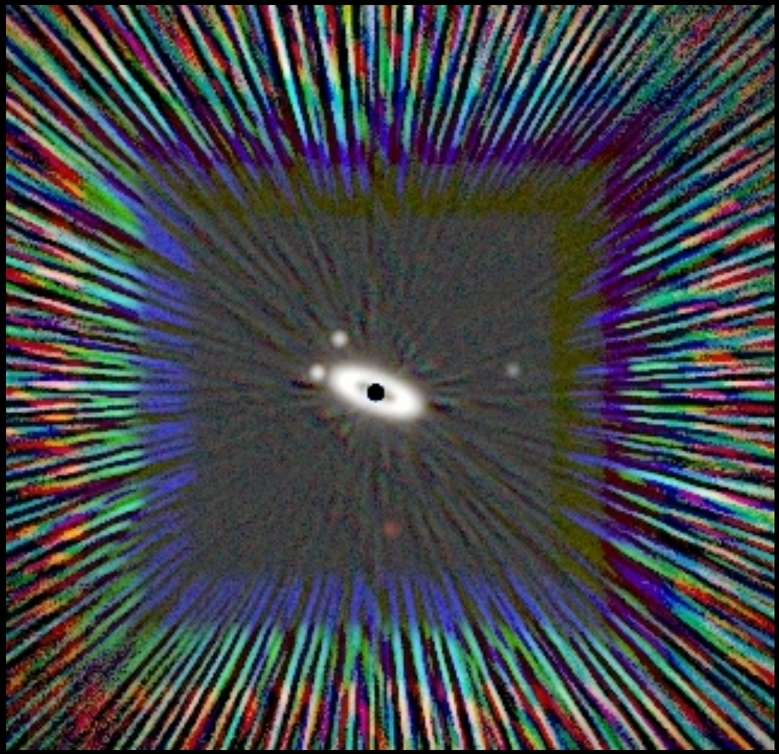
Science and Mission Context for Segmented Aperture Coronagraphy



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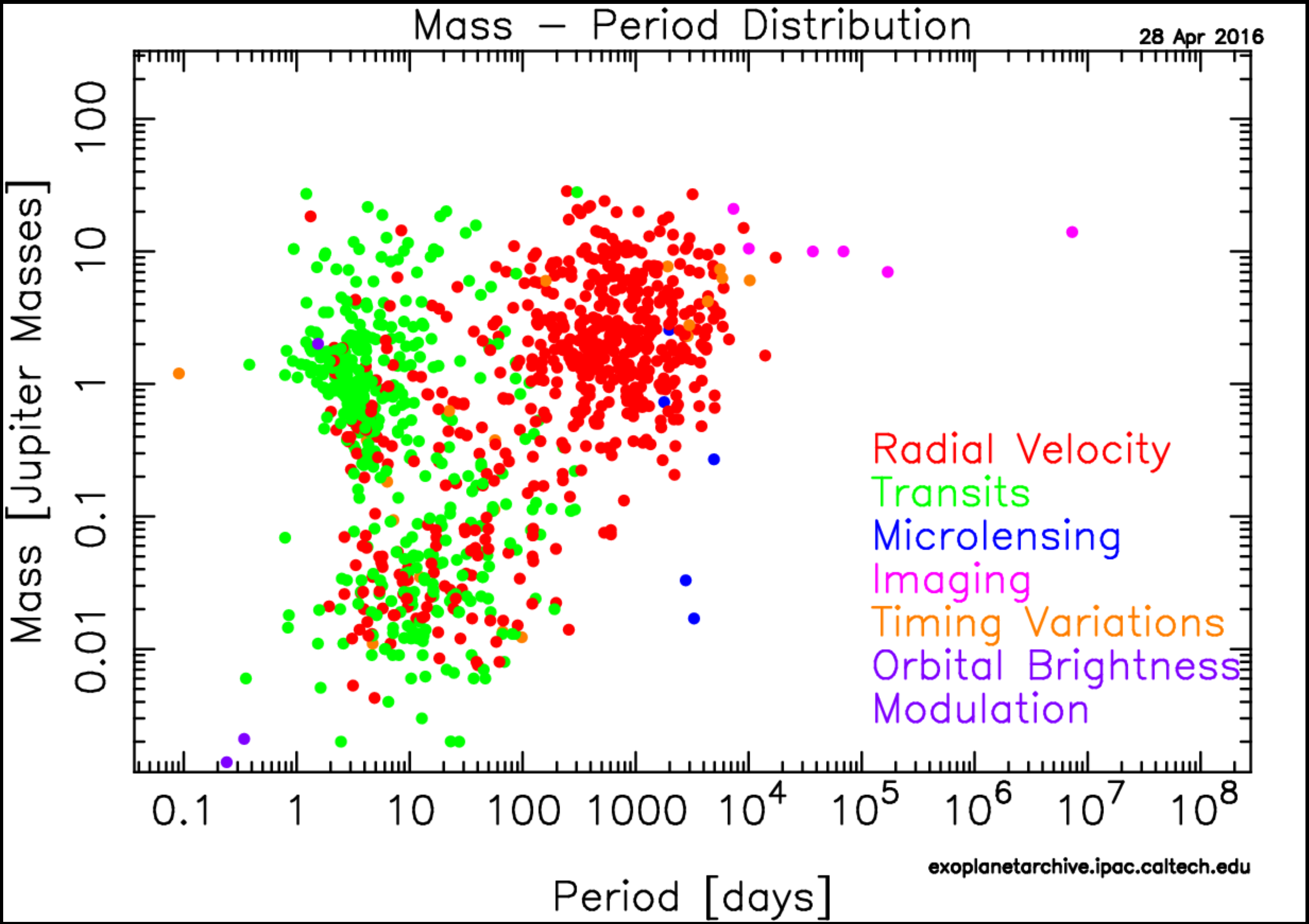
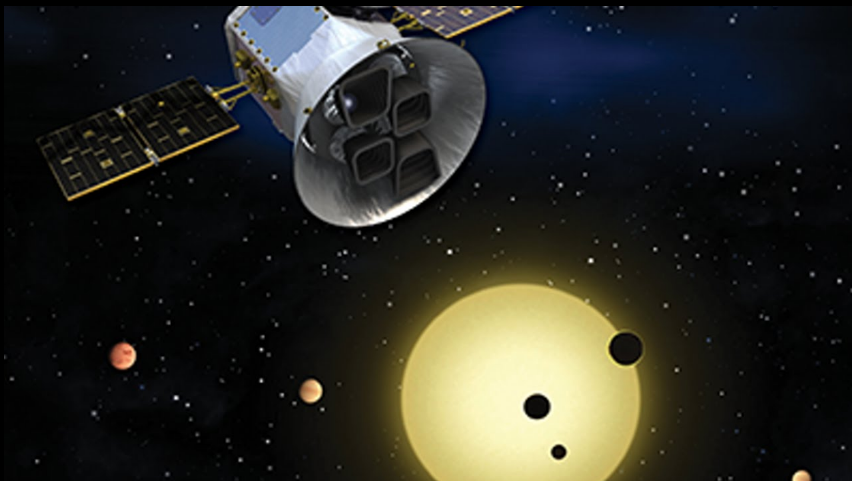
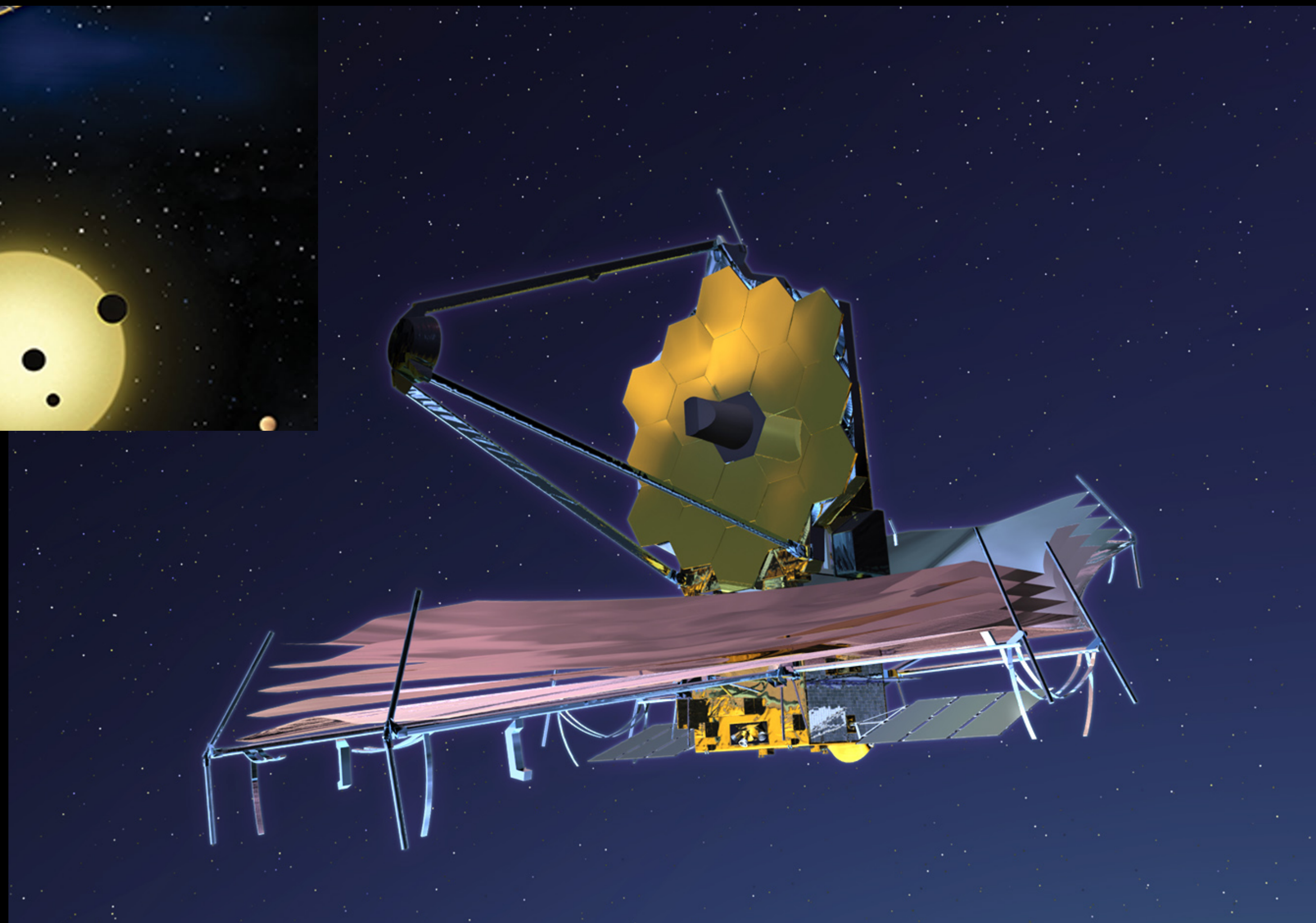
Known exoplanets by discovery technique



Next steps in Exoplanet characterization from space: TESS & JWST



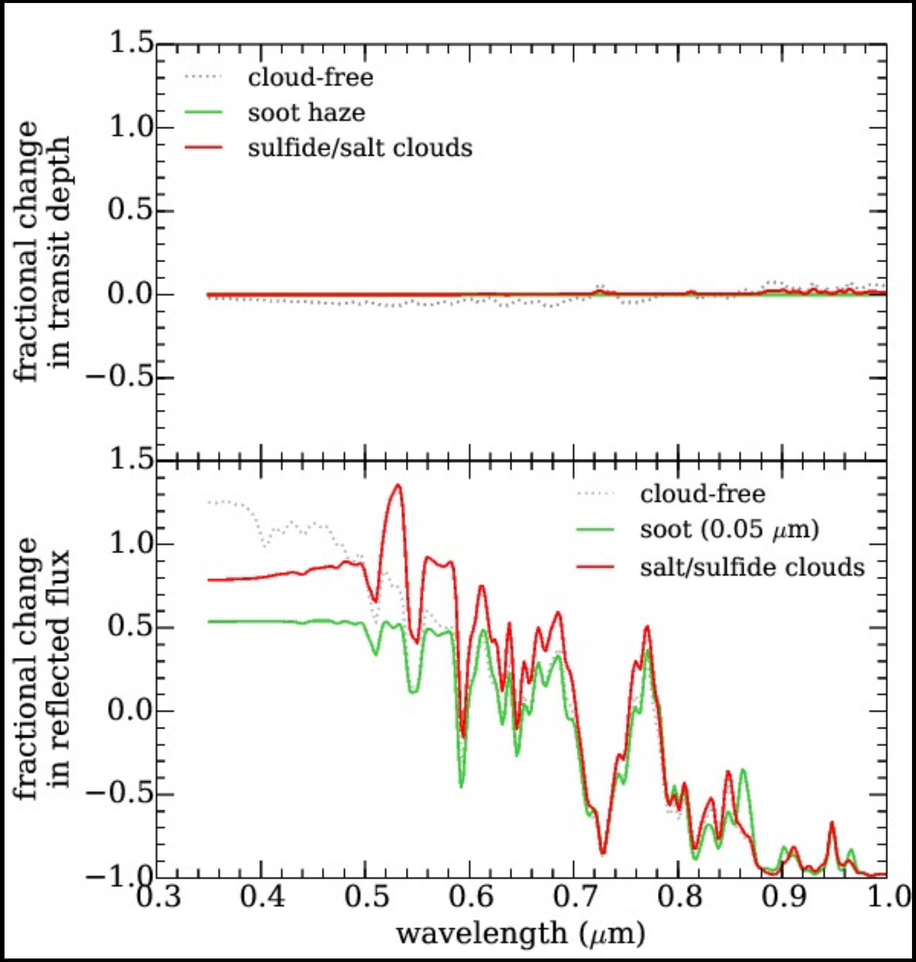


05 May 2016

High Contrast Imaging on
Segmented Apertures

Need for direct detection spectroscopy

- Radial velocity and transit surveys have shown exoplanets are abundant. Spectral characterization is the natural next step; reflected light planets are unique targets.



<u>Atmospheric features are more readily detected by imaging than by transits</u>

Transit spectra probe only the tenuous upper atmosphere

Curves show spectra relative to mean optical flux level

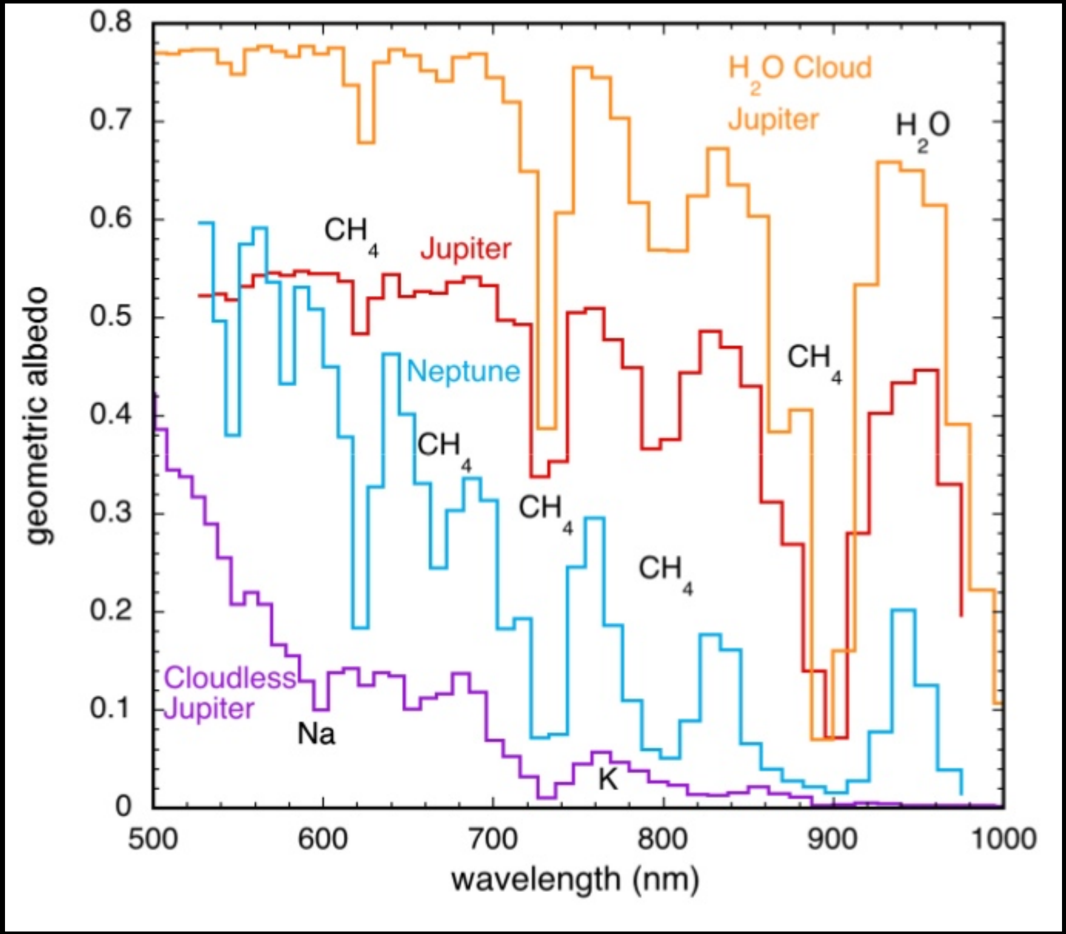
GJ 1214b model spectra by Caroline Morley and Mark Marley

Giant planets well-characterized by 0.5-0.8 μm spectroscopy

Depth of cloud deck determines strength of CH_4 features

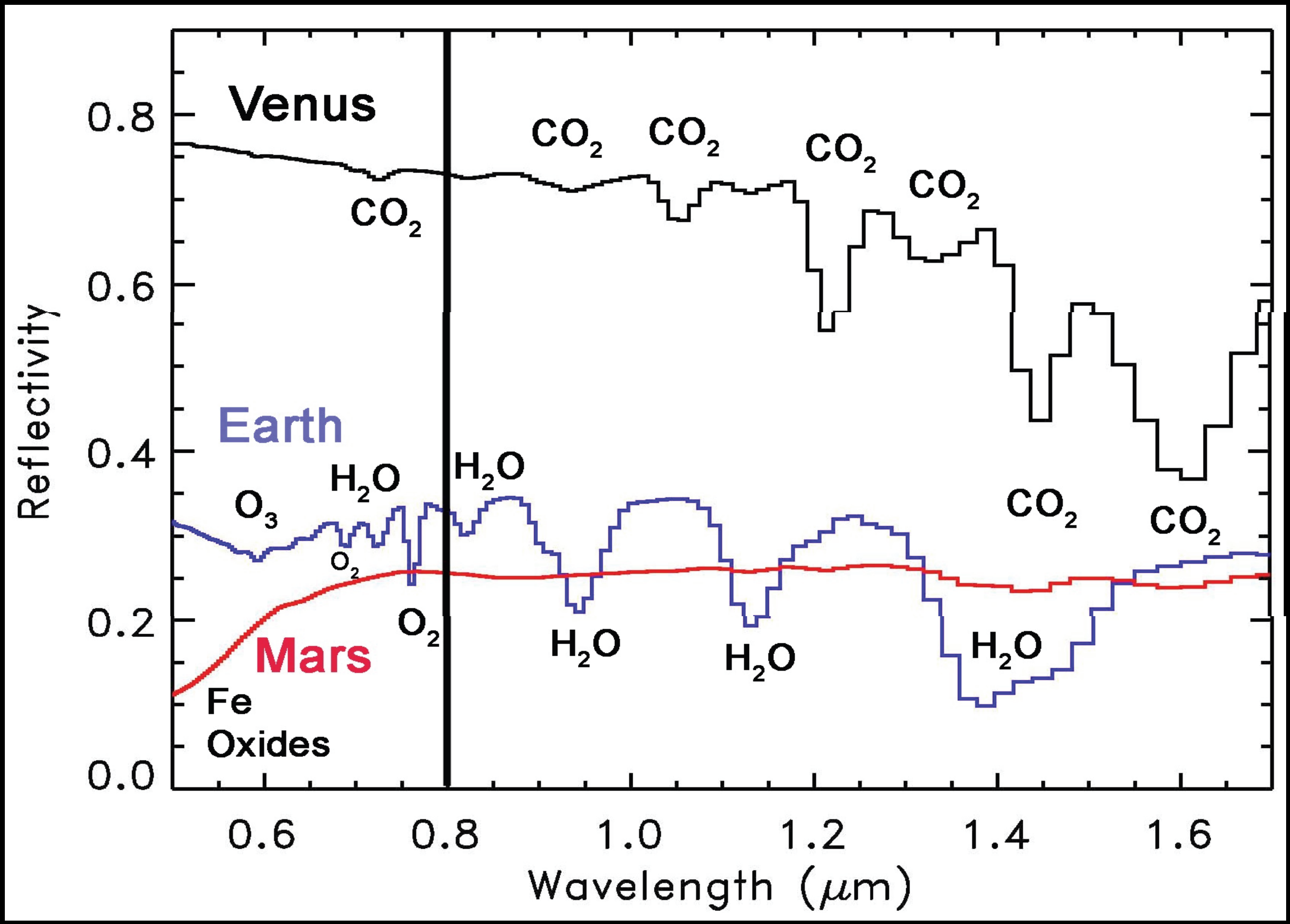
Warm giants lose reflective cloud decks and become dark

Jupiter vs. Neptune easily distinguished



Exo-C STDT report

Reflectance spectra of terrestrial planets at R= 70



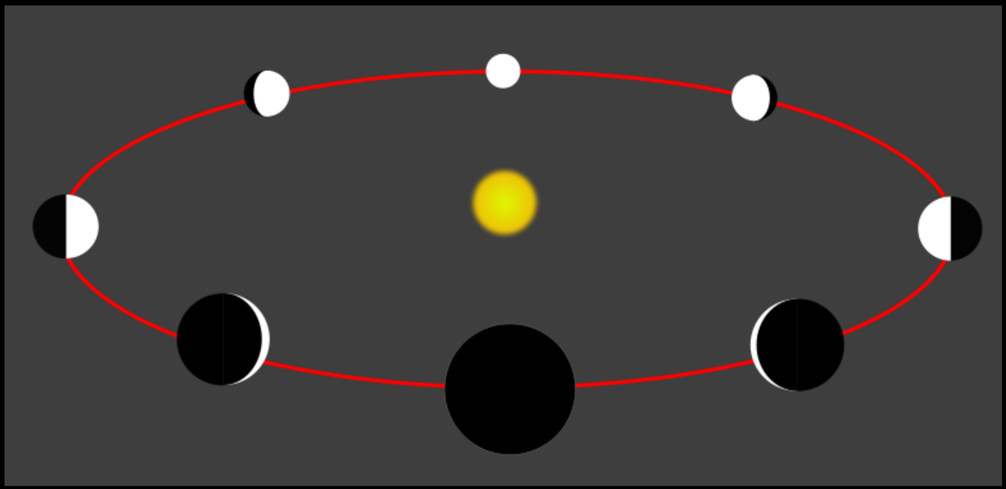
- Wavelength range 0.5-0.8 μm would encompass O_2 and H_2O feature and onset of Rayleigh scattering
- Near-IR is crucial for access to CO_2 and CH_4 (not shown), large ape would enable this

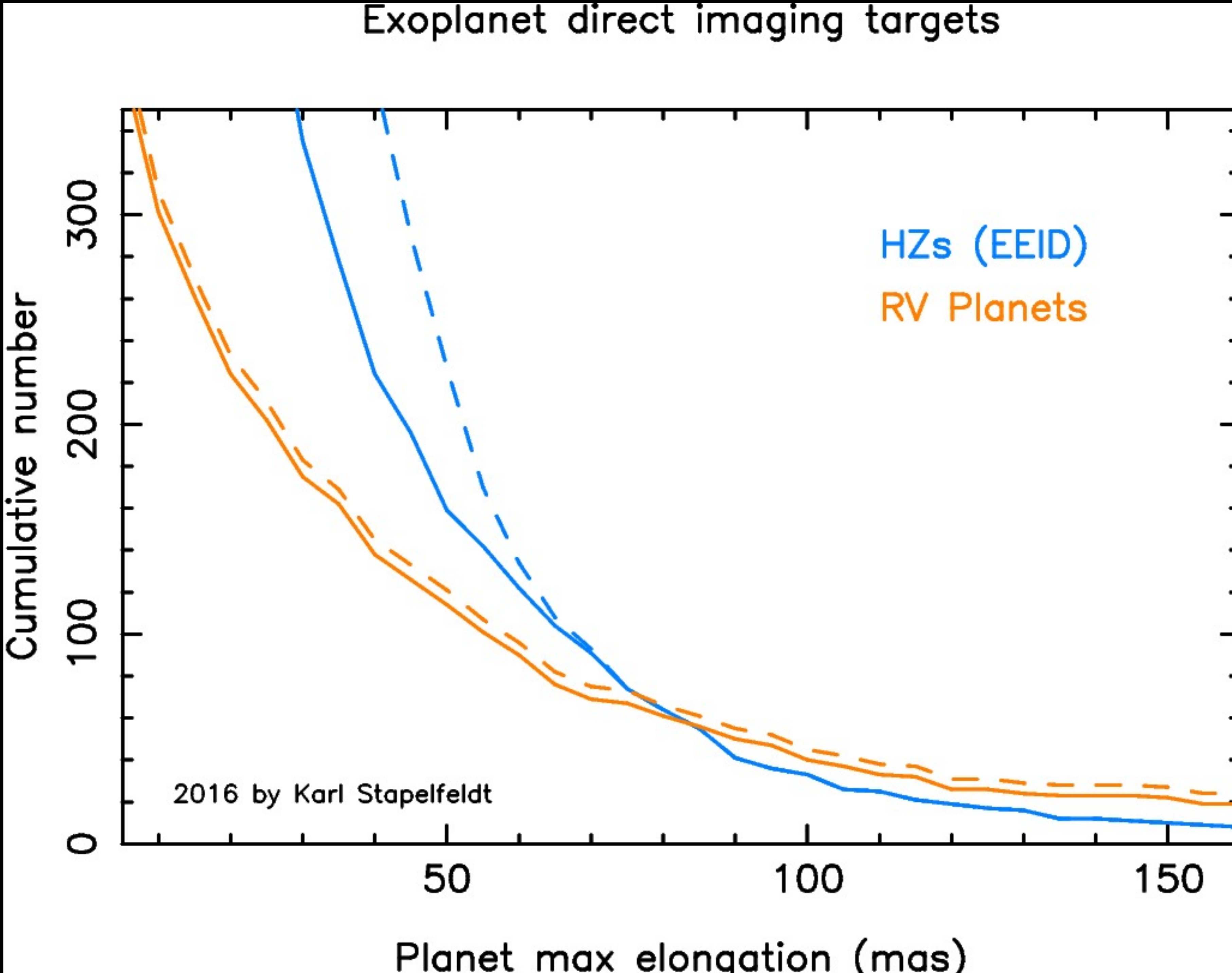
Direct Imaging Science Goals

1. System architectures: Full census of planetary systems around nearby stars: Jupiters, Neptunes, Super-Earths, Earths in the HZ, and dust structures. Measure brightness and constrain orbital parameters
2. Atmospheric composition: Measure planet colors. Detect major molecular bands (H_2O, O_3, O_2, possibly CO_2 and CH_4). Measure Rayleigh scattering.
3. Planet radii and masses need to come from theory or supporting data (RV, astrometry)

Contrast requirement

- The fully illuminated disk of Earth at 1 AU reflects (2/3) x (albedo of 0.3) x $(6{,}378/1.49e{+}8)^2$ = 3.7e-10 of solar output.
- At the most-probable quadrature geometry, the half-illuminated phase is fainter by a factor of π.
- The imager must detect planets at or below the contrast level of 10^{-10} (δmag= 25) in order see them around a major fraction of their orbits




Exoplanet direct imaging targets
HZs (EEID)
RV Planets
2016 by Karl Stapelfeldt
Cumulative number
0
100
200
300
50
100
150
Planet max elongation (mas)

Available HZ Targets vs. max elongation angle a/d

a/d (milliarcsec)	# Targets (HZ EEID > IWA)	Median R mag	Illustrative Telescope Diameter (m) [for IWA = 3 /D @1.0 m]
100	33	29.0	6.2
90	42	29.1	6.9
80	65	29.5	7.7
70	94	29.9	8.8
60	137	30.0	10.3
50	234	30.5	12.4
40	373	30.7	15.5

Planet brightness for spectroscopy: Implications for Aperture Size

Consider sample of 100 FGK stars with largest HZ EEID

Median distance 12.7 pc, Earth in HZ median R mag= 30.0

Capping a spectroscopy observation at 20 days of integration (2x Hubble Deep Field), and requiring S/N= 10 at $\lambda/\Delta\lambda = 70$,

No exozodi: 3.5 m telescope would suffice

1 exozodi requires 4.1 m telescope

5 exozodis requires 5.4 m telescope

10 exozodis requires 6.3 m telescope

20 exozodis requires 7.3 m telescope

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40 exozodis requires 8.7 m telescope

60 exozodis requires 9.7 m telescope

Assumes:
- photon noise from (exo)zodi, planet, dark
- 20% overall throughput
- 20% degraded spatial resolution from apodization

Inner working angle (IWA)

- Habitable zone definition as 0.7-1.8 AU, scaled by sqrt(Stellar luminosity), with 1.0 AU as fiducial
- For the 100 stars with largest angular HZ, the median elongation corresponding to 1 EEID is 86 mas
- If the mission is going to do planet searches, a smaller IWA ~70% of the median elongation. 100 star mission should aim for IWA ~60 mas
- Higher zodi levels drive the mission to larger apertures: for 10 zodis, diameter >= 6.3 m is needed → coronagraph must achieve design contrast at ring radius (0.060/202625)/(0.7e-06 m / 6.3 m)>= 2.7 λ/D.
- If exozodi is at solar system level, a 4.1 m telescope might suffice but needed ring radius is now 1.7 λ/D. Coronagraphy more challenging

Orbit determination is critical for assessment of habitability

- First revisit must remove confusion: show candidate planet does not move like a background star

  At V= 30, galactic background star density varies from 0.001 to 1 per sq arcsec. BG star will be unlikely in many cases

- Assume S/N= 10 measurements in 20% bandpass on R= 30.0 planet (1 day integration with 6.3 m telescope and 10 exozodi), implies astrometric measurement precision of $\lambda/10D$= 2 mas.
- For HZ target planet at 12.7 pc median distance, mean orbital motion rate is ~300 mas/yr and mean projected rate around quadrature is 100 mas/yr
- Revisit time interval must be long enough to resolve this motion: 2 mas / 100 mas/yr= 7 days, scales inversely w/ telescope size. Longer time baselines, astrometry at > 3 epochs preferable for accurate orbit solutions.

Planet photometric variability

- In principle, the planet rotation period and constraints on surface albedo features can be derived from extended timeseries photometry (Cowan et al. 2009)
- In practice the above will be difficult, as few targets will be bright enough for S/N= 10 photometry on timescales of a few hours. Assuming 1 zodi, 12 systems would be accessible to a 4.1 m telescope. A 8m aperture would enable such measurements in 140 stars
- Seasonal variations might be measured, after accounting for changes in illumination phase around the orbit

Probable characteristics* of LUVOIR

* ExoPAG's notional mission parameters

Goals:

- Direct imaging of Earth analogs, search for biosignatures
- Broad range of cosmic origins science from UV to near-infrared

Exoplanet capabilities:

- 10^{-10} contrast achieved with coronagraph and perhaps a starshade
- Optical/near-IR high contrast imager & spectrograph

Architecture:

- 8-16 m aperture, segmented/obscured primary, L2 orbit.

Schedule: 3 year study started in April 2016

The Opportunities

Segmentation enables larger apertures with clear exoplanet science advantages:

- Greater number of accessible targets at any wavelength
- Ability to tolerate larger values of exozodi
- Larger number of targets bright enough for synoptic observations
- More precise astrometry for orbit determination

- Greater number of planet photons collected may allow relaxation of 10^{-10} raw contrast requirement

The Challenges

1) Engineer >70 m diameter starshade(s) and find a way to move them nimbly around the sky; OR
2) Engineer wavefronts & masks on scales of picometers to microns, so that complex segmented apertures can be made compatible with the exoEarth imaging requirements. Leverage lessons from WFIRST CGI.

We are here to pursue option 2). Discussion, new initiatives, and lab demonstrations are needed !

Can coronagraphs with good throughput and IWA, and able to cope with telescope & segment drifts, be developed over the next 5-7 years ?