OVERVIEW OF EXOPLANET DIRECT IMAGING SCIENCE

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Talk Overview

- History of imaging efforts
- Fruition: 2008 - current
- Future prospects for imaging planets in reflected light, including habitable planets

Exoplanet: noun. A planet orbiting a star that is not our sun

- Merriam-Webster dictionary. First use 1996

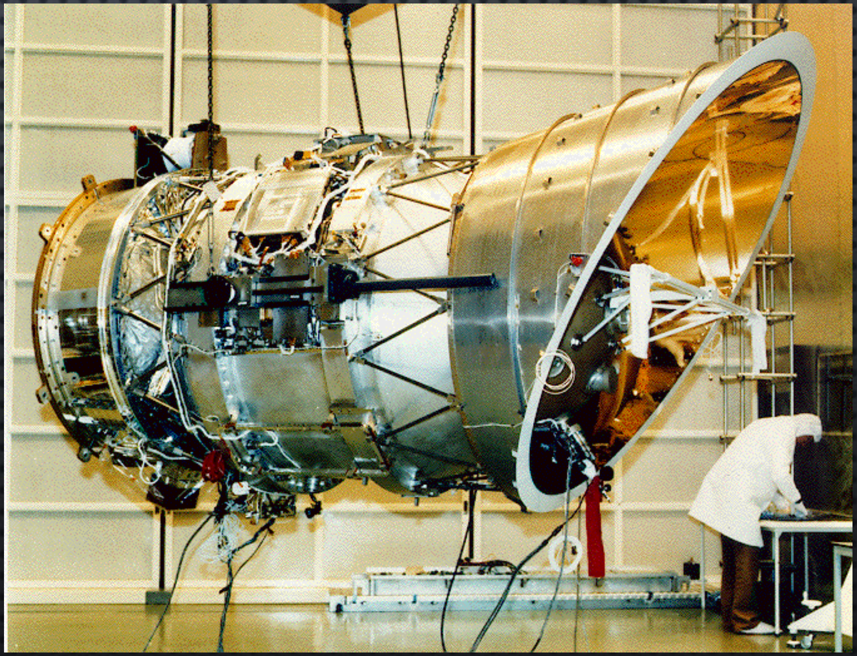
Exoplanets have been imagined by philosophers, writers & artists for generations

Where to look for them ? How to see them ?

Only in the past 30 years have they come into view

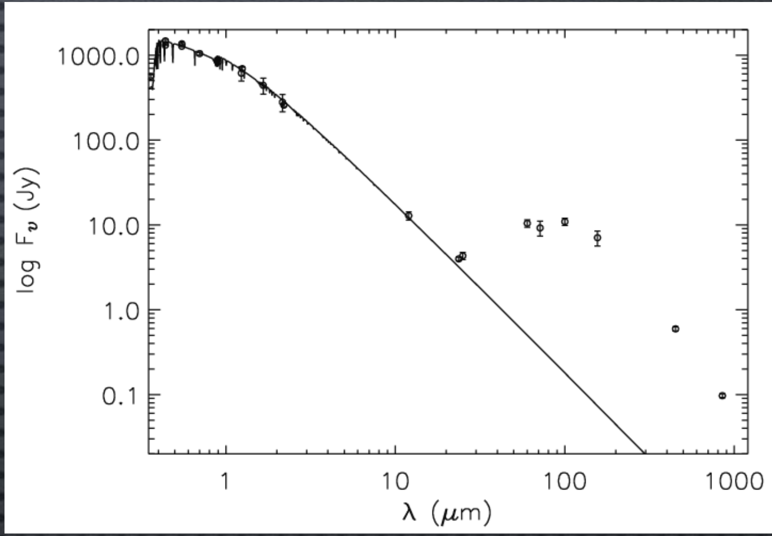
Infrared Astronomical Satellite (IRAS)

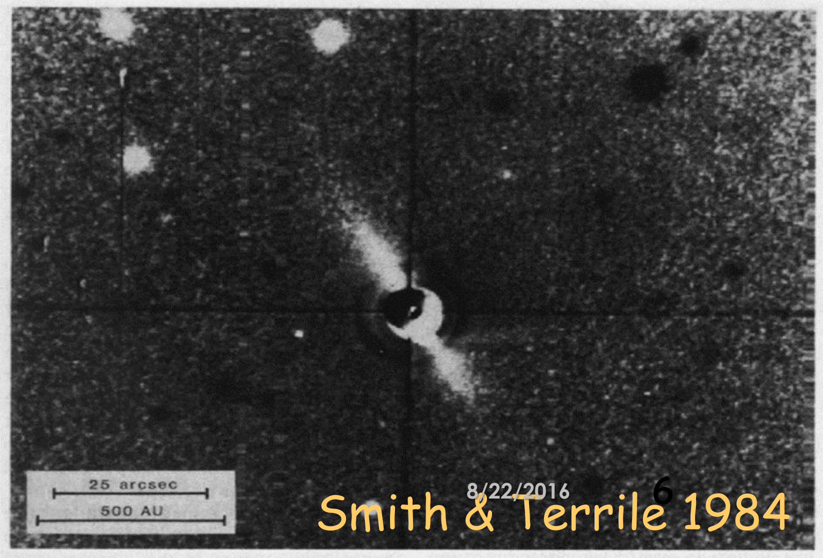
- First space infrared observatory
- 0.5 cm cryogenic telescope
- Operated in low Earth orbit for 10 months in 1983
- Primitive detectors limited spatial resolution to ~1 arcmin; mapping, not detailed imaging
- All-sky survey at 12, 25, 60, and 100 μm (corresponding to cool material at 270, 130, 60, and 30 degrees Kelvin)



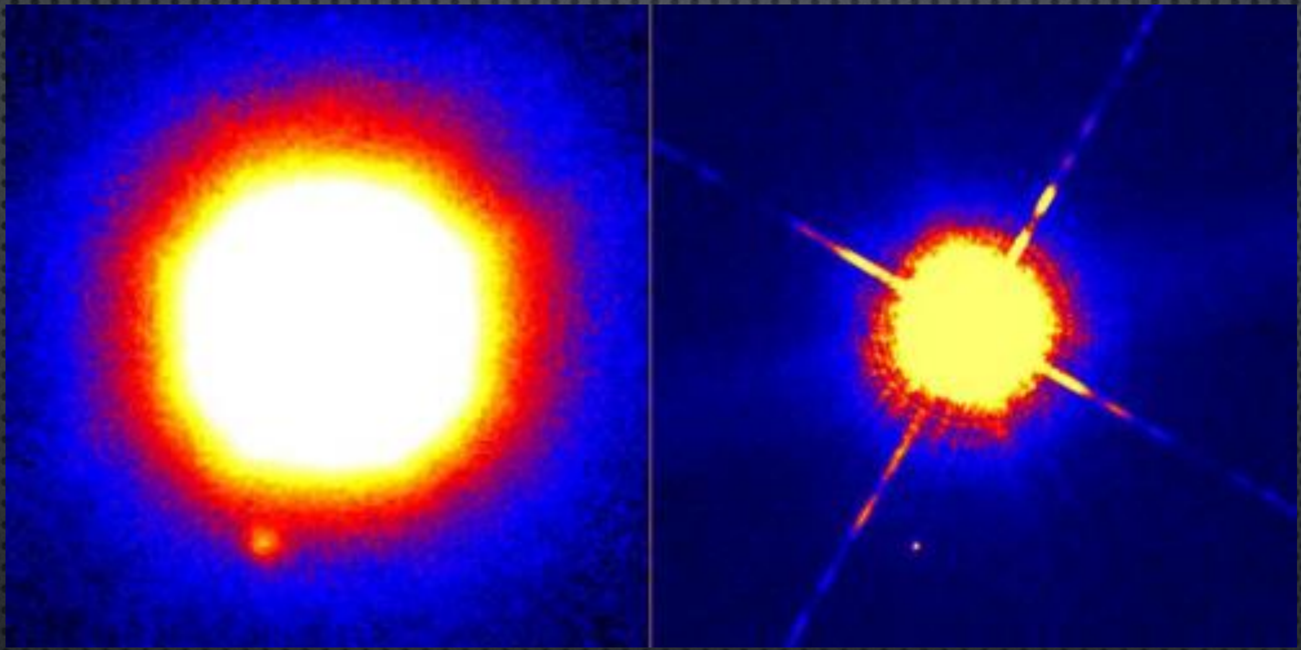
EXTRASOLAR **DEBRIS DISKS** WERE DISCOVERED BY IRAS MEASUREMENT OF EXCESS STELLAR EMISSION IN THE INFRARED:

- Found around nearby main-sequence stars, prominent examples being Vega, Fomalhaut, ε Eridani, and β Pictoris (edge-on disk, lower right)
- Dust clouds created by collisions between asteroids & comets
- Disk masses very small, < few lunar masses. Not a planet-forming disk
- ~100 AU scales: Kuiper Belts
- The best evidence for extrasolar planetary systems prior to 1995



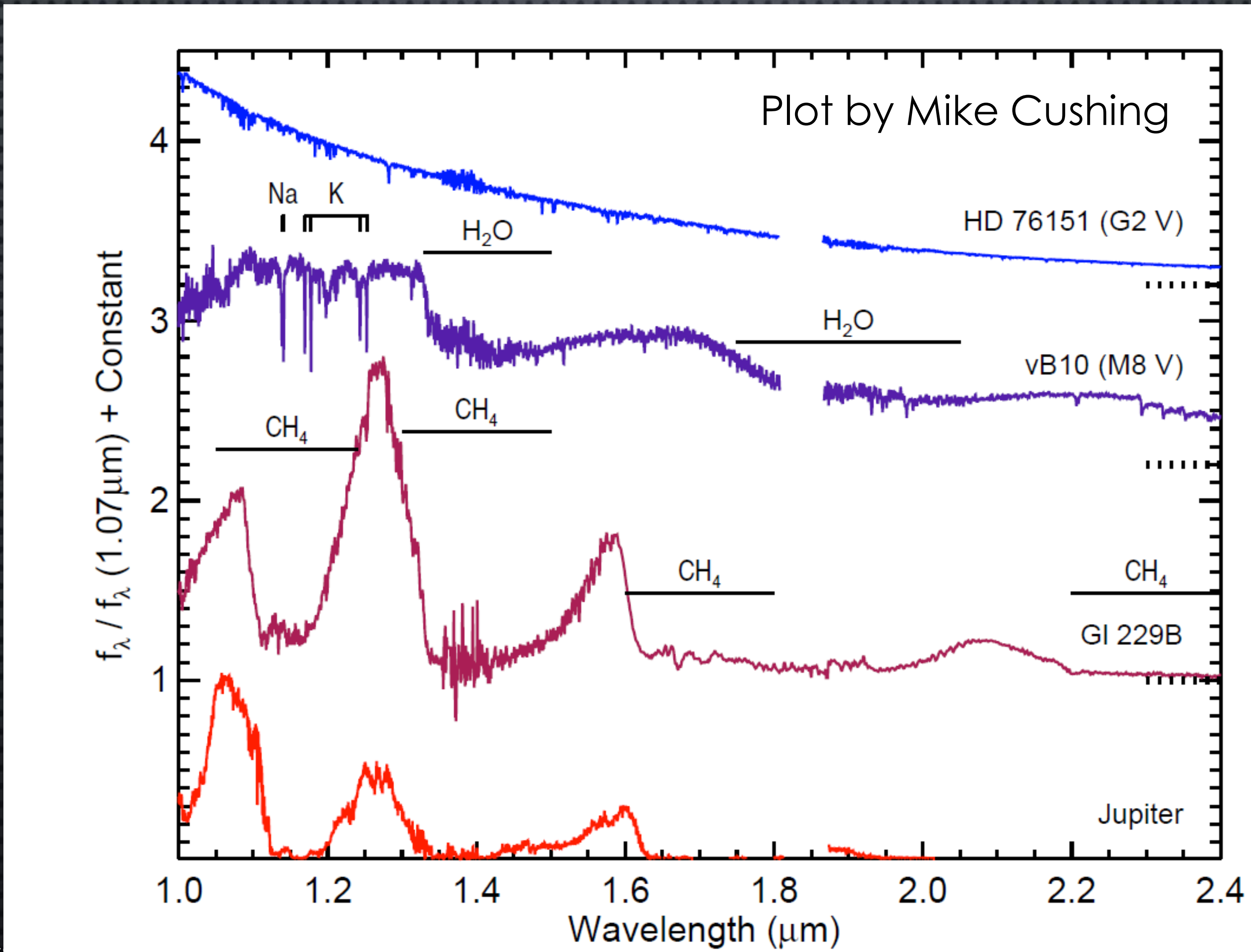


GL 229 B:
The First Confirmed Brown Dwarf



- Discovered at Palomar 60" in coronagraphic imaging survey by Nakajima & Golimowski (1994; left panel. HST image at right)
- Companion to a red dwarf star (M1 V, distance 5.8 pc), separation 36 AU
- Dozens of other Brown dwarf companions are now known, and hundreds of isolated brown dwarfs floating in isolation.

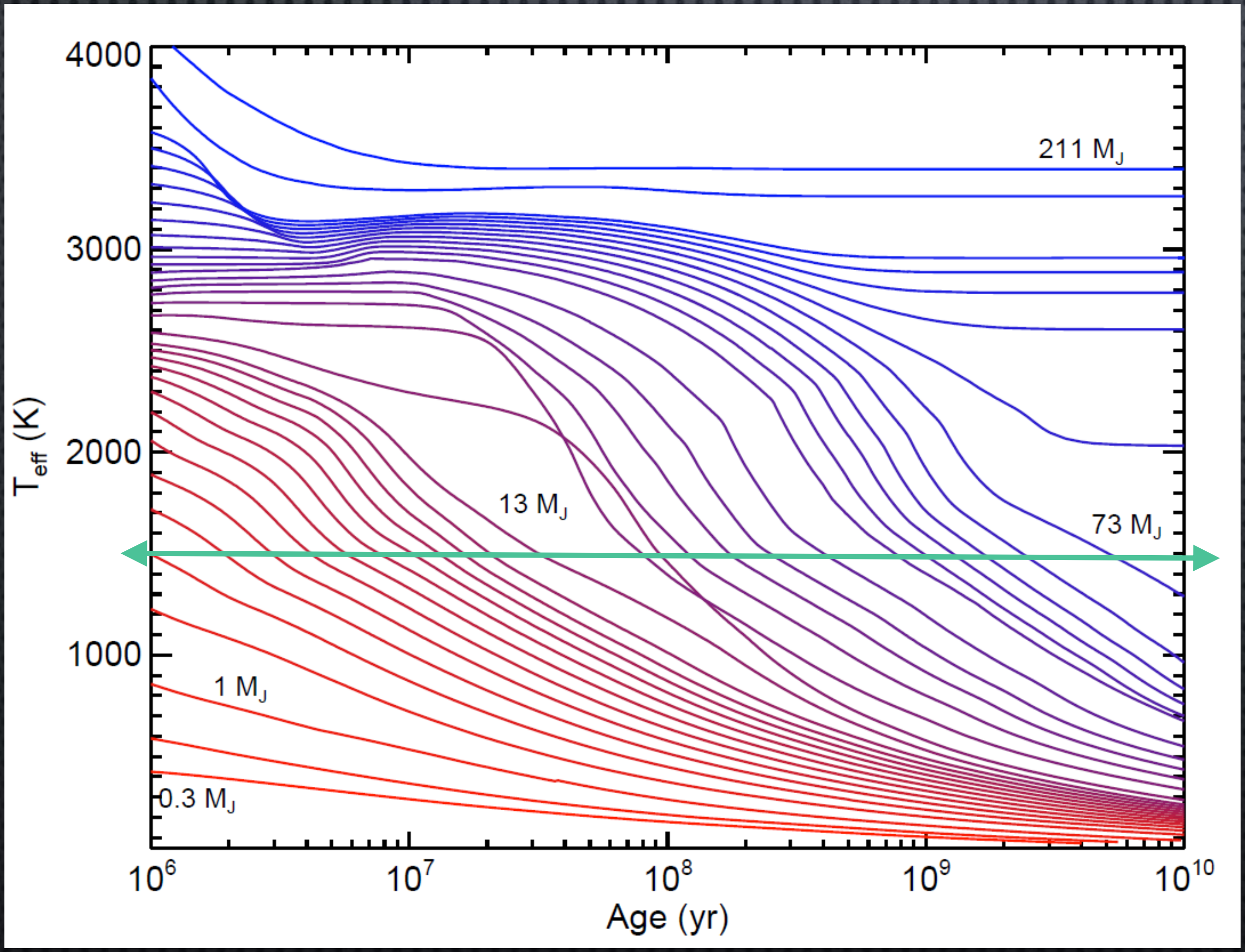
UNLIKE ANY STAR: LIKE JUPITER, SPECTRUM OF GL 229 B IS DOMINATED BY METHANE. 950 K, HOT !



EVOLUTION OF BROWN DWARFS AND LOW MASS STARS

- STARS: LONG LIFE AT A STABLE TEMPERATURE
- BROWN DWARF: CONSTANTLY COOLING DOWN

Plot of Burrows 1997 models by Mike Cushing



Inferred mass of brown dwarf strongly depends on Its age !!

Stars

Brown Dwarfs

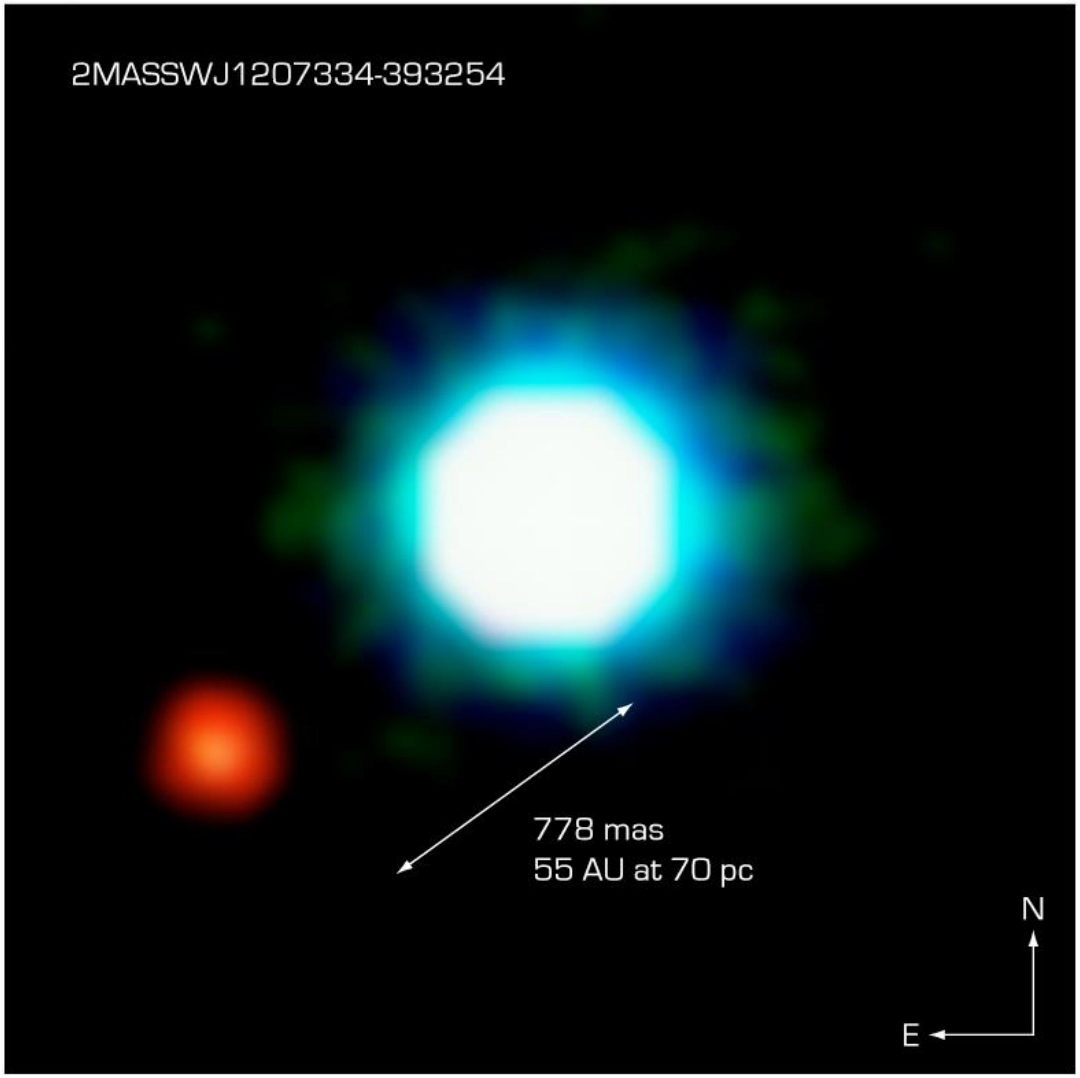
Planets

Since planets are more detectable when young and hot, find them by looking for companions to the youngest stars

- Nearest groups of newly formed stars (Taurus, Ophiuchus, Chamaeleon) are a bit distant: 120-140 pc
- Beta pictoris turns out to be fairly young at 20 Myrs age and only 20 pc away
- Young stars are bright in X-rays. Several nearby stellar "moving groups" identified starting in late 1990s: ideal target stars for imaging young planetary companions
- Many search programs keying on methane
- Planethood depends on accuracy of age determination and cooling models

First exoplanet image ?

- Target is a young brown dwarf in TW Hydrae association, ~25 Jupiter masses
- Companion is inferred to be giant planet with ~6 Jupiter masses
- Chauvin et al. 2004



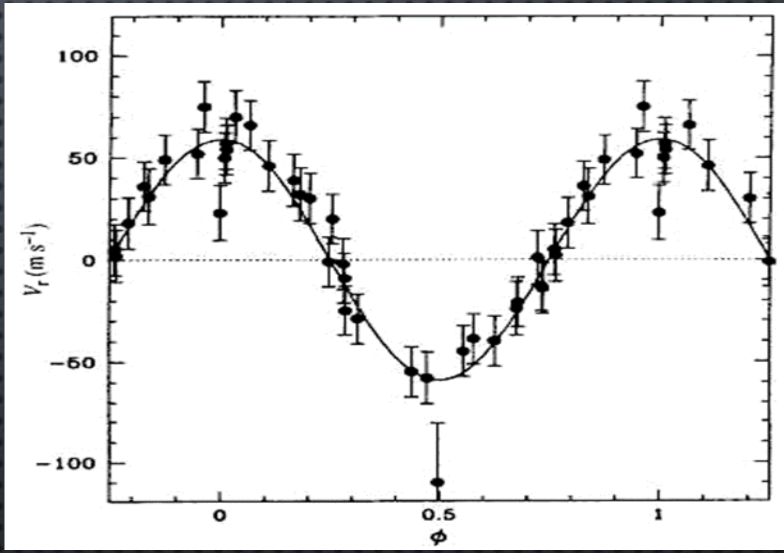
NACO Image of the Brown Dwarf Object 2M1207 and GPCC

ESO PR Photo 26a/04 (10 September 2004)

MEANWHILE, INDIRECT METHODS OF PLANET DETECTION HAD BEEN RAPIDLY PROGRESSING

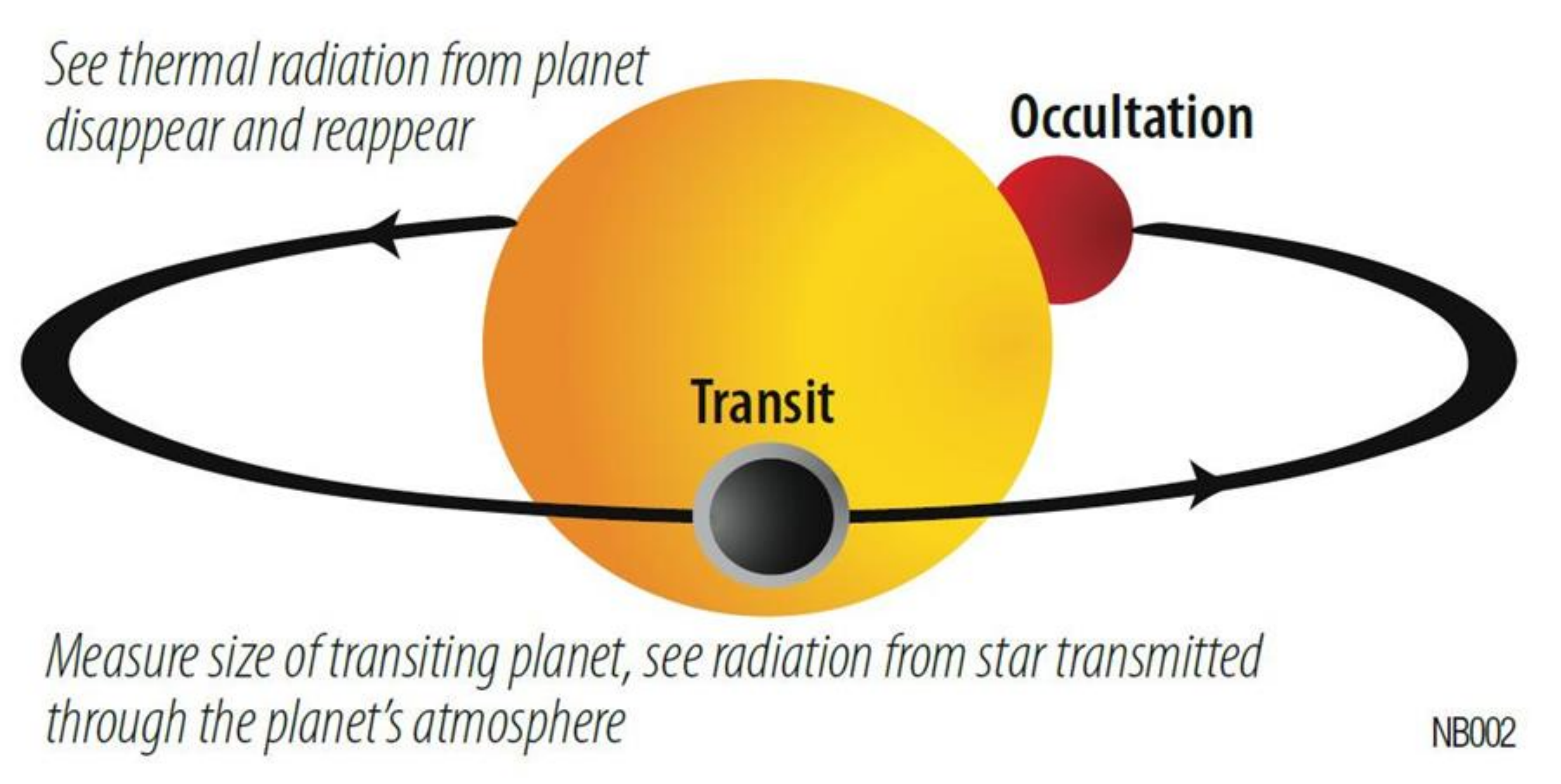
RADIAL VELOCITY TECHNIQUE: MEASURES DYNAMICAL DISTURBANCE OF HOST STAR DUR PLANET'S GRAVITY AND ORBIT

- FIRST PLANET ("HOT JUPITER") DISCOVERED IN 1995
- MASS MEASURED HAS SIN(I) AMBIGUITY
- A COUPLE HUNDRED RV PLANETS KNOWN BY 2005, INCLUDING SOME NEARBY STARS (EPSILON ERIDANI). MOSTLY JUPITERS, BUT SOME NEPTUNES
- METHOD DOES PRODUCE TARGETS FOR IMAGING SEARCHES – THESE WERE INITIALLY AIMED AT FINDING ADDITIONAL PLANETS IN THE SYSTEMS



51 Pegasi
Mayor & Queloz 1995

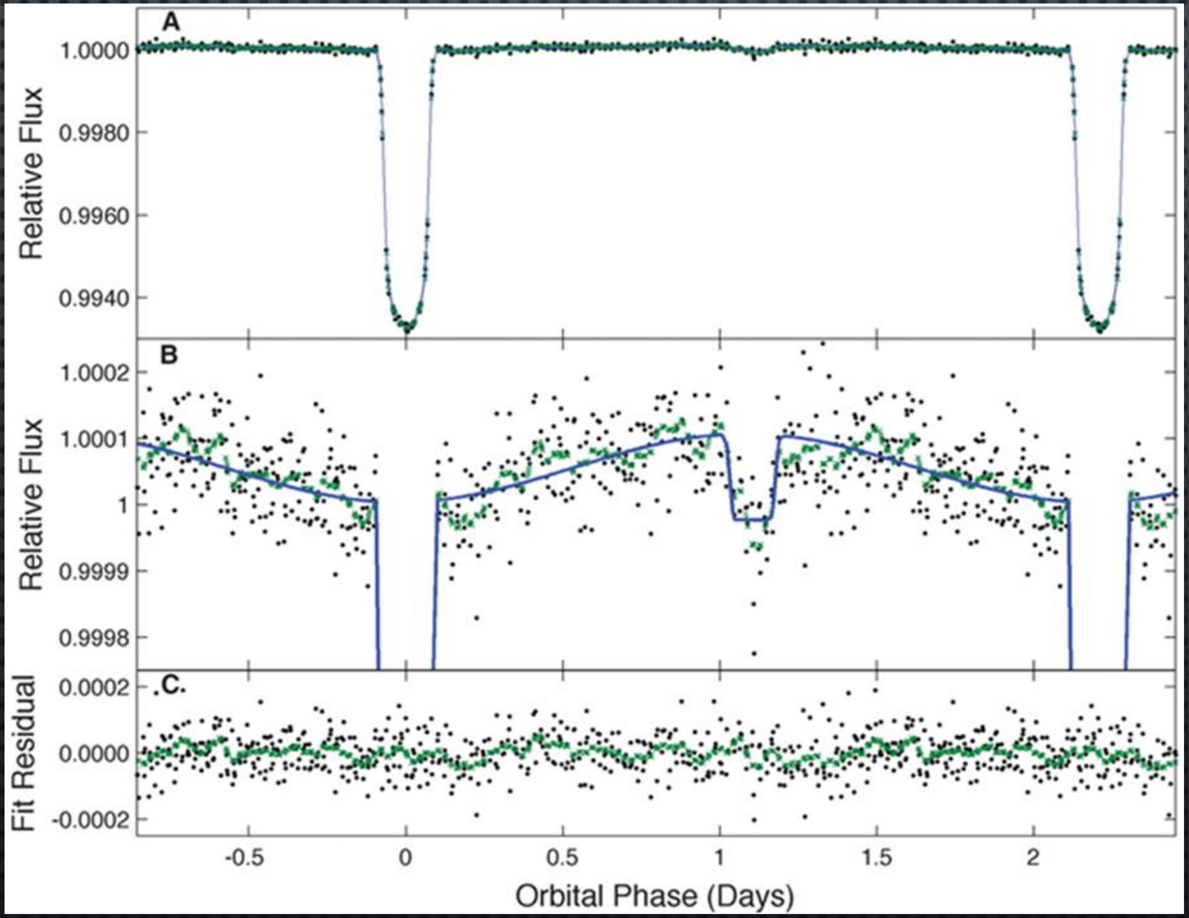
TRANSITING PLANET: IS IN AN EDGE-ON ORBIT THAT BRINGS IT ALTERNATELY IN FRONT OF AND BEHIND ITS STAR.



- Targets not accessible to imaging due to very short orbital periods

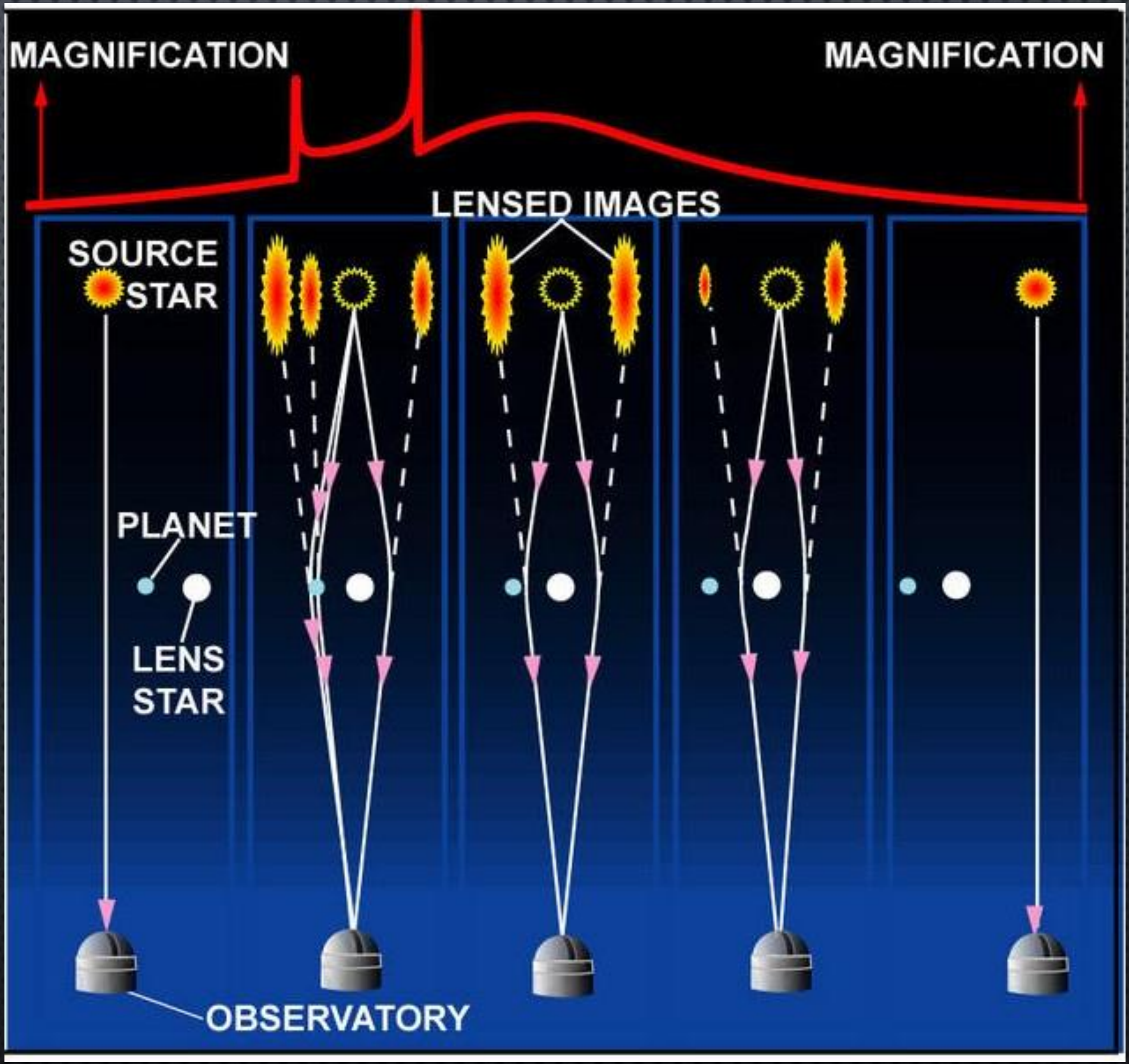
FIRST PHOTONS DETECTED IN TRANSITING PLANET USING SPITZER, 2005

(DEMING ET AL; CHARBONNEAU ET AL.)



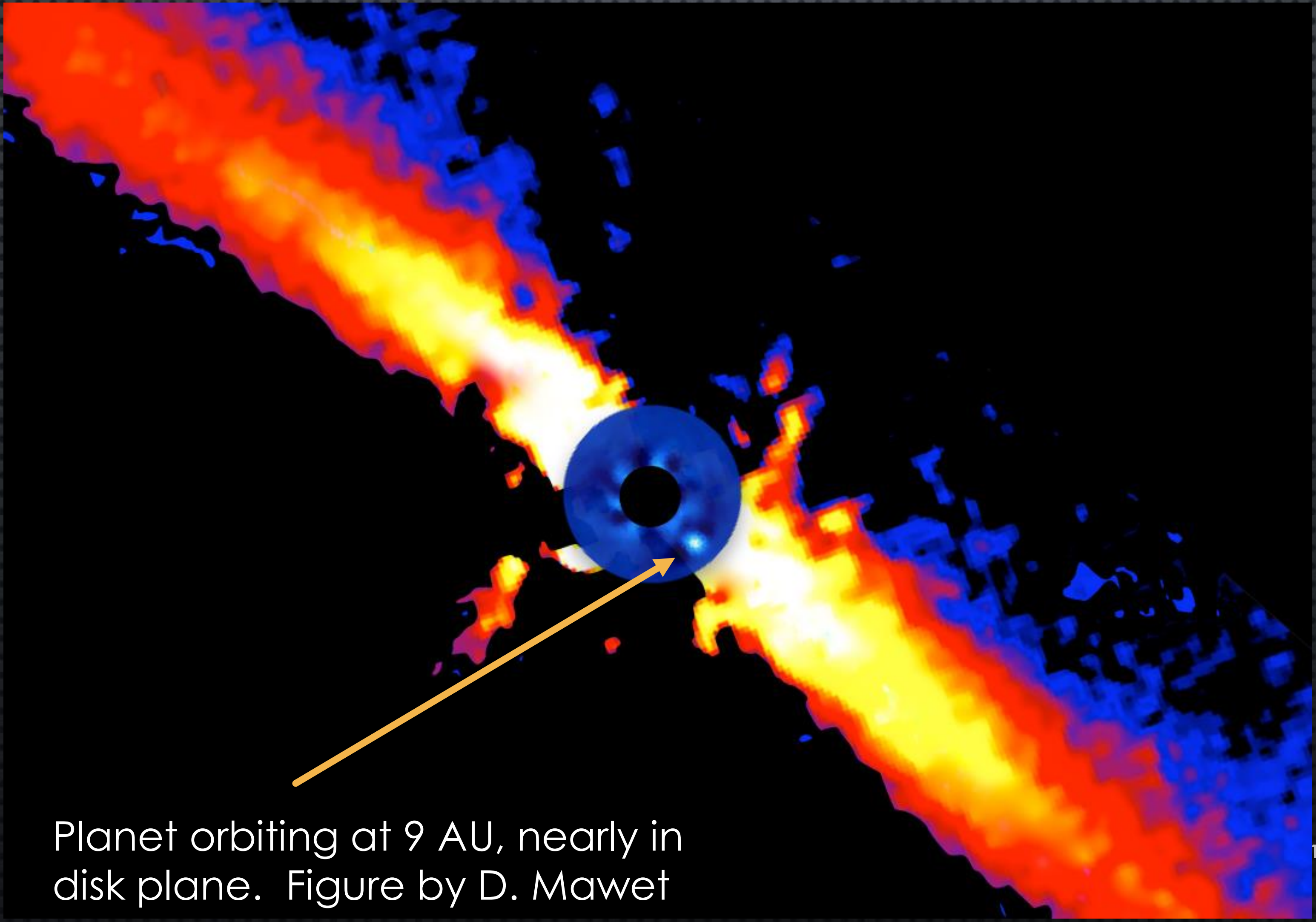
MICROLENSING PLANETS FOUND STARTING IN 2004

- BRIGHTNESS OF BACKGROUND STAR IS MODULATED BY FOREGROUND STAR/PLANETS PASSING IN FRONT OF IT
- PLANETS TOO DISTANT - NOT ACCESSIBLE TO DIRECT IMAGING (OR ANY !) FOLLOWUP



From D. Bennett

FINALLY EXOPLANET IMAGING DETECTIONS: 1. BETA PICTORIS PLANET IN 2009 (LAGRANGE ET AL.)



1. BETA PICTORIS PLANET SPECTRUM: HOT: 1650 K, 10-12 JUPITER MASSES, 20 MYRS. METHANE NOT DETECTED, LIKELY DUE TO DUSTY ATMOSPHERE

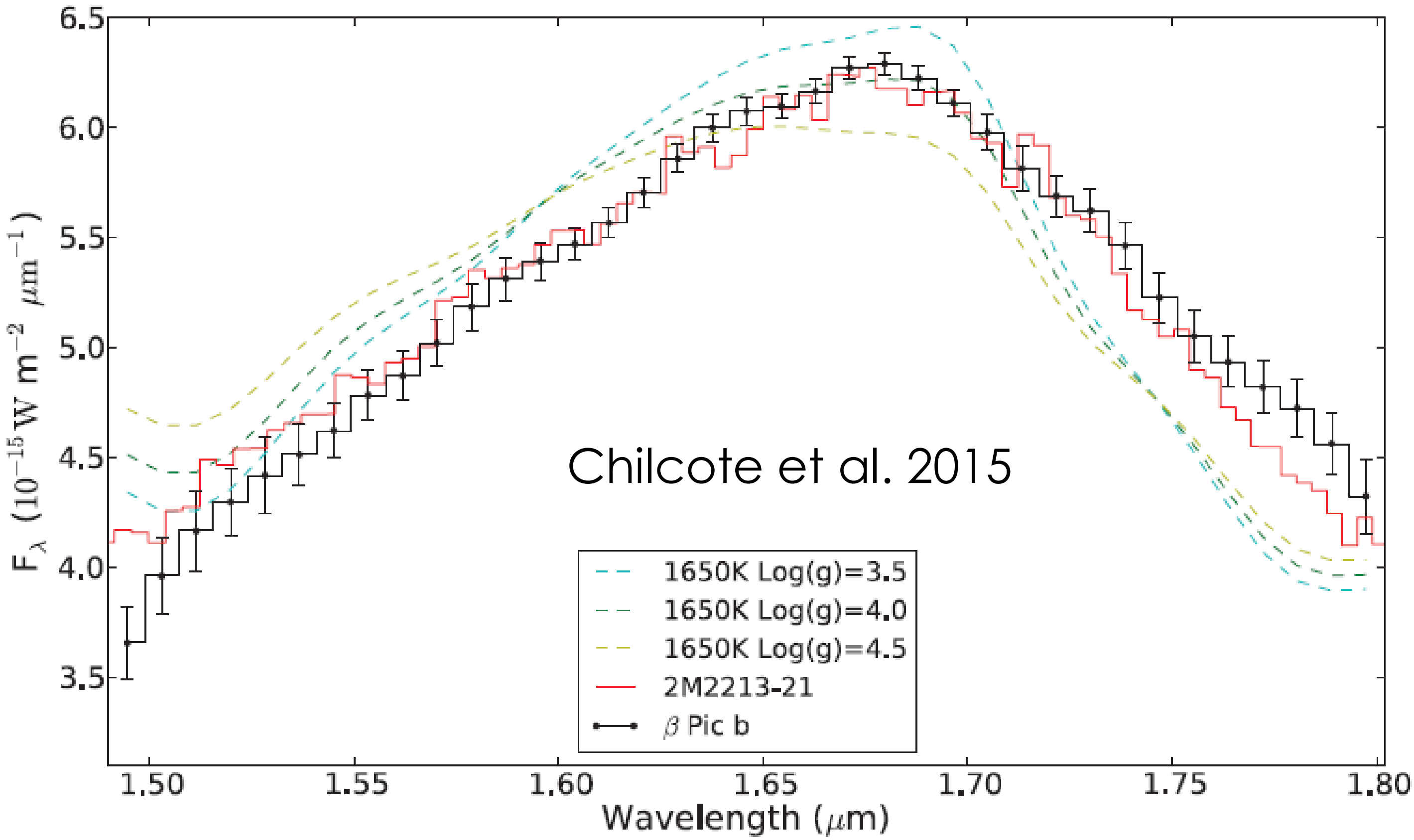
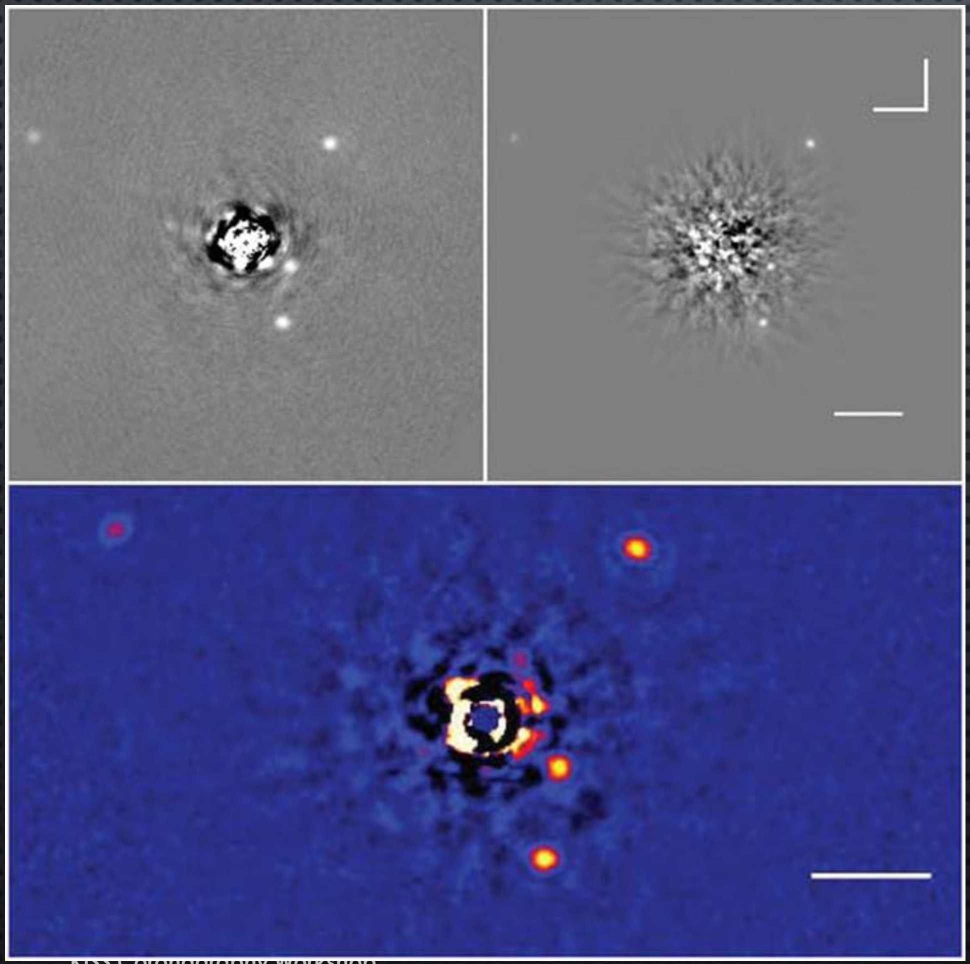


Figure 3. Comparison of the *H*-band spectrum (black) to a 1650 K model with three different gravities. All three models do not provide a perfect match to

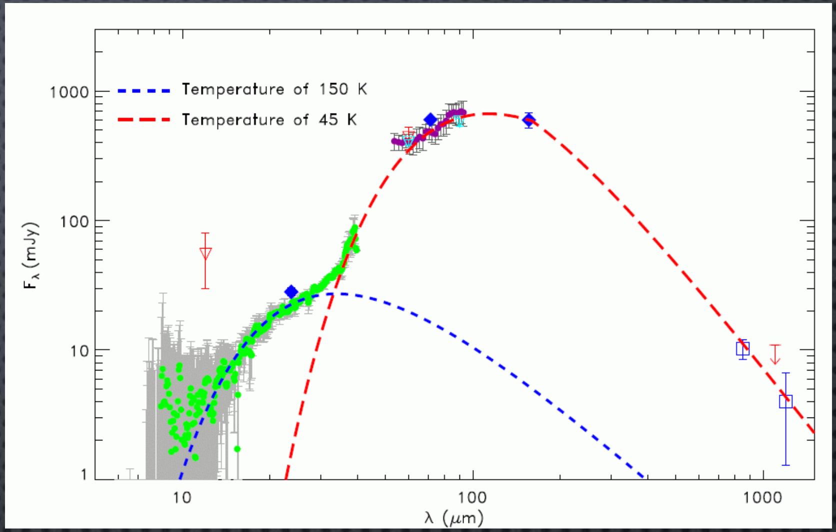
FINALLY EXOPLANET IMAGING DETECTIONS: 2. HR 8799 PLANETS (MAROIS ET AL. 2008, 2010)



- Spectacular system of 4 planets orbiting 40 Myr old A star
- All are massive: ~> 8 Jupiter masses and hot

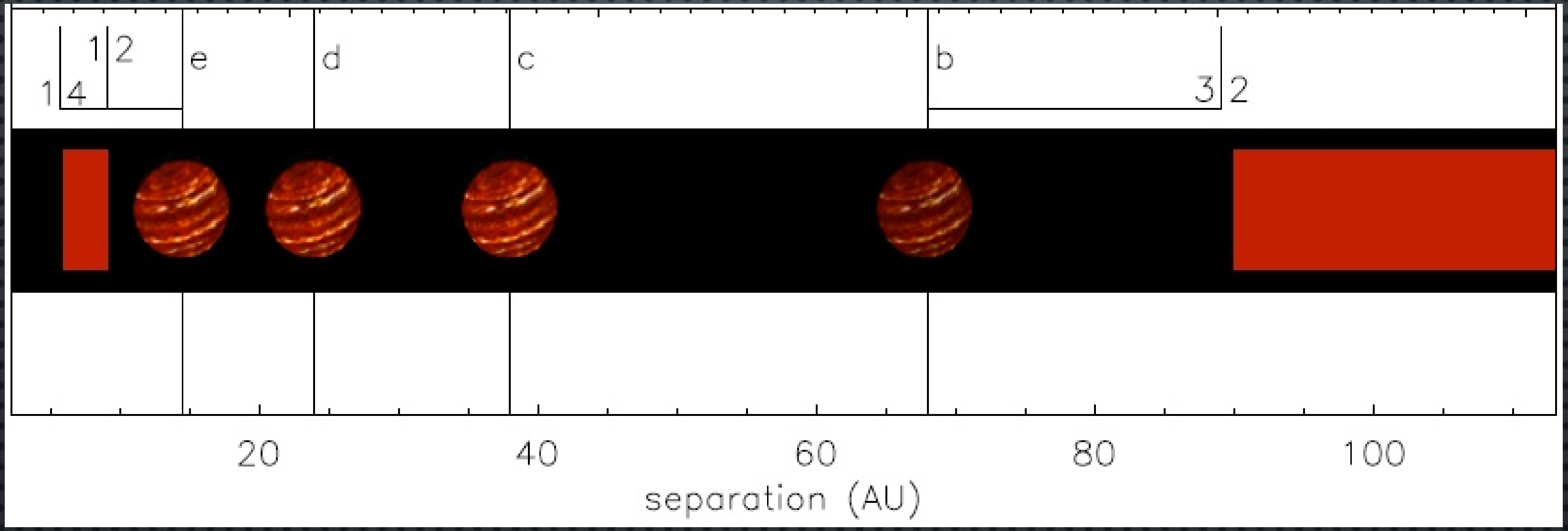
2. The HR 8799 Debris Disk

- Infrared excess shows two blackbody-like components
- Simple blackbody grains would produce this if located in belts at
  - 9 AU (T= 150 K)
  - 95 AU (T= 45 K)
- Dynamically viable: This places the dust interior and exterior to the planets imaged at 15, 27, 43, 68 AU



(Su et al. 2009)
see also
Chen et al. 2009,
Reidemeister et al. 2009

2. DISK/PLANET ARRANGEMENT IN THE HR 8799 SYSTEM MIRRORS THE SOLAR SYSTEM



- Planet e found in the gap between inner belt and planet d
- Suggestion that belt edges may be located at major resonance
- There are many other debris disks with two distinct belts : natural targets for further imaging planet searches

Marois et al. 2010

2. HR 8799 SPECTRUM OF OUTERMOST PLANET HIGH SPECTRAL RESOLUTION & CROSS-CORRELATION DETECTS H_2O, CO, MAYBE CH_4 (BARMAN, KONOPACKY ET AL. 2015)

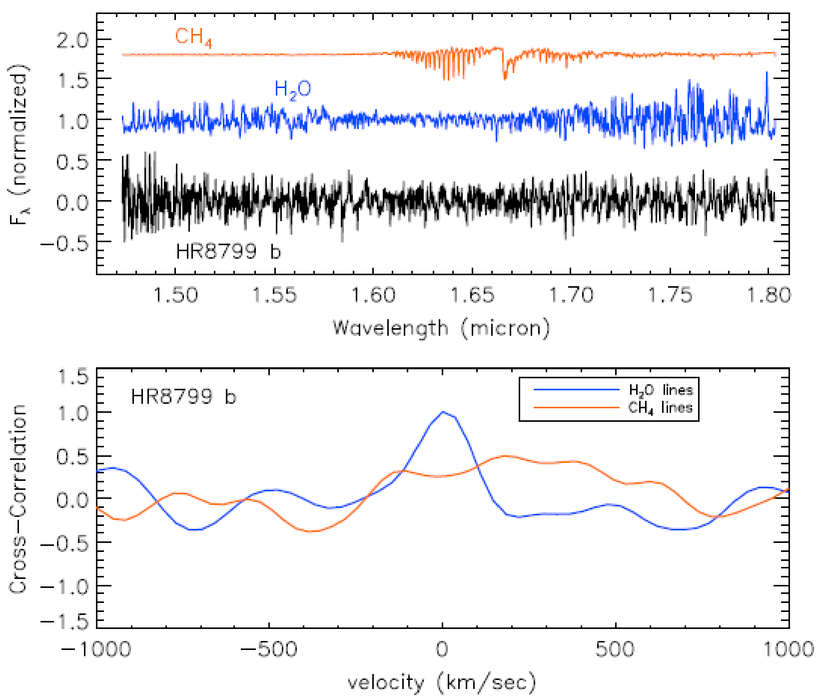


Figure 3. Same as Figure 2, but for *H* band. Only very weak CO lines are present in the *H* band and, therefore, were not searched for. The observed continuum-subtracted spectrum shows no correlation with the CH_4 template.

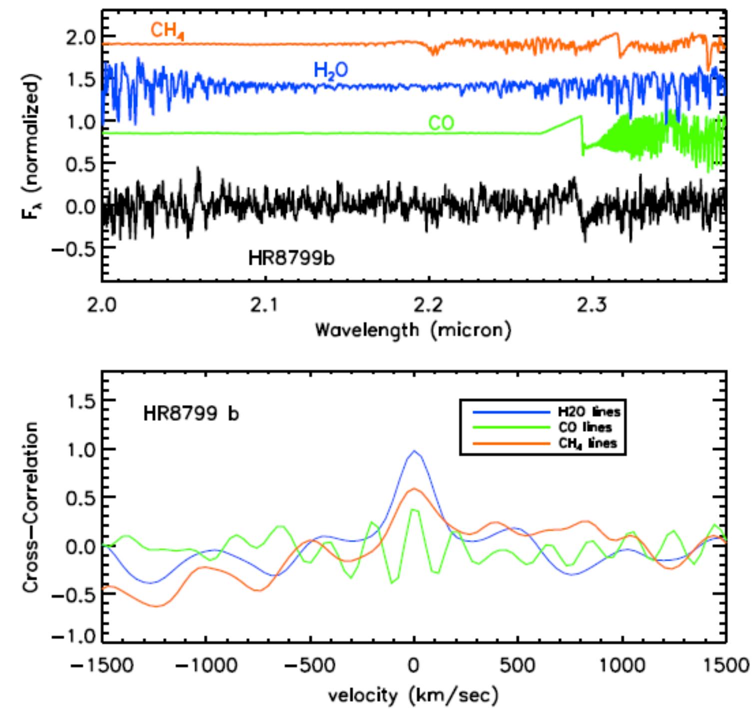
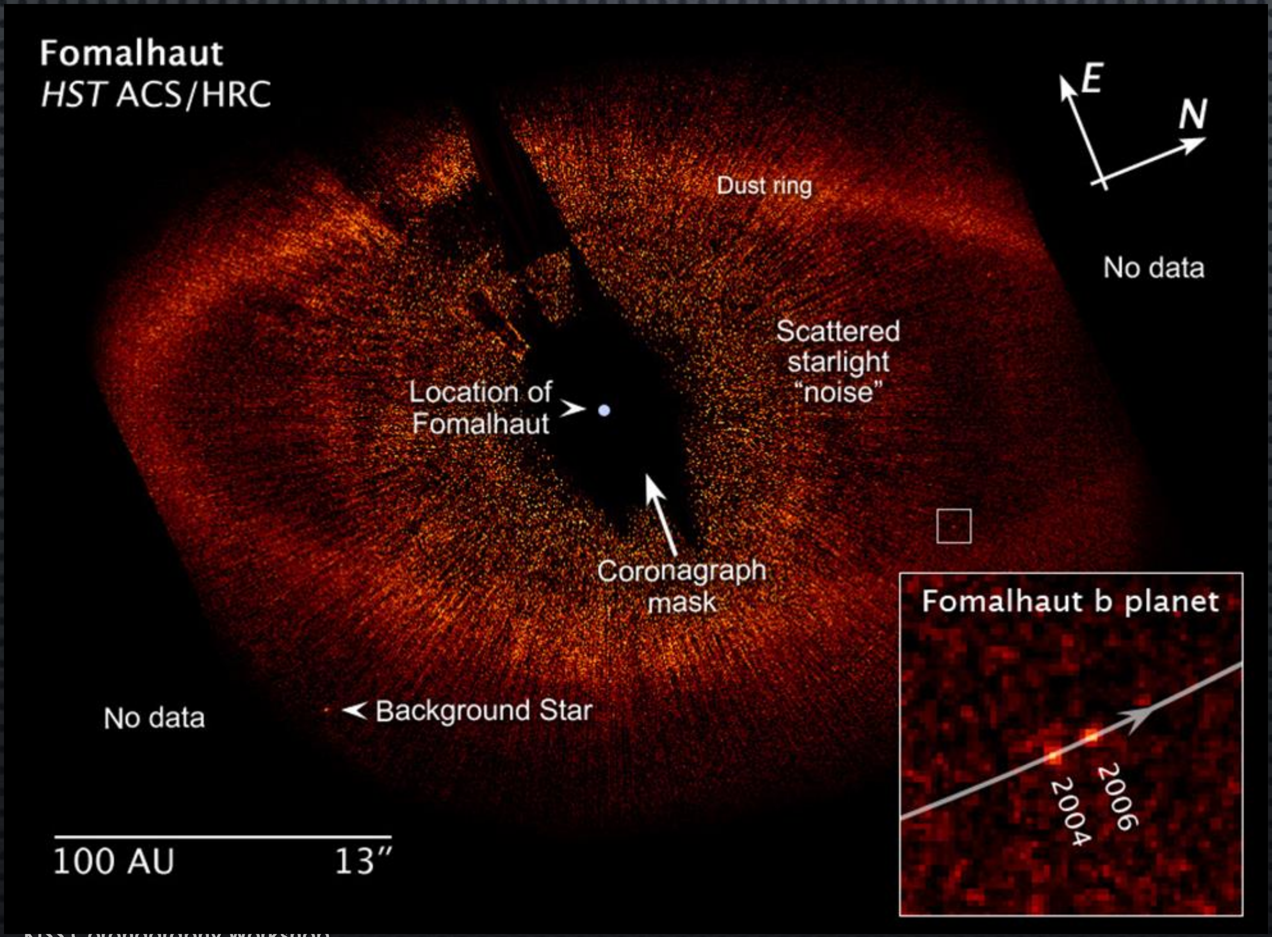


Figure 2. Top: continuum-subtracted spectrum for HR 8799 b. Template spectra for pure CH_4 (orange), H_2O (blue) and CO (green) are also plotted and offset by an arbitrary amount. Bottom: cross-correlation functions for HR 8799 b and the template spectra plotted in the top panel.

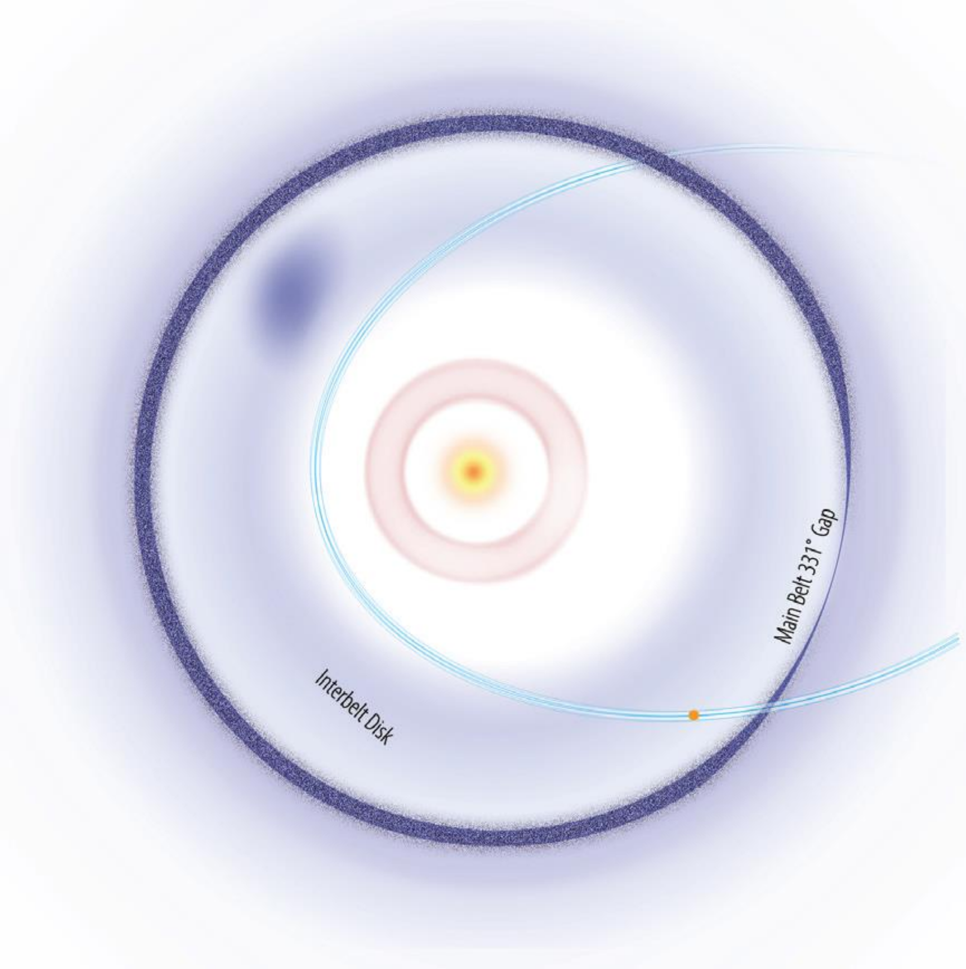
3. THE CURIOUS CASE OF FOMALHAUT: KALAS ET AL. 2008 FOUND OBJECT ORBITING NEAR INNER EDGE OF DUST RING – THE LONG EXPECTED RING PERTURBER ?



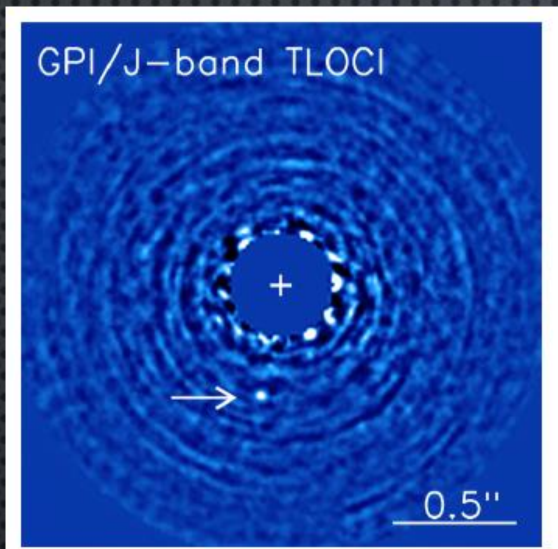
Planet? spectrum is dominated by reflected light – requires a substantial circumplanetary dust disk

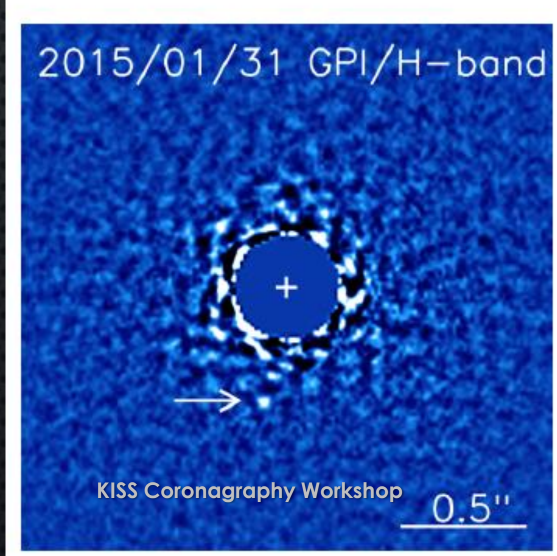
3. THE CURIOUS CASE OF FOMALHAUT: KALAS (2013) IMPROVE ORBIT AND FIND THIS OBJECT CAN'T BE THE RING PERTURBER

- DEPROJECTED OVERHEAD VIEW OF BEST-FIT ORBIT
- WILL CROSS RING ~2032
- ORBIT MAY BE ALIGNED TO UNSEEN DISK PERTURBER AS PLUTO'S IS TO NEPTUNE
- SHOWS IMPORTANCE OF KNOWING ORBITS



STATE OF THE ART FOR EXOPLANET SPECTROSCOPY TODAY: GEMINI PLANET IMAGER





Gemini Planet Imager detection of 51 Eri b
<u>Contrast $2x10^{-6}$ at 0.45″ separation</u>
Hot young planet, ~2 M_{jup}, T_{eff} ~ 700 K
CH4, H2O absorption.   Macintosh et al. 2015
Result illustrates how ground AO does well
at $\lambda \geq 1.5$ μm, and effects of telluric absorption

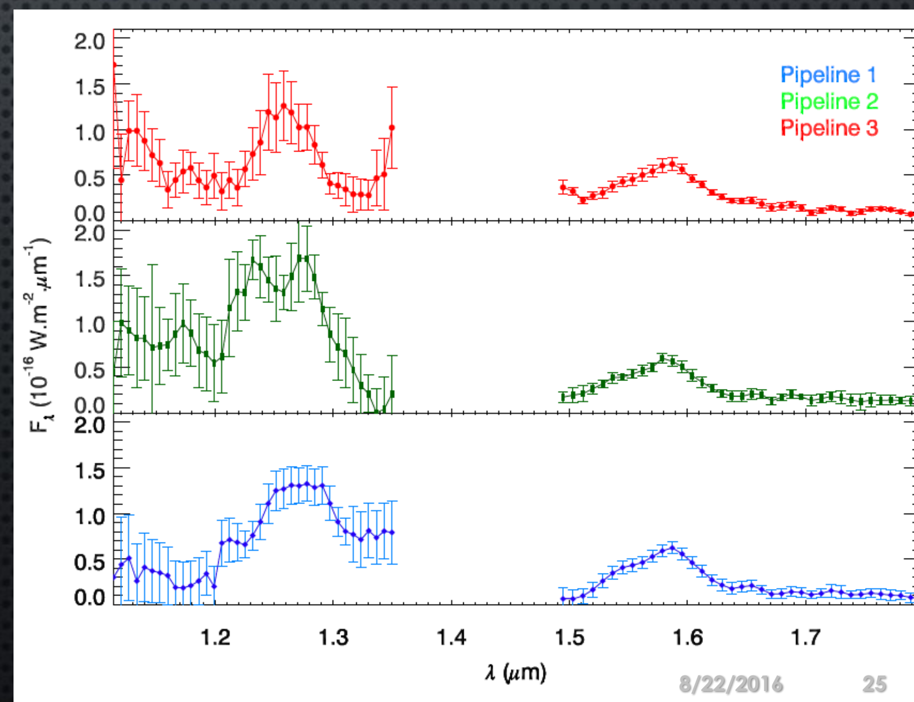
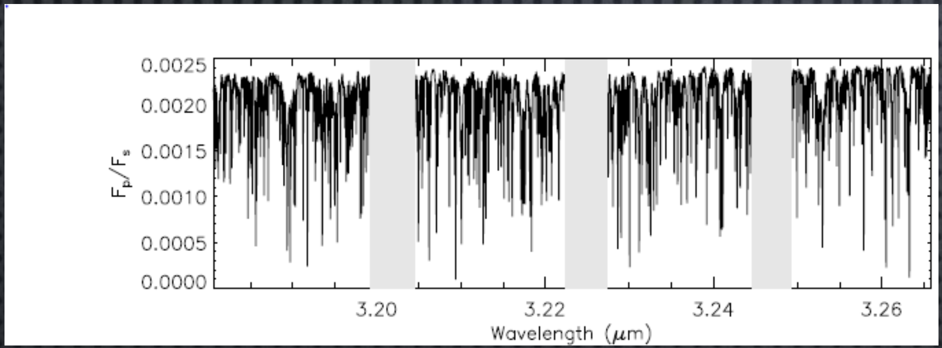


Figure S2: 51 Eri b spectra from the three different pipelines. The *H*-band spectra

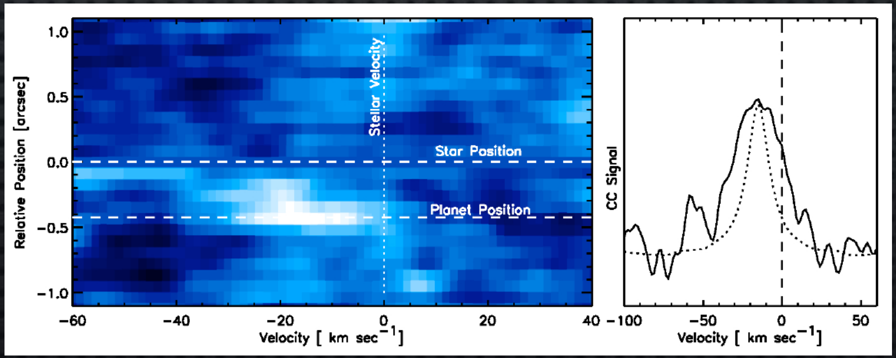
EXOPLANET SPECTROSCOPY: ADVANCES IN TEMPLATE CROSS-CORRELATION

R= 100,000 SPECTRA CAN TAKE ADVANTAGE OF THE MULTIPLICITY OF MOLECULAR BANDS IN EXOPLANET ATMOSPHERES



Left: Spectrum inferred for hot Jupiter HD 189733b by cross-correlating molecular template spectra with integrated light of star+planet (VLT CRIRES; Birkby et al. 2013)

Right: Cross-correlation of CO and H2O lines with the spectrum of young giant planet β Pictoris b. An equatorial rotation velocity of 25 km/sec was inferred for the planet (VLT CRIRES; Snellen et al. 2014
)



BOWLER ET AL. 2016 COMPILATION OF EXOPLANET IMAGING DETECTIONS:

TABLE 1
DIRECTLY IMAGED PLANETS AND PLANET CANDIDATES WITH MASSES $\lesssim$13 M_{Jup}

Name	Mass (M_{Jup})	Luminosity (log ($L_{Bol}/L_{\odot}$))	Age (Myr)	Proj. Sep. (AU)	NIR SpT	Orbital Motion?	Pri. Mult.	Pri. Mass ($M_{\odot}$)	References
Close-in Planets (<100 AU)									
51 Eri b	2 ± 1	–5.6 ± 0.2	23 ± 3	13	T4.5–T6	Yes	S	1.75	1, 2, 3
HD 95086 b	5 ± 2	···	17 ± 4	56	···	No	S	1.6	4, 5
HR 8799 b	5 ± 1	–5.1 ± 0.1	40 ± 5	68	~L/Tpec	Yes	S	1.5	6–9
LkCa 15 b[a]	6 ± 4	···	2 ± 1	20	···	Yes	S	1.0	10–13
HR 8799 c	7 ± 2	–4.7 ± 0.1	40 ± 5	38	~L/Tpec	Yes	S	1.5	6–9
HR 8799 d	7 ± 2	–4.7 ± 0.2	40 ± 5	24	~L7pec	Yes	S	1.5	6, 8, 9
HR 8799 e	7 ± 2	–4.7 ± 0.2	40 ± 5	14	~L7pec	Yes	S	1.5	8, 9, 14
β Pic b	12.7 ± 0.3	–3.78 ± 0.03	23 ± 3	9	L1	Yes	S	1.6	15–18
Planetary-Mass Companions on Wide Orbits (>100 AU)									
WD 0806-661 b	7.5 ± 1.5	···	2000 ± 500	2500	Y?	No	S	2.0[b]	19–21
Ross 458 c	9 ± 3	–5.62 ± 0.03	150–800	1190	T8.5pec	No	B	0.6, 0.09	22–26
ROXs 42B b	10 ± 4	–3.07 ± 0.07	3 ± 2	140	L1	Yes	B	0.89, 0.36	27–31
HD 106906 b	11 ± 2	–3.64 ± 0.08	13 ± 2	650	L2.5	No	B	1.5	32, 33
GU Psc b	11 ± 2	–4.75 ± 0.15	120 ± 10	2000	T3.5	No	S	0.30	34
CHXR 73 b	13 ± 6	–2.85 ± 0.14	2 ± 1	210	≥M9.5	No	S	0.30	35
SR12 C	13 ± 2	–2.87 ± 0.20	3 ± 2	1100	M9.0	No	B	1.0, 0.5	29, 36
TYC 9486-927-1 b	12–15	···	10–45	4500	L3	No	S	0.4	37, 38
Planetary-Mass Companions Orbiting Brown Dwarfs									
2M1207–3932 b	5 ± 2	–4.68 ± 0.05	10 ± 3	41	L3	No	S	0.024	39–42, 9
2M0441+2301 Bb	10 ± 2	–3.03 ± 0.09	2 ± 1	1800/15	L1	Yes	B/S	0.2, 0.018	43–45

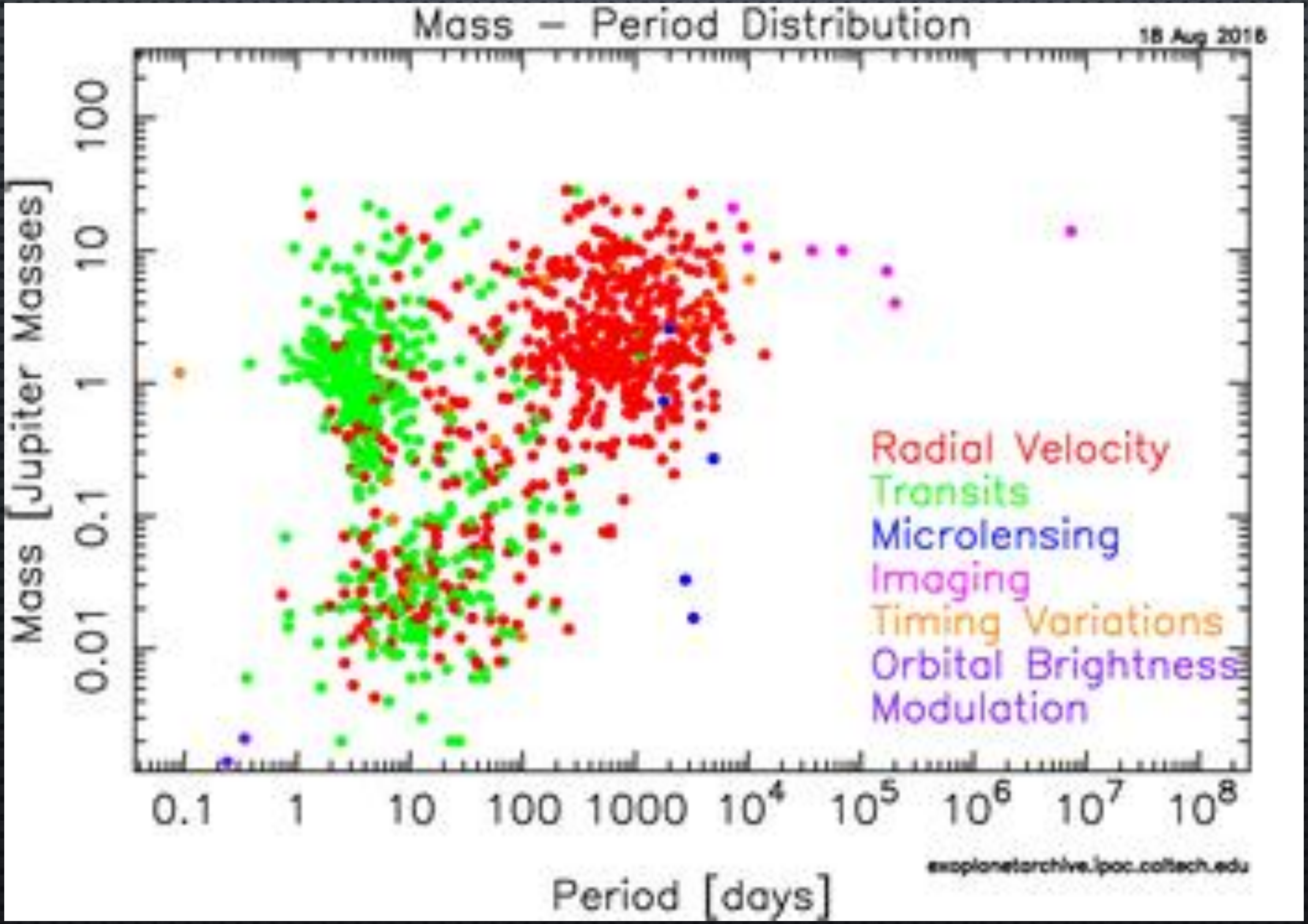
Available information from selected exoplanet samples

Sample	Planet Radius	Planet Mass	Planet Orbit	Characterize Atmosphere	System context view
RV	No	Lower limit	Yes	No	Shorter periods & larger masses
Transit	Yes	Yes if RV, or if TT varies	Yes if RV	Yes for larger planets & scale heights	Short periods and coplanar
µLensing	No	Yes	partially	No	Usually No
Imaging of self-luminous planets	Estimate from radiometry	Yes, estimate from theory and age	Yes	Yes	Larger masses, longer periods
Imaging of reflected light planets	Poorly constrained	No	Yes	Yes	Longer orbital periods

KNOWN EXOPLANETS BY DISCOVERY METHOD

Technique	Number as of 18 Aug 2016
Astrometry	1
Eclipse timing	8
Transit timing	15
Imaging	42
Microlensing	39
Orbital brightness modulation	6
Pulsar timing / pulsation	7
Stellar radial velocity	592
Transit	2664

KNOWN EXOPLANETS BY DISCOVERY METHOD



THE ROAD AHEAD

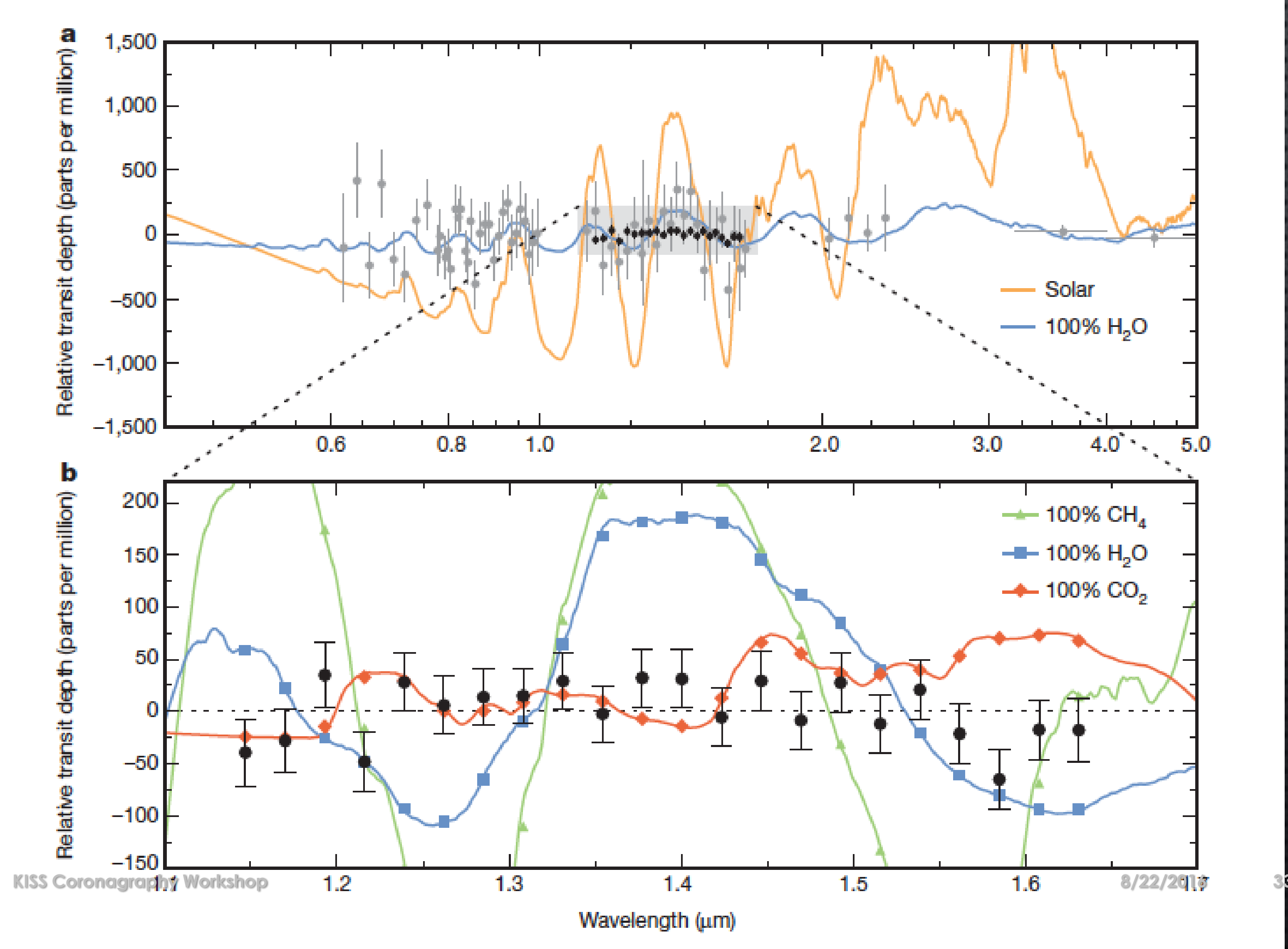
The James Webb Space Telescope

Featuring:

1. 6.5 meter cold aperture
2. Spectroscopy in the IR
3. Major capability for transit spectroscopy. Habitable planets ??
4. Huge sensitivity advance for imaging cool, widely separated exoplanets at wavelengths > 2.3 μm

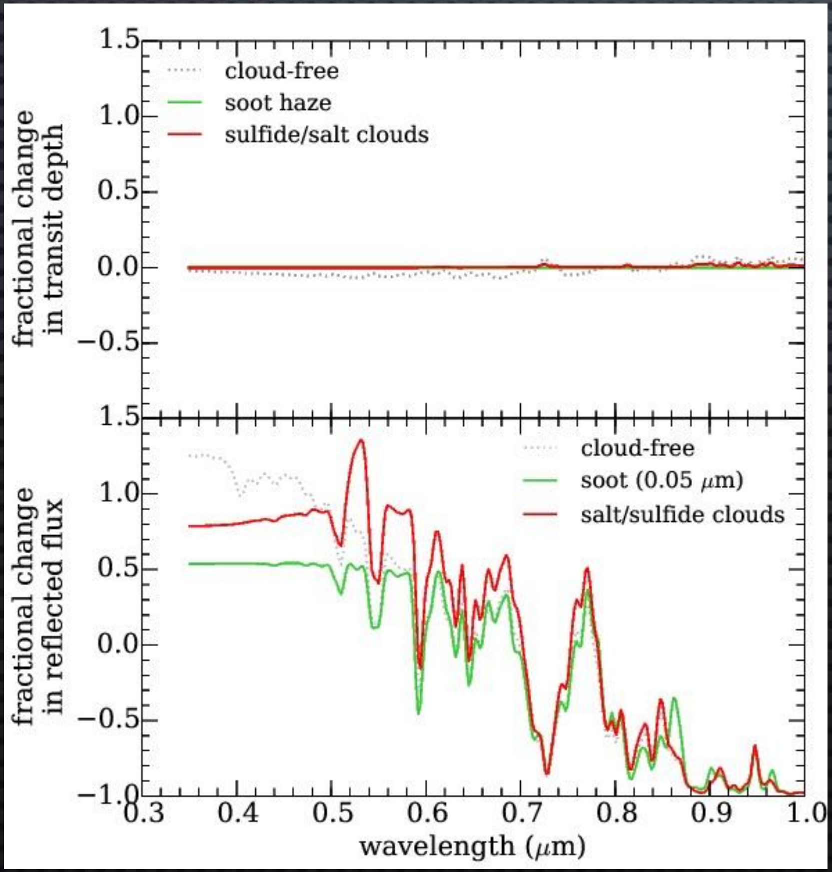
Cautionary tale: So far, HST transit spectra of mini-Neptunes are featureless; Clouds, hazes ?

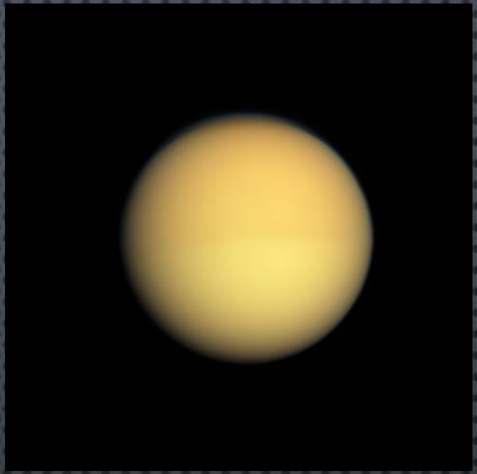
GJ 1214b, Kreidberg et al. 2014

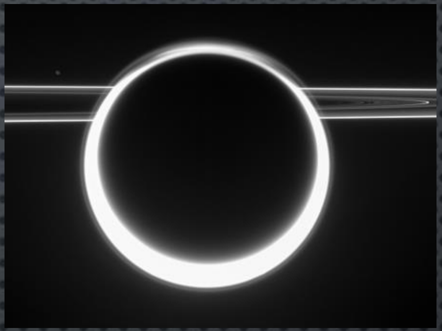


NEED FOR DIRECT IMAGING SPECTROSCOPY

Atmospheric features are more readily detected by imaging than by transits







Transit spectra probe only the tenuous upper atmosphere. Will not detect H2O in troposphere of an Earth-like planet

Curves show spectra relative to mean optical flux level

GJ 1214b model spectra by Caroline Morley and Mark Marley

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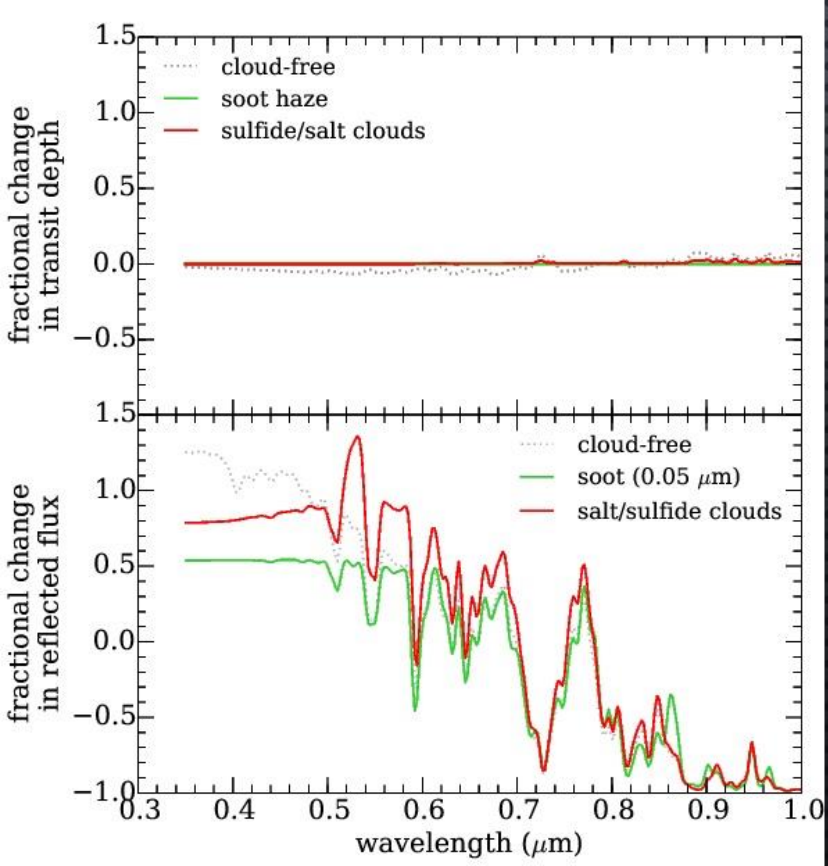

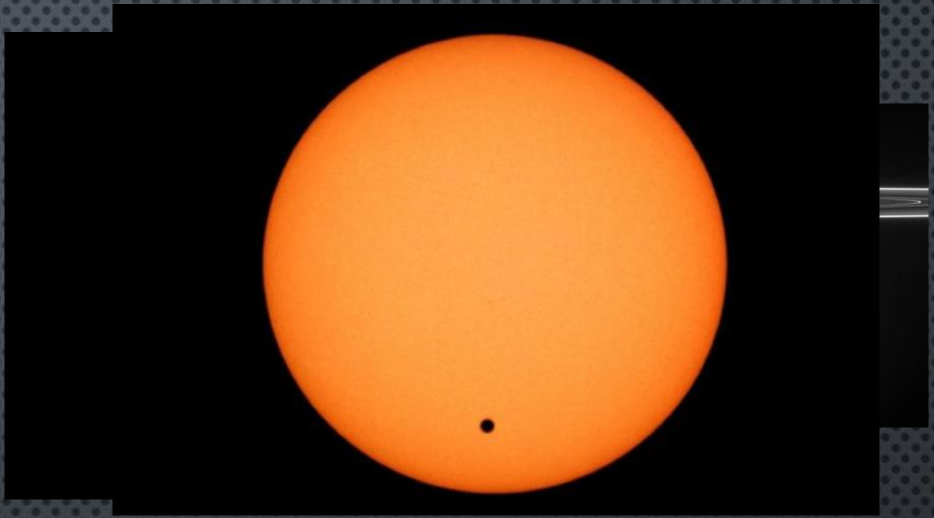

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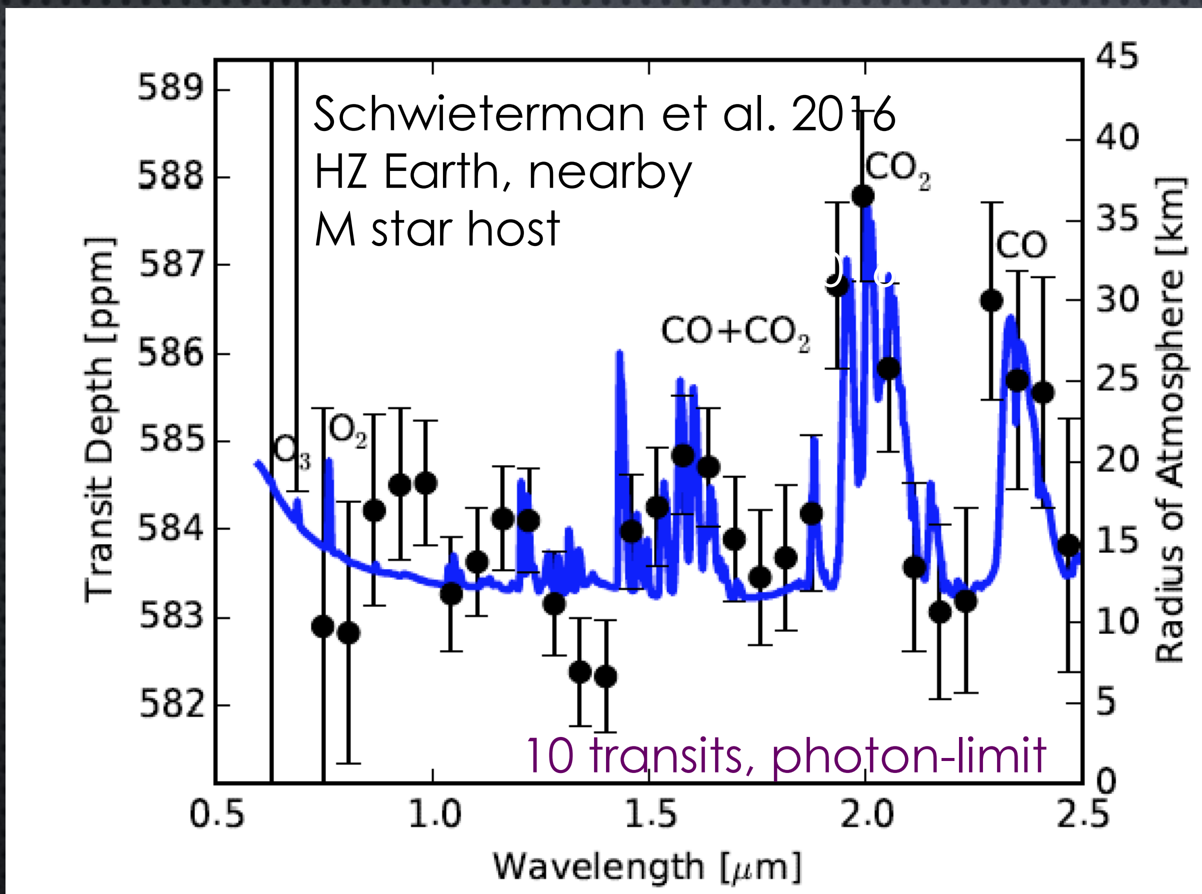
GJ 1214b model spectra by Caroline Morley and Mark Marley

FUTURE EXOPLANET SPECTROSCOPY: TRANSITS WITH JWST, STARTING IN 2019

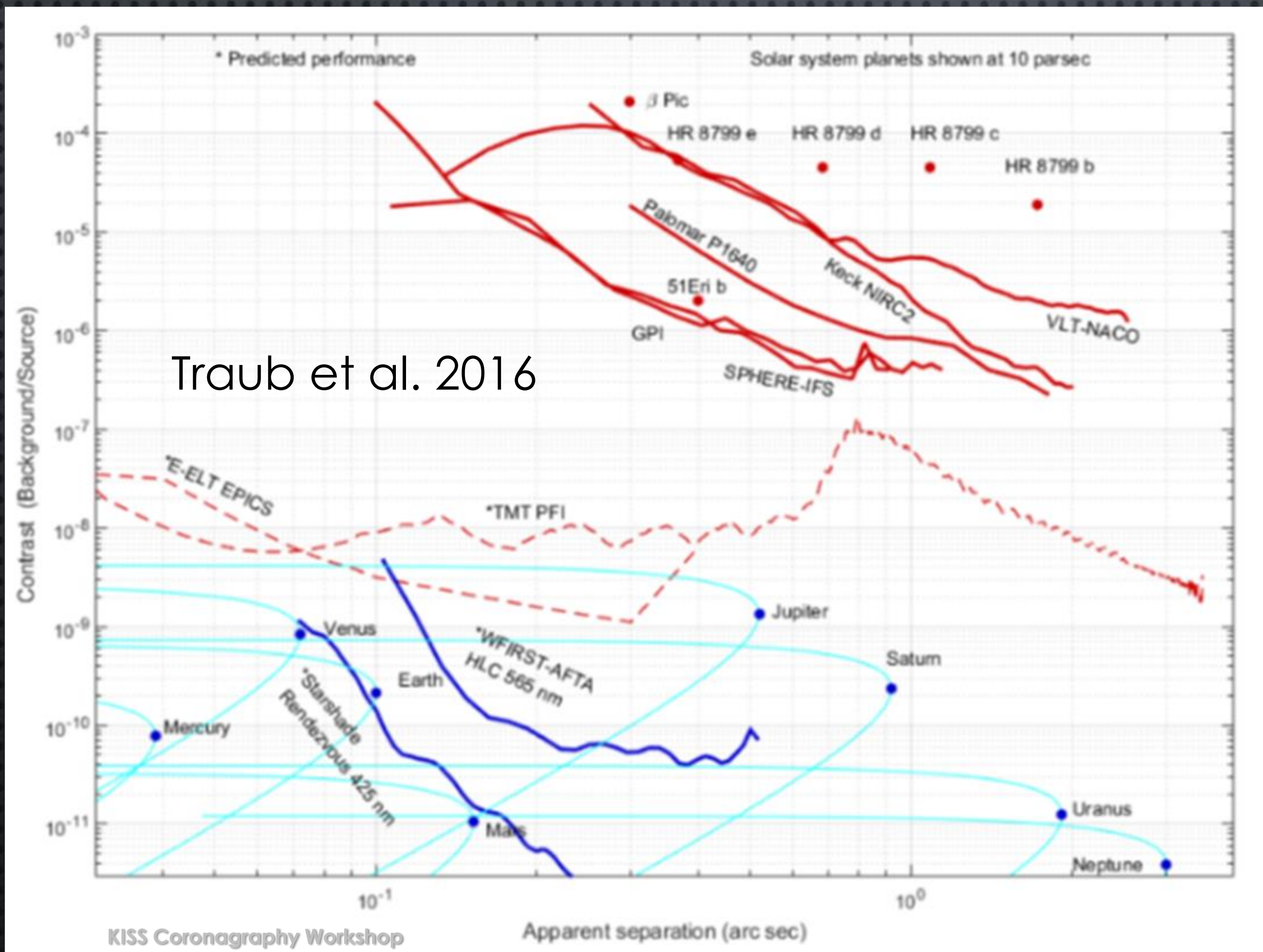
EXCELLENT RESULTS CAN BE EXPECTED FOR MINI-NEPTUNES
BIOSIGNATURES IN SUPER-EARTHS WILL BE EXCEEDINGLY DIFFICULT



SEE PRESENTATIONS FROM 2015 JWST TRANSITING EXOPLANET WORKSHOP, ONLINE AT STSCI

FUTURE EXOPLANET SPECTROSCOPY: EXTREMELY LARGE GROUND TELESCOPES, 2024+

SOLAR SYSTEM ANALOGS OUT OF REACH



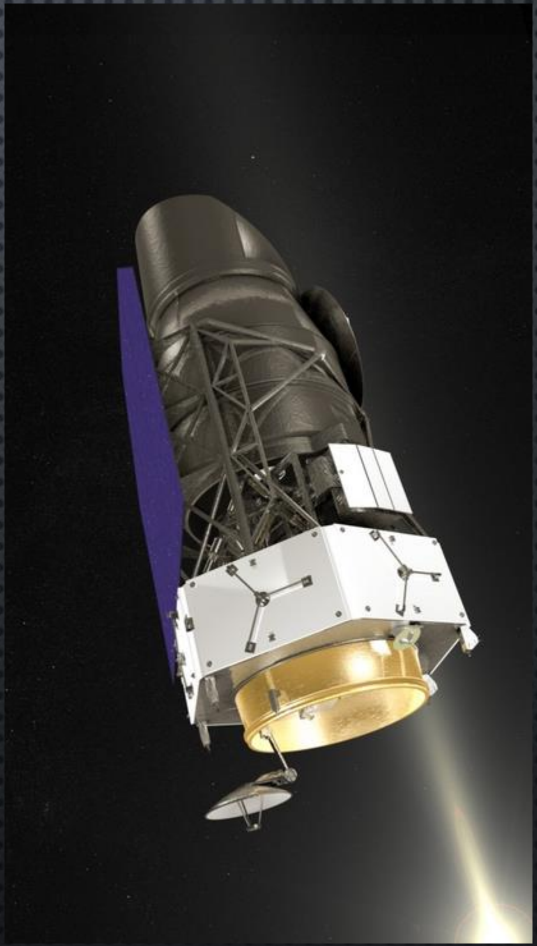
38, 25, and 30 m telescope projects are underway

Instruments for high contrast imaging not available until end of the 2020s

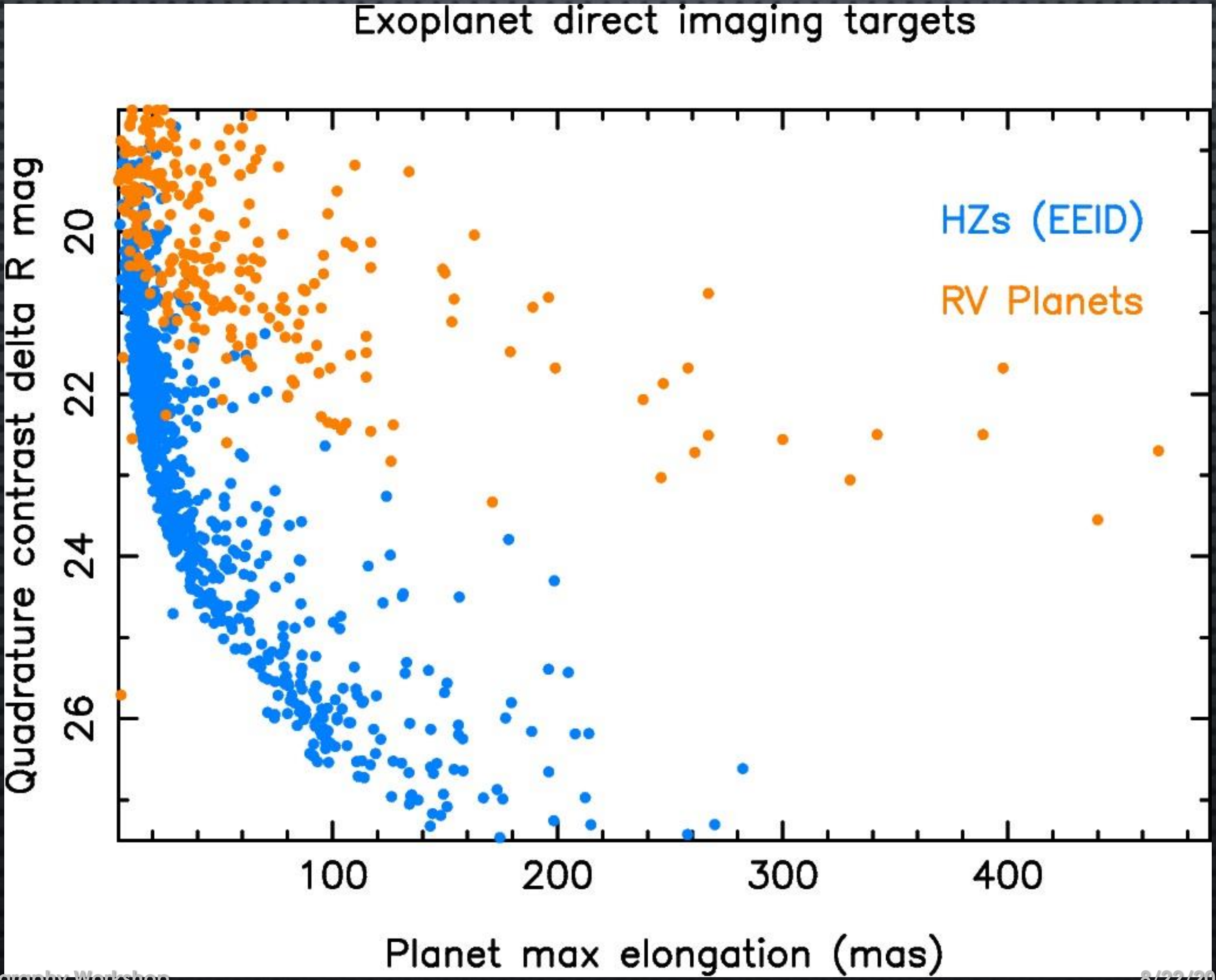
Favorable contrast of 10^{-8} in M4+ star HZs; a dozen targets may be doable

FUTURE EXOPLANET SPECTROSCOPY: WFIRST MISSION, 2025

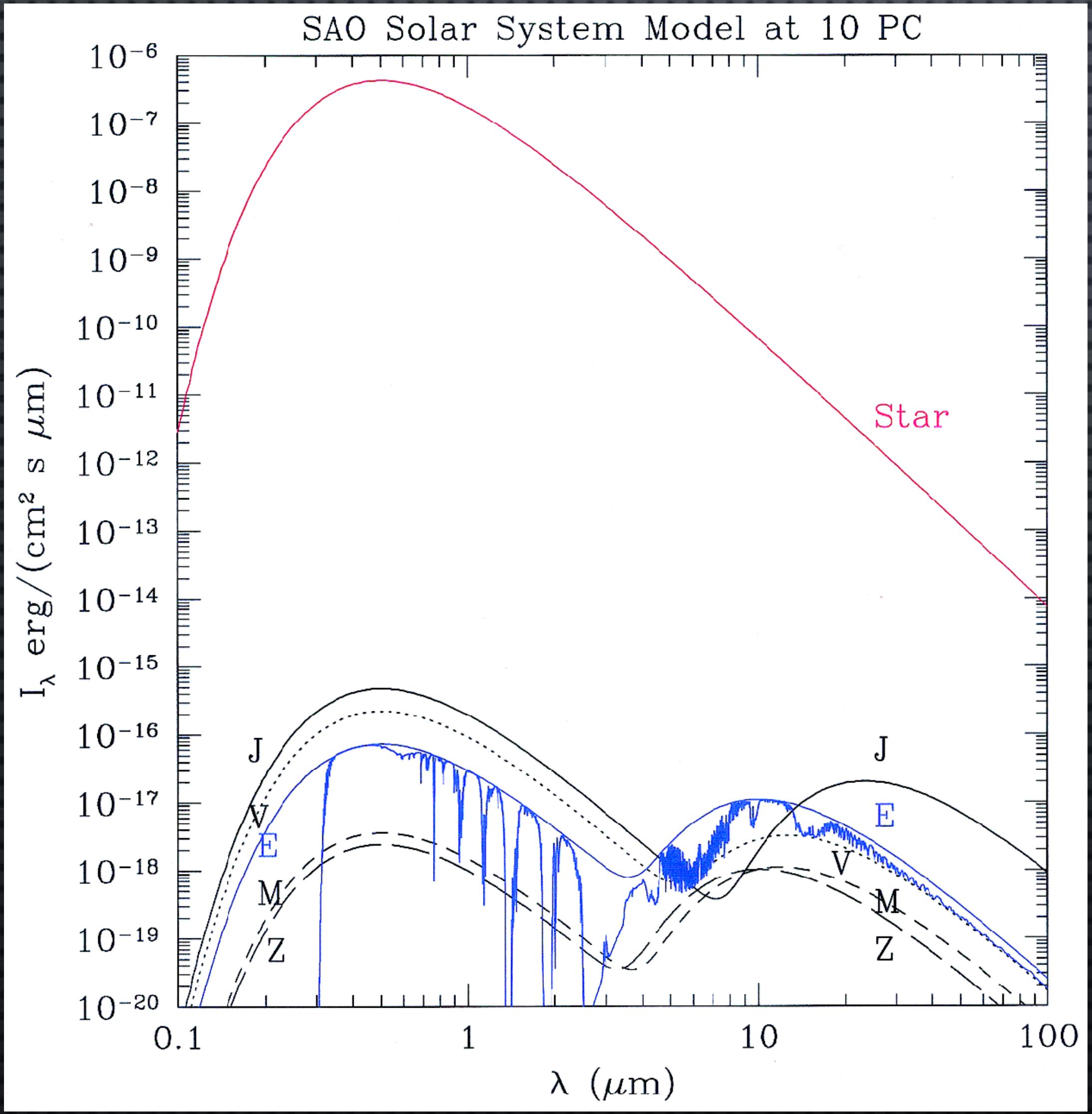
- Space telescope with 2.4 m aperture for wide field near-infrared imaging (dark energy, exoplanet microlensing)
- Coronagraph added in 2014. Will be first flight of wavefront-correcting deformable mirrors that should enable 10^{-9} contrast, 130 milliarcsec inner working angle at 0.55 μm
- Coronagraph is a technology demo that will image & make spectra of known RV planets, dust disks, and maybe a couple super-earths. R= 70.
- Starshade option under consideration



NEARBY RADIAL VELOCITY PLANETS ARE ACCESSIBLE IN REFLECTED LIGHT AT CONTRASTS OF 22 MAG ~ FEW TIMES 10^9



IMAGING DETECTION OF SOLAR SYSTEM PLANETS REMAINS VERY DIFFICULT



10^9 to 10^{10} contrast in reflected light (visible & near-infrared)

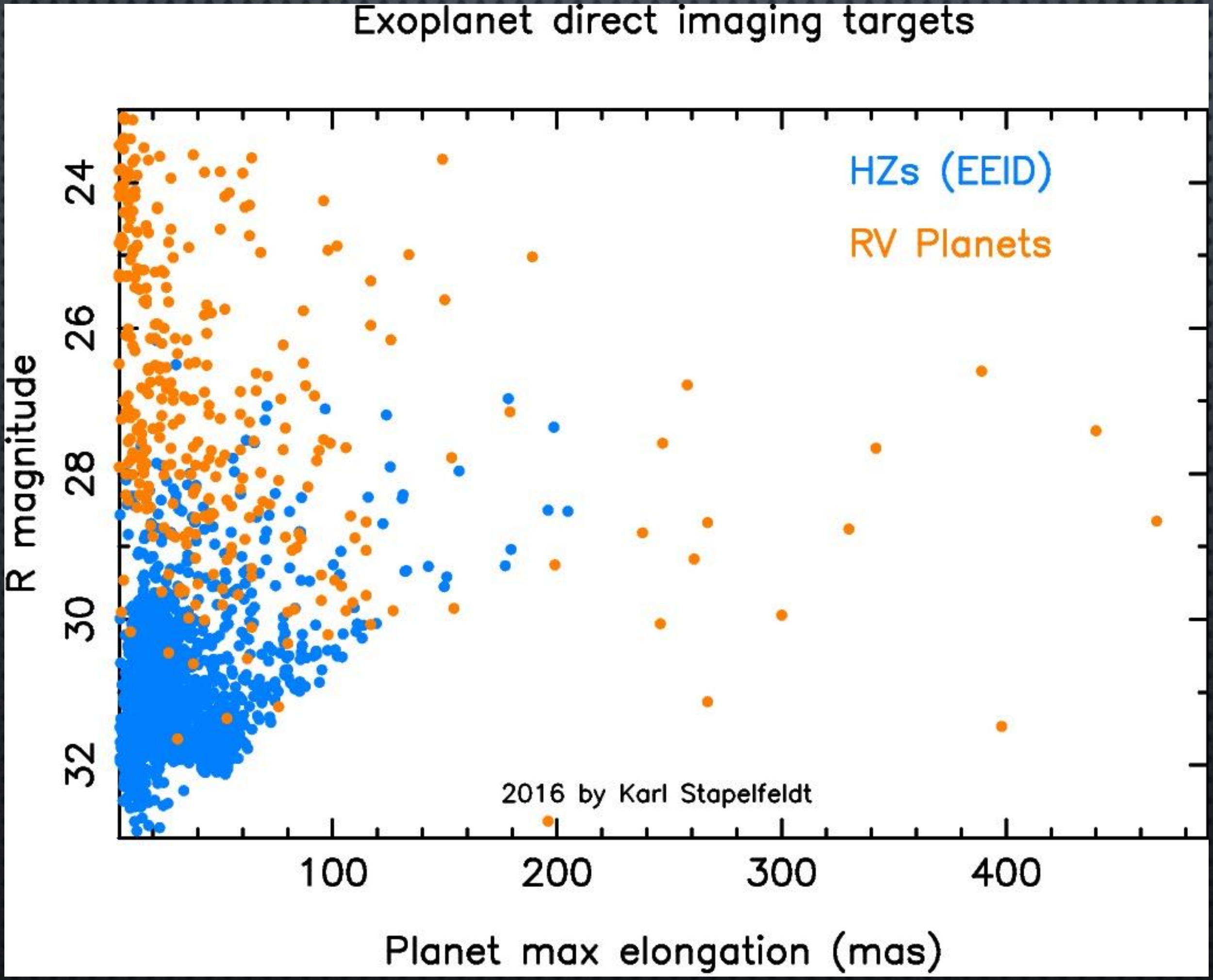
10^5 to 10^7 contrast in thermal emission (mid-infrared)

Des Marais et al. 2002

Observing Requirements for Imaging Habitable Planets in Reflected Starlight

- To get a significant sample of sun-like stars for study, need to be able to study targets out to distances of at least 15 parsecs
- At that distance, angular separation of HZ is ~≤ 67 milliarcsec. Comparable to HST image resolution ! So telescope apertures 2-3 times HST will be needed for studies at visible wavelengths. (HST = 2.4 m)
- In reflected light, the earth's brightness peaks at 0.5 μm. Contrast to the sun is 10^{-10} as seen at quadrature.

EARTH-LIKE PLANETS IN NEARBY HABITABLE ZONES ARE FAINT: LARGE TELESCOPES WILL BE NEEDED TO STUDY THEM



TWO NASA STUDIES JUST STARTED OF POTENTIAL FUTURE MISSIONS TO FIND/CHARACTERIZE EXOEARTHS : HABITABLE EXOPLANET MISSION (HABEX) AND LARGE ULTRAVIOLET OPTICAL NEAR-IR (LUVOIR) SURVEYOR

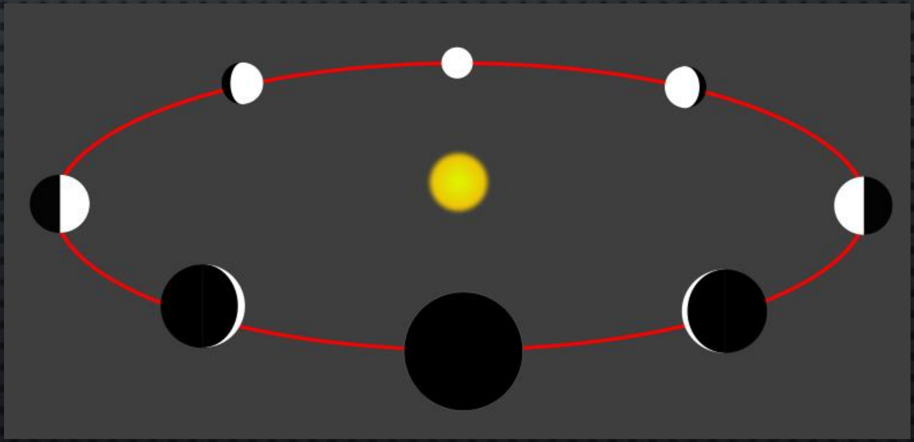
- Both have goal of studying Earthlike planets in reflected light; they differ in levels of ambition, cost, and technical readiness
  - HabEx to "search for" signs of habitability and biosignatures
  - LUVOIR to "constrain the frequency of" habitability and biosignatures = larger statistical survey of exoEarths, larger aperture
- HabEx to focus on exoplanets, "best effort" only on general astrophysics. Starshade most likely here. Study led by JPL/Caltech
- LUVOIR gives equal priority to exoplanets and cosmic origins science, is HST-like, an expansive vision. Study led by NASA Goddard.
- Interim reports late 2017; final reports early 2019. Next Astrophysics Decadal Survey to decide if one of them will go forward

Imaging a Habitable Planet 1.

- Distinguishing planets from residual starlight by repeating the images at different wavelengths or telescope rotations
- Distinguishing planets from background objects:
  - Star has a known proper motion across the sky. By observing it at a second epoch, the star will be seen to move relative to background objects at this rate, allowing them to be rejected as candidate companions
- Orbit tracking: Vital to measure the orbit to establish planet location w.r.t. habitable zone, and to observe illumination phase so that brightness of fully illuminated planet can be derived

Illumination Phase Affects Contrast Requirement

- The fully illuminated disk of Earth at 1 AU reflects (2/3) x (albedo of 0.3) x $(6{,}378/1.49\text{E}{+}8)^2$ = 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

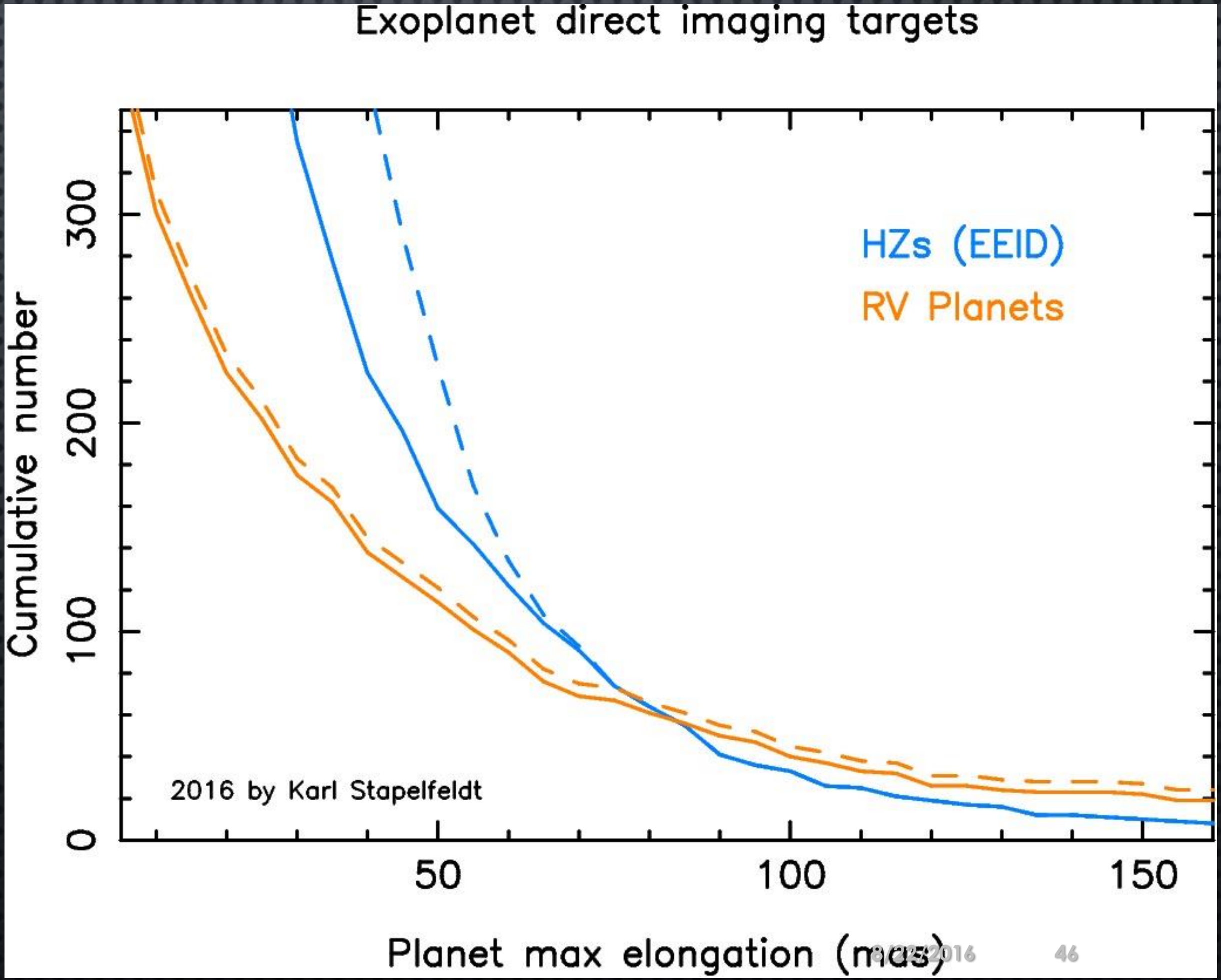


CAPABILITIES OF FUTURE SPACE TELESCOPES FOR EXOPLANET IMAGING CHARACTERIZATION: 1. TARGET SAMPLES

Cumulative number of known RV planets and HZs that can potentially be accessed, as a function of how close to the star one can look.

Values reflect local distribution of star types & their distances from the Sun

Accessing 100 HZs will require looking as close as 60 mas, which at 0.55 μm could require a ~6 m telescope

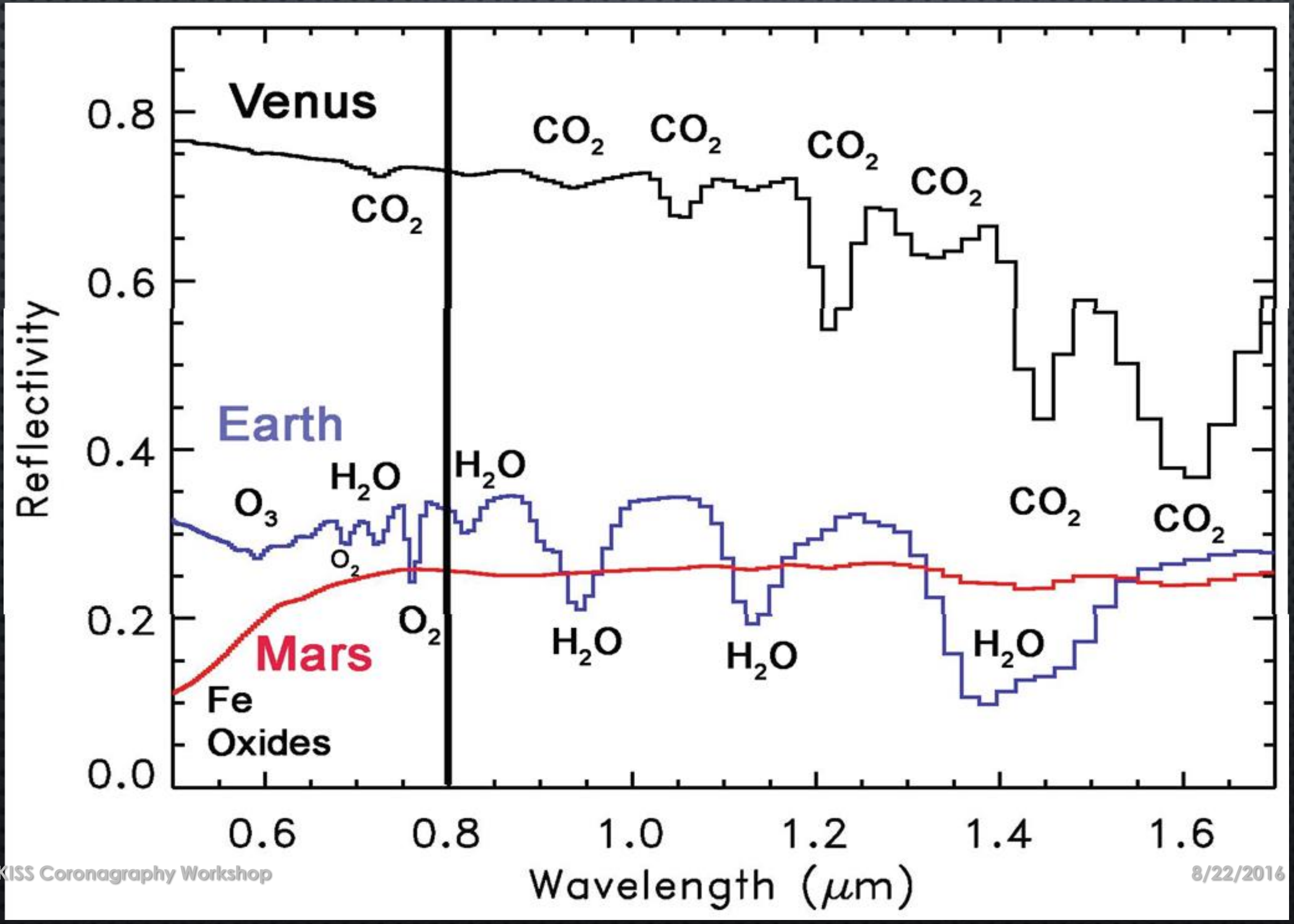


Capabilities of Future Space Telescopes for Exoplanet Imaging Characterization: 2. Wavelength Coverage

- There are strong scientific motivations to maximize wavelength coverage
- But telescope resolution goes as λ/D, giving a decisive resolution advantage to shorter wavelengths
  - Allows a smaller telescope to be used for coronagraphy
  - For a fixed telescope or starshade size, more targets will be accessible at shorter wavelengths (see previous figure)
  - Higher resolution helps separate planet light from the noise of astronomical backgrounds
- Additional factors favoring optical wavelengths:
  - Stars illuminate planets most strongly 0.4-1.0 μm
  - Starshade size needed is proportional to wavelength, so shorter wavelengths allow it to be smaller
- <u>Biosignatures at shorter optical wavelengths have better prospects of being observed in the nearer-term</u>

SPECTRA OF THE 3 "HABITABLE" SOLAR SYSTEM PLANETS: MOTIVATES 0.5-1.5μM WAVELENGTH COVERAGE

FROM TPF-C STDT REPORT



CAPABILITIES OF FUTURE SPACE TELESCOPES FOR EXOPLANET IMAGING CHARACTERIZATION: 3. SPECTROSCOPY COUNTS & INTEGRATION TIMES

- Results below are for 1 solar radiance Earth analogs observed R= 70 and S/N of 10. Counts drop by half for R= 250
- Corresponding starshade numbers should be better but depend on TBD engineering limits (fuel, launch packaging, etc.)
- N.B. multiply targets by eta_Earth to get planet yield estimate !

Source	Count rate (photons/sec)
HZ Earth analog	0.02
Foreground zodi	0.004
One exozodi	0.007
Residual starlight	0.03
Detector dark current	0.03

Aperture	4 m	8 m	12 m
Number of targets accessible to coronagraph	17	76	158
Number of the above with full 0.5-1.0 μm spectra	8	42	106
Median integration time (hrs)	251	116	15

Capabilities of Future Space Telescopes for Exoplanet Imaging Characterization: 4. Scope for Exo-Earth Variability Studies

- Rotational modulation of 15-30% measured for disk-integrated Earth by Cowan et al. 2009.
- Consider 2 hr time sampling of an exo-Earth: shown below is the number of targets bright enough to observe in this time at S/N 10. N.B. multiply targets by eta_Earth to get yield estimate !

Aperture	4 m	8 m	12 m
Photometry (R= 5)	10	63	156
Spectrophotometry (R= 70)	3	7	20

- To detect seasonal variations, the orbit must be well-characterized, the illumination phase effects subtracted out, and rotation averaged over

SUMMARY

- Exoplanet direct imaging reveals
  - the overall system architecture planets & dust
  - Spectral properties of planet atmospheres/surfaces
  - Time variable phenomena
- JWST in 2019 will be the next big step in exoplanet spectroscopy & imaging, followed in 2025 by WFIRST, and then large groundbased telescopes at the end of the 2020s
- Earthlike planets around sunlike stars will remain an exclusive domain of future space telescopes

EPILOG: DISCOVERING PLANETARY SYSTEMS, 1610 AND 2008