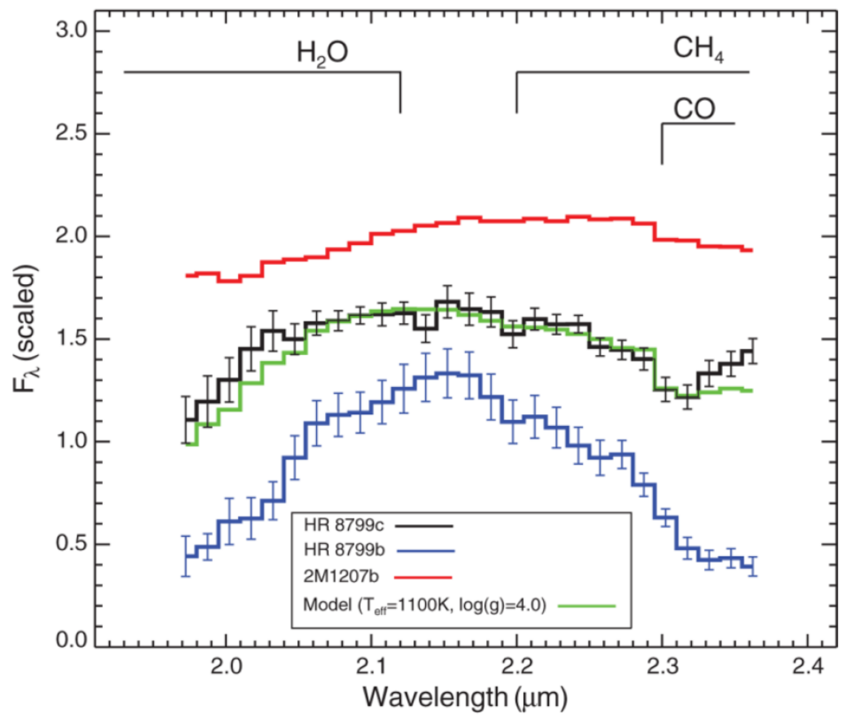
- A decade of effort pays off: Ben Oppenheimer & team report first spectra of 4 planets in one shot.
- The Star: HR 8799 (blocked out in figure).
- The exoplanets: b, c, d, e (marked in figure).
- The instrument ("Project 1640"):
  - AO system (Palm-3000)
  - coronagraph (apodized pupil, Lyot type)
  - calibrator (Mach-Zehnder interferometer)
  - spectrometer (integral field spectrograph)
- The telescope: Palomar 5-m.
- The spectra: 1.0 to 1.8 μm (J & H bands).
- The results:
  - 2 planets (b,d) match L-type brown dwarfs
  - 1 planet (c) matches T-type brown dwarfs
  - 1 planet (e) matches Saturn

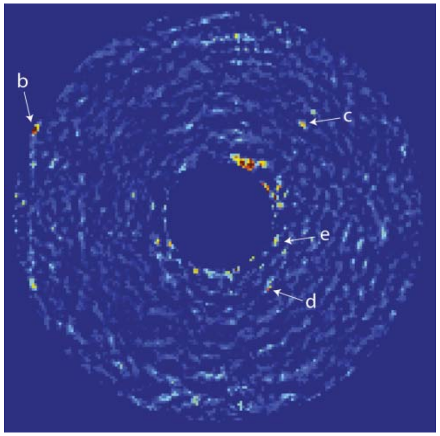


(Ref.: Oppenheimer et al., ApJ, 2013)

Exoplanet Spectrum Hints at Formation Mechanism

- A spectrum of exoplanet HR 8799 c (black line in figure) in K band shows absorption by CO and H_2O, but not CH_4.
- The interpretation is surprising and profound:
- The relative amounts of C and O suggest that the planet was formed by core accretion, at a different distance from its star than where it is today.
- The analysis also tends to rule out the competing planet formation mechanism of gravitational collapse.
- Spectrum is from Keck II telescope, with the OSIRIS integral field spectrograph, and adaptive optics imaging.





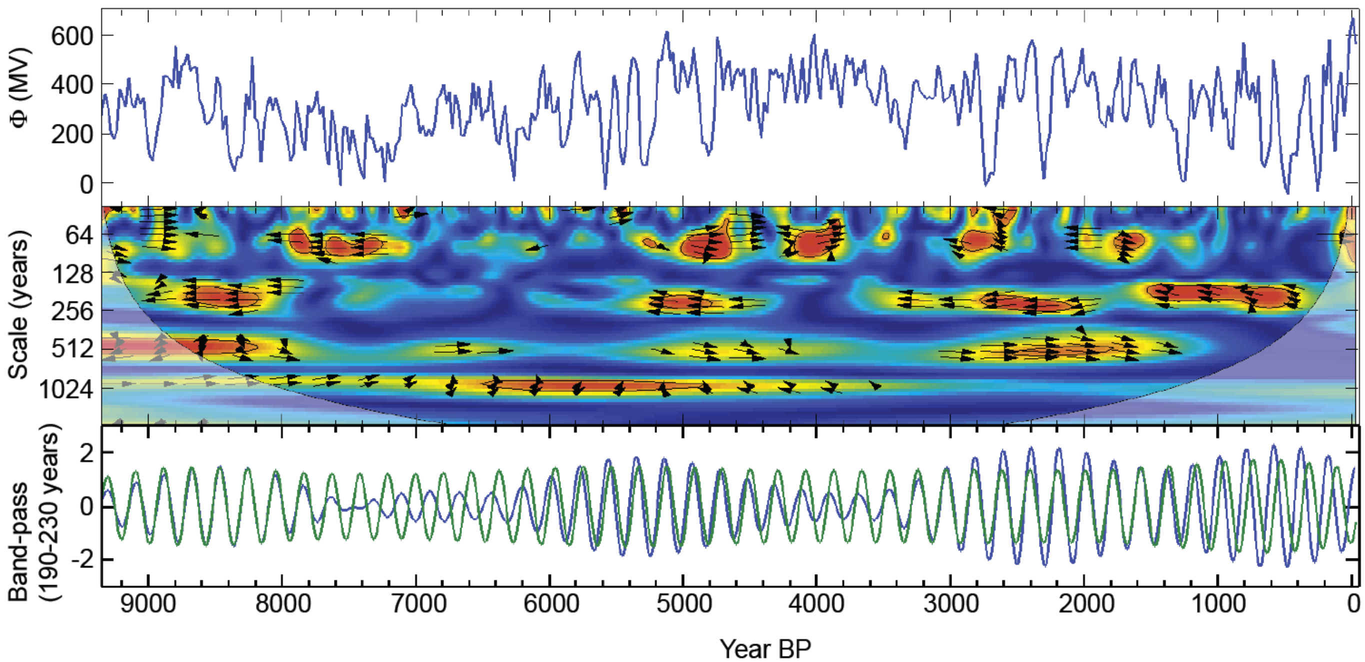
(Ref.: Konopacky et al., Science, 2013)

Does Jupiter control Sunspots?

ExoPlanet Exploration Program

A new study suggests that Jupiter controls the sunspot cycle.

The same may be true for exoplanets.

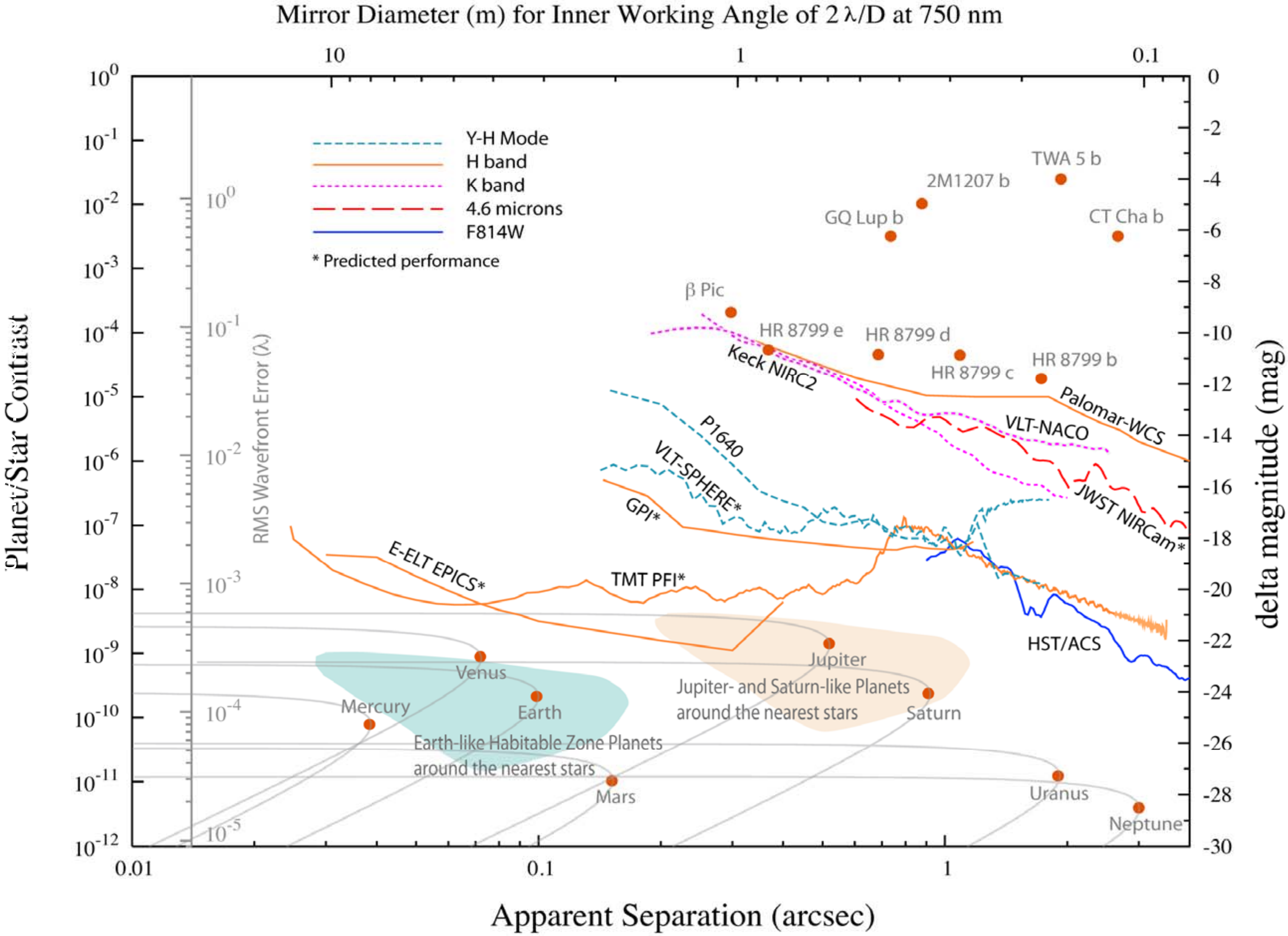


Top: magnetic activity of Sun, over past 9400 years.
Middle: frequency components of the magnetic record, showing periods of 88 years (8x11), 208 years (19x11), etc.
Bottom: average 208-yr torque (blue) **matches very well** the filtered 208-yr component of magnetic activity.

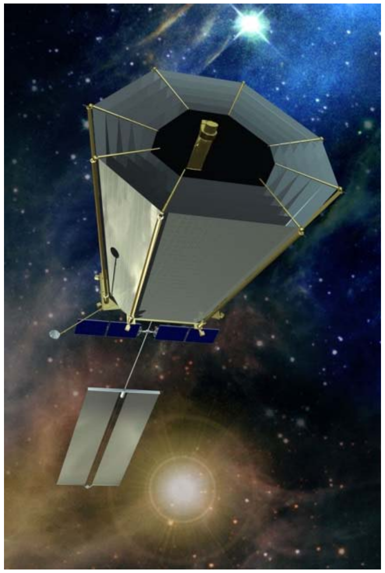
Ref.: J.A. Abreu, et al., Astronomy & Astrophysics, 548, A88, 2012

State of the Art in Exoplanet Imaging

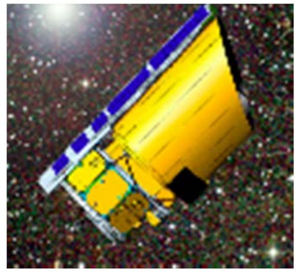
ExoPlanet Exploration Program



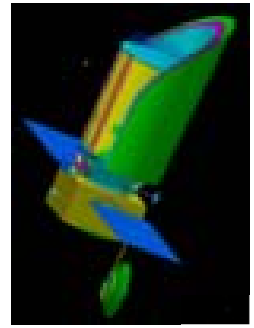
Illustrative Exoplanet Mission Concepts



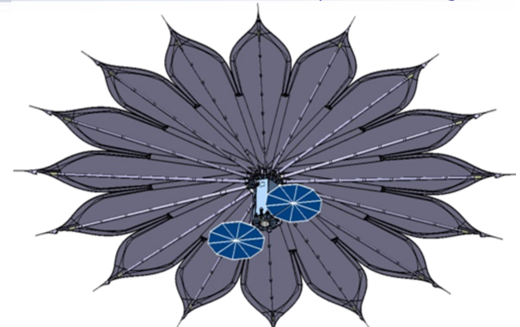
Terrestrial Planet
Finder Coronagraph



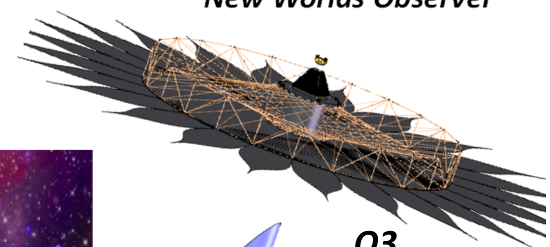
*Pupil-Mapping Exoplanet
Coronagraphic Observer*

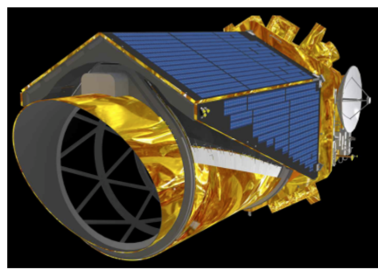


*Actively-Corrected
Coronagraph for
Exoplanet System
Studies*

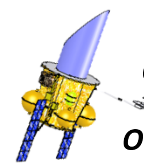


NWO
New Worlds Observer

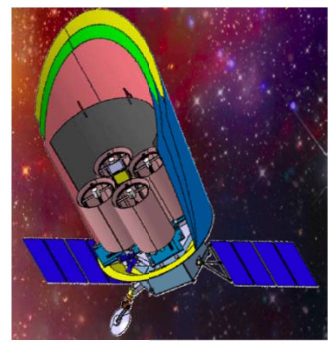




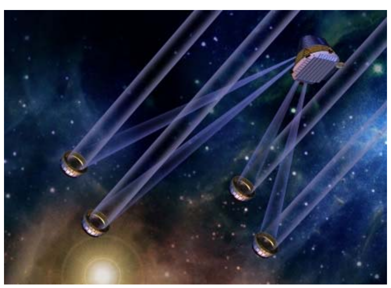
*Extrasolar Planetary Imaging
Coronagraph*



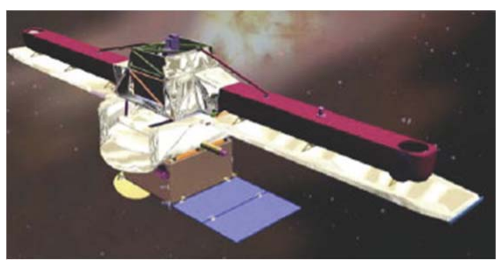
O3
*Occulting
Ozone
Observatory*



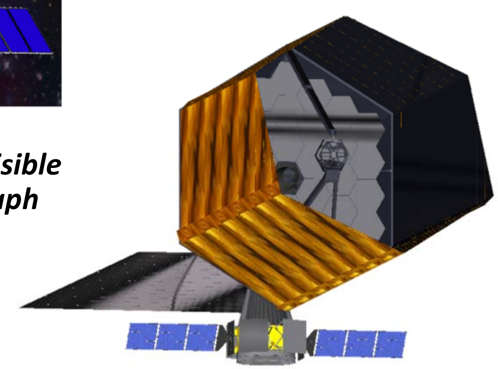
*Dilute Aperture Visible
Nulling Coronagraph
Imager*



*Terrestrial Planet
Finder Interferometer*



*Fourier-Kelvin Stellar
Interferometer*



***ATLAST** Advanced Technology
Large-Aperture Space Telescope*

Selected Coronagraph Concepts

Image Plane Amplitude & Phase Mask (Trauger, JPL)

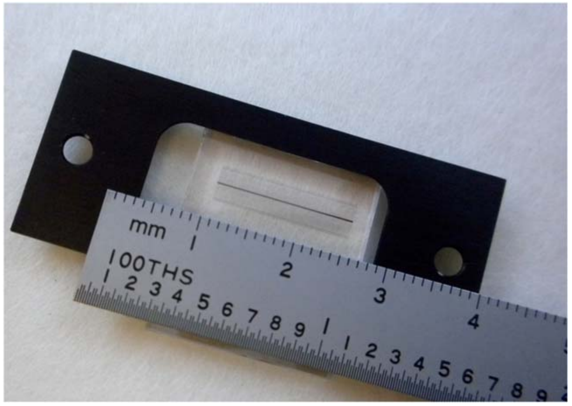
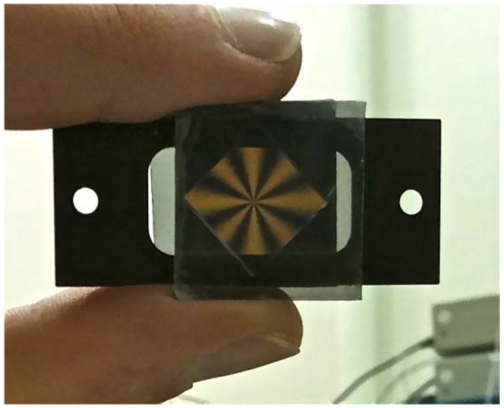
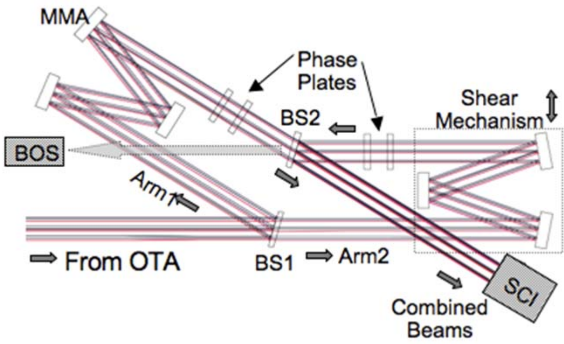
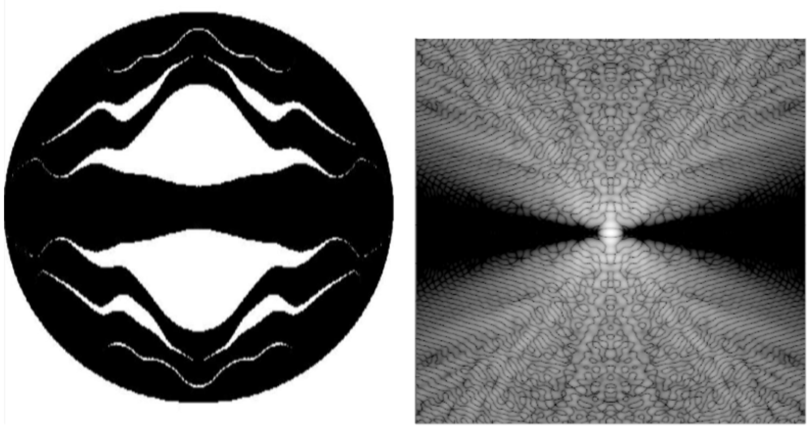


Image Plane Phase Mask (Serabyn, JPL)

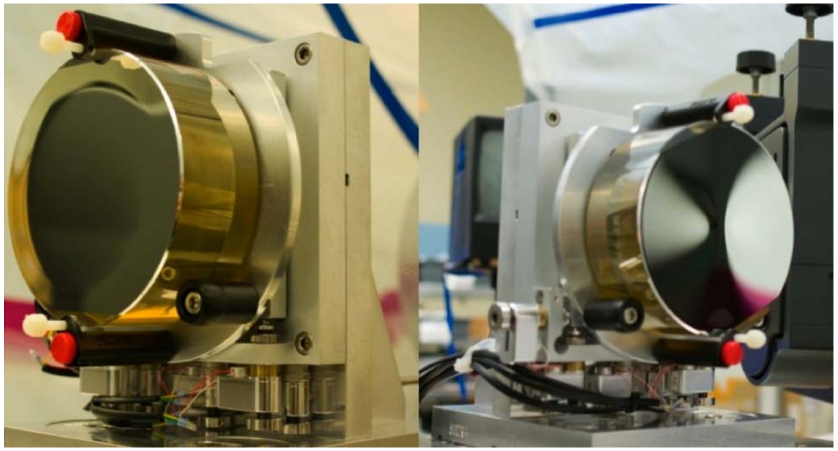


Pupil Shearing (Clampin, NASA GSFC)





Pupil Masking (Vanderbei, Univ. Princeton)

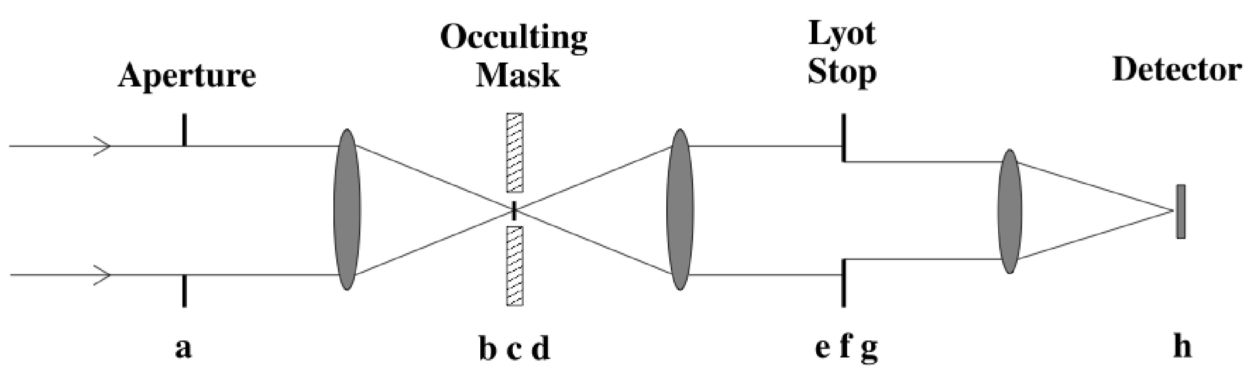


Pupil Mapping (Guyon, Univ. Arizona)

Diffraction control used to selectively reject starlight

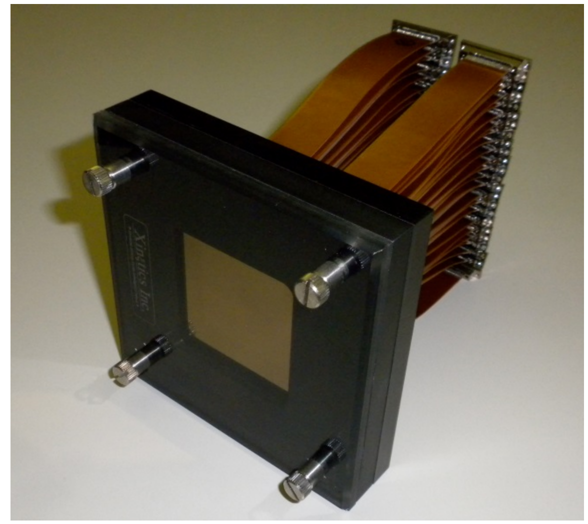
- A diffractive optic is used to remove star-light from the field of view, while allowing the planet light to be detected
  - A fixed optic (does not move)
    - e.g. an image plane mask in a coronagraph, or the occulter of an external coronagraph
  - Mathematically may have perfect performance
  - In practice may have subtle imperfections

- Concepts in Fourier Optics provide a wide variety of possible solutions



Deformable Mirrors

- Xinetics (NGAS) deformable mirrors have been used to demonstrate contrasts of 2×10^{-10}
  - Routinely used in vacuum at HCIT
  - Vibration tested at JPL
- Boston Micromachines (MEMS) deformable mirrors demonstrated contrasts of 10^{-8}
  - Low-power, low mass
  - Flown on PICTURE (Chakrabarti, BU)



48x48 Xinetics DM vibration tested at JPL

DMs have not yet been flown but are at a high TRL

Further advances in MEMS DM technology are of great interest

John Trauger (JPL/Caltech) Hybrid Lyot Masks

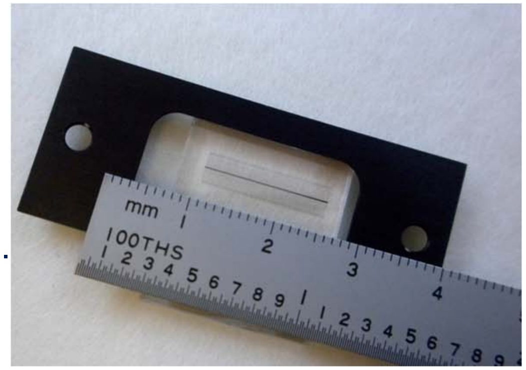
Milestone: ≤ 10^{-9} contrast, 3λ/D, 20% BW

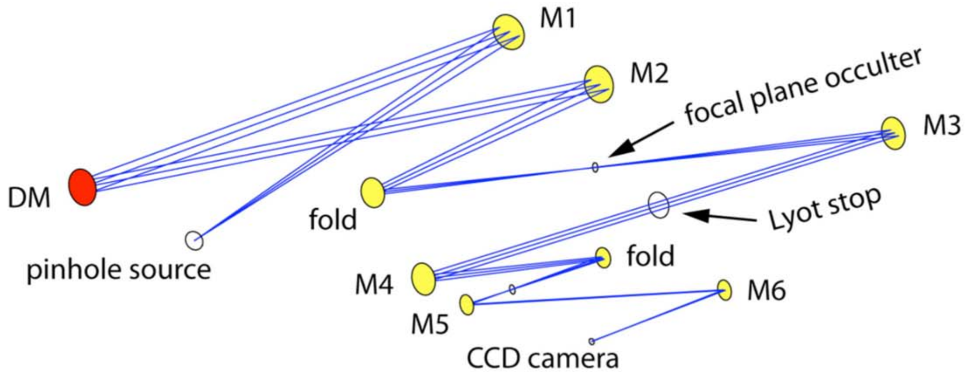
Facility: High Contrast Imaging Testbed 1, JPL

Status: 2 × 10^{-9} contrast, 3-4 λ/D, 20%

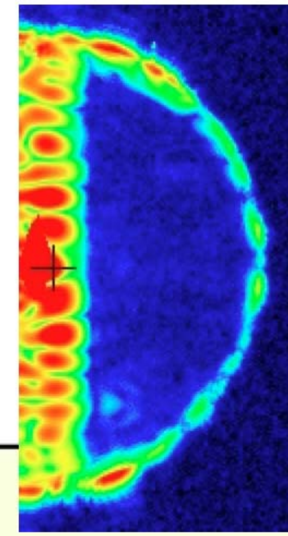
Challenges: Calibrate dielectric layer during manufacturing.

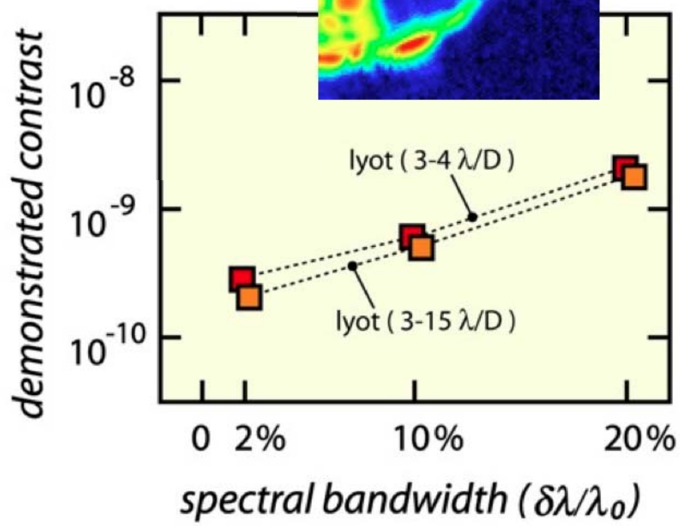
Future: 20% bandwidth, circular masks



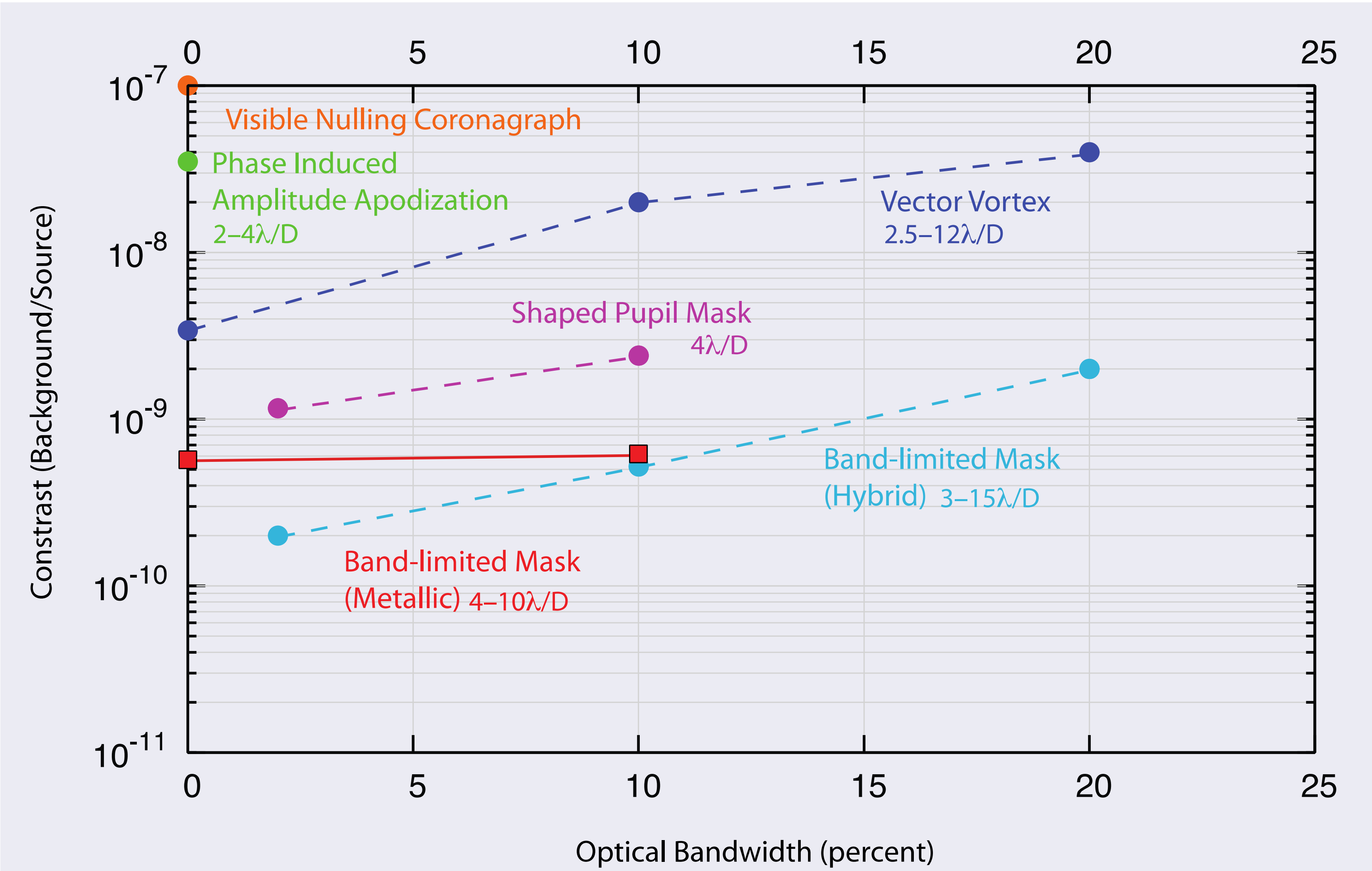


Hybrid Lyot Contrast Achieved to Date (Trauger TDEM)			
	Bandwidth		
Inner Working Angle	2%	10%	20%
3-4 λ/D	3.2 10^{-10}	6.0 10^{-10}	1.9 10^{-9}
3-15 λ/D	2.0 10^{-10}	5.2 10^{-10}	1.9 10^{-9}



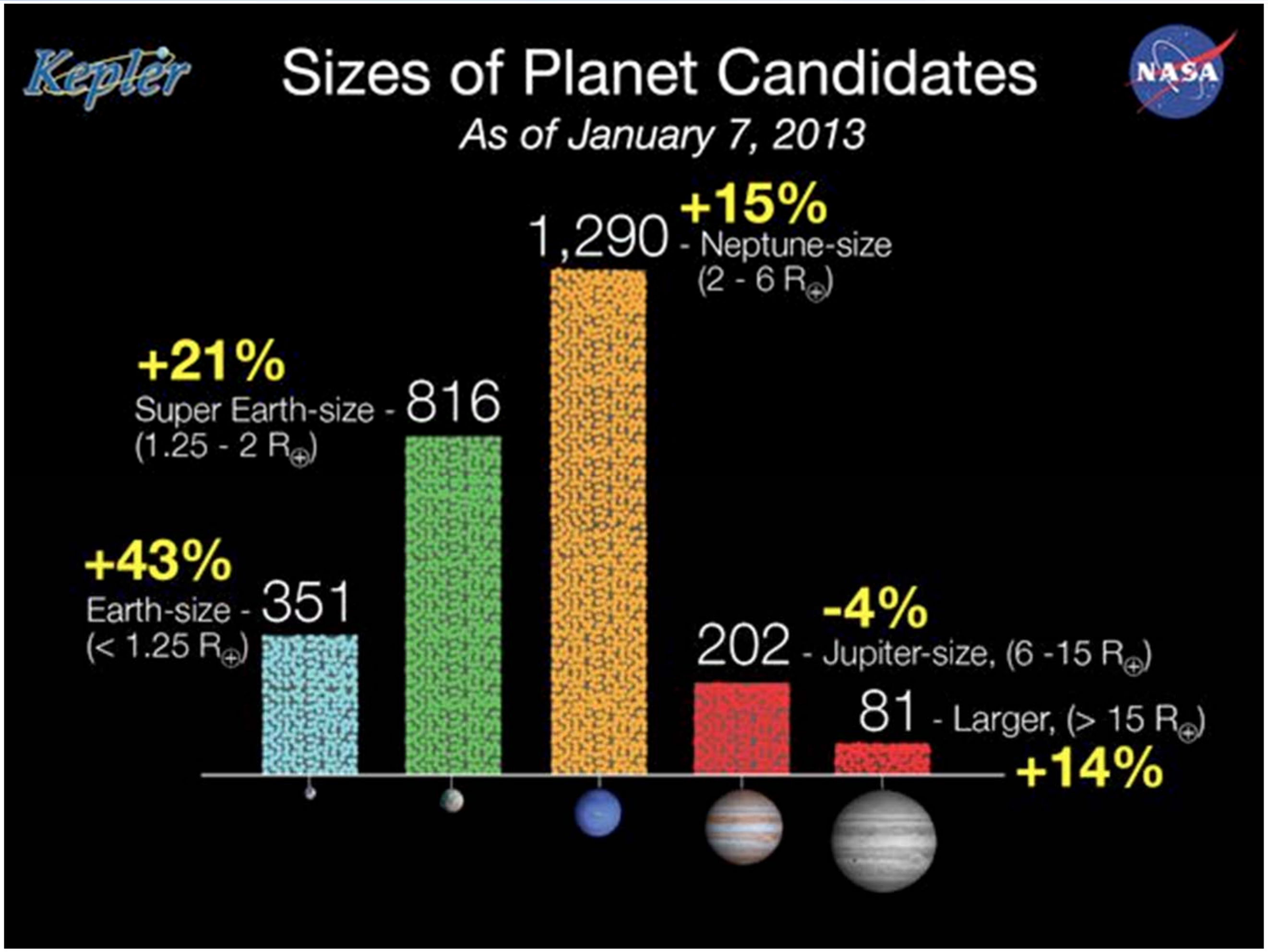


State-of-the-Art in Coronagraph Lab Experiments



Statistics

ExoPlanet Exploration Program

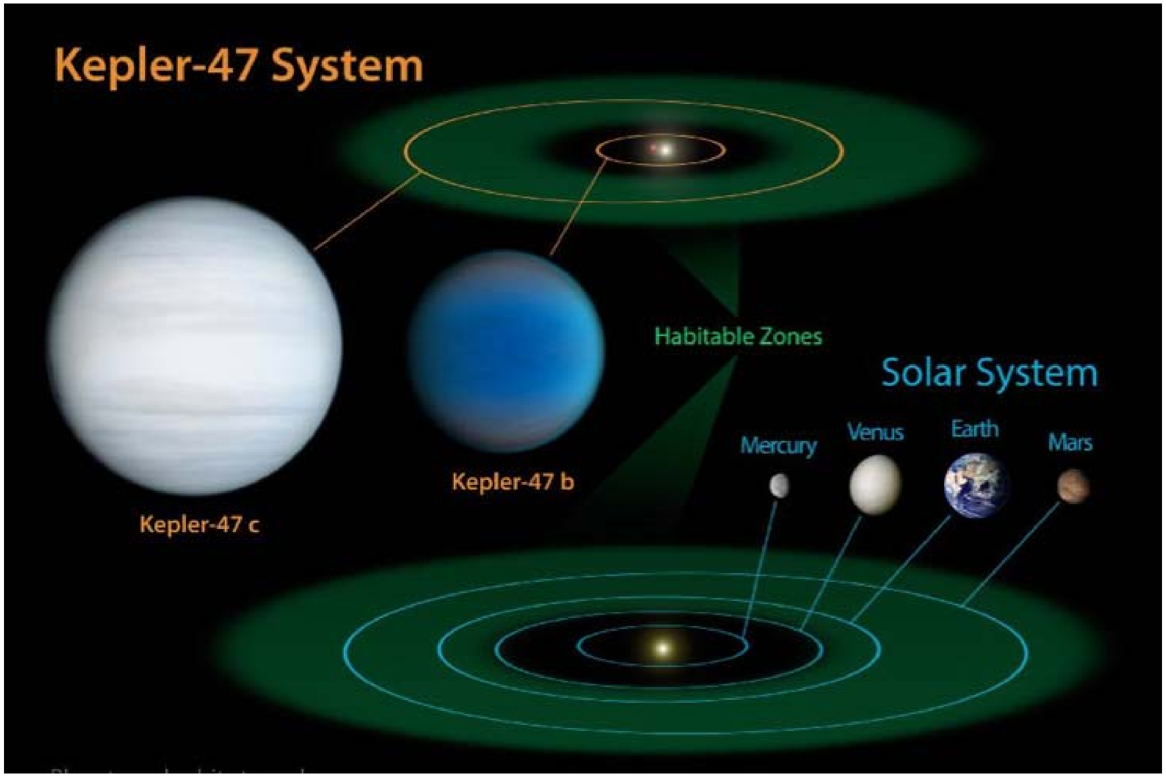


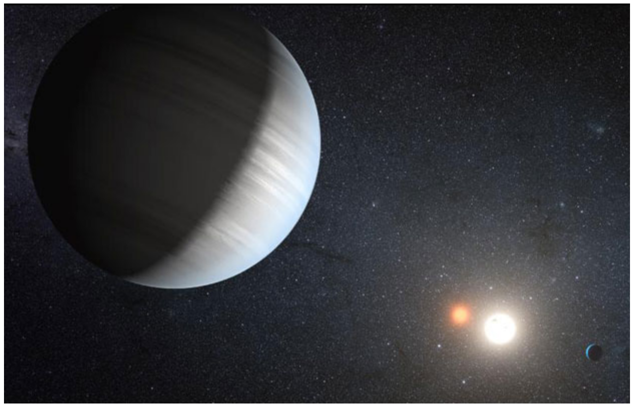
... 50 percent of stars have a planet of Earth-size or larger in a close orbit. By adding larger planets, which have been detected in wider orbits up to the orbital distance of the Earth, this number reaches 70 percent. ...it looks like practically all Sun-like stars have planets -- Francois Fressin (CfA)

Kepler 47

ExoPlanet Exploration Program

The Kepler-47 system: two planets orbiting a
with the orbit of one planet within the habitable zone
of the binary system.

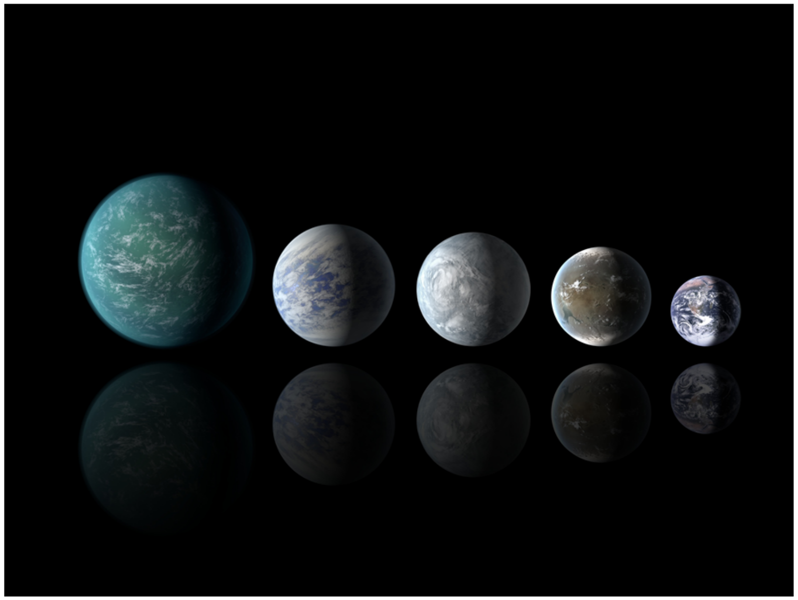




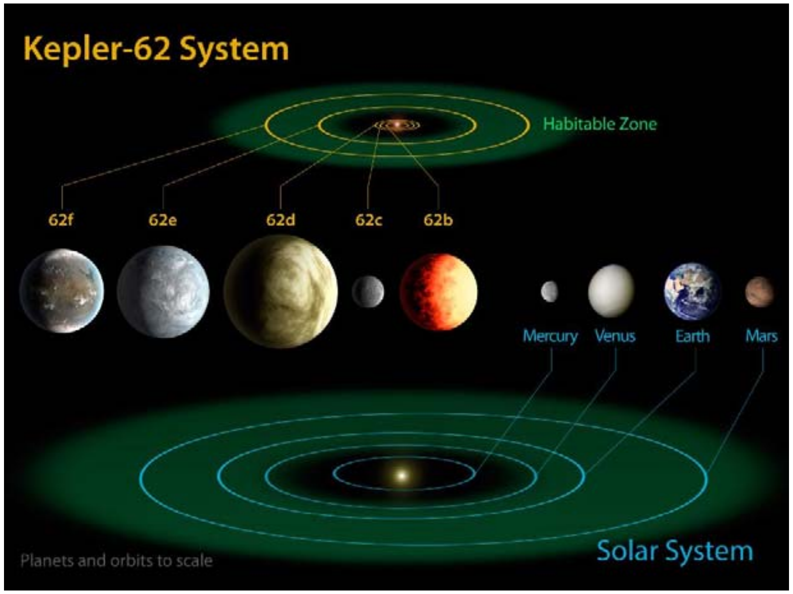
Ref.: "Kepler-47: A transiting circumbinary multiplanet system," Orosz et al. *Science* , 2012.

Kepler 62 and 69

ExoPlanet Exploration Program

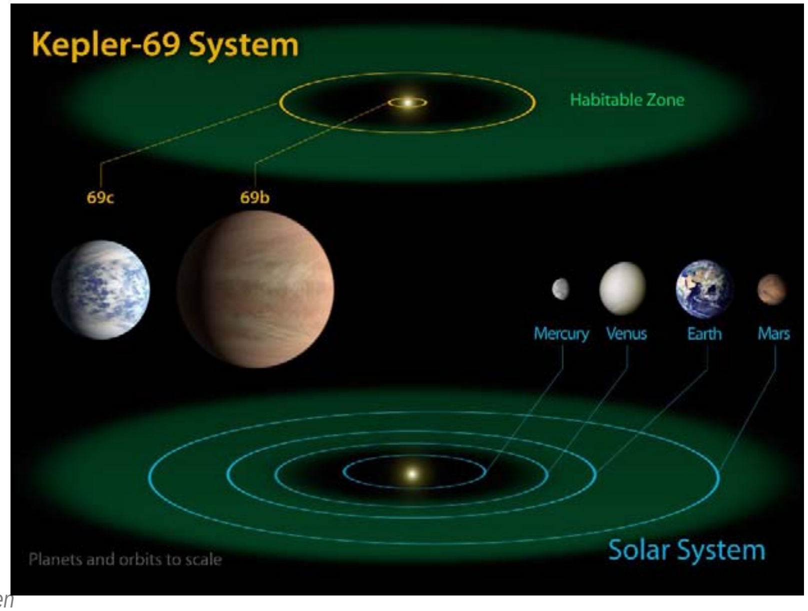


Relative sizes of all of the habitable-zone planets discovered to date alongside Earth. Left to right: Kepler-22b, Kepler-69c, Kepler-62e, Kepler-62f and Earth

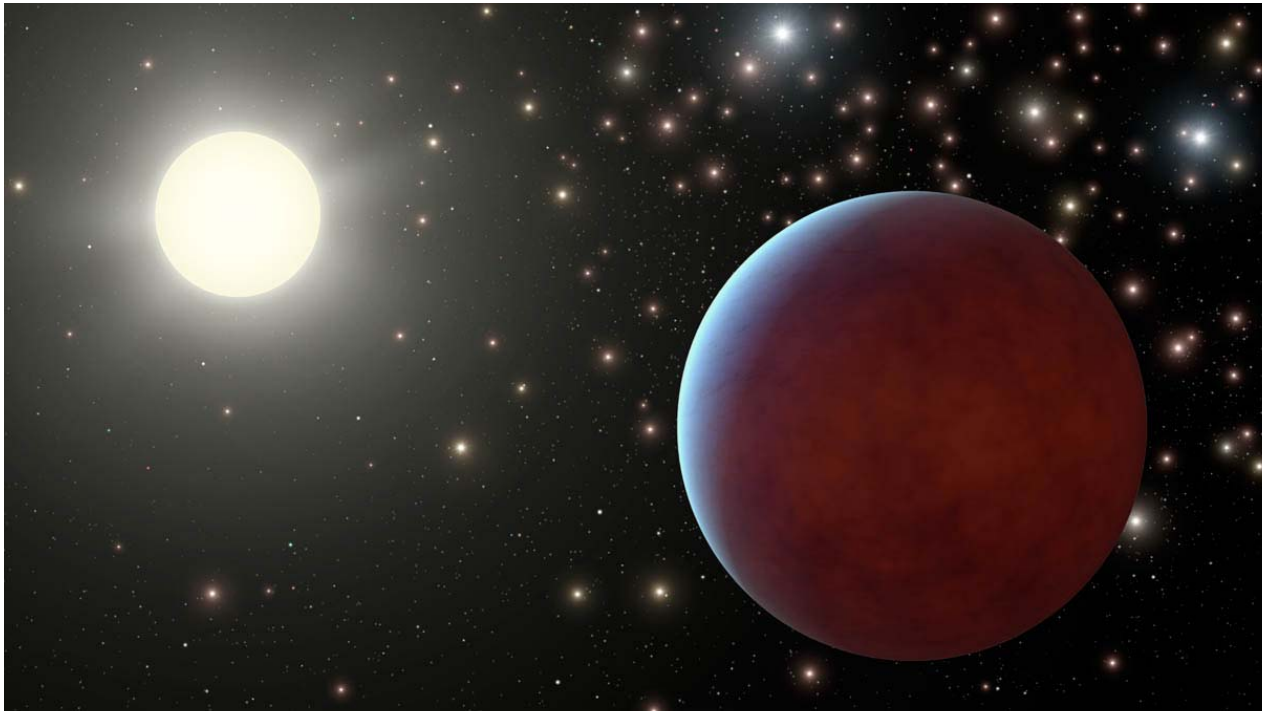


NASA's Kepler mission has discovered two new planetary systems that include three super-Earth-size planets in the "habitable zone," the range of distance from a star where the surface temperature of an orbiting planet might be suitable for liquid water.

The Kepler-62 system has five planets; 62b, 62c, 62d, 62e and 62f. The Kepler-69 system has two planets; 69b and 69c. Kepler-62e, 62f and 69c are the super-Earth-sized planets.



First planets found around Sun-like stars in a cluster

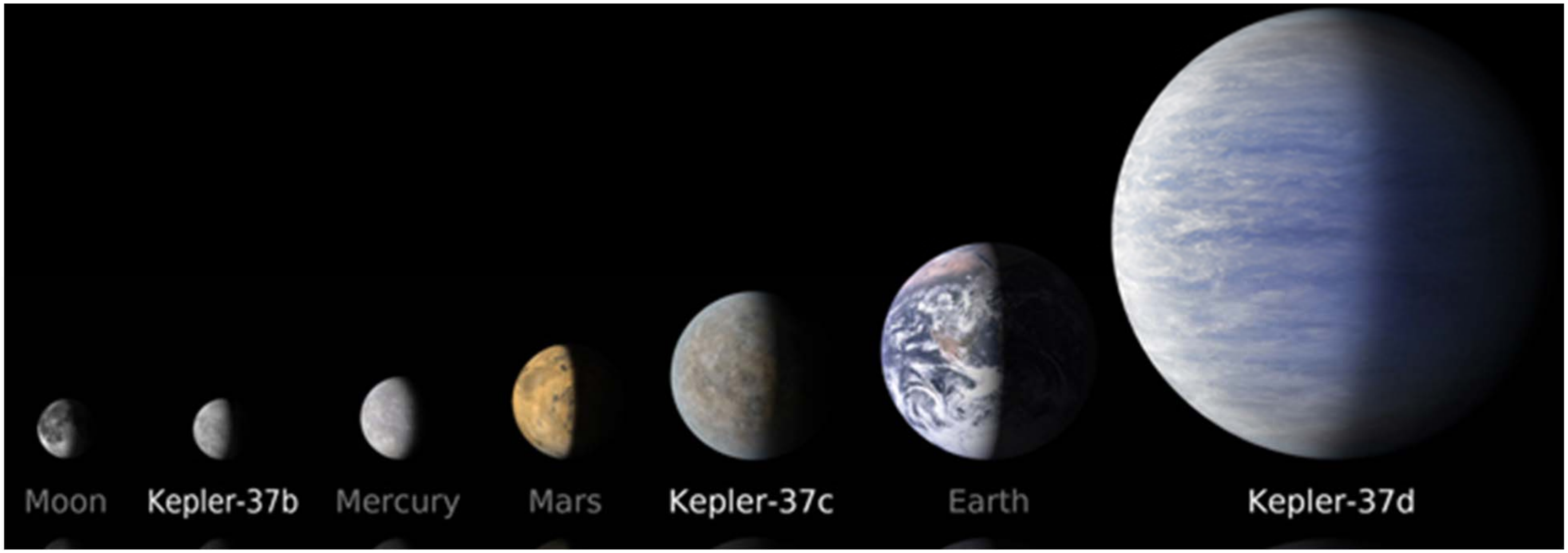


"NASA-funded astronomers have, for the first time, spotted planets orbiting sun-like stars in a crowded cluster of stars. The findings offer the best evidence yet planets can sprout up in dense stellar environments. Although the newfound planets are not habitable, their skies would be starrier than what we see from Earth. ..." *-- NASA News release 9/14/2012*

Two hot Jupiters were detected in *Praesepe* (the 'Beehive' open cluster of ~1000 stars), using the radial velocity method at the SAO Whipple Observatory in Arizona, by Sam Quinn (Georgia State U) and collaborators.

Smallest Kepler Planet Discovered

ExoPlanet Exploration Program



- Kepler found the smallest planet known anywhere, Kepler-37b.
- The planet radius is about 30% of the Earth's; it is slightly smaller than Mercury, but slightly larger than the Moon.
- It orbits its star at 0.1 AU, which is 4 times closer than Mercury.
- This discovery is from the very tip of the Kepler iceberg.
- The star is very bright star (9.7 mag), & very close (53 pc, the 4^{th}-nearest Kepler star.)
- Even so, the SNR (13) is close to the minimum (7), so this may be the only such miniature planet that Kepler will ever find.

Super-dense planets: a new type

ExoPlanet Exploration Program

- Several Kepler planets (68c,22b,46b) are denser than iron, by about 150 to 300%.
- Now a new theory offers an explanation.
- The idea is that these planets are the left-over cores of ice giants, where the envelopes were stripped off by radiation from the star.
- The originally compressed cores will stay compressed for a long time, giving what we see today.

(Ref.: Grasset, Mocquet, and Sotin, 2013)

Eta-Earth: number of Earth-like planets per star

- 2011: Catanzarite & Shao estimated 1-3% from early Kepler data
- 2012: Traub estimated 34 ± 14%, same data
- 2013: Gaidos estimates 46 (± 16) %, from newer Kepler data
- 2013: Dressing & Charboneau est. 15% for M dwarfs from Kepler
- 2013: Kopparapu revised that up to 48 % with new HZ definition
- 2013: Bonfils etal estimate 41% for M dwarfs from RV

- Average value is roughly 25%, about 1 star in 4

- Milky Way has about 200 billion stars (red dwarfs plus Sun-like)
- So there could be about 50 billion Earth-like planets in our Galaxy

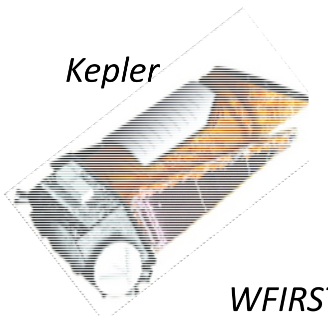
The Exoplanet Exploration Program

ExoPlanet Exploration Program

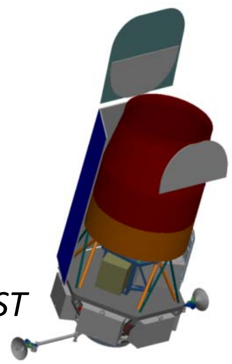
***Exploring** How the Universe Works*
***Discovering** and Characterizing Earth-like Planets*
***Searching** for Life on other Worlds*

Space Missions and Mission Studies

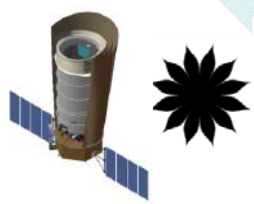
Kepler



WFIRST



Probe-class mission studies

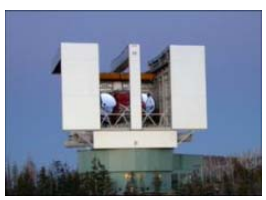


Public Engagement

Supporting Research & Technology

Key Sustaining Research

Keck Single Aperture Imaging and RV



Large Binocular Telescope Interferometer

Technology Development

High Contrast Imaging

Deployable Star Shades

Archives, Tools & Professional Education

NASA Exoplanet Science Institute

AFTA-2.4 Exoplanet Science

The combination of microlensing and direct imaging will dramatically expand our knowledge of other solar systems and will provide a first glimpse at the planetary families of our nearest neighbor stars.

Microlensing Survey

Monitor 200 million Galactic bulge stars every 15 minutes for 1.2 years

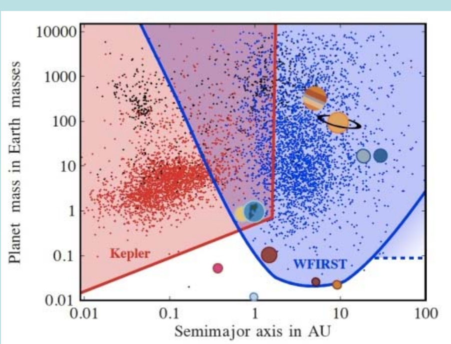
2800 cold exoplanets
300 Earth-mass planets
40 Mars-mass or smaller planets
40 free-floating Earth-mass planets

High Contrast Imaging

Survey up to 200 nearby stars for planets and debris disks at contrast levels of 10^{-9} on angular scales > 0.2”
R=70 spectra and polarization between 400-900 nm

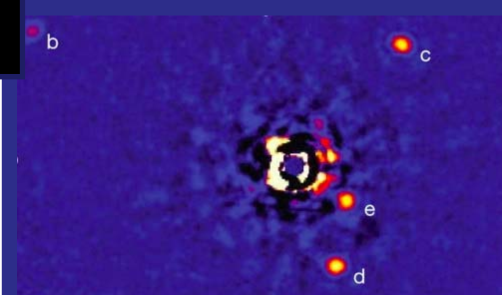
Detailed characterization of up to a dozen giant planets.
Discovery and characterization of several Neptunes
Detection of massive debris disks.

Complete the Exoplanet Census



- **Identification and characterization of nearby habitable exoplanets**
- **How diverse are planetary systems?**
- **How do circumstellar disks evolve and form planetary systems?**
- **Do habitable worlds exist around other stars, and can we identify the telltale signs of life on an exoplanet?**

Discover and Characterize Nearby Worlds



Thank you!