

The background of the slide is Raphael's fresco 'The School of Athens'. It depicts a group of ancient Greek philosophers in a grand, vaulted hall. The figures are engaged in various activities: some are teaching, some are debating, and some are resting. The architecture is highly detailed, with arches, columns, and statues. The overall scene is a representation of classical wisdom and learning.

Are We Alone? Modern Answers to A 2,500 Year Old Question

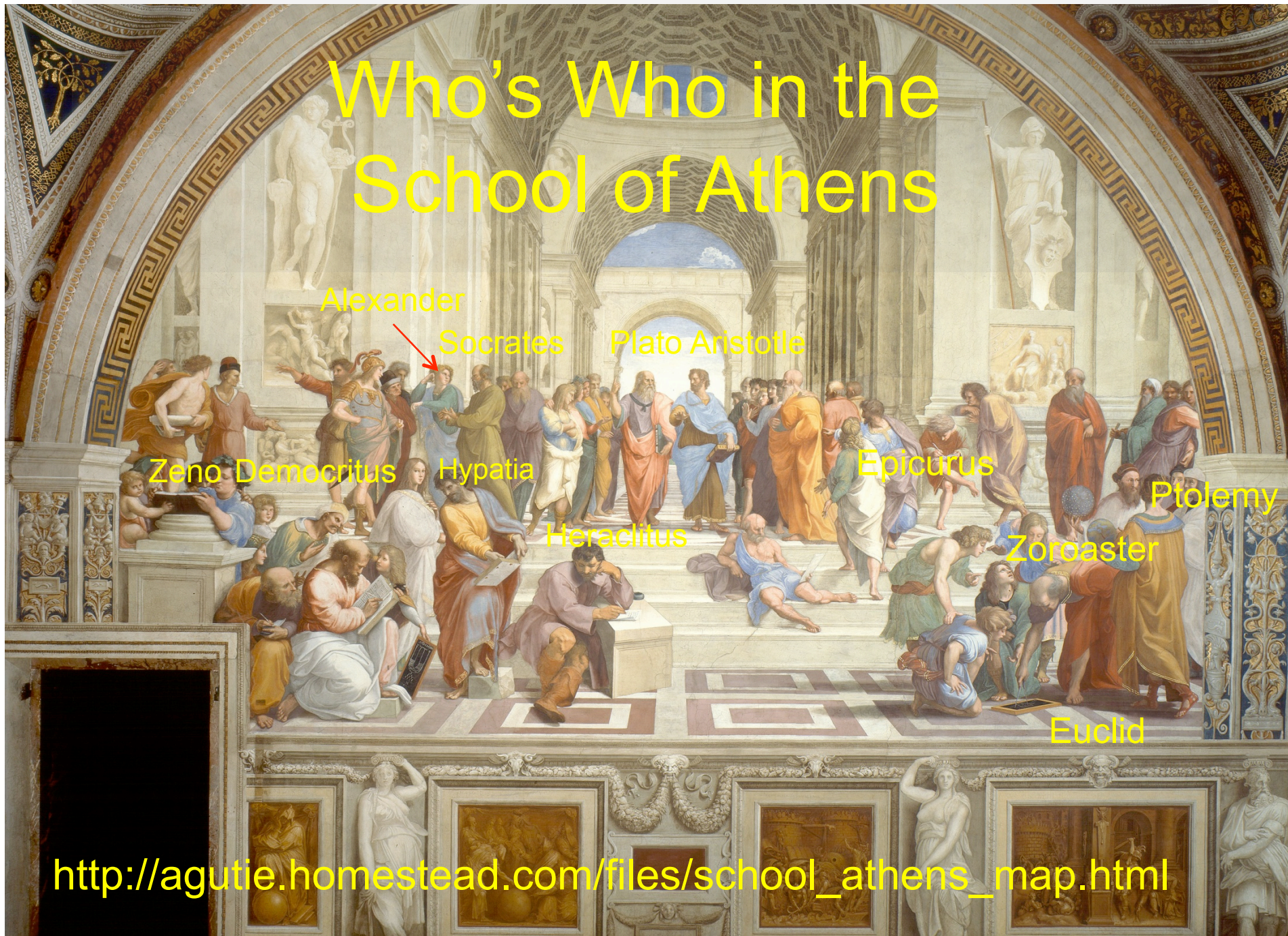
C. Beichman

NASA Exoplanet Science Institute

Caltech/JPL

“There are infinite worlds both like and unlike this world of ours...We must believe that in all worlds there are living creatures and plants and other things we see in this world.” --- Epicurus (c. 300 B.C)

Who's Who in the School of Athens



Alexander



Socrates

Plato Aristotle

Zeno Democritus

Hypatia

Epicurus

Ptolemy

Heraclitus

Zoroaster

Euclid

http://agutie.homestead.com/files/school_athens_map.html

Chinese Scholars Debated Nature of Heavens

- Hun Thien school of the celestial sphere vs. Hsüan Yeh teaching of infinite empty space (100 BC)

“Heaven and Earth are large, yet in the whole of empty space they are but as a small grain of rice It is as if the whole of empty space were a tree and heaven and earth were one of its fruits. Empty space is like a kingdom and heaven and earth no more than a single

individual person in that kingdom. Upon one tree there are many fruits, and in one kingdom many people. How unreasonable it would be to suppose that besides the heaven and earth which we can see there are no other heavens and no other earths!” (Têng Mu, 960-1127 AD, Needham, 3, 221).

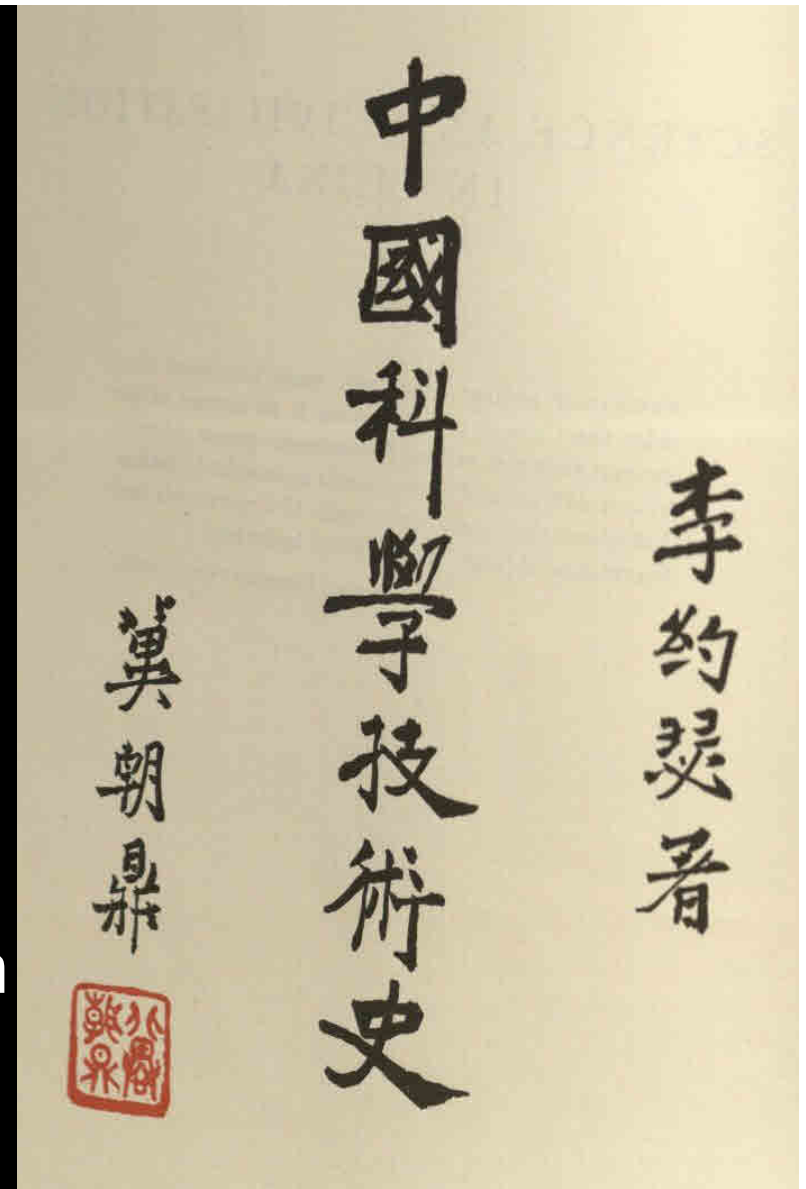


Teng Mu (13th century)

Chinese Understood Proper Role of Astronomers

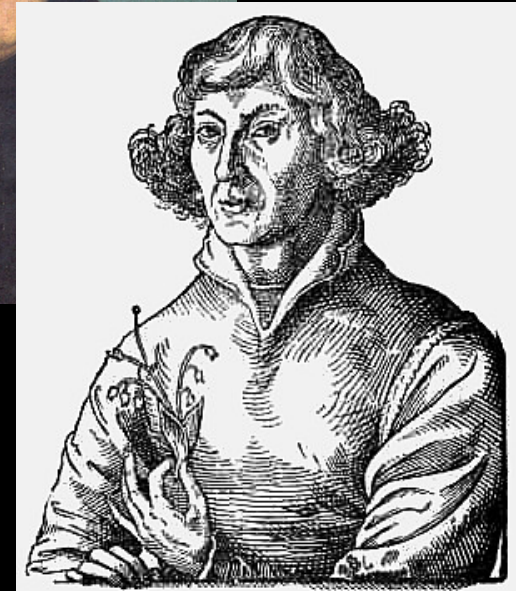
“Probably another reason why many Europeans consider the Chinese such barbarians is on account of the support they give to their Astronomers --- *people regarded by our cultivated Western mortals as completely useless*. Yet there they rank with Heads of Departments and Secretaries of State. What frightful barbarism!”

--- Franz Kühnert (Vienna, 1888)



“I Feel The Earth Move Under My Feet”

“There is talk of a new astrologer who wants to prove that the earth moves and goes around instead of the sky, the sun, the moon, just as if somebody were moving in a carriage or ship might hold that he was sitting still and at rest while the earth and the trees walked and moved. But that is how things are nowadays: when a man wishes to be clever he must . . . invent something special, and the way he does it must needs be the best! The fool wants to turn the whole art of astronomy upside-down. However, as Holy Scripture tells us, so did Joshua bid the sun to stand still and not the earth.”



Martin Luther (1539), speaking of Copernicus's new heliocentric doctrine which was formally published in 1543



"There are countless suns and countless earths all rotating around their suns in exactly the same way as the seven planets of our system... The countless worlds in the universe are no worse and no less inhabited than our Earth" --- Giordano Bruno (1584) , in De L'infinito Universo E Mondi

Technology Ends 1,400 yr Old World View

400 years ago Galileo turned his telescope to the skies, finding craters on the moon, the moons of Jupiter (Jan.1610) and the world changed forever. Nearly 400 years later, the Catholic church relented: “Thanks to his intuition as a brilliant physicist [Galileo] understood why only the sun could function as the centre of the world...as a planetary system. The error of the

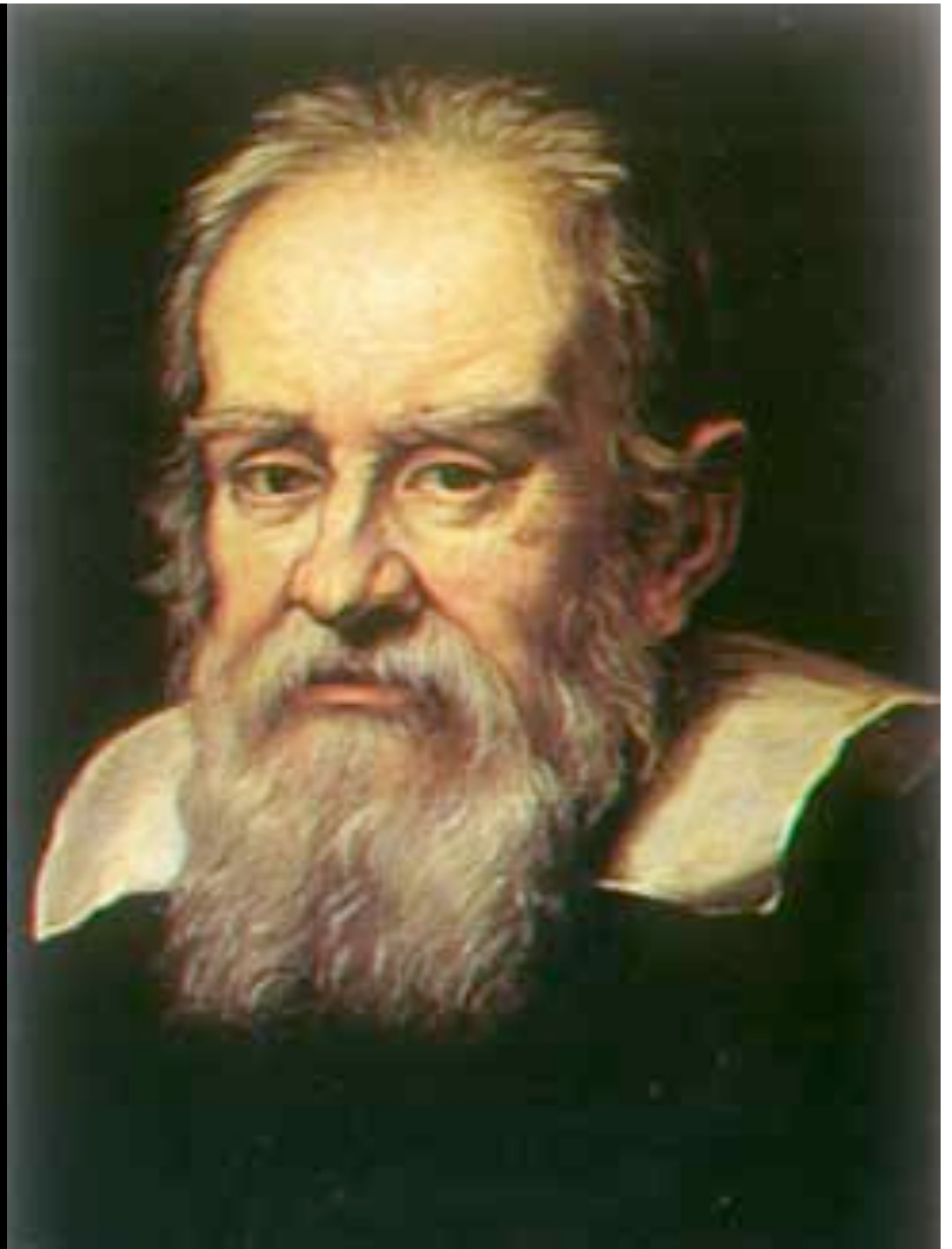
theologians of the time, when they maintained the centrality of the Earth, was to think that our understanding of the physical world's structure was... imposed by the literal sense of Sacred Scripture....” – Pope John Paul II, L'Osservatore 1992



Giuseppe Bertini

But Galileo Denied Any Belief in Life On Other Worlds

But ... *“I [regard]... as false and damnable the view of those who would put inhabitants on Jupiter, Venus, and Saturn, and the moon, meaning by ‘inhabitants’ animals like ours and men in particular.”*



Enlightenment Philosophers Were Enthusiastic



*Christian
Huygens*

*“Cosmotheoros: or Conjectures
concerning the Planetary Worlds”,
London, 1698*



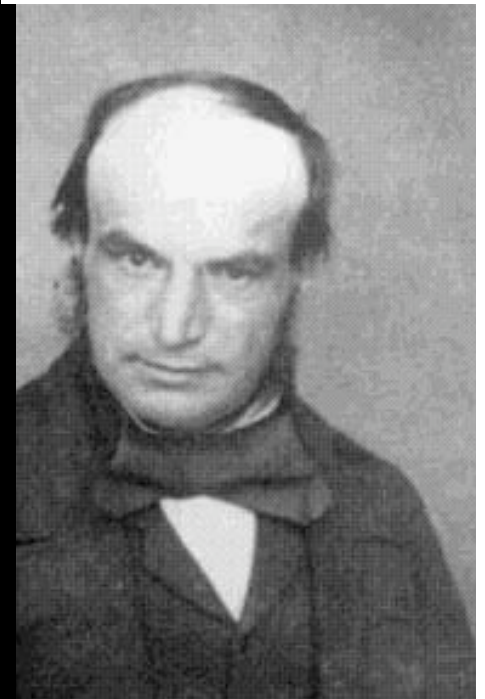
- **Some have already talk'd of the Inhabitants of the Planets**
 - The Objections of ignorant Cavillers prevented
 - Conjectures do not contradict holy Scriptures
 - These Studies useful to Religion
- **Earth justly liken'd to the Planets**
 - The Planets are solid, and not without Gravity
 - Have Animals and Plants
 - Not to be imagin'd too unlike ours
 - Planets have Water but not just like ours
 - Plants grow and are nourish'd
 - The same true of their Animals
- **Rational Animals in the Planets**
 - Vices of Men no hindrance to their being the Glory of the Planet they inhabit
 - Reason not different from what 'tis here
 - They have Senses: Sight, Hearing, Touch, Smell and Taste
 - Men differ from Beasts in the study of Nature
 - They have Astronomy and its subservient Arts: Geometry, Arithmetick, Writing, Opticks



Urbain Le Verrier

New Planets Expand Boundaries of the Solar System

- Patient scanning by William and Caroline Herschel yields Uranus, the first new world since antiquity (1781)
- Theory and observation reveal a new world, Neptune, in 1846



John Couch Adams

- *September, 1845*: Adams communicates preliminary calculations to Challis [Cambridge Observatory] & George Airy. Challis unimpressed.
- *June, 1846*: Le Verrier predicts position of the perturbing body.
- *July 1846*: Airy hears of Le Verrier confirmation, initiates Cambridge observations. Adams produces three new calculations (worse).
- *Sept 23, 1846*: French astronomers show no interest. La Verrier contacts Galle (**Berlin**) who found **Neptune** within 1 deg of prediction

- Finally, Clyde Tombaugh finds Pluto in 1930 which is *redefined* in 2006

**MODERN SCIENCE AND LIFE
ON OTHER WORLDS**

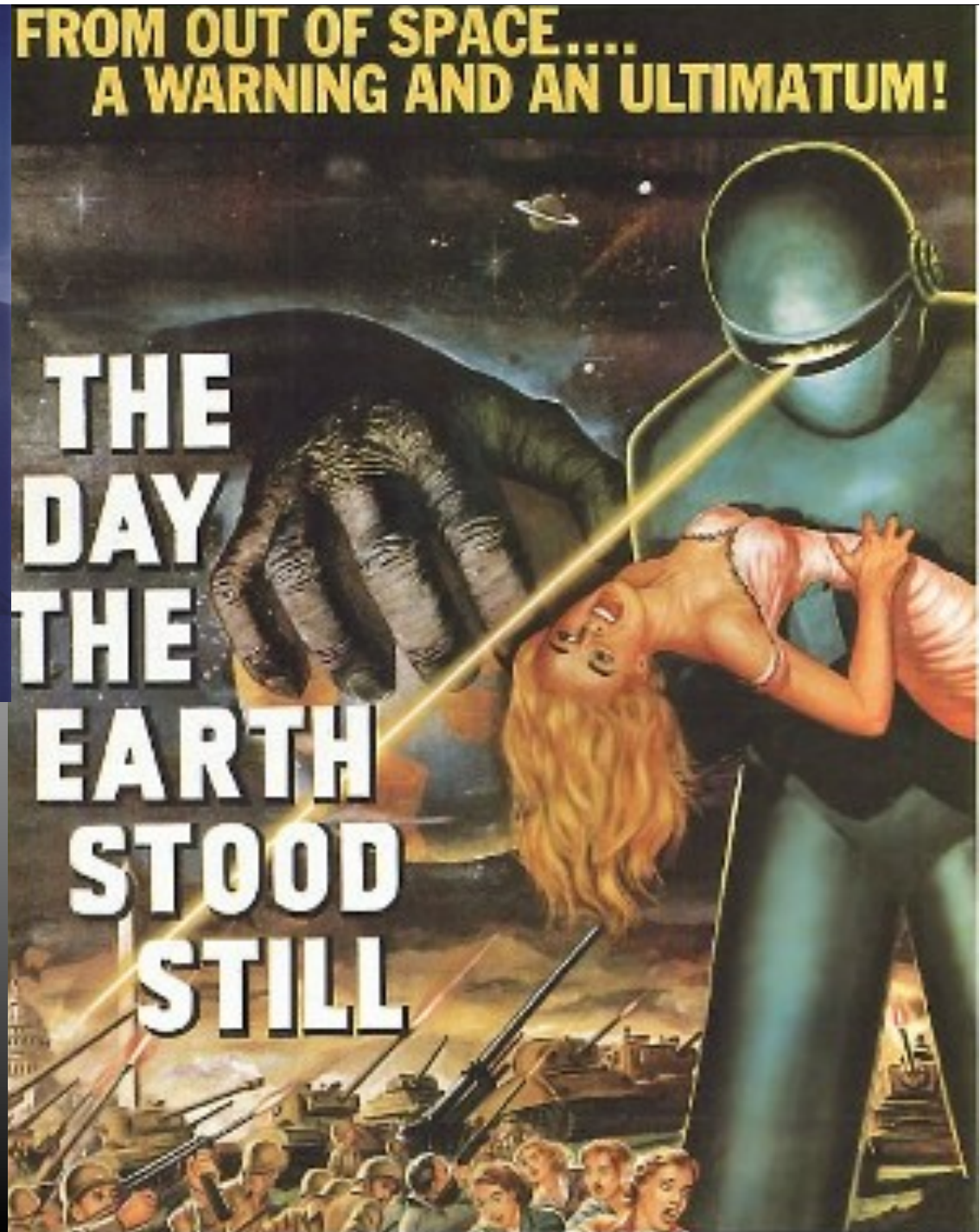
Are We Alone?



The Ultimate Green Warning

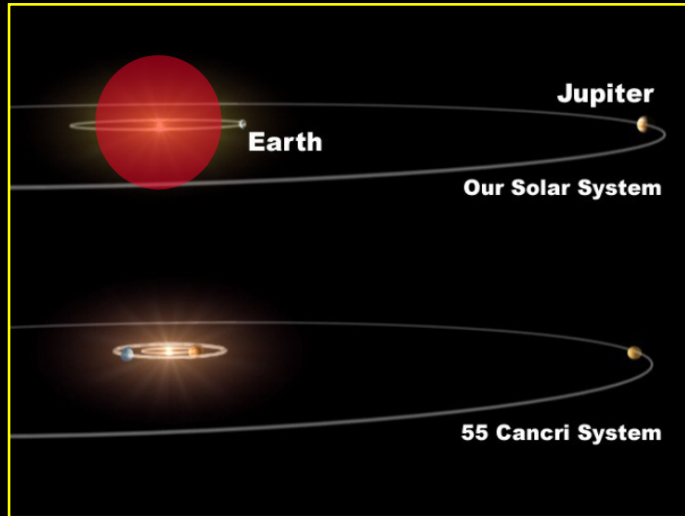
“Klaatu barada nikto”

“Your choice is simple. Join us and live in peace or pursue your present course and face obliteration. We shall be waiting for your answer. The decision rests with you.”

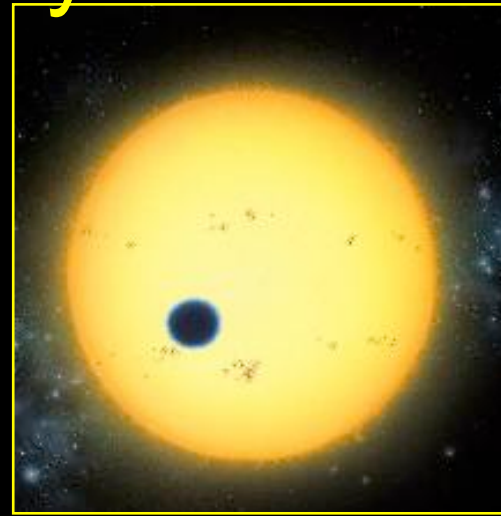


We Find Planets With 20th & 21st Century Tools

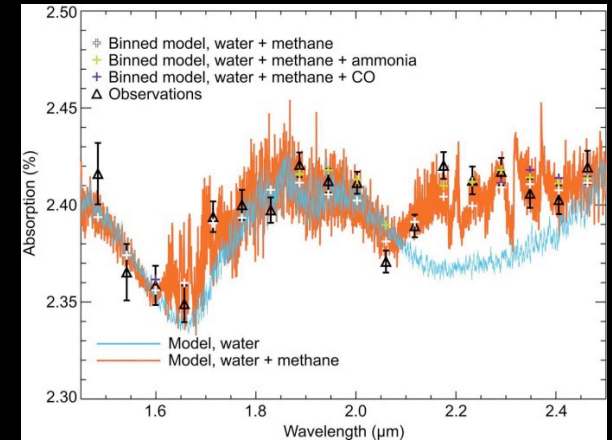
473 and
counting



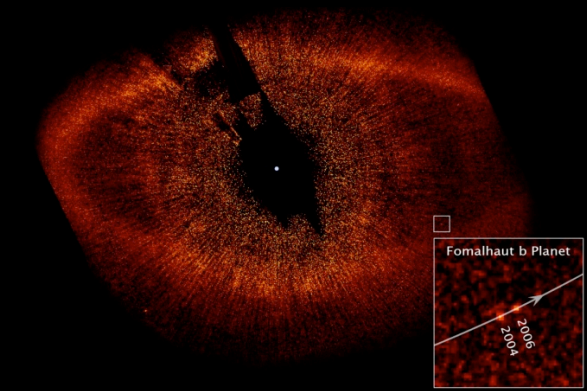
442 RV + 5 Timing Planets



91 Transit Planets

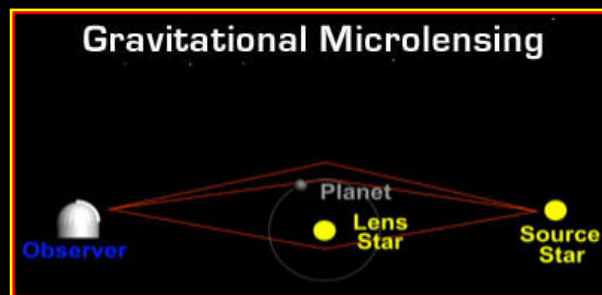


Transit Spectra

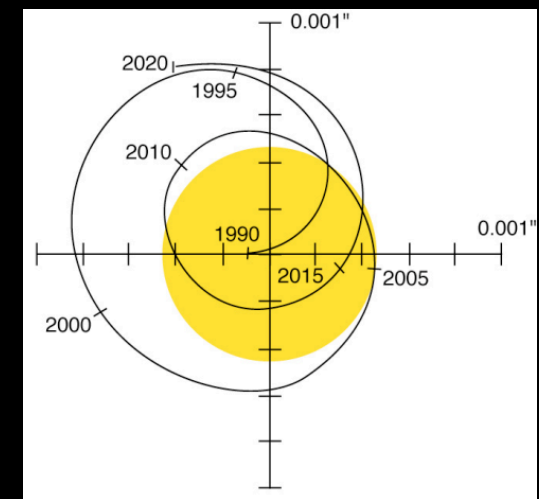


13 Imaging Planets

<http://exoplanet.eu/catalog.php>

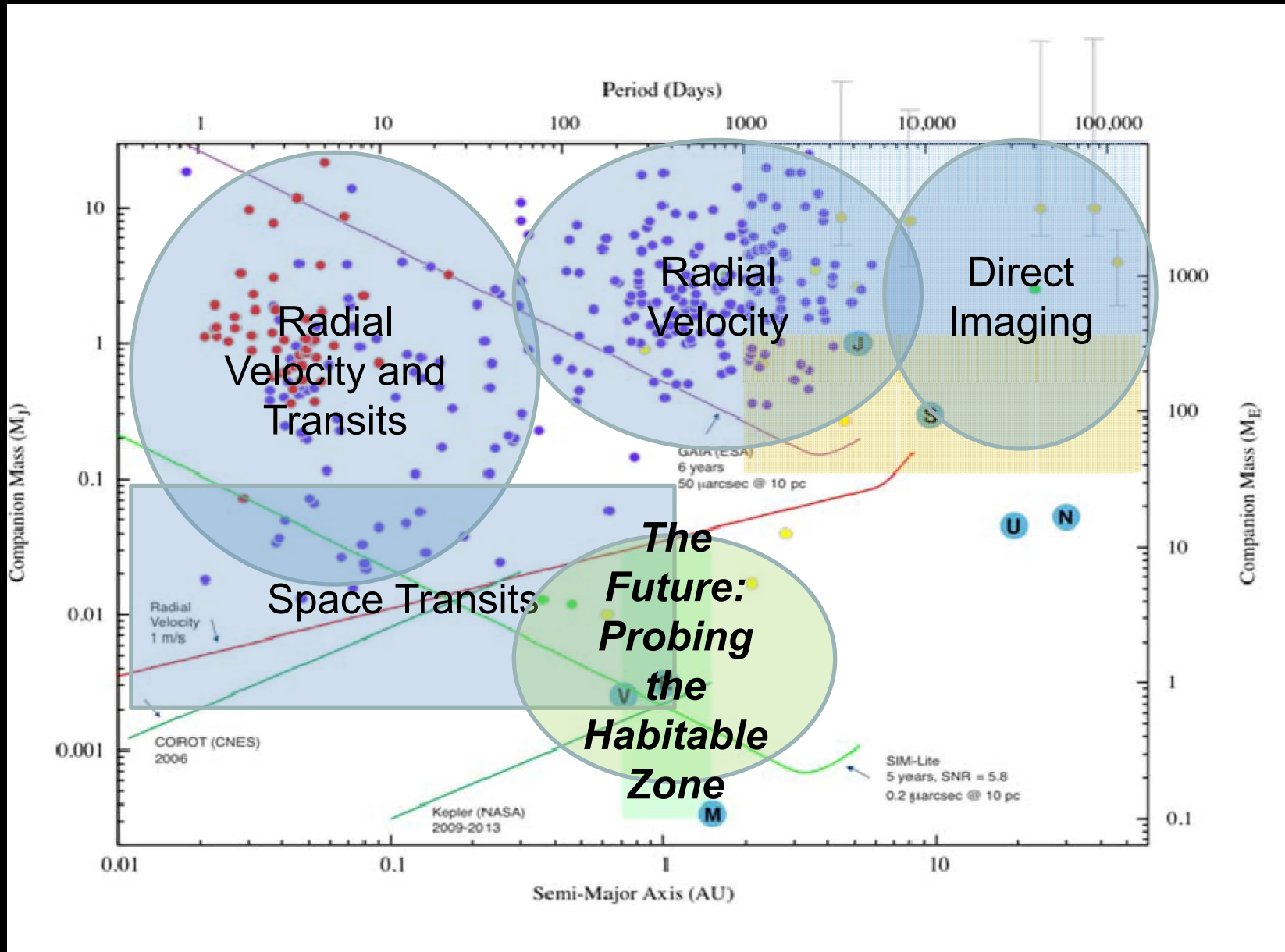


10 Microlensing
Planets



Astrometry could find
Earths

An Exoplanet Census



What Is Left To Do? LOTS!!!

	Ground Techniques	Space Techniques
Nearby Planet Census	RV Multi-object RV	GAIA Astrometry All Sky Transit (ASTrO, TESS) SIM for 1 Mearth/1 AU
M Star Census	RV	All Sky Transit (ASTrO, TESS)
Habitable Planet Census	RV (very tough)	Astrometry with SIM All Sky Transit (ASTrO, TESS)
Kuiper disks	Brightest	Spitzer archival, HST, Herschel WISE, JWST, SPICA
Young Planets	Ground-based imaging, RV	GAIA/SIM astrometry JWST (large orbits, low mass)
Giant Planet Spectra	10 telescopes	JWST on transiting systems Dedicated small telescope (THEISIS)
Habitable Planet Spectra	30-40 m telescopes (???)	JWST on brightest targets with puffy atmospheres. Some version of Terrestrial Planet Finder (TPF)

Future Prospects Are Exciting

Ground based---Imaging, RV, Transits-----→

Spitzer -----→Transits, Young Disks

Kepler -----→Transits, Asteroseismology

WISE--→ Disks, Transits?

GAIA-----→Planet Astrometry

JWST-----→Imaging, Transits

Explorer (ASTRO/TESS/Thesis?)

PLATO

SPICA (disks)

TMT/GSMT/ELT

SIM/Coronagraph

Aug 13 Release of ASTRO2010 Report:
New Worlds, New Horizons

2010

2012

2014

2016

2018

2020

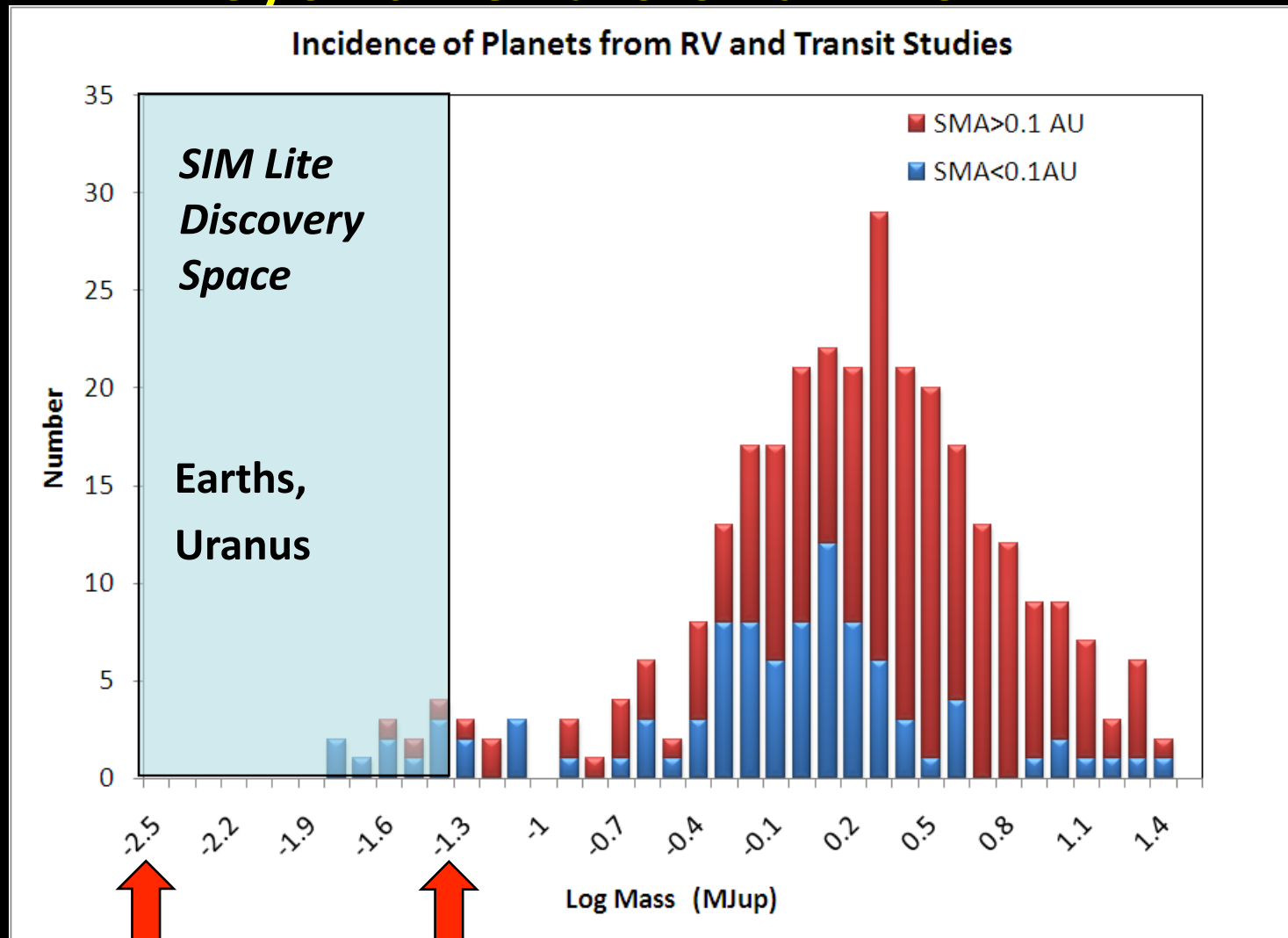
2022



COMPLETING THE CENSUS

SIM Lite Fills Rocky Planet Hole

Beyond Tenths of an AU

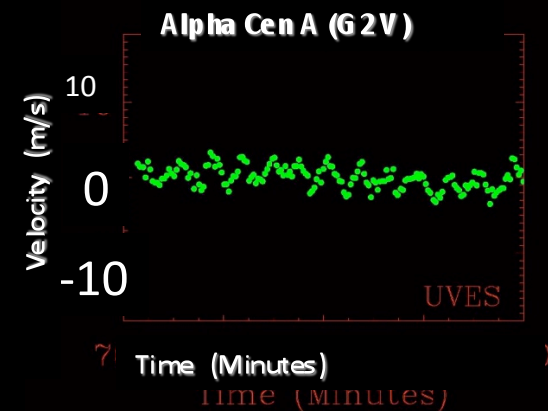


Earth Mass

Uranus Mass

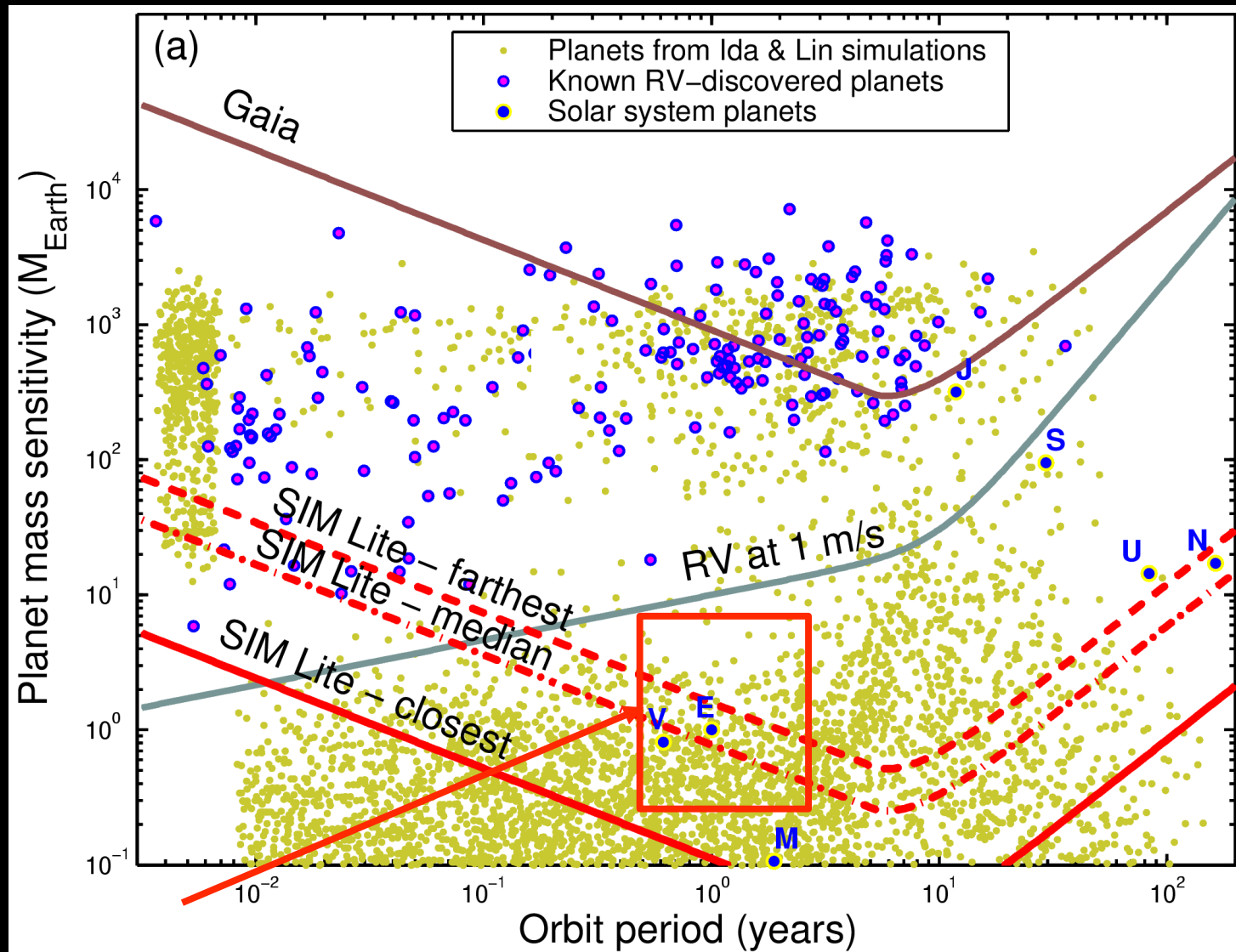
Photospheric Noise Precludes RV Detection of Habitable Zone Earths Around Most AFGK Stars

- Earth induces 0.1 m/s at 1 AU from G star
- Instrument may achieve <0.1 m/s accuracy BUT limiting noise is Photospheric Noise ~ 1 m/s with characteristic time scale of hours to days
 - Spots on Rotating Stars (months)
 - Magnetic cycles (years)
 - P-modes (minutes, hours)
 - Granulation (hours)
 - Active regions (hours, days)
- Need to average $10^3 - 10^4$ observations to achieve sub 0.1 m/s accuracy \rightarrow tens to hundreds of years to detect Earth in habitable zone of solar type star



Comparable astrometric noise floor for solar type stars is $<0.1 \mu\text{as}$, consistent with Earth detection with SIM Lite

Astrometry Will Test Theories of Planet Formation



*Terrestrial planets in
Habitable Zone*

SIM Lite Survey for Earths

- RV and Transits have revealed statistics of medium and large planets around nearby stars → numerous low mass planets
- Deep surveys of relatively small numbers of NEAREST stars for Earths (*Potential future imaging targets*)

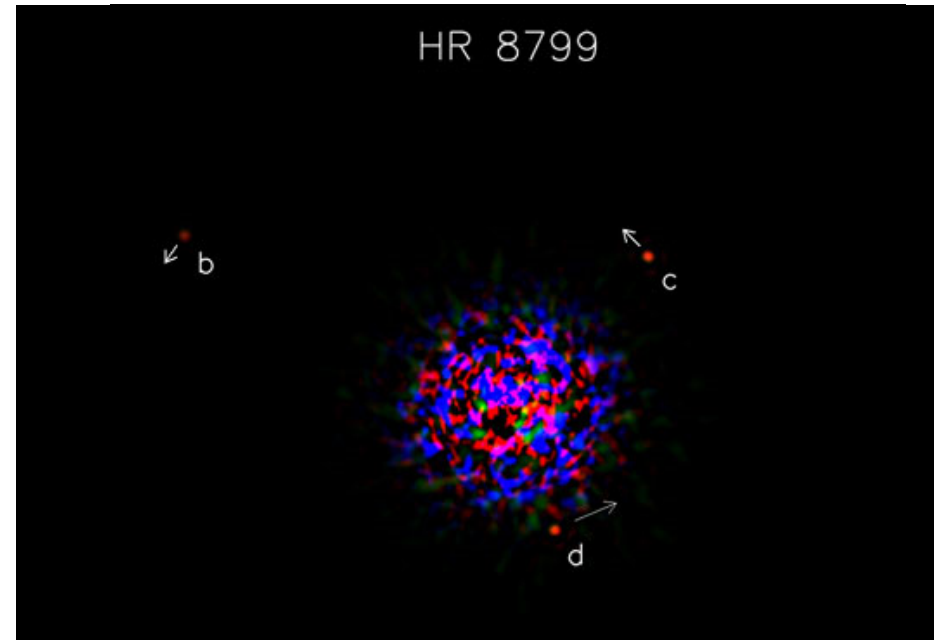
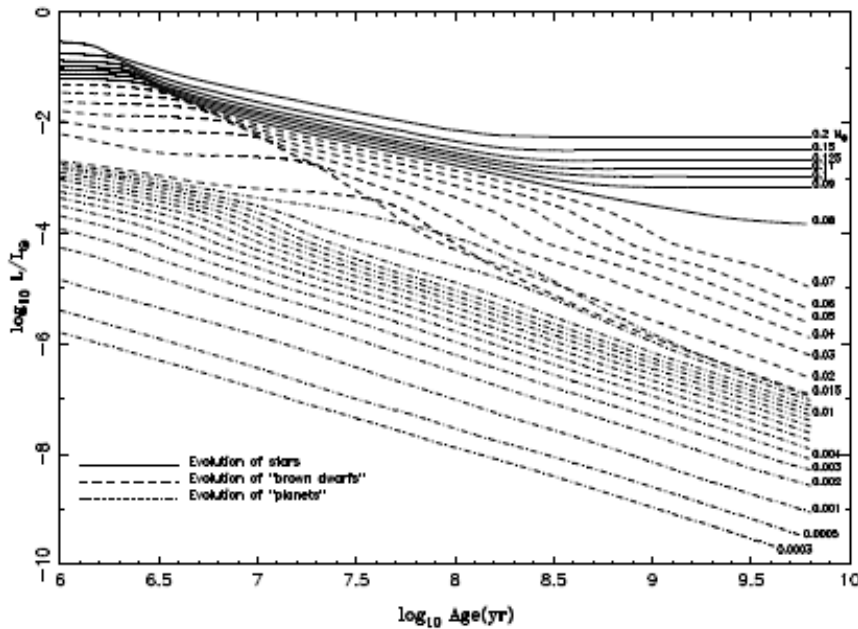
Representative SIM Lite Survey

Mass sensitivity at mid-habitable zone	1 M_{\oplus}	2 M_{\oplus}	3 M_{\oplus}
# of target stars that can be surveyed (1)	69	160	259

1) Nominal SIM Lite with 40% of observing time

~100 Target Stars Located within 25 pc can be surveyed during 5-year mission lifetime

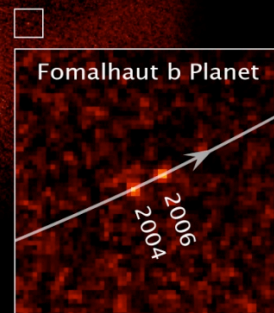
DIRECT DETECTION OF PLANETS



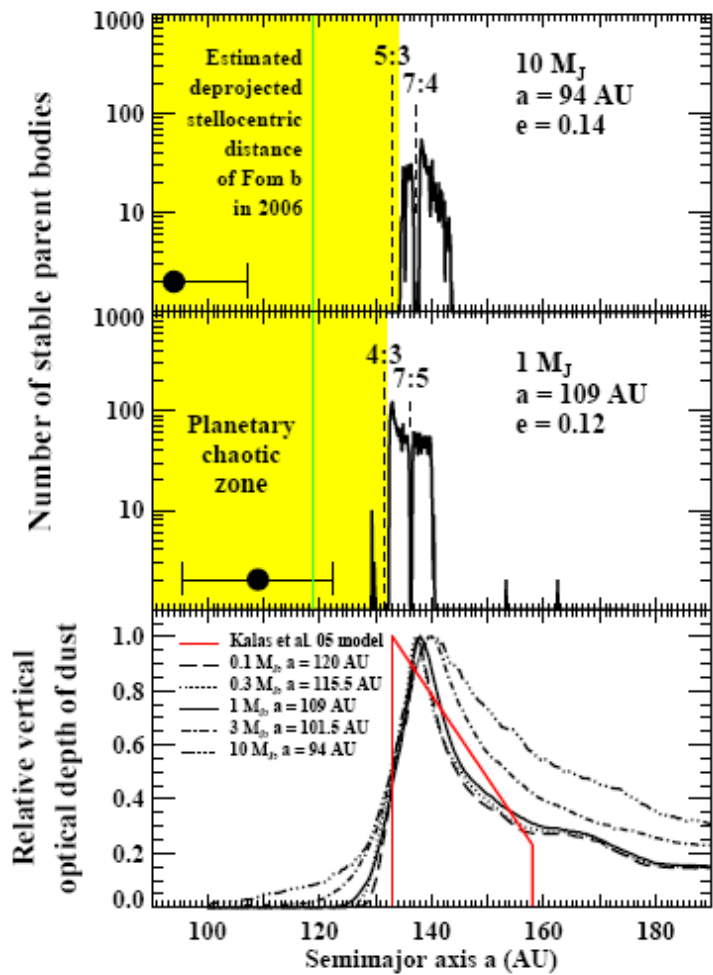
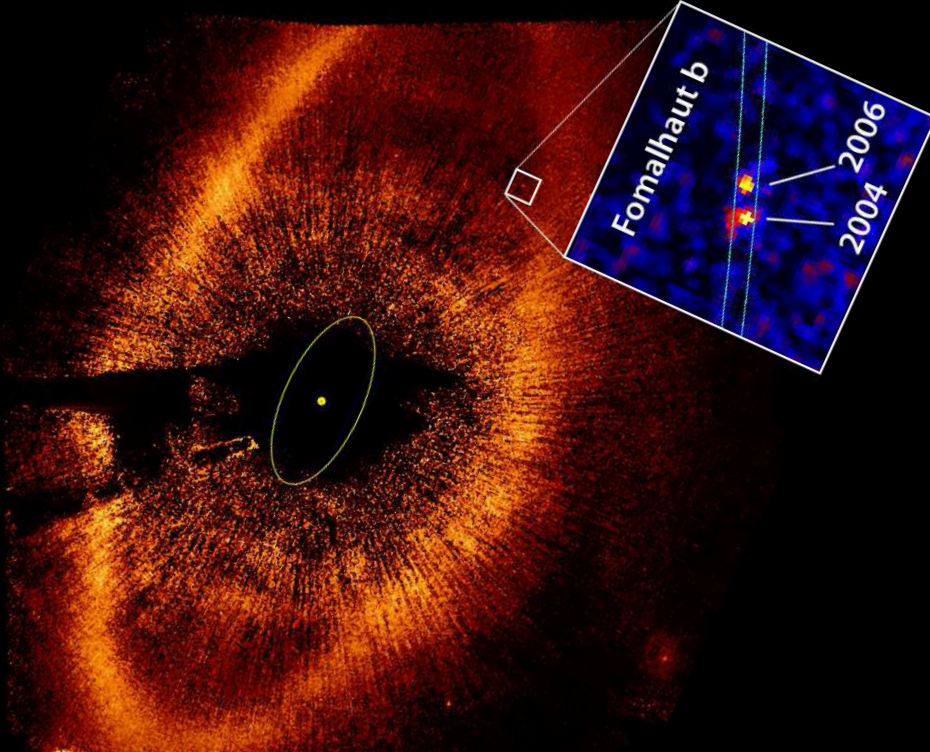
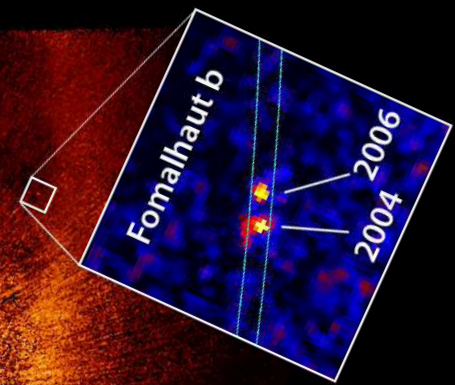
Direct Imaging of Planets Is Just Beginning

0.5"
20 AU

- Large telescopes with adaptive optics or space imaging (HST) allow direct imaging of hot young Jupiters



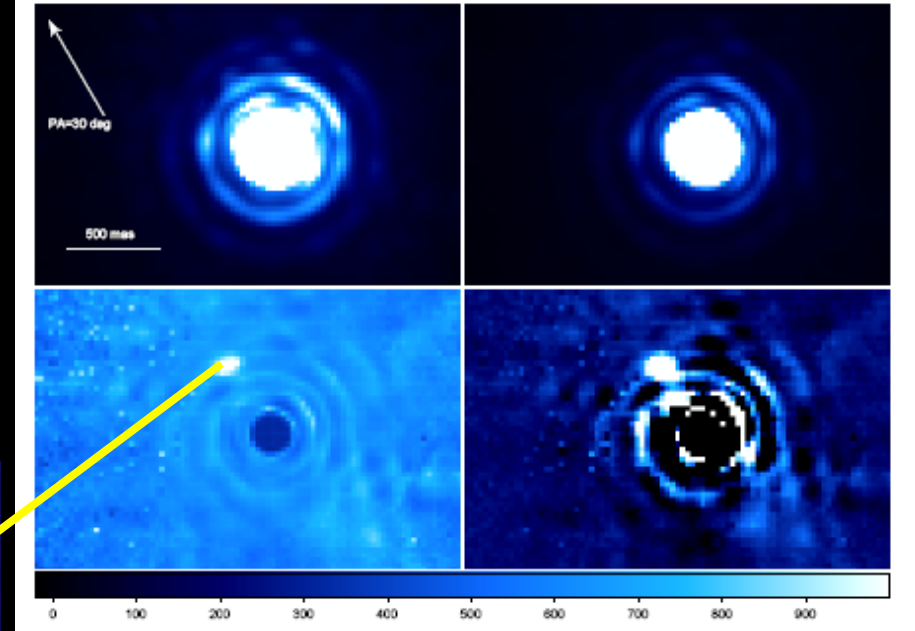
HST/Keck Finds Cause of Disk Offset



- Kalas et al (2009) directly detect Fomalhaut-b at 115 AU, $e \sim 0.13$
- Common Proper Motion and evidence of orbital motion (1.4 AU in 1.7 yr) $\rightarrow P = 872$ yr
- Quasi-dynamical mass: $M \leq 3 M_{Jup}$ to avoid disrupting/spreading disk

Another Planet Disk Interaction?

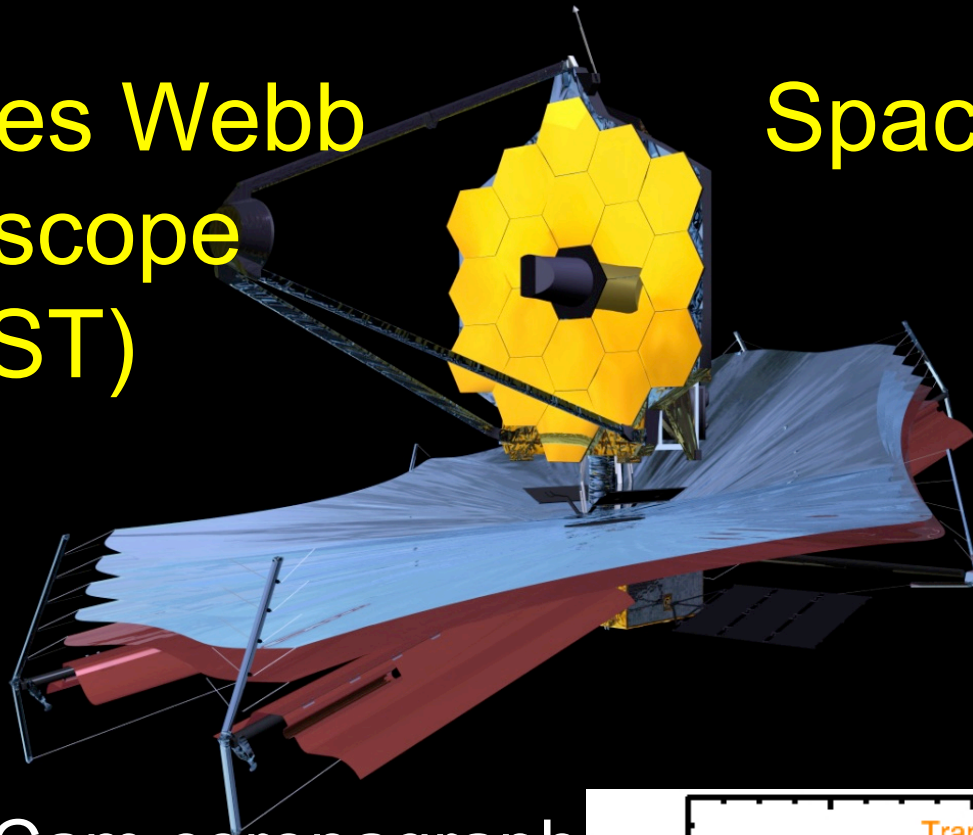
Lagrange et al 2009



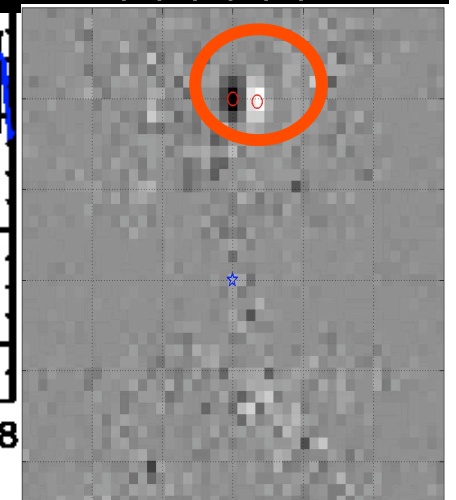
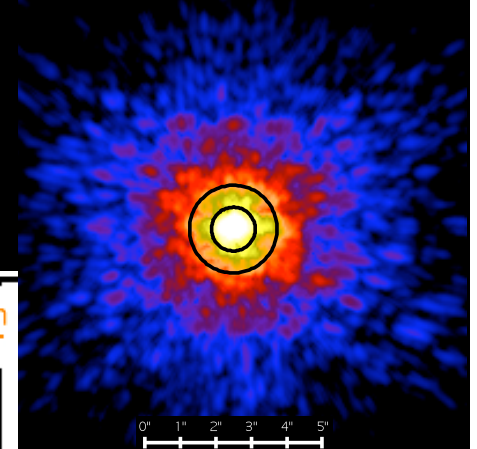
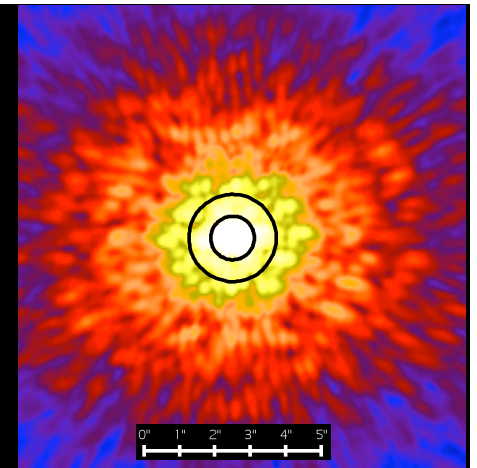
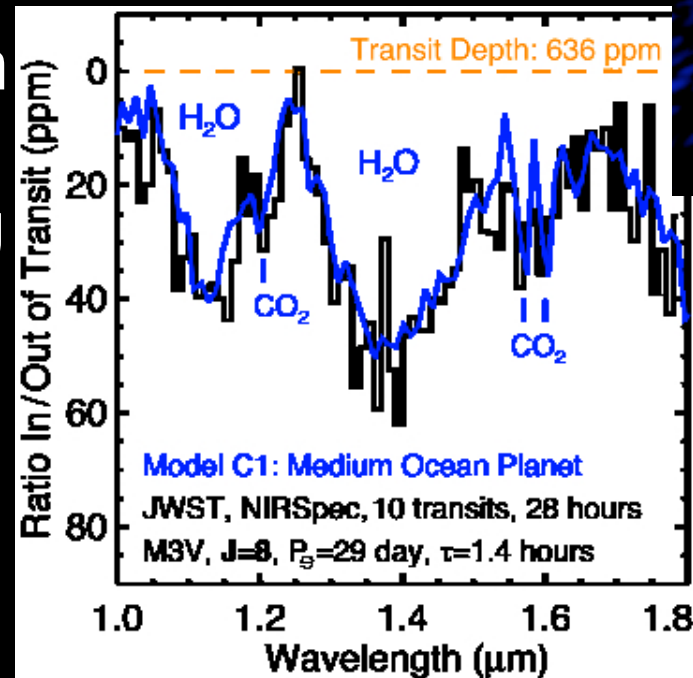
- Canonical IRAS disk with warp and multiple substructures
- Models predict planet 6-13 MJ at 10-8 AU (Mouillet 1997; Heap 2000)
- Deep L-band imaging reveals object 8 AU from β Pic, possibly 8 MJ planet

James Webb Telescope (JWST)

Space



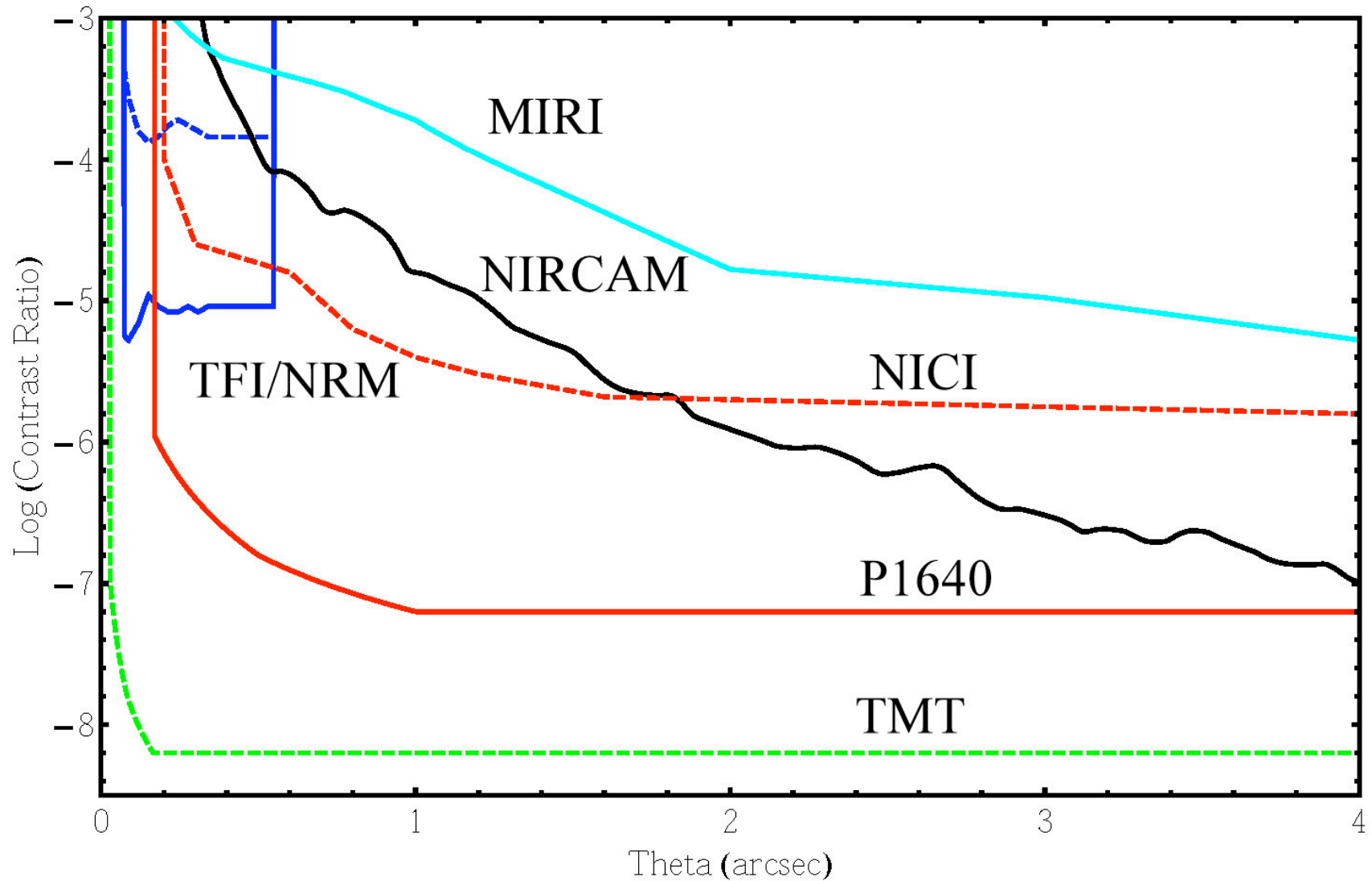
- NIRCам coronagraph & TFI Masking
 - M stars (<10 pc), young stars (50 pc), very young stars (140 pc).
- NIRCам, NIRSpec transits of Jupiters, Saturns and maybe Super Earths



Imaging Planets With JWST

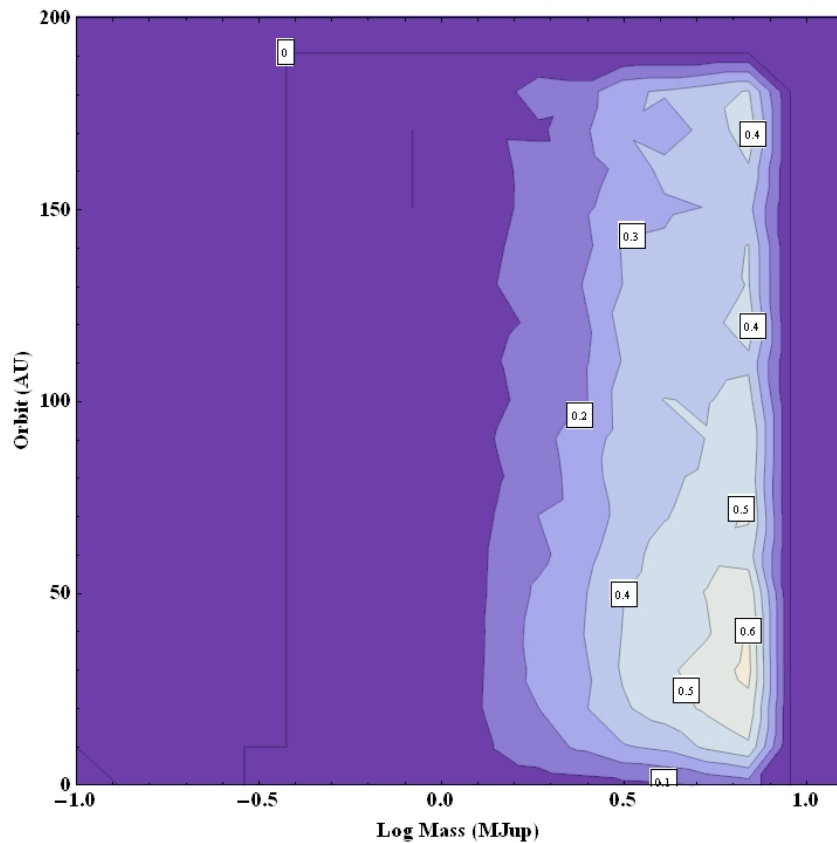
- Disadvantages
 - Poor wavefront accuracy (130 nm) cf Extreme AO on large ground-based telescopes (<50 nm)
 - Modest angular resolution cf 8-10-(30+) telescopes
 - NIRCam Lyot coronagraph has poor Inner Working Angle cf other JWST techniques (TFI/NRM, MIRI/FQPM)
- Advantages
 - High stability for many hours (few 10s of nm predicted), independent of need for bright targets for AO
 - High sensitivity where young gas giants are bright (3-5 μm)
 - Complete spectral coverage
- Search for planets orbiting faint young stars & nearest M stars

Advances in High Contrast Imaging

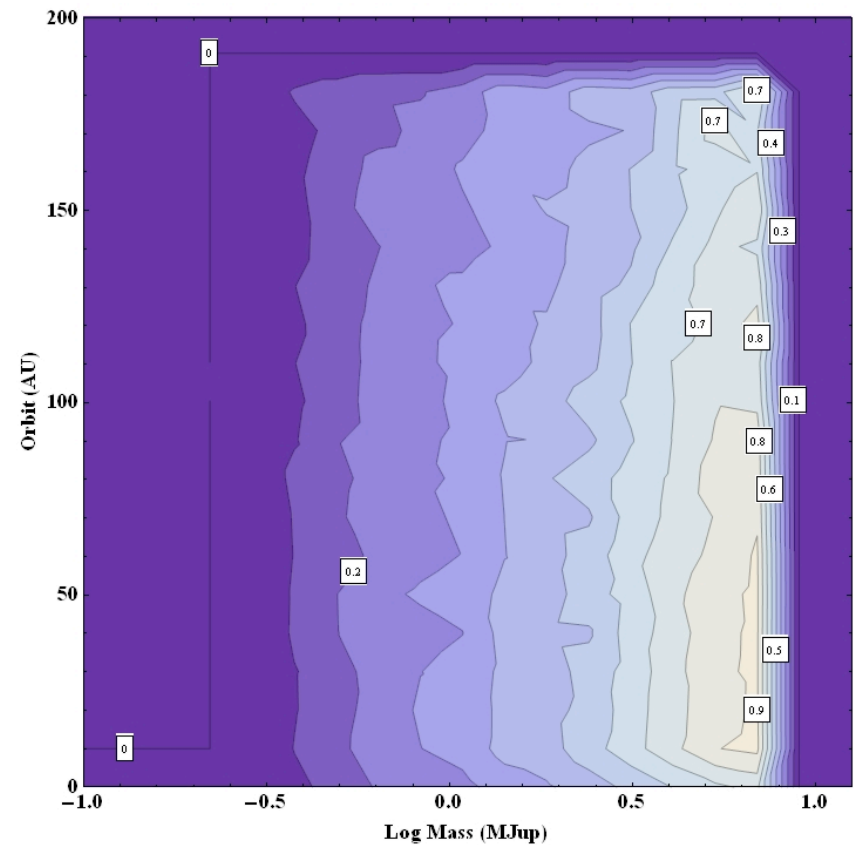


Ground Based Telescopes Probe Small Radii, Large Masses

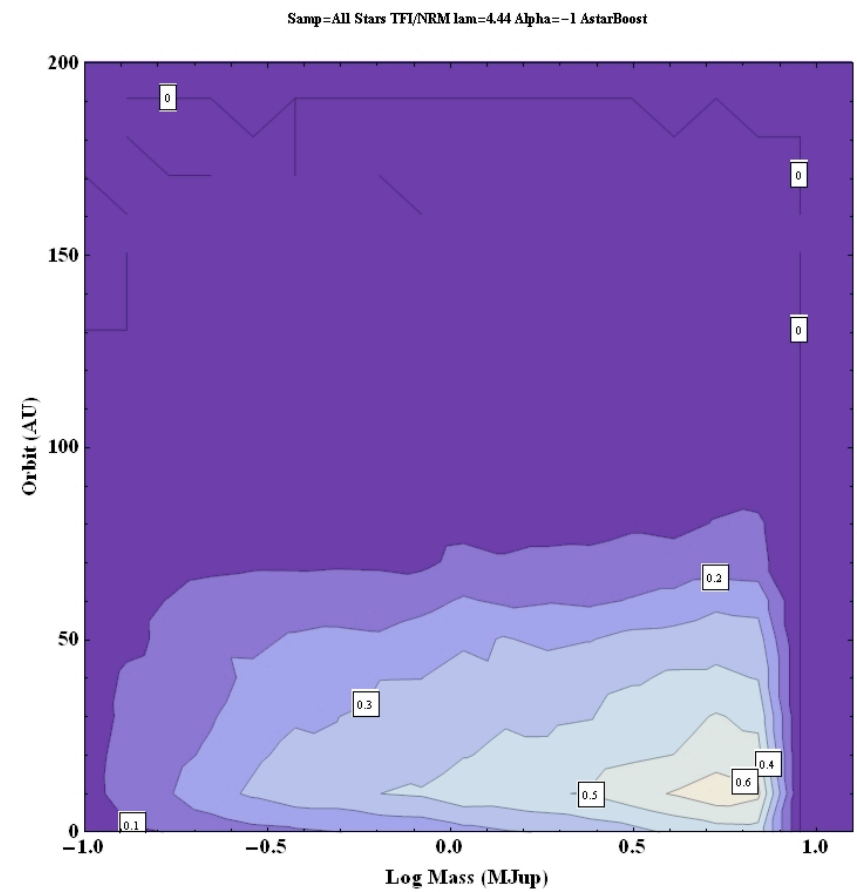
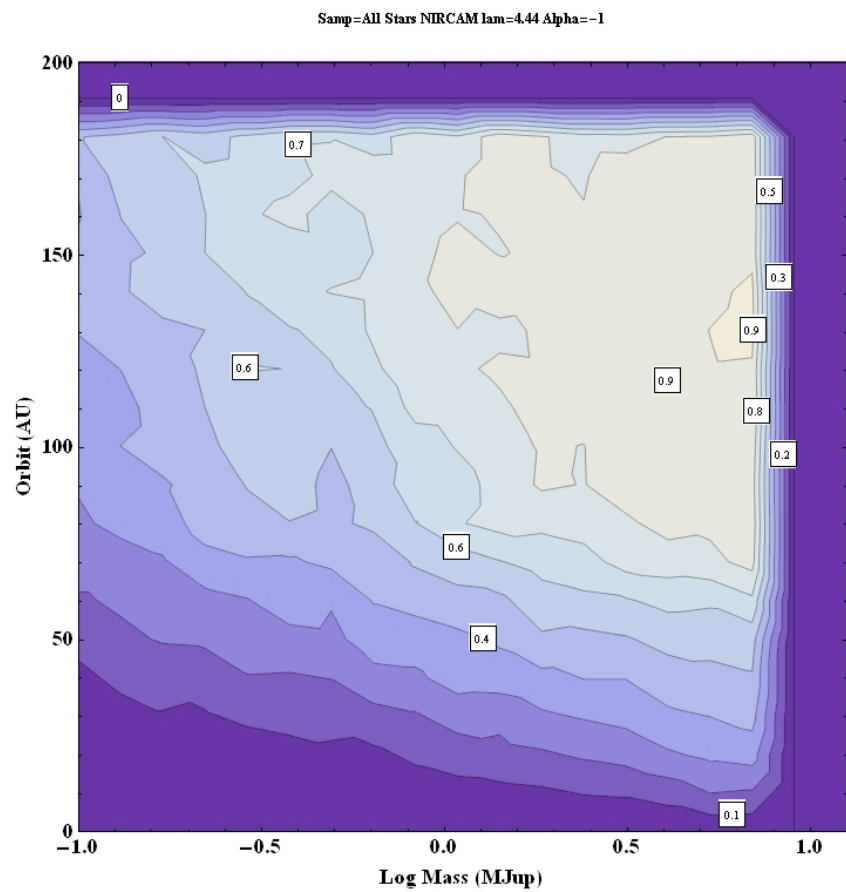
Samp=All Stars Pl640 lam=1.65 Alpha=-1 AstarBoost



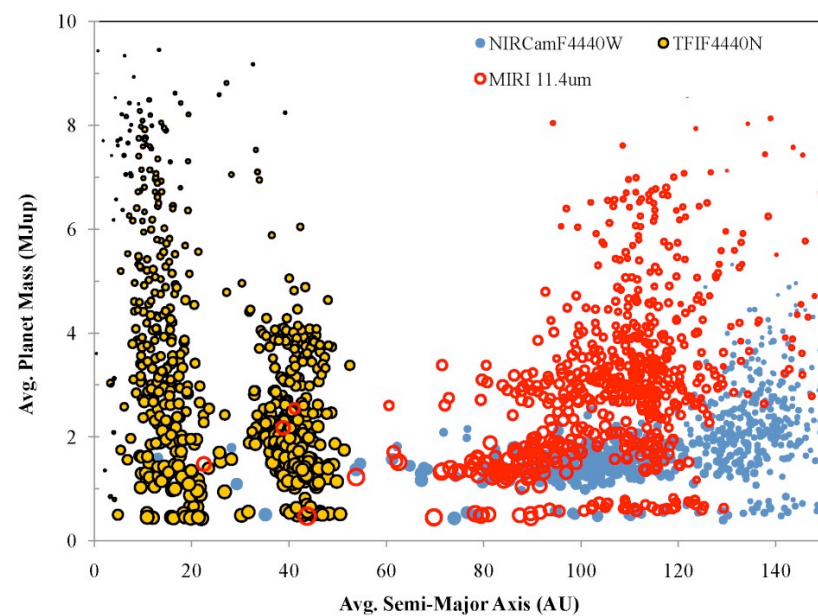
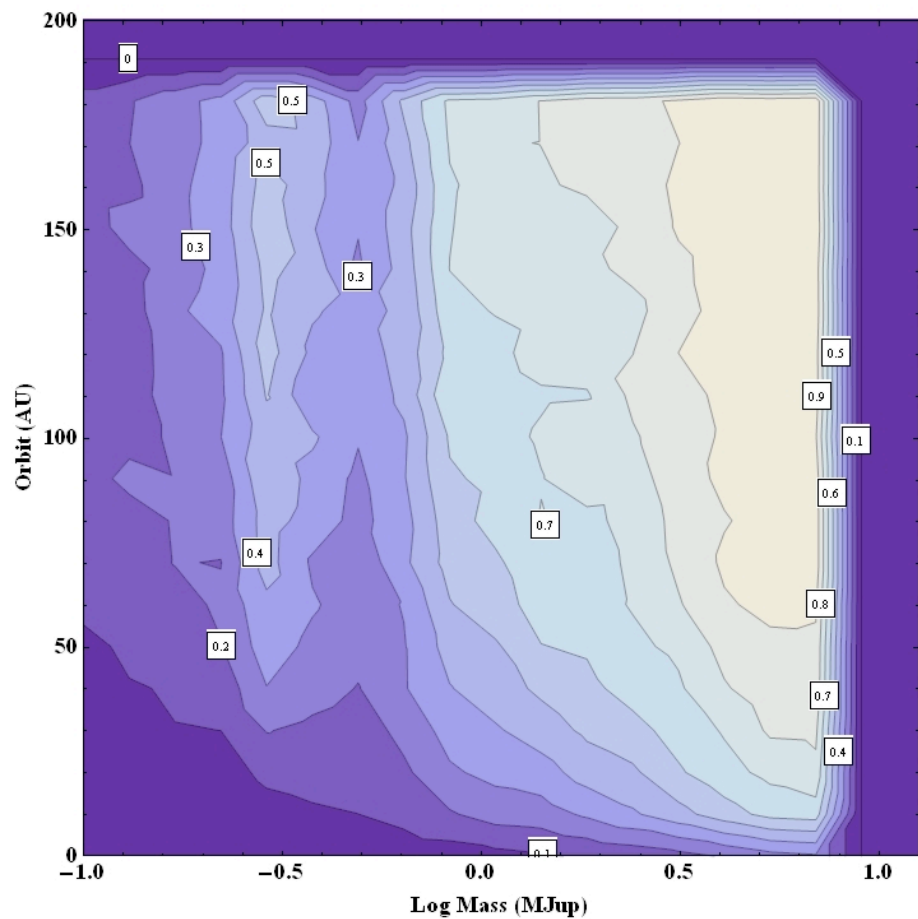
Samp=All Stars TMT lam=1.65 Alpha=-1 AstarBoost

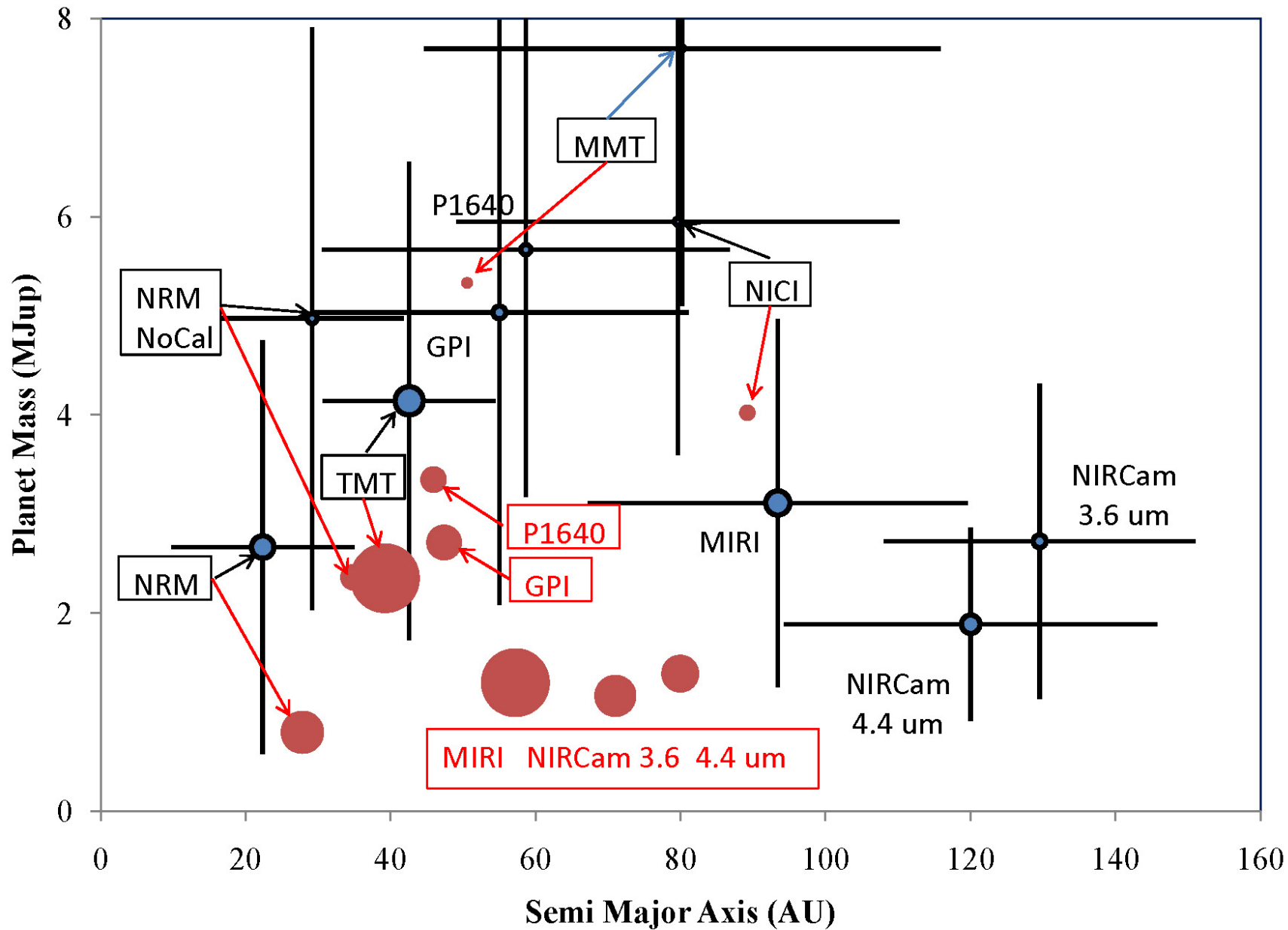


JWST Probes Lower Masses



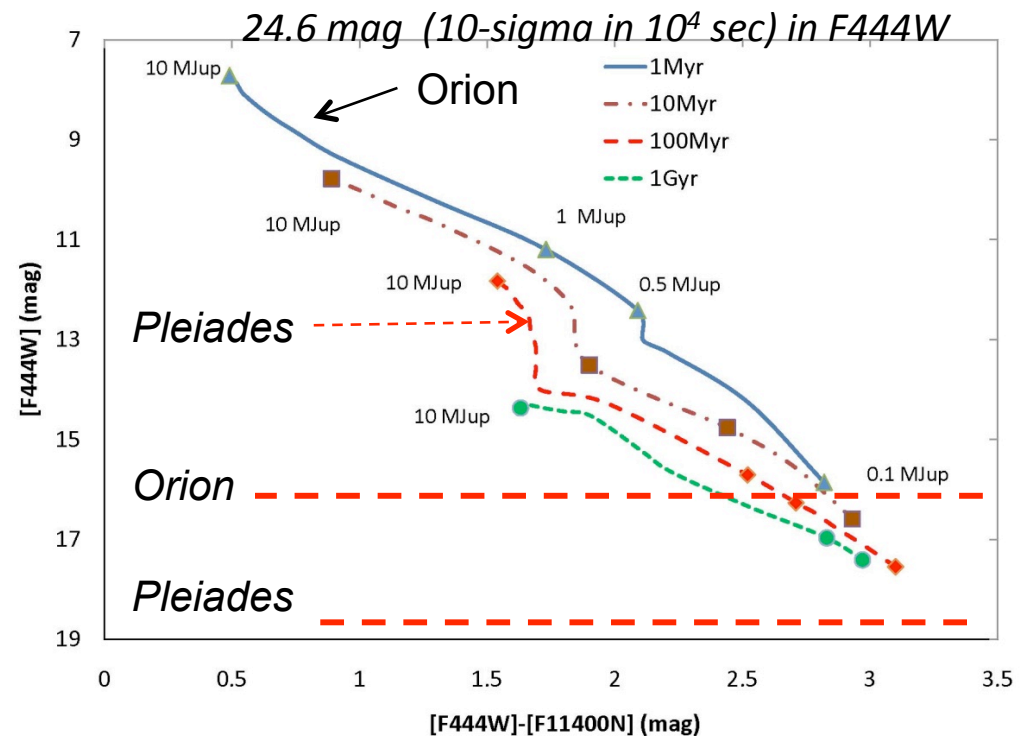
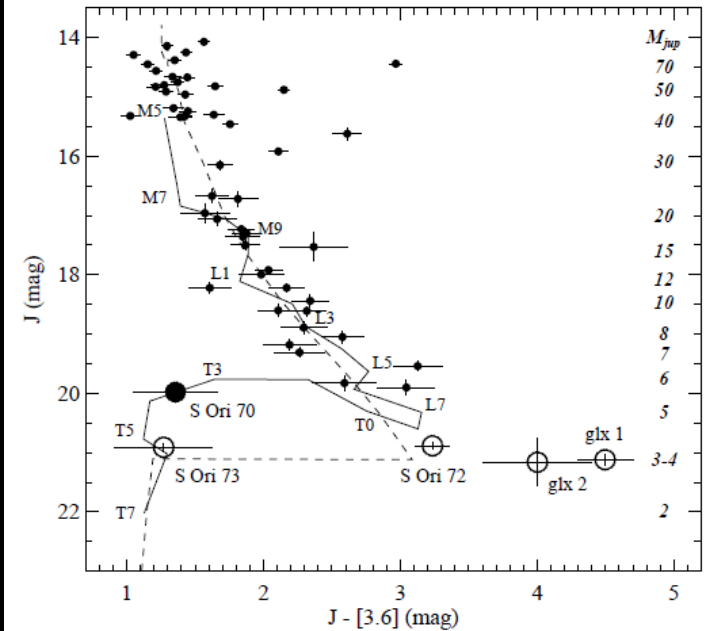
Sampl=All Stars MIRI lam=11.4 Alpha=-1 AstarBoost





Free Floating Planets

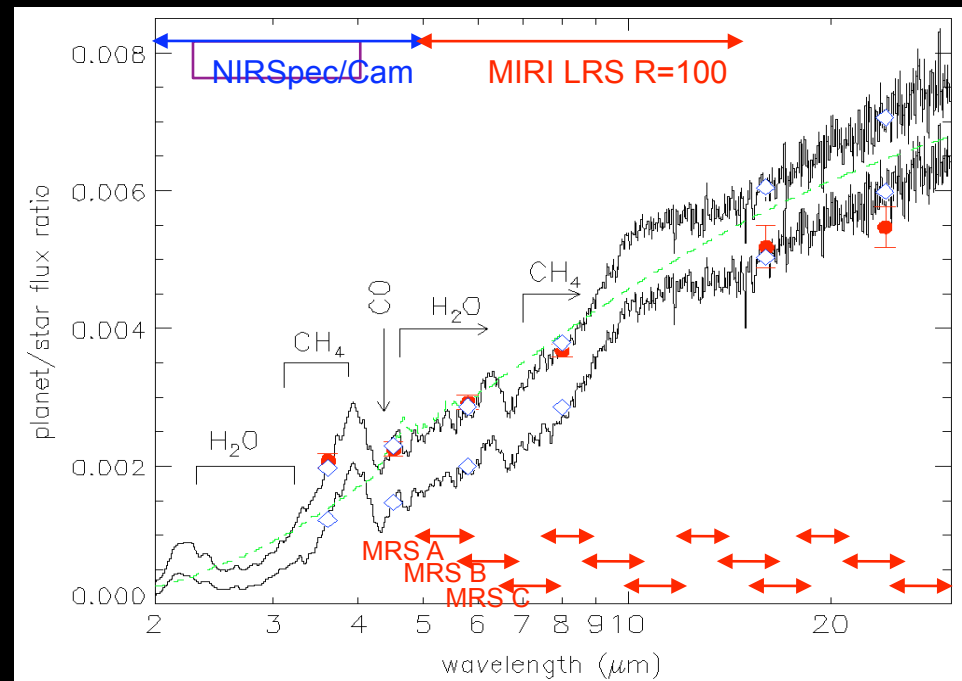
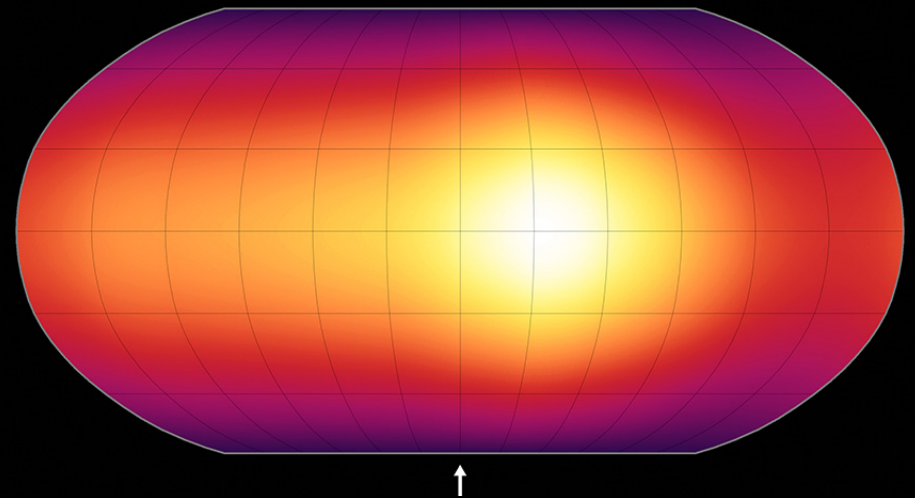
- Searches for young planets underway in near IR, e.g. σ Ori (Bihain et al 2009) identify candidates at $>2 M_{\text{Jup}}$
- Young planets in clusters from Orion (1-10 Myr, $\Delta\text{Mag} = 8.3 \text{ mag}$) to Pleiades (100 Myr, $\Delta\text{Mag} = 5.6 \text{ mag}$) detectable down to 1 (0.1) M_{Jup} .
- Planets bright at 3-5 μm
- Multi-filter mapping with NIRCAM & MIRI for candidate selection and science
- Multiple epochs separated for confirmation via proper motion (1 mas relative positions per image?)



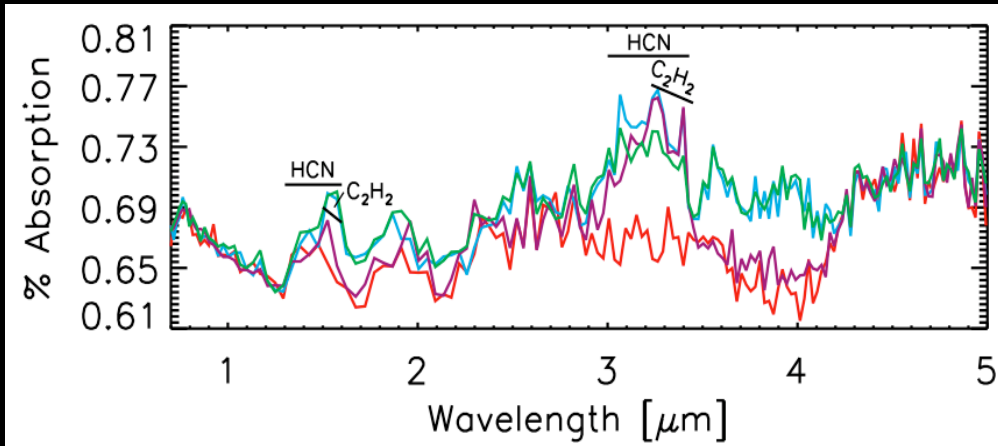
TRANSITING PLANETS

Transiting Planets

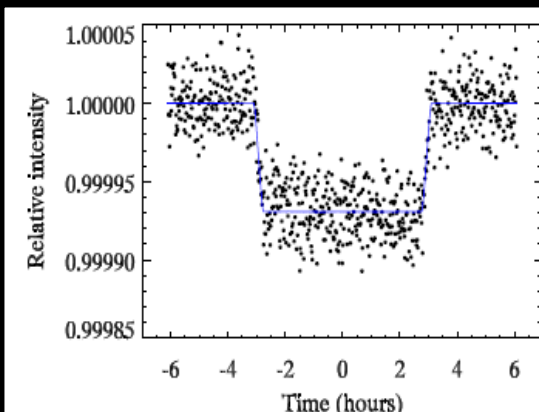
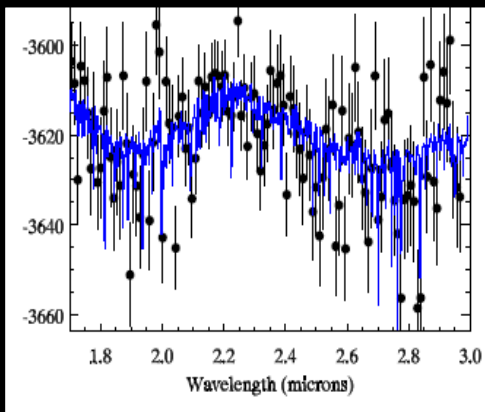
- NIRCams and MIRI photometry
 - Primary and secondary eclipses for albedo, T_{eff}
 - Complete light curves for Wx
- Spectra of gas giant planets: ice giants will take > 10 hr each
 - Determine abundances to learn about formation, understand differences between high / low density and high / low insolation planets
- 3-5 micron grism spectra combined with NIRSPEC prism and 5 – 12 micron MIRI LRS
- Best targets will be nearby bright stars, mostly *not* Kepler/CoRoT stars



JWST Observations Super Earths



Different photo-chemistries can be detected in these simulations of the spectra of the ice giant planet GJ 436b (21 M_{earth}) transiting its M2.5V host star.

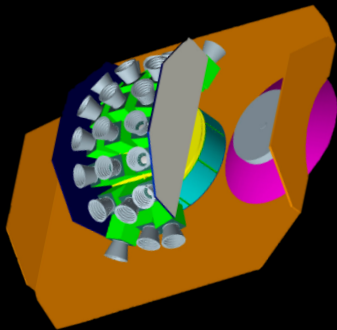


NIRSpec observations of water absorption in a habitable super-Earth ($T = 302\text{K}$ and $R = 1.8R_{\oplus}$) orbiting an M star at 20 pc; JWST/MIRI secondary eclipse photometry at 15 μm for a warm ($T = 500\text{K}$) exo-Neptune for a planet with $R = 4R_{\oplus}$ orbiting at 0.2 AU from a K2V star.

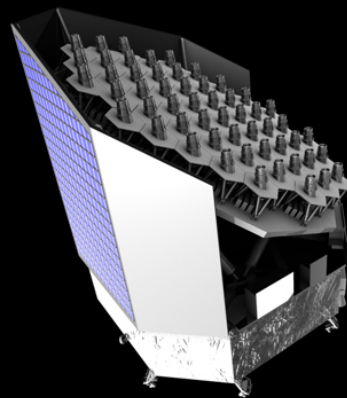
Habitable Earths remain out of reach even for JWST spectroscopy

Finding Transit Targets

- Kepler and CoRoT Targets too faint for significant spectroscopic followup
- Need all sky survey to find transits around brightest targets



ASTrO (L2)

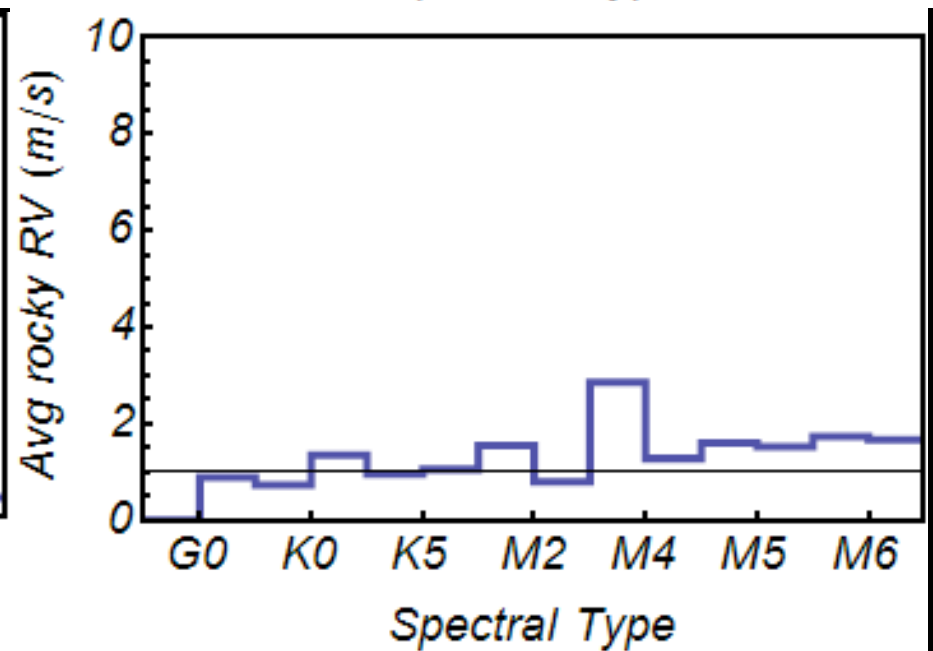
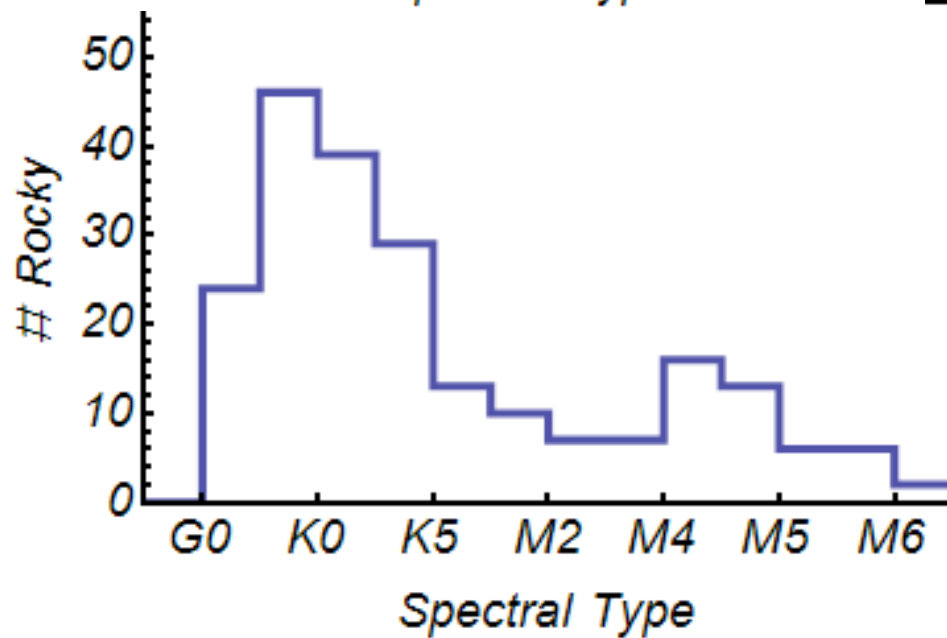
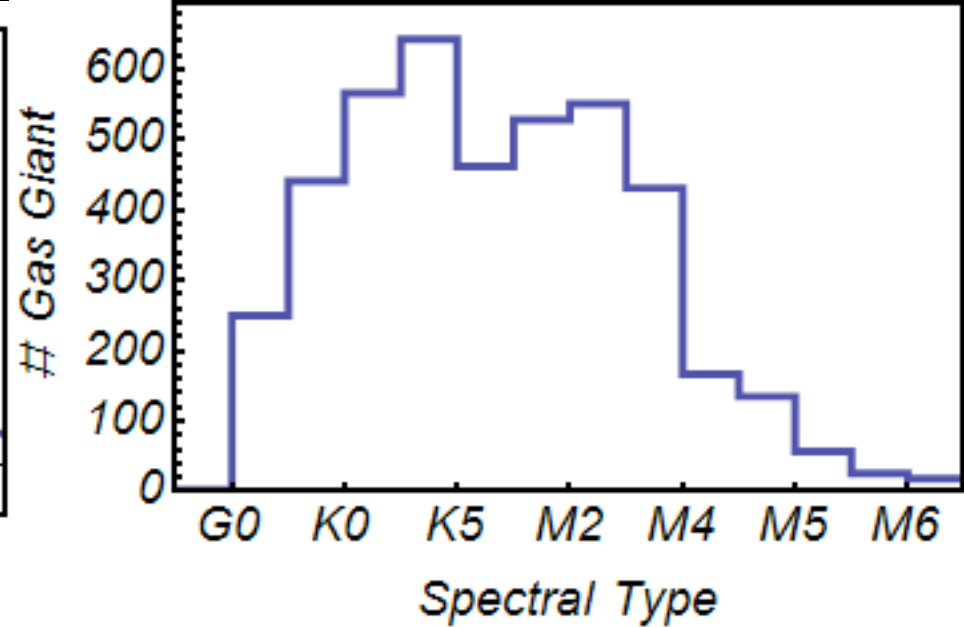
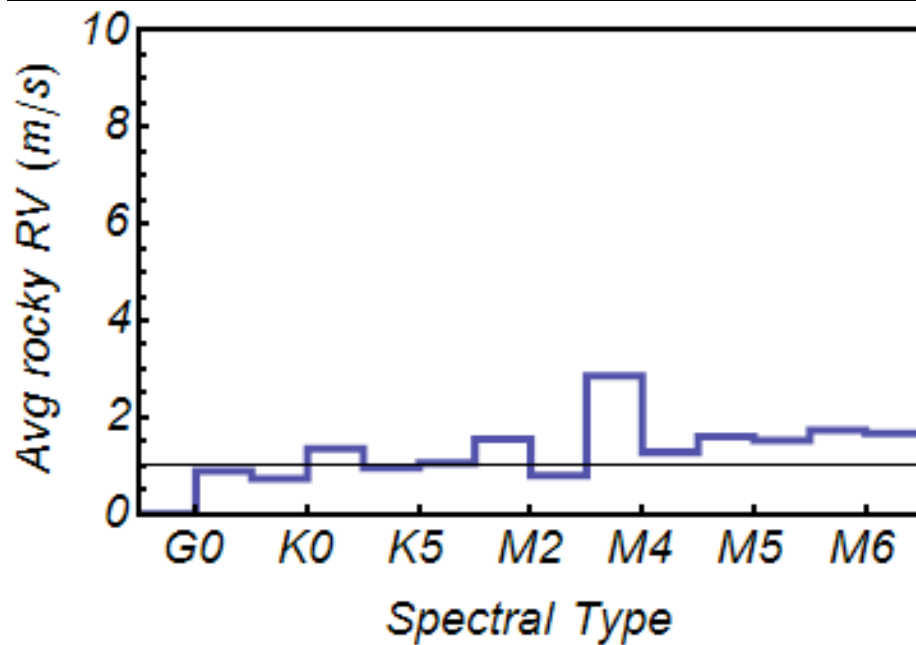


PLATO



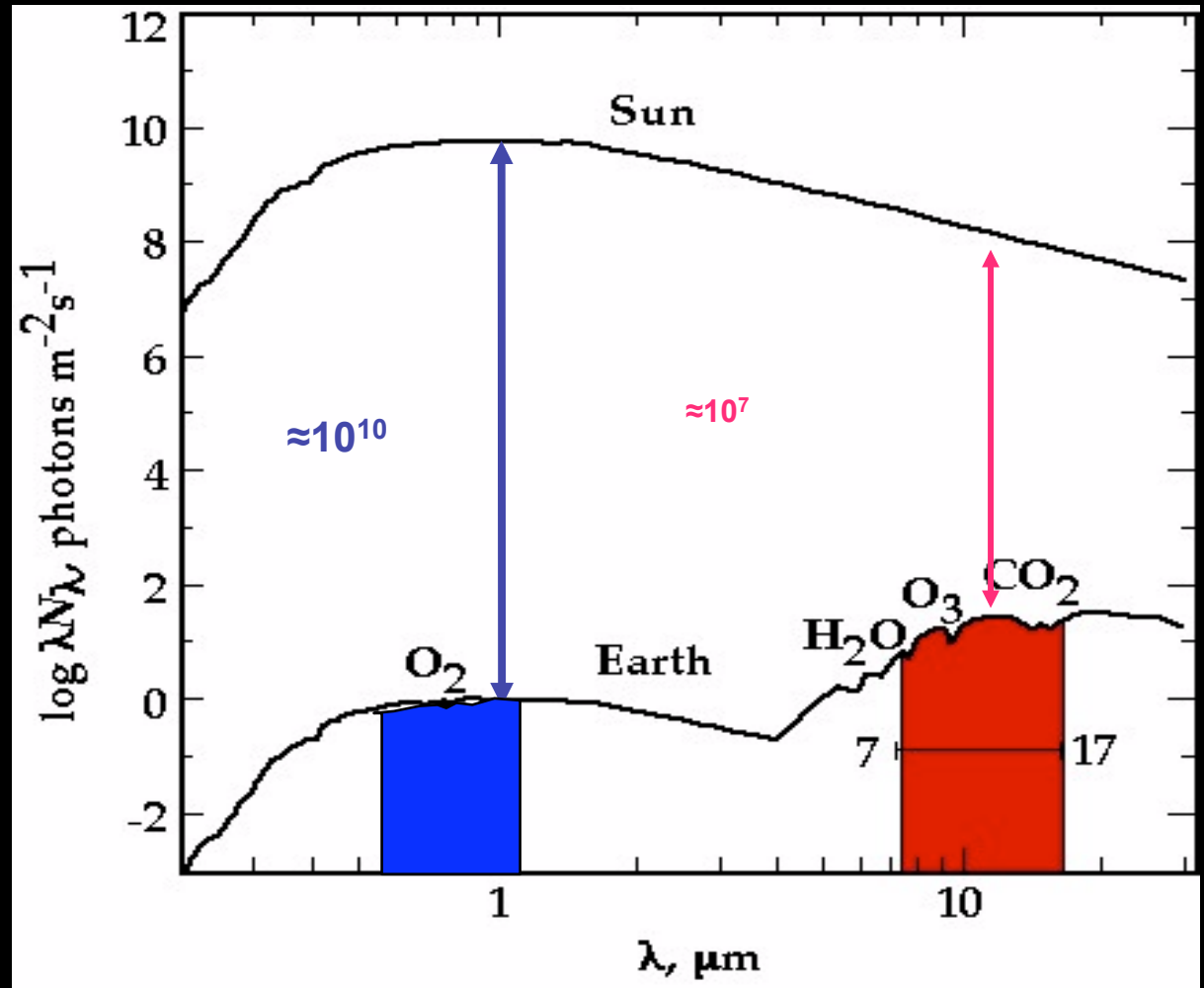
TESS

Planet Yield Of All Sky Near-IR Transit Survey



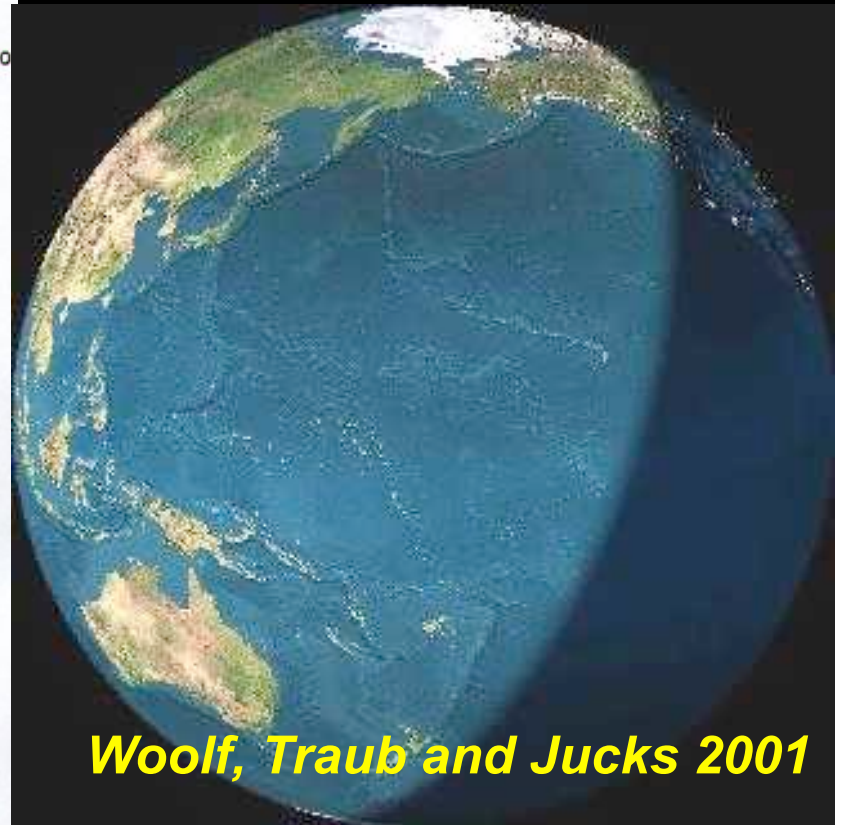
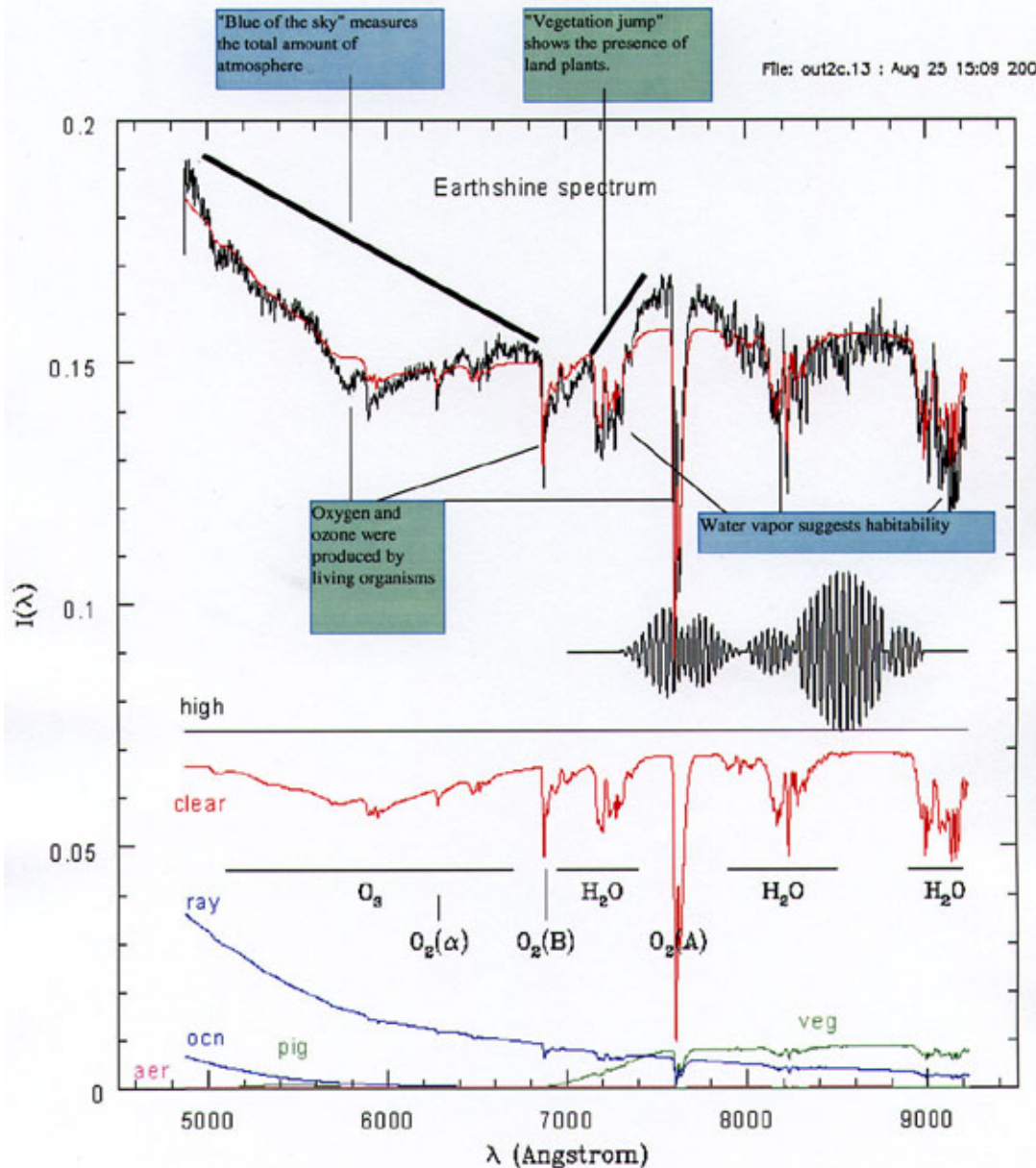
**THE CHALLENGE OF
FINDING LIFE**

The Long Term Challenge of Finding Life



- Contrast ratio of 10^{10} demands stability from space
- Angular resolution and sensitivity to see a habitable zone at 30 light years requires a 4-8 m telescope

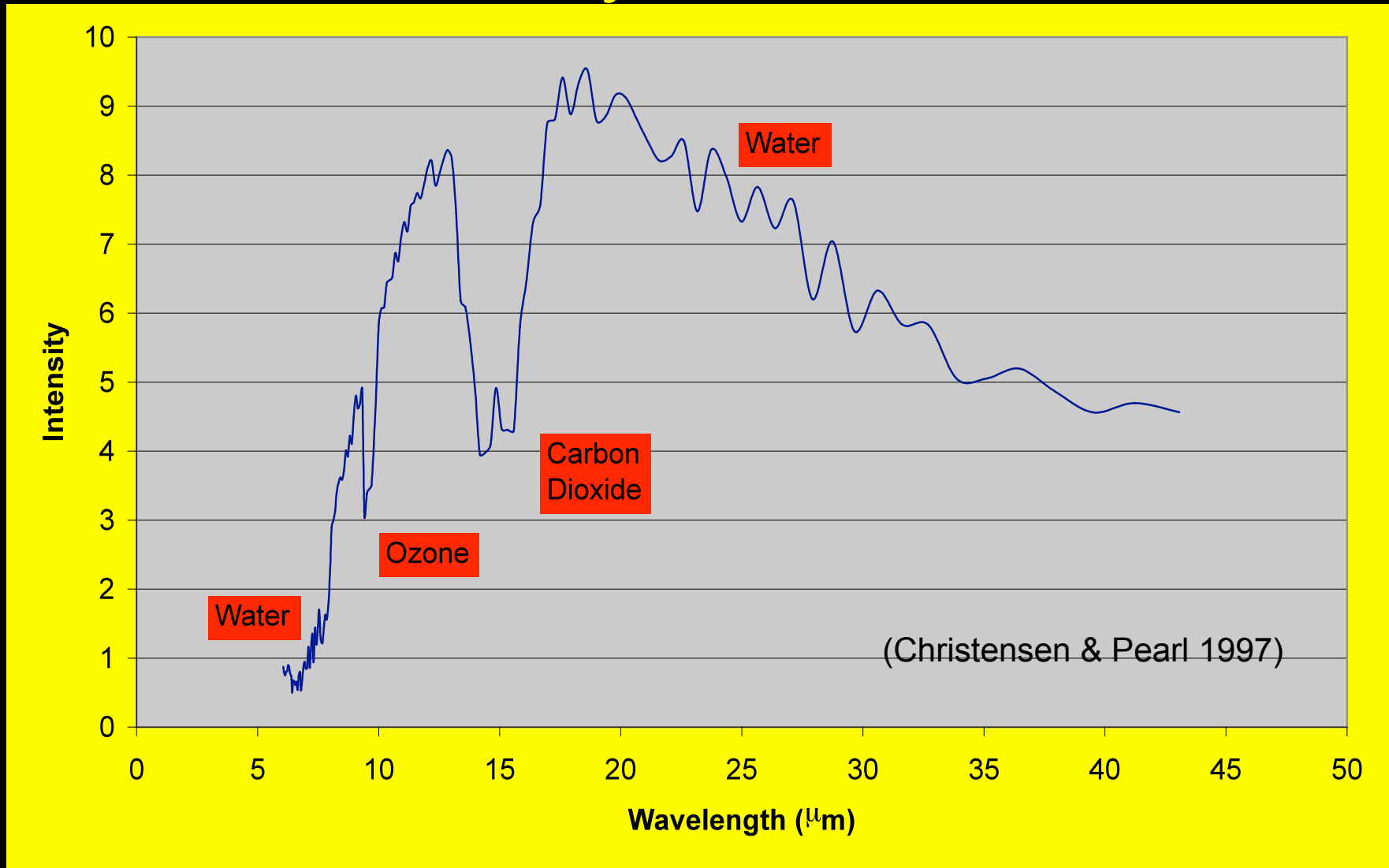
Biosignatures in the Earth's Visible Spectrum



Woolf, Traub and Jucks 2001

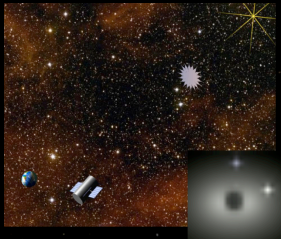
- O_2 (life) & water (habitability) are relatively easy to detect.
- Surface biosignatures such as chlorophyll may also be detectable.

Mars Global Surveyor Finds Life on Earth!

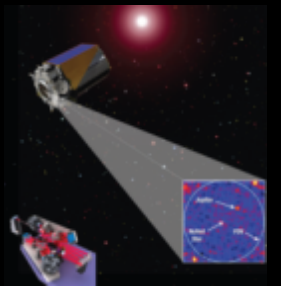


- CO_2 , O_3 , H_2O and CH_4 are dominant species in Earth's spectrum
- Astrobiology helps to define signatures

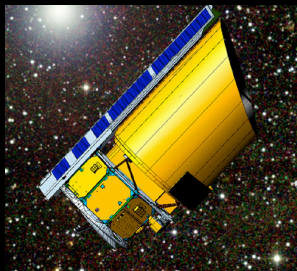
Exoplanet Future Mission Concepts



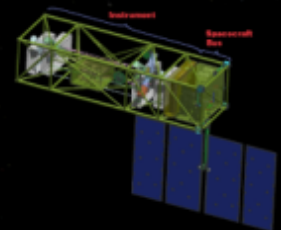
New Worlds Observer
(Cash)



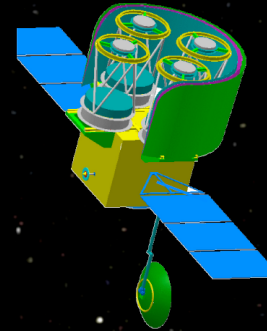
Extrasolar Planetary
Imaging Coronagraph
(Clampin)



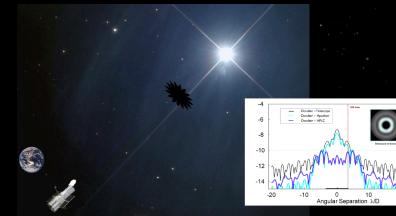
Pupil-Mapping
Exoplanet
Coronagraphic
Observer (Guyon)



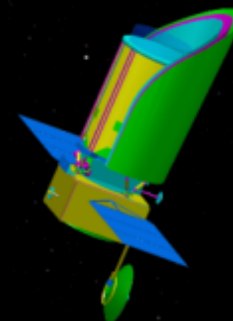
Planet Hunter
(Marcy)



Dilute Aperture
Visible Nulling
Coronagraph
Imager (Shao)

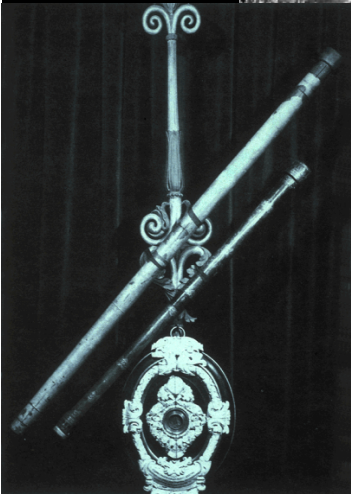
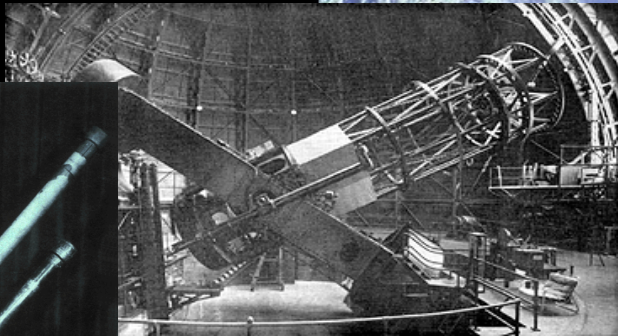
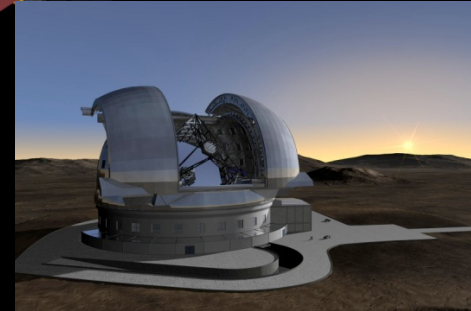
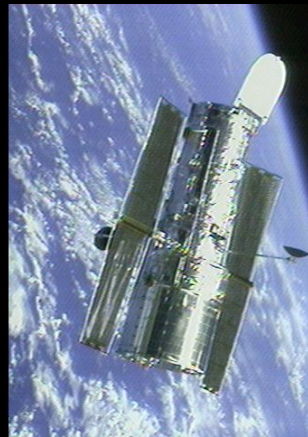
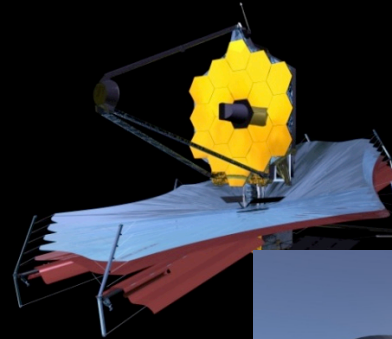
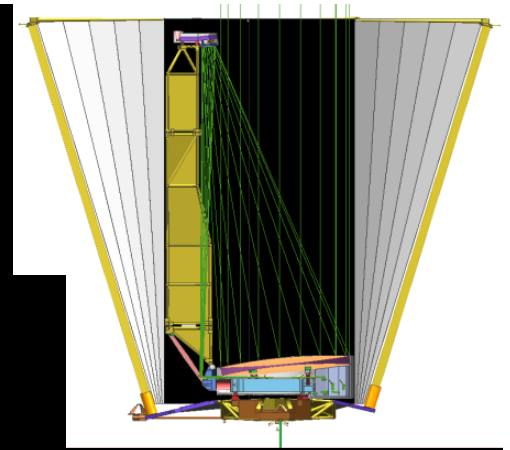


XPC – hybrid
coronagraph &
external
Occulter;
(Spergel)



Actively-
Corrected
Coronagraph for
Exoplanet
System Studies
(Trauger)

Planet Finding Will Be A Decades-Long Undertaking



Addressing
humanity's place
in the Universe

Where do we come from?
Are we alone?