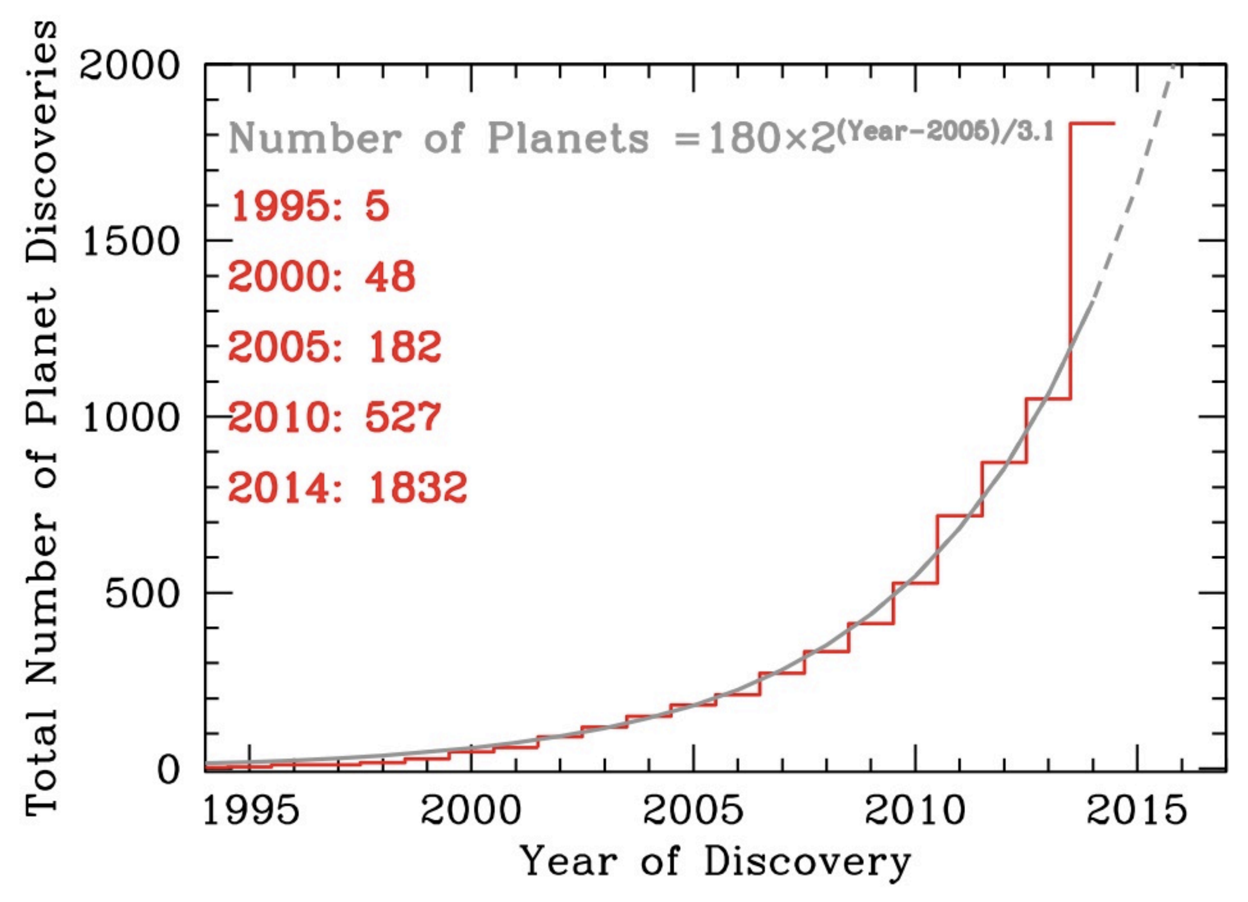
Exploring Outer Exoplanetary Systems.

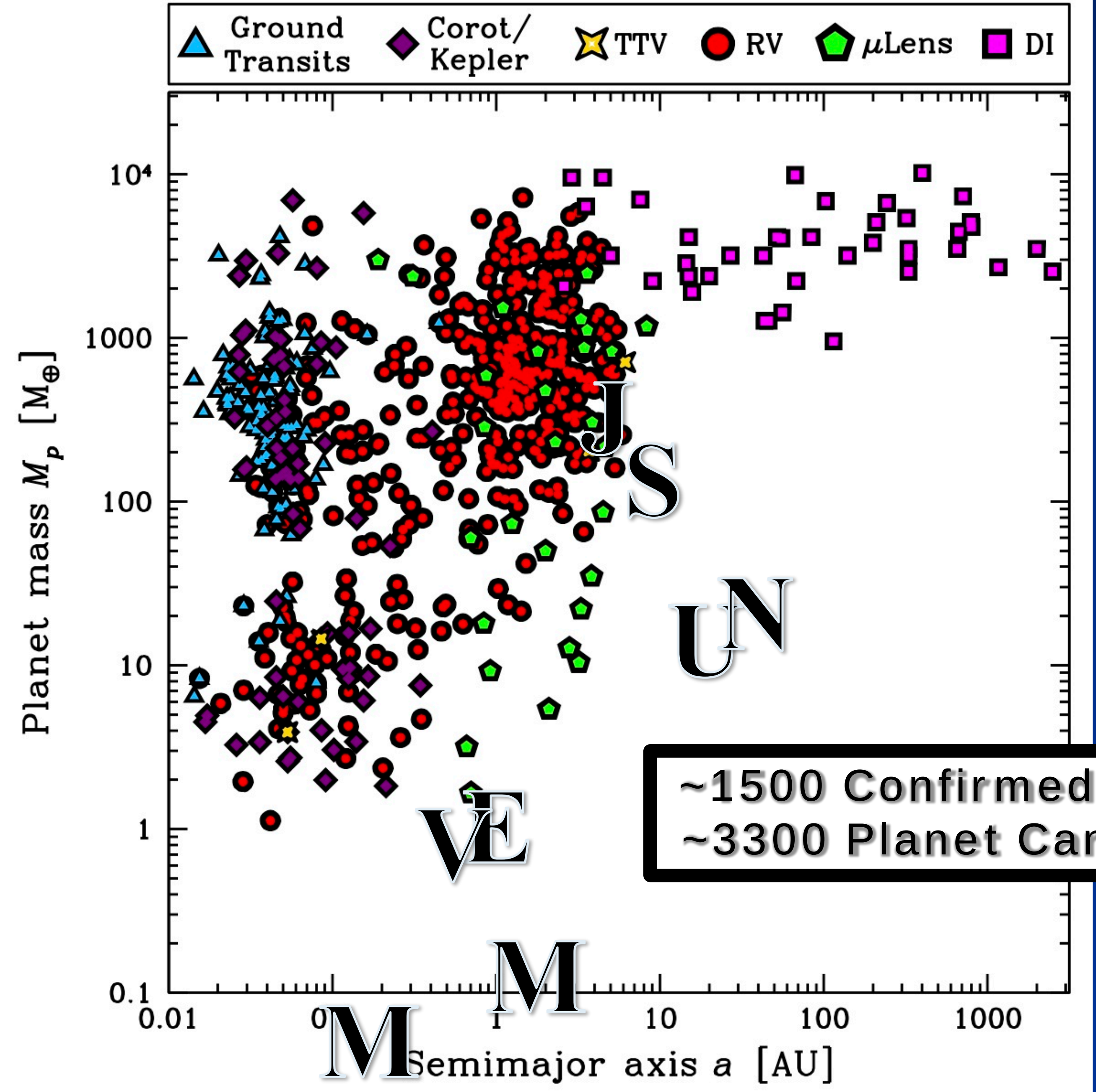
OPAG Meeting
February 20, 2015

Scott Gaudi
The Ohio State University
ExoPAG EC Chair

20+ Years of Exoplanets.



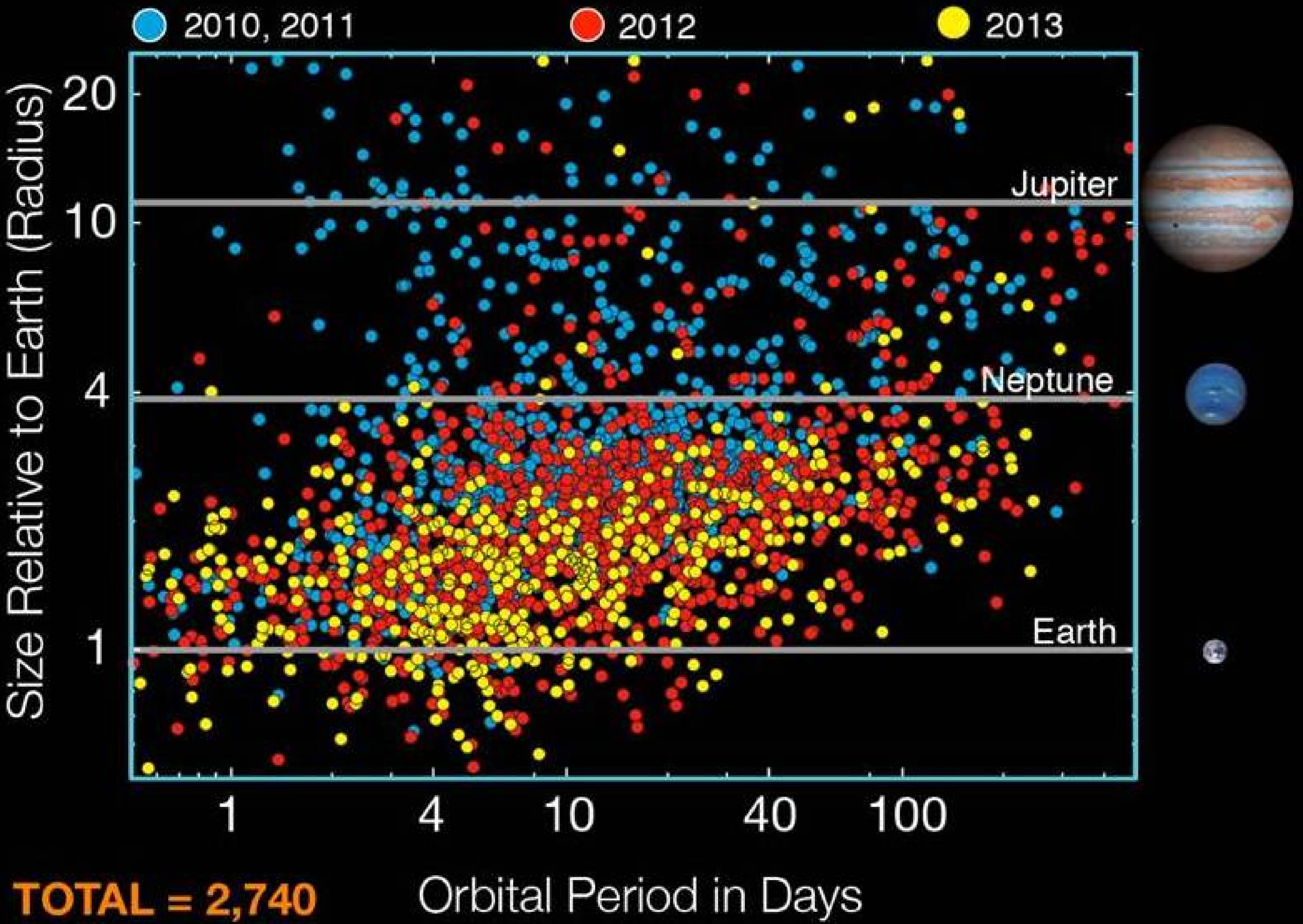
Strange New Worlds.



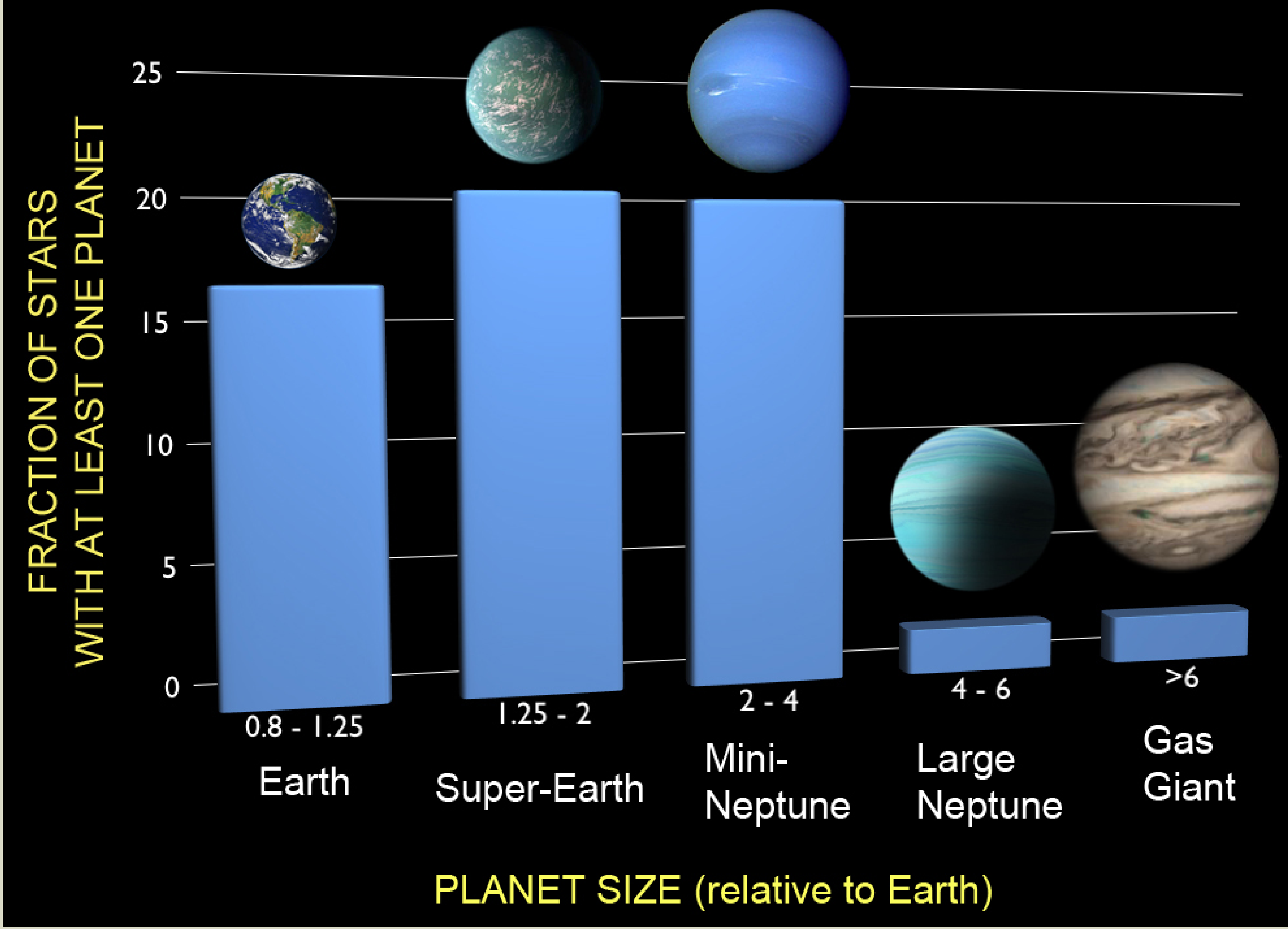
~1500 Confirmed Planets
~3300 Planet Candidates

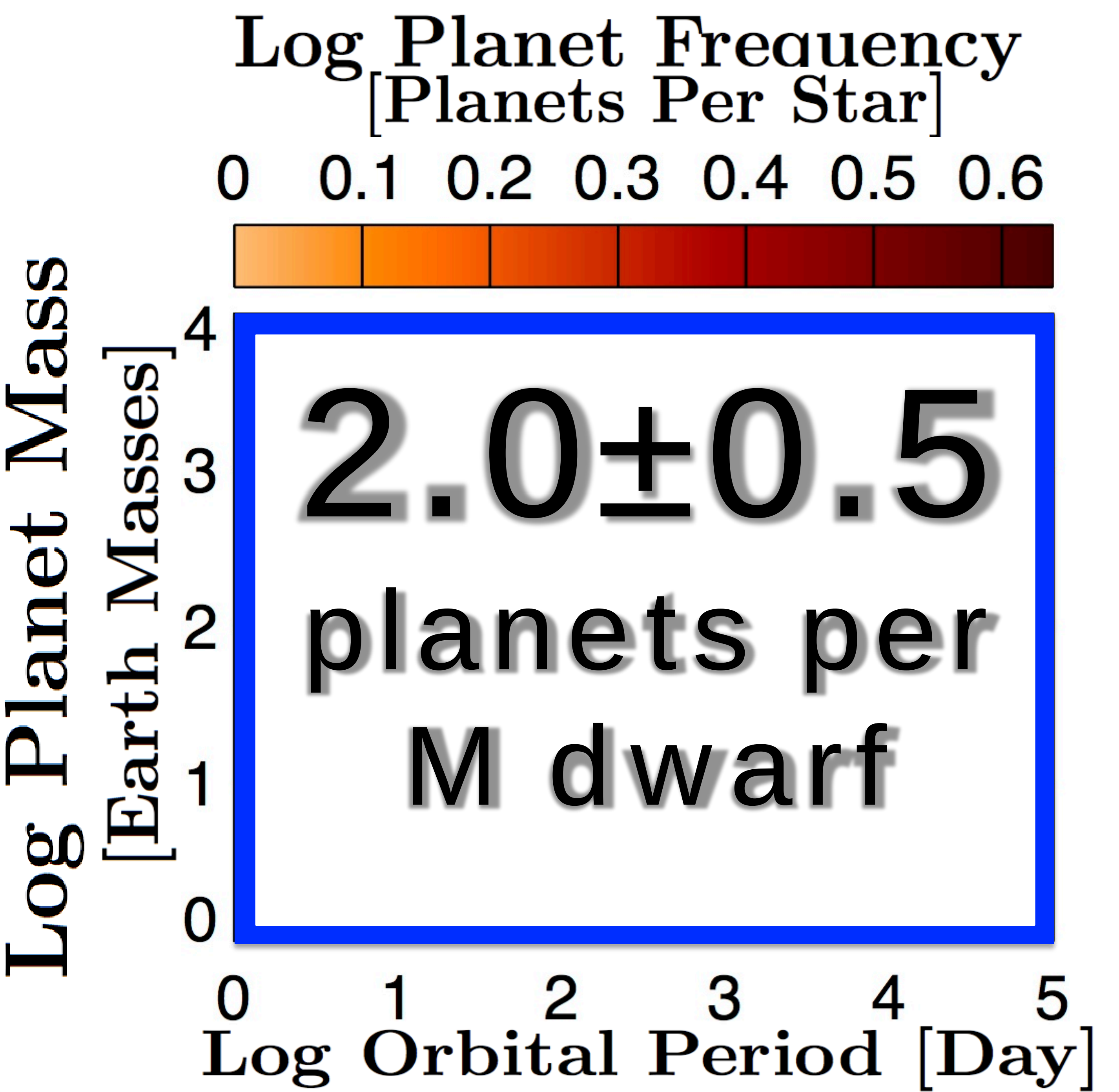
What we've learned.

Mother nature
is more
imaginative
than we are.


2010, 2011
2012
2013
Size Relative to Earth (Radius)
20
10
4
1
Jupiter
Neptune
Earth
1
4
10
40
100
Orbital Period in Days

TOTAL = 2,740


FRACTION OF STARS
WITH AT LEAST ONE PLANET
25
20
15
10
5
0
0.8 - 1.25
Earth
1.25 - 2
Super-Earth
2 - 4
Mini-Neptune
4 - 6
Large Neptune
>6
Gas Giant
PLANET SIZE (relative to Earth)

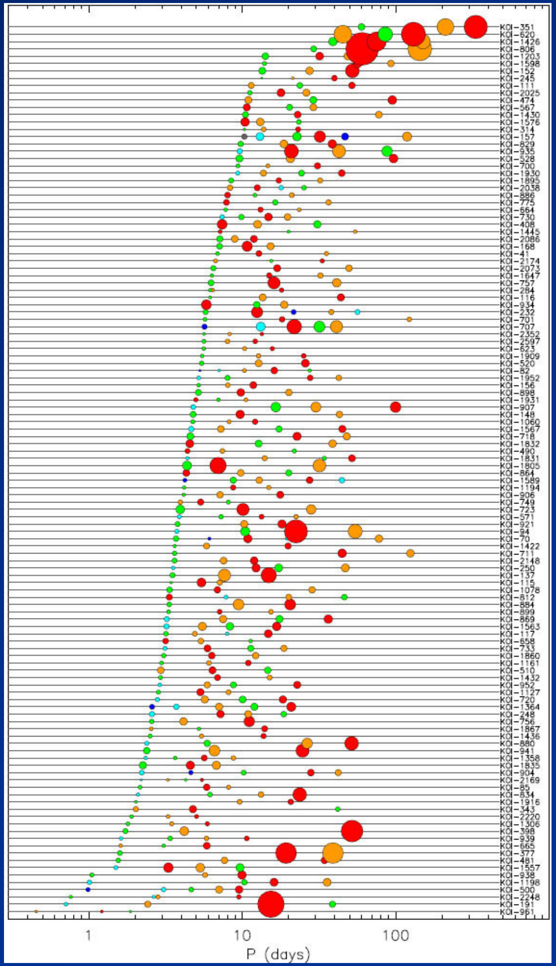


2.0±0.5 planets per M dwarf

(Clanton & Gaudi 2014a,b)

Planets, planets everywhere.

- Planetary systems are ubiquitous and diverse.
  - The majority of stars host planets.
  - Vast range of eccentricities, inclinations, masses, atmospheres, stellar types, architectures.
- Neptune and sub-Neptune mass planets are much more common than giant planets.
- Many stars host compact systems of Neptune and sub-Neptune mass planets.
- Free-floating and/or wide-separation gas giants are common.

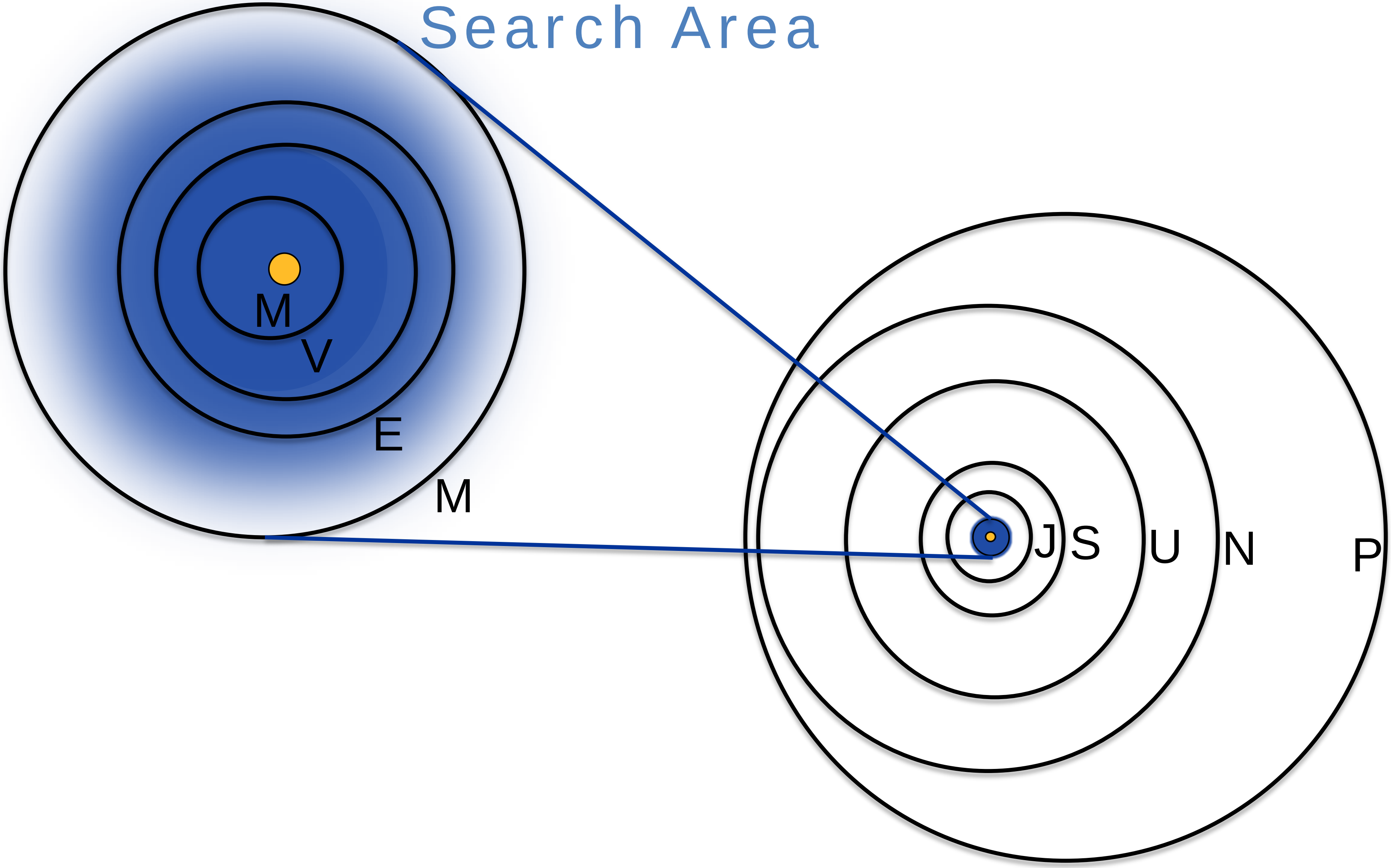


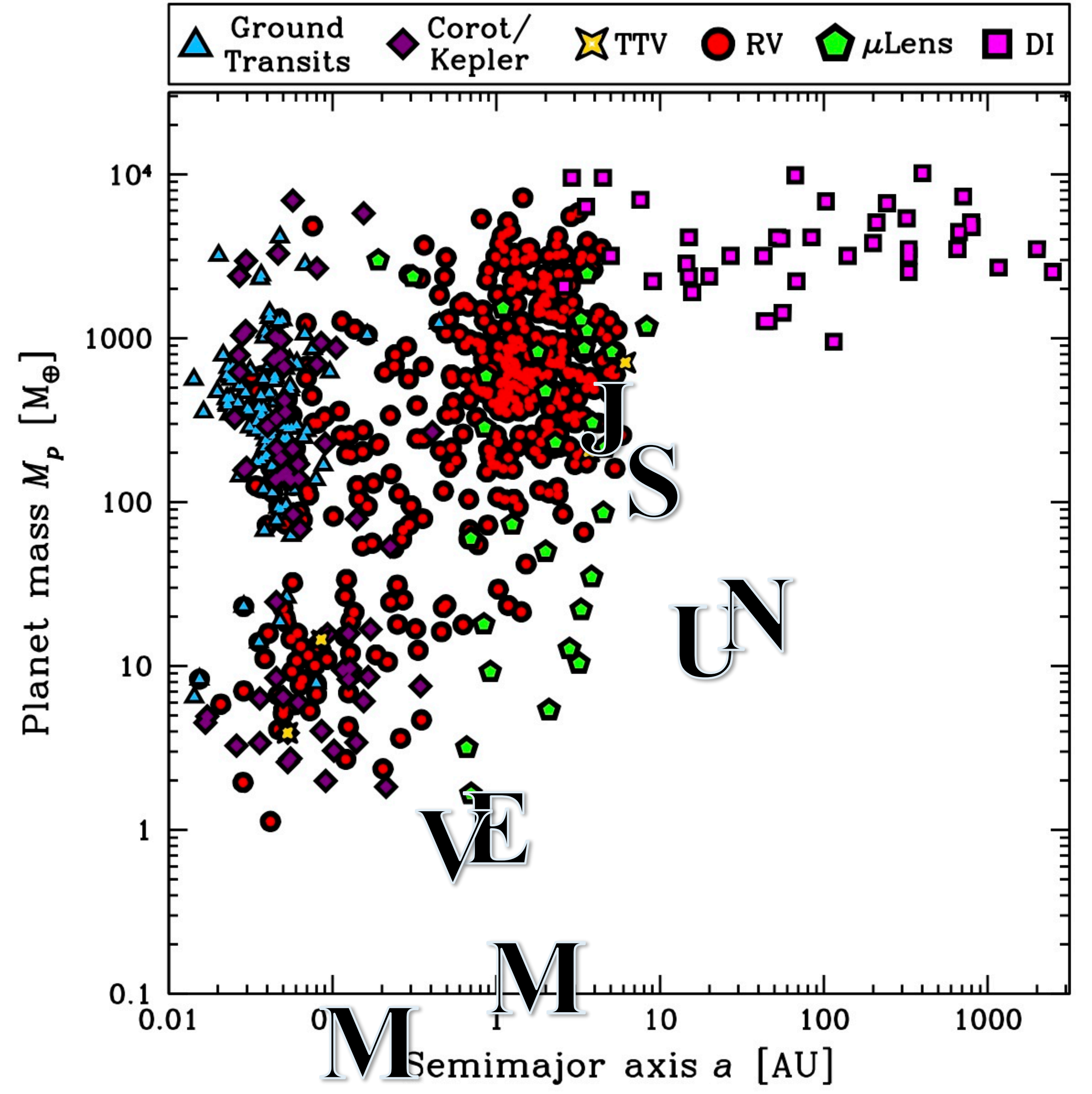
Lessons for our solar system.

- Large-scale migration of giant planets is common.
- Circular orbits for giant planets are not common.
- Jupiter+Saturn analogs exist around a minority of stars.
- The dichotomy seen in our solar system is not universal.
- Potentially habitable planets are probably not rare (of order ~10%).

What we haven’t learned.

Kepler's Search Area



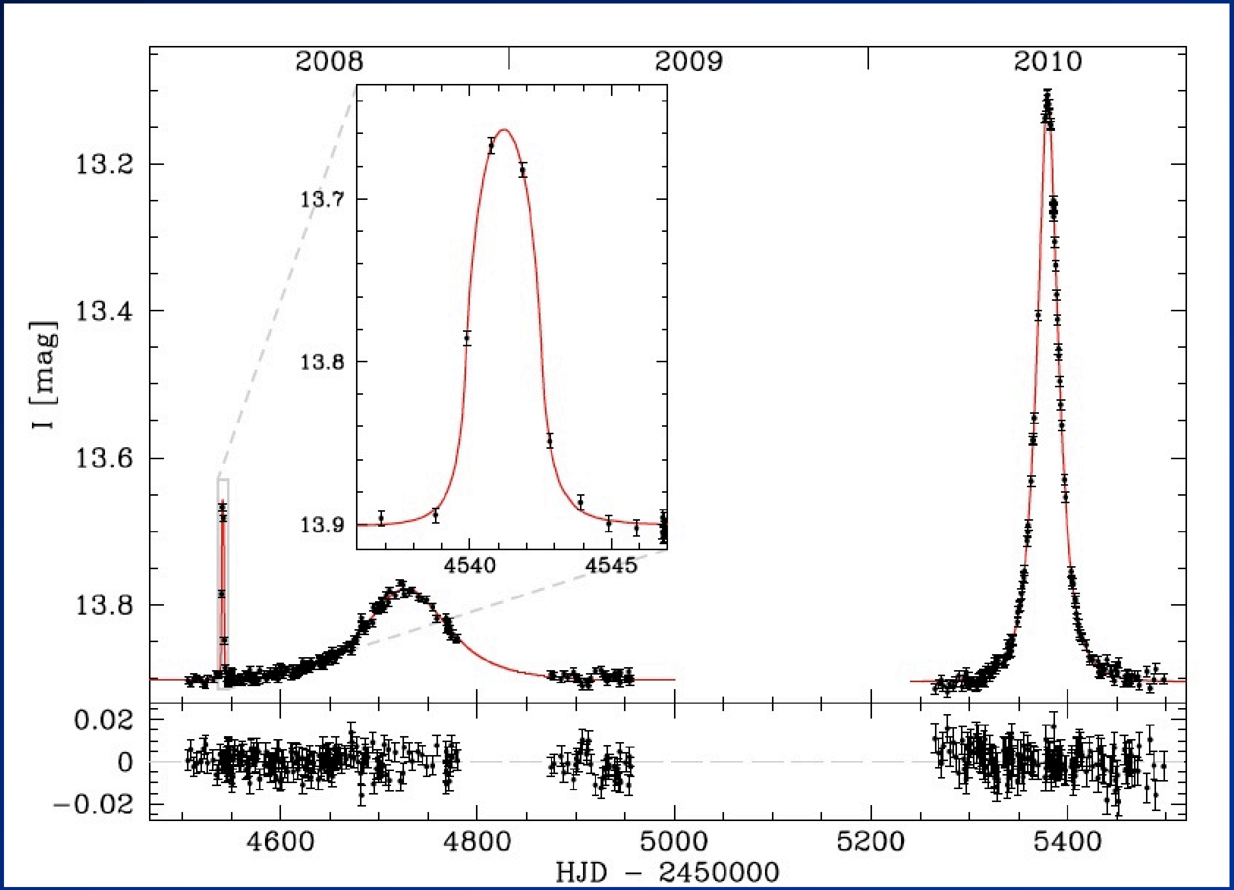

Ground Transits
Corot/ Kepler
TTV
RV
μLens
DI
Planet mass M_p [$M_\oplus$]
10^4
1000
100
10
1
0.1
0.01
0.1
1
10
100
1000
Semimajor axis a [AU]
J
S
U
N
V
E
M
M

A biased view of exoplanetary systems.

- Know very little about outer exoplanetary systems (beyond the snow line).
  - Essentially nothing about analogs to Neptune and Uranus.
- Don’t know how common solar system architectures like our own are.
- Don’t understand the primary mechanisms for migration.
- Don’t really understand the atmospheres and interiors of the planets that we can characterize.
- Don’t know anything about satellite and ring systems.

First ice giant analog.

- Primary
  - ~0.71 M_{Sun}
- Planet
  - ~4 M_{Uranus}
  - ~18 AU.
- Secondary
  - ~0.15 M_{Sun}
  - ~58 AU



(Poleski et al. 2014)

Exoplanet Detection and Characterization Methods.

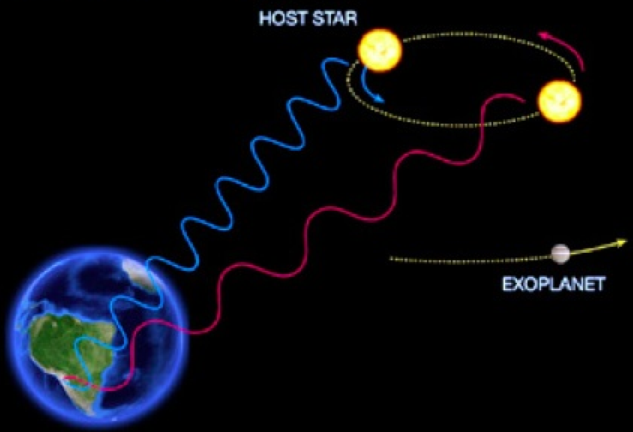
Plethora of Detection Methods.

- Timing.
- Radial velocities.
- Astrometry.
- Transits.
- Microlensing.
- Direct Imaging.

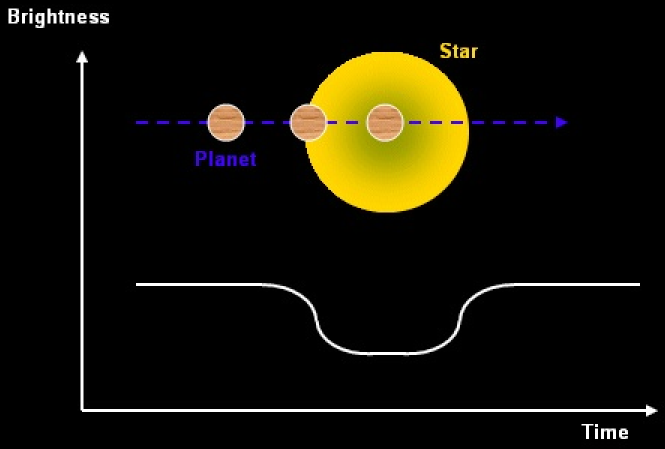
Underlying physics of all of these methods is relatively simple; this physics dictates their sensitivity.

“Big Four”

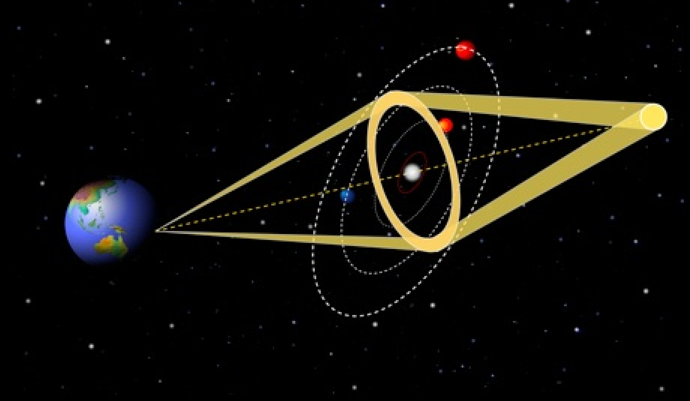
Radial Velocity



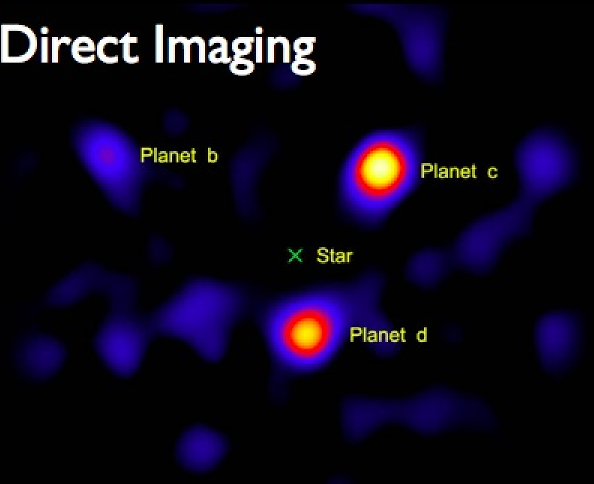
Transit Photometry



Microlensing



Direct Imaging



“Big Questions”

“Big Picture Questions”

- How do planetary systems form and evolve? (Q1,Q2)
- How common are solar systems like our own, and why is our solar system (apparently) unusual? (Q3)
- What are the dominant physical processes that govern the atmospheres and interiors of exoplanets? (Q3,Q7)
- What are the nearest exoplanetary systems like, and do they harbor potentially habitable worlds, and do those worlds harbor life? (Q6)

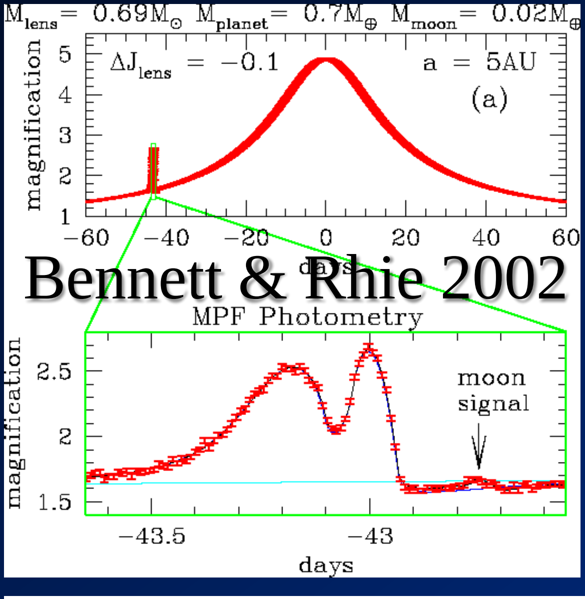
Exoplanet Inquiry Areas.

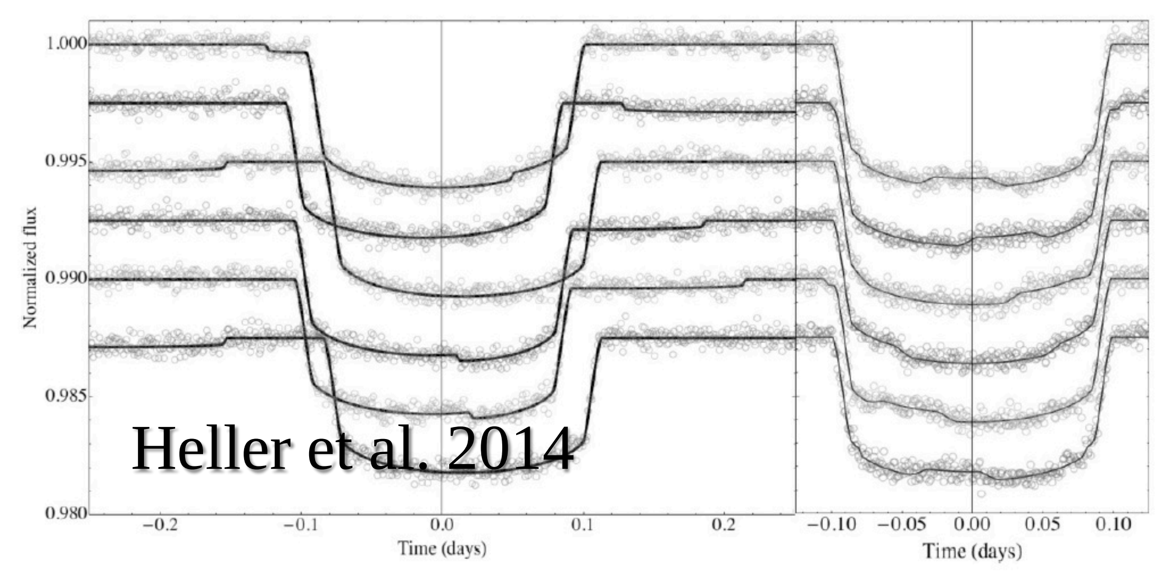
- “The Exoplanet Zoo”
  - What are the demographics of exoplanetary systems?
- “What are exoplanets like?”
  - Comparative exoplanetology: characterize the atmospheric and interior properties of a large diversity of worlds.
- “Our nearest neighbors and the search for life”
  - A census of the nearest planetary systems, the search for potentially habitable worlds, and the search for evidence of life.

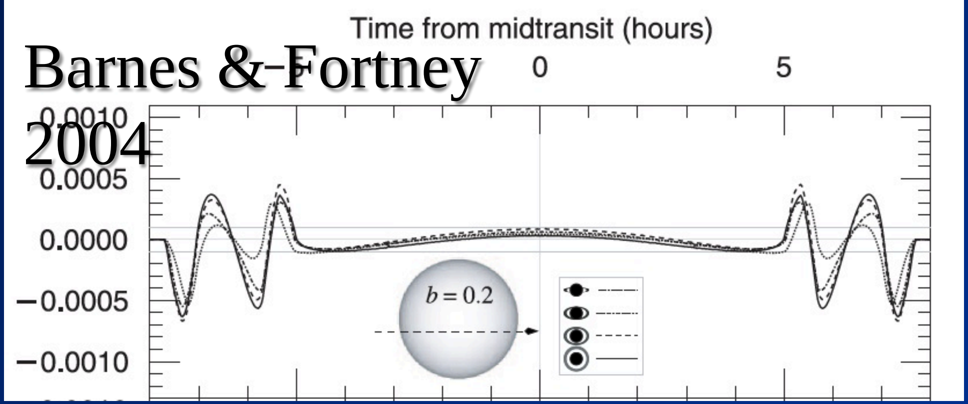
What can we measure?

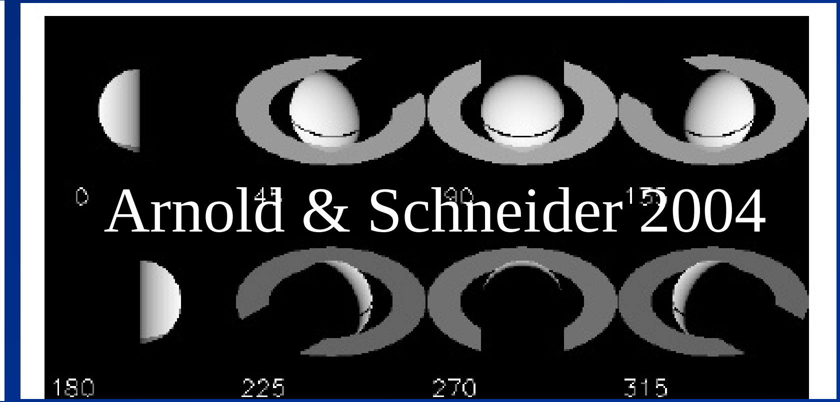
- Orbits and architectures
- Rudimentary physical parameters:
  - Mass, radius, density, surface gravity
- Rudimentary interior and atmosphere constraints:
  - Core mass, presence of an atmosphere
- Atmospheric characterization:
  - P-T profiles, composition, atmospheric dynamics, phase curves, polarization, outflows/exospheres
- Detailed properties:
  - Rotation rates, obliquities, seasons/climate
- Environment:
  - Rings, moons, magnetospheres.

Rings and Moons.


Bennett & Rhie 2002


Heller et al. 2014

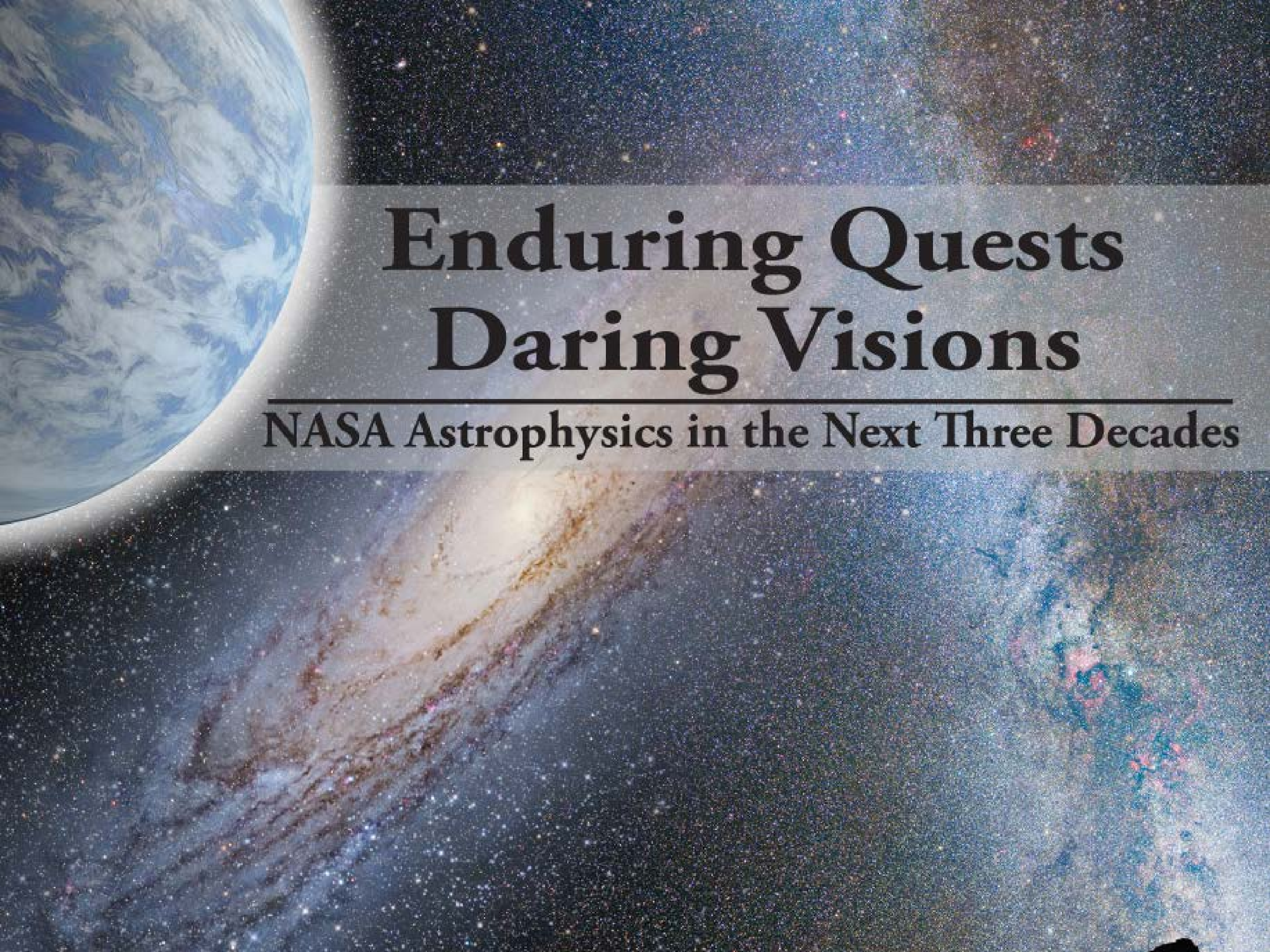

Barnes & Fortney 2004

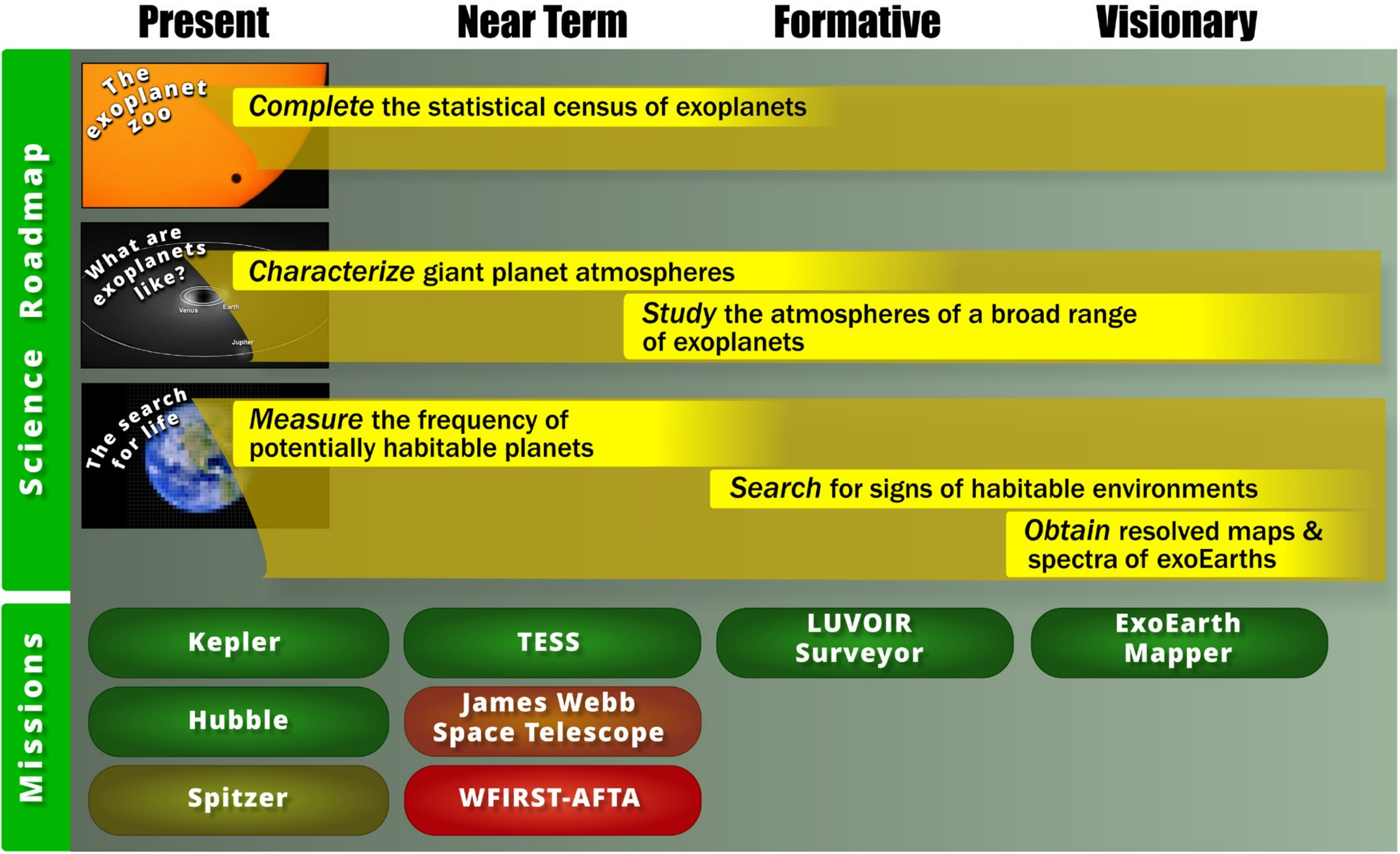

Arnold & Schneider 2004

The Future of Exoplanets.

Enduring Quests
Daring Visions

NASA Astrophysics in the Next Three Decades





Present | **Near Term** | **Formative** | **Visionary**

Science Roadmap

The exoplanet zoo

- *Complete* the statistical census of exoplanets

What are exoplanets like?

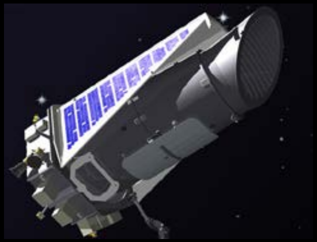
- *Characterize* giant planet atmospheres
- *Study* the atmospheres of a broad range of exoplanets

The search for life

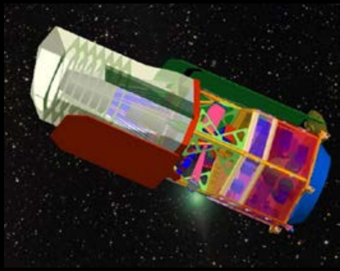
- *Measure* the frequency of potentially habitable planets
- *Search* for signs of habitable environments
- *Obtain* resolved maps & spectra of exoEarths

Missions

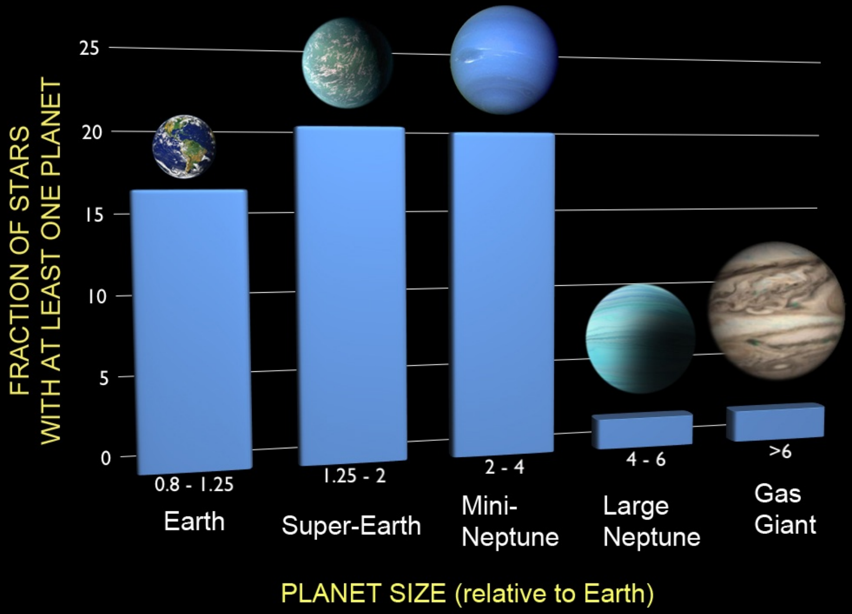
- Present: Kepler, Hubble, Spitzer
- Near Term: TESS, James Webb Space Telescope, WFIRST-AFTA
- Formative: LUVOIR Surveyor
- Visionary: ExoEarth Mapper

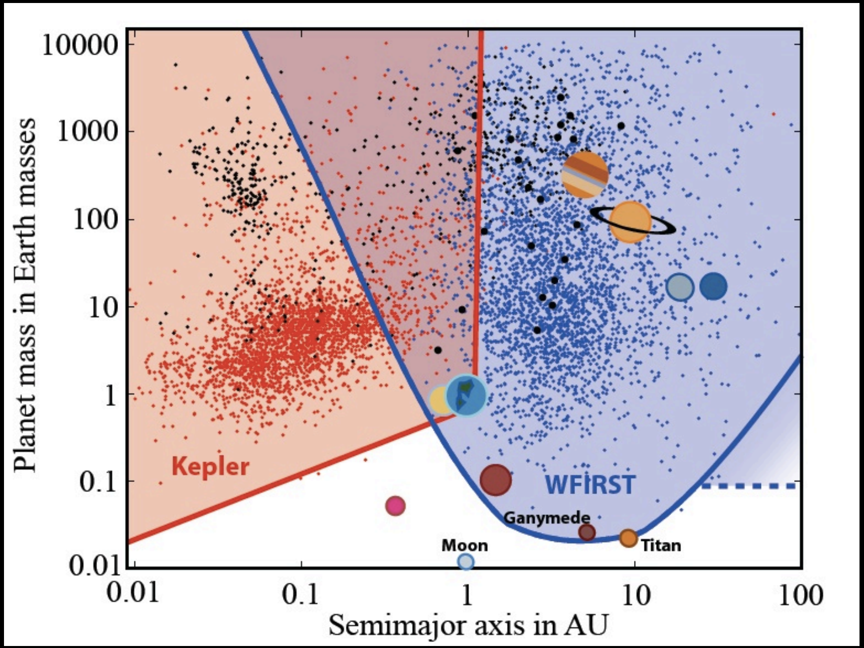


The exoplanet zoo.



***Kepler* has begun the exoplanetary census…**





…that WFIRST will complete.

WFIRST-AFTA.

	WFIRST-AFTA
Eff. Aperture	2.28m
FOV	0.281 deg^2
Wavelengths	0.7-2 µm
FWHM@1µm	0.10”
Pixel Size	0.11”
Lifetime	5+1 years
Orbit	Geosynch.

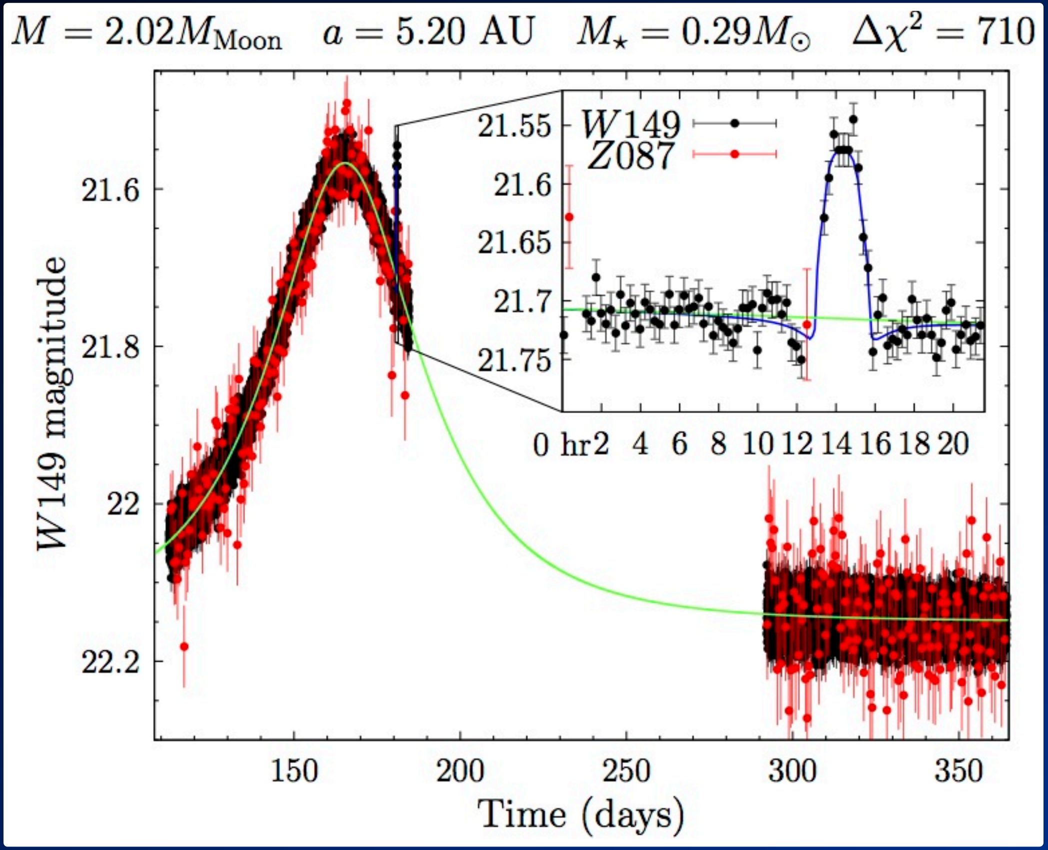
Wide-Field Instrument

- Imaging & spectroscopy over 1000's sq deg.
- Monitoring of SN and microlensing fields
- 0.7 – 2.0 micron bandpass
- 0.28 sq deg FoV (100X JWST FoV)
- 18 H4RG detectors (288 Mpixels)
- 4 filter imaging, grism + IFU spectroscopy

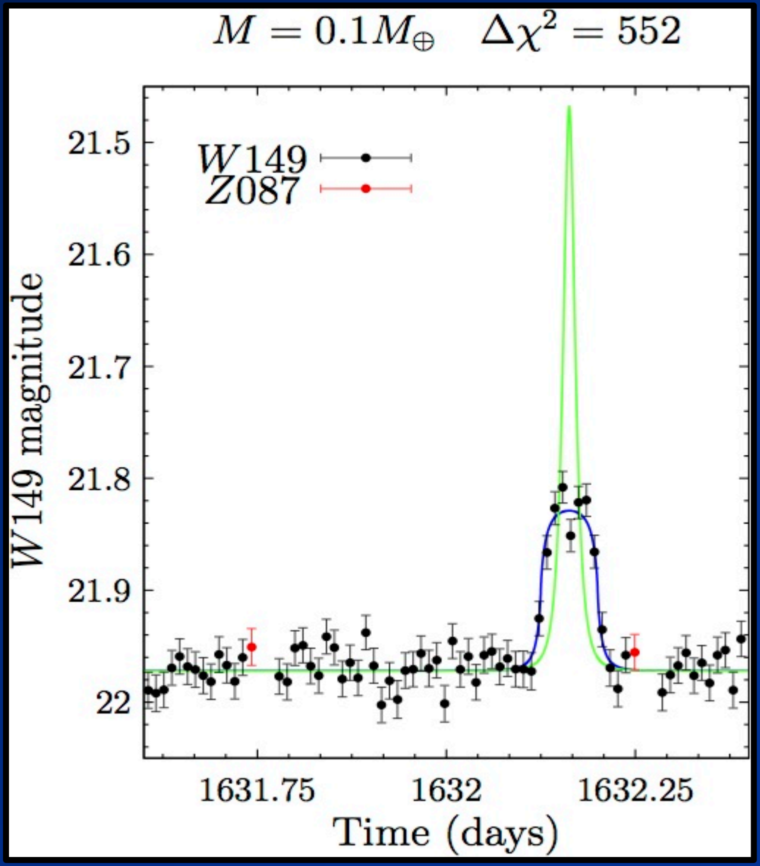
Coronagraph

Imaging of ice & gas giant exoplanets

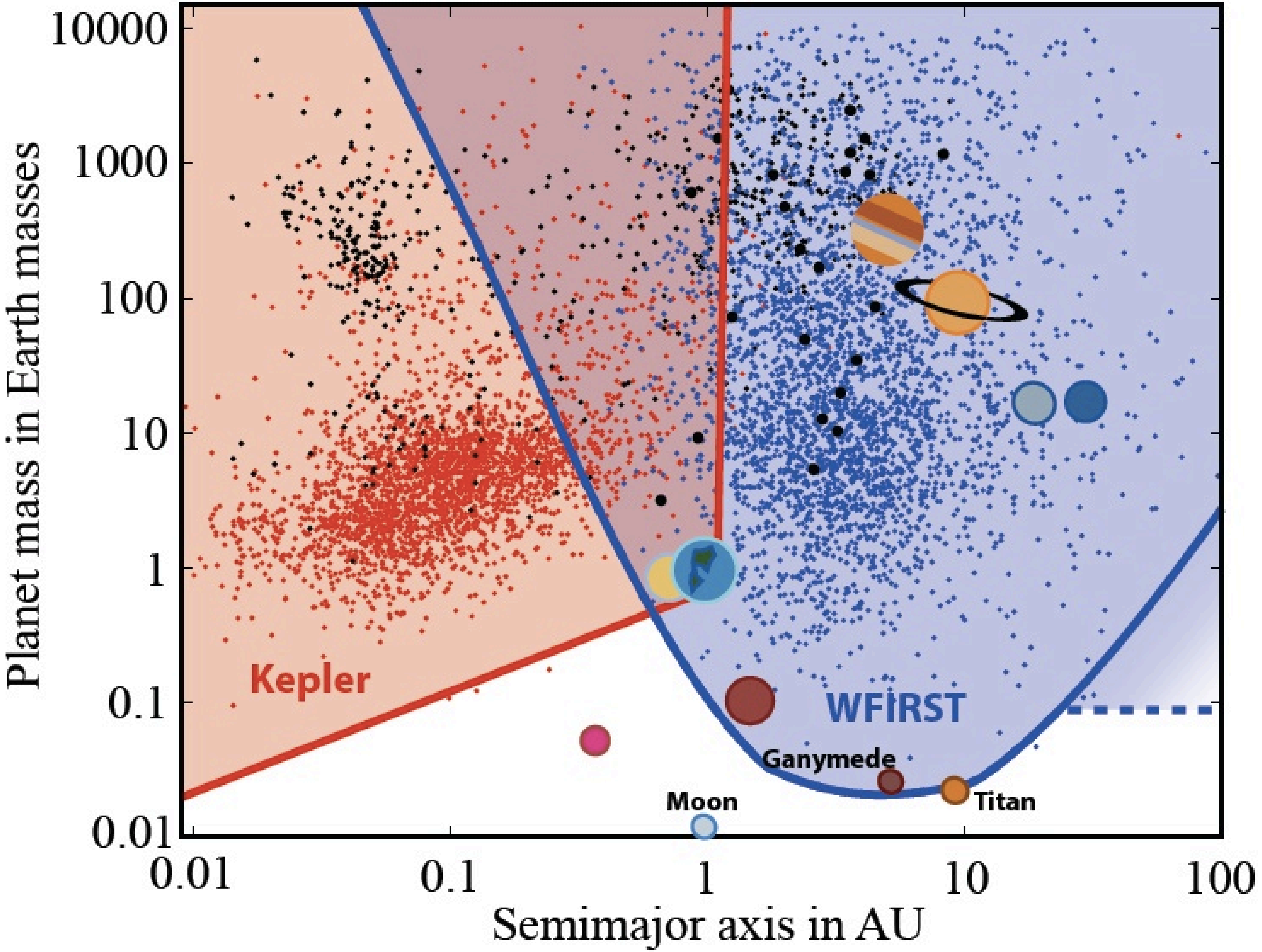
- Imaging of debris disks
- 400 – 1000 nm bandpass
- 10^{-9} contrast
- 200 milli-arcsec inner working angle



2 × Mass of the Moon @ 5.2 AU
(~27 sigma)



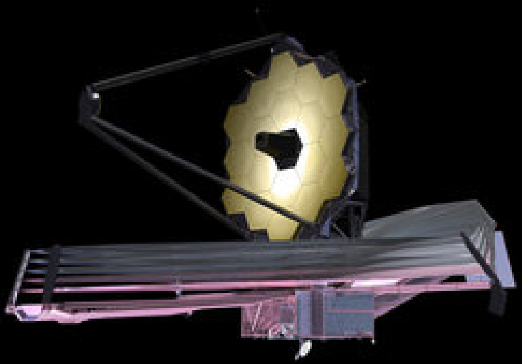
Free floating Mars
(~23 sigma)



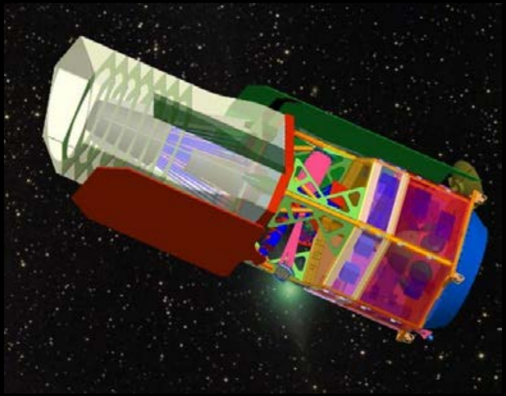
Planet mass in Earth masses
10000
1000
100
10
1
0.1
0.01
0.01
0.1
1
10
100
Semimajor axis in AU
Kepler
WFIRST
Ganymede
Moon
Titan

What are exoplanets like?

We will characterize a broad diversity of planets with…

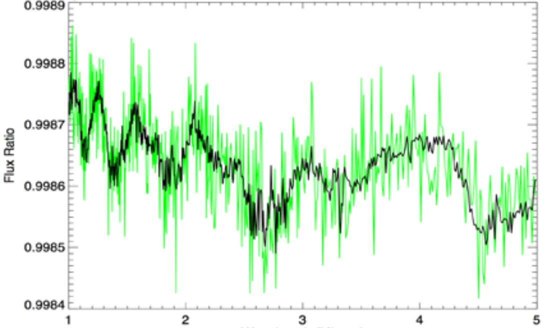


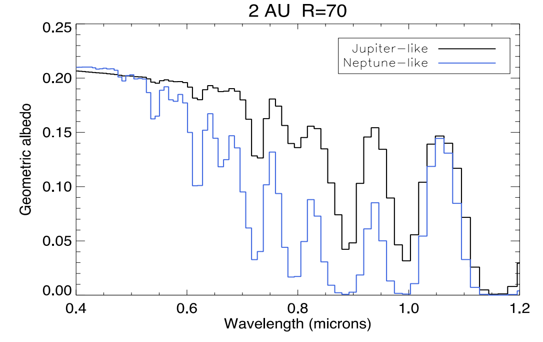
JWST,

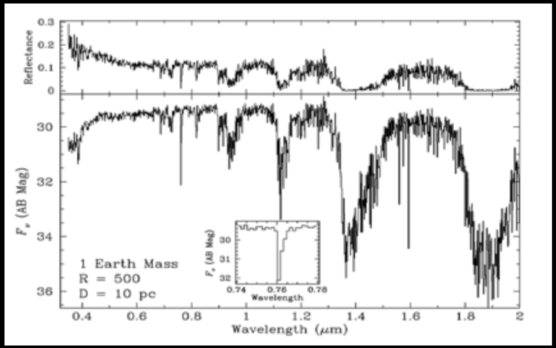


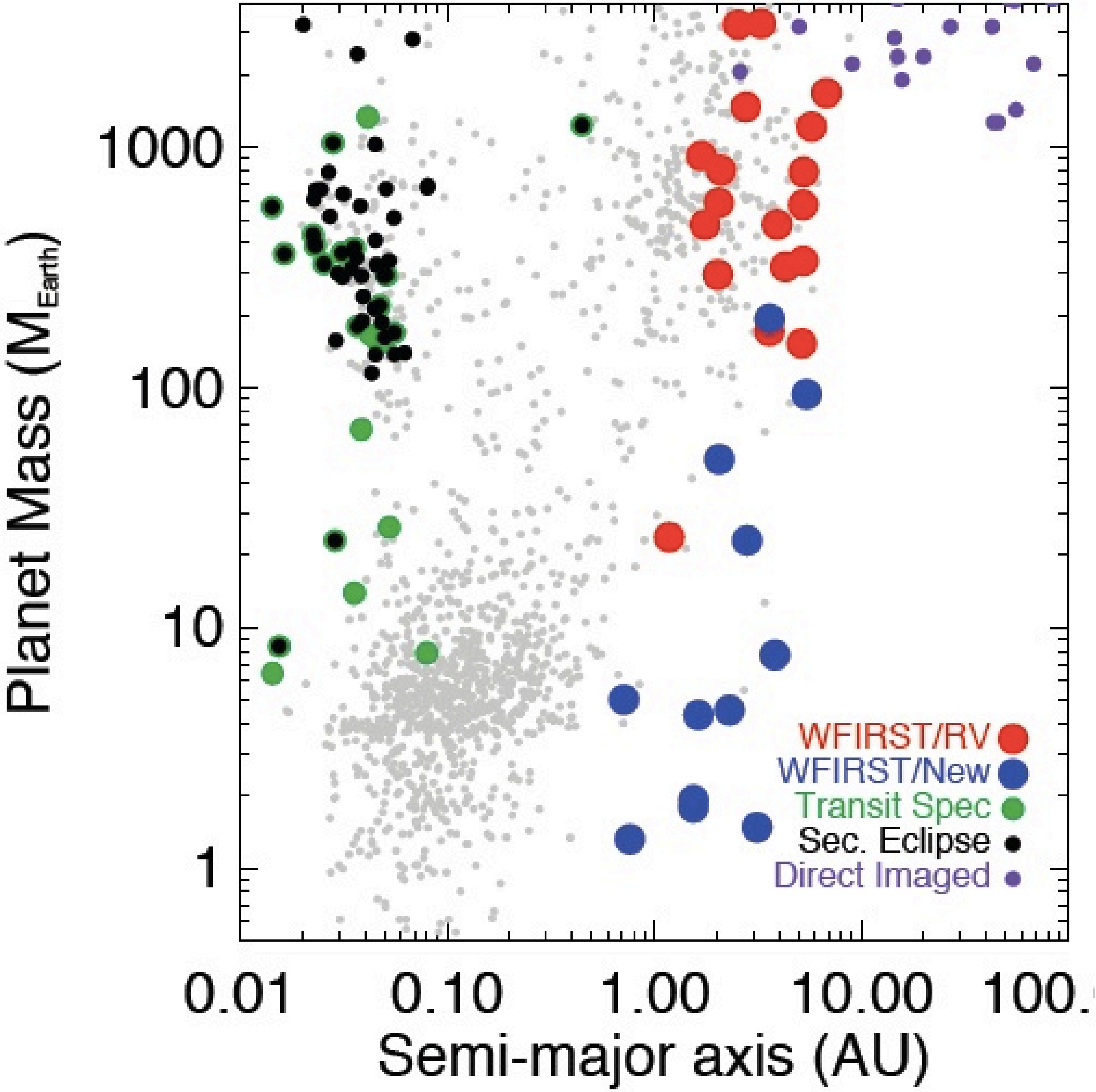
WFIRST-AFTA,

and a large UVOIR telescope…



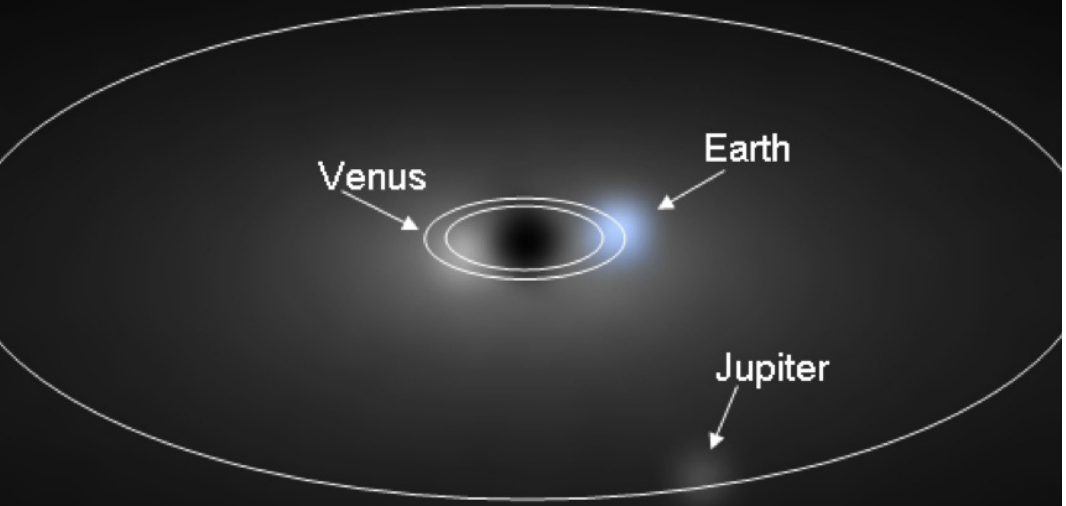


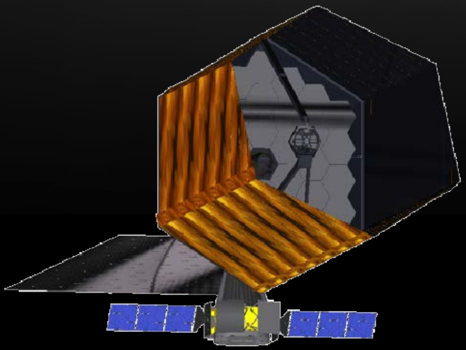


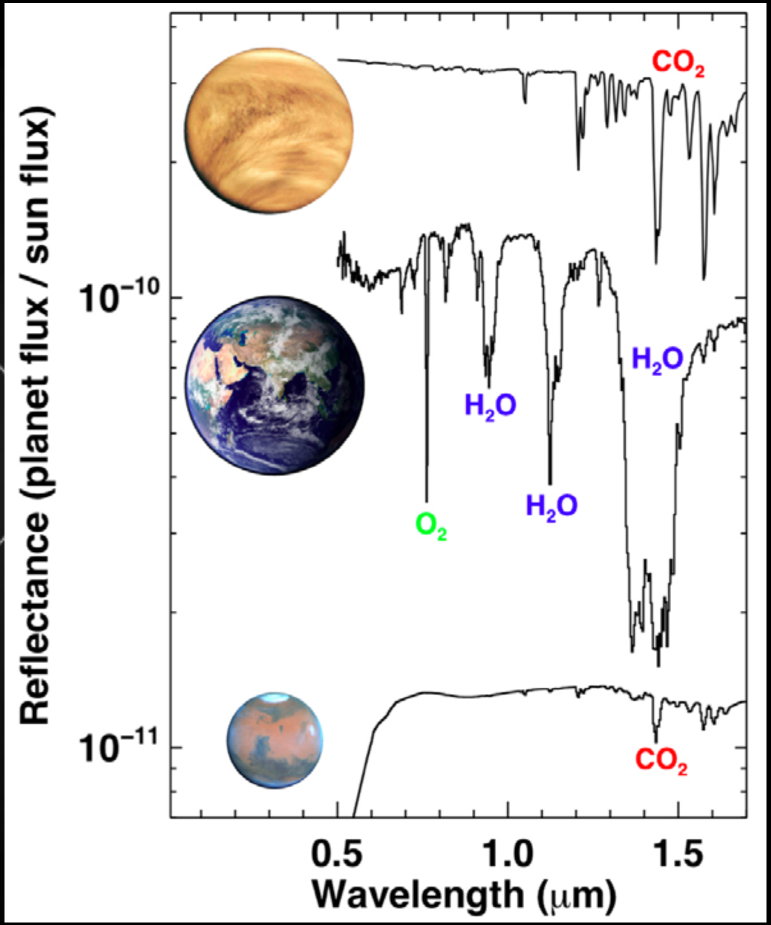

Planet Mass (M_{Earth})
1000
100
10
1
0.01
0.10
1.00
10.00
100.
Semi-major axis (AU)
WFIRST/RV
WFIRST/New
Transit Spec
Sec. Eclipse
Direct Imaged

The Pale Blue Dot.

We will find potentially habitable planets…

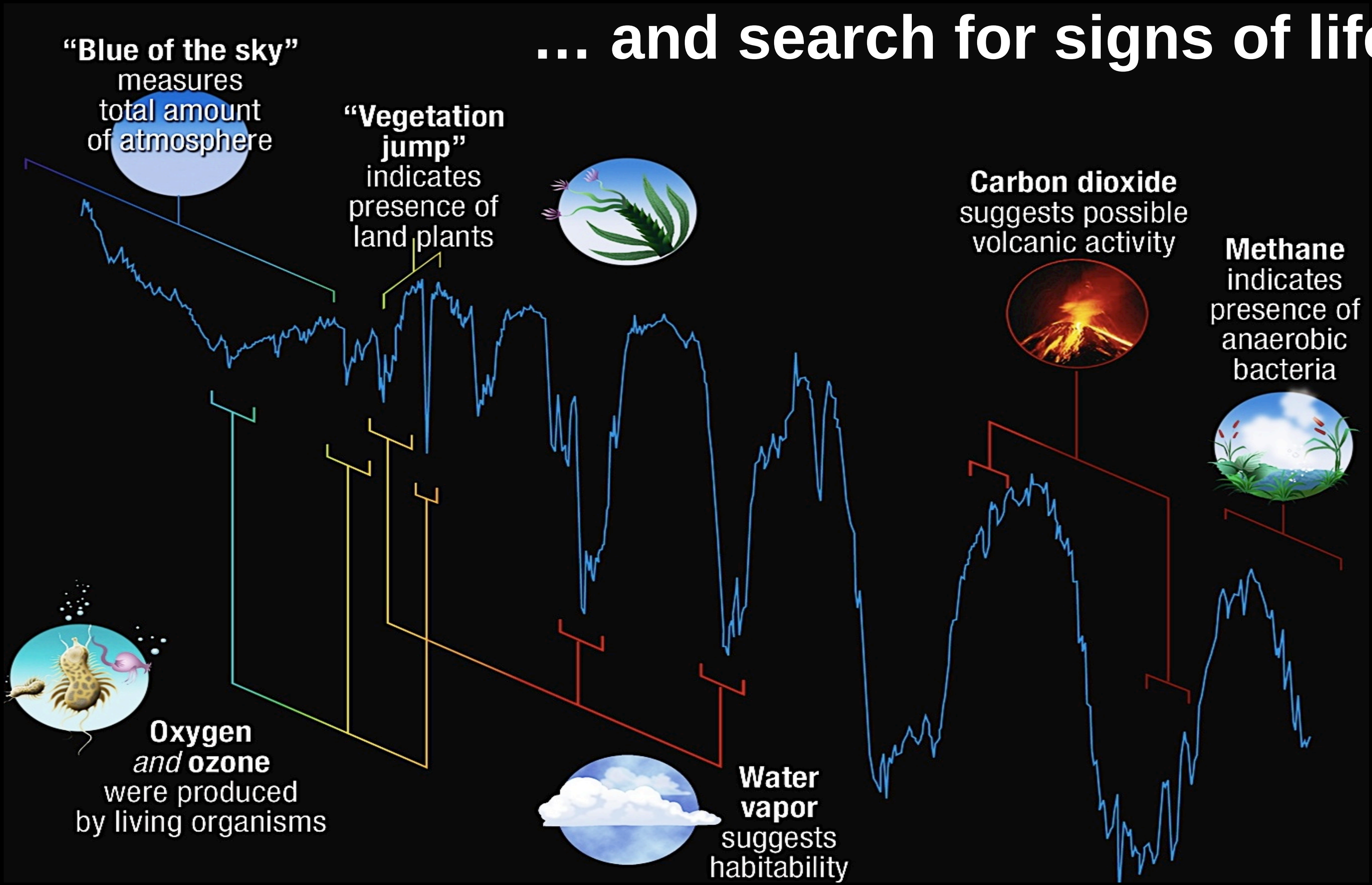




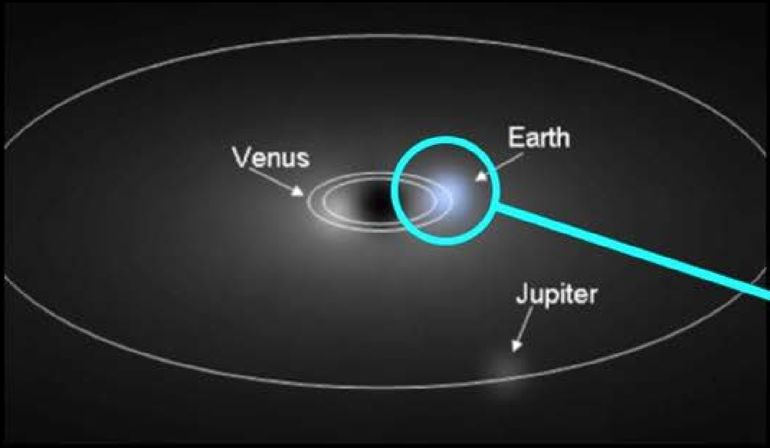


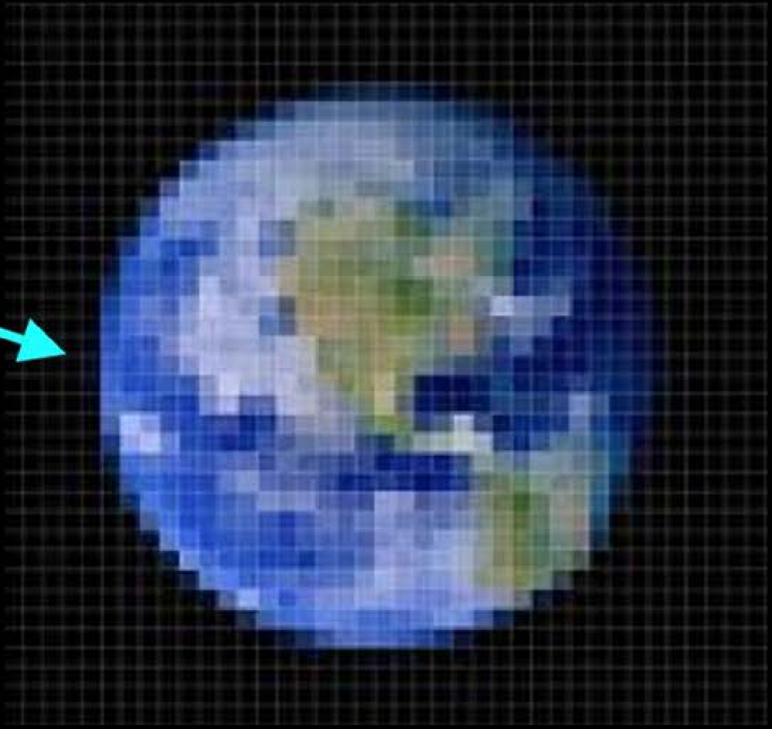
The Search for Life.

… and search for signs of life…



Mapping Earths.





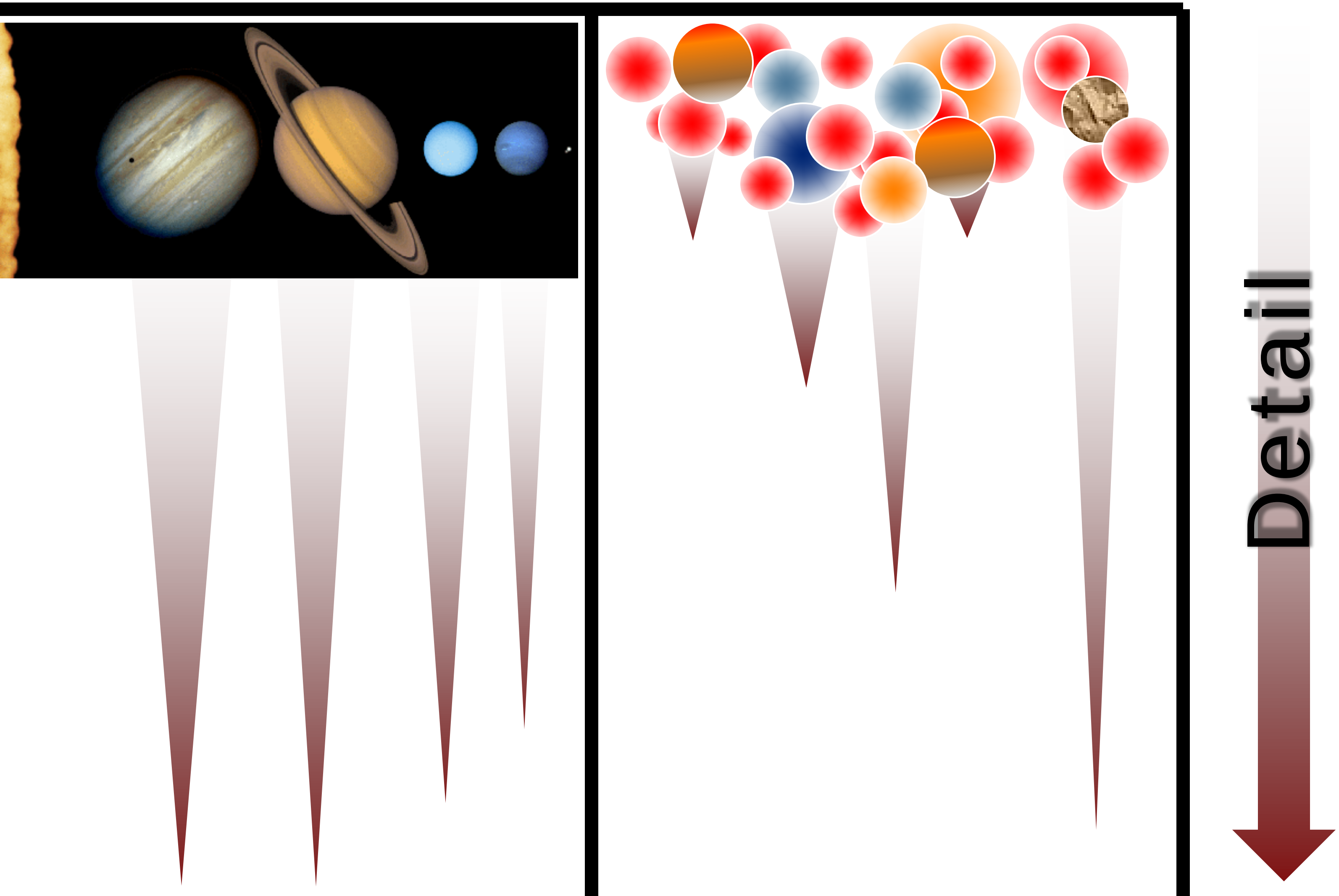
… and ultimately map the surfac
of “ExoEarth 2.0.”

Exoplanet/Outer Solar System Synergy.

Complementarity.

Outer Solar System
(Narrow + Deep)

Exoplanets
(Broad + Shallow)



Orbits and architectures

Rudimentary physical parameters

Rudimentary interior and atmosphere constraints

Atmospheric characterization

Detailed properties

Environment

Connections and Synergies.

- Primary science goals have substantial overlap.
- Approaches are complementary.
  - Broad but shallow, versus narrow but deep.
    - Outer SS: small number of objects with lots of information
    - Exoplanets: large number of objects with much less information.
  - Identify dominant physical parameters that dictate observables:
    - Use detailed physical models developed for SS objects to identify candidate parameters
    - Test these using the wide variations available for exoplanets.
    - i.e., is the total mass in natural satellites proportional to planet mass?

Interactions.

- Now:
  - – Help us understand how to interpret our observations.
    - e.g., interpretation of low R, low SNR spectra
    - e.g., interpretation of unresolved phase curves of exoplanets
- Future:
  - – Help you understand the solar system.
    - e.g., what do the architectures of exoplanetary systems say about the formation of the solar system.

Immediate/Near Future.

- General, programmatic:
  - Cross-PAG participation.
  - Decadal survey coordination.
- Specific, programmatic:
  - Input into Paul Hertz’s charge to the Astrophysics PAGs to recommend large missions for study for the next decadal survey.
- Specific, science:
  - What observations can be made of the giant planets that will enable interpretation of, and planning for, future observations of exoplanets?
  - What do the currently-favored solar system formation models predict about the architectures of other systems?
  - Your ideas here!

NASA's Charge to the PAGs.

"I am charging the Astrophysics PAGs to solicit community input for the purpose of commenting on the small set [of large mission concepts to study], including adding or subtracting large mission concepts."

Initial list of missions.

- Far IR Surveyor
- Habitable-Exoplanet Imaging Mission
  - 4m? 5m? Coronagraph? Starshade?
- UV/Optical/IR Surveyor
  - >8m? Coronagraph? Starshade?
  - 10 m: 0.025'' resolution @ 1 micron (~100 km @ Jupiter, ~550 km at Neptune)
- X-ray Surveyor

Backup Slides.

Detailed Charge, Part 1.

1. Each PAG, under the leadership of its Executive Committee, shall broadly solicit the astronomy and astrophysics community for input to the report in an open and inclusive manner.
    - To accomplish this, each PAG is empowered to envision and use its own process.
2. Each PAG will consider what set of mission concepts should be studied to advance astrophysics as a whole; there is no desire for mission concepts to be identified as “belonging” to a specific Program or PAG.
    - Each PAG shall keep the number of large mission concepts in the set as small as possible.
    - Each PAG is specifically charged to consider modifications and subtractions from the small set, and not just additions.
3. Each PAG shall produce a report, where it shall comment on all large mission concepts in its small set of large missions, including those in the initial small set and those added or subtracted.
    - The PAGs may choose to work together and submit coordinated or joint reports.

Detailed Charge, Part 2.

4. Each PAG may choose to have a face-to-face meeting or workshop I in developing its report; said meeting may be scheduled in proximity to an existing community meeting or conference.
5. Although there is no page limit for the report, each PAG shall strive to be succinct.
6. Each PAG shall submit its report in writing no later than two weeks prior to the Fall 2015 meeting of the NAC Astrophysics Subcommittee (meeting schedule not yet known).