Jet Propulsion Laboratory
California Institute of Technology

Emerging Science of Comparative Solar System Formation - an Exoplanet Exploration Perspective

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AIAA Space 2015, Pasadena CA

Solar System formation theory circa 1994

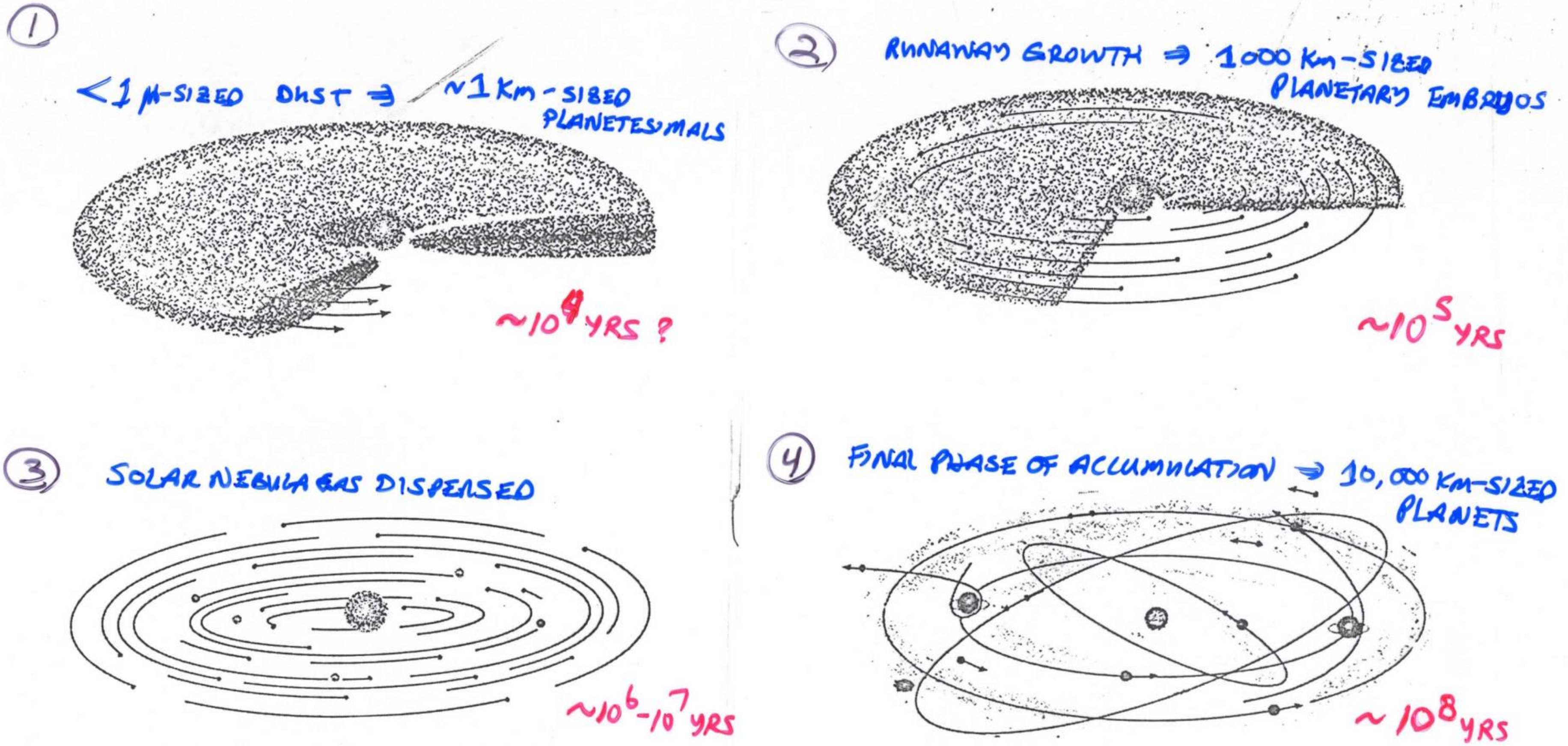
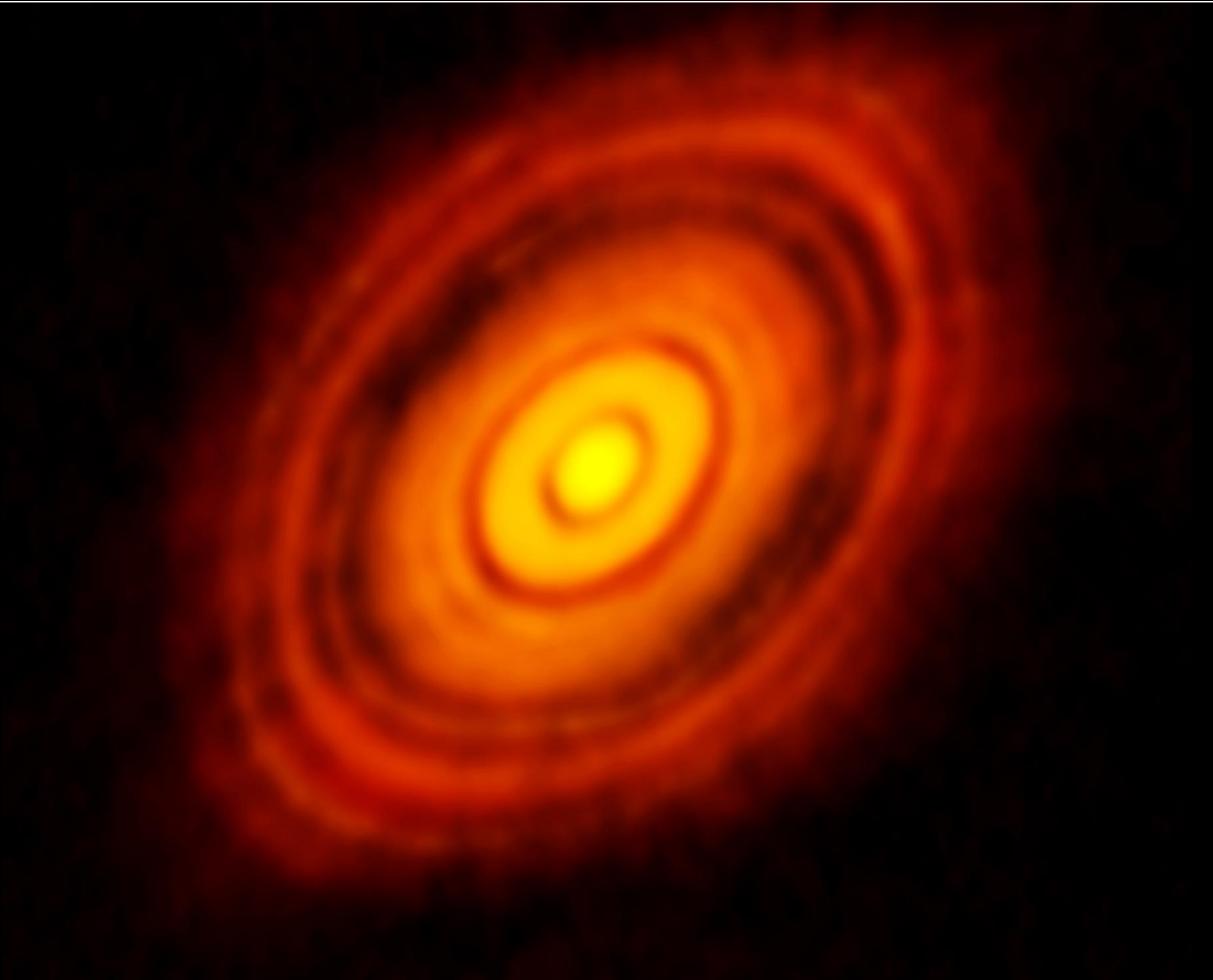


FIGURE 3.2 Possible sequence of events in the terrestrial planet region. (top left) Growth of dust grains into ~10-km-diameter "planetesimals" through nongravitational forces (sticking). (top right) Runaway growth of planetesimals, moving in nearly circular, coplanar orbits, to form ~2000-km-diameter "planetary embryos" on a 10^5-year time scale. (bottom left) Removal of gas from the inner solar system on a 10^6- to 10^7-year time scale. (bottom right) Mutual perturbation of planetary embryos into eccentric orbits and their merger to form the present planets on a 10^8-year time scale. Asteroids are relics of similar processes in the present asteroidal region that failed to complete the runaway growth stage (top right) as a consequence of either gravitational or collisional removal of most of the other bodies in that region. Jupiter's perturbations, beginning at about 5×10^6 years, were primarily responsible for this clearing of the asteroid belt.

HL Tauri - ~1 M_{sun}- ~1 Myr - ~100 AU - ALMA



$\sim 0.5\ M_{Jup}$
$e \sim 0$
$P \sim 4$ days

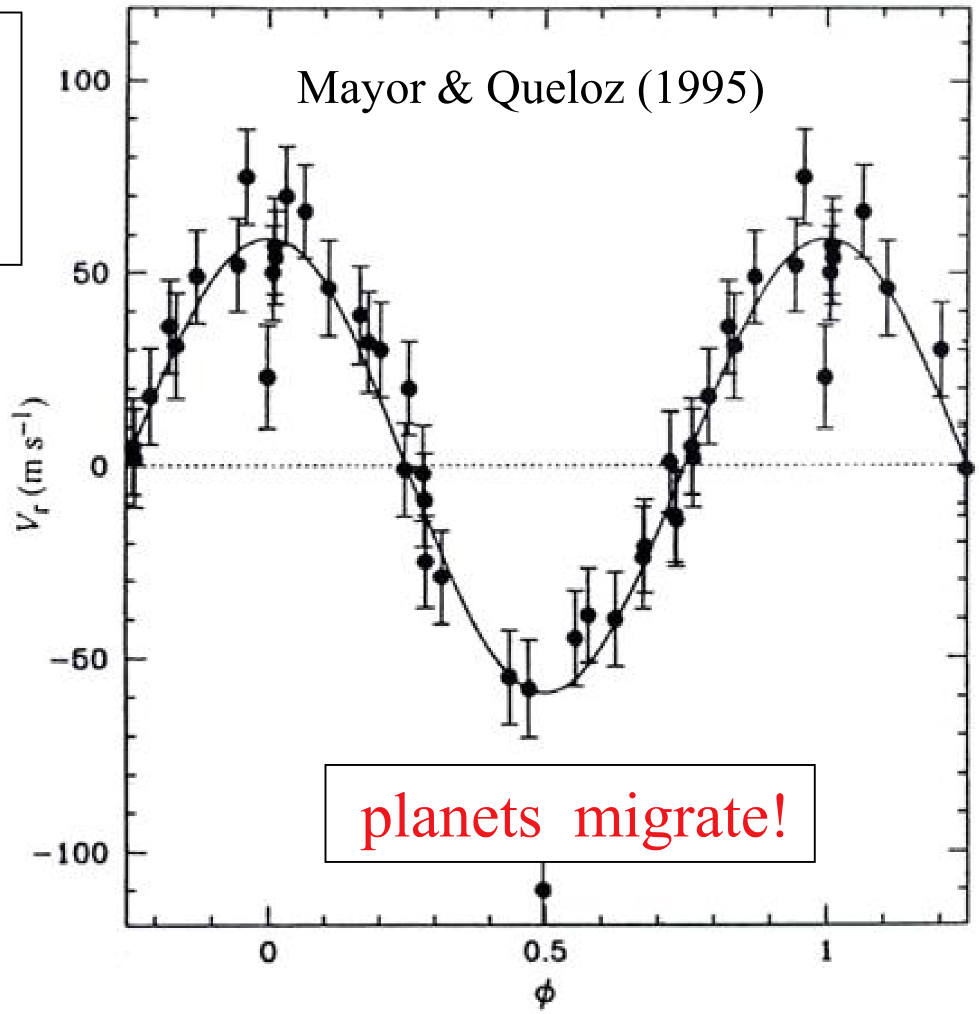
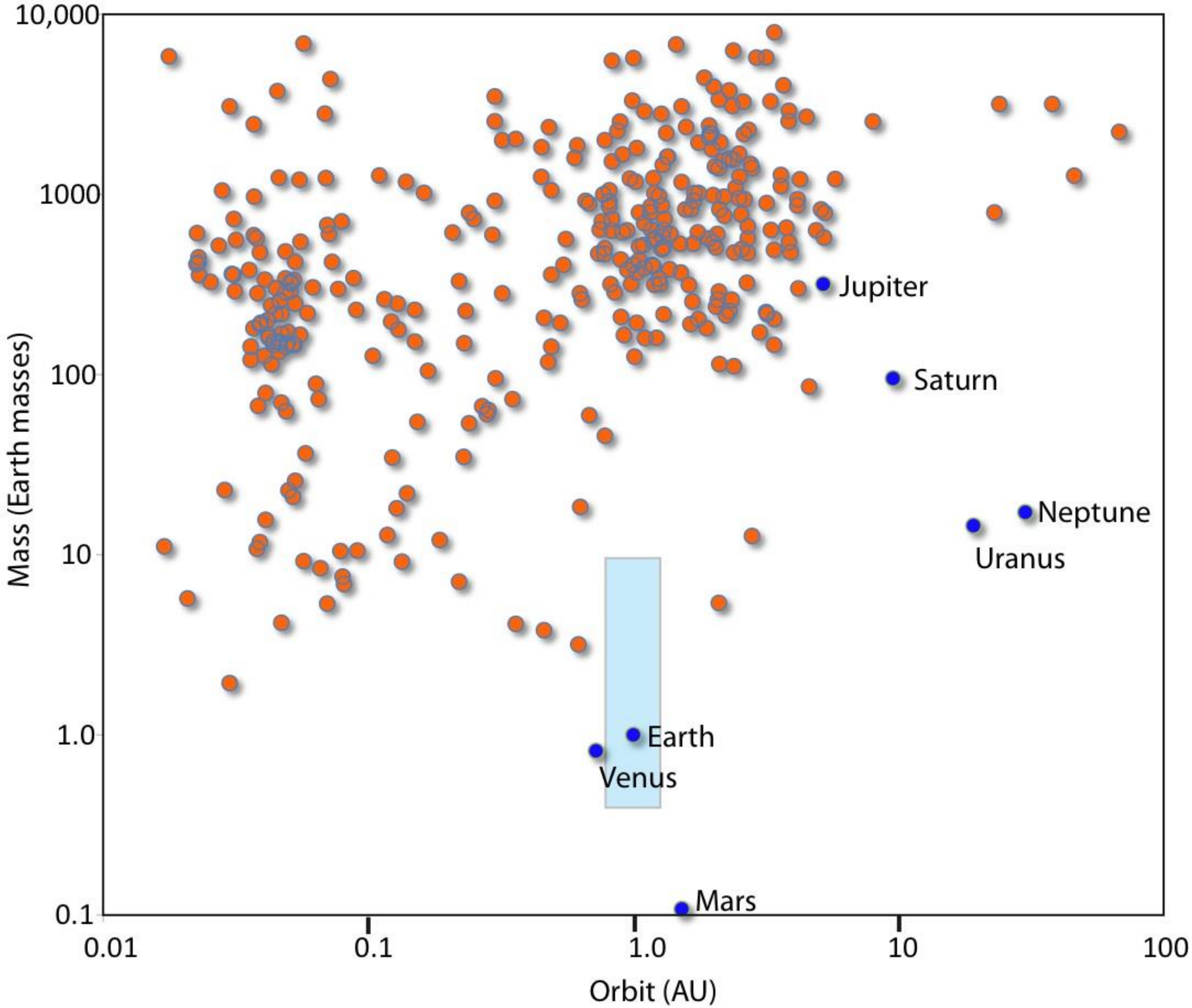


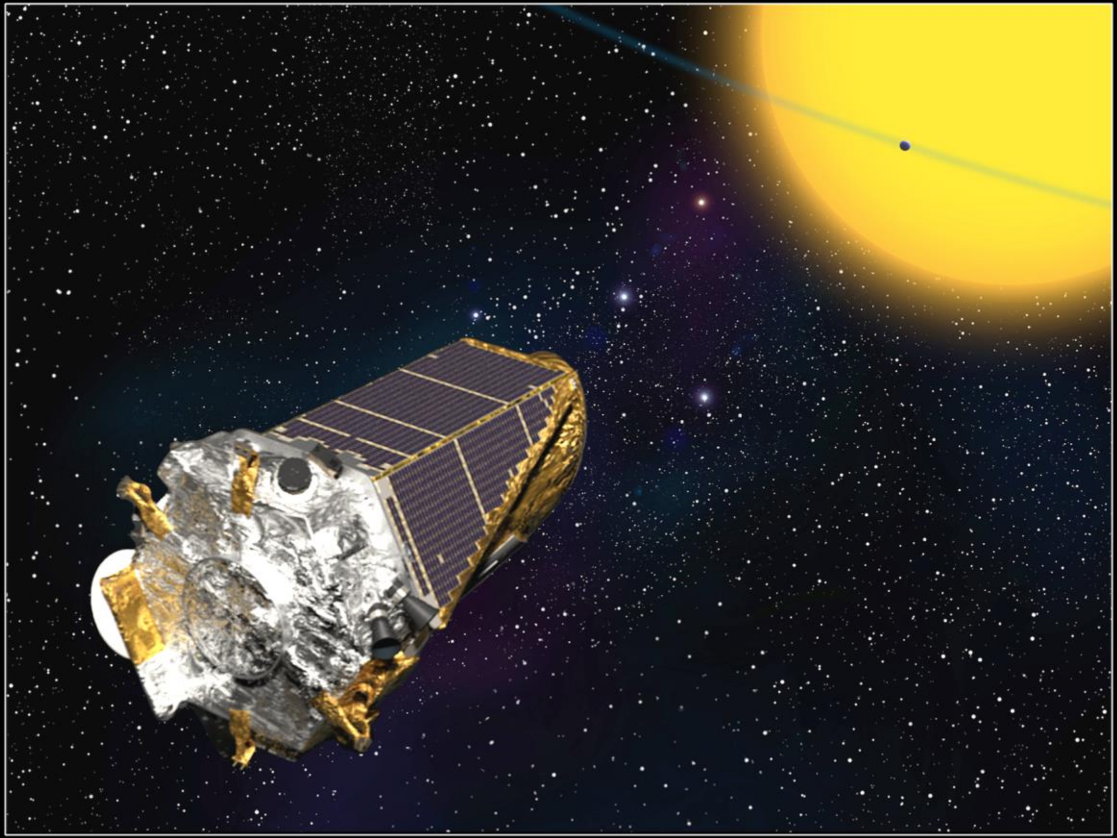
FIG. 4 Orbital motion of 51 Peg corrected from the long-term variation of the γ-velocity. The solid line represents the orbital motion computed from the parameters of Table 1.

Discovery space circa 2010 – mostly Doppler exoplanets



NASA's Kepler Mission

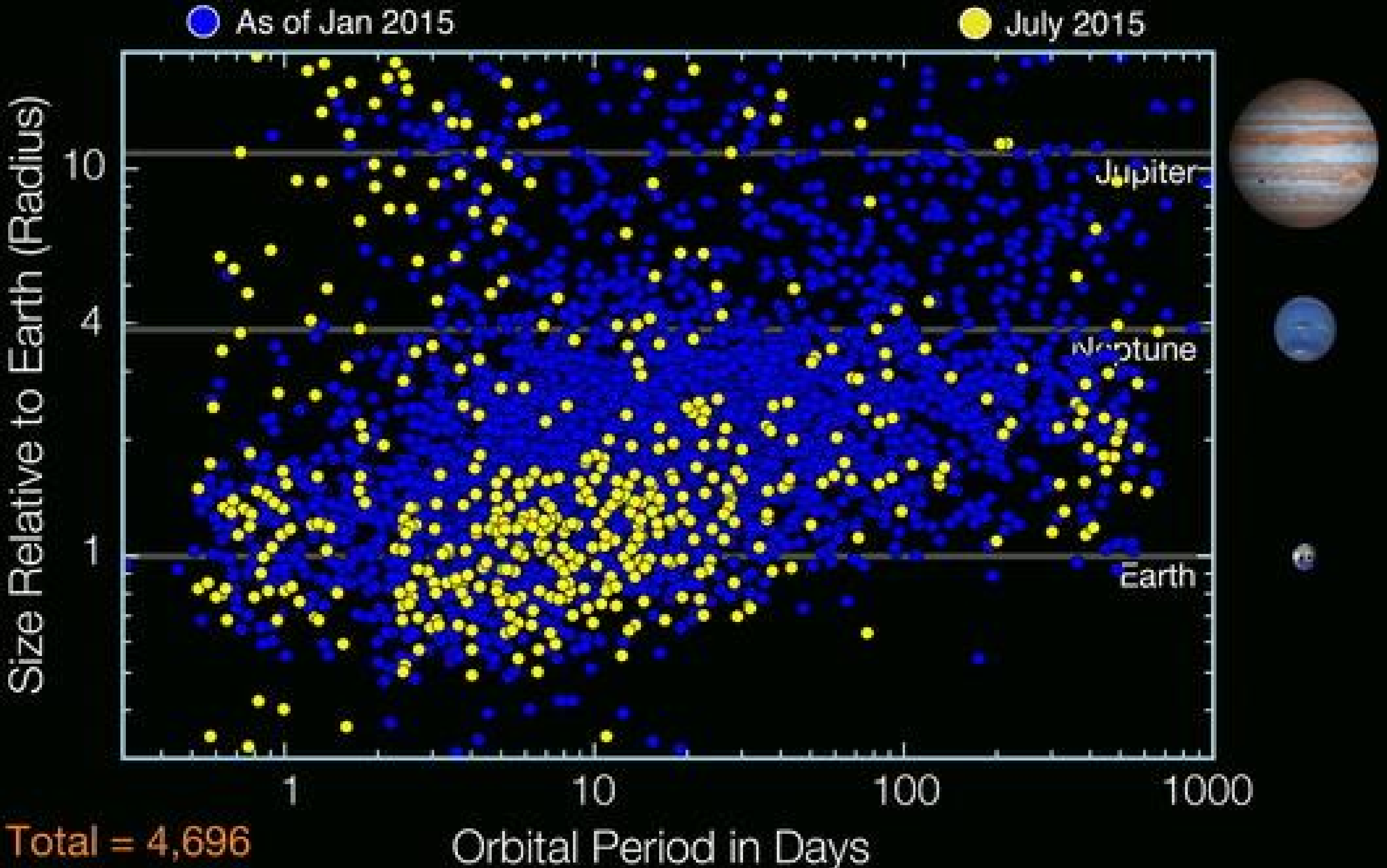
- Determine the frequency of Earth-size and larger planets in the habitable zone of sun-like stars
- Determine the size and orbital period distributions of planets

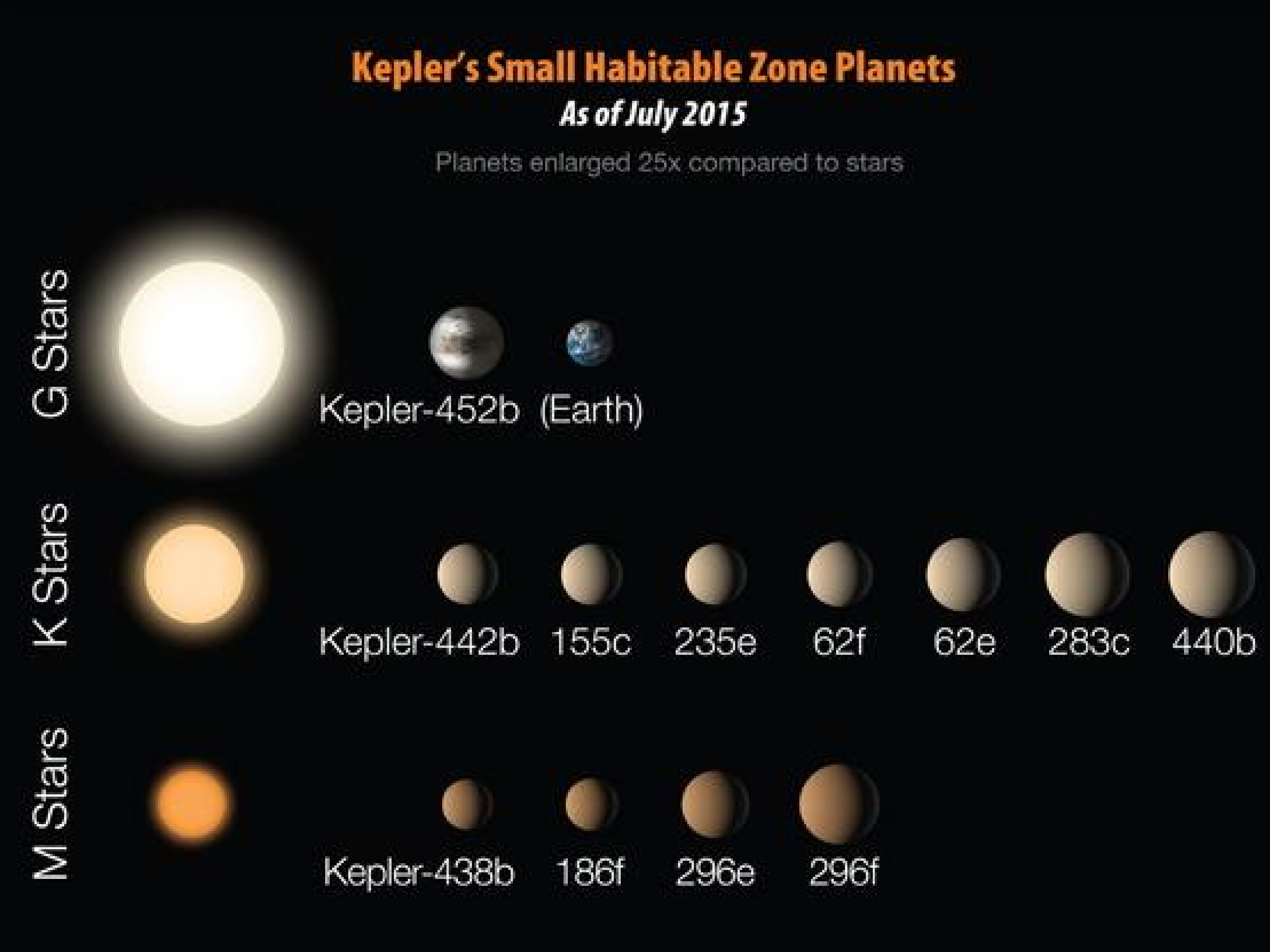


Launched: March 6, 2009

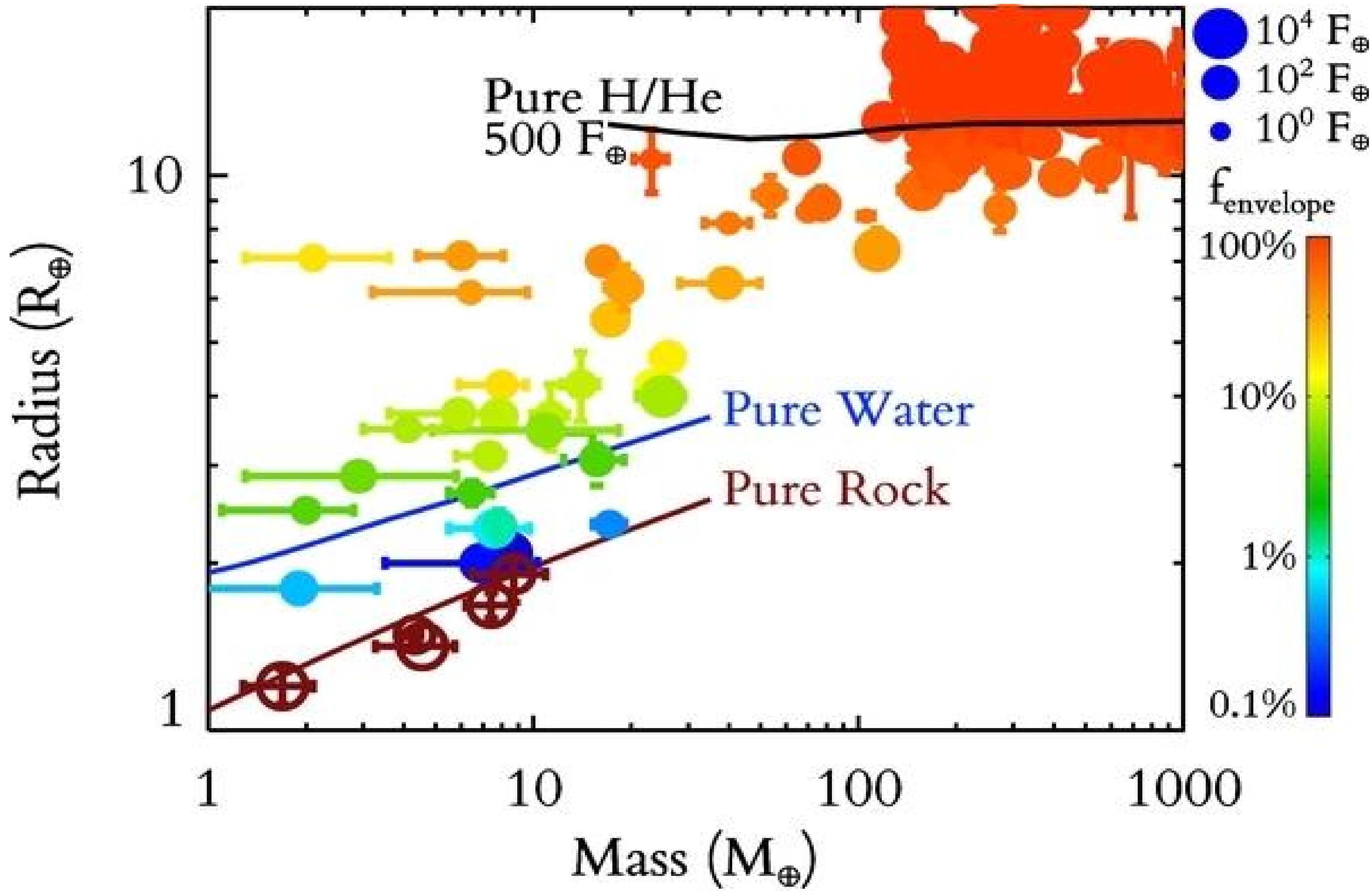
New Kepler Planet Candidates

As of July 23, 2015




Kepler's Small Habitable Zone Planets
As of July 2015
Planets enlarged 25x compared to stars
G Stars
Kepler-452b
(Earth)
K Stars
Kepler-442b
155c
235e
62f
62e
283c
440b
M Stars
Kepler-438b
186f
296e
296f

Lopez & Fortney (2014): M, R for 200 exoplanets



Swain et al. (2008) - HD 189733 b with HST Nicmos

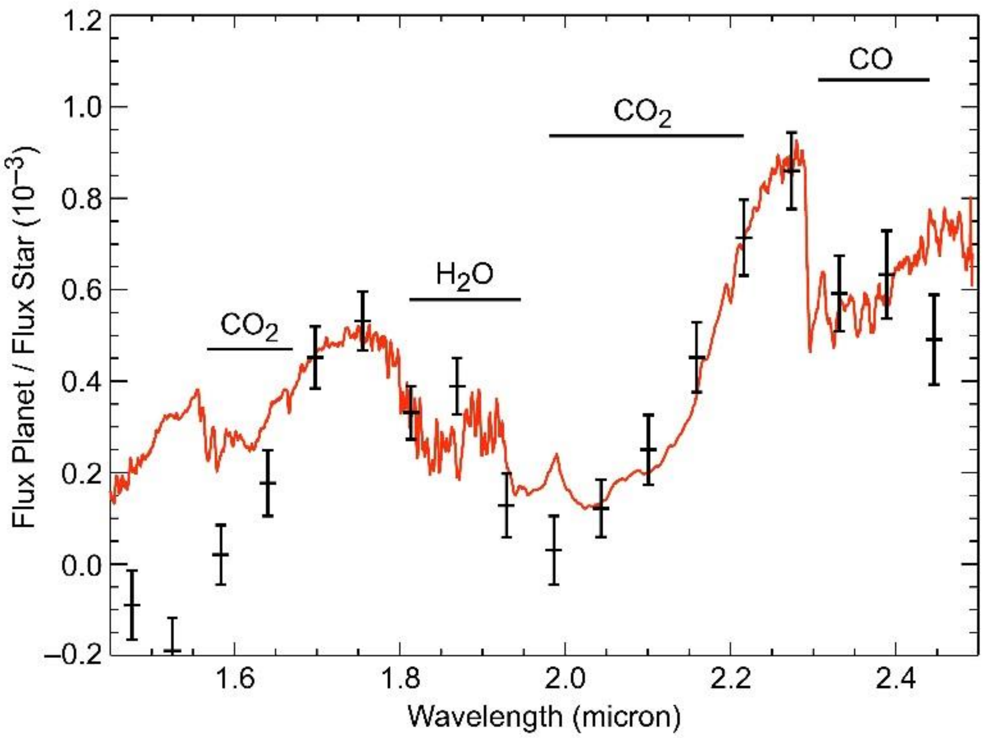
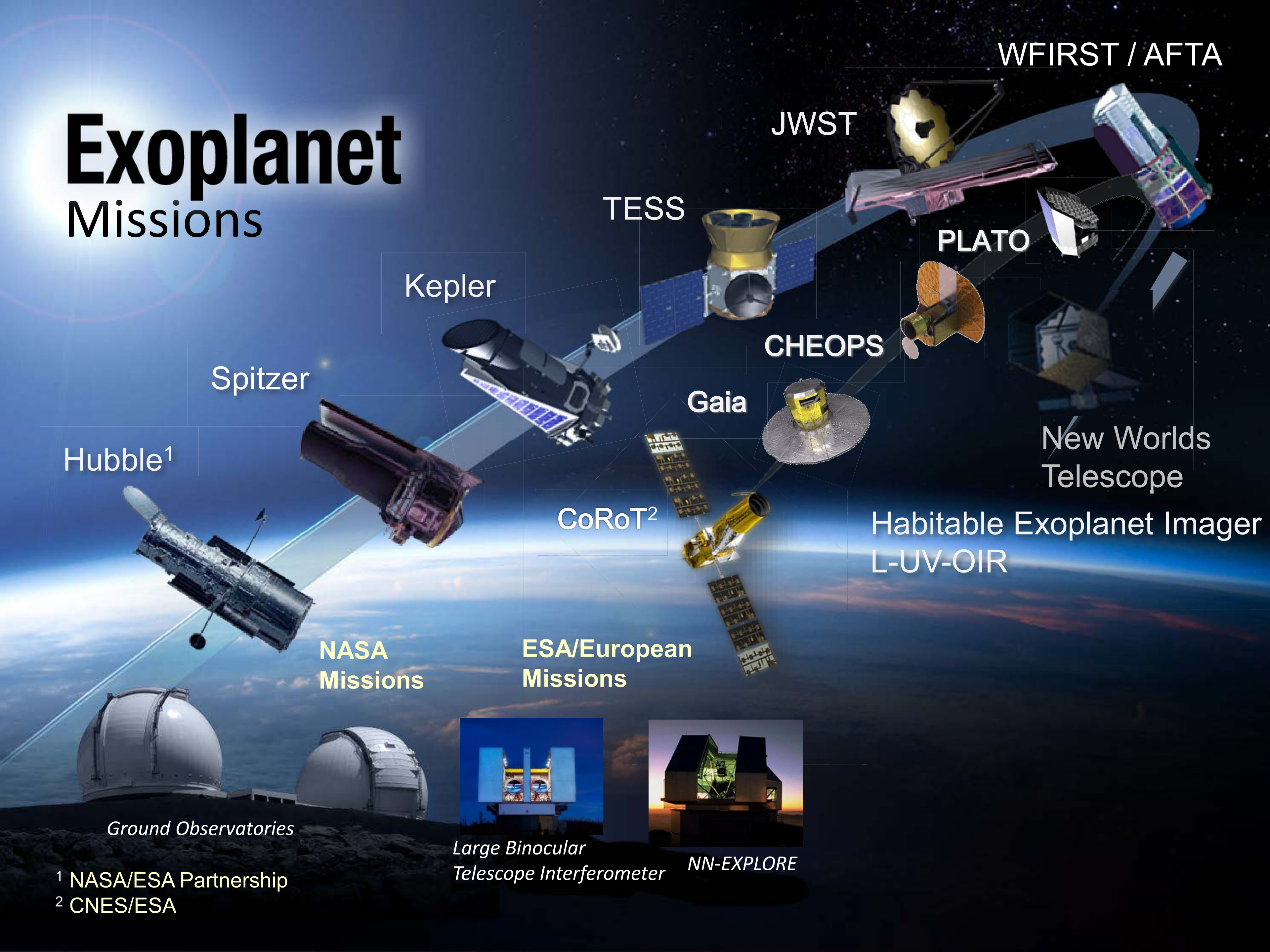
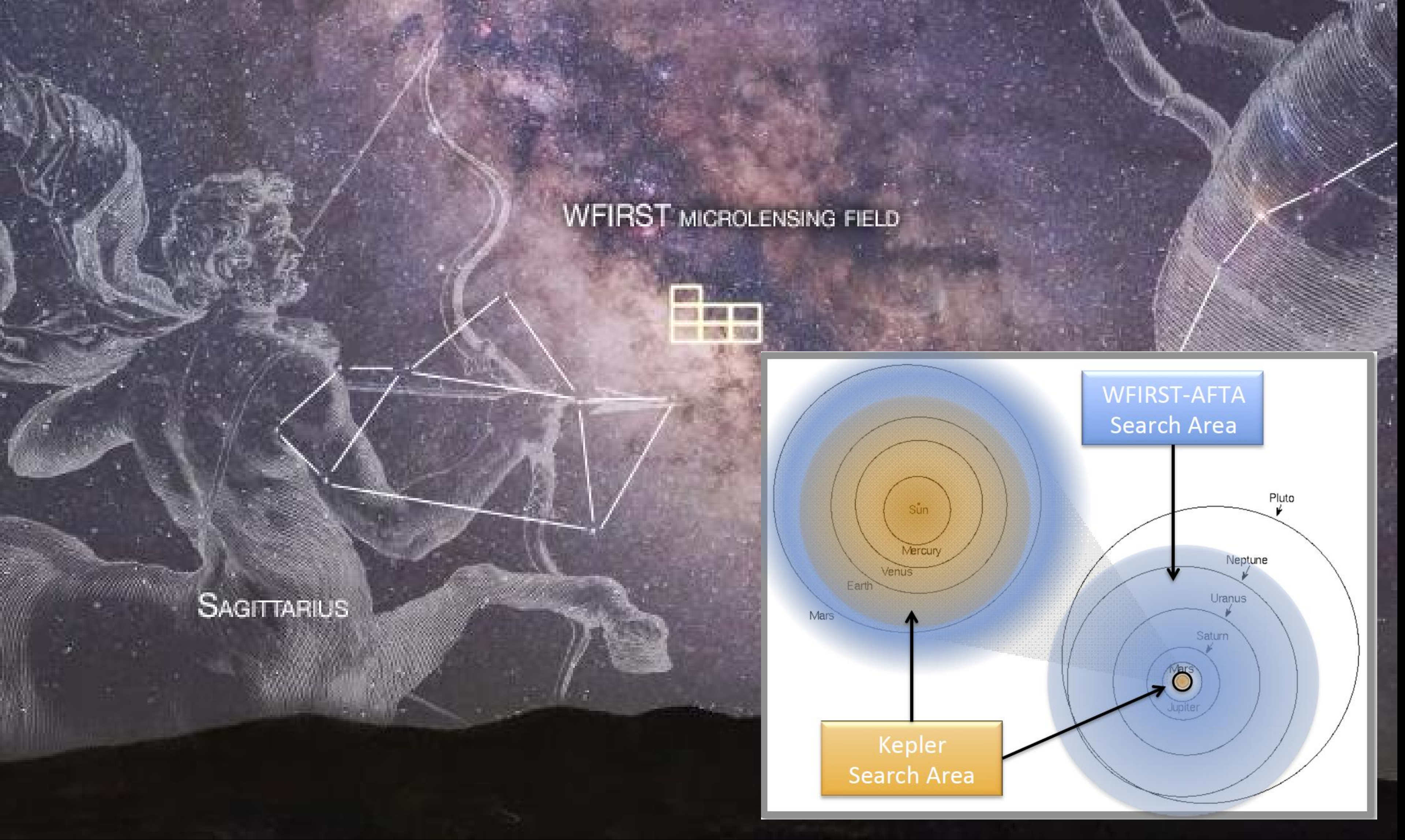


Fig. 3.— The near-IR dayside emergent spectrum used in our analysis with $\pm 1 - \sigma$ errors shown (black), together with a model spectrum (orange) containing the molecules H_2O, CO, CH_4 and CO_2, which are responsible for the absorption features (the strongest of which are identified above). The fit residuals suggest that one or more additional molecular species may be present. Although the fit is improved slightly by including C_2H_2, C_2H_6, or NH_3, additional data is required to make a strong case for the presence of additional molecular species.

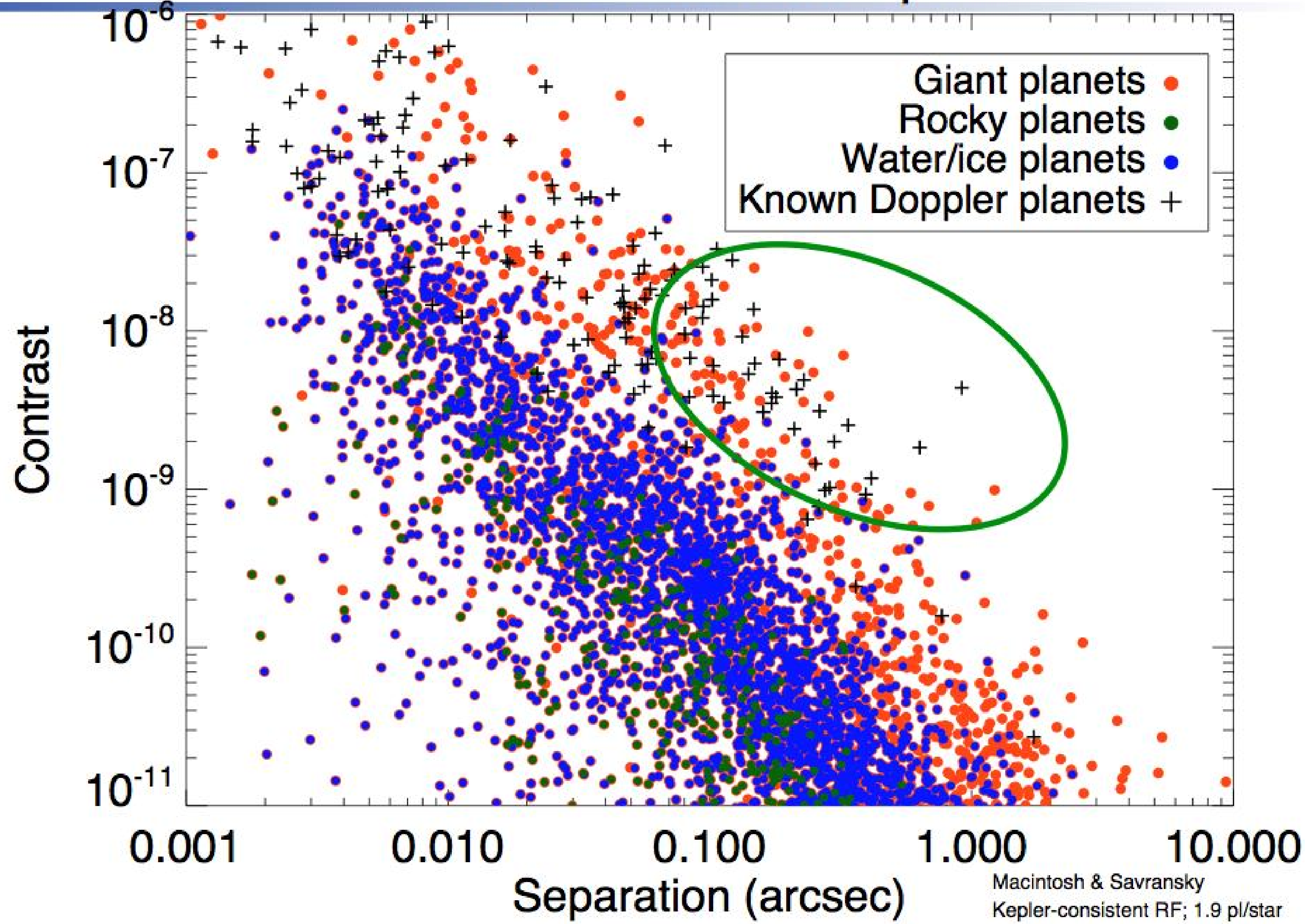

Exoplanet
Missions
WFIRST / AFTA
JWST
TESS
PLATO
Kepler
CHEOPS
Spitzer
Gaia
Hubble[1]
New Worlds
Telescope
CoRoT[2]
Habitable Exoplanet Imager
L-UV-OIR
NASA
Missions
ESA/European
Missions
Ground Observatories
Large Binocular
Telescope Interferometer
NN-EXPLORE
[1] NASA/ESA Partnership
[2] CNES/ESA

WFIRST / AFTA Microlensing for Exoplanets

Completes the Census Begun by Kepler



Planets within 30 pc



Macintosh & Savransky
Kepler-consistent RF; 1.9 pl/star
Main sequence non binary stars

Conclusions

- Comparative planetology between the Solar System and extrasolar planets has been underway now for 20 years
- Kepler has found thousands of exoplanets, ranging from the familiar (Earths, gas & ice giants) to the unexpected (hot Jupiters, super-Earths, STIPs, circumbinary, …)
- Spitzer and Hubble have studied atmospheres of transiting hot exoplanets: O_2, CO, CO_2, H_2O, CH_4 = biomarkers
- Fantastic progress to date, but the best is yet to come, both from the ground (E-ELT, TMT, GMT) and from space
  - ESA: Gaia, CHEOPS, PLATO, …
  - NASA: TESS, JWST, WFIRST/AFTA, New World Telescope, …

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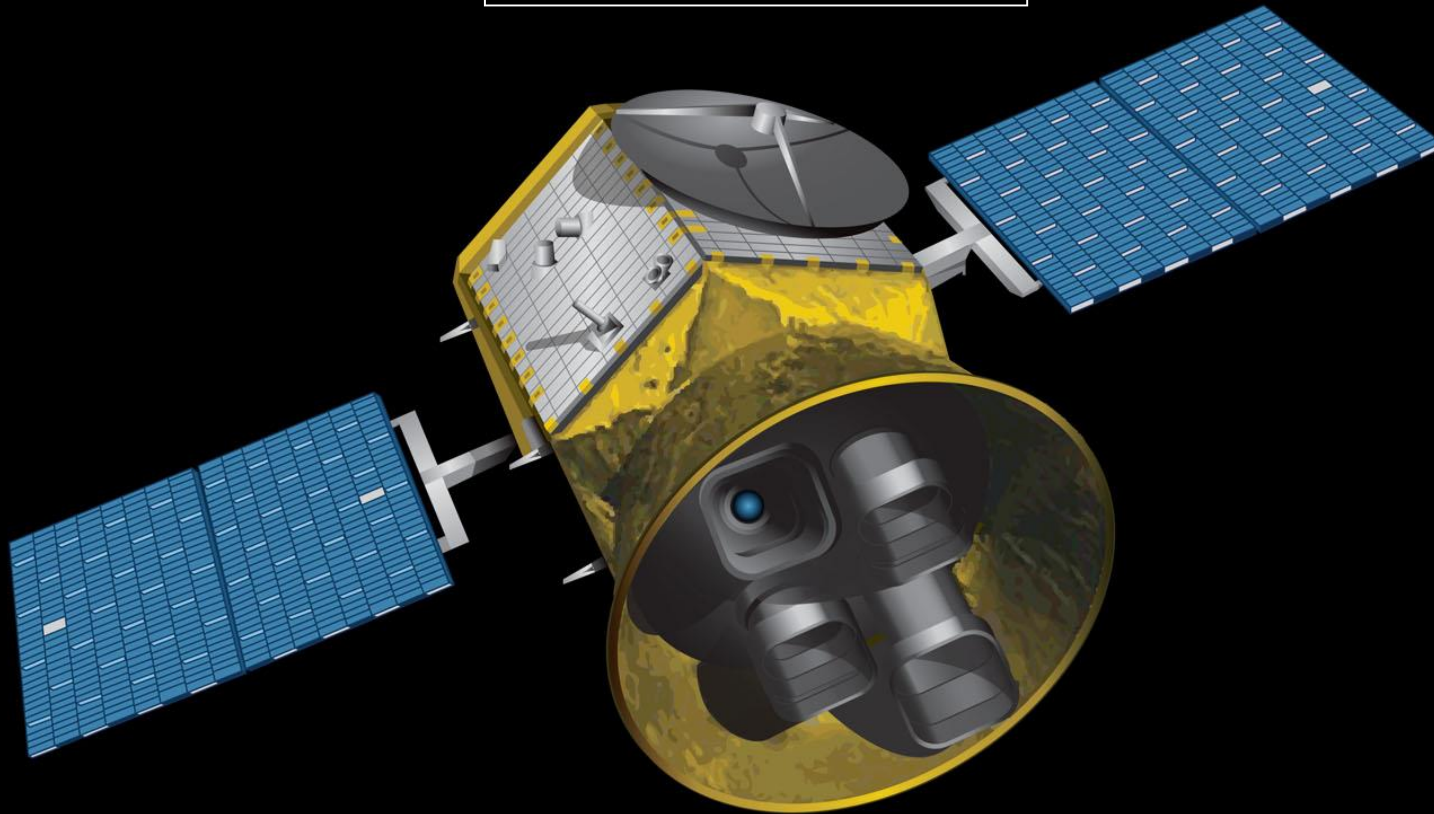
NASA Goddard Space Flight Center

NASA Ames Research Center

Backup

TESS: 2017 launch

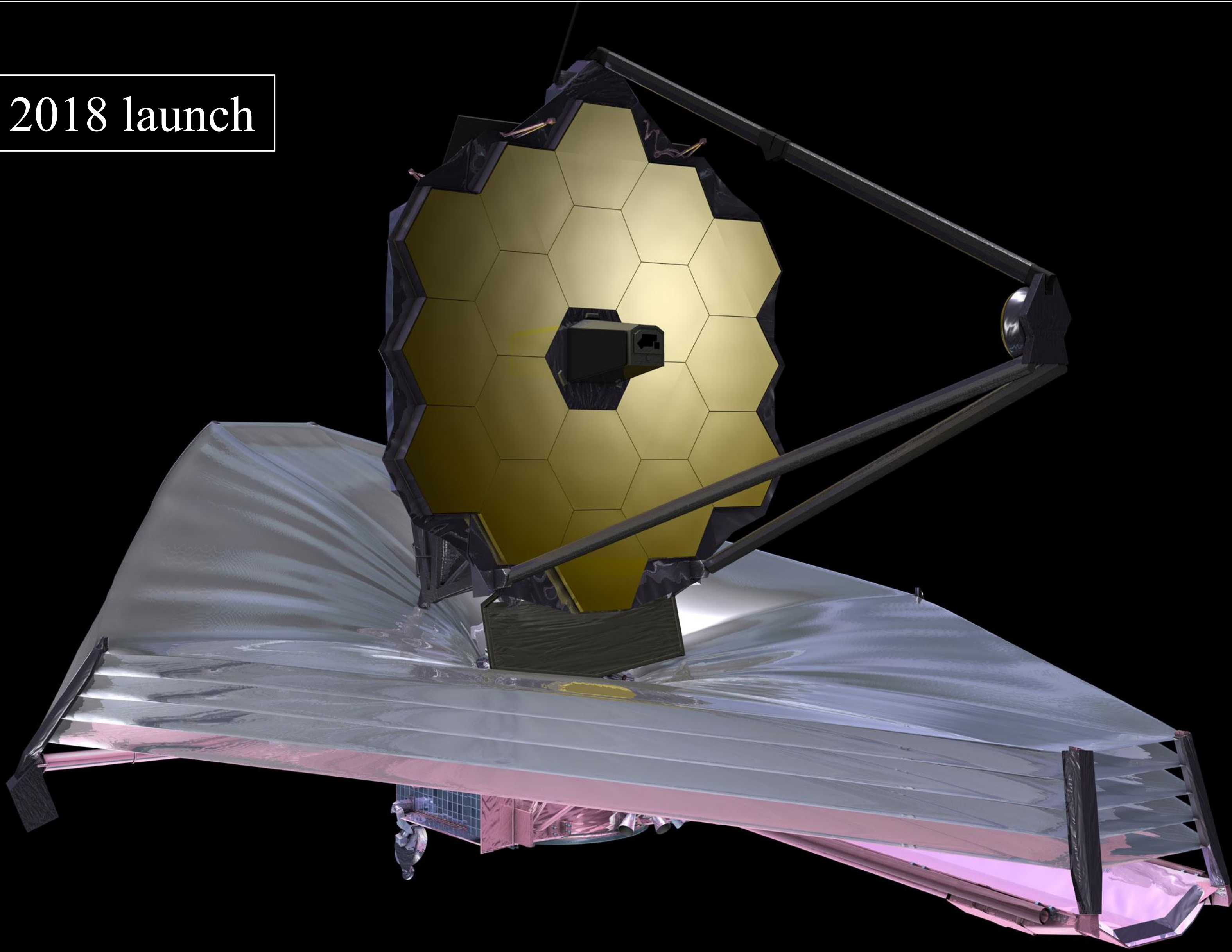


TRANSITING EXOPLANET SURVEY SATELLITE

DISCOVERING NEW EARTHS AND SUPER-EARTHS IN THE SOLAR NEIGHBORHOOD

TESS and JWST (Deming et al. 2009): 1 to 4 habitable super-Earths?

JWST: 2018 launch



WFIRST/AFTA 2.4m NRO Space Telescope

New Worlds Telescope?
~ TPF Coronagraph?
~ NWO Star Shade?