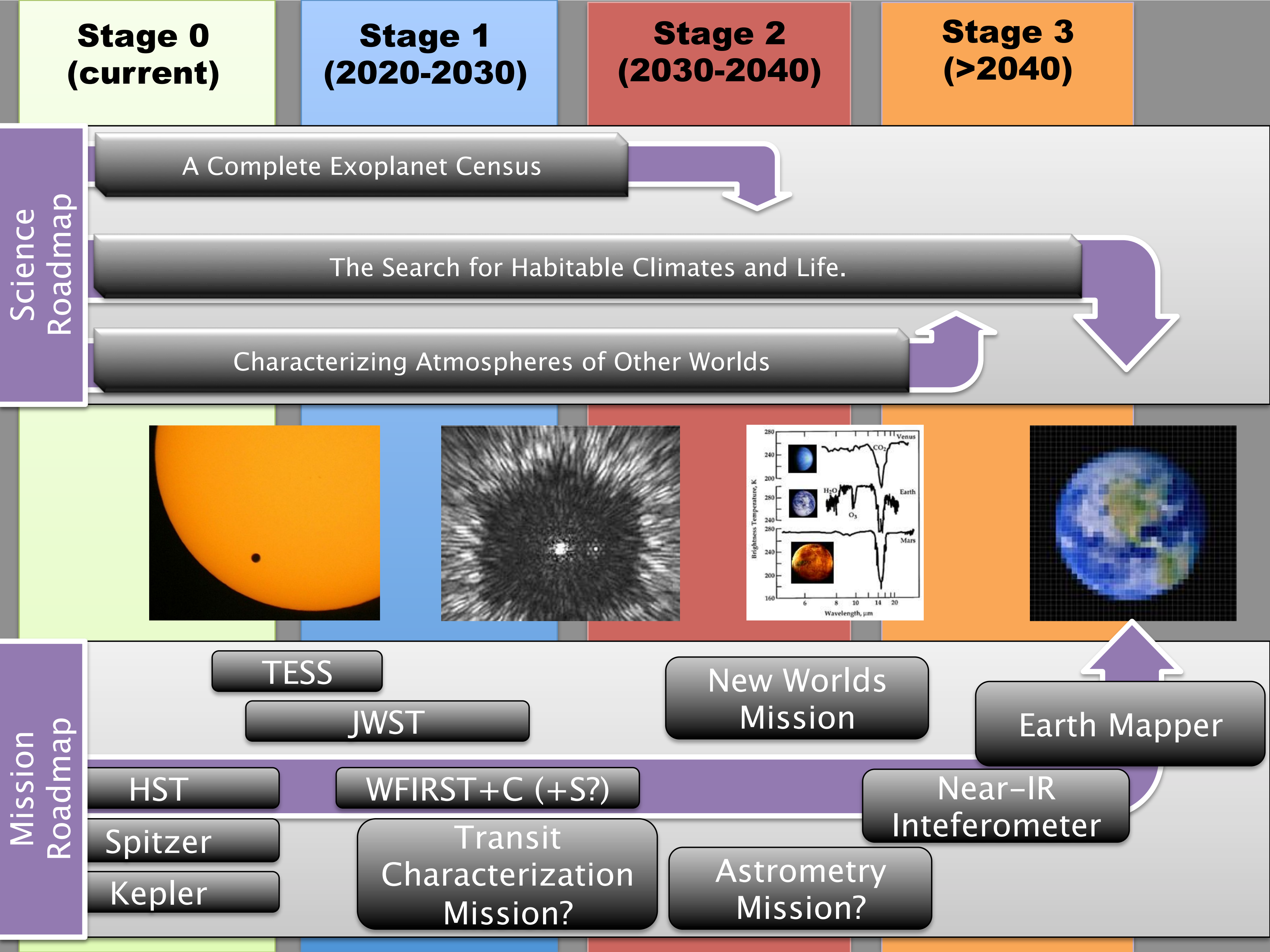
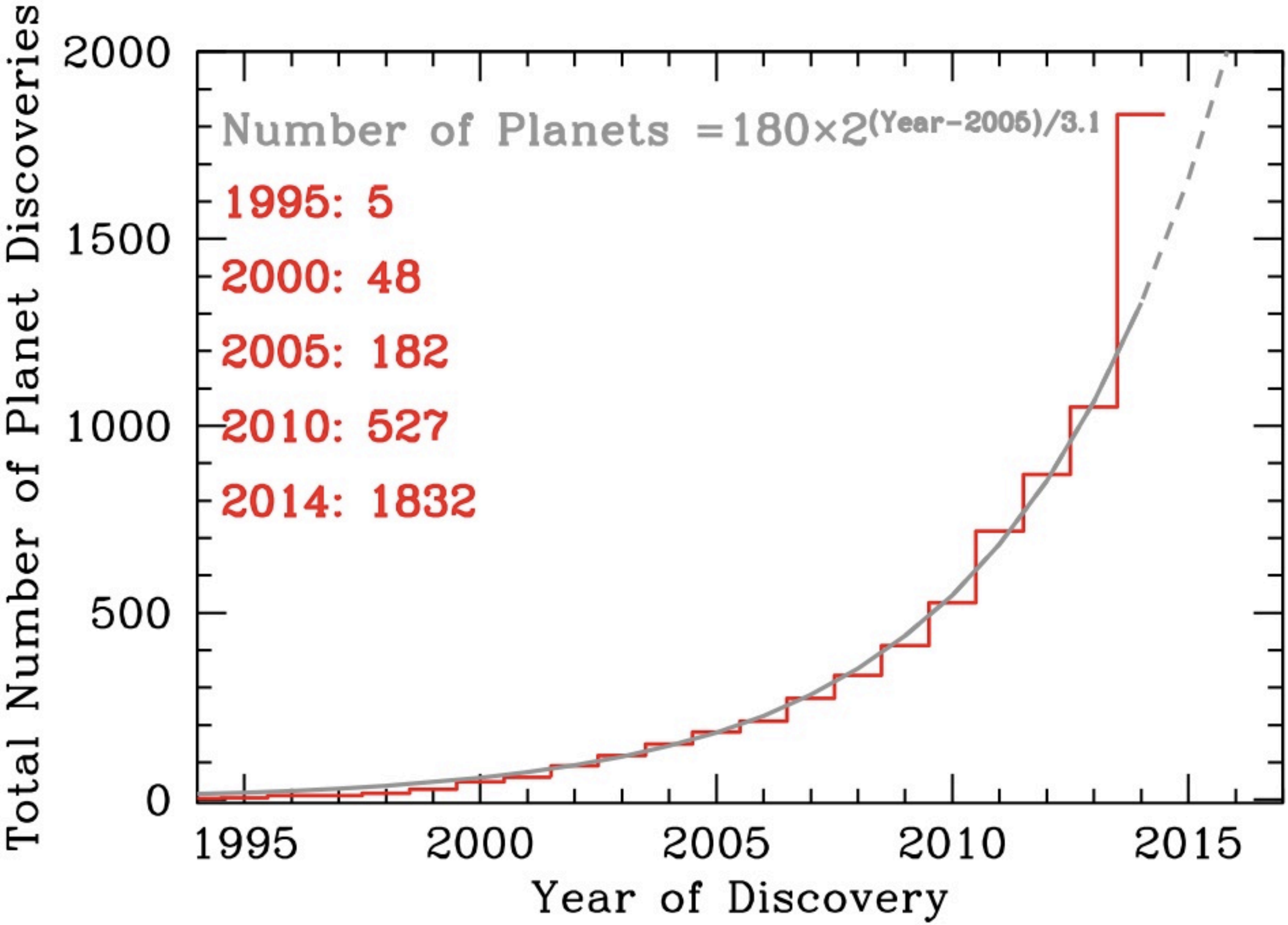
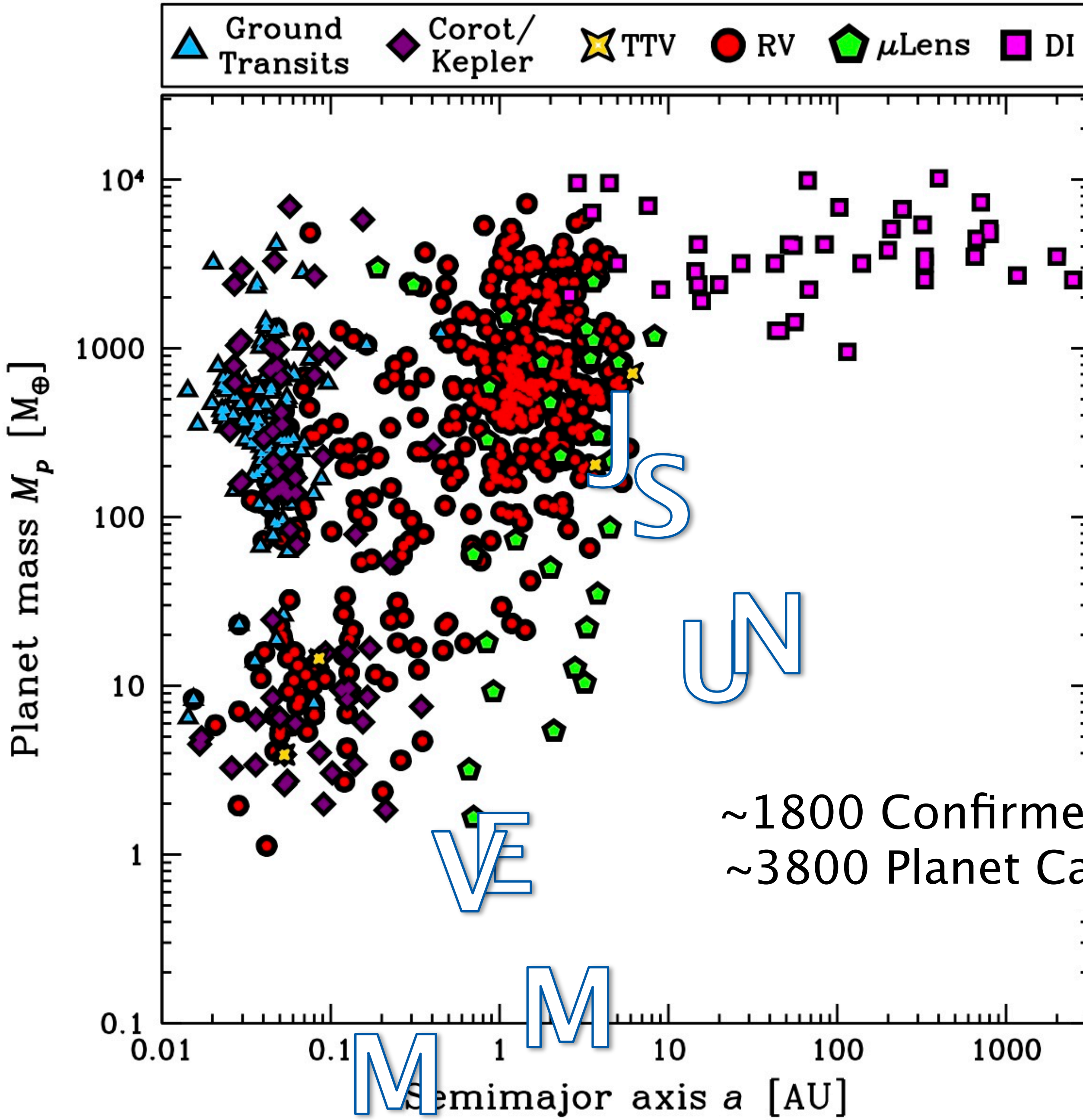

Stage 0 (current)
Stage 1 (2020-2030)
Stage 2 (2030-2040)
Stage 3 (>2040)
Science Roadmap
A Complete Exoplanet Census
The Search for Habitable Climates and Life.
Characterizing Atmospheres of Other Worlds
Venus
Earth
Mars
Brightness Temperature, K
Wavelength, μm
Mission Roadmap
TESS
JWST
New Worlds Mission
Earth Mapper
HST
WFIRST+C (+S?)
Near–IR Inteferometer
Spitzer
Kepler
Transit Characterization Mission?
Astrometry Mission?



Number of Planets =180×2^(Year-2005)/3.1
1995: 5
2000: 48
2005: 182
2010: 527
2014: 1832
Total Number of Planet Discoveries
Year of Discovery
0
500
1000
1500
2000
1995
2000
2005
2010
2015

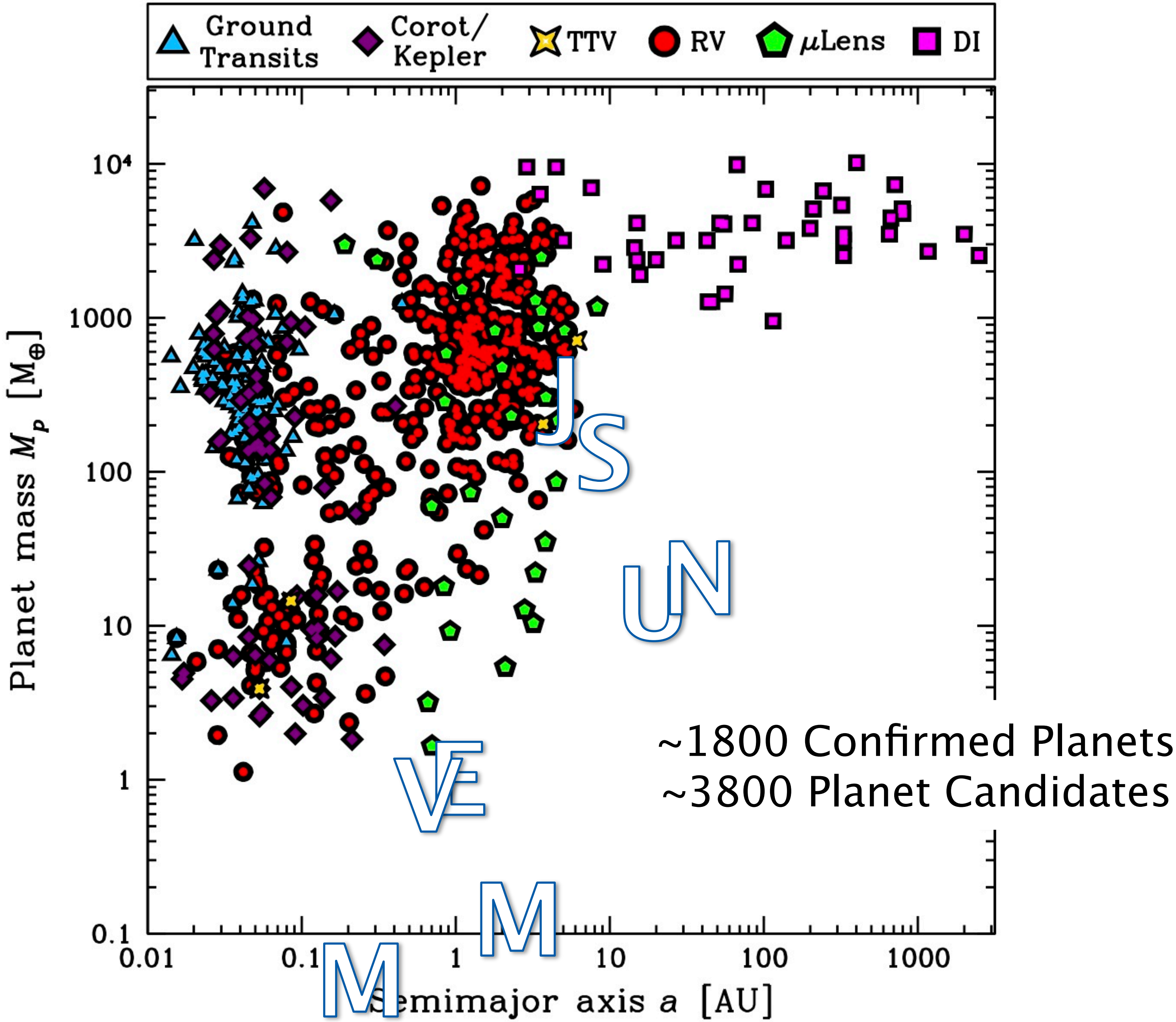


~1800 Confirmed Planets
~3800 Planet Candidates

What we’ve learned.

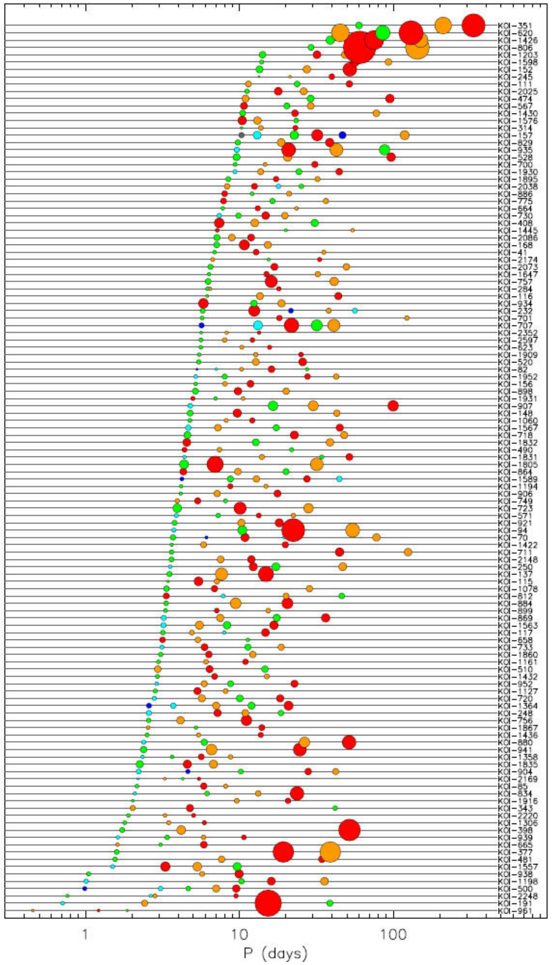
What we've learned about: Demographics

Mother nature is more imaginative than we are.

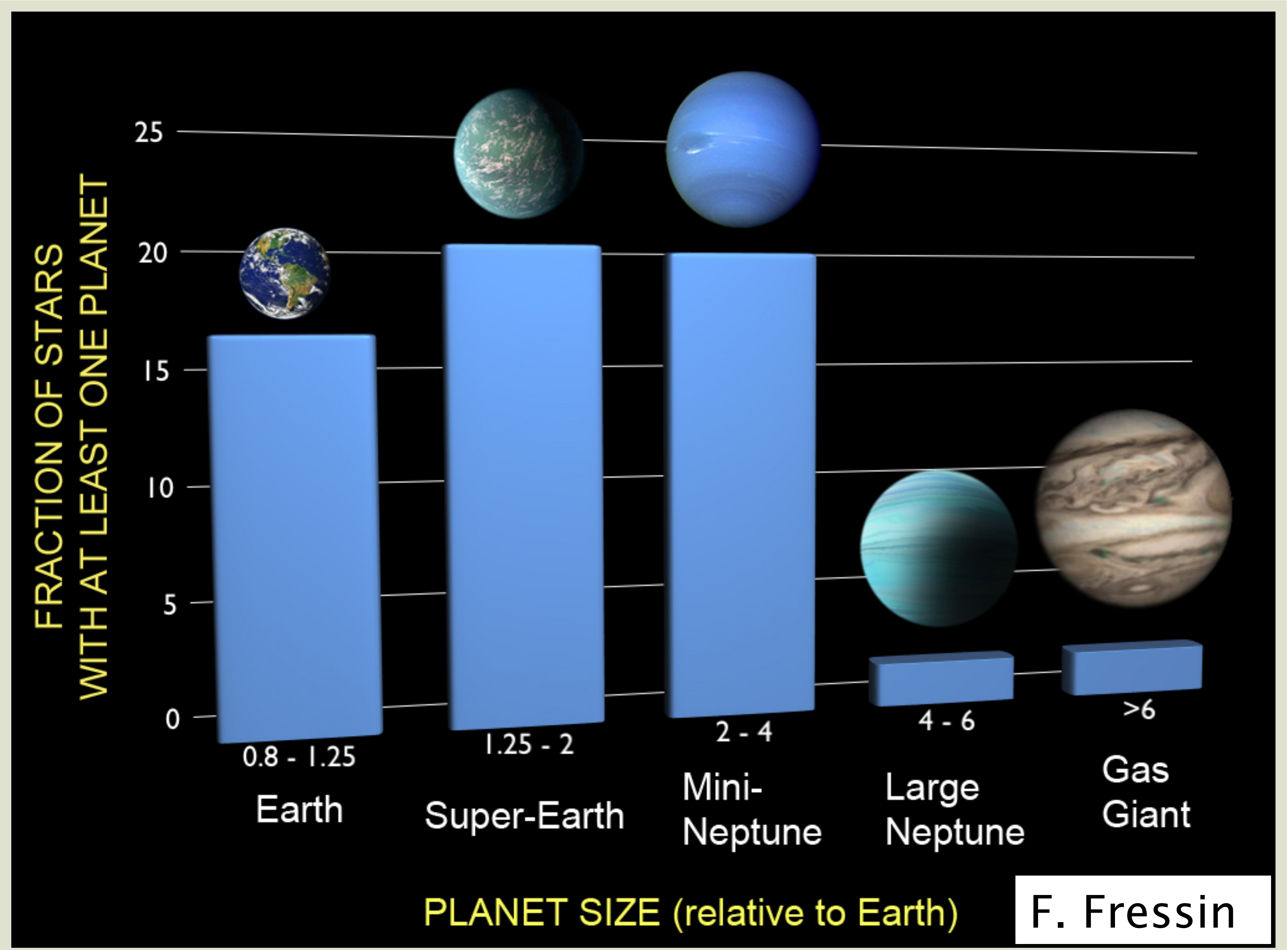

Ground Transits
Corot/ Kepler
TTV
RV
μLens
DI
Planet mass M_p [$M_\oplus$]
Semimajor axis a [AU]
J
S
U
N
V
E
M
M
~1800 Confirmed Planets
~3800 Planet Candidates

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.

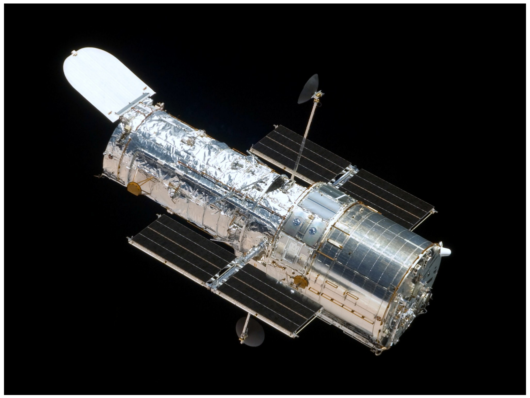


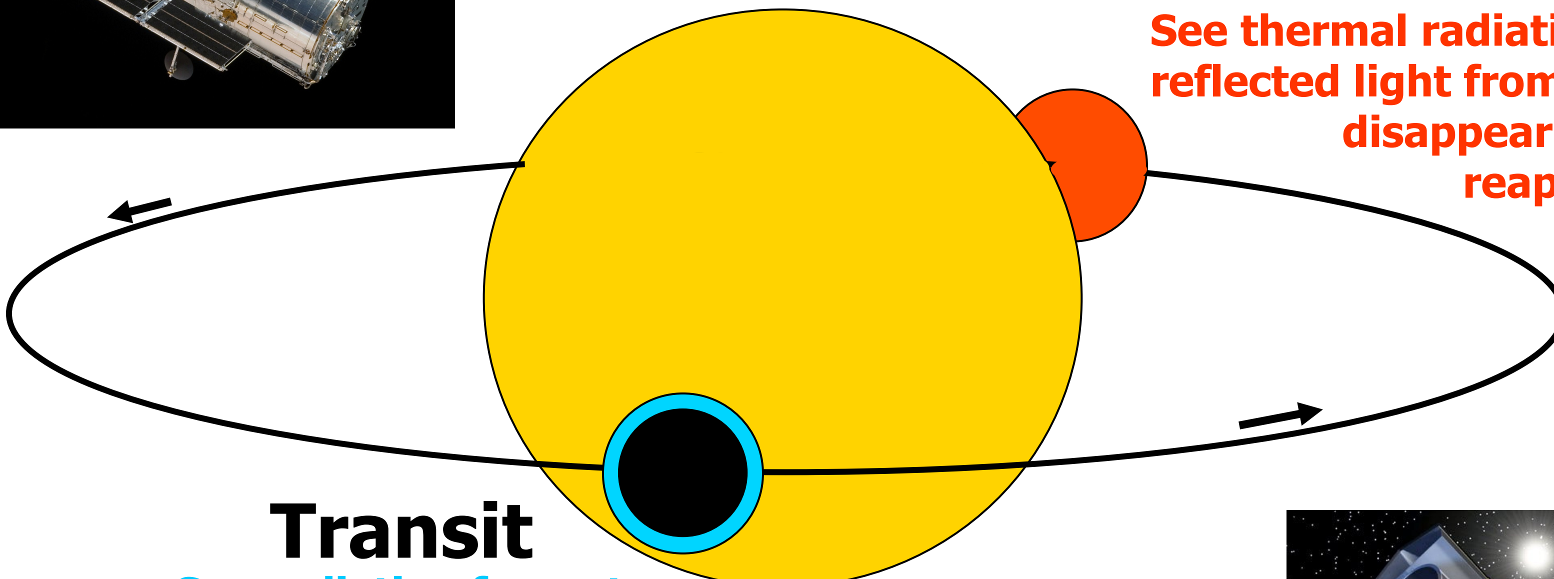
D. Fabrycky


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)
F. Fressin

What we’ve learned about: Characterization.

Mostly from transiting planets, and *mostly* from Hot Jupiters.

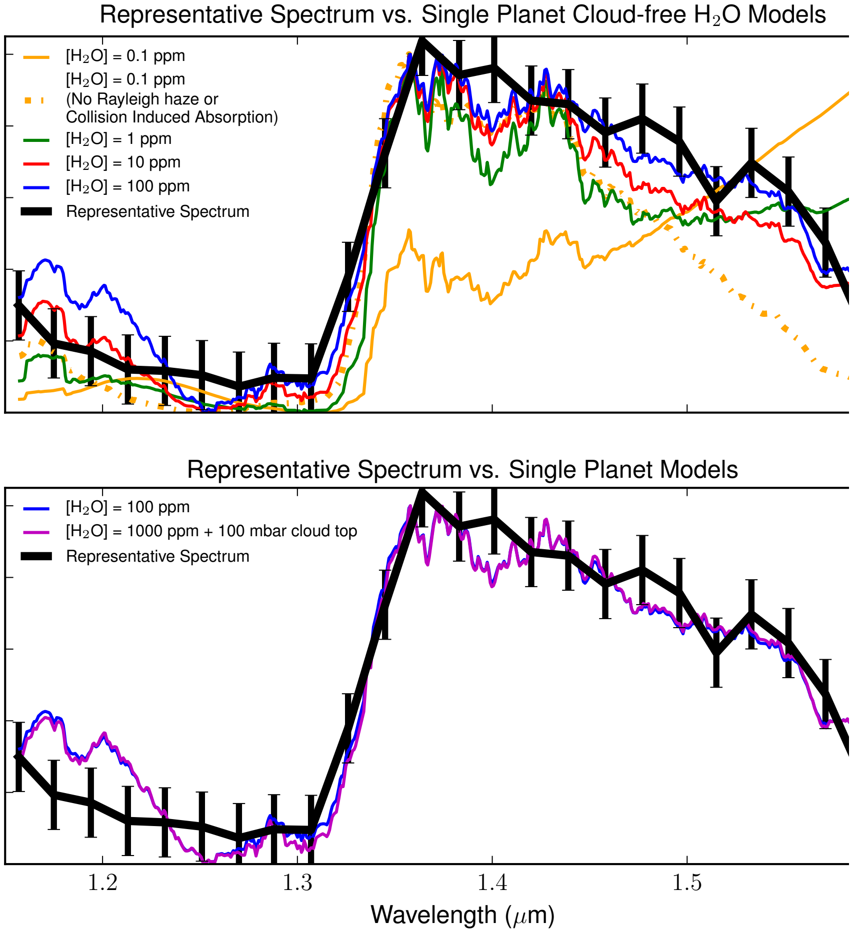




S. Seager

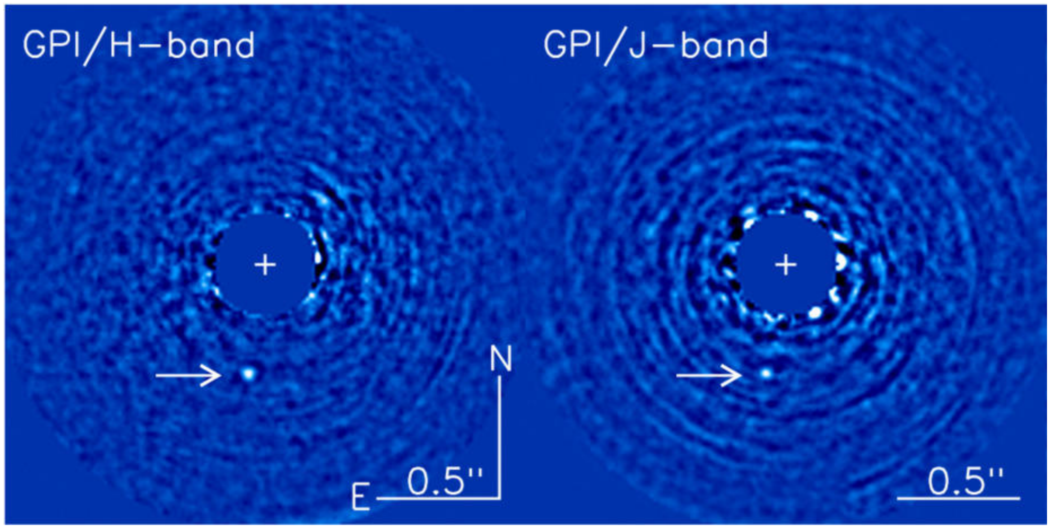
What we've learned.

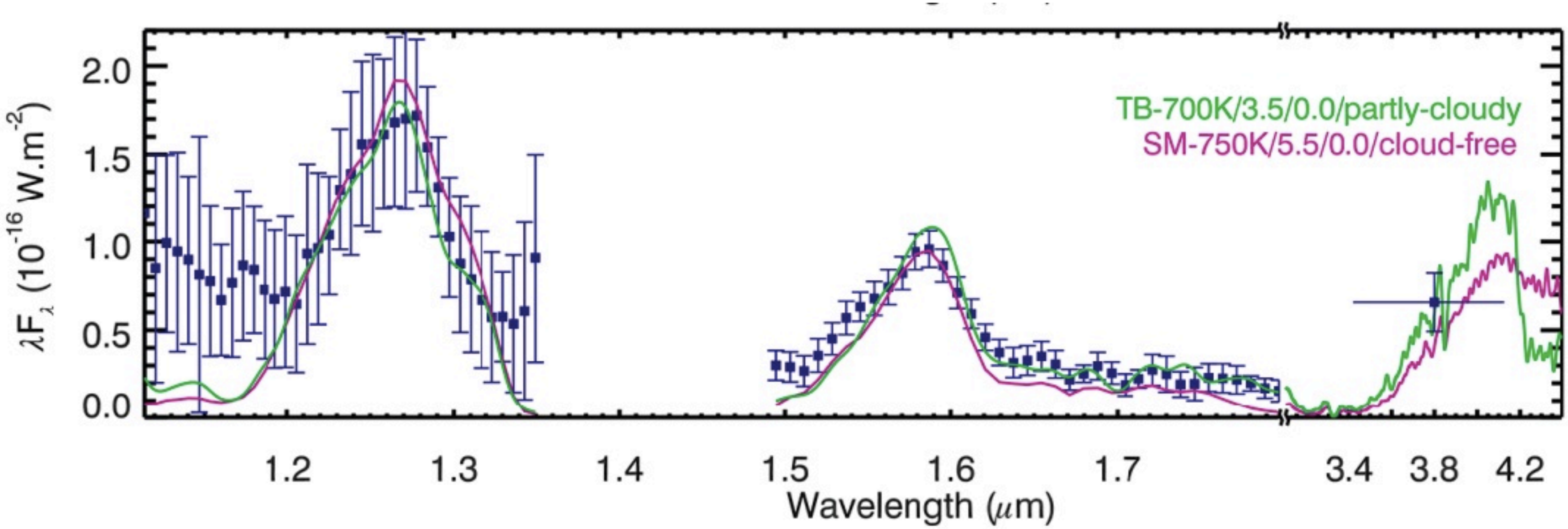
- Water appears to be ubiquitous.
- Clouds/hazes are likely important.
- Range of the amount of thermal redistribution.
- Controlling systematics is key.
- Really just scratching the surface:
  - For transits, a large, comprehensive, coordinated survey with broad wavelength coverage, better control of systematics, and larger range of planet properties is needed.
  - Need to directly image and characterize old planets in reflected light.



Iyer et al. 2015

Some results from directly-imaged young planets: stay tuned!





MacIntosh et al. 2015

What we’ve learned about: The Search for Life.

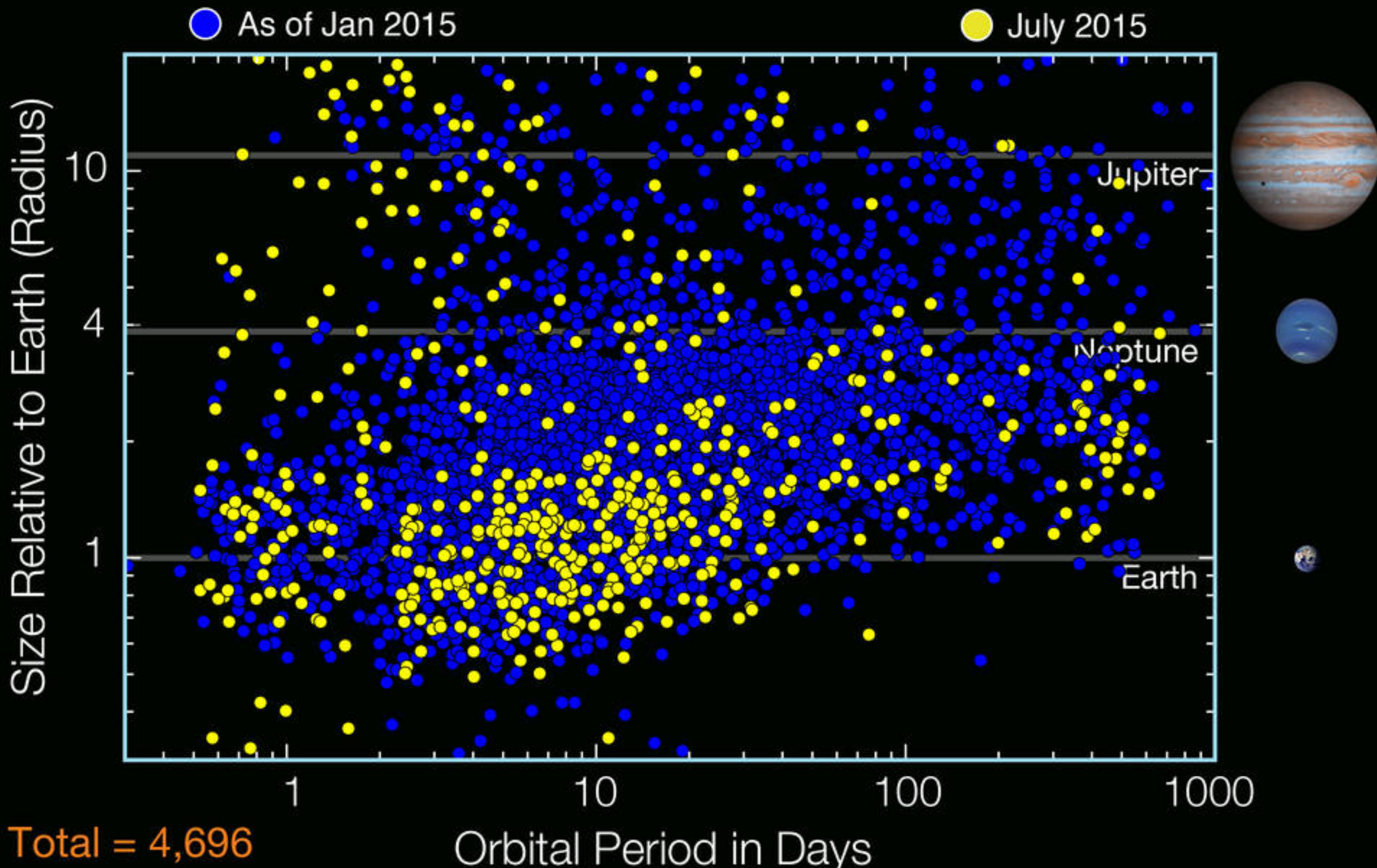
The Search for Life.

- Small planets are common.
- Estimates of the frequency of potentially habitable planets (η_{Earth}) vary by more than an order of magnitude.
- Technology to detect Earth analogs is advancing rapidly.
- There are two (or four) paths you can go by.
- False positives may be more of a concern than previously thought.

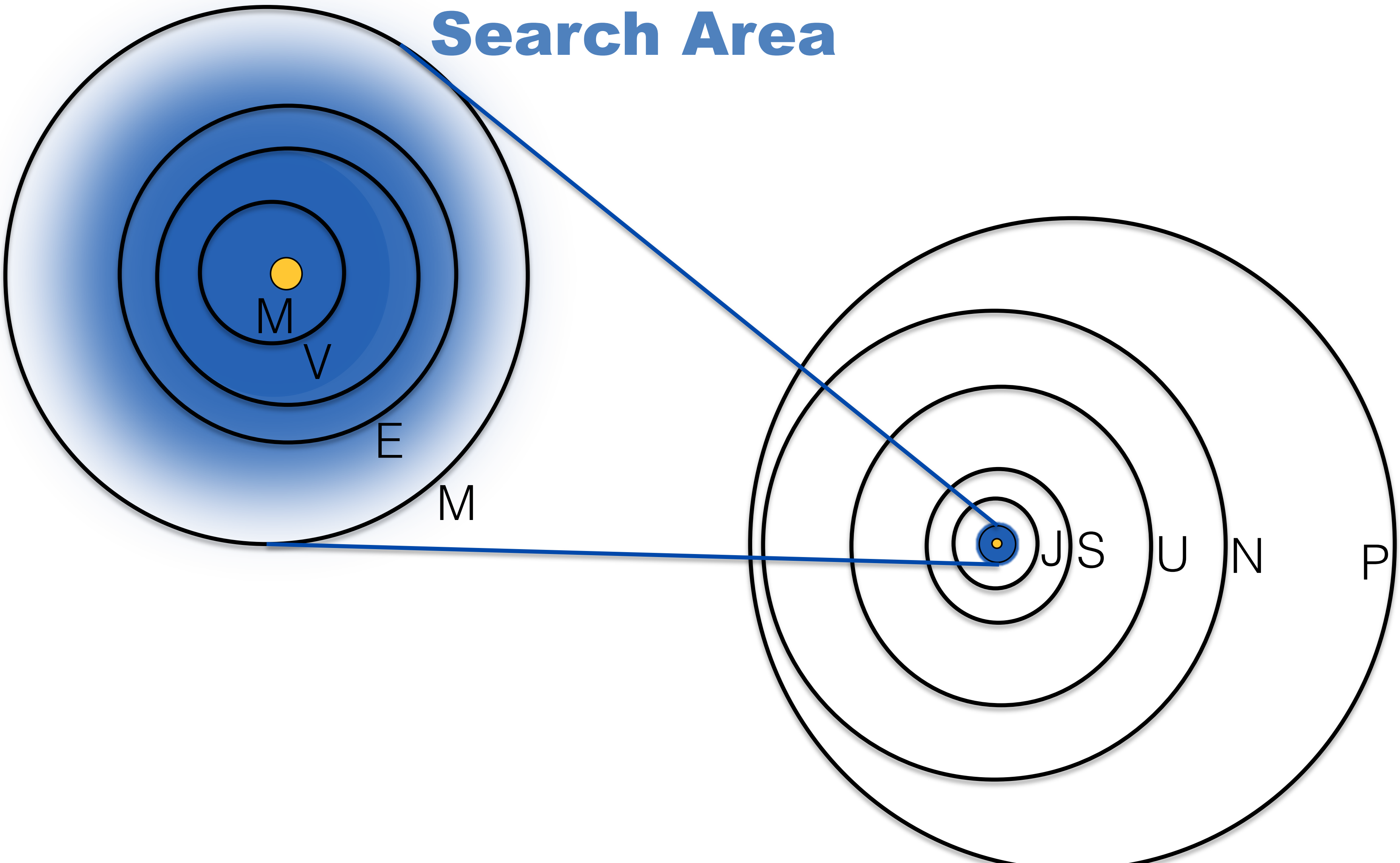
A Complete Exoplanet Census.

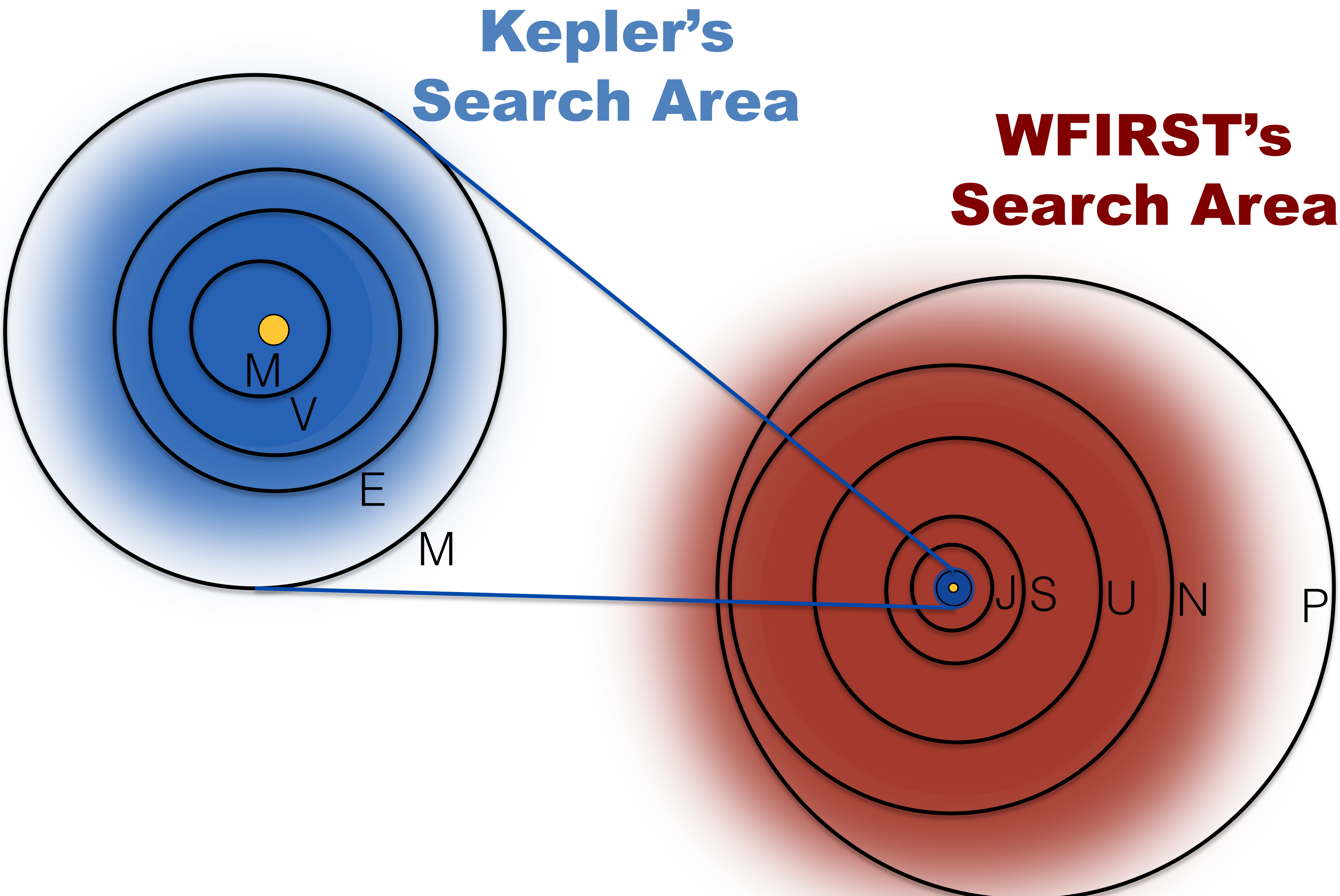
New Kepler Planet Candidates

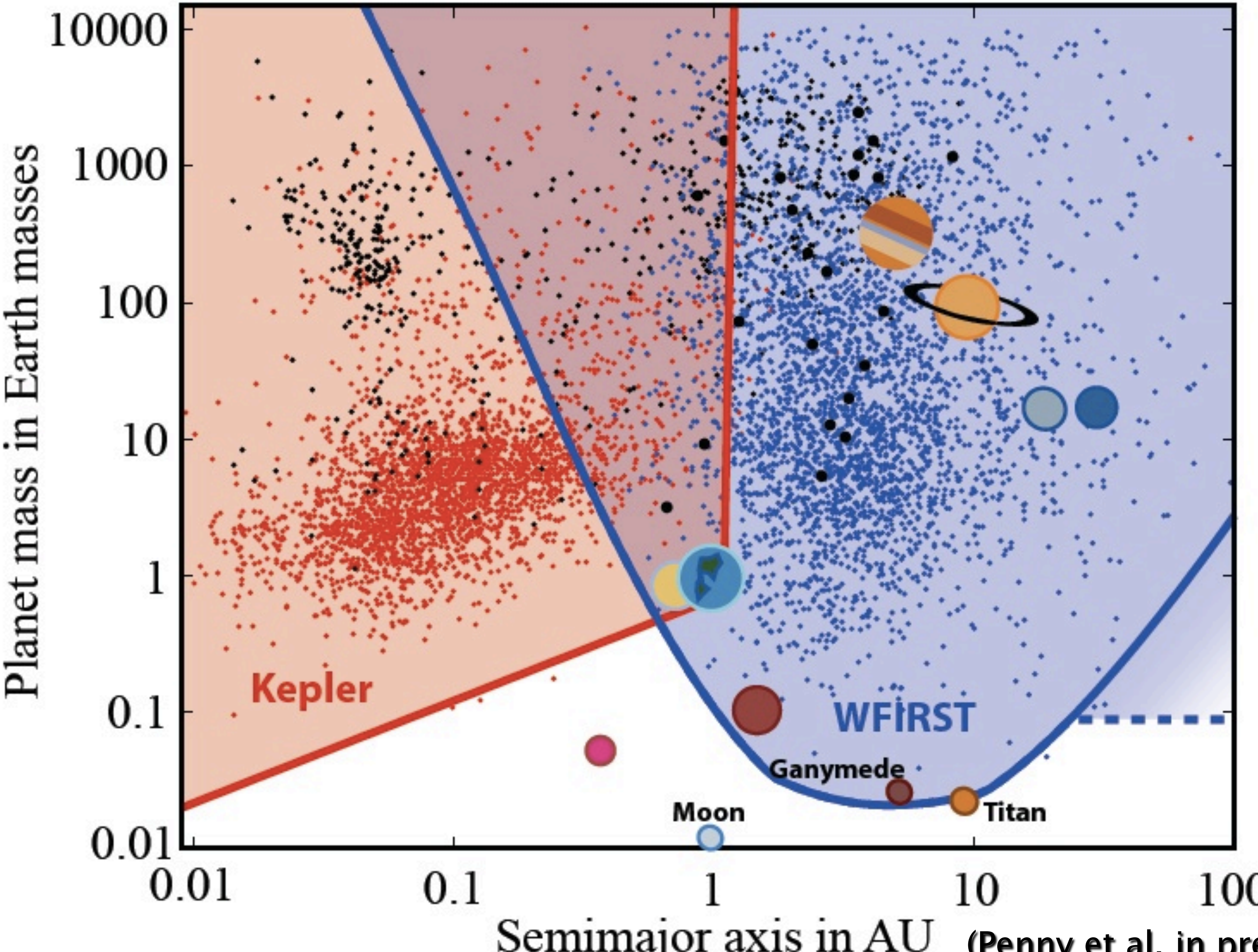
As of July 23, 2015



Kepler's Search Area




Kepler's
Search Area
WFIRST's
Search Area
M
V
E
M
J
S
U
N
P



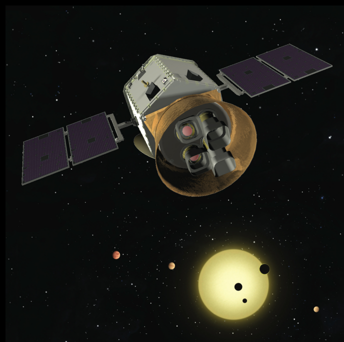
(Penny et al. in prep)

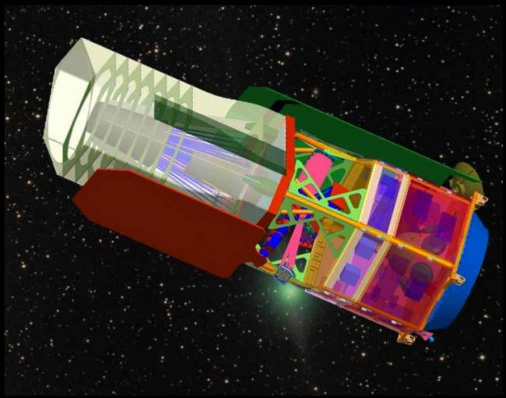
Characterizing the Atmospheres of Other Worlds.

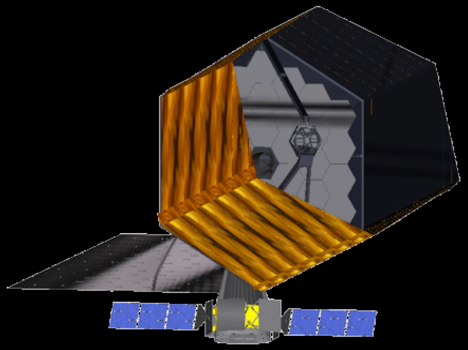
TESS+JWST+?: Transit spectrscopy

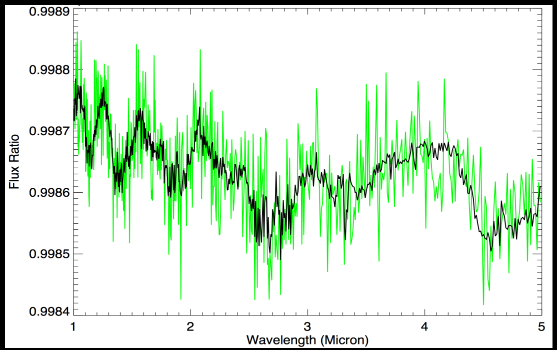
WFIRST-C: Direct Imaging

Future Flagship Mission: Direct Imaging

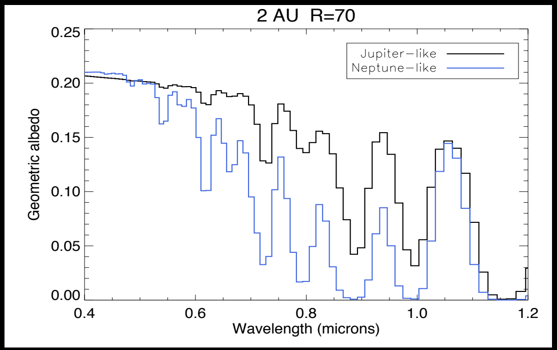




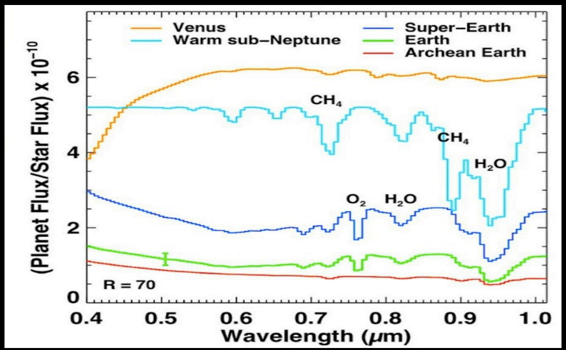




Batalha et al. 2015



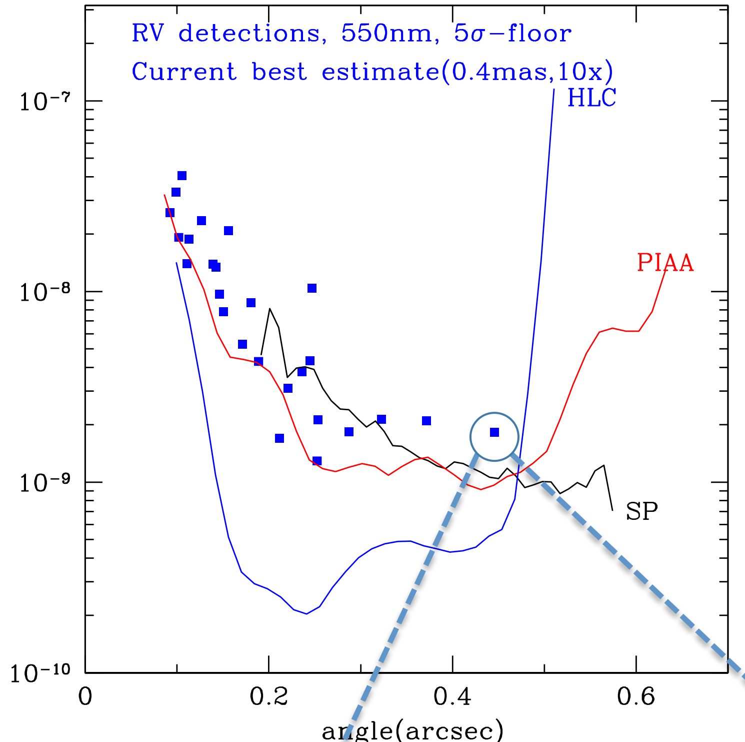
Cahoy et al. 2010

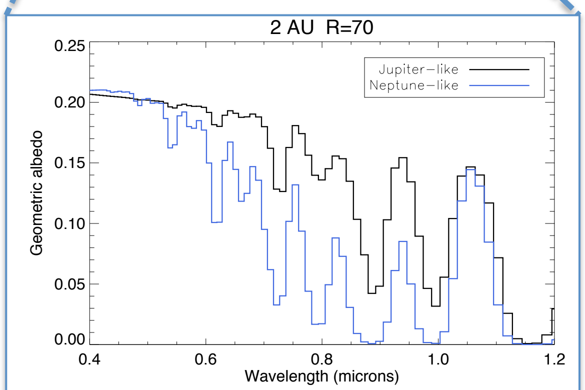


A. Roberge/HDST Report

Exoplanet Direct Imaging with WFIRST-C.

Spergel et al.2015

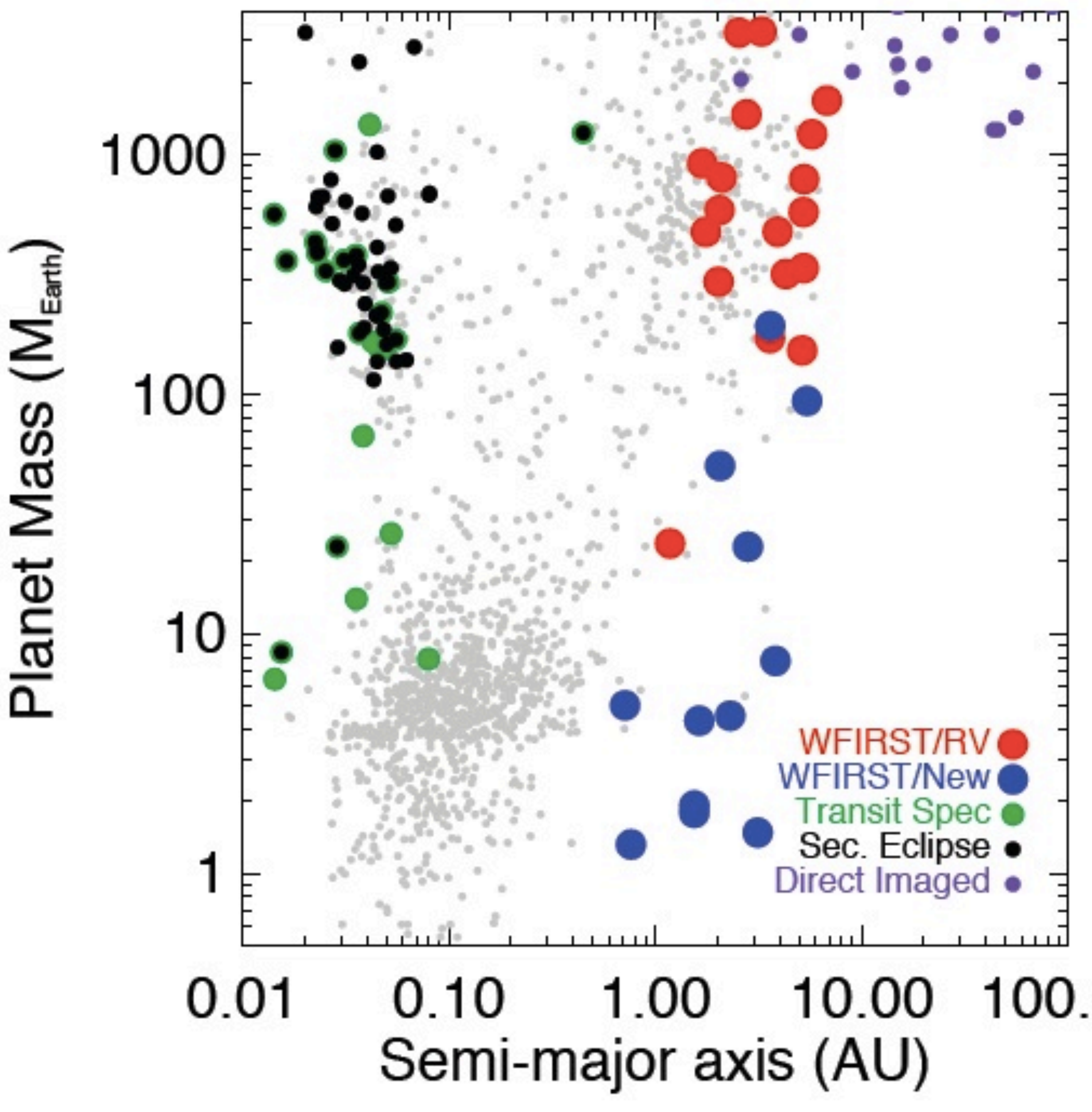




Spectra at R=70 easily distinguishes between a Jupiter-like and Neptune-like planet at 2 AU about stars of different metallicity.

WFIRST-C will:

- Characterize the spectra of roughly 20 radial velocity planets.
- Detect a dozen Neptunes/Super Earths.
- Provide crucial information on the physics of planetary atmospheres and clues to planet formation.
- Respond to decadal survey to mature coronagraph technologies.



Spergel et al. 2015

WFIRST-C 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

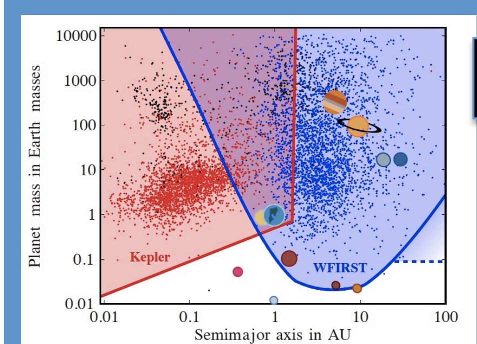
2600 cold exoplanets
300 Earth-mass planets
40 Mars-mass or smaller planets
40 free-floating Earth-mass planets

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.

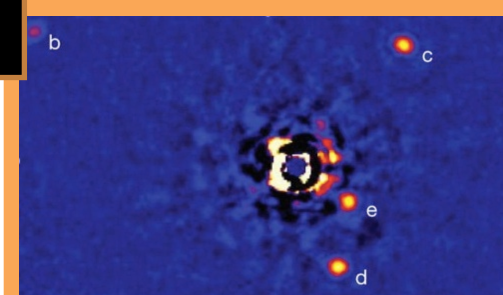
Complete the Exoplanet Census



Penny et al., in prep

- How do planetary systems form and evolve?
- What are the constituents and dominant physical processes in planetary atmospheres?
- What kinds of unexpected systems inhabit the outer regions of planetary systems?
- What are the masses, compositions, and structure of nearby circumstellar disks?
- Do small planets in the habitable zone have heavy hydrogen/helium atmospheres?

Discover and Characterize Nearby Worlds

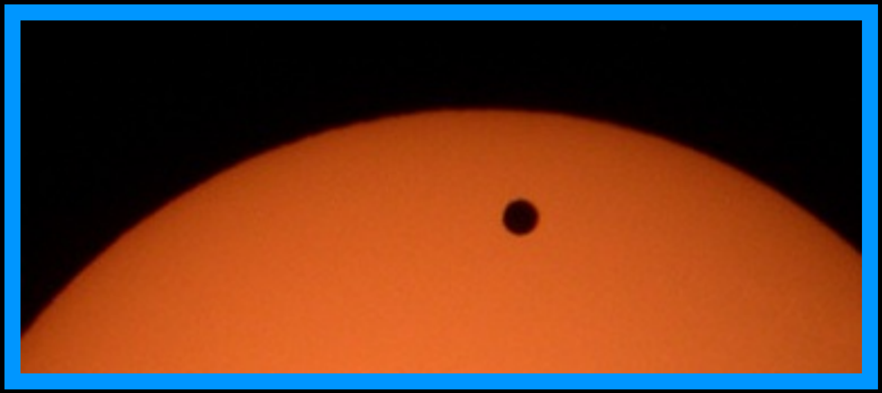


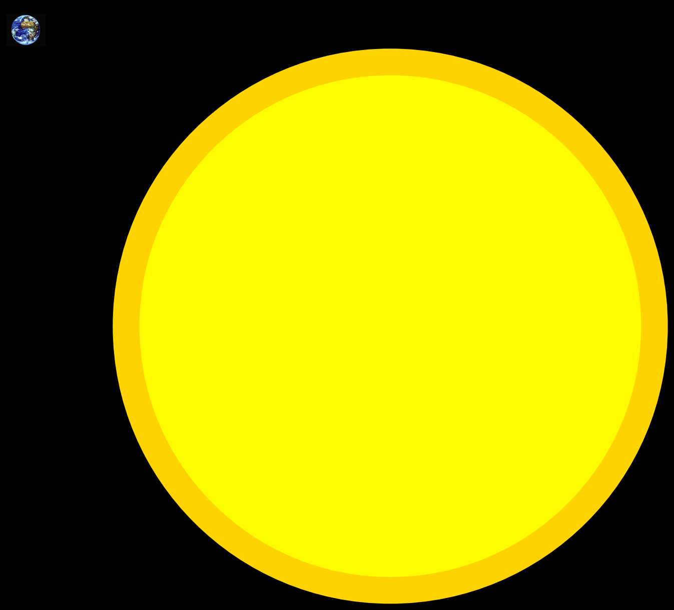
Marois et al. 2008

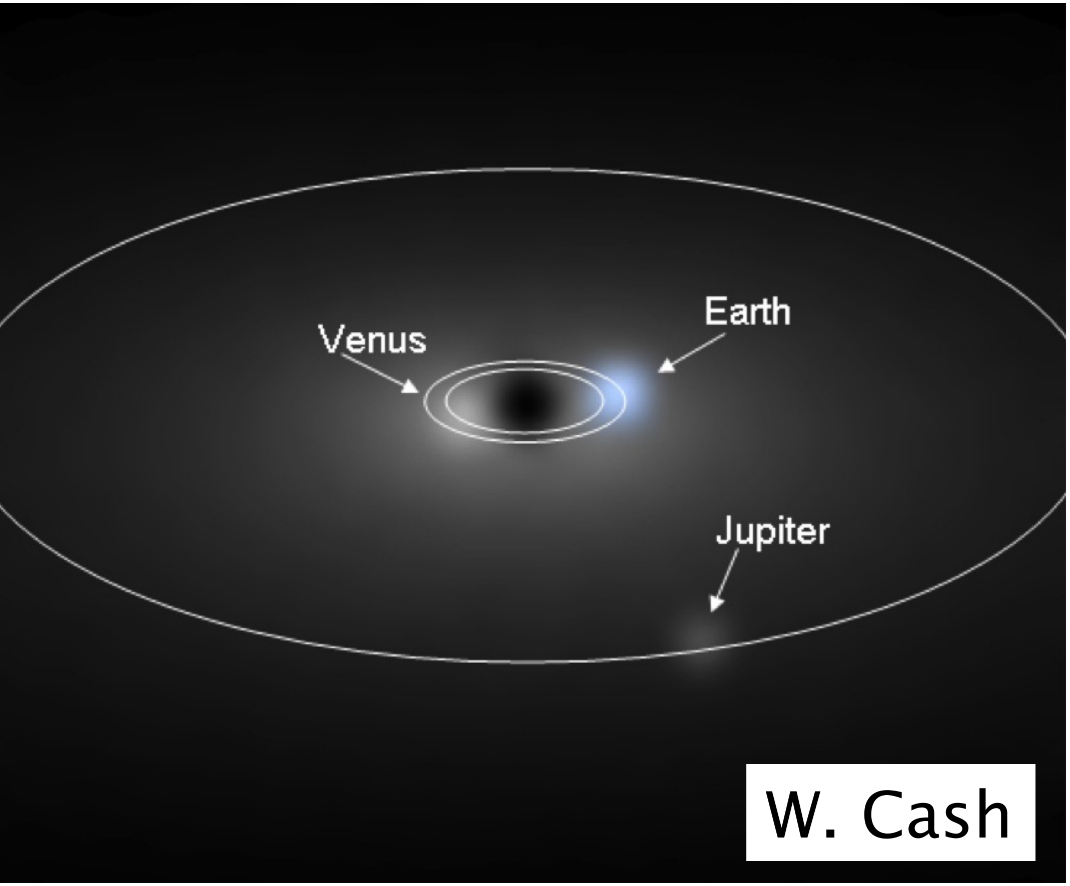
The Search for Habitable Climates and Life.

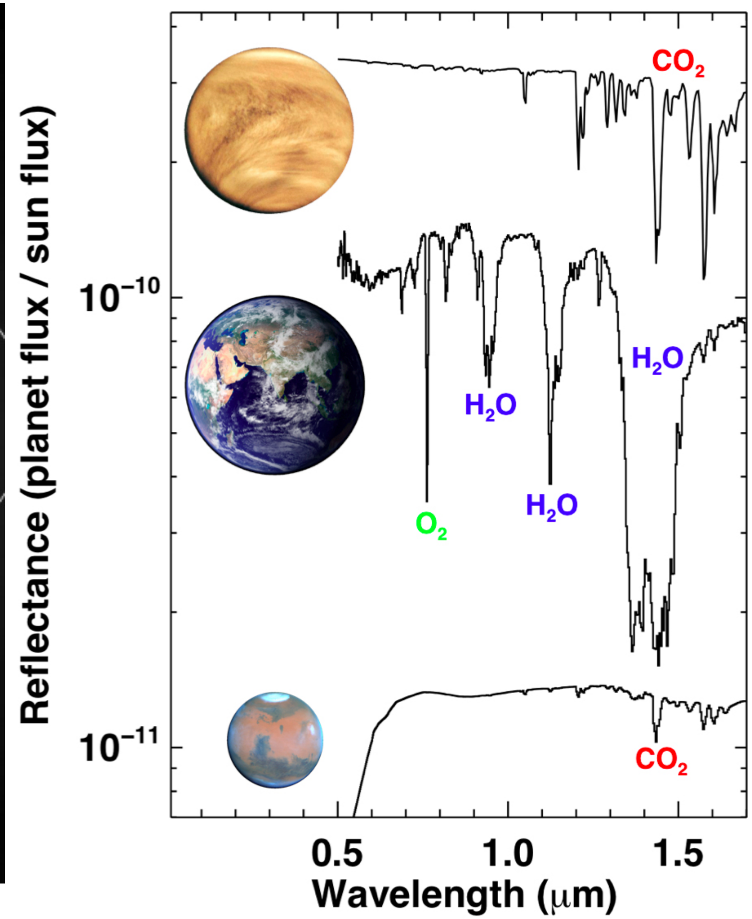
Pale Blue Dots

Small Black Shadows

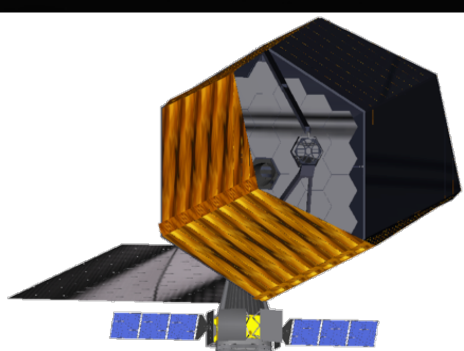








V. Meadows and A. Roberge



Toward the "Pale Blue Dot"

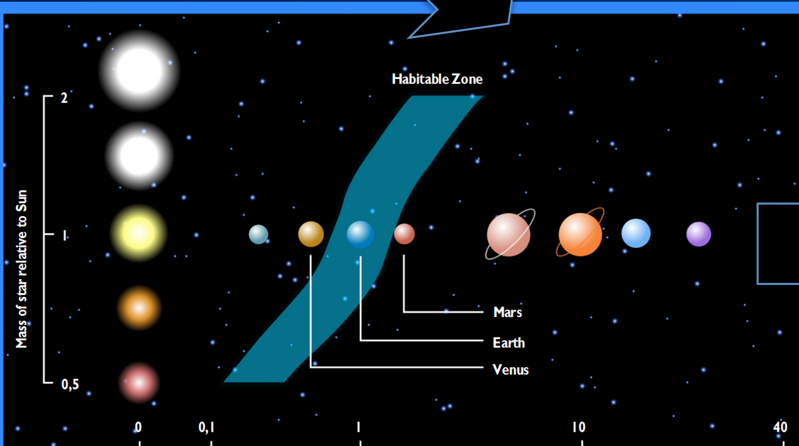
WFIRST-C will lay the foundation for a future flagship direct imaging mission capable of the detection and characterization of Earthlike planets.

Microlensing Survey

- Inventory the outer parts of planetary systems, potentially the source of the water for habitable planets.
- Quantify the frequency of solar systems like our own.
- Confirm and improve Kepler's estimate of the frequency of potentially habitable planets.
- When combined with Kepler, provide statistical constraints on the densities and heavy atmospheres of potentially habitable planets.

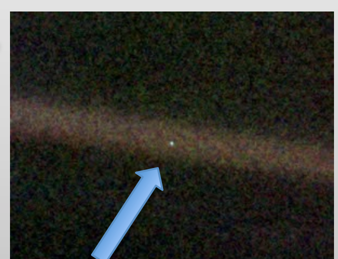
High Contrast Imaging

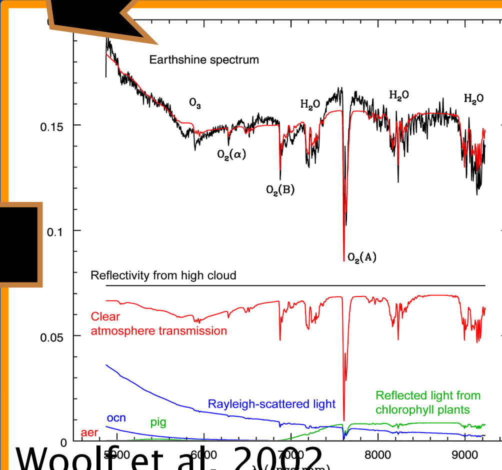
- Provide the first direct images of planets around our nearest neighbors similar to our own giant planets.
- Provide important insights about the physics of planetary atmospheres through comparative planetology.
- Assay the population of massive debris disks that will serve as sources of noise and confusion for a flagship mission.
- Develop crucial technologies for a future mission, and provide practical demonstration of these technologies *in flight.*



Courtesy of Jim Kasting.

Science and technology foundation for the New Worlds Mission.





Woolf et al. 2002

The Search for Life.

- Need to complete the planet census and characterize a diversity of planetary atmospheres.
- Low-mass stars:
  - TESS+RV+JWST + ? (luck + control of systematics)
  - GSMT with extreme AO
- High-mass stars:
  - **Technology development** (coronagraph *and* starshade)
  - Need a robust estimate of η_{Earth}.
  - Need a robust estimate of exozodi levels (LBTI).
  - Need to figure out how to measure masses and if we can identify the targets first (and if that helps).
  - Need to understand false positives.

Radial Velocities in NWNH.

- “NASA and NSF should support an aggressive program of ground-based high-precision radial velocity surveys of nearby stars to identify potential candidates.”
- “The role of target-finding for future direct-detection missions, one not universally accepted as essential, can be done at least partially by pushing ground-based radial velocity capabilities to a challenging but achievable precision below 10 centimeters per second.”

Detecting Earth Analogs with RV.

Signal:

- Semiamplitude ~ 10 cm/s and Period ~1 yr

Requirements:

- Statistical SNR ~ $(N/2)^{1/2}$ (K/σ)
- Wavelength and instrument calibration stable to ~ 1 cm/s over many years
- Removal/suppression/separation of intrinsic stellar noise to ~1 cm/s.

Removal/suppression of intrinsic Doppler noise to ~1 cm/s.

Impossible (in principle)?

- No: Doppler variation due orbiting bodies has a unique signature: all the lines move by the same amount without changing their shape.

But!

- This won't be solved using current methods, specifically:
  - Current instruments and telescopes.
  - Current detection algorithms.
- The problem of stability is hard, but likely tractable and on its way to being solved.
- Need to solve the problem of intrinsic stellar noise.

PRV “Dream Machine”.

Attributes:

- Large aperture (one large or many medium)
- Dual Optical + IR channel
- Very high optical resolution (R>150,000)
- High IR resolution (>50,000)
- Broad wavelength coverage (0.4–1.7μm)
- Fiber-fed, bench mounted, stable
- Advanced wavelength calibration (e.g., LFC)
- Advanced fiber scrambling techniques (e.g., octagonal fibers, double fiber scrambling, etc.)

Resources:

- Cost: O($20M) per instrument (?)
- Lots of observing time (~>25% of time for 10 years for N~50)

The Roadmap is Clear and Has Broad Community Support.

- Demographics:
  - Kepler + WFIRST.
- Characterization:
  - TESS+JWST, WFIRST+C+S, future direct imaging mission.
- Search for Life:
  - TESS+JWST+GSMT
  - Measure η_{Earth} and exozodi levels.
  - Technology development (WFIRST+C+S)
  - Architecture downselect.
  - Figure out how to measure masses.

Questions.

- Do we need a dedicated transit characterization mission?
- How do we measure η_{Earth} if Kepler is unsuccessful?
- Can we reach ~1 cm/s with RV? If not, then do we consider an astrometry mission?